CRC Project No. CM-137-11-1

REVIEW TO DETERMINE THE BENEFITS OF INCREASING OCTANE NUMBER ON GASOLINE ENGINE EFFICIENCY: TASK 1

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COORDINATING RESEARCH COUNCIL, INC.
3650 MANSELL ROAD·SUITE 140·ALPHARETTA, GA 30022

Task 1 Report

Review to Determine the Benefits of Increasing Octane Number on Gasoline Engine Efficiency

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Submitted to:
Mr. Brent K. Bailey
Coordinating Research Council, Inc.

Submitted by:
H-D SYSTEMS International
Washington, DC 20016

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1. INTRODUCTION AND PROBLEM SCOPE

The CRC[1] is interested in documenting the relationship between fuel octane ratings and spark-ignition (SI) engine efficiency. Engine efficiency can be measured in different ways, and the CRC has more broadly defined alternative measures of efficiency such as vehicle fuel economy in terms of energy use per unit distance travelled. Moreover, since engine efficiency is a function of the engine operating point in terms of speed (revolutions per minute, or RPM) and load (brake mean effective pressure, or BMEP), engine based data at single or a limited number of load and speed points may provide only a partial view on how engine efficiency changes would affect vehicle fuel economy over a driving cycle. In addition, the issues of SI engine efficiency and fuel octane number are made more complex by the fact that engine efficiency is itself a function of the engine technology including the type of fuel system, engine aspiration and combustion chamber design, and any evaluation must address all of these issues, as required by CRC.

The intent of this effort is to compile and summarize the findings from existing studies and theories that link octane number to engine efficiency. Hence, this project was focused on collecting relevant data on this issue and documenting the findings from these data and from theories or models that link fuel properties to knock and engine compression ratio. The CRC also requires analysis of the effects of fuel composition and of gasoline-ethanol blends of varying blend ratios on both octane number and engine response. It should be noted that the research octane number (RON) and motor octane number (MON) evaluation procedures were set many decades ago, and it is possible that they no longer are representative of typical operating conditions that lead to knock in modern high speed SI engines.

This report documents the findings from the literature review or Task 1 of this effort. The findings encompass a detailed review of about 50 papers of which 45 were directly relevant. As noted above, the papers report on a range of output variables that are, in many instances, only indirectly connected to efficiency.

1 Acronyms in this report can be found on page 25.

The analysis of these findings and the conversion of reported results into a common set of descriptors is not part of this task, but will be completed under Tasks 2 to 4, when funding for these tasks is approved. Task 2 will develop an analysis of the data and also “fill in the blanks” in the data by obtaining the views of experts and additional unpublished data from auto-manufacturers and research institutions. Task 3 will present an understanding of engine efficiency and octane number in terms of a quantitative linkage between the two parameters for different engine types. Task 4, will offer expertise/views on proposing a potential maximum SI engine efficiency improvement that is determined to be possible assuming specific required changes to fuel properties. Recommendations for future work are to be made under Task 5.

2. OVERVIEW OF LITERATURE SEARCH

2.1 PRELIMINARY SEARCH

The stated objective of the project is to **c**onduct a broad and comprehensive literature review to determine the effects of gasoline octane number on light-duty SI engine efficiency. The literature review is to be used to create a comprehensive database on the relationship between fuel properties and engine efficiency using the collected information. The literature review is expected to be the largest part of this work effort, and the statement of work from CRC makes it clear that coverage of all different engine technologies is expected, with the three different classes of engines defined - "traditional," "advanced," and "future" engine configurations. CRC has defined “Traditional” to include port fuel injection (PFI) and naturally-aspirated (NA) engines; “Advanced” to include boosted and NA spark ignition direct injected (SIDI) engines; and “Future” to include Atkinson cycle, lean burn, and high rates of cooled exhaust gas recirculation (EGR) with boosted SIDI. Homogeneous Charge Compression Ignition (HCCI) engines were specifically excluded from consideration.

Due to the desire to be as relevant to modern engines as possible, we first restricted our search to papers published over the last 20 years; i.e., 1992 and later papers. The searches focused on English language publications using the keywords of “octane” and “efficiency” together and “knock” and “efficiency” together, and we searched the following databases:

- SAE papers including JSAE English language translations
- Combustion Science and Technology
- International Journal of Engine Research
- International Federation of Automotive Engineering Societies (FISITA)
- Vienna Motor Symposium (since 1999)

Our searches were based on paper titles as searches on the entire paper using the keywords are generally not feasible. We obtained about 60 responses, and a study of the titles suggested that 40 were relevant to this study (this was a subjective determination). One paper was an interim report and not used, while the remaining 39 papers were obtained for review, and the titles circulated to the CRC Committee.

2.2 ADVANCED SEARCH AND FINAL LIST OF REVIEWED PAPERS

The CRC Committee requested a more comprehensive search for papers in this area and suggested that we compile a list of all of the references in the 39 papers, and extend the age limit of papers to 25 to 30 years. We compiled the list and found approximately 275 unique references (since many papers appeared more than once). However, many of the titles of the 275 references made it clear that they were unrelated to the subject being investigated, such as those referring to regulations, laws and test procedures, or those referring to the supply and economics of alternative fuels, or those referring to engine deposits and octane requirements. Eliminating only those papers where the irrelevance was very obvious from the title, resulted in a database of 148 papers. Of the 148 papers, 27 included those in our primary sample of 39 papers, leaving 121 additional papers of potential interest to the study. The CRC Committee suggested that we obtain and review the abstracts of the 121 papers to decide how many papers should be added from this list to the study. We were unable to obtain abstracts in only 2 instances and reviewed 119.

The comprehensive list of the 119 papers and the results of our abstract review is provided in Table 1. We rated the papers as follows, with the ratings signifying that:

- 1 the paper was likely irrelevant
- 2 there was only a low probability of relevance
- 3 a moderate probability of relevance
- 4 a high probability of relevance

Twelve papers and one CRC report were rated “4”in this search, and were added to the original list. The original 39 papers and the added 12 papers, for a total of 51, were reviewed in detail. Review of the CRC report was deferred to Task 2 due to an oversight in the paper collection process. The 27 papers included in the primary sample as well as the 12 papers and CRC report are identified at the end of Table 1 in colored background (page 7). The 12 additional papers in the primary sample are listed in Table 2.

