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Potential Impacts of High-Octane Fuel Introduction in a Naturally Aspirated, Port Fuel-Injected Legacy Vehicle

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Abstract

In recent years there has been an increased interest in raising the octane level of gasoline to enable higher compression ratios (CR) in spark-ignition engines to improve vehicle fuel efficiency. A number of studies have examined opportunities to increase efficiency in future vehicles, but potential impacts on the legacy fleet have not received as much attention. This effort focused on experimental studies on an engine using high-octane fuels without changing the engine's CR. Spark timing was advanced until maximum torque was reached or knock was encountered for each engine condition, using each individual fuel to maximize engine efficiency. Knock-limited conditions occurred as the output brake mean effective pressure (BMEP) neared the maximum attainable output at a given engine speed. Increasing research octane numbers generally enabled knock-free operation under a greater number of operating conditions. Vehicle modeling using Autonomie was used to project vehicle energy use, fuel economy, and tailpipe CO_2 emissions for the Urban Dynamometer Driving Schedule (UDDS), the Highway Fuel Economy Test (HWFET), and the US06 cycle. Results show that decreases in energy consumption of up to 2% for a small SUV are possible through the use of a 97 RON fuel compared to a baseline using 91 RON fuel, provided that the formulation of the fuel does not cause unanticipated operational issues such as lower maximum BMEP. Greater improvements using high-octane fuels are possible if the CR is increased, but there is no opportunity to increase the CR in legacy vehicles. Thus, these vehicles realize an improvement from increased octane rating in accordance with their ability to spark advance to take advantage of a fuel with a higher octane rating. For the modeled vehicle, improvements of up to 2% in volumetric fuel economy may be possible through the use of a 97 RON fuel with the largest gains expected on the US06 cycle. Fuel economy impacts are strongly coupled to the heating value of the fuels in addition to changes in engine efficiency. Similarly, decreases in tailpipe CO_2 emissions are also achievable. However, simultaneous improvements in energy consumption, fuel economy, and tailpipe CO_2 emissions are not guaranteed and are dependent upon fuel formulation.

Keywords

Octane, Legacy fleet, Fuel economy

Introduction

For the past several years, the environmental impact of light-duty vehicles has come under increased scrutiny. Fuel economy standards for new vehicles are increasing as efforts to mitigate greenhouse gas (GHG) emissions take on increased focus. Automobile manufacturers are responding to the challenge posed by these increased fuel economy standards by investigating multiple means for improving vehicle energy efficiency, including the use of fuels with improved octane ratings. Octane ratings are the dominant fuel characteristics that describe resistance to knock during engine operation. Knock is a form of undesirable autoignition, so named because of the sound it produces when it occurs. Increasing a fuel's resistance to knock enables automobile manufacturers to design engines with higher compression ratios (CRs), which in turn allow improvements in the energy efficiency of the engine. CR is the volume of an engine cylinder when the piston is at bottom dead center divided by its volume at top dead center.

There have recently been several studies aimed at estimating the potential energy efficiency and GHG benefits that could be achieved if future automobiles were optimized for fuels with higher-octane ratings. Leone et al. present a thorough model based on the data from multiple studies to project efficiency and fuel economy improvement possible for future vehicles using high-octane fuels [1]. Sluder et al. studied the potential efficiency, fuel economy, and CO_2 impacts on future vehicles using an extensive matrix of fuels designed to investigate the research octane number (RON), octane sensitivity, and ethanol content [2]. Although there has long been an understanding that engine efficiency improves with increased CR, Smith et al. found that data to describe this relationship were scarce. Their investigation studied modern engines with a range of CRs, allowing them to produce an equation based on these data to predict efficiency improvements associated with the CR [3]. This work was extended to provide a projected benefit to future vehicles in the U.S. light-duty fleet by Speth et al. This study found that fleet fuel consumption could be reduced by 4.5-6.0% by using high-octane fuels [4]. Leech et al. studied the potential benefits of increasing octane using a 1.2-liter engine and found that increasing to 102 RON enabled a CR of 12.2. This higher CR in turn produced efficiency gains of 4-15% depending on the operating condition [5]. West et al. investigated the potential fuel economy and emissions changes in two vehicles using a 25% ethanol fuel [6]. This study highlighted the importance of both engine efficiency and fuel heating value on vehicle fuel economy. Leone et al. examined the potential fuel economy gains that are possible in the future light-duty pickup truck associated with ethanol-blended high-octane fuels that were created both by splash blending and match blending. Their results showed that splash blends (allowing ethanol to increase octane ratings) provided efficiency benefits [7]. Using match-blended fuels resulted in no opportunity for efficiency gain. Sluder et al. expanded on existing data using ethanol blending by including two non-oxygenated paths to high-octane fuels [8]. This study examined the impact of high-octane fuels on future vehicles of the U.S. light-duty fleet and found that using high-octane fuels could provide reductions in tailpipe CO_2 emissions and fuel consumption.

Despite the wealth of information available on the impact of high-octane fuels on future vehicles, existing nonoptimized "legacy" vehicles that are already in use have not been investigated thoroughly. This study seeks to provide information about the impact of potential high-octane fuel formulations on the energy use and fuel economy of vehicles such as those in the legacy fleet.

Retirement and replacement of legacy vehicles occur over an extended time period. On average, about 5% of vehicles in the United States are replaced annually, with 73.4% of in-use vehicles at least 5 years old, 44.5% at least 10 years old, and 18.8% at least 15 years old [9]. If the lower limit of octane number in the marketplace is increased, the use of the higher octane fuel in legacy vehicles is likely to be significant for about two decades past the introduction of the fuel. Some formulations (such as increased ethanol blending) may not be compatible with the legacy fleet and could be introduced into legacy vehicles over this time period unless measures are taken to prevent these vehicles from using the new fuel. In the United States, the legacy light-duty fleet includes a large number of cars that use port-fuel injected, naturally aspirated engines. The energy use and GHG emission impacts for these cars while using the new fuel may be quite different from those of new vehicles designed to take advantage of the increased octane rating.

Unlike potential future vehicles that could be designed to take advantage of increased octane rating, there is no opportunity to increase the CR in legacy vehicles that are already in use. Hence, increased fuel octane rating may not result in significant engine efficiency or vehicle fuel economy increases in these vehicles. The present study focused on using a combined experimental and modeling approach to estimate the fuel economy impacts of some high-octane fuel formulations on vehicles in the legacy fleet. High-octane fuel formulations of interest were first studied experimentally in an engine to establish how they influenced engine fuel consumption. Once these data were gathered, they were then used in a vehicle modeling study to estimate the impacts that the measured engine fuel consumption may have on vehicle energy consumption, fuel economy, and tailpipe CO_2 emissions.

