DRIVING RESEARCH AND INNOVATION FOR
VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

U.S. DRIVE Fuels Working Group Engine and Vehicle Modeling Study to Support Life-Cycle Analysis of High-Octane Fuels

by
C. Scott Sluder, David E. Smith
Oak Ridge National Laboratory

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

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The U.S. DRIVE Fuels Working Group members contributed to this report in a variety of ways, ranging from work in multiple study areas to involvement on a specific topic, as well as drafting and reviewing proposed materials. Involvement in these activities should not be construed as endorsement or agreement with the assumptions, analysis, statements, and findings in the report. Any views and opinions expressed in the report are those of the authors and do not necessarily reflect those of Argonne National Laboratory, BP America, Chevron Corporation, ExxonMobil Corporation, FCA US LLC, Ford Motor Company, General Motors, Marathon Petroleum Corporation, the National Renewable Energy Laboratory, Oak Ridge National Laboratory, Phillips 66 Company, Shell Oil Products US, U.S. Council for Automotive Research LLC, or the U.S. Department of Energy.

Table of Contents

List of Figures

List of Tables

List of Acronyms

AKI	Anti-knock index
ANL	Argonne National Laboratory
ATDC	After Top Dead Center
AVFL	Advanced Vehicle/Fuel/Lubricants
BMEP	Brake Mean Effective Pressure
BOB	Blendstock for Oxygenate Blending
BRS	Bioreformate surrogate
CA50	Crank angle where 50% of fuel has burned
CAD	Crank Angle Degrees
CAFE	Corporate Average Fuel Economy
CFD	Computational Fluid Dynamics
CR	Compression Ratio
CRC	Coordinating Research Council
E10	Gasoline blend containing 10% ethanol by volume
E20	Gasoline blend containing 20% ethanol by volume
E30	Gasoline blend containing 30% ethanol by volume
ECU	Engine Control Unit
FWG	Fuels Working Group
GHG	Greenhouse Gas
HP	Horsepower
HWFET	Highway Fuel Economy Test
kPa	Kilopascals
LCA	Life Cycle Analysis
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
OS	Octane Sensitivity
RON	Research Octane Number
RPM	Revolutions per Minute
SUV	Sport Utility Vehicle
UDDS	Urban Dynamometer Driving Schedule

US06	US06 driving schedule
USCAR	United States Council for Automotive Research
USDOE	United States Department of Energy
WBG	Wood-derived Biogasoline

Preface

Fuels used in light-duty vehicle transportation have undergone a diversification in the United States over the past few decades. These fuels include liquid and gaseous fuels and electricity, which are derived from solid, liquid, gaseous, and renewable energy sources. The search for relevant and appropriate transportation fuels has been driven by economic, national security, and environmental concerns. Fuel economy improvements can lead to significant annual fuel cost savings for Americans,[1] and producing fuels from domestic resources has the potential to increase U.S. jobs, support rural economies, reduce tailpipe carbon dioxide (CO_2) emissions, and, by keeping energy financial resources in the United States, add to U.S. energy security and resiliency. The three reports U.S. DRIVE is publishing in 2019 on behalf of its Fuels Working Group (FWG) are focused on an assessment of the potential of a range of higher octane conventional and renewable fuels to enable increased light-duty vehicle efficiency and reduced well-to-wheels (WTW) greenhouse gas (GHG) emissions, and their potential impact on fueling infrastructure.

Liquid fuels continue to hold significant potential in light-duty vehicle transportation for several reasons: (1) liquid fuels have high energy density; (2) energy companies know how to make liquid fuels on the billion-gallon annual scale efficiently; (3) there exists a ready means to transport and dispense such fuels; and, (4) transitioning the market of vehicles to a new or modified fuel is simplified if it is a liquid. Auto manufacturers are interested in knowing in advance what fuels are likely to be developed and deployed successfully because it can take from 5 to over 10 years to design, develop, and bring to market. Additionally, considering the large current vehicle population and vehicle lifetimes of 15 to 20 years, these factors confirm that conventional engine technologies will continue to comprise a significant portion, if not the majority, of the nation's light-duty vehicle fleet for the next several decades.

Varying fuel composition to increase the octane rating of fuel for spark-ignition engines (e.g., gasoline) is widely recognized as a potential means to address economic, national security, and environmental concerns associated with transportation energy. Such fuels can enable higher fuel economy and achieve associated reductions in carbon emissions from vehicles. For example, blending with low-carbon biofuels, some of which have inherently high octane ratings, can increase the finished fuel octane ratings and reduce its environmental impact.[2] Producing fuels with elevated octane ratings through the modification of fuel composition, however, may have the unintended consequence of increasing energy use and associated emissions from fuel production, due, for example, to both the conversion of biomass to biofuels and/or the production of different base gasoline blend stocks.

U.S. DRIVE, a government-industry consortium that includes the U.S. Department of Energy, energy companies (including utilities), and auto manufacturers, works in 16 technical areas collaborating to find new solutions to pre-competitive research questions regarding new energy sources, efficiency, and emissions. In the arena of future fuels, U.S. DRIVE Partners' expressed an interest to learn more about potential new high-octane liquid fuels for conventional and hybrid vehicles. Energy companies are interested in ensuring customers have access to fuels with which to operate their vehicles, and auto manufacturers are interested in ensuring the public can purchase vehicles that meet both government

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[1] Greene, D., and J. Welch. 2017. The impact of increased fuel economy for light-duty vehicles on the distribution of income in the U.S.: A retrospective and prospective analysis. Knoxville, TN: Howard Baker Center for Public Policy. Online at http://bakercenter.utk.edu/white-paper-onthe-impact-of-increased-fuel-economy-for-light-duty-vehicles, accessed June 21, 2017.

[2] Han, J., et al. 2015. *Well-To-Wheels Greenhouse Gas Emissions Analysis of High Octane Fuels with Various Market Shares and Ethanol Blending Levels*, Report ANL/ESD-15/10. Argonne National Laboratory, Argonne, IL.

vehicle fuel economy requirements and customer desires. Therefore, U.S. DRIVE is interested in learning whether, if a vehicle and engine were designed as a system, a more optimal fuel that addresses economic, national security, and environmental concerns could be realized.

Toward these ends, U.S. DRIVE formed the FWG, to study fuel effects on combustion, and the FWG evaluated several fuel and engine combinations to determine if there are more optimal fuel/engine combinations that could be designed and deployed in the future. In the broadest perspective, the research compares various high-octane number fuels in the context of engine performance and their relative life-cycle carbon impacts, as well as potential impacts on fueling infrastructure and associated costs. The FWG specifically examined three areas: (1) how these fuels might function in conventional spark-ignition engines under a variety of operating conditions; (2) what the life-cycle impact on efficiency and environmental metrics, including GHG emissions, for such fuels might be; and (3) how these fuels fit within the existing U.S. fuel refinery and transport infrastructure.

With regard to the first area of research, the FWG built on an existing Coordinating Research Council (CRC) study, AVFL-20, that explored the potential vehicle energy use, volumetric fuel economy, and tailpipe CO_2 emissions effects of different research octane ratings (research octane number (RON)), octane sensitivity (OS), and ethanol content in gasoline.[3] Because there are potential non-ethanol biofuel pathways to increased octane that were not included in the scope of AVFL-20, the FWG set about to address these gaps by expanding on the AVFL-20 project to include fuels with non-ethanol bio-derived feedstocks.

In the second area of research, the FWG examined life-cycle impacts, specifically the changes in tailpipe CO_2 emissions in relation to changes in fossil CO_2 emissions from fuel production (both petroleum and renewable biofuels). The FWG understood that because production of gasoline with increased octane ratings together with production of renewable biofuels at the national scale may require additional energy input, it is important to consider this energy requirement in combination with potential energy savings enabled in the light-duty vehicle engines that automakers produce. Conducting a life-cycle analysis (LCA), or WTW assessment, for each of the potential pathways towards a high-octane fuel is an effective means of estimating the energy consumption and GHG emissions impacts for each pathway. Completing an LCA for each fuel blend examined in the engine studies report uses estimates of vehicle energy efficiency for typical driving patterns and potential energy production requirements for each fuel blend.

In the third area of research, the FWG identified other important considerations in assessing the potential of a fuel blend to a succeed in the marketplace. Specifically, the FWG is interested in understanding the compatibility of potential high-octane biofuel formulations with the existing refinery, transport, and fueling infrastructure. Developing a fuel that requires an entirely new fueling and fuel transport infrastructure is clearly an obstacle.

The following report addresses engine studies of the fuels examined, and while it stands alone for its method, results, and conclusions and so may be viewed individually, it is best read, considered, and understood in association with the companion reports, entitled *Well-to-Wheels Energy and Greenhouse*

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[3] Sluder, et al., Report # AVFL-20, Coordinating Research Council, November 2017. https://crcao.org/reports/recentstudies2017/AVFL-20/AVFL20_Final%20Report_11032017.pdf.

Gas Emission Analysis of Bio-Blended High-Octane Fuels for High-Efficiency Engines,[4] and *Potential Impacts of Increased Ethanol Blend-Level in Gasoline on Distribution and Retail Infrastructure*.[5] As such, this report is part of a larger coordinated effort on the part of the U.S. DRIVE Partnership.

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[4] Sun, P., Elgowainy, A., Wang, M. 2019. *Well-to-Wheels Energy and Greenhouse Gas Emission Analysis of Bio-Blended High-Octane Fuels for High-Efficiency Engines*. Prepared by Argonne National Laboratory, Argonne IL. https://www.energy.gov/eere/vehicles/downloads/us-drive-fuels-working-group-high-octane-reports.

[5] Monroe, R., Kass, M. and McConnell, S. 2019. *Potential Impacts of Increased Ethanol Blend-Level in Gasoline on Distribution and Retail Infrastructure*. Prepared by General Motors Company, Oak Ridge National Laboratory and Marathon Petroleum Company, https://www.energy.gov/eere/vehicles/downloads/us-drive-fuels-working-group-high-octane-reports.

Executive Summary

Efforts are underway globally to reduce the energy use and greenhouse gas footprint of transportation. In the United States, corporate average fuel economy (CAFE) standards describe the minimum fuel economy that must be attained by each vehicle manufacturer each year based on vehicle sales. Average tailpipe CO_2 emissions standards have additionally been established. These standards will require substantial improvements in fuel economy in the coming decade. As a result, automakers are examining many ways to provide greater fuel efficiency and lower greenhouse gas (GHG) emissions. Within this context, there is renewed interested in the potential benefits that may be realized through improving the anti-knock performance of gasoline blends in the marketplace.

Since production of gasoline with increased octane rating at the national scale may require additional energy input, it is important to consider this input in combination with potential energy savings enabled in the end-use vehicles produced by the automakers. Conducting a life-cycle analysis (LCA) for each of the potential pathways towards a high-octane fuel is an effective means of estimating the energy and greenhouse gas emissions impacts that each pathway may impose. A recent Coordinating Research Council (CRC) project, AVFL-20, explored the potential vehicle energy use, volumetric fuel economy, and tailpipe CO_2 emissions effects of different research octane number (RON) levels, octane sensitivity (OS), and volumetric ethanol content in gasoline [1]. However, assessment of the upstream energy use to produce these fuels was beyond the scope of the AVFL-20 project. Additionally, there are potentially non-ethanol biofuel pathways to increased octane that were not included in the scope of that project. The current U.S.DRIVE Fuels Working Group (FWG) study addresses these gaps by expanding on the AVFL-20 results to include non-ethanol bio-derived feed stocks and the completion of a life-cycle analysis (LCA) for each fuel blend. The LCA was led by Argonne National Laboratory and is reported in a separate publication. Studies at ORNL were funded by the U.S.DOE's Office of Vehicle Technologies, Fuels Technology Subprogram under the leadership of Kevin Stork.

The U.S.DRIVE Fuels Working Group (FWG) fuels matrix was developed to include non-ethanol biofuel formulations as well as ethanol at 20% volumetric blend level. Additionally, use of engine study results from fuels studied in CRC project AVFL-20 Phase 3 are included in the LCA analysis. The AVFL-20 project investigated the importance of RON, octane sensitivity (OS), and volumetric ethanol content on engine efficiency, vehicle fuel economy, and tailpipe CO_2 emissions. Fuels containing 10% ethanol (E10) and 30% ethanol (E30) were assessed for vehicle efficiency, while fuels containing 20% ethanol (E20) were only investigated at a screening level. The FWG matrix addresses additional fuel blends not included in AVFL-20 to enable a more complete study of the potential impacts of increasing octane ratings.

Engine studies were performed at Oak Ridge National Laboratory (ORNL) using a model year 2013 Ford EcoBoost 1.6-liter, 4-cylinder engine. This engine incorporates twin-independent cam phasing, center-mount direct fuel injection, and a single-stage turbocharger. In addition to the production 10.5 compression ratio (CR) pistons, pistons were machined by ORNL from blanks with a reduced bowl volume to increase the CR [1]. Pistons were produced with CRs of 11.4 and 13.2.

The nominal 97 RON fuels in the FWG fuel matrix were studied using the CR11.4 pistons. Experiments for the present study were conducted in accordance with methods used and previously reported for the AVFL-20 study. Engine fuel consumption maps were developed by collecting data at engine speeds of 1,000; 1,500; 2,000; 2,500; and 5,000 revolutions per minute (RPM), capturing the full range of engine torque output. Additionally, maximum torque points were collected at 3,000–4,500 RPM. Although studies with the 101 RON fuels in the FWG matrix were originally planned, these studies were discontinued because of performance issues with the CR13.2 pistons that were discovered during the AVFL-20 project plus an engine failure not related to the pistons that required an engine replacement [1].

Vehicle modeling allows the engine data gathered during this project to be used to estimate the energy consumption, volumetric fuel economy, and tailpipe CO_2 emissions from vehicles that might use engines with the different compression ratios and fuels studied in this project. This study adopted the vehicle models used for AVFL-20 to assure compatibility of results from the two projects. The Autonomie vehicle simulation software package was used to develop models for a mid-size sedan and a small sport utility vehicle (SUV) [1]. Autonomie 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 [2][3][4][5]. The drive cycles studied include the urban dynamometer driving schedule (UDDS), the highway fuel economy test (HWFET), and the US06 cycle. Results for the US06 cycle were divided into results for both the city and highway portions of the cycle.

Vehicle energy consumption over a drive cycle is a metric that provides insight into directional changes in engine efficiency afforded by different fuels and compression ratios. For the nominal 97 RON fuels studied at 11.4 CR, the results show that the range of improvements in energy consumption on a given cycle are between 0.4% to 2.3% for the sedan and 0.9% to 3.1% for the SUV, depending on the test cycle. The similarity in results is expected, given that the fuels had very similar RON and sensitivity, and were tested at constant CR. Volumetric fuel economy depends both on the vehicle energy consumption for a given cycle and on the volumetric heating value of the fuel. Differences among the volumetric fuel economy values for the non-ethanol fuels were small relative to the difference between these fuels and the E20 fuel, consistent with their volumetric heating values. These trends were observed for both the mid-size sedan and small SUV. Compared to the wood-derived biogasoline (WBG) fuel WBG4 (a nominal 97 RON fuel blend with 27% by volume wood-based biogasoline), the E20 fuel has about 7% poorer (lower) fuel economy on the UDDS and HWFET drive cycle for both the sedan and SUV and 4.7%–6.7% poorer (lower) fuel economy on the US06 drive cycles. Tailpipe CO_2 emissions for a given drive cycle depend on both the vehicle energy consumption for the cycle and the carbon intensity of the fuel. In this case, the carbon intensity is defined as the mass of tailpipe CO_2 emitted per unit fuel energy combusted (BTU) and should not be confused with the CO_2 required to produce the fuel. The E20 fuel provided the lowest overall tailpipe CO_2 emissions. The difference between maximum and minimum values of tailpipe CO_2 emissions among these fuels ranged from 2.0% to 3.7% for the sedan and from 2.3% to 4.3% for the SUV over the four cycles.