Author	Title	Paper No.	Date	Organization	Ref. Source	Relevancy
Konig	End Gas Autoignition and Knock in a Spark Ignition Engine	902135	1990	SAE	2005-01-0240	1
Celta	Octane Blending Values calculated through Gas Chromatography	922216	1992	SAE	Committee	1
Major	Gasoline Effects on ORI and Combustion Chamber Deposits	922258	1992	SAE	Committee	1
Leppard	The Auto-Ignition Chemistries of Primary reference Fuels	922325	1992	SAE	Committee	1
Brinkman	The Development of Improved Fuel Specifications for Methanol (M85) and Ethanol (EDd85)	940764	1994	SAE	2007-01-0473	1
DePetris	High Efficiency Stoichiometric Spark Ignition Engines	941933	1994	SAE	Brusstar et al	1
Pan	A Theoretical and Experimental Study of the Modes of End Gas Autoignition Leading to Knock in S.I.	942060	1994	SAE	2005-01-0240	1
Goodfellow	European Programs on Emissions, Fuels and Engine Technologies (EPEFE) - Gasoline Aromatics Stud	961072	1996	SAE	2000-01-2019	1
Kelly	FTP Emissions Test Results from Ethanol Variable Fuel Vehicle Chevrolet Luminas	961092	1996	SAE	2007-01-0473	1
Kume	Combustion Control Technologies for a DISI engine	960600	1996	SAE	2003-01-3186	1
Bradley	Low-temperature combustion and autoignition	Comprehensive Ch	1997	Elsevier	2004-01-1970	1
Faure	ORI: Assessment methodology and influence of engine running parameters	972933	1997	SAE	2004-01-2001	1
Harada	Development of direct injection gasoline engine	970540	1997	SAE	2004-01-1950	1
Iwamoto	Development of Gasoline Direct Injection Engine	970541	1997	SAE	2000-01-0253	1
Kalghatgi	Effects of combustion chamber deposits, compression ratio and combustion chamber design on pov	972886	1997	SAE	2001-01-3584	1
Sato	Combustion and NOx Emission Characteristics in a DI Methanol Engine Using Supercharging with EC	971647	1997	SAE	Brusstar et al	1
Brehob	Stratified-Charge Engine Fuel Economy and Emission Characteristics	982704	1998	SAE	2000-01-0253	1
Grandin	Knock Suppression in a Turbocharged SI Engine by Using Cooled EGR	982476	1998	SAE	2009-01-0138	1
Pan	End Gas In homogeneity Autoignition and Knock	982616	1998	SAE	2005-01-0240	1
Takagi	Simultaneous Attainment of Low Fuel Consumption High Output Power and Low Exhaust Emissions	980149	1998	SAE	2006-01-1259	1
Yang	Fuel Injection Strategies to Increase Full-Load Torque Output of a Direct-Injection SI Engine	980495	1998	SAE	2006-01-1259	1
Geiger	Direct Injection Gasoline Engines - Combustion and Design	1999-01-0170	1999	SAE	2000-01-0253	1
Chon	Performance Scaling of SI engines-correlation and historical analysis	2000-01-0565	2000	SAE	2009-01-2622	1
Kanda	Application of a New Combustion Concept to Direct Injection Gasoline Engine	2000-01-0531	2000	SAE	2006-01-1259	1
Stokes	A Gasoline Engine Concept for Improved Fuel Economy	2000-01-2902	2000	SAE	2007-01-2007	1
Westin	Influence of Residual gases on Knock in Turbocharged SI engines	2000-01-2840	2000	SAE	2004-01-2001	1
Wirth	Turbocharging the DI Gasoline Engine	2000-01-0251	2000	SAE	2009-01-0138	1
George	Design of a High Compression, Direct Injection, Spark-Ignition, Methanol Fueled Research Engine w	2001-01-3651	2001	SAE	Bromberg et al. 2008	1
Bradley	Amplified pressure waves during autoignition: relevance to CAI engines	2002-01-2868	2002	SAE	2004-01-1970	1
Goodwin	An Open-Source, Extensible Software Suite for CVD Process Simulation	pp. 155-162	2003	The Electroc	2007-01-0473	1
Kalghatgi	A method of defining ignition quality of fuels in HCCI engines	2003-01-1816	2003	SAE	2004-01-1970	1
Kitano	Effects of fuel properties on pre-mixed charge compression ignition combustion in a direct injection	2003-01-1815	2003	SAE	2005-01-0239	1
Petitjean	Advanced Gasoline Engine Turbocharging Technology for Fuel Economy Improvements	2004-01-0988	2004	SAE	2007-01-3623	1
Risberg	The influence of EGR on auto-ignition quality of gasoline-like fuels in HCCI engines	2004-01-2952	2004	SAE	2005-01-0239	1
Lang	Boosting and Direct Injection - Synergies for Future gasoline Engines	2005-01-1144	2005	SAE	2009-01-0138	1
Sadakane	Development of a New V-6 High Performance Stoichiometric Gasoline Direct Injection Engine	2005-01-1152	2005	SAE	2006-01-1259	1
Bandel	The Turbocharged GDI Engine: boosted Synergies for High Fuel Economy Plus Ultra-Low Emissions	2006-01-1266	2006	SAE	2007-01-3625	1
Cairns	Exhaust Gas Recirculation for Improved Part and Full Load Fuel Economy in a Turbocharged Gasolin	2006-01-0047	2006	SAE	2007-01-3625	1
Kleeberg	Future Potential and Development Methods for High Output Turbocharged Direct Injected Gasoline	2006-01-0046	2006	SAE	2007-01-3625	1
Sellnau	2-Step Variable Valve Actuation: System Optimization and Integration on an SI Engine	2006-01-0040	2006	SAE	2011-01-0900	1
Boretti	Experimental and Theoretical Study of a Direct Injection Spark Ignition Engine	2007-01-1419	2007	SAE	2007-01-3623	1
Cleary	Unthrottled Engine Operation with variable Intake Valve Lift, Duration, and Timing	2007-01-1282	2007	SAE	2010-01-0619	1
Donghee	Development of 2.0L Turbocharged DISI Engine for Downsizing Application	2007-01-0259	2007	SAE	2007-01-3623	1
Stansfield	Unthrottled Engine Operation using Variable Valve Actuation: The Impact on the Flow Field, Mixing	2007-01-1414	2007	SAE	2011-01-0900	1
Sugiyama	Technology for Improving Engine Performance using Variable Mechanisms	2007-01-1290	2007	SAE	2011-01-0900	1
West	Enhanced Ethanol Engine and Vehicle Efficiency (Agreement 13425)	http://www1.eere	2008	EERE	2010-01-2154	1
Moore	Charge Motion Benefits of Valve Deactivation to Reduce Fuel Consumption and Emissions in an GDI	2011-01-1221	2011	SAE	2011-01-0900	1
Adams	Analysis of the Combustion Process of a Spark Ignition Engine with a Variable Compression Ratio	870610	1987	SAE	932746	2
Chun	Estimating Heat Release and Mass of Mixture Burned from SI Engine Pressure Data	Vol. 54, pp. 133-1 4	1987	Combustion	2007-01-0473	2

Table 1: List of References Examined from Primary Papers

Author	Title	Paper No.	Date	Organization	Ref. Source	Relevancy
Chun	Prediction of Knock Occurrence in a Spark-Ignition Engine	Twenty-Second Syr	1988	The Combust	2007-01-0473	2
Leppard	Auto-ignition Characteristics of Octane Enhancing Ethers and Cyclic Ethers	912313	1991	SAE	Committee	2
Avella	Evaluation of the Antiknock Quality of Gasoline by the "Energetic Cirterion"	912391	1991	SAE	Committee	2
Bruetsch	Evaluation of a Passenger Car Equipped with a Direct Injection Neat Methanol Engine	920196	1992	SAE	Brusstar et al	2
Brustle	Exhaust Gas turbocharged SI engines and their ability of meeting future demands	C484/039/94	1994	IMechE	2009-01-0138	2
Moran	Fuel Evaporation and the High Speed Knock Phenomenon of Methanol-gasoline Blended Fuels	942063	1994	SAE	2009-01-0324	2
Anderson	Understanding the Thermodynamics of DISI engines	962018	1996	SAE	2009-01-1490	2
Jackson	Stratified and Homogeneous Charge Operation for the Direct Injection Gasoline Engine - High Power	970543	1997	SAE	2004-01-1950	2
Sandquist	Influence of fuel volatility on emissions and combustion of a DISI engine	982701	1998	SAE	2003-01-3186	2
Whelan	An acceleration based method to determine the octane number requirement of knock sensor vehicle	982721	1998	SAE	2005-01-0244	2
Davis	The Development and Performance of a High Blend Ethanol Fueled Vehicle	2000-01-1602	2000	SAE	2007-01-0473	2
Alkidas	Contributors to the Fuel Economy Advantage of DISI Engines over PFI Engines	2003-01-3101	2003	SAE	2004-01-1950	2
Duchaussoy	Dilution Interest on Turbocharged SI Engine Combustion	2003-01-0629	2003	SAE	2007-01-3625	2
Lecointe	Downsizing a Gasoline Engine Using Turbocharging With Direct Injection	2003-01-0542	2003	SAE	2007-01-3625	2
Leduc	Downsizing of gasoline engine: an efficient way to reduce CO2 emissions	Vol. 58, No. 1, pp. 1	2003	Oil and Gas S	2005-01-0239	2
Sellnau	Two-Step Variable Valve Actuation for Fuel Economy, Emissions, and Performance	2003-01-0029	2003	SAE	2011-01-0900	2
Burluka	The influence of simulated residual and NO concentrations on knock onset of PRFs and gasolines	2004-01-2998	2004	SAE	2005-01-0244	2
Fraser	Engine Downsizing and the Application of Gasoline Direct Injection to a High Specific Output Turbocharged Engine		2004	IMechE Fuel	2009-01-0138	2
Hiroshi	The Potential of Lean Boost Combustion	2004-05-0417	2004	SAE	2009-01-0138	2
Hisato	Effects of High Turbulence Flow on Knock Characteristics	2004-01-0977	2004	SAE	2005-01-0240	2
Lake	Turbocharging Concepts for Downsized Di Gasoline Engines	2004-01-0036	2004	SAE	2007-01-3625	2
Landenfield	gasoline direct Injection - SULEV Emission Concept	2004-01-0041	2004	SAE	2006-01-1259	2
Lippert	Development and Optimization of a Small-Displacement Spark-Ignition Direct-Injection Engine - Full-L	2004-01-0034	2004	SAE	2006-01-1259	2
Jeuland	Potential of Ethanol as a Fuel for Dedicated Engine	2-7108-0851-X	2004	IFP Internatio	2007-01-3625	2
Palucka	The Wizards of Octane		2005	Invention an	2009-01-2622	?
Le Berr	Modeling of Turbocharged SI Engine with Variable Camshaft Timing for Engine Control Purposes	2006-01-3264	2006	SAE	2009-01-0324	2
Rothe	Knock Behavior of SI Engines: Thermodynamic Analysis of Knock Onset Locations and Knock Intensitie	2006-01-0225	2006	SAE	2007-01-3623	2
Bergstrom	The new ECOTEC Turbo Biopower Engine from GM Powertrain-Utilizing the Power of Nature's Resources		2007	International	2011-01-0900	2
Brusstar	High Efficiency with Future Alcohol Fuels in Stoichiometric Medium Duty Spark Ignition	2007-01-3993	2007	SAE	2009-01-2621	2
Kapus	Ethanol Direct Injection on Turbocharged SI engines	2007-01-2036	2007	SAE	2009-01-1490	2
Nakajima	Development of an Engine for Flexible Fuel vehicles (FFV)	2007-01-3616	2007	SAE	2009-01-0138	2
Pana	Aspects of the Use of Ethanol in Spark-Ignition Engines	2007-01-2040	2007	JSAE	2009-01-2621	2
Mittal	Phenomena that determine knock onset in spark-ignited engines	2007-01-0007	2007	SAE Trans	2010-01-0617	2
Alger	Synergies between High EGR Operation and GDI Systems	1(1):101-114	2008	SAE Int. J. En	2009-01-0138	2
Christie	Parameter Optimization of a Turbo Charged Direct Injection Flex Fuel SI Engine	2009-01-0238	2009	SAE Int. J. En	2011-01-0900	2
Anderson	Octane Numbers of Ethanol-and Methanol-Gasoline Blends Estimated from Molar Contractions	24,6576-6585	2010	Energy and F	2011-01-0900	2
Pannone	Methanol as a Fuel for a Lean Turbocharged Spark Ignition Engine	8904535	1989	SAE	Brusstar et al	3
Frank	The Effect of Fuel Characteristics on Combustion in a Spark-Ignited Direct-Injection Engine	902063	1990	SAE	2010-01-2094	3
Leppard	The chemical origin of fuel octane sensitivity	902137	1990	SAE	2005-01-0244	3
Salih	The Influence of Gasoline/Ethanol Blends on Emissions and Fuel Economy	922378	1992	SAE	2006-01-3380	3
Sinor	Current and Potential Future Performance of Ethanol Fuels	930376	1993	SAE	Brusstar et al	3
Kalghatgi	Fuel effects on knock, heat release and 'CARS' temperatures in a spark ignition engine	Vols 110-111, pp20	1995	Combust.Sci.	2005-01-0244	3
Millo	Octane Rating Methods at High Revolution Speed	952520	1995	SAE	2001-01-3584	3
Abdel-Rahman	Experimental Investigation on Varying The Compression Ratio of SI Engine Working Under Different E	Vo1. 21, pp. 31-40	1997	International	2007-01-0473	3
Griffiths	Spontaneous ignition delays as a diagnostic of the propensity of alkanes to cause engine knock	111, pp. 327-337	1997	Combustion	2005-01-0239	3
Sugawara	Effects of gasoline properties on acceleration performance of commercial vehicles	971725	1997	SAE	2005-01-0244	3
Bradley	Autoignition in spark-ignition engines	Vol. 35	1997	Elsevier Scier	2001-01-3585	3
Gardiner	Improving the Fuel Efficiency of Light-Duty Ethanol Vehicles-An Engine Dynamometer Study of Dedica	1999-01-3568	1999	SAE	Brusstar et al	3
Brusstar	High Efficiency and Low Emissions from a Port-Injected Engine with Neat Alcohol Fuels	2002-01-2743	2002	SAE	Brusstar et al	3
Wyszynski	The Volumetric Efficiency of Direct and Port Injection Gasoline Engines with Different Fuels	2002-01-0839	2002	SAE	2004-01-1950	3
Yates	An Investigation of the Anamolies Identified with the ASTM Research and Motor Octane Scales	2003-01-1771	2003	SAE	Committee	3

