

Impact of Octane Number on Fuel Efficiency of Modern Vehicles

Shi-Jin Shuai, Yinhui Wang, Xinyan Li, Haichao Fu, and Jianhua Xiao
Tsinghua Univ

ABSTRACT

Fuel quality, including antiknock rating, plays a critical role in enabling optimal operation of advanced gasoline engines. As new designs introduced into the market implement technologies to improve fuel efficiency, the overall octane level of the gasoline pool may need to be increased to ensure optimal performance. Turbocharging, higher compression ratios and downsized displacement all lead to higher combustion pressures and temperatures that make engines more susceptible to knocking. All modern gasoline engines are equipped with knock sensors that detect abnormal combustion resulting from autoignition caused by insufficient octane quality. The ability of an engine to account for the use of lower octane fuel by retarding spark timing and enriching air-fuel ratio to reduce knock is limited, and engine efficiency is directly and adversely impacted when the use of lower octane gasoline is accommodated, resulting in higher fuel consumption.

In this paper, the impact of gasoline octane quality on the fuel efficiency of advanced vehicles in China is investigated. Five in-use vehicles equipped with various fuel efficient engine technologies were subject to fuel economy and emissions testing on multiple commercial fuels spanning the relevant range of octane quality for this market. Results demonstrated that the use of high octane gasoline consistently enabled advanced gasoline engines to achieve maximum energy savings in the form of approximately 1% better fuel economy per octane number increase.

CITATION: Shuai, S., Wang, Y., Li, X., Fu, H. et al., "Impact of Octane Number on Fuel Efficiency of Modern Vehicles," *SAE Int. J. Fuels Lubr.* 6(3):2013, doi:10.4271/2013-01-2614.

INTRODUCTION

Market Trends

Significant improvements in passenger car fuel efficiency are being driven by a combination of consumer pressure for improved performance and regulatory mandates for higher fuel economy in all markets, including the United States, the European Union and China. Gasoline engine designs for new vehicle models entering these markets have shifted rapidly to incorporate fuel efficient design features like direct injection, turbocharging, exhaust gas recirculation, higher compression ratios and downsized displacement in order to meet these needs. In the U.S., for example, from 2010 to 2012 the percentage of new light duty vehicles with gasoline direct injection (DIG) tripled from 8.3% to 23.7% and turbocharging or supercharging roughly doubled from 3.5% to 8.9%. [1] Similarly in Europe, DIG vehicles composed about 21% of all new gasoline passenger cars in 2011, up from 12% in 2009. [2] The continued rapid adoption of fuel

efficient gasoline engine technologies is expected to continue over the next several years in all vehicle markets. [3]

Recent data for China suggest that DIG technology is penetrating that market in a fashion comparable to that in the U.S., while turbocharging is penetrating at slightly faster rate in China than in the U.S. [4] Trends in the new gasoline vehicle markets in the U.S. and especially in China are more relevant globally than those in Europe due to differences in sales volume. Sales of new light duty gasoline vehicles in the China were 14.4 million units in 2011 and 15.0 million units in 2012, of which 2.5 million were DIG in 2012. Comparable sales in the U.S. were 12 million units in 2011, while those in Europe in 2011 were much lower, approximately six million units. [1,2] Furthermore, because the existing light duty vehicle fleet in China is substantially smaller than those in either the U.S. or Europe, implementation of new vehicle technology in China is likely to have a more immediate impact on the vehicle pool as a whole in that country.

Employment of DIG and turbocharged designs varies widely across different segments of the Chinese passenger car

fleet. As in Europe, DIG technology is most prevalent in the medium and large size vehicle segments in China, while the mini and small vehicle markets are predominantly characterized by the use of port-fuel injected (PFI) engines, as these are extremely cost-sensitive market segments.

While per capita consumption is lower than many OECD countries, China as a nation is the largest energy consumer globally and ranks second worldwide in gasoline consumption. [5] Because of continuing high sales and fast growth in the new vehicle market, the implementation of fuel efficient technologies in China is a critical part of a future energy strategy.

Technology Impact

The engine efficiency improvement enabled by the use of higher compression ratios in spark-ignited gasoline engine design is well-known. A critical factor limiting the use of higher compression ratios to deliver higher gasoline engine efficiencies is the corresponding impact on knock, as engines with higher compression ratios show a greater disposition toward engine knock. Engine knock, specifically spark knock, occurs when the air-fuel mixture in the end gas region of the combustion chamber autoignites ahead of the flame front generated by the spark kernel. The resulting combustion leads to rapid pressure rise that produces a characteristic noise termed knock. Mild knock may cause consumer dissatisfaction due to objectionable noise, while high levels of knock can lead to catastrophic engine damage. [6] Gasoline with higher octane quality has a reduced tendency to autoignite in the end gas region, therefore reducing the tendency for knock to occur.