The engine and vehicle modeling study outlined previously was used in combination with other published results to establish energy consumption metrics that represent the light-duty U.S. fleet. While the engine used in this study may not have been fully optimized for higher compression ratio operation, a range of ON/CR values were included when estimating the vehicle efficiency to account for further optimization. Specifically, a value of 3.0 ON/CR was selected to represent an optimized engine. ON/CR values of 5.6 and 3.7 from the AVFL-20 and FWG studies were also included. The three values of ON/CR were used in combination with the measured RON values for the fuels in both the AVFL-20 Phase 3 and the FWG matrices to project the efficiency benefit of CR increase expected to be enabled by each fuel. The methodology detailed in a U.S. Council for Automotive Research (USCAR) study was used for this purpose [6]. The vehicle modeling conducted for both the AVFL-20 and FWG studies focused on the UDDS cycle, the HWFET cycle, and the US06 cycle. However, two additional cycles are used in calculation of the 5-cycle fuel economy value that is included on the window sticker of new vehicles. For the purposes of estimating the "on-road" fuel economy effects of fuel properties and compression ratio, the energy consumption values for the UDDS were used in place of those of the SC03 and cold CO tests in the 5-cycle weighting factor calculation. For the purpose of the LCA study, it was deemed beneficial to identify a single energy consumption metric that could approximate energy use of the entire light-duty fleet. The small-SUV results from the vehicle modeling study were selected to represent the entire light-duty fleet as an input to the LCA for each fuel. The total energy consumption for city and highway driving is calculated by summing the contributions of all of the cycles. An overall weighted average energy consumption is calculated by multiplying a 0.55 weighting factor by the city energy consumption and a 0.45 weighting factor by the highway energy consumption and adding the results. The same procedure was used with the energy consumption values for AVFL-20 fuel #10 at CR10.5 and the results for fuels #1 (4,068 BTU/mile) and #10 (4,110 BTU/mile) were averaged to provide a baseline energy consumption value of 4,089 BTU/mile to represent the light-duty fleet. The fuel-specific vehicle efficiency gains (including the downsizing factor of 1.1 for turbocharged engines) were used in combination with the fleet-average on-road energy consumption value to calculate fuel-specific fleet average energy use for each fuel.

All of the fuels provided a decrease in total energy consumption, ranging from 1.5%–6.0%. Impacts to volumetric fuel economy ranged from 6.6% poorer to 10.7% better. The difference in efficiency improvements projected for 3.0 ON/CR compared to 5.6 ON/CR ranged from 1.4%–1.8% depending upon the fuel. Most fuels were projected to provide a volumetric fuel economy increase (improvement) for at least one of the ON/CR values studied. Improvements (increases) in volumetric fuel economy ranged from 0.4%–10.7%. Most of the fuels were projected to provide a decrease (improvement) in total tailpipe CO_2 emissions for at least one of the ON/CR values studied. The ethanol-blended fuels provided the greatest reductions (improvements) in total tailpipe CO_2 emissions, ranging from 1.5%–6.9%. The ethanol-free blends were all projected to provide a decrease (improvement) in total tailpipe CO_2 emissions at the lowest ON/CR value, and all except WBG4 were projected to provide an improvement at 3.7 ON/CR. These improvements ranged from 0.1%–1.8%.

1. Introduction

Efforts are underway globally to reduce the energy use and greenhouse gas footprint of transportation. In the United States, corporate average fuel economy, or CAFE, standards describe the minimum fuel economy that must be attained by each vehicle manufacturer each year based on vehicle sales. Tailpipe CO_2 emissions standards have additionally been established as a part of vehicle emissions certification tests. These standards will require substantial improvements in fuel economy in the coming decade. As a result, automakers are examining many ways to provide greater fuel efficiency and lower greenhouse gas (GHG) emissions. Within this context, there is renewed interested in the potential benefits that may be realized through improving the anti-knock performance of gasoline blends in the marketplace.

Engine efficiency improves as the compression ratio (CR) of the engine increases [7]. However, increasing CR also causes increased likelihood of knock. Knock is the autoignition of a portion of the fuel-air mixture in the cylinder before the expanding flame front initiated by the spark plug reaches it. This premature combustion causes the pressure in the cylinder to increase rapidly, giving rise to an audible sound that became the name of the phenomenon: knock. The rapid rise in pressure can also cause engine degradation and failure if left unchecked. This issue is why automakers have for many years designed engines and engine control algorithms to prevent the occurrence of knock.

The linkage between fuel anti-knock performance and engine efficiency has been known since the early days of automotive engineering [8] [9] [10]. Increasing the anti-knock performance of a fuel is one of several ways to provide increases in engine efficiency. The anti-knock performance of a fuel is characterized by measurements of the research octane number (RON) and motor octane number (MON). In the United States, RON and MON are averaged to obtain the anti-knock index (AKI), which is posted on fuel dispensers and is used to differentiate between regular, mid, and premium gasoline grades in the United States. In recent years, research has shown that the mathematical difference between RON and MON, known as octane sensitivity (OS), is also an important characteristic of gasoline blends [11] [12] [13]. Recently, fuel heat-of-vaporization has also been investigated for its potential to impact the anti-knock performance of fuel blends, particularly those that include ethanol (having a considerably higher heat of vaporization than gasoline hydrocarbons) [14].

Historically, reliable high-volume production of a fuel with high anti-knock performance required additional processing of petroleum streams at refineries, or the use of lead-alkyl antiknock additives that have subsequently been abandoned due to toxicity and deleterious effects on emission controls. This increased processing requirement arose as fuel specifications became more demanding and because of variability in the makeup of crude oil from sources around the world. There are different approaches available for increasing the RON and MON of gasoline, depending upon refinery configuration and the crude oil sources being used by a given refinery. One pathway is blending of greater amounts of reformate, which is high in aromatic compounds. Another pathway is increased blending of alkylate, a blend stock that is rich in isoparaffins. Oxygenates (including ethanol, methyl tertiary butyl ether, and ethyl tertiary butyl ether) have also been used to improve octane ratings in finished gasoline blends [15]. Generally, additional processing at the refinery to produce sufficient volumes of high-octane blend stocks means that additional energy is invested, and additional CO_2 is generated in production of petroleum products, including gasoline.

Refinery operations and product mix are governed by the requirement to have uses for the entirety of the products produced, to produce products that meet the required specifications, and within those constraints, to maximize profit. During the oil crisis of the 1970s, the increased cost of production of gasoline with increased octane in sufficient volume to satisfy national demand was assessed to be greater than the savings captured by improving engine efficiency [16]. A similar analysis conducted in Europe led to the adoption of a higher-octane requirement (95 RON) [17]. More recently, the emergence of tight oil and gas as a significant resource in the U.S. petroleum supply has resulted in an increase in the cost of production of octane enhancers at the refinery [18]. This impact is at first counter-intuitive and highlights the complexity of refinery operations and the global petroleum marketplace. Incorporation of biologically-derived feedstocks in gasoline formulations potentially provides an additional means for improving gasoline anti-knock performance that may require less energy input (and therefore cost) and/or may enable efficiency improvements at the refinery through rebalancing of the product slate [19][20] [21]. Furthermore, powertrain trends since the 1970s such as engine downsizing, downspeeding, and higher compression ratio have resulted in more frequent knock-limited operation [22].

Since production of gasoline with increased octane rating at the national scale may require additional energy input, it is important to consider this input in combination with potential energy savings enabled in the end-use vehicles produced by the automakers. Conducting a life-cycle analysis (LCA) for each of the potential pathways towards a high-octane fuel is an effective means of estimating the energy and greenhouse gas (GHG) emissions impacts that each pathway may impose. Completing the LCA for each blend requires obtaining estimates of the vehicle energy efficiency for typical driving patterns as well as the potential production energy requirements for each of the candidate fuel blends [19] [23].

A recent Coordinating Research Council (CRC) project, AVFL-20, explored the potential vehicle energy use, volumetric fuel economy, and tailpipe CO_2 emissions effects of different RON levels, octane sensitivity (OS), and volumetric ethanol content in gasoline [1]. However, assessment of the upstream energy use to produce these fuels was beyond the scope of the AVFL-20 project. Additionally, there are potentially non-ethanol biofuel pathways to increased octane that were not included in the scope of that project. The current U.S.DRIVE Fuels Working Group (FWG) study addresses these gaps by expanding on the AVFL-20 results to include non-ethanol bio-derived feed stocks and the completion of an LCA for each fuel blend.

Conducting LCAs for each fuel addresses the important energy use and GHG aspects of potential new fuel blends, but there are also other important considerations in assessing the potential of a fuel blend to achieve substantial success in the marketplace. Compatibility of potential high-octane biofuel formulations with the existing infrastructure is one important consideration.

2. Fuel Matrix

The U.S.DRIVE FWG fuels matrix was developed to include non-ethanol biofuel formulations as well as ethanol at 20% volumetric blend level. Additionally, use of engine study results from fuels studied in CRC project AVFL-20 Phase 3 is planned in the LCA analysis. The AVFL-20 project investigated the importance RON, OS, and volumetric ethanol content on engine efficiency, vehicle fuel economy, and tailpipe CO_2 emissions. E10 and E30 fuels were assessed for vehicle efficiency, while E20 fuels were only investigated at a screening level. The FWG matrix addresses additional fuel blends not included in AVFL-20 to enable a more complete study of the potential impacts of increasing octane ratings.

2.1 FWG Fuel Matrix

The fuels formulated for the FWG fuel matrix included two blends containing a wood-derived biogasoline (WBG), four fuels blended using a surrogate for bioreformate, and two fuels containing 20% ethanol (Figure 2-1). The bioreformate surrogate was produced from petroleum-based reformate that was further processed to be similar to anticipated high-octane bioreformate compositions [24]. The compounds present in the neat bioreformate surrogate blendstock at concentrations greater than 0.5 wt% are shown in Figure 2-2 and consist of aromatic hydrocarbons.

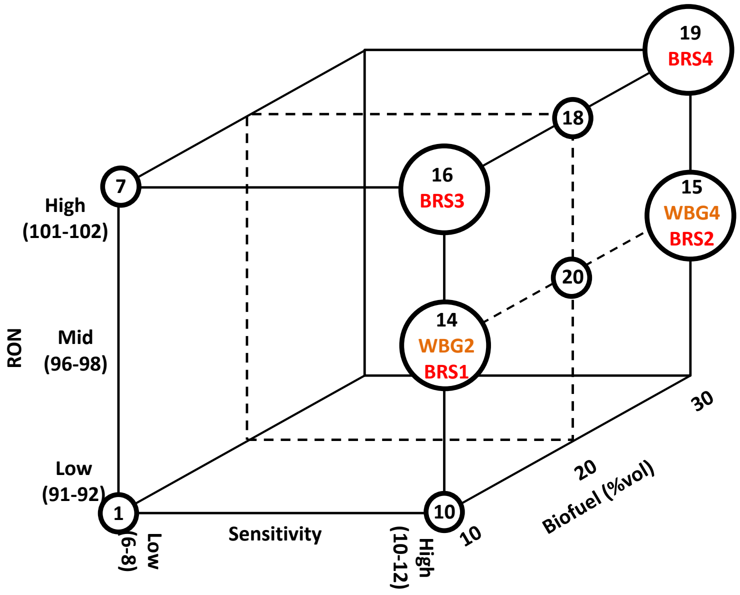


Figure 2-1. Graphical layout of the study fuels. Black text indicates an ethanol blend, orange text indicates a wood-derived biogasoline blend, and red text indicates a bioreformate surrogate blend. Wood-derived biogasoline and bioreformate surrogate blends were produced at 9 and 27 volume percent, while ethanol blends were produced at 10, 20, and 30 volume percent.

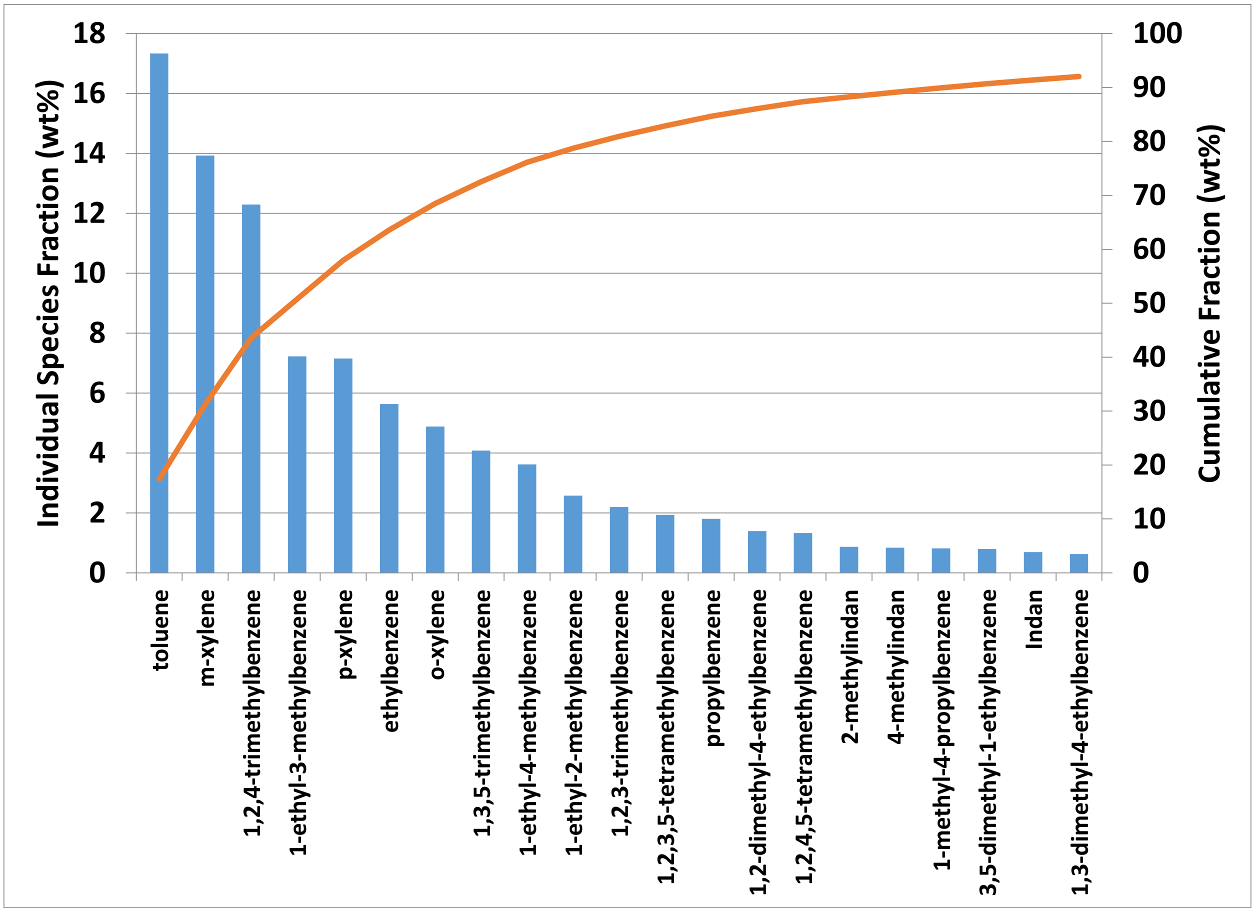


Figure 2-2. Compositional analysis of bioreformate surrogate blendstock.

Phillips 66 provided the WBG blend, which was produced in a prior USDOE project [25]. The WBG, which had 85 vol% renewable content, was used to produce the fuels used in this project that had lower renewable content. The bioreformate surrogate (BRS) fuels and the WBG fuels were formulated to contain 9% and 27% bio-derived content by volume to approximate the renewable energy contributions of the ethanol in the E10 and E30 blends for the AVFL-20 fuels. The 20% ethanol (E20) fuels were added to the FWG test matrix because the AVFL-20 Phase 3 results contained 10% (E10) and 30% (E30) blends but no intermediate blend levels. Table 2.1 shows the fuels formulated for the FWG fuel matrix. As was the case for the AVFL-20 fuels, analyses were obtained for the petroleum-derived portions of these fuels to facilitate refinery modeling activities. The results of these analyses are contained in Appendix 2. Examination of the ASTM D6729 detailed hydrocarbon analysis for each fuel was used to qualitatively assess the biologically-derived compound content of the fuels. This examination confirmed that the finished fuels contained approximately the target amount of biologically derived compounds.

Table 2-1. RON, MON, and nominal biologically-derived compound content for the FWG matrix fuels.