Table 1: List of References Examined from Primary Papers (Continued)

Author	Title	Paper No.	Date	Organization	Ref. Source	Relevancy	Reference
Baeta	Optimization Performance of Multi-Fuel Spark Ignition Engine Using a Turbocharging System	2006-01-2641	2006	SAE	2007-01-3625	3	NA
Gerty	An Investigation of Gasoline Engine Knock Limited Performance and the Effects of Hydrogen Enhance	2006-01-0228	2006	SAE	2007-01-3623	3	NA
West	Fuel Economy and Emissions of Saab 9-5 Biopower	2007-01-3994	2007	SAE	2009-01-1490	3	NA
Blumberg	High Efficiency Heavy Duty SI Engines using DI of alcohol for Knock avoidance	p1186	2008	SAE Journal	2009-01-1490	3	NA
Gingrich	Ethanol Flex-fuel Engine Improvements with Exhaust Gas Recirculation and Hydrogen Enrichment	2009-01-0140	2009	SAE Int. J. Fu	2011-01-0900	3	NA
Bradley	Combustion and the design of future engine fuels	Vol. 223 Part C		J. Mechanica	2010-01-2154	3	NA
Muranaka	Factors Limiting the Improvement in Thermal Efficiency of S.I. Engine at Higher Compression Ratio	870548	1987	SAE	2007-01-2007	4	36
McNally	The effect of gasoline octane quality on vehicle acceleration performance - A CRC study	912394	1991	SAE	2005-01-0244	4	43
Millo	The effect of unleaded gasoline formulation on antiknock performance	941862	1994	SAE	2005-01-0244	4	42
CRC	Vehicle performance effect of octane on knock sensor equipped vehicles	Report No. 597	1995	CRC	2005-01-0244	4	see text
Bradley	Fuel blend and mixture strength effects on autoignition heat release rates and knock intensity in S.I. e	962105	1996	SAE	2005-01-0244	4	13
Russ	A Review of the Effect of Engine Operating Conditions on Borderline Knock	960497	1996	SAE	2007-01-0473	4	41
Esterhuyse	Study to assess the effect of Octane on engine emissions	2002-01-1664	2002	SAE	2004-01-2001	4	deleted
Al-Hasan	Effect of Ethanol-Unleaded Gasoline Blends on Engine Performance and Exhaust Emissions	Vol.44, pp. 1 547-1	2003	Energy Conve	2007-01-0473	4	deleted
Taniguchi	Feasibility Study of Ethanol Applications to a DI Gasoline Engine	2007-01-2037	2007	SAE	2009-01-0138	4	44
Mittal	The relevance of fuel RON and MON to Knock Onset in Modern SI Engines	2008-01-2414	2008	SAE	2010-01-0617	4	28
Nakama	Effect of Ethanol on Knock in Spark Ignition Gasoline Engines	1(1):1366-1380	2008	SAE Int. J. En	2010-01-0619	4	incl. in 14
Beck	Impact of Gasoline Octane on FE in Moern Vehicles	2006-01-3407	2006	SAE	Kalghatgi	4	40
Bell	Modern SI engine Control Paramemter Responses and Altitude Effcts with Fuels of Varying Octane Se	2010-01-1454	2010	SAE	Kalghatgi	4	43
Hashimoto	Effects of fuel properties on the combustion and emissions of DISI engines	2000-01-0253	2000	SAE	2003-01-3186		33
Takei	Fuel property requirement for advanced technology engine	2000-01-2019	2000	SAE	2005-01-0244		deleted
Fukui	Effects of octane number on stratified charge combustion in a direct injection gasoline engine	2001-01-1964	2001	SAE	2004-01-1950		32
Kalghatgi	Fuel anti-knock quality - Part I, Engine Studies	2001-01-3584	2001	SAE	2005-01-0244		9
Kalghatgi	Fuel anti-knock quality - Part II, Vehicle Studies - how relevant is Motor Octane Number (MON) in mo	2001-01-3585	2001	SAE	2004-01-1950		10
Farrell	Fuel Effects on SIDI Efficiency and Emissions	2003-01-3186	2003	SAE	2004-01-1950		4
Okamoto	Study of Antiknock Performance under various octane numbers and CR in a DISI engine	2003-01-1804	2003	SAE	2004-01-2001		3
Akihama	Fuel octane and composition effects on efficiency and emissions in a high compression ratio SIDI engi	2004-01-1950	2004	SAE	2005-01-0244		6
Bradley	Relevance of Research and Motor Octane numbers to the prediction of engine autoignition	2004-01-1970	2004	SAE	2005-01-0244		35
Duchaussoy	Impact of Gasoline RON and MON on a Turbocharged MPI SI Engine	2004-01-2001	2004	SAE	2009-01-0324		1
Kalghatgi	Octane Appetite Studies in Direct Inject Spark Ignition (DISI) Engines	2005-01-0244	2004	SAE	2010-01-0617		11
Kalghatgi	Auto-ignition quality of practical fuels and implications for fuel requirements of future SI and HCCI en	2005-01-0239	2005	SAE	2005-01-0244		12
Ayala	Effects of Combustion Phasing, Relative Air-fuel Ratio, Compression Ratio, and Load on SI Engine Effic	2006-01-0229	2006	SAE	2010-01-0619		34
Ikoma	Development of V-6 3.5-liter engine adopting new direct injection system	2006-01-1259	2006	SAE	Nakata et al		deleted
Nakata	The effect of ethanol fuel on a spark ignition engine	2006-01-3380	2006	SAE	Nakata et al		14
Brewster	Initial Development of a Turbo-charged Direct Injection E100 Combustion System	2007-01-3625	2007	SAE	2010-01-2154		19
Caton	An Experimental and Modeling Investigation into the Comparative Knock and Performance Character	2007-01-0473	2007	SAE	2010-01-0619		18
Nakata	The Impact of RON on SI Engine Thermal Efficiency	2007-01-2007	2007	SAE	2010-01-2094		15
Cairns	A Study of Gasoline-Alcohol Blended Fuels in and Advanced Turbocharged DISI Engine	2009-01-0138	2009	SAE Int. J. Fu	2011-01-0900		25
Milpied	Impact of Fuel Properties on the Performances and Knock Behaviour of a Downsized Turbocharged D	2009-01-0324	2009	SAE Int. J. Fu	2011-01-0900		5
Szybist	Investigation of Knock Limited Compression Ratio of ethanol Gasoline Blends	2010-01-0619	2010	SAE	2011-01-0900		8
Brusstar	Economical, high-efficiency engine technologies for alcohol fuels	http://www.epa.go	2004	EPA	2010-01-2154	4	7
Cohn	Direct Injection Ethanol Boosted Gasoline Engines: Biofuel Leveraging For Cost Effective Reduction of	2005-001	2005	MIT LFEE	Bromberg et al. 2008	4	incl. in 22
Bromberg	Calculations Of Knock Suppression In In Highly Turbocharged Gasoline/Ethanol Engines Using Direct E	LFEE 2006-001	2006	MIT	2009-01-1490	4	24
Bromberg	Effective Octane and Efficiency Advantages of DI Alcohol Engines	LFEE 2008-001	2008	MIT	2009-01-1490	4	22
Williams	Impact of Butanol and Other Bio-Components on the Thermal Efficiency of Prototype and Convention	2009-01-1908	2009	SAE	2010-01-2094	4	17
Moore	Engine Efficiency Improvements Enabled by Ethanol Fuel Blends in a GDi VVA Flex Fuel Engine	2011-01-0900	2011	SAE	Committee	4	20