Engine Study

The first step in the current study was to gather engine data with a series of fuels of interest to the study. This section details the engine setup and fuels used for the study.

Engine Setup

An engine was identified for use in an investigation of the potential improvements in engine efficiency that may be achievable with engines such as those that are used by the legacy light-duty vehicle fleet in the United States when high-octane fuels are used. A model year 2015 1.4-liter fully integrated robotized engine naturally aspirated engine with MultiAir manufactured by FCA US LLC was available for this purpose. This engine has a 72 mm bore and 84 mm stroke. This configuration produces a four-cylinder engine with a displacement of 1.4 liters. The engine used in this study had a CR of 10.8 and a port fuel injection (PFI). The engine was controlled with an engine control unit that provided access for modification of the relevant control parameters to execute the study.

This engine was equipped with the MultiAir variable valve actuation (VVA) system that allows early intake valve closure (EIVC) at light loads to enhance efficiency. For the purpose of this study, the intake valve closing angle that yielded the maximum torque at each engine speed was determined and used as data that were collected at individual engine speed and load points. This approach approximated VVA strategies of older, less capable systems typical of engines in the legacy fleet. The maximum achievable torque observed in this study was lower than the torque achieved in the original calibration of the engine; hence, the VVA settings may not agree with those of the original calibration at maximum torque. The engine was installed in a research facility at Oak Ridge National Laboratory (ORNL) that provided a dynamometer for load absorption, industry-standard exhaust gas instrumentation, and a Coriolis fuel mass flow meter. The engine was outfitted with an AVL optical encoder to measure the crankshaft position and Kistler 6052CU20 piezoelectric pressure transducers to measure the in-cylinder pressures. Custom combustion analysis software was used to assess combustion phasing, heat release rate, and knock onset.

The engine was operated in a fully warmed state using intake air conditioned to 25°C and with a dew point of 15°C.

Brake mean effective pressure (BMEP) increments of nominally 100 kPa were studied from near-zero brake output to maximum torque at five engine speeds (1000 RPM, 1500 RPM, 2000 RPM, 2500 RPM, and 5000 RPM) to permit the development of fuel consumption data. Maximum BMEP conditions were also included at intermediate speeds. Combustion phasing was kept approximately constant at 8 crank angle degrees (CAD) after top dead center (ATDC) for part-load conditions where knock did not occur. As the engine output torque increased, the engine entered a knock-limited operation, requiring the combustion phasing to be retarded to avoid knock. Although the engine was equipped with a knock sensor, knock-limited combustion phasing was set individually for each operating condition and for each fuel being studied. A manual adjustment was deemed to be necessary to assure reliable results because fuel #15 was outside the designed fuel characteristics for the engine. A combination of maximum amplitude of pressure oscillation (MAPO) and feedback from the engine control unit's knock avoidance algorithms was used to identify the onset of knock. Since the engine was operated over a range of speeds, a single value of MAPO could not be used as a reliable knock threshold. Instead, the spark was advanced until a nonlinear MAPO increase with marginal spark advance was observed at each load and speed condition. Once this point was identified, spark timing was retarded slightly to remove the knocking condition.

Fuels

This study is related to a previous study that investigated the potential efficiency benefits of high-octane fuels in a gasoline turbocharged, direct-injection (GTDI) engine [2]. Fuels used in the previous GTDI engine study were also used with the PFI engine. The fuels were designed to enable a comparison of the effects of RON, octane sensitivity, and volumetric ethanol content. To examine the potential impacts of high-octane fuels in legacy vehicles, four fuels were studied. Two fuels (#1 and #10) were nominally 91 RON fuels containing 10% ethanol, while two fuels (#14 and #15) were nominally 97 RON fuels formulated with 10% and 30% ethanol. Table 1 provides more detail on the characteristics of these fuels.

TABLE 1 Fuel characteristics.

Characteristic	Method	Fuel number 1	10	14	15
RON	D2699	91.8	91.4	96.6	96.5
MON	D2700	84.5	81	85.5	84.9
Sensitivity	(RON-MON)	7.3	10.4	11.1	11.6
Net heating value (MJ/kg)	D4809	41.861	41.544	41.581	38.06
Carbon (wt%)	D5291	80.91	82.78	83.6	75.07
Hydrogen (wt%)	D5291	14.12	13.47	13.88	13.67
Ethanol (vol%)	D4815	10.4	10	10.35	30.37
CO_2 intensity (mg CO_2/kJ)	Calculated	71.69	73.16	72.67	72.56
Density (kg/l)	D4052	0.737	0.758	0.752	0.755

Experimental Results

Increasing the RON provides greater fuel knock resistance, reducing the need for combustion-phasing retardation to avoid knock, all other things being equal. Reducing the combustion phasing retardation produces more advanced phasing that allows the engine to extract a greater amount of work from the combustion products, increasing engine efficiency. Figure 1 shows a comparison of the 50% burn combustion phasing (CA50) for the four fuels at 2,000 RPM. Knock onset for all four fuels occurs at a BMEP of approximately 800-900 kPa. Once CA50 phasing retardation to avoid knock occurs, fuels #14 and #15 provide the ability to avoid knock while operating with less combustion phasing retardation, providing greater engine efficiency. The BMEP level where knock onset was observed increased with increasing engine speed. The greater knock resistance offered by fuels #14 and #15 allowed a wide-open-throttle operation without knock onset, beginning at engine speeds as low as 2,500 RPM. At 5,000 RPM the maximum achievable BMEP for this study could be attained without retarding the combustion phasing regardless of the fuel being used. Figure 2 shows an overall view of the engine conditions used to generate fuel consumption data for fuel #14. Fuels #1 and #10 produced peak BMEP values similar to those observed with fuel #14. Fuel #15 produced lower peak BMEP values, particularly at higher engine speeds. Figure 3 shows the data resulting from experiments with fuel #15. Figure 4 shows the maximum observed BMEP for all of the fuels. In this plot, the lower maximum output for fuel #15 is particularly evident.

The specific reason for this reduced maximum torque with fuel #15 is unclear, although it appeared to have been related to reduced trapped charge mass. This difference may have arisen because of the larger volume of fuel vapor in the port for the E30 blend, which could displace air and reduce overall stoichiometric charge mass. It may also have been an artifact of an unforeseen reaction by the engine's control algorithm to the combination of the fuel and VVA operational

FIGURE 1 Combustion phasing (CA50) trends at 2,000 RPM for the four study fuels show that the engine is knock limited at high-BMEP conditions; 97 RON fuels (#14 and #15) provide combustion phasing benefits at these conditions.