The relationships between the physical and chemical nature of fuel autoignition properties, methods used to quantify gasoline octane quality, and interactions with various engine design parameters have been the subject of extensive investigation in several recent studies. [7, 8, 9, 10, 11, 12] Advances in air induction, improvements in engine cooling and better fuel delivery (injection) technology in particular have significantly altered conventional understanding of the correlation between gasoline octane quality, as defined by the standardized Research Octane Number (RON) and Motor Octane Number (MON) tests, and engine performance. In general terms, modern engine designs continue to exhibit a substantially positive correlation between RON octane quality and engine performance, but an inconsistent relationship with MON. At a given RON quality, the typical normally aspirated modern PFI engine shows essentially no correlation to MON, while modern turbocharged DIG engines are, on average, slightly negatively correlated to MON (better performance at lower MON).

These studies and others were recently analyzed by the U.S. auto-oil Coordinating Research Council (CRC) to examine potential benefits of incorporating this modern understanding of gasoline engine response to octane quality into advanced engine designs optimized to achieve high

efficiency when operating on high octane quality gasoline. [13] CRC concluded that the use of turbocharged DIG engine designs, along with reduced engine displacement, appears especially attractive in a scenario where higher octane quality gasoline is available. CRC predicted that an increase of “4 to 5 octane numbers” could lead to a “5% to 7%” improvement in fuel economy in a turbocharged, DIG engine where displacement was reduced by 20% to 25%. Other scenarios with PFI engines yielded smaller improvements, on the order of about 2% to 3%. It was unclear whether the “four to five octane numbers” increase was in terms of RON, MON or some combination thereof, although presumably this was intended to mean $(RON+MON)/2$, as commercial U.S. gasoline octane is determined on that basis.

Recent literature is largely lacking performance data from studies specifically designed to measure the influence of gasoline octane quality on whole vehicle fuel economy in modern gasoline engines on regulated test cycles. This is a critical data gap as changes in future specifications for gasoline octane were proposed in the draft China Phase V National Gasoline Standard released in Fall 2012 and discussed in the preliminary Notice of Public Rulemaking (NPRM) for Tier 3 gasoline from U.S. EPA released in March 2013. Interestingly, the draft Chinese standards include a reduction in gasoline octane quality by grade, while the U.S. Tier 3 NPRM suggested that higher octane gasoline may be needed in the market. [14,15]

One study from 2006 showed that an increase in octane (RON and MON) of three to four numbers, analogous to octane increasing from German 91 RON unleaded grade to German 95 RON unleaded grade, could yield fuel economy improvements of about one to four percent in a custom high speed, high load cycle. [16] These results were obtained using three vehicles, two of which had DIG engines. In that same study with the same vehicles, slightly lesser improvements (0.9% to 1.9%) were measured on more familiar, relatively severe cycles like ARTEMIS and US06. Based upon prior testing in a different program, the response to octane for fuel economy on a percentage basis was concluded to be similar to that observed for power and acceleration.

Conventional wisdom is that efficiency improvements from higher octane gasoline are primarily observed under high load operating conditions, such as those used for WOT acceleration, and that there is less impact on fuel economy under lower speed, lighter load conditions typical of regulated fuel economy cycles like the Federal Test Procedure (FTP) or New European Driving Cycle (NEDC). The balance between performance and fuel economy is dictated by decisions made by the automaker during the design and calibration processes.

The objective of this study was to survey the potential impact, if any, of octane quality across a range of commercial gasolines in China on the fuel economy and emissions of several vehicles representative of modern designs in that country. The focus was fuel economy performance under

regulated test conditions of the Type I (NEDC) test, with additional testing to monitor fuel efficiency under off-cycle conditions for comparison against other studies. This study was not intended to scrutinize fundamental technical aspects of potential relationships between different methods of octane rating, vehicle performance, cycle severity and other factors. Results from this study, however, do support the conclusion that those factors warrant further research.