Table 1: List of References Examined from Primary Papers
(Papers in orange background were part of original 39Primary Papers; papers in yellow background were added)

Table 2: List of 12 Primary References not in Table 1

1.Williams et al., BP Toyota, SAE 2010-01-2094 (Ref. 2)
The Impact of Fuel Consumption on the Combustion and Emissions of a Prototype Lean-Boosted PFI Engine

2.Nakata et al., Toyota, International Journal of Engine Research, Oct 2010 (Ref. 16)
The effect of fuel properties on thermal efficiency of advanced spark-ignition engines

3.Boretti, University of Ballarat, SAE 2010-01-2154 (Ref. 21)
Performances of a Turbocharged E100 Engine with Direct Injection and Variable Valve Actuation

4.Bromberg and Cohn, MIT Paper 3/15/07, 2007 (Ref. 23)
Effect of CR and Manifold Pressure on Ethanol Utilization in Gasoline/Ethanol Engines

5.Caton, Texas A&M University, SAE 2009-01-2621 (Ref. 26)
A Thermodynamic Evaluation of the Use of Alcohol Fuels in a Spark-Ignition Engine

6.Stein et al., Ford, SAE 2009-01-1490 (Ref. 27)
Optimal Use of E85 in a Turbocharged Direct Injection Engine

7.Mittal and Heywood, MIT, SAE 2009-01-2622 (Ref. 29)
The Shift in Relevance of Fuel RON and MON to Knock Onset in Modern SI Engines Over the Last 70 Years

8.Mittal et al., MIT, SAE 2010-01-0617 (Ref. 30)
The Underlying Physics and Chemistry behind Fuel Sensitivity

9.Morikawa et al., Fuji. SAE 2005-01-0240 (Ref. 31)
A Study on New Combustion Method of High Compression Ratio Spark Ignition Engine

10.Jaaskelainen and Wallace, University of Toronto, SAE 932746 (Ref. 37)
Effect of increasing CR in a light-duty natural gas-fueled engine on efficiency and emissions

11.Munoz et al., Ford, SAE 2005 -01 -0100 (Ref. 38)
Effect of CR on stratified charge DI Gasoline Combustion

12.Haghgooie, Ford, SAE 902134 (Ref. 45)
Effect of fuel octane and inlet air temperature on knock characteristics of a single cylinder engine

2.3 PAPER REVIEW AND DATABASE DEVELOPMENT

The 51 selected papers, which dated from 1987 to 2011, were reviewed in detail to document the types of tests conducted and the results. The papers included a wide range of test types, fuels, test methods, and measured or calculated outputs. Reducing these variables to a set that can be represented in a searchable data base proved to be a challenging task.

Tests were broadly separated into simulation studies, engine tests, and vehicle tests (one paper was a review of results from all test types). Engine and vehicle specifications, to the extent provided, are documented; but, it should be noted that vehicle specifications were for the most part, not fully provided. For example, most papers dealing with vehicle tests rarely provided the compression ratio, the presence of a knock sensor, or the presence of variable valve timing. Engine specifications were generally more completely documented. Engine tests were conducted on an engine dynamometer, but the test conditions varied significantly and were not always fully documented. We attempted to document the speed and load conditions of all the tests which sometimes included load sweeps at specific RPM, or a RPM sweep at fixed intake pressure or wide-open throttle (WOT). In general, intake air pressure or BMEP are specified, but intake air temperature and operating air-fuel ratio were not always given. Vehicle tests included accelerations at specific throttle settings or rear-wheel torque measurements at fixed RPM and specified throttle settings on a chassis dynamometer.

A wide range of fuels were tested across the 51 papers, and we have separated them into 5 categories in the database. Commercial gasoline (CG) includes all pump fuels ranging from regular unleaded to super-premium fuels. Oxygenate blends (OB) include ethanol and butanol gasoline blends (but no methanol gasoline blends), and a few instances of ETBE or MTBE blends. Special gasoline blends (SGB) were also common and included mixes of paraffin, olefin and aromatic compounds to attain specific combinations of Research Octane Number (RON) and Motor Octane Number (MON). A subset of these fuels is labeled Primary Reference Fuel (PRF) which are n-heptane/ iso-octane blends or Toluene Standardization Fuel (TSF) which are toluene/n-heptane/iso-octane blends. A few tests utilized single component (SC) fuels such as neat iso-octane, iso-butanol or neat ethanol, E100.

Study results and outputs proved to be the most difficult to report in a standard format. Vehicle tests reported acceleration times or rear wheel torque, and sometimes the vehicle octane requirement. Engine tests reported on a wide range of variables, all at widely varying test conditions, including:

- Knock limited spark advance (KLSA), knock intensity
- BMEP or IMEP and/or torque, and indicated or brake thermal efficiency
- Emissions of criteria pollutants and carbon dioxide
- Fuel consumption or specific fuel consumption, and
- Combustion duration (burn rate) and end gas temperatures.

In most papers, the outputs were reported in the form of figures, which can be difficult to convert to numeric or digital data. As a result, we have reproduced the important figures into the database with a separate Excel® worksheet for each paper.

All papers were also reviewed in detail for the findings relevant to the project. Important findings from the point of view of this analysis are summarized as bullet points and included in the worksheets in the database. A summary of each paper is also provided in Appendix A of this report, along with the bullet point summary of findings. Of the 51 papers reviewed in detail, 3 papers were found to have no real data on the relationship between fuel properties and efficiency, while one paper had undefined test conditions and the results were not usable. Another 2 papers had information that was repeated in other papers by the same authors. Six papers were thus eliminated; the database and reviews in Appendix A summarize 45 relevant papers. The 45 papers by research type are as follows:

- 10 papers on single cylinder research engines
- 24 papers on prototype or production engines
- 4 papers on vehicle tests
- 6 papers that use simulation models, and
- 1 review paper.

The major findings are summarized in Section 3.

3. SUMMARY OF PAPERS REVIEWED

3.1 BACKGROUND

Historically, the relationship between octane number of the fuel and the engine efficiency has been linked through the engine compression ratio (CR). A fuel's propensity to auto-ignite and cause "knock" is quantified in terms of the fuel's octane number (ON). The ON is measured on a standard engine called the CFR engine (for Cooperative Fuel Research), where the engine is set to run at fixed intake conditions and RPM. The engine CR is increased until the engine knocks at a specified intensity as measured by a pressure transducer. The procedure is then repeated using a primary reference fuel (PRF). The volumetric percentage of iso-octane is adjusted until a PRF is found that knocks at the same intensity and at the same CR as the fuel whose octane index is being measured. The ON of the fuel is equal to the percentage of iso-octane of the PRF that has the same knocking tendency.

The PRF is a combination of paraffin compounds, but the ON of typical hydrocarbon (HC) fuels depends on the test conditions since olefin and aromatic HC do not have the same temperature sensitivity to auto-ignition. Hence, the octane number is measured at two test conditions; one termed "Research Octane Number" (RON) which specifies a 52°C intake air temperature and an engine speed of 600 RPM, with a fixed spark timing of 13°C before top dead center. The second is termed "Motor Octane Number" (MON) which specifies a 149°C intake air temperature and an engine speed of 900 RPM, with spark timing varied according to CR and the air-fuel ratio (A/F) adjusted to maximize knock intensity.

This would suggest a direct two step procedure to link fuel octane to efficiency – first, the given fuel's RON and MON would imply a specific maximum CR; second, the CR of the engine can be linked directly to maximum engine thermal efficiency. Unfortunately, modern engines do not resemble the CFR engine and the measurement conditions do not represent typical engine intake air temperatures, cylinder pressures, or operating RPM. These conditions of RPM, pressures, and intake air temperature in modern engines are very different, with most modern SI engines operating between 1000 to 5000 RPM during normal driving, and intake air temperatures being close to ambient (usually in the 0° to 40° C range). In addition, the combustion chamber shape and air turbulence in the chamber in modern engines promote substantially faster burn rates than in the CFR engine. Hence the relationship between CR and fuel octane number could be substantially different for modern engines, and other factors such as new technologies and different calibrations can also affect the relationship between octane and fuel economy.

As noted in the introduction, the list of engine technologies considered for review includes the following but excludes HCCI combustion:

- Port fuel injection (PFI), naturally aspirated and turbocharged engines
- Direct injection (DI), naturally aspirated and turbocharged engines
- DI stratified charge lean burn, naturally aspirated, and turbocharged engines

In general, measurements of torque and efficiency changes with CR and octane number are conducted at MBT or KLSA spark timing, unless specifically stated.

3.2 PORT FUEL INJECTION (PFI) ENGINES

3.2.1 Single Cylinder Engine and Simulation Studies

The relationship between thermal efficiency and CR is well known, and the factors affecting the relationship have been studied in detail. One example is the simulation study by Nissan (Muranaka, et al., 1987, Ref. 36) that found the fuel-air cycle benefited more from CR increases than an air cycle, although the absolute efficiency was always lower. The study found that the:

- Smaller the swept volume, the lower the efficiency due to cooling loss. The surface to volume ratio at TDC is a good indicator of cooling loss.
- Higher the engine speed and the higher the load, the greater the indicated efficiency.
- Effects of combustion duration are small over a wide range, although the optimal duration is about 30 CAD.
- Simulation results show similar trends as measured values but over-predict the efficiency by 4% to 5%, possibly due to errors in estimating heat transfer and unburned fuel-related losses.