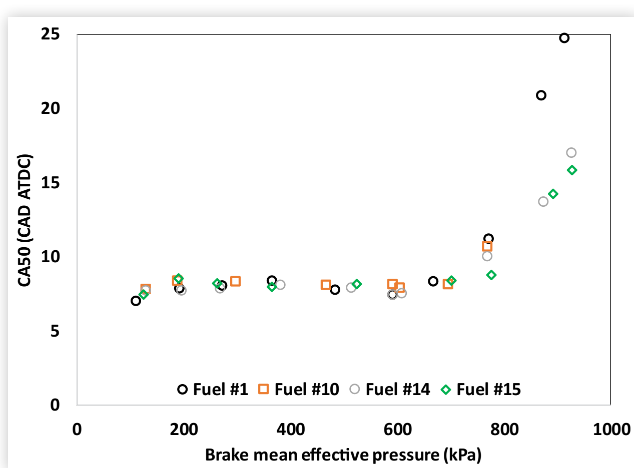


FIGURE 2 Operation with fuel #14 resulted in a knock-limited operation at high-BMEP conditions at engine speeds of up to 2,500 RPM, but at higher engine speeds, knock was not observed. Knock-limited conditions are denoted by the open symbols.

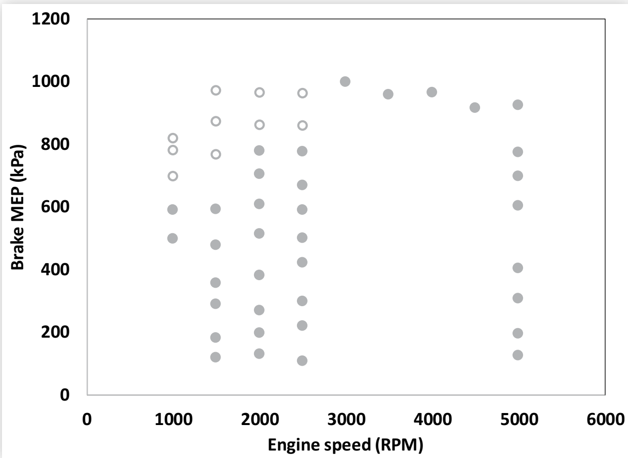
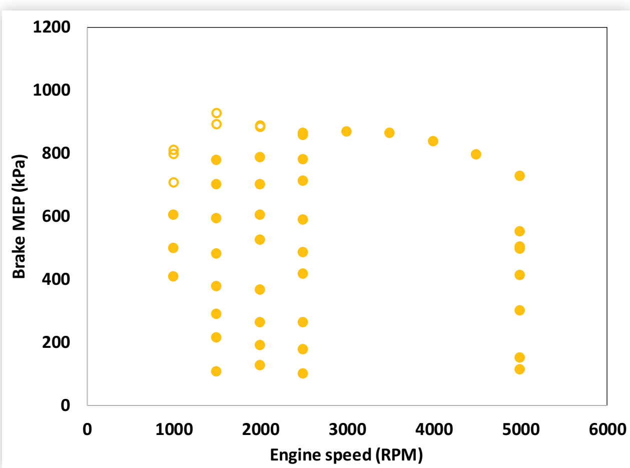


FIGURE 3 Operation with fuel #15 resulted in a knock-limited peak BMEP values of up to 2,000 RPM. Peak BMEP levels at higher engine speeds declined relative to the other fuels.



approach. Unfortunately, it wasn't within the project scope to conduct experiments to add clarity to this situation.

Figures 2 and 3 for fuels #14 and #15 show filled symbols for the conditions where knock does not influence the combustion phasing. Fuels #1 and #10 have a lower RON rating and therefore are expected to have a smaller knock-free operating space than fuels #14 and #15. Results for fuels #1 and #10 are shown in Figures 5 and 6. At a given engine speed, the onset of knock occurs at BMEP levels between 600 kPa and 1,000 kPa. These levels are fairly similar to those where knock onset was observed for fuels #14 and #15. However, knock was observed at the maximum BMEP condition at engine speeds of up to 4,500 RPM for fuels #1 and #10. Maximum BMEP

FIGURE 4 Maximum observed BMEP versus engine speed shows the lower maximum output that was observed for fuel #15 compared to the other fuels.

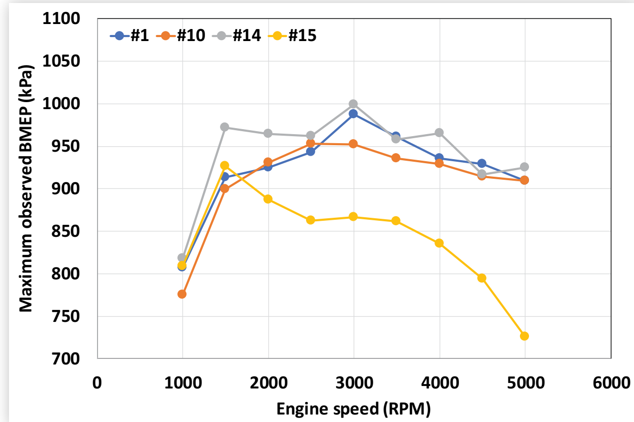
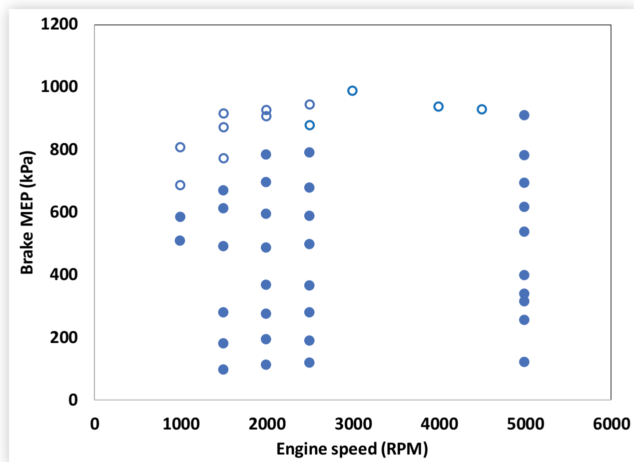


FIGURE 5 BMEP and RPM data collected for fuel #1 show that knock-limited conditions persisted at maximum BMEP of up to 4,500 RPM.

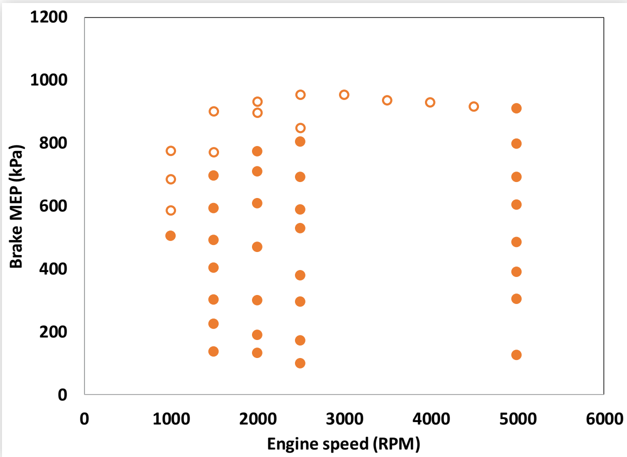


was attainable without knock for fuels #14 above 2,500 RPM and #15 above an engine speed of 2,000 RPM.