FWG Fuel	RON	MON	Sensitivity	Biofuel Content (Vol%)	Volumetric Heating Value (BTU/Gallon)	CO_2 Intensity (mg CO_2/BTU)
#18	101.0	89.0	12.0	20.1	108,358	76.955
#20	97.3	86.6	10.7	20.1	108,736	77.011
BRS1	97.6	87.2	10.4	9.0	116,602	77.660
BRS2	97.3	87.0	10.3	27.0	116,652	78.118
BRS3	101.1	90.0	11.1	9.0	117,738	79.065
BRS4	101.0	90.3	10.7	27.0	118,278	78.570
WBG2	97.7	87.5	10.2	9.0	116,607	78.191
WBG4	97.3	87.1	10.2	27.0	116,663	78.470

2.2 CRC AVFL-20 Fuels

The CRC AVFL-20 project produced engine fuel consumption maps using fuels with varied RON, octane sensitivity, and ethanol content [1]. The characteristics of the AVFL-20 Phase 3 fuels are listed in Table 2.2. Engine fuel consumption maps were produced for six fuels. Similar maps were anticipated using fuels with ~101 RON, but the nominally CR13:1 pistons intended for use with these fuels did not provide acceptable combustion performance. In addition, engine failure—unrelated to the pistons—occurred during the studies with these pistons that required engine replacement. Hence, the engine mapping and vehicle modeling activities planned for the 101 RON fuels were discontinued. Additional details for the AVFL-20 fuels are available in the project final report [1]. The U.S.DRIVE FWG LCA study required information about the characteristics of the petroleum portion of the fuels prior to ethanol blending in order to support refinery modeling efforts. The petroleum portion of an ethanol-blended fuel is often referred to as a blendstock for oxygenate blending (BOB), reflecting the fact that the petroleum portion typically does not meet all of the required properties for a finished fuel, but is designed to meet all of the required properties once a predetermined amount of ethanol or other oxygenate is added to it to create the finished fuel. Small volumes of the BOBs for the AVFL-20 fuels were purchased and analyzed to provide the information needed for refinery modeling efforts, including RON, MON, volatility-related properties, and hydrocarbon composition. The results of these analyses are included in Appendix 1.

Table 2-2. AVFL-20 Phase 3 fuel properties.

AVFL-20 Fuel	RON	MON	Sensitivity	Ethanol Content (Vol%)	Volumetric Heating Value (BTU/Gallon)	CO_2 Intensity (mg CO_2/BTU)
1	91.8	84.5	7.3	10.4	110,840	75.582
6	96.0	88.5	7.5	30.0	101,917	74.657
7	100.1	92.5	7.6	10.1	108,373	73.913
10	91.4	81.0	10.4	10.0	113,131	77.137
14	96.6	85.5	11.1	10.4	112,486	76.621
15	96.5	84.9	11.6	30.4	103,097	76.503
16	101.1	89.3	11.8	10.2	112,572	76.791
19	101.0	89.0	12.0	29.9	101,966	75.647

3. Engine Studies

3.1 Engine Hardware and Laboratory Facilities

The hardware and laboratory facilities used to support this work have been reported in detail previously, but are discussed here briefly [1] [26]. Engine studies were performed at Oak Ridge National Laboratory (ORNL) using a model year 2013 Ford EcoBoost 1.6-liter, 4-cylinder engine. This engine incorporates twin-independent cam phasing, center-mount direct fuel injection, and a single-stage turbocharger. The production pistons nominally produce a CR of 10.1, though subsequent measurements by ORNL of the hardware used for this project yielded a CR 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 revolutions per minute (RPM) and a peak torque of 184 pound-feet (lb-ft) at 2,400 RPM. Vehicles equipped with this engine are designed to operate using regular grade (87 AKI) gasoline with an ethanol content of up to 15% by volume. The owner's manual for the Ford 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 [27].

In addition to the production pistons, pistons were machined by ORNL from blanks with a reduced bowl volume to increase the CR [1]. Pistons were produced with CRs of 11.4 and 13.2. A photograph of the three piston designs is shown in Figure 3-1. Initially, experiments were planned within this study using both the CR11.4 and CR13.2 pistons. However, as mentioned in the previous section, ongoing work during the AVFL-20 project found that the CR13.2 pistons did not provide as much efficiency gain as expected. Computation fluid dynamics (CFD) studies found that the bowl design for these pistons resulted in delayed and lengthened combustion [1]. In addition, there was an engine failure in the middle of the CR13.2 studies that damaged the engine and required an engine replacement. As a result, experiments with these pistons were discontinued for both AVFL-20 and the U.S.DRIVE studies.

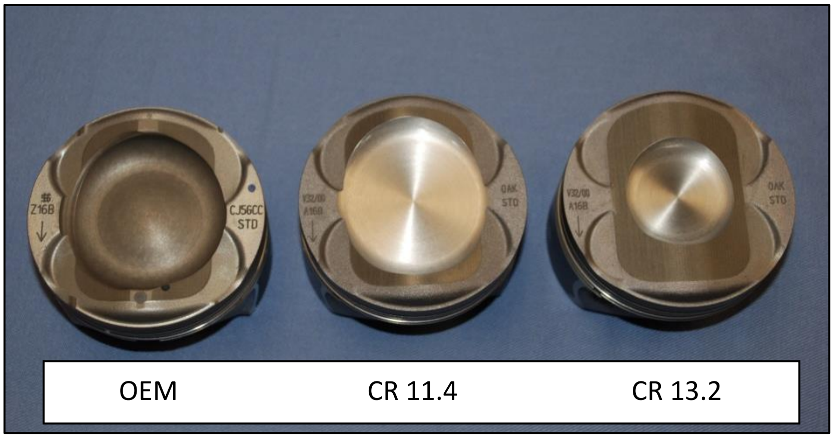


Figure 3-1. Photograph of the pistons used for this study.

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) were disabled to facilitate operation in an engine test cell. Manual adjustments to spark timing were used to avoid knock as reported previously. Limitations on CA50, exhaust temperature, and air/fuel ratio were established based on recommendations provided by staff from Ford Motor Company [1] [26].

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 rotation of the crankshaft. Cylinder pressure in each cylinder was measured using a Kistler 6052CU20 piezoelectric pressure transducer. 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.

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 time-based measurement as used to supply a signal for knock detection within the µDCAT software. The ECU anti-knock features were disabled during this study in order to allow the operator to manually control spark timing to avoid knock based on feedback from the µDCAT knock detection algorithms. Further details are available in the CRC AVFL-20 project report [1].

The engine was installed in an engine research facility using an alternating current dynamometer to absorb the output torque of the engine. Temperature and humidity-controlled air was provided to the engine air intake. The air supply temperature was maintained at 75 °F, with a dew point of 58 °F. Fuel consumption was measured using a Micro-motion Coriolis mass flow meter. Other standard laboratory instrumentation for measuring pressures, temperatures, and so on were also used.

3.2 Engine Study Results for FWG Fuel Matrix

The nominal 97 RON fuels in the FWG fuel matrix were studied using the CR11.4 pistons. Experiments for the present study were conducted in accordance with methods used and previously reported for the AVFL-20 study. Engine fuel consumption maps were developed by collecting data at engine speeds of 1,000; 1,500; 2,000; 2,500; and 5,000 RPM, capturing the full range of engine torque output. Additionally, maximum torque points were collected at 3,000–4,500 RPM. Although studies with the 101 RON fuels in the FWG matrix were originally planned, these studies were discontinued because of performance issues with the CR13.2 pistons that were discovered during the AVFL-20 project plus an engine failure not related to the pistons that required an engine replacement [1]. Figure 3-2 shows the engine speed and brake mean effective pressure (BMEP) points for fuel #20 using CR11.4, and is typical of the range of conditions used to measure the fuel consumption for all of the study fuels.

3.2.1 Combustion Phasing Results

A common metric for describing the phasing of the combustion event relative to the crankshaft position is the crank angle position at which 50% of the fuel mass has burned, or CA50. CA50 is measured in crank angle degrees (CAD) after top-dead-center (ATDC). BMEP is a metric that describes the torque output of the engine per cycle per unit of displacement. BMEP is frequently measured in kilopascals (kPa). BMEP is a useful metric because it allows results and trends from engines of differing displacement to be compared directly with one another. Figure 3-3 shows the combustion phasing results for the 5 FWG matrix fuels at an engine speed of 2,000 RPM. The trends for all five fuels show nearly constant combustion phasing in the maximum brake torque (MBT) region where knock does not occur. As the engine encounters knock, combustion phasing is retarded to avoid the knocking condition. The results for the four ethanol-free fuels are similar, which is expected given their relatively tightly-controlled RON and sensitivity values. The E20 fuel required slightly less retarded combustion phasing for several conditions at 2,000 RPM. CA50 results at other engine speeds showed similar trends and less difference between the E20 and ethanol-free fuels.

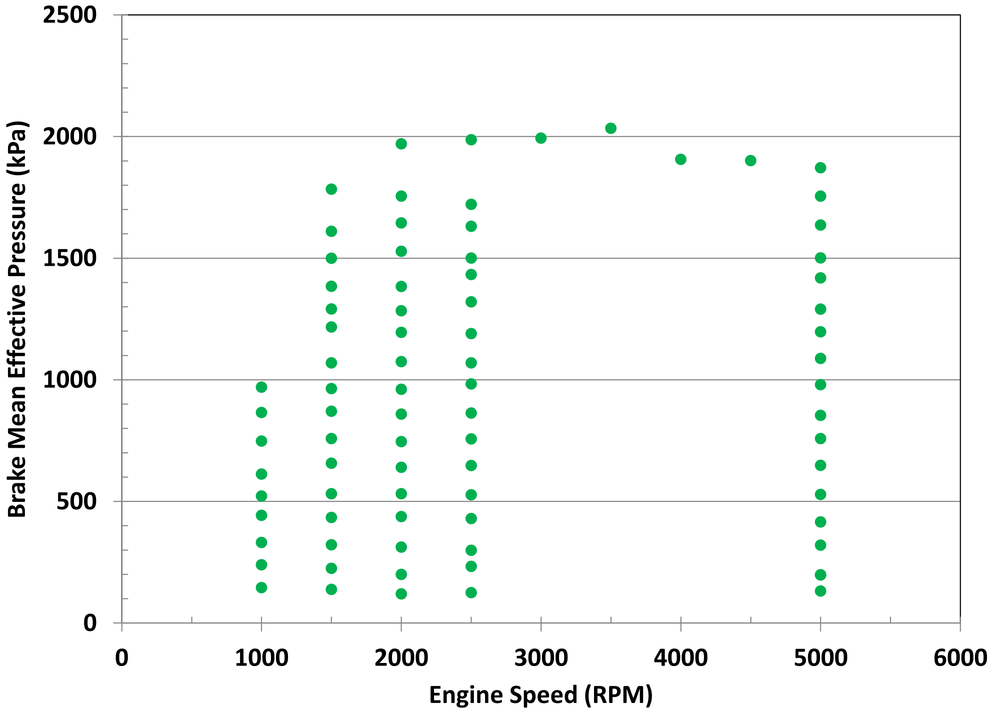
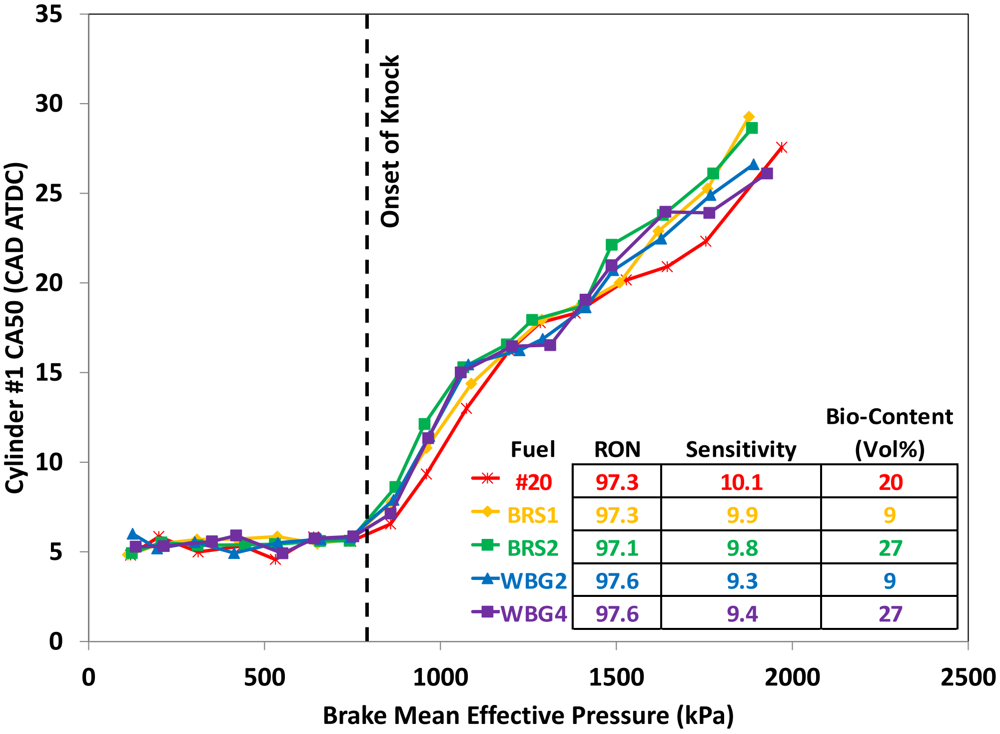


Figure 3-2. Engine speed and BMEP conditions included in the engine map for fuel #20 at CR11.4.



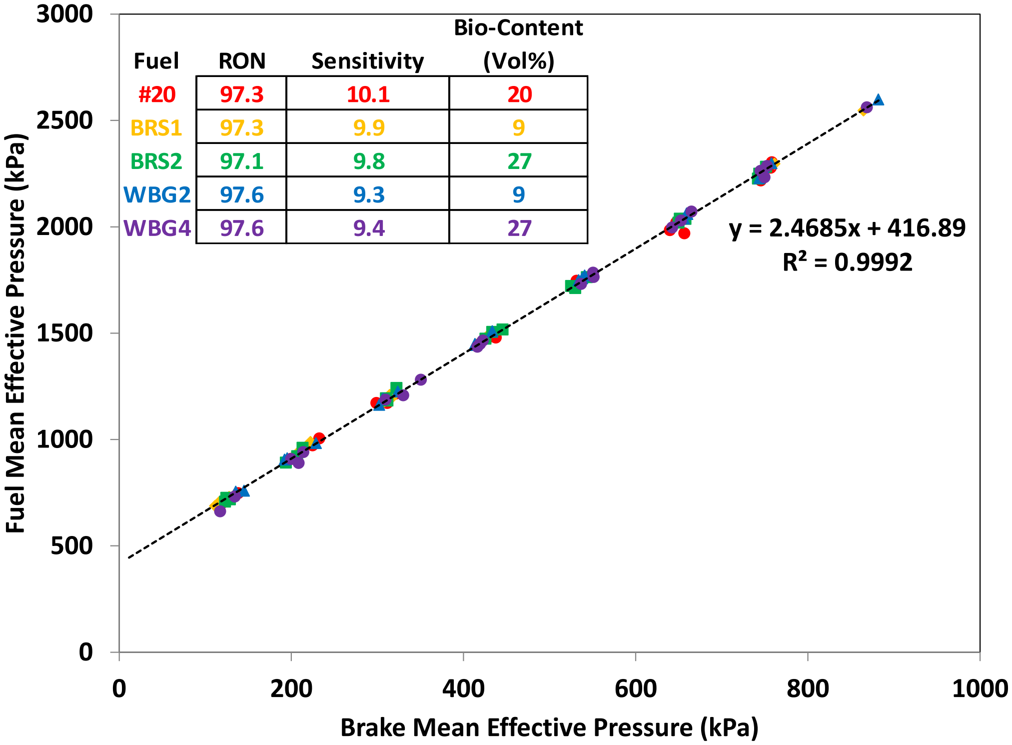
Fuel	RON	Sensitivity	Bio-Content (Vol%)
#20	97.3	10.1	20
BRS1	97.3	9.9	9
BRS2	97.1	9.8	27
WBG2	97.6	9.3	9
WBG4	97.6	9.4	27

Figure 3-3. Combustion phasing results for the 97 RON FWG matrix fuels at 2,000 RPM with the CR11.4 pistons.