EXPERIMENTAL

Vehicles

Five vehicles certified to China Phase 4 (equivalent to Euro 4) emissions standards were used for this program. Basic information about the vehicles is shown in Table 1. All five vehicles were mid-sized, four-door sedans. Three vehicles were equipped with DIG engines, two of which were turbocharged. The other two vehicles had PFI engine designs and both were normally aspirated. Vehicles were selected to include a relatively broad cross section of vehicles available in China, with an emphasis on modern technology designs. Vehicle A in particular was deemed to be representative of leading edge designs, having an advanced technology engine combining turbocharging and DIG together with downsized displacement. Vehicle B had a modern turbocharged DIG engine, but did not have downsized displacement relative to the China market. Vehicle C also had a DIG design, but was normally aspirated and had a relatively large 2.4L displacement. Vehicle D was equipped with a 2.0L PFI engine. Vehicles A through D were manufactured by joint venture (JV) automakers. Vehicle E was equipped with a 2.4L PFI engine and was manufactured by a domestic Chinese automaker.

Table 1. Test Vehicle Information

Vehicle ID	A	B	C	D	E
Induction	turbo	turbo	NA	NA	NA
Injection system	DIG	DIG	DIG	PFI	PFI
Displacement (ml)	1390	1984	2384	1995	2378
Compression ratio	10.0	10.2	11.3	10.8	9.8
Recommended Octane (RON)	93	95	93	97	93
Weight (kg)	1470	1750	1750	1460	1570
Transmission	7sp DCT	7sp CVT	6sp AT	8sp AT	4sp AT
Mileage (km)	18,400	40,000	5,000	34,500	13,900

The manufacturers of Vehicles B and D both recommended the use of higher octane gasoline, 95 RON (or higher) for Vehicle C and 97 RON (or higher) for Vehicle D. The manufacturers of Vehicle A, C and E recommended the use of 93 RON grade (or higher) gasoline. Vehicle D was

from an automaker generally associated with higher performance, sport-oriented designs. This vehicle was specifically included in the program to maximize odds of demonstrating a measurable response to octane in at least one vehicle under some test conditions.

Fuels

Table 2. Test Fuel Analysis

Fuel ID	90#	90#-M	93#	93#-M	97#	97#-M
RON	91.9	93.4	94.0	95.4	97.4	98.4
MON	81.6	82.2	82.3	82.8	85.0	85.3
Sensitivity	10.3	11.2	11.7	12.6	12.4	13.1
Density (g/ml)	0.747	0.748	0.753	0.753	0.763	0.763
NHV (MJ/l)	32.1	32.1	32.2	32.2	32.2	32.2
Sulfur (ppmw)	80	77	21	21	16	15
Benzene (vol %)	1.23	1.24	0.55	0.56	0.62	0.62
Aromatics (vol %)	35.6	35.9	33.2	33.6	35.2	35.1
Olefins (vol %)	17.9	17.8	22.3	22.1	16.8	17.0
Manganese (mg Mn/l)	1.8	14.9	1.6	14.9	0.1	14.3

Batches of three different base fuels, hereafter called 90#, 93# and 97#, consistent with the three major gasoline grades in China, were obtained in large quantities for testing purposes. The three base fuels were commercial gasoline blends of typical local quality, and were not contrived fuels blended to meet artificial requirements for testing purposes. Approximately half of the volume of each base fuel was treated with methylcyclopentadienyl manganese tricarbonyl (MMT) at a target treat rate of 16 milligrams of manganese per liter, and labeled as 90#-M, 93#-M and 97#-M respectively. The use of MMT enabled the effect of octane quality on fuel economy to be evaluated without impacting other fuel properties. The octane quality, manganese content and other typical properties of each test fuel were measured by SGS China and are shown below in Table 2. The octane quality of every base fuel was higher than expected based upon its commercial grade by anywhere from 2 RON numbers for the 90# fuel to 0.4 RON numbers for the 97# fuel. This upward shift in the octane quality limited the amount of test data generated by the program for investigating potential incompatibility with low octane gasoline in vehicles with high octane gasoline OEM recommendations (for example, operating a vehicle with a 97 RON gasoline recommendation on 90 RON gasoline). The upward shift in octane nevertheless proved sufficient and perhaps even enhanced the test data generated with respect to

the higher level objective of examining vehicle response to octane quality for fuel economy effects.

All references to fuel octane quality, whether absolute octane values or increments of octane, in this paper are stated in terms of RON unless otherwise specified.

Test Facility

All vehicle emissions and fuel economy tests were conducted at the China Automotive Technology and Research Center (CATARC)-Beijing Auto Test Center. Testing was performed on a Euro 5/LEV2/Tier 2-capable climate controlled test cell on a 48-inch single-roll chassis dynamometer. A Horiba MEXA-7400LE gasoline emission gas analyzer system was used to measure exhaust gas composition collected through a conventional constant volume sampling (CVS) system.