These conclusions are well supported but do not offer a direct connection to fuel octane index.

The relevance of RON and MON ratings to modern engines has been examined at the research engine, production engine, and vehicle levels in a number of papers. The basic principle is that the octane index (OI) of a fuel can be expressed as a linear combination of the RON and MON values with K as the weighting factor such that

$$OI = (1-K)*RON + K* MON$$

which can be rearranged as

$$OI = RON - K*(RON - MON)$$

$$= RON - K * S$$

The term RON – MON is called the sensitivity, S, of the fuel. In a study by Shell (Kalghatgi, 2001, Part I Ref. 9), 21 SGB and PRF fuels with a wide range of RON and MON were tested on two single-cylinder engines with PFI and a more modern combustion chamber configuration, and a CR of 10.5 (CR could be reduced to 8 in one engine). The spark timing was advanced until a limiting level of knock was reached with each fuel, and the engine brake torque and knock intensity were measured. As is well known, the engine torque increased almost linearly with spark advance, flattening out at a maximum for best torque (MBT) value spark level and declining with further increases in spark advance. Many fuels had too high a knock intensity at levels of spark advance much less than the MBT level so that they were tested only to the knock limit. The analysis found that the knock limited spark advance was poorly correlated with a fuel's MON and better correlated with RON, but the best correlation was with the OI. Here, K was determined for each RPM/ load test condition and was found to be negative at low RPM (<2000) and high load. K increased with RPM, but decreased with increased CR and load. The K value at any speed/ load condition appeared to be largely independent of fuel type or RON. **The implication of a negative K value is that the OI of fuel with high sensitivity (S) is greater than either the RON or MON of the fuel.** K was found to decrease with increasing octane number requirement (ONR) of the engine at the different speed/load and CR values evaluated, so that as the ONR of the engine increased, K became more negative.

These findings were largely replicated by MIT (Mittal and Heywood, 2008, Ref. 28) on a CFR engine using PRF, TSF and ethanol-heptane blend fuels as well as a commercial gasoline (CG), and the authors also noted a linear increase in peak pressure with spark advance. The analysis also found that K was:

- Only weakly dependent on spark plug location and CR.
- Non-linearly dependent on air-fuel ratio, being highest at lambda = 1, which was also confirmed by Ayala, et al. (2006, Ref. 37).
- A strong function of RPM and increased almost linearly with RPM.
- Increased linearly with intake air temperature.
- Decreased almost linearly with increased intake air pressure (boost).

Other single cylinder engine studies have provided some quantitative inputs on the sensitivity of fuel consumption and efficiency to the various operating factors that also affect the octane number requirements of the engine (ONR). A study by Ford (Russ, 1996, Ref. 41) estimates the effect per unit octane number increase on spark advance, intake temperature, compression ratio (CR) and cylinder head/block temperature using an experimental engine and SGB fuels. The study reported the following major findings:

- Spark advance can increase by 1°C per 1 octane number (ON) increase
- Intake air temp increase by 7°C requires 1 ON increase
- ONR is highest at lambda = 0.95 and decreases by 2 ON per 1 A/F
- ONR increases by 3 to 4 ON per 10kPa manifold air pressure (MAP)
- ONR increases by 5 ON per 1 compression ratio (CR)
- ONR increases by 1 ON per 30kPa back pressure increase
- ONR increases by 1 ON per 10° C, with an equal effect of cylinder head and block temperature

An earlier study by Ford (Haghgooie, 1990, Ref. 45) examined the relationship between intake air temperatures and knock limited spark advance with CG fuels, and found sensitivities very similar to that reported by Russ. The Ford study also found that the crank angle at which knock occurs was linearly proportional to the spark advance, and the frequency of knock was inversely proportional to the bore diameter.

A similar study at the US Naval Academy (Caton, et al., 2007, Ref. 18) examined the tradeoff between spark advance and CR and found that both CG and AB (E10) required 5 degrees spark retard from MBT per unit CR increase while E85 required only 2 degrees per unit CR increase. This paper also reported flat thermal efficiency between a CR of 8 and 11 for gasoline and E10, but the absolute thermal efficiency seemed very low even for a CFR engine. A MIT study (Ayala, et al., 2006, Ref. 34) on a single cylinder Ricardo engine with TSF and CG fuels showed the good correlation between IMEP and the ratio of the crank angle for 50% mass burn relative to the crank angle for 50% mass burn at MBT spark, with the duration measured in CAD. Peak efficiency was found to occur at a burn duration of 30 CAD across a variety of operating conditions, identical to the findings by Nissan. Effects of fuel composition appear to correlate closely with changes in burn duration, but these effects were small.

Bradley and Kalghatgi (1996, Ref. 13) measured the pressure, knock intensity, and end gas temperatures in a single cylinder engine with an optical window using CG and AB fuels and found that for similar temperatures and pressures, the maximum auto-ignition heat release rates for paraffinic fuel are higher than those for aromatic fuel. They suggested that initial heat release as a function of temperature can delineate auto-ignition modes. Mittal, et al., (2010, Ref. 30) examined the underlying physics and chemistry of auto-ignition using a single cylinder engine and a wide variety of fuels including PRF, TSG, AB, SGB and CG fuels, and found that paraffins tended to have lower octane number sensitivity relative to olefins, aromatics and ethers, but did not find any explanation for their sensitivity as a function of chemical bond structure. They used simulation models to analyze 3 different fuels with an RON of 96 but with different sensitivities, and found very similar auto-ignition CAD for all 3 fuels at intake temperatures of 50°C (which is similar to the temperature specified for the RON test). At lower intake temperatures, auto-ignition occurs later for more sensitive fuels, but this reverses at temperatures above 50°C. Fuels with higher sensitivity have a stronger temperature dependence of the auto-ignition time.

An unusual method to reduce the time available for auto-ignition was examined by researchers from Fuji (Morikawa, et al., 2005, Ref. 31). They used a special crank mechanism to accelerate the piston motion near top dead center (TDC) to realize a higher CR. A “leaf shaped” gear with a turbulence enhancing port allowed operation of an SI engine with a CR of 12 using a 91 RON

CG fuel. Efficiency was improved by 12% relative to the base engine with a CR of 10 and the same 91 RON fuel, while HC and NOx emissions were reduced.

3.2.2 Prototype and Production Engines

Several studies have examined fuel and octane effects on multi-cylinder prototype or production engines. An earlier study by Fiat and Marzano Polytechnic Institute (Millo, et al., 1994, Ref. 42) with a 1.6L 4 cylinder engine examined the OI of several SGB and AB fuels across the RPM range. The study concluded that the OI of all fuels decreased with increasing RPM, consistent with the findings that K increases with RPM. However, the study contradicted the findings from Kalghatgi and from Mittal and Heywood by finding that K was not independent of the fuel; K was higher for higher olefin fuels, while the K values for the 15% ethanol and 15% methanol blends showed very sharp increases with speed, compared to the increases for hydrocarbon fuels.

A study by Nippon Oil and Nissan (Okamoto, et al, 2003, Ref. 3) on a 2L 4 cylinder engine that could be switched from PFI to DI with PRF and TSF, found that the base engine configuration with PFI and 10.5 CR had an ONR of 100 at 1200 RPM, and maximum torque increases almost linearly with RON from 90 to 98 but is quite flat at higher octane numbers. The engine ONR was found to increase almost linearly from 100 to 118 as CR was increased from 10.5 to 15. The DI version of the same engine had an ONR that was 4 points lower than the ONR of the PFI engine at 10.5 CR but was almost 10 points lower at a CR of 15 while, oddly, was almost equal at 12 CR. At high load conditions, torque declined as CR increased using a 90 RON fuel while torque increased up to 13.5 CR with a 114 RON fuel. These trends are consistent with findings that fuel octane increases result in increased peak torque up to the point where fuel OI equals engine ONR.

A large number of studies have been reported by Toyota on octane effects. In a study (Nakata, et al., 2006, Ref.14) on the effect of ethanol blends on a 1.5L 4 cylinder engine with a CR of 13, torque was found to increase by 20% for E100 fuel relative to a 91.5 RON US regular gasoline and by 5% relative to a 99.6 RON Japanese premium gasoline. Torque was found to be maximized for an E50 blend, when MBT spark timing was possible, but decreased at E100 due to volumetric efficiency loss. In another study (Nakata, et al., 2007, Ref. 15), 5 engines that spanned a range of engine designs from PFI conventional, PFI Atkinson cycle, PFI-Turbo, and

PFI+DI – Turbo were tested with CG fuels. They concluded that for high CR engines, turbocharged engines and lean-boosted engines, high RON fuels improved thermal efficiency, with lean-boosted engines having the largest potential to improve efficiency by increasing RON. In a 2010 paper, Nakata et al. (Ref. 16) found that an Atkinson cycle engine with a CR of 13 tested with a variety of SGB and AB fuels showed a 10% efficiency improvement when RON was increased from 90 to 100, but no additional improvement beyond that RON level. The lean boosted engine with a CR of 13 showed a 7.4% improvement in efficiency when RON was increased from 90 to 100, and by 12.8% when RON was increased from 90 to 109 (which is the RON for E100). The lean boosted engine could operate at 1.4 Mpa BMEP with E100 but only at 1Mpa with a 100 RON gasoline with no ethanol content.