The BMEP values at the onset of knock for this naturally aspirated engine are similar to those observed for a turbocharged engine in previous studies using the same fuels [2, 8]. However, the turbocharged engine produced maximum BMEP levels that were much higher than those produced in the naturally aspirated engine reported herein [2]. This difference causes the range of knock-limited operation for the turbocharged engine to be much larger than for the naturally aspirated engines. Thus, the benefit of increasing RON in this naturally aspirated engine is considerably more limited than for turbocharged engines.

Fuel mean effective pressure (fuel MEP) is a measure of the fuel energy consumed by the engine per engine cycle normalized by the displacement of the engine [10, 11, 12, 13]. The fuel consumption measurements for the four study fuels

FIGURE 6 BMEP and RPM data collected for fuel #10 show that knock-limited conditions persist at maximum BMEP of up to 4,500 RPM.



were used to calculate fuel MEP and examine its relationship to BMEP. Published work has established that the two quantities are related linearly, with the slope of the regression line related to the marginal engine efficiency and the intercept term related to friction and pumping loads on the engine [10, 13]. At the onset of knock, the need to retard the combustion phasing causes the relationship between fuel MEP and BMEP to depart from linearity. Figure 7 shows fuel MEP versus BMEP for each of the four study fuels.

Linear regressions were performed for each of the sets of fuel MEP data. Table 2 shows the slope and intercept for each regression. Fuels #1, #10, and #14 exhibit good agreement in both slope and intercept. Fuel #15 exhibits a lower slope than the other fuels, possibly a result of an efficiency gain derived from its ethanol content. A previous paper by researchers at Ford Motor Company has shown that ethanol blending provides an efficiency benefit at part-load conditions [14]. The difference between the slope for fuel #15 and the slopes of the

FIGURE 7 Fuel MEP data for the study fuels plotted versus BMEP shows the expected linear relationship.

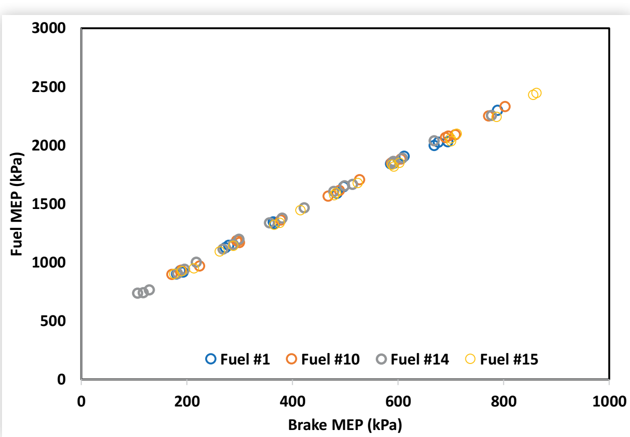


TABLE 2 Regression of fuel MEP with BMEP shows that the E10 fuels have marginally higher slopes than fuel #15 and that there is good agreement among the intercept values.

Fuel	Slope	Intercept (kPa)
#1	2.2559	505.5
#10	2.2775	499.7
#14	2.2818	503.5
#15	2.2275	505.5
E10 fuels	2.2725	503.3
All fuels	2.2614	503.7

E10 fuels in this study suggests that this may be the case for this engine as well, but the difference in slope for fuel #15 compared to the E10 fuels is not statistically significant at the 90% confidence level.

The linear regression between fuel MEP and BMEP, shown in Table 2 for each fuel, was used to calculate fuel consumption rates for each BMEP level in the maximum brake torque (MBT) operating space. The measured fuel consumption values were used for knock-limited conditions. This approach was also used in previous studies for the purpose of minimizing the impact of the experimental error on vehicle modeling results.

Vehicle Modeling

The next step in the study focused on using the data generated during the engine study to support vehicle modeling. Vehicle modeling was used to project the impacts that changes in knock behavior observed during the experimental engine study may have on vehicle fuel efficiency. An industry-average small sport-utility vehicle (SUV) was selected as the target vehicle for this study. The parameters needed to describe this vehicle in the Autonomie model were adopted from a previous study and are shown in Table 3 [2]. Since this vehicle would be equipped with an engine larger than a 1.4-liter PFI engine to achieve consumer-acceptable performance, the fuel consumption and brake torque data from the experimental

TABLE 3 Parameters used to describe the midsize SUV in Autonomie.

Parameter	Value
Target coefficient A (lbf)	31.3622
Target coefficient B (lbf/MPH)	0.3408
Target coefficient C (lbf/MPH^2)	0.0235
Equivalent test weight (lb)	4000
1st Gear ratio	4.584
2nd Gear ratio	2.964
3rd Gear ratio	1.912
4th Gear ratio	1.446
5th Gear ratio	1.000
6th Gear ratio	0.746
Final drive ratio	3.21
Tire rolling radius (m)	0.32775

FIGURE 8 Scaling the naturally aspirated engine up from 1.4 liters to 2.95 liters displacement provides an approximate match to the torque curve produced by a 1.6-liter turbocharged engine.

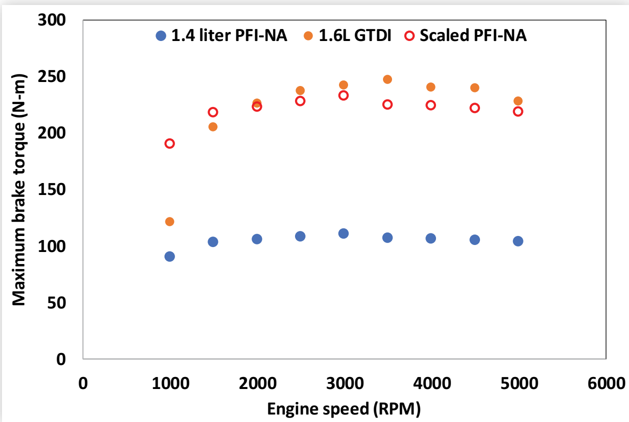
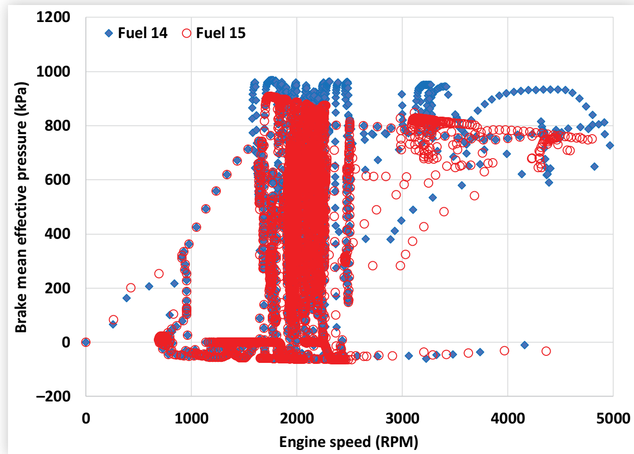