3.2.2 Fuel Mean Effective Pressure Results

Fuel mean effective pressure, or fuel MEP, is a metric that describes the fuel energy consumption of the engine per cycle per unit of displacement. As with BMEP, fuel MEP is reported in units of pressure, kPa. In the MBT region, fuel MEP is linearly proportional to BMEP and is not very sensitive to engine speed [28] [29] [30]. Fuel MEP results in the MBT region for the five 97 RON fuels are shown in Figure 3.3. The results for all five fuels fall onto one line, indicating low scatter or "noise" in the collected engine data and self-consistency between the engine data and the heating value analyses for all of the fuels. The regression results shown in Figure 3.4 were developed using data in the MBT region at engine speeds between 1,500 and 2,500 RPM and were used to calculate the fuel consumption rates within the MBT region for all of the fuels. This approach offers the advantage of minimizing the impact of experimental noise in the MBT region on modeled fuel economy predictions. The measured fuel consumption values for each fuel were used for conditions in the knock-limited region. The same approach was used in the AVFL-20 project.

The fuel MEP correlation for the FWG fuel matrix, as shown in Figure 3.4, had a slope of 2.4685 and an intercept of 416.89. The correlation determined for the AVFL-20 fuel set at CR11.4 had a slope of 2.4314 and an intercept of 417.56 [1]. These differences result in different fuel consumption values for the two fuel matrices, with the AVFL-20 fuels demonstrating marginally higher efficiency in the MBT space. Fuel MEP values for the FWG matrix fuel #20 (an E20 blend) were directionally more similar to the AVFL-20 results than the ethanol-free fuels. These observations suggest that fuel formulation may contribute to the difference in the fuel MEP regressions in the MBT space. For example, part-load benefits from ethanol blending that could explain the differences noted in this study have been reported previously [31]. The differences in the fuel MEP correlations result in a difference in engine brake thermal efficiency of up to 0.4 engine efficiency points in the MBT region.



Fuel	RON	Sensitivity	Bio-Content (Vol%)
#20	97.3	10.1	20
BRS1	97.3	9.9	9
BRS2	97.1	9.8	27
WBG2	97.6	9.3	9
WBG4	97.6	9.4	27

Figure 3-4. Fuel MEP for the five 97 RON fuels in the MBT region at engine speeds 1,500–2,500 RPM.

4. Vehicle Modeling

Vehicle modeling allows the engine data gathered during this project to be used to estimate the energy consumption, volumetric fuel economy, and tailpipe CO_2 emissions from vehicles that might use engines with the different CRs and fuels studied in this project. This study adopted the vehicle models used for AVFL-20 to assure compatibility of results from the two projects. The Autonomie vehicle simulation software package was used to develop models for a mid-size sedan and a small SUV [1]. Autonomie 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 [2][3][4][5]. The drive cycles studied include the urban dynamometer driving schedule (UDDS), the highway fuel economy test (HWFET), and the US06 cycle. Results for the US06 cycle were divided into results for both the city and highway portions of the cycle.

4.1 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 equivalent test weight that are available in the EPA certification test database for all vehicles sold in the United States [32]. The forces at the tire 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. The AVFL-20 report contains details of the data-mining process that was used to determine the parameters used to describe the mid-size sedan and small SUV [1]. This study adopted the same parameters that were selected for AVFL-20. These parameters are summarized in Table 4.1.

Table 4-1. Parameters used in the Autonomie model for the midsize sedan and small SUV.

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
Engineering 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

4.2 Vehicle Model Results

The vehicle model provides a means of comparing the potential impacts of fuel and CR, but is subject to some limitations. Specifically, steady-state engine maps are used to provide fuel consumption information to the model. These steady-state maps do not provide a reliable means of examining the important impacts from cold-start, for example. Furthermore, steady-state conditions in an engine research laboratory can result in hotter conditions during the combustion process than occur in transient excursions at high BMEP levels. These differences between the model environment and on-road operation are significant, however, this approach remains useful for comparing the potential impacts of fuel formulations and compression ratio, since the modeled conditions are consistent among the fuels and compression ratios being studied.

4.2.1 Results for the FWG Matrix Fuels using CR11.4 Pistons

Vehicle energy consumption over a drive cycle is a metric that provides insight into directional changes in engine efficiency afforded by different fuels and compression ratios. Figures 4-1 and 4-2 show the energy consumption for the mid-size sedan and small SUV, respectively, using the CR11.4 pistons. The results show that differences from the maximum to minimum value on a given cycle vary between 0.4% to 2.3% for the sedan and 0.9% to 3.1% for the SUV. The similarity in results is expected, given that the fuels had very similar RON and sensitivity, and were tested at the same CR.

Volumetric fuel economy depends both on the vehicle energy consumption for a given cycle and on the volumetric heating value of the fuel. Figure 4.3 shows the volumetric heating value for each fuel. There is little variation in the volumetric heating value of the ethanol-free fuels, but the E20 blend has a heating value that is 6.7% lower than the BRS1 fuel, for example. In order for the E20 fuel to achieve a higher volumetric fuel economy than the other fuels, it would need to offset at least 6.7% energy consumption on a given drive cycle. Thus, the volumetric fuel economy for the E20 fuel is lower relative to the other 97 RON fuels at this CR, as shown in Figures 4.4 and 4.5, despite slightly lower energy consumption for this fuel as noted above. Compared to WBG4, the E20 fuel has about 7% poorer (lower) fuel economy on the UDDS and HWFET drive cycle for both the sedan and SUV and 4.7%–6.7% poorer (lower) fuel economy on the US06 drive cycles. Differences among the volumetric fuel economy values for the non-ethanol fuels were small relative to the difference between these fuels and the E20 fuel, consistent with their volumetric heating values. These trends were observed for both the mid-size sedan and small SUV.

Tailpipe CO_2 emissions for a given drive cycle depend on both the vehicle energy consumption for the cycle and the carbon intensity of the fuel. In this case, the carbon intensity is defined as the mass of tailpipe CO_2 emitted per unit fuel energy combusted (BTU) and should not be confused with the CO_2 required to produce the fuel. Figure 4.6 shows the carbon intensity of the FWG matrix fuels studied at CR11.4, as the fuels were produced for the engine study.

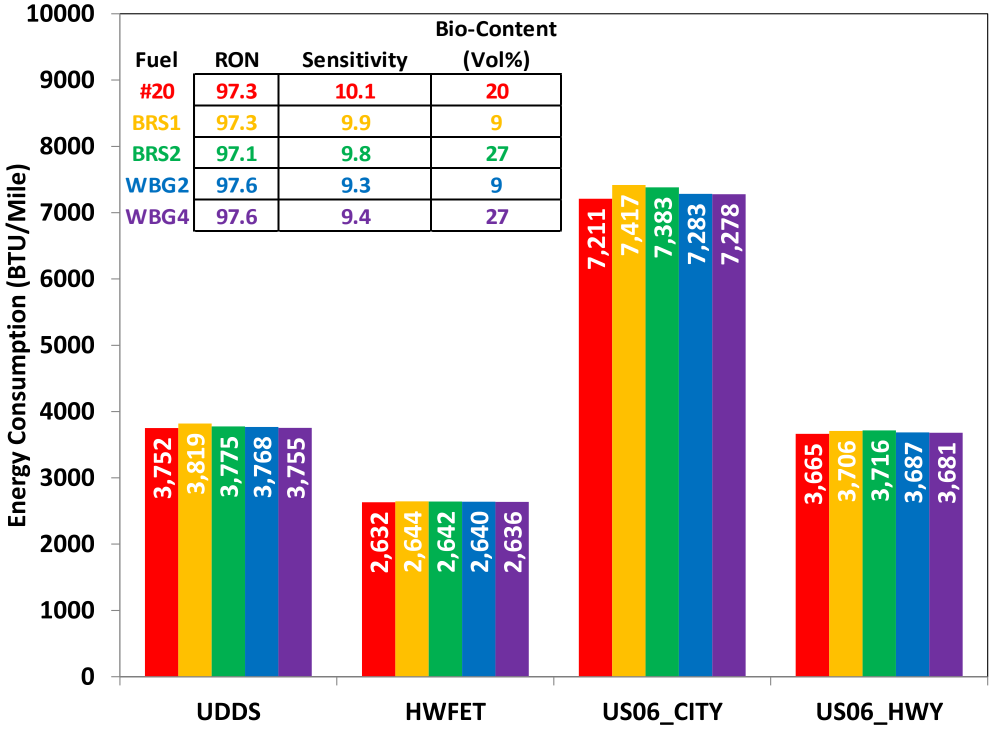


Figure 4-1. Modeled energy consumption results for the mid-size sedan using the FWG matrix fuels and the CR11.4 pistons.

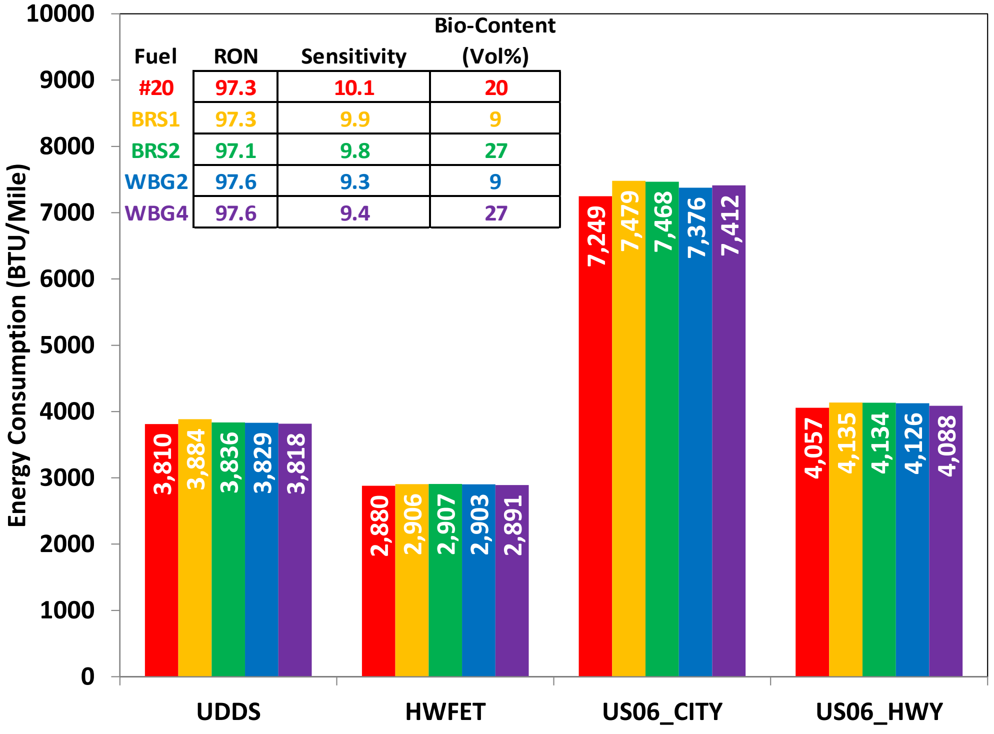


Figure 4-2. Modeled energy consumption results for the small SUV using the FWG matrix fuels and CR11.4 pistons.

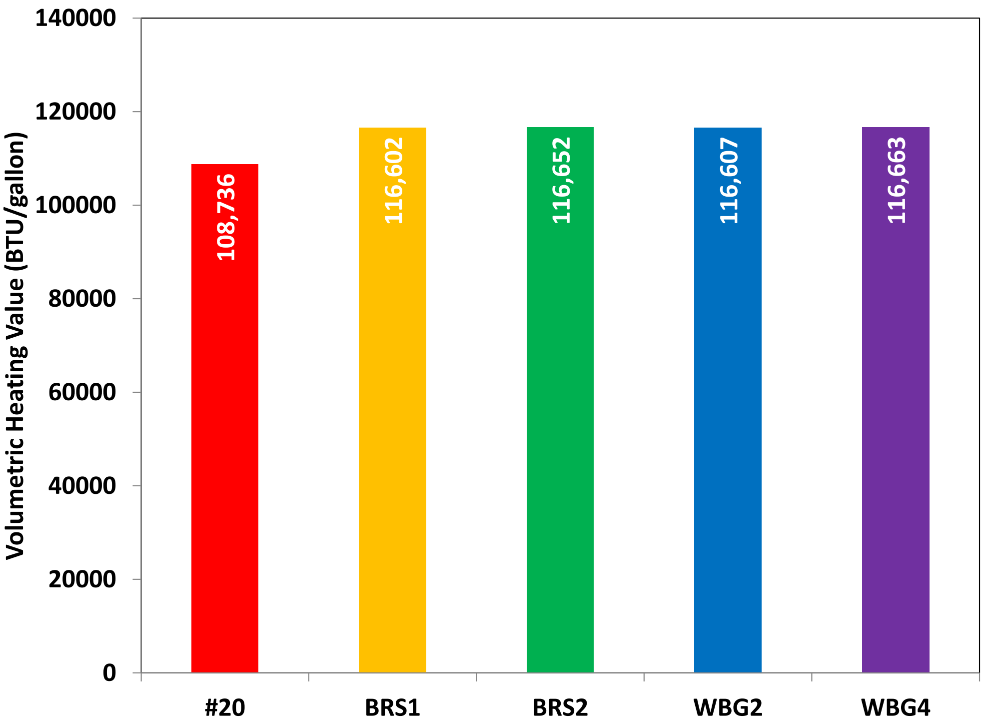
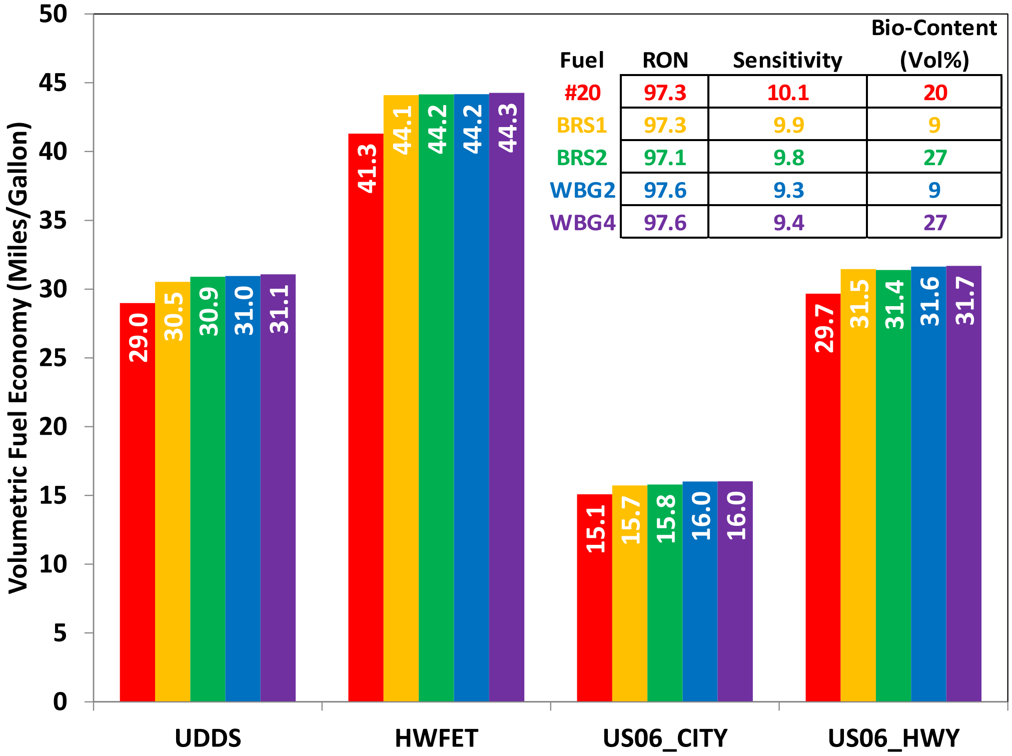
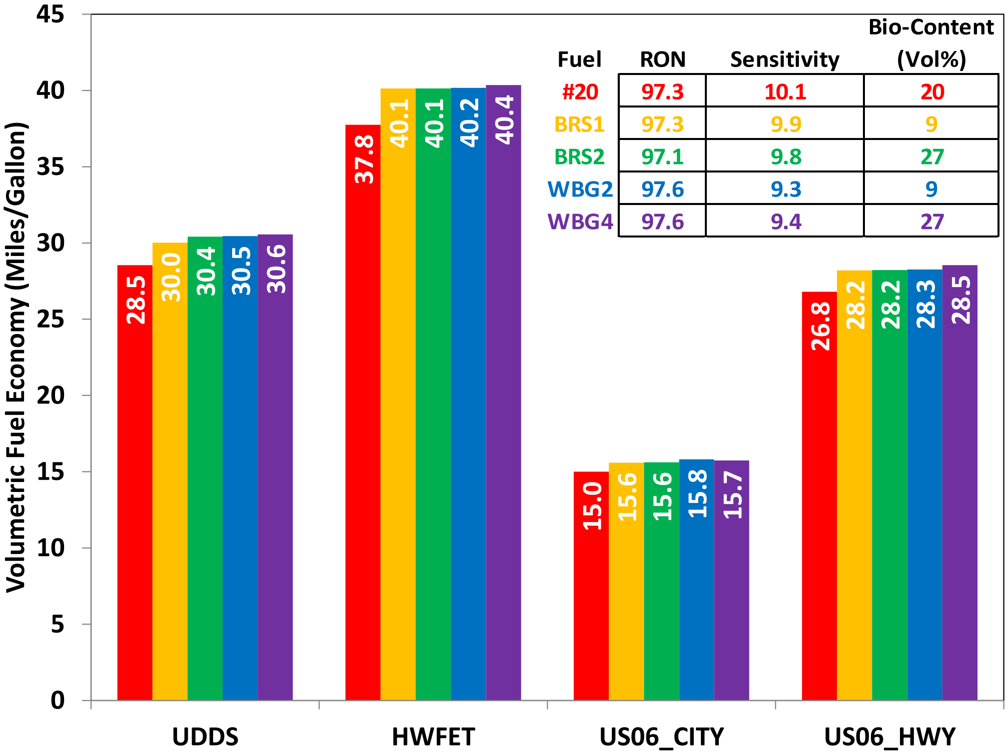


Figure 4-3. Volumetric heating value for the FWG matrix fuels studied at CR11.4.