A paper with similar data as the 2010 Nakata et al., paper (Ref. 16) that was published by authors from BP and Toyota (Williams, Nakata, et al., 2009, Ref. 17) showed a near linear relationship between thermal efficiency gains and fuel RON for the lean-boosted engine run on a variety of SGB and AB fuels, but further gains beyond 102 RON were constrained by cylinder pressure limits and exhaust gas temperature limits rather than by the thermodynamic potential. In a 2010 study by the same authors (Williams, et al., 2010, Ref. 2), the fuel effects of SGB and SGB with ignition improvers were examined on the lean-boosted PFI engine. At an equivalence ratio of 1.6, the study found a linear response of thermal efficiency to fuel RON. However, only the E85 fuel and gasoline with a nitro-methane additive increased the lean limit from 1.85 for all other fuels to 1.95. The Toyota-BP studies stated that thermal efficiencies of over 44% percent could be attained with the high RON of E100, exceeding the efficiency of a light-duty diesel engine.

Other studies of turbocharged PFI engines do not fully agree with the Toyota and BP findings regarding the lack of significance of MON. In a study by Renault and Total (Duchaussoy and Barbier, 2004, Ref.1) using a 2L turbocharged engine with SGB fuels, the impact of improved RON was found to be amplified in the turbocharged engine relative to a naturally-aspirated engine, but found that only the intermediate RPM region benefits from increased octane (1500 to 4000 RPM). Below 1500 RPM, the available boost was limited by turbo performance, while above 4000 RPM, the thermal constraints on the turbine become the over-riding factor. The paper found the impact of MON increase at constant RON up to 3000 RPM, where a 3 point decrease in sensitivity (i.e. a 3 point increase in MON) provided a 3% torque gain. According to the analysis by Kalghatgi and by Heywood and Mittal, the effect of MON becomes somewhat higher at higher RPM as K decreases. The Renault- Total paper also showed that multiple factors affect the relationship including spark advance, waste gate control, and the level of enrichment at WOT, making general conclusions difficult.

3.2.3 Vehicle Studies

The CRC has conducted many studies on vehicle ONR, but a special study conducted in 1989-90 (McNally et al., 1991, Ref. 39) focused on the effect of fuel octane number on vehicle acceleration performance, as measured on a 0 to 30 mph, 0 to 60 mph and 0 to 70 mph acceleration time at WOT, as well as 40 to 70 mph at maximum throttle to stay in top gear. 155 passenger cars and 27 light trucks, many with knock sensors, were tested on full boiling range unleaded (FBRU) fuels with a wide range of octane numbers to determine their ONR, and retested with fuels 4 octane points below and 4 and 8 octane points above the ONR, which are designated as (ONR–4), (ONR+4) and (ONR+8) fuels respectively. Knock sensor equipped vehicles showed a 1.5% increase in acceleration time with an (ONR–4) fuel, but even here, only 30% of the vehicles showed a statistically significant increase. The vehicles also showed a small decrease in acceleration time with the (ONR + 8) fuel. The vehicles without knock sensors did not show any statistically significant changes in acceleration times with any of the fuels. The relatively small increase in time with an (ONR – 4) fuel may not be consistent with the observed changes in peak torque on an engine operating at KLSA for knock sensor-equipped vehicles, but the lack of response in vehicles without knock sensors is also surprising, as engines experiencing knock will also likely have lower torque output.

Kalghatgi (2001, Ref. 10) examined the acceleration times going from 1500 to 3500 RPM in fourth gear at WOT and 75% throttle, on a chassis dynamometer for 23 cars (15 MPFI, 5 DI and 3 PFI-turbo) fueled with 19 SGB fuels varying in RON from about 86 to 101, and with varying sensitivities. The paper did not identify which vehicles were equipped with a knock sensor. The results were found to correlate well with the OI, and the acceleration times were found to decrease with fuel OI, flattening out when the fuel OI was nearly equal to the vehicle ONR. The results are in contrast to the CRC study results reported above, since K values were computed for every vehicle, implying that acceleration times changed significantly for every vehicle in the sample. The majority of K values were negative or close to zero, consistent with the findings from simulation and engine studies. However, the differences in K values between technologies or as a function of the OR of the vehicles were not obvious, nor explored in the paper. In a similar test of a Toyota Avensis (Kalghatgi, Nakata and Mogi, 2005, Ref. 11) equipped with a 2L DISI engine using 10 different PRF, TSF and CG fuels with RON ranging from 86.3 to 101.1 and varying sensitivities, K was found to be negative for all acceleration and torque tests conducted. Good correlation was found between acceleration time and fuel OI, as well as between vehicle tractive energy and fuel OI.

Mittal and Heywood (2009, Ref. 28) examined the historical relevance of RON and MON based on the results from CRC octane surveys from 1950 to 1990 where identical tests had been performed to determine vehicle OI with primary reference fuels and full boiling range fuels. K was determined by the equation

$$K = (RON - ON)/\ S$$

Where RON is the research octane number for the full boiling range fuel and S its sensitivity, and ON is the octane number of the primary fuel. The computations showed that K values had decreased over time with average K values declining from 0.28 in 1951 to just under 0.1 in 1991. This was in spite of the fact that the average knock-limited engine speed increased from 1500 RPM in 1951 to about 2400 in 1991, as K increases with increasing RPM. The paper suggested that increasing CR, the reduction of intake air temperature by eliminating intake air pre-heat, improved volumetric efficiency, improved engine cooling, and decreased bore size were the contributing factors. Simulation modeling of typical engine designs for a 1951 engine and a modern turbocharged engine supported the calculated values of K. The authors suggested that with the use of DI and turbo-charging, K would decline further. In an earlier review paper, Kalghatgi (2005, Ref 12) came to a similar conclusion suggesting that future engines would prefer fuels with a lower MON and higher RON.

Vehicle fuel consumption and its relationship to fuel ON were measured on 5 relatively modern vehicles by Shell (Beck, et al., 2006, Ref. 40). Vehicles were tested on a chassis dynamometer with a variety of SGB fuels, but the ONR of the vehicles was not specified. The paper found that vehicle fuel consumption (FC) could be modeled as a (negative) exponential function of the fuel octane index, OI, and that the model explained over 80 percent of the fuel consumption variability. Paired comparisons indicate statistically significant FC improvements for all vehicles tested when fuel RON increases from 91 to 95. The paper did not indicate whether the vehicles were equipped with a knock sensor. A Sasol study (Bell, 2010, Ref. 43) examined the effects of altitude on engine response to octane number using PRF, TSF and SGB fuels. Naturally-aspirated PFI vehicles were not knock limited at an altitude of 1535m on any of the fuels tested, but the octane sensitivity of turbo-charged vehicles was very inconsistent, even with different vehicles of the same model type.

Hence, the data on vehicle tests are limited and quite incomplete in terms of detailed vehicle descriptors, including their emissions certification level.

3.3 DIRECT INJECTION ENGINES - GASOLINE

Several recent papers have examined the response of DI engines to fuel octane. Most studies are based on multi-cylinder engine tests, although a few DI vehicles were included in the vehicle tests described in Section 3.2.3 above. However, most of the literature on DI is focused on the benefits of ethanol use in this type of engine.

In a study by Exxon and Toyota (Farrell, et al., 2003, Ref. 4), the response of a DI engine with CR of 9.8 to SGB, CG and AB fuels with different aromatic, olefin, and ethanol composition but nearly identical RON of about 92 was examined. Higher volumetric fuel economy was correlated with higher olefin content and higher drivability index. The efficiency benefit was linked to the burning velocity, as olefins and ethanol have higher burning velocity relative to aromatics and paraffins. The study also found a qualitative correlation between engine tests results and vehicle tests with a Toyota Avensis using the same engine. As noted in Section 3.2.3, similar testing was conducted by Shell and Toyota (Kalghatgi, Nakata and Mogi, 2005, Ref. 11) on a prototype DISI engine at two CR values, 11 and 12.5. Tests were conducted at WOT at 1200, 2000, 4000 and 6000 RPM and at a lambda of 0.85. K values were found to be negative and the KLSA was found to be quadratic function of the OI. The knock limited torque value was found to be well correlated with KLSA. In line with earlier results, K was found to increase with engine speed and K decreased approximately linearly with increasing engine ONR.

The Nippon Oil-Nissan study referenced in Section 3.2 (Okamoto, et al., 2003, Ref. 3) examined the ONR of a DI engine using CR values ranging from 10.5 to 15 and PRF and TSF. The ONR increase with CR was non-linear for this DI engine. At 10.5 CR, the ONR of the DI engine was 4 points lower than that of a PFI engine with the same CR, but at 12 CR, the ONR of the 2 engines was nearly equal. At 15 CR, the ONR for this DI engine was 108, nearly 10 points lower than the ONR for the PFI engine at 15 CR. Peak torque increased with CR up to 13.5 but decreased at higher CR values. At high CR, the brake specific fuel consumption (BSFC) actually got worse at low speed high load conditions, but was better at light loads. However, the paper concluded that the effect of increased CR on FTP fuel economy was quite small.

A paper by Toyota-Exxon (Akihama et al., 2004, Ref. 6) examined the response to different PRF, TSF and Japanese CG fuels of a 2L DI engine with a CR of 13. The analysis found that high RON fuels, especially those with high aromatic content, yielded significant torque benefit at WOT and an equivalence ratio (the inverse of lambda) of 1.15. The high RON (103), high aromatic fuel exhibited significant torque and efficiency benefits over iso-octane. Surprisingly, at light loads and very lean (lambda = 1.92) conditions, a low RON fuel (84 RON) yielded 5.5% higher brake thermal efficiency than the base (91 RON) gasoline. The higher efficiency under light load stratified charge conditions is further examined in Section 3.5.