FIGURE 9 The lower maximum BMEP levels produced by fuel #15 caused it to exhibit vehicle operation at lower BMEP and higher engine speed than for the other fuels. Fuel #14 is shown for comparison.



study were scaled to approximate those of a larger engine. A previous study [2] had investigated a 1.6-liter turbocharged engine in this vehicle. Comparing the maximum torque available at each engine speed for the turbocharged engine compared with the naturally aspirated engine shows that the naturally aspirated engine needs to produce additional torque to approximate the torque values produced by the turbocharged engine. Scaling the naturally aspirated engine to a displacement of 2.95 liters provides approximately 95% of the peak torque and a reasonable match to the remainder of the torque curve of the turbocharged engine. These comparisons are shown in Figure 8. Scaling was accomplished by using the measured fuel MEP and BMEP values from the experimental study and using 2.95 liters rather than 1.4 liters as the engine displacement when calculating brake torque and fuel consumption rate results. The scaled values for brake torque and fuel consumption rate were then used as input to the Autonomie model to describe the engine performance when each fuel is used.

Vehicle Model Results

Three drive cycles were used to study vehicle efficiency projections for the four study fuels. The U.S. Environmental Protection Agency (EPA)'s Urban Dynamometer Driving Schedule (UDDS) is the driving schedule that is used in the Federal Test Procedure, or FTP. The UDDS contains driving segments that are typical of city driving. These segments are typically low speed, have relatively low acceleration rates, and are separated by periods of idle operation. The Highway Fuel Economy Test (HWFET) examines driving that is more typically encountered during operation on highways. Vehicle speeds on this cycle are faster than on the UDDS, and there is little idle operation on the HWFET. The US06 cycle contains more aggressive driving segments than either the UDDS or HWFET. The US06 includes high rates of acceleration and high speeds. It is divided into a city portion and a highway portion for use in calculating fuel economy values for new vehicles.

Shift Points for Fuel #15 During vehicle modeling, the reduced maximum BMEP observed for fuel #15 caused Autonomie to select different gear shift points for this fuel relative to the other fuels. This difference was most significant for the US06 cycle. Figure 9 shows the BMEP and engine speed conditions Autonomie projected for fuel #15 compared with those of fuel #14 on the city portion of the US06 cycle. The difference in maximum BMEP causes the model to use conditions that are lower in BMEP and higher in engine speed than fuel #14. This difference is likely to produce a reduction in engine efficiency when fuel #15 is used relative to when fuel #14 is used.

To aid in separating potential impacts from fuel properties for fuel #15, modeling was also conducted using a low-torque version of the fuel map for fuel #14. This map was constructed by artificially lowering the maximum output torque for fuel #14 to match that of fuel #15. Figure 10 shows a comparison between the predicted operating conditions for fuel #15 and the #14 low-torque map. The predicted operating points for these two cases agree well, suggesting that the #14 low-torque map will be useful in separating impacts from the different shift points from those that result from fuel properties for fuel #15.

Vehicle Energy Consumption Vehicle energy consumption is closely linked to the fuel consumption rates determined from the engine experiments. This metric provides a means to examine the impacts that changes in engine efficiency have on the vehicle's energy use. Figure 11 shows the energy consumption for each fuel (including the low-torque map for fuel #14) on the UDDS, HWFET, and the city and highway portions of the US06 cycle. The results for the fuel #15 and low-torque fuel #14 map are shown hatched to highlight the fact that they have a different shift schedule than fuels

FIGURE 10 Predicted conditions for fuel #15 and the low-torque map for fuel #14 on the city portion of the US06 cycle agree well.

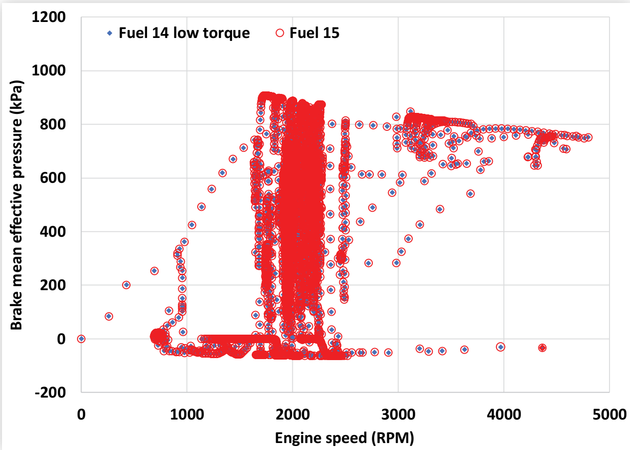
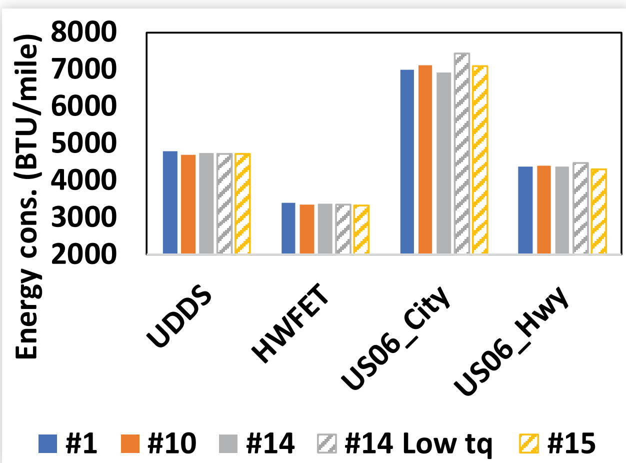


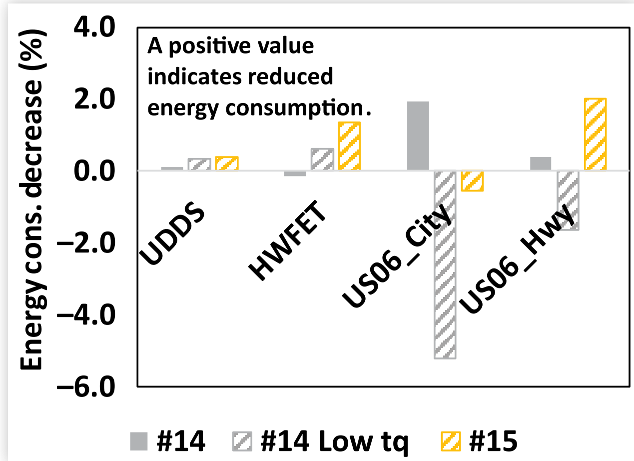
FIGURE 11 Energy consumption results for the study fuels on the UDDS, HWFET, and the city and highway portions of the US06 cycle.