Test Protocol

A comprehensive testing methodology was developed to explore the potential impact of gasoline octane quality on fuel economy and emissions during regulated testing procedures and also under off-cycle operating conditions.

Approach and cycle

The profile for testing each fuel in each vehicle comprised one cold-start Type I test (standard NEDC), followed by three hot start NEDCs, and finally a combination of four segments of specific driving modes typical of prone-to-knock engine operating regimes. The four modes of off-cycle operation are characterized as follows:

1. Low speed, high load (50 km/hr, 5° incline); A/C off
2. Medium speed, high load (80 km/hr, 3° incline); A/C on
3. Rapid acceleration (WOT from 40 to 80 km/hr); A/C off
4. High speed, medium load (120 km/hr, 0° incline); A/C on

One or more of these modes was expected to elicit octane response through changes in ignition timing by the engine control module (ECM) based upon input from the knock sensor. A speed versus time trace of the entire testing profile is shown in [Figure 1](#) below, and the four mode off-cycle speed versus time trace is shown in [Figure 2](#).

Each fuel was tested once in each vehicle. Fuels were tested in increasing octane quality through each vehicle. Duplicate testing and a randomized matrix of fuel test order may have been preferable for statistical and validation purposes, but capacity limitations and resource constraints at the CATARC-Beijing facility did not facilitate that approach. Tests with different fuels in a given vehicle were conducted (including pre-soak cycles) at the same time of day with each fuel in order to minimize potential intraday variance as much as possible. All fuels were tested in a given test vehicle before testing in another vehicles was initiated. Vehicles were

tested in the order A, E, B, D, C. A select number of duplicate tests were performed to validate repeatability and evaluate suspected outliers.

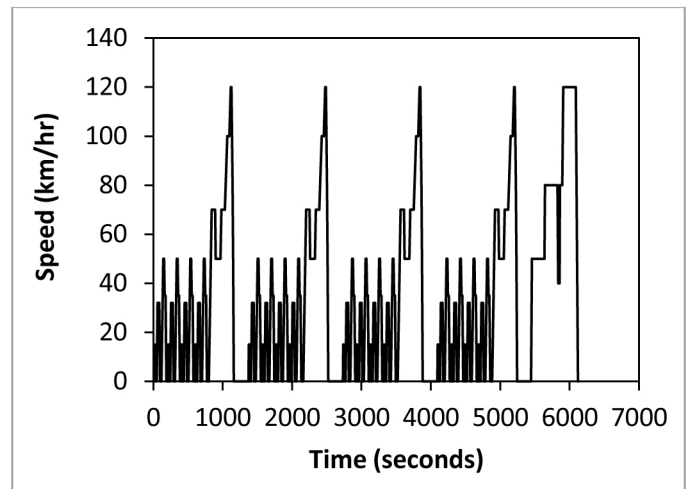


Figure 1. Complete speed versus time testing profile: 1 cold start NEDC + 3 hot start NEDC + off-cycle modes

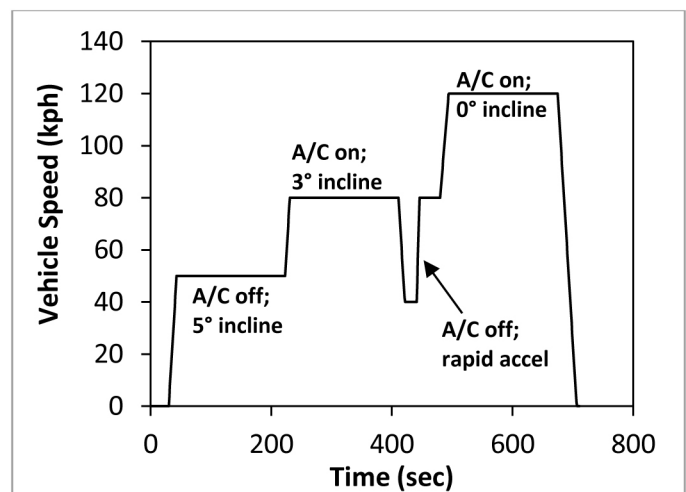


Figure 2. Speed versus time profile for off-cycle modes

Procedure

Vehicles were procured from reliable sources in the Beijing area, including from individuals and rental cars agencies. All vehicles were maintained in a manner consistent with recommendations from owner's manuals and local 4S shops (dealer service centers) according to information supplied by the owners. Upon procurement, vehicles were given a thorough mechanical inspection to verify proper working order for testing purposes. For each test, the fuel-switching procedure was as follows:

1. Empty fuel tank.