Toyota (Nakata, et al., 2007, Ref.15) examined octane effects on modified turbocharged production engines with both DI and PFI systems and a CR of 13, using CG and AB fuels. The engines were operated lean and were equipped with tumble ports. They noted a nearly linear response of thermal efficiency with octane number, but only minimal details are provided in the paper on this engine.

3.4 DIRECT INJECTED AND PORT FUEL INJECTED ENGINES WITH ETHANOL

The focus of many papers investigating the benefits of DI engines has been the use of high volumetric blends of ethanol (E85) or E100. A series of papers from MIT (2006, 2007, and 2008, References 22, 23, and 24) have examined the effects of ethanol (as well as methanol) in engines. These papers have modeled the use of gasoline introduced with either a PFI or DI system and ethanol supplied via a DI system. Simulation was used to examine potential benefits of different strategies. In an engine with CR of 12, direct injection of ethanol is used at MAP over 0.7 bar in conjunction with 87 ON gasoline (research or motor not specified) inducted via the PFI system, to suppress knock. The paper found that the ethanol fraction could be kept below 5% for the FTP cycle (higher for the US06 cycle) with significant gasoline fuel economy improvements. The effective blending octane number using this method of direct injection of E100 was 160 (average of RON and MON basis). A similar evaluation of methanol resulted in an equivalent blending octane number of 180. The paper asserts that the use of methanol in a lean burn system could lead to an efficiency improvement of 40% to 45% relative to a PFI engine but no computations to support this statement are shown in the paper. Ford (Stein, et al., 2009 Ref. 27) tested the MIT strategy on a 3.5L V-6 prototype engine. They found that at 12 CR, no E85 injection is required up to 6 bar BMEP with regular gasoline, but 40% of total fuel use (mass) is ethanol at 10 bar BMEP. Over the FTP cycle, only 1% of fuel consumption was E85, but the E85 fraction increased to 16% on the US06 cycle.

Ethanol use in DI engines with more conventional fueling strategies is reported in several papers. A study by the IFP (Milpied, et al., 2009, Ref. 5) on a single-cylinder engine found that RON increases allowed maximum torque to increase at all RPM. The study focused on the cooling effect of fuel vaporization and found that a 2 to 8kJ/kg increase of cooling due to latent heat of vaporization had the same effect as a unit increase in RON. The high latent heat of vaporization and high RON of ethanol was found to allow a large increase in IMEP, and E30 blend with a base gasoline of 95.6 RON allowed IMEP at 2000 RPM to increase by 7.5 bar over the use of base gasoline alone. EPA has also found from its in-house research that alcohol fuels in DI engines can provide high thermal efficiency. An EPA publication (Brusstar, et al., undated, Ref. 7) described the conversion of a turbo-diesel engine with a CR of 19.5 to spark ignition. High EGR was used to prevent knock enabling spark timing near MBT at stoichiometric AF ratio. The paper states that over 40% brake thermal efficiency was obtained using E100 or M100. With E30, a fuel economy benefit of 10 to 12 percent was estimated, substantially higher than the benefits at light loads claimed by others.

Researchers from Oak Ridge National Laboratory and Delphi (Szybist, et al., 2010, Ref. 8) conducted a study of a DI engine where the geometric CR could be varied from 9.2 to 12.9, and the engine was also equipped with camless valve actuation. Actual CR could be controlled through early or late intake valve closing strategies. They found that with increasing ethanol content, both power and efficiency increase simultaneously. The increase is due to the increased air flow from evaporative cooling, the higher energy flow per unit air mass, and the mole multiplier effect (number of moles of products is higher than the number of moles of reactants with alcohol fuels). The study also found that both Early Intake Valve Closing (EIVC) and Late Intake Valve Closing (LIVC) strategies improve thermal efficiency relative to throttling. The authors concluded that the fuel consumption penalty associated with E85 can be reduced by 20% by operating at a high mechanical CR and utilizing the EIVC and LIVC control strategies to maintain compatibility with regular gasoline at WOT.

Toyota (Nakata, et al., 2006 Ref. 14) examined the use of ethanol in a PFI engine, and found that CR could be increased with increased volumetric content of ethanol. Highest torque was obtained with an E50 blend, and the study found efficiency increases for all blends. Other papers by Nakata, et al. discussed above show that alcohol fuels can extend the lean limit when used in lean burn DI engines. In another Toyota study (Taniguchi, et al., 2007, Ref. 44), an E100 DI engine with a CR of 13 was compared to a 11.5 CR gasoline engine. The E100 engine showed a 7.6% improvement in maximum torque over the gasoline engine. Spark had to be retarded from MBT in the gasoline engine with a 96.4 RON fuel at speeds below 2400 RPM, but the E100 engine could use MBT spark at all speeds and loads. Oddly, the authors found only very small improvements in efficiency but believed that it may have been due to increased blow-by with the high CR E100 engine. Orbital Corp (Brewster, 2007, Ref. 19) found that the ethanol use resulted in the need for lower boost and airflow at the same torque relative to using premium gasoline of 98 RON, and estimated a CO_2 benefit by between 7 to 13 percent over gasoline but the cycle was unspecified.

Simulation analysis at the University of Ballarat (Boretti, 2010, Ref. 21) found that a CR increase by 4 points is possible with E100 relative to a base 95 RON fuel gasoline in a PFI engine, with a thermal efficiency increase of 5.7 to 6.25 percent. However, the comparisons did not appear to be at the same level of engine output torque.

Mahle and BP (Cairns, et al., 2009, Ref. 25) examined the use of ethanol and butanol blends with CG at part load in a turbo-charged DI engine with a CR of 9. Not surprisingly, they found no efficiency benefit at part loads of 2 bar and 4 bar BMEP, and they concluded that fuel economy would be achieved only through engine downsizing. Similarly, a Texas A&M University study (Caton, 2009, Ref. 26) performed a simulation study that showed no benefit to ethanol use at part load in an 8.1 CR MPFI V-8. Efficiency was projected to increase by 0.5% at WOT due to a drop in intake temperature of 25 C. BMEP was also projected to increase by 8.5%. Since the fuel specific energy is slightly less for an ethanol air stoichiometric mixture, the throttle needs to be opened slightly more than with gasoline at the same load leading to a small gain in efficiency from reduced pumping loss.

Only one paper on natural gas (NG) use was included in the data set, and a summary is presented here. The study by University of Toronto researchers (Jaaskelainen and Wallace, 1993, Ref. 37) used a 4 cylinder 2L engine with a CR of 10 and 11.5 fueled on natural gas with 95.3% methane content. The major findings were that increasing CR from 10 to 11.5 increased WOT torque by 3.2% with NG fuel, but the authors noted that base torque at 10 CR was 13 to 15 % lower than on the same engine fueled with gasoline. Increasing CR from 10 to 11.5 with natural gas fuel improved BSFC by 2 to 3% over the entire load range, indicating ISFC increased more than the pumping loss increase at constant load. HC emissions increased by 30 to 50% with increased CR but NOx emissions were comparable.

3.5 STRATIFIED CHARGE LEAN BURN ENGINES

Only three references to stratified charge lean burn engines in relation to octane effects were available in the 50 paper sample. As noted in Section 3.3, a 2004 Toyota Exxon paper (Akihama, et al., 2004, Ref. 6) alluded to the fact that the DI engine operating at very lean air fuel ratios showed substantially higher thermal efficiency with a lower octane fuel, but it was not clear if the engine used stratified charge combustion. An earlier paper by the Cosmo Research Institute (Fukui et al., 2001, Ref. 32) examined the effect of several single component fuels in a stratified charge single cylinder DI engine with a CR of 12. They concluded that low RON fuels provide higher efficiency for stratified charge lean combustion at lambda values of 2. This is potentially explained by very lean mixtures near the cylinder wall auto-igniting with low octane fuel. The paper was not able to gauge the effect of MON rating of the fuels. Analysis by JOMO Research (Hashimoto, et al. 2000, Ref. 33) on a stratified charge DI engine operating at lambda = 2 with SGB and CG fuels found paraffins (which may imply low RON fuel) to have the same IMEP as Japanese premium gasoline, but the paper did not specifically find that low octane fuels were uniformly better. Tests at Ford (Munoz, et al., 2005, Ref. 38) on a stratified engine, however, did not specifically reveal any benefit of lower octane fuel (fuel type unspecified). In fact, at light loads, the tests found no benefit to operating at higher MAP and leaner air fuel ratio, but found that increasing CR from 10 to 12 increased thermal efficiency by 2.6% at light loads of 1 bar and 2.5% at 2 bar.

4. SUMMARY OF DATA AVAILABILITY FOR FUTURE ANALYSIS

The detailed examination of the data in the 45 papers used for this analysis suggests the following:

1. Comprehensive data on the relationship between fuel octane/composition and efficiency exist for naturally aspirated PFI engines at near full load. Data at light-load conditions and vehicle data on the FTP are more limited. However, many different output metrics are provided and an analytical framework to present the results of different papers on a comparable basis is required. This issue of different output metrics is true for all engine technologies examined in this study.

2. Data for turbocharged PFI engines are more limited than for naturally-aspirated engines. Data on turbocharged engines have the additional complication that many factors such as boost availability (at low RPM), enrichment, waste-gate control, and turbine inlet temperature limitations affect the findings and are sometimes undocumented.