#1, #10, and #14. Figure 12 shows energy consumption as a percentage change from the baseline condition. The baseline condition was taken to be the average result from fuels #1 and #10, as was used in a previous study using a turbocharged engine [2].

The results for the UDDS and HWFET cycles are comparable for all fuels. On these relatively lightly loaded drive cycles, there is minimal operation under knock-limited conditions, and consequently, no significant benefit from the higher octane of fuels #14 and #15 is observed. Fuel #14 exhibits little change from baseline on either cycle. A comparison of the results for the low-torque map for fuel #14 and fuel #15 shows that the difference in shift schedule caused a small decrease in energy consumption. Fuel #15 had a greater decrease in energy consumption, indicating an efficiency benefit relative to fuel #14. This occurrence is consistent with the difference in the fuel MEP regression discussed previously. However, considering that a portion of the improvement is caused by

FIGURE 12 Energy consumption results shown as a percentage decrease compared to baseline, with the baseline case taken as the average result for fuels #1 and #10.



the difference in shift schedule, the improvement derived from ethanol blending is likely about 1% or less for the UDDS and HWFET cycles.

Fuel #14 exhibits a decrease in energy consumption on both portions of the US06 cycle. This decrease is a result of its increased RON compared to the baseline fuels, which enables more efficient operation under knock-limited conditions. On the aggressive US06 cycle, the octane benefit is less than 2% for the city portion of the cycle and less than 1% on the highway portion. Fuel #15 exhibits an increase in energy consumption on the city portion of the US06, which is a consequence of the difference in operating points illustrated in Figure 8. The low-torque map for fuel #14 produces a greater increase in energy consumption than fuel #15. The difference between these two results suggests that fuel #15 may have exhibited an efficiency improvement in this cycle in the absence of the shift schedule difference.

Both fuels #14 and #15 exhibit a decrease in energy consumption on the highway portion of the US06 cycle. The decrease in fuel #14 is less than 1%. The comparison of the results for the low-torque map for fuel #14 to fuel #15 shows that the difference in shift schedule again causes an overall increase in energy consumption. In this cycle the increased efficiency of fuel #15 compared to #14 allows it to overcome the disadvantage posed by the shift schedule change. For this reason, fuel #15 was projected to produce an overall energy consumption decrease approaching 2%. Had the shift schedule change not been a factor, fuel #15 may have provided greater benefit.

It is important to highlight the difference in maximum attainable BMEP with fuel #15 as the cause of the shift schedule difference for this fuel compared with other fuels. It was not possible to precisely determine the root cause of this detriment in BMEP during this project. As a result, it is not possible to conclude with certainty whether the difference is a direct result of the use of a fuel containing 30% ethanol or whether it resulted from the operating strategy adopted for the VVA system in this study. In light of this limitation, the results for fuel #15 should not be taken to broadly represent the effects this fuel may have on legacy vehicles. It is important to note that the introduction of an E30 fuel into the legacy fleet could pose risks for the fuel system, engine, or emissions control failures. For this reason, the potential use of E30 fuel in legacy vehicles would be subject to reviews similar to those conducted when E15 was introduced in the United States.

Vehicle Fuel Economy Volumetric fuel economy is dependent on energy use for a given cycle but also includes the important effects of the heating value of the fuel. Volumetric fuel economy and percent improvement projections for the study fuels are shown in Figures 13 and 14.

Fuel #10 exhibits the highest projected fuel economy on the UDDS and HWFET cycles. This occurrence is consistent with the energy consumption results for both cycles and the fact that fuel #10 has the highest volumetric energy content of the study fuels. Fuel #14 is projected to provide a fuel economy higher than fuel #1 but less than that of fuel #10, with a small improvement compared to the baseline case of less than 1%. The low-torque map for fuel #14 exhibits a fuel economy increase marginally larger than that of fuel #14 (E10), while the projected fuel economy for fuel #15 (E30) is 7.6% lower. The combined effects of energy consumption and a volumetric heating value of 8.3% lower than that of fuel #14 cause the fuel economy for fuel #15 to be lower than that of the #14 low-torque map.

Fuel #14 is also projected to provide a fuel economy benefit compared to the baseline on both portions of the US06 cycle. The energy consumption results showed that fuel #14 did exhibit lower energy consumption; this occurrence is consistent with fuel #14 gaining an advantage from its higher RON rating. However, the fuel economy results show that fuel #10 produces a fuel economy that is very similar to that of fuel #14. This occurrence is a result of the 0.7% higher volumetric heating value of fuel #10 compared to fuel #14.

Fuel #15 and the low-torque map for fuel #14 are projected to reduce fuel economy on both portions of the US06 cycle. The directional agreement between the fuels shows that the difference in shift schedule is responsible in part for the decreased fuel economy of fuel #15. However, the 8.3% decrease in the volumetric heating value of fuel #15 compared to fuel #14 is responsible for the largest portion of the fuel economy decrease relative to the baseline.

FIGURE 13 Projections show that the volumetric fuel economy is in most cases consistent with the heating value of the fuel.

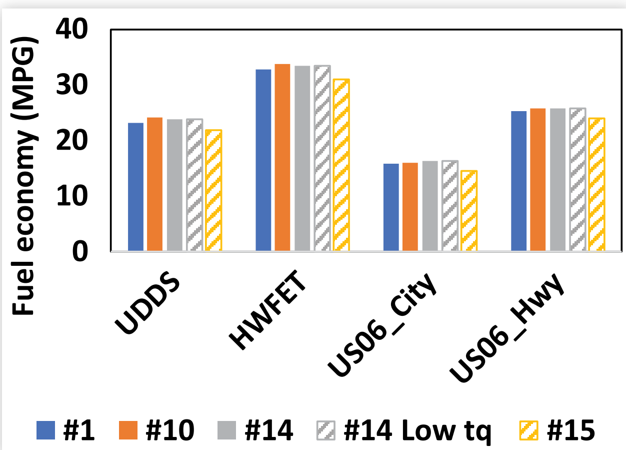
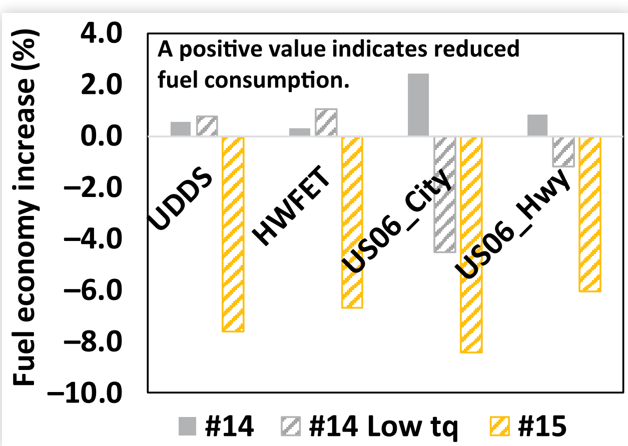