Fuel	RON	Sensitivity	Bio-Content (Vol%)
#20	97.3	10.1	20
BRS1	97.3	9.9	9
BRS2	97.1	9.8	27
WBG2	97.6	9.3	9
WBG4	97.6	9.4	27

Figure 4-4. Modeled volumetric fuel economy for the mid-size sedan using the 97 RON FWG matrix fuels and CR11.4 pistons.



Fuel	RON	Sensitivity	Bio-Content (Vol%)
#20	97.3	10.1	20
BRS1	97.3	9.9	9
BRS2	97.1	9.8	27
WBG2	97.6	9.3	9
WBG4	97.6	9.4	27

Figure 4-5. Modeled fuel economy for the small SUV using the 97 RON FWG matrix fuels and CR11.4 pistons.

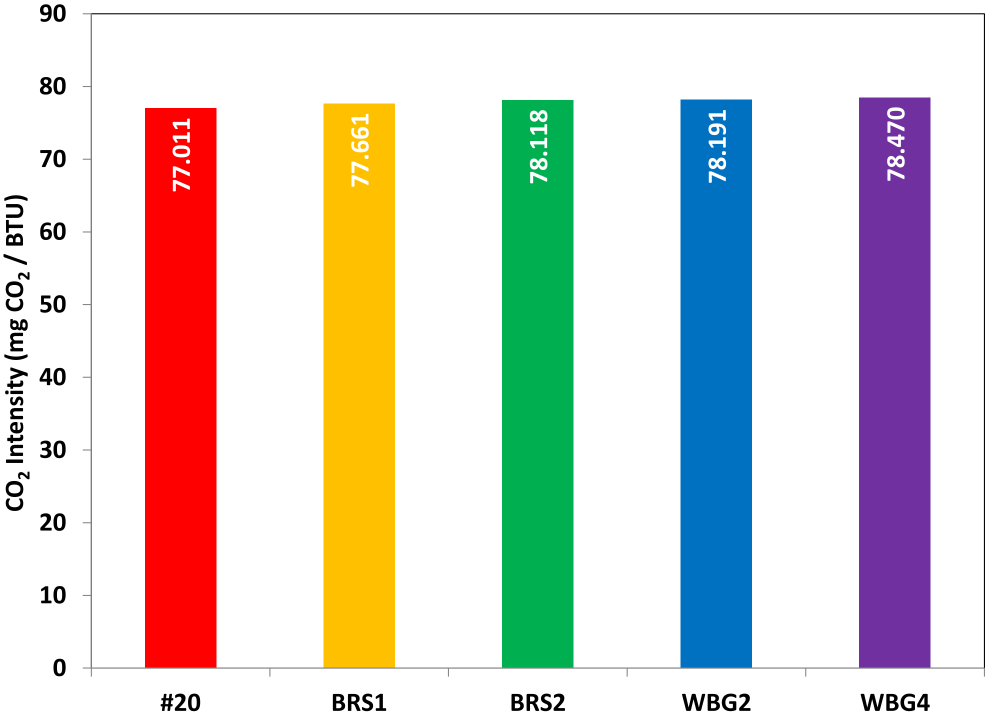


Figure 4-6. CO_2 intensity for the 97 RON FWG matrix fuels.

Figures 4-7 and 4-8 show the modeled tailpipe CO_2 emissions for the mid-size sedan and small SUV, respectively. These values are based on the total carbon content of each fuel, and are thus the total of both biogenic and petroleum-derived tailpipe CO_2 emissions. In all cases, the largest tailpipe CO_2 emissions were observed for either BRS1 or BRS2, though the marginal difference between these fuels and the other ethanol-free fuels is probably not significant. The E20 fuel provided the lowest overall tailpipe CO_2 emissions. The difference between maximum and minimum values of tailpipe CO_2 emissions among these fuels ranged from 2.0% to 3.7% for the sedan and from 2.3% to 4.3% for the SUV over the four cycles. Table 4-2 summarizes the modeled energy use, volumetric fuel economy, and tailpipe CO_2 emissions for the FWG fuels.

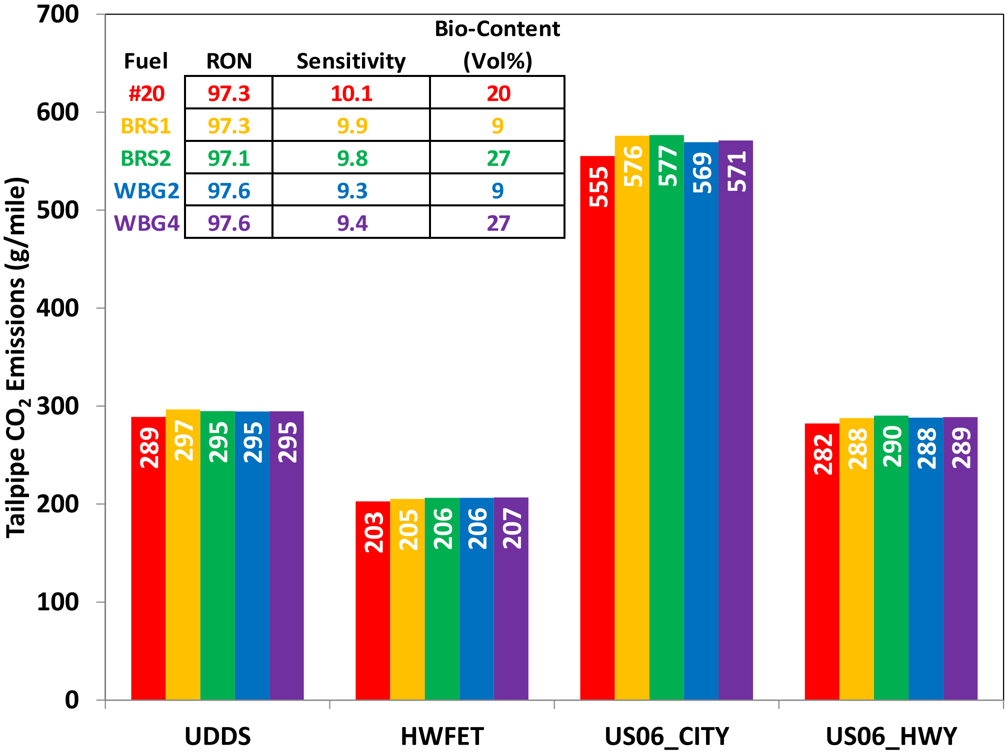


Figure 4-7. Modeled tailpipe CO_2 emissions for the mid-size sedan using the FWG matrix fuels and CR11.4 pistons.

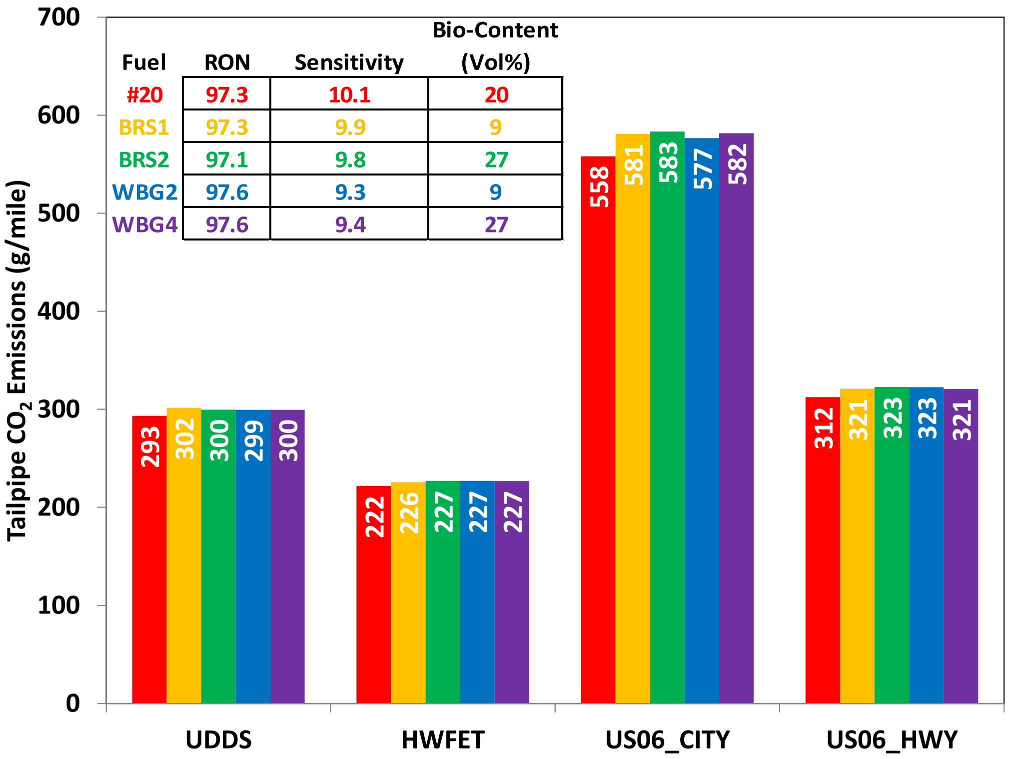


Figure 4-8. Modeled tailpipe CO_2 emissions for the small SUV using the FWG matrix fuels and CR11.4 pistons.

Table 4-2. Summary of vehicle model results for the mid-size sedan and small SUV using FWG 97 RON fuels and CR11.4.

Vehicle model results for the mid-size sedan and small SUV for CR11.4											
		Fuel #20		**BRS1**		**BRS2**		**WBG2**		**WBG4**	
	Drive	97.3 RON, 10.1 S, E20		97.3 RON, 9.9 S, 9% Bio		97.1 RON, 9.8 S, 27% Bio		97.6 RON, 9.3 S, 9% Bio		97.6 RON, 9.4 S, 27% Bio	
	Cycle	**Sedan**	**SUV**	**Sedan**	**SUV**	**Sedan**	**SUV**	**Sedan**	**SUV**	**Sedan**	**SUV**
Energy Consumption (BTU/Mile)	UDDS	3,752	3,810	3,819	3,884	3,775	3,836	3,768	3,829	3755	3818
	HWFET	2,632	2,880	2,644	2,906	2,642	2,907	2,640	2,903	2636	2891
	US06 City	7,211	7,249	7,417	7,479	7,383	7,468	7,283	7,376	7278	7412
	US06 Hwy	3,665	4,057	3,706	4,135	3,716	4,134	3,687	4,126	3681	4088
Volumetric Fuel Economy (MPG)	UDDS	29.0	28.5	30.5	30.0	30.9	30.4	31.0	30.5	31.1	30.6
	HWFET	41.3	37.8	44.1	40.1	44.2	40.1	44.2	40.2	44.3	40.4
	US06 City	15.1	15.0	15.7	15.6	15.8	15.6	16.0	15.8	16	15.7
	US06 Hwy	29.7	26.8	31.5	28.2	31.4	28.2	31.6	28.3	31.7	28.5
Tailpipe CO_2 Emissions (g/mile)	UDDS	289	293	297	302	295	300	295	299	295	300
	HWFET	203	222	205	226	206	227	206	227	207	227
	US06 City	555	558	576	581	577	583	569	577	571	582
	US06 Hwy	282	312	288	321	290	323	288	323	289	321

The AVFL-20 project adopted a baseline case for comparison of vehicle modeling results. The baseline was defined as the average result for E10 fuels #1 and #10 at CR10.5. Both of these fuels nominally contain 10% ethanol and have 91 RON. Fuel #1 has a low sensitivity (7.3) and fuel #10 has a high sensitivity (10.4). The results for the FWG matrix fuels were also compared in this way, and are shown in Table 4-3. At a CR of 11.4:1, these fuels enabled reductions in energy use up to 5.0% depending on the fuel, vehicle, and drive cycle with two UDDS results (for BRS1) showing 0.6%–0.9% energy use increases compared to baseline. The E20 fuel (#20) showed poorer (lower) volumetric fuel economy on the UDDS and HWFET (1.4%–2.3% lower than the baseline), with a range from -0.4% up to a 2% improvement (increase) in fuel economy on the US06 cycles. The non-ethanol biofuels all demonstrated improvements in volumetric fuel economy (3.3 to 7.9%), due largely to their increased volumetric energy content relative to the E10 baseline fuels from AVFL-20. The E20 fuel provided the only decreases in tailpipe CO_2 emissions (0.2 – 0.7%) for the UDDS and HWFET cycles, while the non-ethanol biofuels produced higher tailpipe CO_2 emissions (1.5 to 2.5%). Tailpipe CO_2 impacts on the US06 cycle were mixed depending on the fuel and vehicle, ranging from worse (by as much as 1.2%) to better (by as much as 3.5%).

Table 4-3. Relative changes for the FWG matrix fuels at CR11.4 compared to the AVFL-20 baseline case (average of fuels #1 and #10 at CR10.5).

Changes with CR11.4 relative to baseline (avg. of AVFL-20 fuels #1 and #10 at CR10.5)											
	Drive Cycle	#20 97.3 RON, 10.1 S, E20		BRS1 97.3 RON, 9.9 S, 9% Bio		BRS2 97.1 RON, 9.8 S, 27% Bio		WBG2 97.6 RON, 9.3 S, 9% Bio		WBG4 97.6 RON, 9.4 S, 27% Bio	
		Sedan	SUV	Sedan	SUV	Sedan	SUV	Sedan	SUV	Sedan	SUV
Energy Use Reduction	UDDS	0.9%	1.3%	-0.9%	-0.6%	0.3%	0.6%	0.5%	0.8%	0.8%	1.1%
	HWFET	0.5%	1.5%	0.1%	0.6%	0.2%	0.6%	0.2%	0.7%	0.4%	1.1%
	US06 City	4.3%	5.0%	1.6%	2.0%	2.1%	2.1%	3.4%	3.3%	3.5%	2.8%
	US06 Hwy	2.5%	3.8%	1.4%	1.9%	1.1%	2.0%	1.9%	2.1%	2.1%	3.0%
Fuel Economy Increase	UDDS	-1.9%	-1.6%	3.3%	3.5%	4.6%	4.9%	4.7%	5.0%	5.1%	5.4%
	HWFET	-2.3%	-1.4%	4.3%	4.8%	4.4%	4.8%	4.4%	4.9%	4.6%	5.4%
	US06 City	1.5%	2.0%	5.9%	6.1%	6.4%	6.3%	7.8%	7.6%	7.9%	7.1%
	US06 Hwy	-0.4%	0.9%	5.6%	6.2%	5.3%	6.3%	6.1%	6.4%	6.3%	7.5%
CO_2 Emissions Reduction	UDDS	0.2%	0.5%	-2.5%	-2.3%	-1.9%	-1.6%	-1.8%	-1.5%	-1.8%	-1.5%
	HWFET	-0.4%	0.7%	-1.7%	-1.0%	-2.2%	-1.6%	-2.2%	-1.6%	-2.4%	-1.5%
	US06 City	3.5%	4.2%	-0.1%	0.3%	-0.2%	-0.2%	1.0%	1.0%	0.8%	0.2%
	US06 Hwy	1.7%	2.8%	-0.3%	0.1%	-1.2%	-0.4%	-0.4%	-0.4%	-0.7%	0.2%

4.2.2 Results for the AVFL-20 Fuels

Extensive discussion of the results of the AVFL-20 project is included in the CRC project report [1]. Since the AVFL-20 results are needed to support the LCA modeling effort in the FWG study, the AVFL-20 results are enumerated here. Table 4-4 shows the modeled energy consumption, volumetric fuel economy, and tailpipe CO_2 emissions for the mid-size sedan and small SUV using the AVFL-20 fuels at CR10.5. Table 4-5 shows the same results for the fuels studied at CR 11.4. Table 4-6 shows the relative impacts of the fuel studied at CR11.4 relative to the baseline case.

Of all the fuels studied in the CRC AVFL-20 and the U.S.DRIVE FWG projects, fuel #14 (mid-RON, high sensitivity, E10) was the only fuel at CR11.4 which had lower energy consumption, better fuel economy, and lower CO_2 emissions than the baseline E10 fuels at CR10.5 over all drive cycles. (i.e., all green “markers” in Tables 4-3 and 4-6.)

Table 4-4. Vehicle model results for the mid-size sedan and small SUV using the CR10.5 pistons and fuels studied in AVFL-20. [1]

Vehicle model results for the mid-size sedan and small SUV for CR10.5							
	Drive Cycle	Fuel #1		Fuel #10		Fuel #15	
		92 RON, 7 S, E10		91 RON, 10 S, E10		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 4-5. Vehicle model results for the mid-size sedan and small SUV using the CR11.4 pistons and fuels studied in AVFL-20 [1].

Vehicle model results for the mid-size sedan and small SUV for CR11.4									
	Drive Cycle	Fuel #6		Fuel #7		Fuel #14		Fuel #15	
		96 RON, 8 S, E30		100 RON, 8 S, E10		97 RON, 11 S, E10		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 4-6. Impacts of AVFL-20 fuels studied at CR11.4 relative to the baseline case (average of fuels #1 and #10 at CR10.5) [1].

Changes with CR11.4 relative to baseline (avg. of fuels #1 and #10 at CR10.5)									
		Fuel #6		**Fuel #7**		**Fuel #14**		**Fuel #15**	
	Drive Cycle	96 RON, 8 S, E30		100 RON, 8 S, E10		97 RON, 11 S, E10		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%

5. Vehicle Characteristics to Support LCA Modeling

The engine and vehicle modeling study outlined previously was used in combination with other published results to establish energy consumption metrics that represent the light-duty U.S. fleet. This section outlines the process used to cascade the vehicle model results into the inputs needed to support LCA for the study fuels. Although the measured fuel properties of the study fuels in general compared favorably with target values, small deviations are an unavoidable part of experimental studies. The actual compression ratio enabled by each fuel therefore differs slightly from the fixed compression ratios that were used in the engine studies. The vehicle efficiency gain for each fuel was estimated through a multi-step process that is outlined in the following sections of the report. This process provided a consistent means of estimating the benefits that may be enabled by both the 97 RON and 101 RON fuels.

5.1 Compression Ratio Increase Enabled by Each Fuel

The combustion phasing screening results at 2,000 RPM from the AVFL-20 and FWG engine studies showed that the 97 RON fuels in both matrices enabled CR 11.4 and also that the 101 RON fuels enabled CR 13.2. Results from the 97 RON fuels at CR 11.4, compared with the 91 RON fuels at the baseline CR 10.5, show that 5.6 octane numbers (ON) are needed per unit CR increase. Similarly, the 101 RON fuels at CR 13.2 show that 3.7 ON are needed per CR increase. Two previously-published studies also investigated the ON/CR relationship in modern engines. The first of these studies, conducted at the University of Birmingham in the United Kingdom, summarized the CR improvements enabled by high-octane fuels in multiple studies at multiple research organizations. The ON/CR values ranged from 2.4 to 5.0, with a mean value of 3.9 and a median of 3.5 [33]. The second study was conducted by the member companies of USCAR. It also reported ON/CR values, ranging from 2.5 to just over 9.0 [6]. Typically, studies that investigate benefits from increasing CR use a well-optimized production engine as a baseline case and increase CR through piston replacement using pistons that are less optimized. Thus, it is possible that engines developed by the automotive manufacturers using increased CR will require lower values of ON/CR compared with existing studies. The range of values for ON/CR suggests that multiple values be studied to capture the potential breadth of the effect of increasing octane rating on vehicle fuel efficiency. The AVFL-20 and FWG result of 5.6 ON/CR was selected for study, as it is a reasonable representation of the upper end of the ON/CR range (though it is not the maximum value). Similarly, the 3.7 ON/CR result from the AVFL-20 study was also selected, as it is similar to the mean and median values of the ON/CR results enumerated in the University of Birmingham study and USCAR studies. Finally, a value of 3.0 ON/CR was selected to represent the ON requirements for more fully-optimized engines that could potentially be developed by the automakers, and it represents the lower end of the reported ON/CR range (though it is not the minimum value). Table 5-1 shows the CR levels that are projected to be enabled for each fuel at the three ON/CR levels studied.

Table 5-1. Projected compression ratios enabled by RON increase above baseline for the study fuels.

Fuel ID	RON	Sensitivity	Ethanol Content	Compression Ratio Enabled by RON		
				3 ON/CR	3.7 ON/CR	5.6 ON/CR
14	96.6	11.1	10.4	12.2	11.8	11.4
20	97.3	10.7	20	12.4	12.0	11.5
6	96	7.5	30	12.0	11.6	11.3
15	96.5	11.6	30.4	12.1	11.8	11.3
BRS1	97.6	10.4	0	12.5	12.1	11.5
BRS2	97.3	10.3	0	12.4	12.0	11.5
WBG2	97.7	10.2	0	12.5	12.1	11.6
WBG4	97.3	10.2	0	12.4	12.0	11.5
7	100.1	7.6	10.1	13.3	12.7	12.0
16	101.1	11.8	10.2	13.7	13.0	12.2
18	101	12	20	13.6	13.0	12.1
19	101	12	29.9	13.6	13.0	12.1
BRS3	101.5	11.1	0	13.8	13.1	12.2
BRS4	101.6	11.2	0	13.8	13.1	12.3

5.2 Efficiency Gain Enabled by Increased Octane Rating

The ON/CR values of 5.6, 3.7, and 3.0 were used in combination with the measured RON values for the fuels in both the AVFL-20 Phase 3 and the FWG matrices to project the CR increase expected to be enabled by each fuel. The methodology detailed in a USCAR study was used for this purpose [6]. The methodology includes the benefit of increased RON through increased CR and through additional downsizing that is projected to be enabled by increased CR. Increasing CR provides added efficiency and torque output, resulting in an increase in the maximum torque output of the engine. The downsizing term reflects an efficiency benefit that may be obtained by downsizing the engine so that the maximum output torque at the higher compression ratio remains constant with the baseline case. Finally, the methodology also incorporates a term to capture efficiency benefits offered by ethanol blending beyond its effect on knock resistance. Some of these benefits (including volumetric efficiency improvement, lower losses due to heat transfer, etc.) are derived from the relatively high heat-of-vaporization of ethanol relative to other fuel components. Other benefits (burn rate differences, specific heat ratio effects, etc.) are associated with ethanol blending and are derived from combustion chemistry effects [6] [31]. The calculation of total efficiency increase by this method is shown in equations (1) and (2).

$$\boldsymbol{\Delta\epsilon_{total} = 100\% * \left(\left(1 + \frac{F_{downsize} * \Delta\epsilon_{CR}}{100\%}\right) * \left(1 + \frac{\Delta\epsilon_{ethanol}}{100\%}\right) - 1\right)} \tag{1}$$

$$\boldsymbol{\Delta\epsilon_{CR} = -0.207\% * \left(CR_{new}^{2} - CR_{base}^{2}\right) + 6.44\% * (CR_{new} - CR_{base})} \tag{2}$$

In equation (1), $\Delta\varepsilon_{total}$ is the total efficiency increase and $F_{downsize}$ is the efficiency increase multiplier from additional downsizing; in this case, a fixed value of 1.1 is used, as suggested for turbocharged engines [6]. This factor is an estimate of the additional efficiency that can be gained by downsizing the engine to retain fixed maximum output torque which would otherwise increase as the engine efficiency increases. In the absence of a downsizing factor, efficiency gains attained through CR and ethanol content would result in increased maximum torque output, with increases in torque equivalent to the efficiency gain. The value of 1.1 reflects an additional 1% efficiency gain achieved through downsizing for 10% increased efficiency gain achieved through compression ratio and ethanol content. The value of the downsizing factor of 1.1 $\Delta\varepsilon_{CR}$ is the efficiency increase associated with increased CR, and $\Delta\varepsilon_{ethanol}$ is the efficiency increase from ethanol content. Equation 2 calculates $\Delta\varepsilon_{CR}$ based on the new CR (CR_{new}) and the baseline CR (CR_{base}). Table 5.2 shows the calculated efficiency benefit based on the USCAR method for each of the study fuels and each of the three ON/CR values.

Using the USCAR model to project fuel efficiency improvements for a fixed compression ratio of 11.4 allows comparison of the model directly against the efficiency results obtained through the engine and vehicle modeling study. This comparison is shown in Figure 5.1. If the USCAR model is used without a term to capture efficiency gains from ethanol blending, it predicts an increase in efficiency of 1.7%, shown by the broken line. However, the results from the engine and vehicle modeling study demonstrate a trend of increasing efficiency gain with increasing ethanol content. Including the ethanol dependency term in the USCAR model provides a better fit to the engine and vehicle modeling results, as shown by the solid line.

Table 5-2. Projected vehicle efficiency increases based on the USCAR method, both with and without the effects of the downsizing factor of 1.1 for turbocharged engines.

Fuel ID	RON	Sensitivity	Ethanol Content (Vol%)	Projected Efficiency Increase With (Without) Downsizing Factor		
				3 ON/CR	3.7 ON/CR	5.6 ON/CR
14	96.6	11.1	10.4	3.2% (2.9%)	2.6% (2.4%)	1.8% (1.6%)
20	97.3	10.7	20.0	4.0% (3.7%)	3.4% (3.1%)	2.5% (2.3%)
6	96.0	7.5	30.0	3.9% (3.6%)	3.3% (3.1%)	2.6% (2.4%)
15	96.5	11.6	30.4	4.2% (3.9%)	3.6% (3.3%)	2.8% (2.6%)
BRS1	97.6	10.4	0	3.2% (2.8%)	2.5% (2.2%)	1.6% (1.4%)
BRS2	97.3	10.3	0	3.0% (2.7%)	2.4% (2.1%)	1.5% (1.3%)
WBG2	97.7	10.2	0	3.2% (2.9%)	2.6% (2.3%)	1.6% (1.4%)
WBG4	97.3	10.2	0	3.0% (2.7%)	2.4% (2.1%)	1.5% (1.3%)
7	100.1	7.6	10.1	4.7% (4.3%)	4.0% (3.6%)	2.9% (2.6%)
16	101.1	11.8	10.2	5.0% (4.5%)	4.3% (3.9%)	3.2% (2.9%)
18	101.0	12.0	20.0	5.5% (5.0%)	4.8% (4.4%)	3.7% (3.4%)
19	101.0	12.0	29.9	6.0% (5.5%)	5.3% (4.9%)	4.2% (3.9%)
BRS3	101.5	11.1	0	4.6% (4.1%)	3.9% (3.5%)	2.8% (2.5%)
BRS4	101.6	11.2	0	4.6% (4.1%)	4.0% (3.6%)	2.8% (2.5%)

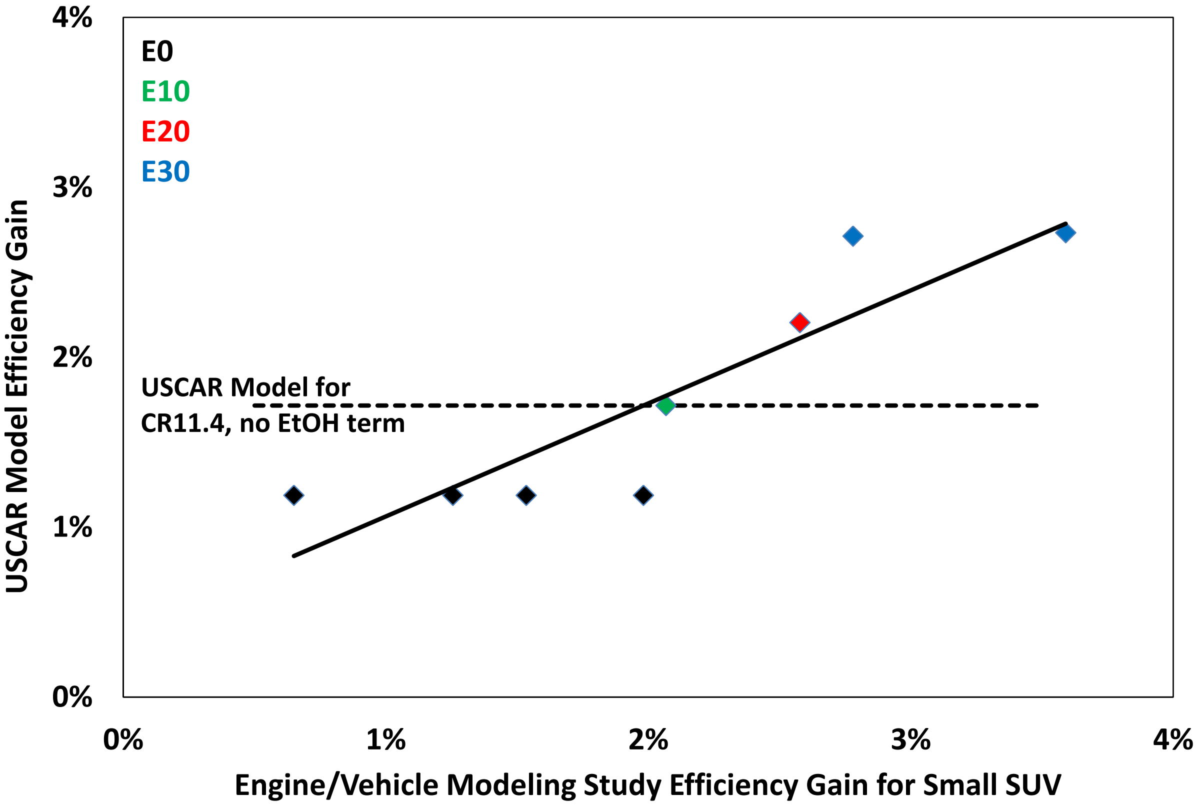


Figure 5-1. Comparison of the efficiency improvements projected by the USCAR method for CR11.4 and the values determined from the engine and vehicle modeling study.

5.3 Fleet Average on-road Energy Consumption Value

The vehicle modeling conducted for both the AVFL-20 and FWG studies focused on the UDDS cycle, the HWFET cycle, and the US06 cycle. However, two additional cycles are used in calculation of the 5-cycle fuel economy value that is included on the window sticker of new vehicles. The 5-cycle fuel economy label was developed by EPA to be more representative of on-road driving [34]. These two additional cycles are the SC03 cycle and the cold-CO test. The SC03 cycle characterizes the impact of air conditioning loads on vehicle fuel efficiency, and is conducted under elevated temperature conditions. The cold-CO test is designed to characterize higher levels of CO and HC emissions that result from vehicle startup and operation at 20 degrees Fahrenheit. The complex conditions of these two cycles make vehicle modeling results for them unreliable. In the absence of model results for the SC03 and cold-CO tests, a surrogate for the 5-cycle fuel economy value that is based on results from 3 cycles (UDDS, HWFET, and US06) was developed. The drive cycles for the SC03 and cold CO tests are both similar to the UDDS in terms of the speeds and loads experienced by the engine. The propensity for knock on the SC03 is higher given the higher temperature, but is lower on the cold CO test. The impact of knock on efficiency for these two cycles was assumed to be of similar magnitude but opposite in direction. For the purposes of estimating the "on-road" fuel economy effects of fuel properties and compression ratio, the energy consumption values for the UDDS were used in place of those of the SC03 and cold CO tests in the 5-cycle weighting factor calculation. Weighting factors of 0.55 and 0.45, respectively, were retained to calculate a composite energy consumption value from the city and highway drive cycles.