FIGURE 14 Percent increases in volumetric fuel economy of up to 2% are projected for fuel #14. Fuel #15 is projected to produce greater decreases in fuel economy than the low-torque map for fuel #14, consistent with its reduced heating value.



Tailpipe CO_2 Emissions Figures 15 and 16 show the tailpipe CO_2 emissions projected during the vehicle modeling study. Fuel #14 is projected to marginally increase tailpipe CO_2 emissions on the UDDS and HWFET cycles. This outcome is a result of the similar energy consumption for the two fuels combined with the higher carbon content of fuel #14. The low-torque map for fuel #14 results in CO_2 emissions that are nearly the same as the baseline. Fuel #15 is projected to provide reduced tailpipe CO_2 emissions relative to the low-torque map for fuel #14.

FIGURE 15 Projected tailpipe CO_2 emissions for the study fuels.

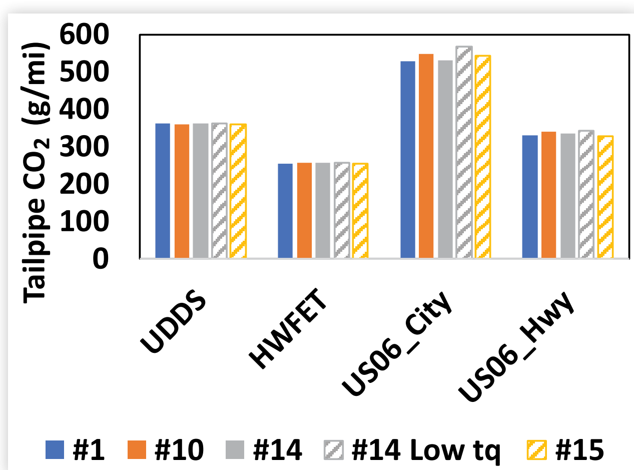
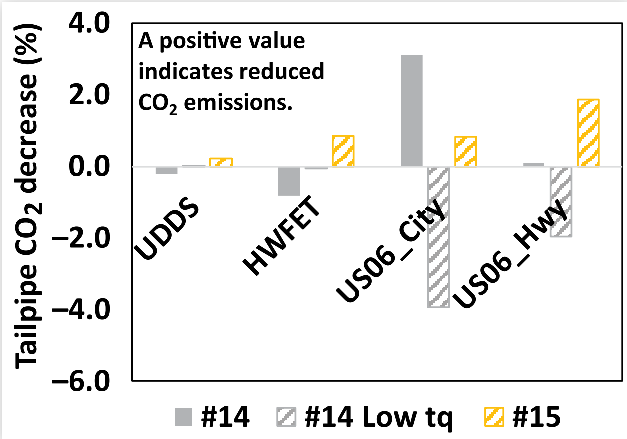


FIGURE 16 Projected percent decreases in tailpipe CO_2 emissions highlight mixed results.



Fuel #14 is projected to provide reduced tailpipe CO_2 emissions on both portions of the US06 cycle, with the greater benefit on the city portion exceeding a 2% improvement. The low-torque map for fuel #14 is projected to increase tailpipe CO_2 emissions as a result of the change in shift points. Despite this detriment, fuel #15 is projected to provide reduced tailpipe CO_2 emissions.

Legacy Fleet Impacts of High-Octane Fuels

The results of this study show that the use of 97 RON fuel compared to a 91 RON fuel baseline case enables energy consumption for the engine and vehicle studied to decrease by up to 2%, depending upon the drive cycle used. Very little benefit was projected on the UDDS and HWFET cycles, with the greatest potential benefit projected for the US06 cycle. This trend is a result of the low occurrence of knock-limited operation on the UDDS and HWFET cycles and a higher level of occurrence on the US06 cycle. While the engine experiments conducted as a part of this study allowed the engine to gain efficiency when a high-RON fuel was used, it is important to note that not all engines present in legacy vehicles are likely to gain this advantage. Some engines may lack the ability to advance combustion phasing when a high-RON fuel is present because either of cylinder pressure limitations that prevent a manufacturer from gaining an advantage through phasing advance or their control algorithms were not designed to allow it. It is also conceivable that OEMs could design and optimize their engines in a way that could gain a greater advantage than was observed in this study, but this situation would be limited by EPA regulations, as discussed previously [15].

The results of this study showed that fuel #14 (97 RON, E10) could produce an increased fuel economy. As was observed with energy consumption, the greatest benefits are obtained on the US06 driving cycle. The increase in fuel economy was 2% or less, which is consistent with an EPA requirement that vehicles certified using a premium-grade certification fuel must not experience more than a 3% decrease in fuel economy if a regular-grade fuel had been used for certification [15].

Fuel #15, an E30 fuel, had a reduced volumetric energy content than the other fuels, which were E10 fuels. This reduced volumetric energy content caused the fuel economy to decrease for fuel #15 despite efficiency gains that were also observed for this fuel. This result occurs because the efficiency gain produced noted during the engine experiments was not large enough to offset the reduced heating value of the fuel. Within the constraints of the adopted engine operating procedure, Fuel #15 produced a lower maximum BMEP in the study engine that led to differing shift point selection in the vehicle model. Although this result may not be generally applicable, it is nevertheless important to consider that such unexpected results may occur when an unanticipated fuel formulation is introduced into legacy vehicles. In such a circumstance, unforeseen changes to the operation (including those arising from the incompatibility of elastomers and plastics with the fuel) of those vehicles may occur that can impact their fuel economy.

Tailpipe CO_2 emissions for fuel #14 were projected to rise marginally on the UDDS and HWFET, while declining on the US06 cycle compared to the baseline. Fuel #15 was projected to provide decreases in tailpipe CO_2 emissions despite the disadvantageous impact of the difference in shift points. This outcome is a result of the lower carbon content of the E30 fuel.

Conclusions

This study examined the potential impact that the introduction of high-octane fuel could have on an unmodified port fuel-injected, naturally aspirated engine. Further, the study examined how this impact could influence vehicle energy consumption, fuel economy, and tailpipe CO_2 emissions.

- Provided that the engine control unit can advance combustion phasing, efficiency losses resulting from knock avoidance can be reduced in legacy engines. These reductions occur as the engine nears its peak BMEP at the given engine speed.
- Knock-limited conditions for this engine occur for a small fraction of the engine operating range investigated. Thus, the benefit of increasing RON in this naturally aspirated engine is considerably more limited than for turbocharged engines.
- For the engine operating strategy adopted for this investigation, the 30% ethanol fuel (#15) caused a reduction in the maximum attainable BMEP for the engine. The specific root cause could not be determined within the project scope but appeared to be either a result of fuel vapor displacing fresh air in the port or an

artifact of the variable valvetrain operating strategy used during experiments.

- Fuel #15 (97 RON E30) produced higher engine efficiency than the other fuels when considered at the same operating conditions, as shown by the lower fuel MEP values at a given BMEP.
- Vehicle modeling using the data collected from engine experiments projected that decreases in energy consumption of up to 2% were possible for a small legacy SUV, depending upon the fuel and drive cycle.
- Vehicle model projections show that volumetric fuel economy may decrease up to 8% (with fuel #15, 97 RON E30) or increase up to 2% (with fuel #14, 97 RON E10) when high-octane fuels are used in the modeled legacy vehicle. While shift schedule differences make a direct comparison to baseline difficult, the results point to a likelihood of decreased volumetric fuel economy for fuel #15 (E30).
- The 97 RON E10 fuel #14 is projected to increase tailpipe CO_2 emissions relative to the baseline by up to 0.8% on the UDDS and HWFET, but to provide decreased CO_2 emissions of up to 3.1% on the US06. Fuel #15 (E30) appears likely to provide tailpipe CO_2 emissions decreases despite the effects of the difference in shift schedule.

Fuel economy and tailpipe CO_2 trends highlight the importance of heating value and carbon intensity in determining vehicle performance attributes when CR is not increased to take advantage of increased octane rating.

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Definitions/Abbreviations

ATDC - After top dead center
BMEP - Brake mean effective pressure
CA50 - Crank angle location of 50% burn point
CAD - Crank angle degrees
CR - Compression ratio
E10 - Fuel containing 10 vol% ethanol
E30 - Fuel containing 30 vol% ethanol
EIVC - Early intake valve closure
FCA - Fiat Chrysler Automobiles, N.A.
GHG - Greenhouse gas
GTDI - Gasoline turbocharged, direct-injection engine
HWFET - Highway Fuel Economy Test
MBT - Maximum brake torque
MEP - Mean effective pressure
MON - Motor octane number
ORNL - Oak Ridge National Laboratory
PFI - Port fuel injection
RON - Research octane number
RPM - Revolutions per minute
SUV - Sport utility vehicle
UDDS - Urban Dynamometer Driving Schedule
US06 - US06 driving schedule
VVA - Variable valve actuation

References

1. Leone, T.G., Anderson, J.E., Davis, R.S., Iqbal, A. et al., “The Effect of Compression Ratio, Fuel Octane Rating, and Ethanol Content on Spark-Ignition Engine Efficiency,” *Environ. Sci. Technol.* 49:10778-10789, 2015, https://doi.org/10.1021/acs.est.5b01420.
2. Sluder, C., Smith, D., Wissink, M., Anderson, J. et al., “Effects of Octane Number, Sensitivity, Ethanol Content, and Engine Compression Ratio on GTDI Engine Efficiency, Fuel Economy, and CO_2 Emissions,” Report# AVFL-20, Coordinating Research Council, Nov. 2017.
3. Smith, P., Heywood, J., and Cheng, W., “Effects of Compression Ratio on Spark-Ignited Engine Efficiency,” SAE Technical Paper 2014-01-2599, 2014, https://doi.org/10.4271/2014-01-2599.
4. Chow, E., Heywood, J., and Speth, R., “Benefits of a Higher Octane Standard Gasoline for the U.S. Light-Duty Vehicle Fleet,” SAE Technical Paper 2014-01-1961, 2014, https://doi.org/10.4271/2014-01-1961.
5. Leach, B.P.R. and Williams, J., “CO_2 Emission Reduction Synergies of Advanced Engine Design and Fuel Octane Number,” SAE Technical Paper 2014-01-2610, 2014, https://doi.org/10.4271/2014-01-2610.
6. West, B.H., Sluder, C.S., and Smith, D.E., “An Engine and Modelling Study on Potential Fuel Efficiency Benefits of a High-Octane E25 Gasoline Blend,” ORNL/TM-2017/357, 2017.

7. Leone, T., Oline, E., Anderson, J., Jung, H. et al., “Effects of Fuel Octane Rating and Ethanol Content on Knock, Fuel Economy, and CO2 for a Turbocharged DI Engine,” *SAE Int. J. Fuels Lubr.* 7(1):9-28, 2014, https://doi.org/10.4271/2014-01-1228.
8. Sluder, C., Smith, D., Anderson, J., Leone, T. et al., “U.S. DRIVE Fuels Working Group Engine and Vehicle Modeling Study to Support Life-Cycle Analysis of High-Octane Fuels,” U.S. Department of Energy, 2019.
9. Davis, S.C. and Boundy, R.G., *Transportation Energy Data Book* 38th Edition (Oak Ridge: Oak Ridge National Laboratory, 2020).
10. Phlips, P., “SI Engine Model for Vehicle Fuel Consumption Estimation,” in *FISITA World Automotive Congress*, F2014-CET-140, 2014.
11. Ross, M. and An, F., “The Use of Fuel by Spark Ignition Engines,” SAE Technical Paper 930329, 1993, https://doi.org/10.4271/930329.
12. Shayler, P., Chick, J., and Eade, D., “A Method of Predicting Brake Specific Fuel Consumption Maps,” SAE Technical Paper 1999-01-0556, 1999, https://doi.org/10.4271/1999-01-0556.
13. Phlips, P., “Analytic Engine and Transmission Models for Vehicle Fuel Consumption Estimation,” *SAE Int. J. Fuels Lubr.* 8(2):423-440, 2015, https://doi.org/10.4271/2015-01-0981.
14. Jung, H., Shelby, M., Newman, C., and Stein, R., “Effect of Ethanol on Part Load Thermal Efficiency and CO2 Emissions of SI Engines,” *SAE Int. J. Engines* 6(1):456-469, 2013, https://doi.org/10.4271/2013-01-1634.
15. United States Environmental Protection Agency, “EPA Letter to Manufacturers, VPCD-97-01,” 1997.

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