The vehicle modeling study focused on two vehicle platforms: an industry-average mid-size sedan and an industry-average small SUV. These two vehicle types make up a large part of the US light-duty fleet, and are therefore important benchmarks in assessing potential fuel economy improvement. However, for the purpose the LCA study, it was deemed beneficial to identify a single energy consumption metric that could approximate energy use of the entire light-duty fleet. The EPA publishes a report annually that summarizes the fuel economy of the light duty fleet. The latest of these “trends” reports includes data through model year 2016, and indicates that the adjusted fuel economy of new cars sold in 2016 was 24.7 MPG [22]. The report also includes data on the fuel economy of specific vehicle types. The mid-size sedan included in the vehicle modeling study is typical of the car (non-SUV) category in the trends report, and the small SUV is typical of the car SUV category. The reported fuel economy values for model year 2016 were 29.2 MPG for the car (non-SUV) category and 26.2 MPG for the car SUV category. The car SUV fuel economy value is closer to that of the entire light-duty fleet than that of the car (non-SUV). Based on this information, the small-SUV results from the vehicle modeling study were selected to represent the entire light-duty fleet as an input to the LCA for each fuel. Table 5-3 shows the 5-cycle weighting factors and energy consumption values for the small SUV that were used to calculate a combined energy consumption for the small SUV using AVFL-20 fuel #1 at CR10.5. Each row calculates the contribution of a given cycle to the overall city and highway energy consumption by multiplying the appropriate weighting factor by the energy consumption for the cycle. The total energy consumption for city and highway driving is calculated by summing (down the column) the contributions of all of the cycles. An overall weighted average energy consumption is calculated by multiplying the 0.55 weighting factor by the city energy consumption and the 0.45 weighting factor by the highway energy consumption and adding the results. As discussed above, the modeled energy consumption values for the UDDS cycle were used for all three phases of the FTP, the SC03, and the cold CO test. The same procedure was used with the energy consumption values for AVFL-20 fuel #10 at CR10.5 and the results for fuels #1 (4,068 BTU/mile) and #10 (4,110 BTU/mile) were averaged to provide a baseline energy consumption value of 4,089 BTU/mile to represent the light-duty fleet.

Table 5-3. Weighting factors and energy consumption values used to calculate combined energy consumption for the small SUV for AVFL-20 fuel #1.

Drive Cycle	City Energy Consumption Weighting Factor	Highway Energy Consumption Weighting Factor	Small SUV Energy Consumption Value (BTU/mile)	Contribution to City Energy Consumption (BTU/mile)	Contribution to Highway Energy Consumption (BTU/mile)
FTP Phase 1*	0.187	0.015	3838	717.7	57.6
FTP Phase 2*	0.332	-0.087	3838	1274.2	-333.9
FTP Phase 3*	0.113	-0.071	3838	433.7	-272.5
HWFET	0	0.21	2918	0.0	612.8
Cold CO Phase 1*	0.059	0.005	3838	226.4	19.2
Cold CO Phase 2*	0.076	0	3838	291.7	0.0
Cold CO Phase 3*	0.017	-0.005	3838	65.2	-19.2
SC03*	0.122	0.143	3838	468.2	548.8
US06 City	0.093	0	7561	703.2	0.0
US06 Hwy	0	0.79	4200	0.0	3318.0
Total Energy Consumption (BTU/mile)				**4180**	**3931**
Combined City and Highway Energy Consumtion (BTU/mile)				**4068**	

*Use the modeled energy consumption value for the UDDS cycle.

5.4 Applying Fuel-Specific Efficiency Gains to the Baseline Case

The fuel-specific vehicle efficiency gains (including the downsizing factor of 1.1 for turbocharged engines) were used in combination with the fleet-average on-road energy consumption value to calculate fuel-specific fleet average energy use for each fuel. Additionally, the biofuel content and biofuel properties of each blend were used to project the amount of energy use that was derived from biogenic sources and the amount derived from petroleum sources. These values, provided as inputs to the LCA conducted at Argonne are included in Appendix 4.

Calculating volumetric fuel economy and tailpipe CO_2 emissions values for each fuel additionally requires the volumetric heating value (in BTUs per gallon) and carbon intensity (in mg CO_2/BTU) for each fuel. The measured fuel property information for the AVFL-20 and FWG fuels were used for this purpose. Biofuel content and property information was again used to establish the amount of tailpipe CO_2 emissions that were biogenic and those that were derived from petroleum. These values are also included in Appendix 4.

The relative improvements obtained in energy consumption, volumetric fuel economy, and tailpipe CO_2 emissions for "on-road" driving are shown in Table 5.4. The chart is structured so that a positive numerical result is the desired outcome, and is indicated by a green bar. These results are calculated from the totals of biogenic and petroleum-derived quantities for both the energy consumption and tailpipe CO_2 emissions impacts.

Table 5-4. Total energy consumption decrease, volumetric fuel economy increase, and total tailpipe CO_2 emission decrease for the study fuels relative to the baseline case.

Fuel			Total Energy Consumption Decrease			Volumetric Fuel Economy Increase			Total Tailpipe CO_2 Emissions Decrease		
			3.0 ON/CR	3.7 ON/CR	5.6 ON/CR	3.0 ON/CR	3.7 ON/CR	5.6 ON/CR	3.0 ON/CR	3.7 ON/CR	5.6 ON/CR
Nominal RON	96 - 98	14	3.2%	2.6%	1.8%	3.8%	3.1%	2.3%	2.9%	2.3%	1.5%
		20	4.0%	3.4%	2.5%	1.2%	0.5%	-0.4%	3.2%	2.6%	1.7%
		6	3.9%	3.3%	2.6%	-5.3%	-5.9%	-6.6%	6.0%	5.5%	4.8%
		15	4.2%	3.6%	2.8%	-3.9%	-4.5%	-5.3%	4.0%	3.4%	2.6%
		BRS1	3.2%	2.5%	1.6%	7.5%	6.8%	5.8%	1.5%	0.9%	-0.1%
		BRS2	3.0%	2.4%	1.5%	7.4%	6.7%	5.8%	0.8%	0.1%	-0.8%
		WBG2	3.2%	2.6%	1.6%	7.6%	6.9%	5.9%	0.9%	0.2%	-0.7%
		WBG4	3.0%	2.4%	1.5%	7.4%	6.7%	5.8%	0.3%	-0.3%	-1.2%
	101-102	7	4.7%	4.0%	2.9%	1.5%	0.8%	-0.3%	7.7%	7.1%	6.0%
		16	5.0%	4.3%	3.2%	5.8%	5.1%	3.8%	4.5%	3.8%	2.6%
		18	5.5%	4.8%	3.7%	2.4%	1.7%	0.4%	4.7%	4.1%	2.9%
		19	6.0%	5.3%	4.2%	-3.1%	-3.8%	-5.0%	6.9%	6.2%	5.1%
		BRS3	4.6%	3.9%	2.8%	10.2%	9.4%	8.1%	1.2%	0.5%	-0.7%
		BRS4	4.6%	4.0%	2.8%	10.7%	10.0%	8.7%	1.8%	1.2%	0.0%

All of the fuels provided a decrease in total energy consumption, ranging from 1.5%–6.0%. Impacts to volumetric fuel economy ranged from 6.6% poorer to 10.7% better. The difference in efficiency improvements projected for 3.0 ON/CR compared to 5.6 ON/CR ranged from 1.4%–1.8% depending upon the fuel.

Most fuels were projected to provide a volumetric fuel economy increase (improvement) for at least one of the ON/CR values studied. Improvements (increases) in volumetric fuel economy ranged from 0.4%–10.7%. However, the 30% ethanol blends (#6, #15, and #19) did not achieve a high enough efficiency improvement to overcome their lower volumetric heating value, and were thus projected to experience volumetric fuel economy decreases (detriments) at all three ON/CR levels, ranging from 3.1%–6.6%. Fuel #20, a 20% ethanol blend, and fuel #7, a low-aromatic, 10% ethanol blend were projected to experience marginal volumetric fuel economy losses (detriments) at the highest ON/CR level of 5.6, but at lower ON/CR levels provided up to 1.5% volumetric fuel economy increase (improvement). Examination of the results for fuels #18 and #20 suggests that the projected energy consumption improvements are sufficient to overcome the lower volumetric heating value of these 20% ethanol blends at both the 96–98 and 101–102 RON levels except for the 5.6 ON/CR level for 96–98 RON fuels. As discussed previously, all of the E30 blends failed to provide a projected volumetric fuel economy increase at any ON/CR level studied, highlighting the fact that their volumetric heating values are too low to be overcome by projected decreases in energy consumption, even at the 101–102 RON level. The ethanol-free fuel blends (BRS and WBG fuels) provided the largest improvements in volumetric fuel economy, consistent with their higher volumetric heating values.

Most of the fuels were projected to provide a decrease (improvement) in total tailpipe CO_2 emissions for at least one of the ON/CR values studied. The ethanol-blended fuels provided the greatest reductions (improvements) in total tailpipe CO_2 emissions, ranging from 1.5%–6.9%. The ethanol-free blends were all projected to provide a decrease (improvement) in total tailpipe CO_2 emissions at the lowest ON/CR value, and all except WBG4 were projected to provide an improvement at 3.7 ON/CR. These improvements ranged from 0.1%–1.8%. BRS4 was projected to have no change in total tailpipe CO_2 emissions at 5.6 ON/CR, but all of the other ethanol-free fuels were projected to provide poorer (increased) total tailpipe CO_2 emissions, ranging from 0.1%–1.2%.

6. Conclusions from the Engine and Vehicle Modeling Studies

Compression Ratio 11.4:

- The FWG matrix fuels had closely-matched RON and sensitivity values, hence the combustion phasing trends of these fuels at CR11.4 were also similar to one another.

- For the UDDS and HWFET cycles, the energy use for all of the fuels was similar, a range of 1.8% or less from the maximum to the minimum for the sedan and 1.9% or less for the SUV. The E20 fuel provided the lowest energy consumption (0–1.9% better than the ethanol-free blends), lowest tailpipe CO_2 emissions (1-3% lower), and the lowest volumetric fuel economy (5%–7% poorer) for these cycles.

- The difference in energy consumption from fuel to fuel was greater for the city portion of the US06 cycle, with the minimum 2.8% lower than the maximum for the sedan and 3.1% lower for the SUV. The E20 fuel again provided the lowest energy use (0.4%–2.8% better than then ethanol-free blends), lowest tailpipe CO_2 emissions (2.1%–4.0% lower), and lowest volumetric fuel economy (4.0%–6.7% poorer) for both portions of the US06 cycle.

Compared to the baseline case (Average results from AVFL-20 fuels #1 and #10 at CR10.5):

- In general, the FWG matrix fuels at CR11.4 enabled reductions in energy use on the UDDS and HWFET cycles, ranging from 0.2% to 1.5% depending upon the fuel and the vehicle. However, fuel BRS1 produced increases in energy use on the UDDS cycle of 0.6% to 0.9%. The improvements noted for most of these fuels were directionally the same as noted for the AVFL-20 fuels and of similar magnitude. Decreases in energy use for the US06 cycle were larger than for the UDDS and HWFET, ranging from 1.1% to 5.0%. These impacts were also directionally the same as the AVFL-20 fuels, but of marginally lower magnitude.

- With the exception of the E20 fuel (#20), the FWG matrix fuels produced increases in volumetric fuel economy, due both to improvement in energy use as noted previously and because of higher volumetric energy content compared with the two E10 baseline fuels (AVFL-20 #1 and #10). The volumetric fuel economy of the ethanol-free blends increases (improvements) ranged from 3.3% to 7.9%, depending on the fuel, drive cycle, and vehicle. Fuel #20 produced mixed results, with increases in volumetric fuel economy of up to 2% noted on the US06 cycle, though the results for the UDDS and HWFET cycles were lower (worse) by 1.4% to 2.3%. The results for the E20 fuel fall within the range of results from AVFL-20, which studied both E10 and E30 fuels at CR11.4. The results for the non-ethanol biofuels are directionally similar to E10 fuel #14 from AVFL-20, and are consistent with the fuels having comparable energy use but higher volumetric energy content than the baseline case.

- On the UDDS and HWFET cycles, the non-ethanol biofuels caused modeled tailpipe CO_2 emissions to increase (worsen) by 1.0% to 2.5%. The E20 fuel produced mixed results, ranging from a 0.4% increase (detriment) to a 0.7% decrease (improvement). The E20 fuel enabled tailpipe CO_2 emissions reductions (improvements) of 1.7% to 4.2% on the US06 cycle. The non-ethanol biofuels had mixed results on the US06 cycle, ranging from an increase of 1.2% (detriment) to a decrease (improvement) of 1.0% in tailpipe CO_2 emissions depending on the fuel and the vehicle.

- Of all the fuels studied at CR11.4 in the CRC AVFL-20 and U.S.DRIVE FWG projects, only fuel #14 (mid-RON, high sensitivity, E10) had lower energy consumption, better fuel economy, and lower tailpipe CO_2 emissions than the baseline E10 fuels at CR10.5 across all drive cycles.

Conclusions Based on the Fleet-Average Inputs to the LCA Modelling Study:

- Combining energy use from all of the drive cycles to produce an “on-road” energy consumption estimate for the light-duty fleet enables reduction of the results to three performance metrics for each fuel: energy use, volumetric fuel economy, and tailpipe CO_2 emissions.
- Parameterizing the ON/CR ratio was identified as a useful means to examine the sensitivity of the results to the ability for an engine use greater knock resistance to achieve higher efficiency.
- All of the fuels provided a decrease in total energy consumption, ranging from 1.5%–6.0%.
- Impacts to volumetric fuel economy ranged from 6.6% poorer to 10.7% better.
- The difference in efficiency improvements projected for 3.0 ON/CR compared to 5.6 ON/CR ranged from 1.4%–1.8% depending upon the fuel.
- Most fuels were projected to provide a volumetric fuel economy increase (improvement) for at least one of the ON/CR values studied. Improvements (increases) in volumetric fuel economy ranged from 0.4%–10.7%.
- Most of the fuels were projected to provide a decrease (improvement) in total tailpipe CO_2 emissions for at least one of the ON/CR values studied. These improvements ranged from 0.1%–1.8%. BRS4 was projected to have no change in total tailpipe CO_2 emissions at 5.6 ON/CR, but all of the other ethanol-free fuels were projected to provide poorer (increased) total tailpipe CO_2 emissions, ranging from 0.1%–1.2%.

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Appendix 1 – Analyses of AVFL-20 Blendstocks for Oxygenate Blending

	AVFL-20 Blendstocks for Oxygenate Blending (BOBs) - Phase 3 Fuels							
	#1 BOB	#6 BOB	#7 BOB	#10 BOB	#14 BOB	#15 BOB	#16 BOB	#19 BOB
D86 Distillation								
Initial Boiling Point, F	94.7	89.5	89.4	103.7	99.3	96	97.7	99.2
5% Evaporated Temperature, F	118.5	129.9	138.8	129	123.2	129.2	130.3	134.3
10% Evaporated Temperature, F	135.3	151.5	160.2	141.3	133.7	144.6	147.4	158
20% Evaporated Temperature, F	159.1	182.5	190.6	158.5	149.8	166.2	172.2	184.6
30% Evaporated Temperature, F	181.1	207.6	208.5	174.6	167.9	183.5	195.2	203.3
40% Evaporated Temperature, F	205.4	223.3	216.2	195.6	191.9	199.7	215.4	217.3
50% Evaporated Temperature, F	233.7	235.7	220.9	231.4	227.3	220.6	232.6	230
60% Evaporated Temperature, F	258.1	250.5	224.8	274.1	262.4	247.3	247.9	248
70% Evaporated Temperature, F	278.8	278.7	231	291	285.9	279.4	268.4	276.3
80% Evaporated Temperature, F	302.8	324.3	242	302.7	307.8	320.5	307	323.7
90% Evaporated Temperature, F	330.9	342.9	288.6	326.4	334	359.5	338.2	338.4
95% Evaporated Temperature, F	347.6	352.1	337.7	347.8	355.3	375.3	353.5	347.5
End Point, F	379.4	366.4	380	370	379.7	386.4	379.8	362.9
D5191 Vapor Pressure								
RVP, psi	6.98	7.33	6.98	6.58	7.05	6.92	6.43	6.56
D4052 Density								
Density at 15.56 C, g/mL	0.733	0.7169	0.7066	0.7546	0.7499	0.7401	0.7492	0.7313
Octanes (D2699 and D2700)								
Research Octane Number (RON)	85.2	69.2	94.3	86	92	76.5	98.5	83.4
Motor Octane Number (MON)	81.5	70	91.2	79.7	84.9	71.2	90	81.1
Sensitivity	3.7	<1.0	3.1	6.3	7.1	5.3	8.5	2.3

Appendix 2 – Analyses of Fuels Working Group Fuels Matrix Blendstocks for Oxygenate Blending

	FWG Fuels Matrix - BOBs					
	#18 BOB	**#20 BOB**	**BRS1 BOB**	**BRS 2 BOB**	**BRS 3 BOB**	**BRS 4 BOB**
D86 Distillation						
Initial Boiling Point, F	93	97.7	90.3	82.5	86.3	84.5
5% Evaporated Temperature, F	127.9	130.4	117.1	109.5	115.4	109.5
10% Evaporated Temperature, F	147.9	149.3	129.7	121.1	133.1	128.4
20% Evaporated Temperature, F	178.9	178.6	151.3	138.5	165.9	156.7
30% Evaporated Temperature, F	203.9	203.1	172.6	155.9	200.2	184.1
40% Evaporated Temperature, F	225	227.7	194.4	174.4	224.8	210.5
50% Evaporated Temperature, F	243.4	252	216.2	193.9	237.6	225.1
60% Evaporated Temperature, F	262.8	273.9	235.6	214.1	248.3	234.2
70% Evaporated Temperature, F	289	296.2	253	232.6	262.5	243.6
80% Evaporated Temperature, F	319.9	317.8	278.7	249.7	289.2	261
90% Evaporated Temperature, F	338.2	336.8	327.1	282.5	326.1	307.4
95% Evaporated Temperature, F	350.8	349.5	354.1	324.3	346.9	337
End Point, F	377.8	375.2	382.2	374	376.3	373.2
D5191 Vapor Pressure						
RVP, psi	6.86	6.41	8.65	9.92	8.55	10.02
D4052 Density						
Density at 15.56 C, g/mL	0.752	0.756	0.737	0.707	0.753	0.724
Octanes (D2699 and D2700)						
Research Octane Number (RON)	92.3	86.4	96.1	91.3	100.4	98
Motor Octane Number (MON)	86.1	82.2	87	85.6	90.2	89.8
Sensitivity	6.2	4.2	9.1	5.7	10.2	8.1

The finished bioreformate surrogate and wood-derived biogasoline fuels were not blended with oxygenates; the term BOB (blendstock for oxygenate blending) was retained for the petroleum-based hydrocarbon portion of these fuels. No analyses of the BOBs for the wood-derived biogasoline fuels were completed.

Appendix 3 – Analyses of Fuels Working Group Finished Fuels

	FWG Fuels Matrix - Finished Fuels							
	#18	**#20**	**BRS1**	**BRS2**	**BRS3**	**BRS4**	**WBG2**	**WBG4**
D86 Distillation								
Initial Boiling Point, F	102	102	91	90	87	90	83	84
5% Evaporated Temperature, F	128	126	116	118	115	118	102	106
10% Evaporated Temperature, F	140	140	131	134	135	140	118	123
20% Evaporated Temperature, F	152	152	156	161	174	183	146	151
30% Evaporated Temperature, F	159	159	180	187	211	219	177	180
40% Evaporated Temperature, F	163	163	204	213	233	237	205	206
50% Evaporated Temperature, F	166	167	227	236	244	248	225	225
60% Evaporated Temperature, F	236	245	245	254	256	261	240	239
70% Evaporated Temperature, F	268	278	264	272	273	280	254	255
80% Evaporated Temperature, F	304	306	293	299	301	306	277	277
90% Evaporated Temperature, F	335	331	329	327	330	332	310	310
95% Evaporated Temperature, F	347	346	353	348	349	349	338	334
End Point, F	369	365	375	373	374	374	382	381
D5191 Vapor Pressure								
RVP, psi	7.76	7.60	7.86	7.59	7.91	7.49	10.43	9.75
D4052 Density								
Density at 15.56 C, g/mL	0.7596	0.763	0.7511	0.7549	0.7657	0.7672	0.7541	0.7568
Octanes (D2699 and D2700)								
Research Octane Number (RON)	101.3	97.3	97.3	97.1	101.5	101.6	97.6	97.6
Motor Octane Number (MON)	88.8	87.2	87.4	87.3	90.4	90.4	88.3	88.2
Sensitivity	12.5	10.1	9.9	9.8	11.1	11.2	9.3	9.4
D5291 Elemenal Composition								
Carbon Content (wt%)	79.10	79.08	86.87	86.98	87.60	87.28	87.12	87.16
Hydrogen Content (wt%)	13.70	13.60	13.42	13.26	12.82	12.86	12.90	12.84
D4809 Heat of Combustion								
Gross (kJ/kg)	42,645	42,584	46,092	45,859	45,555	45,676	45,811	45,666
Net (kJ/kg)	39,737	39,698	43,244	43,045	42,833	42,945	43,074	42,941
D5599 Oxygenate Determination								
Ethanol Content (vol%)	20.08	20.12	0	0	0	0	0	0
Total Oxygen (wt%)	7.28	7.27	0	0	0	0	0	0

	FWG Fuels Matrix - Finished Fuels							
	#18	**#20**	**BRS1**	**BRS2**	**BRS3**	**BRS4**	**WBG2**	**WBG4**
D6729 Summary by Group (Vol%)								
Paraffin	8.172	10.740	8.040	8.300	6.989	6.843	12.798	10.581
I-Paraffins	38.710	31.553	41.767	40.113	39.873	42.217	38.791	39.780
Aromatics	23.560	23.887	34.401	35.910	46.218	44.557	41.200	41.494
Mono-Aromatics	22.522	22.869	33.044	34.780	45.000	43.192	40.307	40.738
Naphthalenes	0.052	0.047	0.078	0.064	0.061	0.070	0.284	0.209
Naphtheno/Olefino-Benzs	0.986	0.971	1.278	1.066	1.157	1.295	0.607	0.546
Indenes	0	0	0	0	0	0	0.003	0.001
Naphthenes	7.065	10.447	7.932	7.755	3.440	2.664	5.363	5.860
Mono-Naphthenes	7.065	10.447	7.932	7.755	3.440	2.664	5.363	5.860
Di/Bicyclo-Naphthenes	0	0	0	0	0	0	0	0
Olefins	0.992	1.580	5.400	5.465	0.348	0.522	0.874	0.876
n-Olefins	0.219	0.189	4.902	4.833	0.110	0.111	0.305	0.272
Iso-Olefins	0.746	1.221	0.313	0.374	0.218	0.240	0.471	0.502
Naphtheno-Olefins	0.028	0.170	0.185	0.258	0.020	0.172	0.099	0.102
Di-Olefins	0	0	0	0	0	0	0	0
Oxygenates	20.146	20.280	0	0	0	0	0	0
Unidentified	1.355	1.513	2.461	2.457	3.131	3.197	0.974	1.409
Plus	0	0	0	0	0	0	0	0
D6729 Summary by Carbon # (Vol%)								
2	20.146	20.280	0	0	0	0	0	0
4	4.086	3.831	4.918	4.925	5.649	5.463	8.391	6.680
5	8.238	7.718	14.839	13.908	13.814	11.405	14.222	14.247
6	8.128	11.976	14.623	14.081	3.693	3.511	10.082	11.291
7	8.225	9.012	11.570	10.215	16.497	11.865	22.071	22.658
8	25.130	18.039	29.609	30.848	33.445	38.520	28.046	28.227
9	11.712	14.961	12.397	15.294	15.391	16.850	10.251	10.548
10	9.943	9.853	7.251	6.362	6.524	7.146	4.291	3.860
11	2.785	2.585	1.954	1.606	1.551	1.696	1.283	0.818
12	0.242	0.226	0.366	0.294	0.298	0.337	0.357	0.247
13	0.004	0.003	0.012	0.004	0.003	0.004	0.014	0.003
14	0.006	0.004	0.001	0.006	0.004	0.005	0.015	0.010
15	0	0	0	0	0	0	0.003	0.002

Appendix 4 – Values from Engine/Vehicle Study Provided as Inputs to Life-Cycle Analysis

Volumetric Fuel Economy Values

Fuel ID	RON	Heating Value (BTU/gallon)	Ethanol Content (Vol%)	Fleet-Average On-Road Fuel Economy, MPG		
				3 ON/CR	3.7 ON/CR	5.6 ON/CR
14	96.6	112486	10.4	28.4	28.2	28.0
20	97.3	108736	20	27.7	27.5	27.3
6	96	101917	30	25.9	25.8	25.6
15	96.5	103097	30.4	26.3	26.1	25.9
BRS1	97.6	116602	0	29.4	29.2	29.0
BRS2	97.3	116652	0	29.4	29.2	29.0
WBG2	97.7	116607	0	29.5	29.3	29.0
WBG4	97.3	116663	0	29.4	29.2	29.0
7	100.1	108373	10.1	27.8	27.6	27.3
16	101.1	112572	10.2	29.0	28.8	28.4
18	101	108358	20	28.0	27.8	27.5
19	101	101966	29.9	26.5	26.3	26.0
BRS3	101.5	117738	0	30.2	30.0	29.6
BRS4	101.6	118278	0	30.3	30.1	29.8

Fuel ID	RON	Heating Value (BTU/gallon)	Ethanol Content (Vol%)	Fleet-Average On-Road Fuel Economy, MPG_{E10}		
				3 ON/CR	3.7 ON/CR	5.6 ON/CR
14	96.6	112,486	10.4	28.3	28.1	27.9
20	97.3	108,736	20	28.5	28.4	28.1
6	96	101,917	30	28.5	28.3	28.1
15	96.5	103,097	30.4	28.6	28.4	28.2
BRS1	97.6	116,602	0	28.3	28.1	27.8
BRS2	97.3	116,652	0	28.2	28.1	27.8
WBG2	97.7	116,607	0	28.3	28.1	27.8
WBG4	97.3	116,663	0	28.2	28.1	27.8
7	100.1	108,373	10.1	28.7	28.5	28.2
16	101.1	112,572	10.2	28.8	28.6	28.3
18	101	108,358	20	29.0	28.8	28.4
19	101	101,966	29.9	29.1	28.9	28.6
BRS3	101.5	117,738	0	28.7	28.5	28.2
BRS4	101.6	118,278	0	28.7	28.5	28.2

E10 equivalent volumetric fuel economy values are calculated based on the average properties of CRC AVFL-20 fuels #1 and #10 (111,986 BTU/gallon).

Biogenic Energy Use and Tailpipe CO_2 Emissions Values

Fuel ID	RON	Sensitivity	Ethanol Content	Fleet-Average On-Road Energy Use, BTU/mile 3 ON/CR	3.7 ON/CR	5.6 ON/CR
14	96.6	11.1	10.4	277	279	281
20	97.3	10.7	20	553	557	562
6	96	7.5	30	880	886	892
15	96.5	11.6	30.4	878	883	890
BRS1	97.6	10.4	0	392	395	398
BRS2	97.3	10.3	0	1178	1186	1196
WBG2	97.7	10.2	0	206	207	209
WBG4	97.3	10.2	0	619	623	628
7	100.1	7.6	10.1	277	279	282
16	101.1	11.8	10.2	268	270	273
18	101	12	20	545	549	555
19	101	12	29.9	869	875	886
BRS3	101.5	11.1	0	382	385	390
BRS4	101.6	11.2	0	1143	1151	1165

Fuel ID	RON	Total CO_2 Intensity (mg CO_2 / BTU)	Ethanol Content (Vol%)	Fleet-Average On-Road Biogenic Tailpipe CO_2, g/mile 3 ON/CR	3.7 ON/CR	5.6 ON/CR
14	96.6	76.621	10.4	21	21	21
20	97.3	77.011	20	41	42	42
6	96	74.657	30	66	66	67
15	96.5	76.503	30.4	66	66	67
BRS1	97.6	77.661	0	34	34	34
BRS2	97.3	78.118	0	101	101	102
WBG2	97.7	78.191	0	21	21	21
WBG4	97.3	78.47	0	63	63	64
7	100.1	73.913	10.1	21	21	21
16	101.1	76.791	10.2	20	20	20
18	101	76.955	20	41	41	42
19	101	75.647	29.9	65	66	67
BRS3	101.5	79.065	0	33	33	33
BRS4	101.6	78.57	0	98	98	100

Petroleum-Derived Energy Use and Tailpipe CO_2 Emissions Values

Fuel ID	RON	Sensitivity	Ethanol Content	Fleet-Average On-Road Energy Use, BTU/mile 3 ON/CR	3.7 ON/CR	5.6 ON/CR
14	96.6	11.1	10.4	3,681	3,704	3,734
20	97.3	10.7	20	3,370	3,393	3,424
6	96	7.5	30	3,050	3,068	3,091
15	96.5	11.6	30.4	3,040	3,060	3,085
BRS1	97.6	10.4	0	3,568	3,592	3,625
BRS2	97.3	10.3	0	2,788	2,806	2,831
WBG2	97.7	10.2	0	3,752	3,777	3,813
WBG4	97.3	10.2	0	3,347	3,369	3,399
7	100.1	7.6	10.1	3,621	3,647	3,689
16	101.1	11.8	10.2	3,617	3,642	3,686
18	101	12	20	3,320	3,343	3,384
19	101	12	29.9	2,975	2,996	3,033
BRS3	101.5	11.1	0	3,520	3,544	3,586
BRS4	101.6	11.2	0	2,758	2,777	2,810

Fuel ID	RON	Total CO_2 Intensity (mg CO_2 / BTU)	Ethanol Content (Vol%)	Fleet-Average On-Road Petroleum-Derived Tailpipe CO_2, g/mile 3 ON/CR	3.7 ON/CR	5.6 ON/CR
14	96.6	76.621	10.4	282	284	286
20	97.3	77.011	20	261	262	265
6	96	74.657	30	227	229	230
15	96.5	76.503	30.4	234	235	237
BRS1	97.6	77.661	0	274	276	278
BRS2	97.3	78.118	0	209	210	212
WBG2	97.7	78.191	0	289	291	293
WBG4	97.3	78.47	0	249	250	253
7	100.1	73.913	10.1	267	269	272
16	101.1	76.791	10.2	278	280	284
18	101	76.955	20	256	258	261
19	101	75.647	29.9	225	227	230
BRS3	101.5	79.065	0	276	278	281
BRS4	101.6	78.57	0	209	210	213

Total Energy Use and Tailpipe CO_2 Emissions Values

Fuel ID	RON	Sensitivity	Ethanol Content (Vol%)	Fleet-Average On-Road Total Energy Use, BTU/mile		
				3 ON/CR	3.7 ON/CR	5.6 ON/CR
14	96.6	11.1	10.4	3,958	3,983	4,015
20	97.3	10.7	20	3,924	3,950	3,986
6	96	7.5	30	3,930	3,953	3,983
15	96.5	11.6	30.4	3,918	3,943	3,975
BRS1	97.6	10.4	0	3,960	3,986	4,023
BRS2	97.3	10.3	0	3,966	3,992	4,027
WBG2	97.7	10.2	0	3,958	3,985	4,022
WBG4	97.3	10.2	0	3,966	3,992	4,027
7	100.1	7.6	10.1	3,898	3,925	3,971
16	101.1	11.8	10.2	3,885	3,912	3,959
18	101	12	20	3,865	3,892	3,939
19	101	12	29.9	3,844	3,871	3,919
BRS3	101.5	11.1	0	3,902	3,929	3,976
BRS4	101.6	11.2	0	3,901	3,927	3,975

Fuel ID	RON	Total CO_2 Intensity (mg CO_2 / BTU)	Ethanol Content (Vol%)	Fleet-Average On-Road Total Tailpipe CO_2, g/mile		
				3 ON/CR	3.7 ON/CR	5.6 ON/CR
14	96.6	76.621	10.4	303	305	308
20	97.3	77.011	20	302	304	307
6	96	74.657	30	293	295	297
15	96.5	76.503	30.4	300	302	304
BRS1	97.6	77.661	0	308	310	312
BRS2	97.3	78.118	0	310	312	315
WBG2	97.7	78.191	0	310	312	314
WBG4	97.3	78.47	0	311	313	316
7	100.1	73.913	10.1	288	290	293
16	101.1	76.791	10.2	298	300	304
18	101	76.955	20	297	300	303
19	101	75.647	29.9	291	293	296
BRS3	101.5	79.065	0	309	311	314
BRS4	101.6	78.57	0	307	309	312