3. Data on the octane effects for DI engines are also limited and many papers on DI engines have focused on the benefits of ethanol. However, there is enough data to develop at least a preliminary estimate of octane effects and fuel composition effects. The data set on turbo-charged DI engines has drawbacks similar to those for the turbocharged PFI engine data set.

4. Data on stratified charge lean burn engines are very limited but interesting in that some of the available data suggests that increasing octane number reduces engine efficiency, which is not noted for any other technology reviewed in this study.

5. Vehicle data are poorly supported with documentation of engine specifications, and the results from different vehicle studies appear somewhat contradictory, at least in this initial review.

6. A large fraction of the relevant literature in the public domain has been contributed by six organizations: MIT, BP, Shell, Exxon, Ford and Toyota. Follow-up with these organizations may allow recovery of some missing specifications.

LIST OF ACRONYMS

AB	- Alcohol Blends
A/F	- Air Fuel ratio
BP	- British Petroleum
BMEP	- Brake mean effective pressure
BSFC	- Brake Specific Fuel Consumption
CAD	- Crank Angle Degrees
CFR	- Cooperative Fuels Research
CG	- Commercial Gasoline
COV	- Covariance of Mean Effective Pressure
CR	- Compression Ratio
CRC	- Coordinating Research Council
DI	- Direct Injection
DISI	- Direct Injection Spark Ignition
Dyno	- Dynamometer
EGR	- Exhaust Gas Recirculation
ETBE	- Ethanol Tert-Butyl Ether
EIVC	- Early Intake Valve Closing
Exx	- Ethanol gasoline blend with the volumetric content of ethanol as a percent, xx
FBRU	- Full Boiling Range Unleaded Fuel
FC	- Fuel consumption
FISITA	- International Federation of Automotive Engineering Societies
HC	- Hydrocarbons
HCCI	- Homogeneous Charge Compression Ignition
IJER	- International Journal of Engine Research
IMEP	- Indicated Mean Effective Pressure
ISFC	- Indicated Specific Fuel Consumption
JSAE	- Japan Society of Automotive Engineers
K	- Sensitivity weighting factor between RON and MON
KLSA	- Knock Limited Spark Advance

kPa	- kilo-Pascal
LIVC	- Late Intake Valve Closing
MAP	- Manifold Air Pressure
MBT	- Maximum for Best Torque (refers to spark advance)
MIT	- Massachusetts Institute of Technology
MON	- Motor Octane Number
MPa	- Mega-Pascal
MTBE	- Methyl Tert-Butyl Ether
MY	- Model Year
NA	- Naturally Aspirated
NIMEP	- Net Indicated Mean Effective Pressure
NG	- Natural gas
NOx	- Nitrogen Oxides
OB	- Oxygenated Blend of gasoline and alcohol or ether
OI	- Octane Index of fuel
ON	- Octane number
ONR	- Octane Number Requirement of engine
PFI	- Port Fuel Injection
PRF	- Primary Reference fuel
RON	- Research Octane number
RPM	- Revolutions Per Minute
SAE	- Society of Automotive Engineers
SC	- Single Component fuel
SGB	- Special Gasoline Blends
SI	- Spark ignition
SICI	- Spark Induced Compression Ignition
SIDI	- Spark Ignition Direct Injection
SPFI	- Single Point Fuel Injection
SULEV	- Super Ultra Low Emitting Vehicle
TDC	- Top Dead Center (piston position)
TSF	-Toluene Standardization Fuel

VVT	- Variable Valve Timing
WOT	- Wide Open Throttle

APPENDIX A
SUMMARY OF REVIEWED PAPERS

1. **Duchaussoy and Barbier, Renault/Total, SAE 2004-01-2001**
Impact of Gasoline RON and MON on a Turbocharged MPI SI Engine Performance

Engine: 2L 4 cylinder, 4valve, turbocharged, MPI, no VVT, 9.5 CR
Fuels: Refinery stock blends, s=10, RON at 92.5, 94.6, 98.3, 100.2 and 106.5 (5 fuels)
4 additional fuels with sensitivity from 7 to 13 tested.
Test conditions: Engine dyno, steady state, 1000 to 5000 RPM, WOT
Measured: Max Torque, BSCF (corrected for fuel LHV), KLSA
Important figures: 2 and 6

Major findings

- Impact of RON is amplified on turbocharged engine and there are great benefits of an increase RON at RPM>1500. (Boost limited below 1500 RPM?)
- Intermediate RPM region is area of greatest octane benefit as thermal constraint on turbo becomes overriding factor over 4000 RPM.
- Paper is unclear about use of enrichment, which is treated separately but only at 5000 RPM.
- Multiple factors on turbo: spark advance, waste-gate, base CR, and enrichment make general conclusions difficult.
- The impact of MON increase at constant RON was only at low (<1700)and middle speed (up to 3000 RPM) of turbocharged engine, providing 3% torque gain for 3 points decrease in sensitivity, and similar decrease in BSFC at 2000 RPM.
- High RON level is a key to combine high specific performances and high compression ratio, necessary to ensure benefits of downsizing. High specific performances level can be obtained with less enrichment at high speed to reduce consumption and emissions.

2. **Williams et al., BP Toyota, SAE 2010-01-2094**

The Impact of Fuel Consumption on the Combustion and Emissions of a Prototype Lean-Boosted PFI Engine

Engine: 1.8L 4 cylinder, 4valve, turbocharged, MPI, no VVT, 13 CR
Fuels: Refinery stock blends, 100 and 102 RON, 7 fuels with ignition improvers or ethers added to 102 RON fuel, E85, high aromatic 108 RON fuel
Test conditions: Engine dyno, steady state, 2000 and 2800 RPM, 0.2 to 1.4 MPa BMEP
Measured: Lean limit Covariance of IMEP< 5%, Max Torque, BSFC (corrected for fuel LHV)
Important figures: 8 and 9

Major findings

- The thermal efficiency of the lean burn PFI engine is primarily dependent on the anti-knock performance RON of the fuel. Figures indicate nearly linear response at 1.6 and 1.0 lambda.

- Only E85 and a nitro-methane additive increased the lean limit from 1.85 to 1.95 lambda. These 2 fuels had very similar combustion duration.
- Two fuels containing nitrogen were tested and while they offered significant benefits in combustion duration and auto-ignition resistance, they led to significant increases in NOx emissions, particularly when operating at very lean conditions.

3. **Okamoto et al., Nippon Oil-Nissan, SAE 2003-01-1804**

Study of Antiknock Performance under Various Octane Numbers and CR in a DISI Engine

Engine: 2L, 4 cylinder, 4valve, MPI or DI, no VVT, CR variable from 10.5 to 15 in steps of 1.5
Fuels: Reference fuel + toluene blends, variable RON from 90 to 114 by blending.
Test conditions: Engine dyno, steady state, 1200 RPM, WOT, lambda = 0.8; 3 part load points at 1200 and 2400 RPM.
Measured: Max Torque, BSFC (corrected for fuel LHV), ONR
Important figures: 4, 9, and 11

Major findings

- At 10.5 CR, max. torque climbs from 90 to 98 RON by 8% for MPI, almost flat from 98 to 100 RON. Torque is almost flat over 94 RON for DISI.
- ONR at 10.5 CR was 100 RON for MPFI and 96 RON for DI.
- ONR increased linearly from 100 to ~118 (estimated) from CR 10.5 to 15 for MPFI. ONR for DI was non linear, equal to MPI at 12 CR but only 108 at 15 CR. Torque increased in both engines up to 13.5 CR with 114 RON fuel but decreased steadily with increasing CR using 90 RON fuel.
- With high compression ratios, the brake specific fuel consumption (BSFC) got worse under the low speed, high load conditions. However, the BSFC improved under the low speed, low load, and middle speed conditions due to the better thermal efficiency.
- High compression ratios and high octane gasoline improved fuel economy by very small amounts on LA4 cycle based on simulation (percent change not given).

4. **Farrell et al., Exxon Toyota, SAE 2003-01-3186**

Fuel Effects on SIDI Efficiency and Emissions

Engine: 2L 4 cylinder, 4valve, DI, VVT unspecified, CR = 9.8, Toyota Avensis 3000 lb. IWT with lean NOx storage catalyst.
Fuels: 6 blends with aromatics from 15% to 35%, Olefins from 8 to 25%, DI from 1020 to 1220 and one 7.5% EtOH blend with 15% A and 8% O. RON almost constant for all fuels at 92 to 93. MON not measured.
Test conditions: Vehicle: FTP and Engine dyno: steady state, 1200 and 2400 RPM, WOT, stratified and homogeneous operation, 3 part load points at 1200 and 2400 RPM.
Measured: Burning Velocity, FTP FE, FTP FE corrected for density and LHV, all emissions
Important figure: Table 6

Major findings

- Fuels were blended to the same RON with varying levels of aromatics, olefins, ethanol, and volatility.
- Higher fuel economy (volumetric) correlates with increased olefin content, and DI (and a debit for ethanol). Maximum difference on FTP was 4.3%.
- There is an efficiency benefit for increasing burning velocity and a debit for aromatics. Olefins and ethanol increase burning velocity.
- Qualitative correlation between engine dyno and vehicle tests.
- Most of the THC emissions occur during the first 30 seconds following start-up but variation among fuels was due to hardware effects.
- WOT torque highest for high olefin fuel with higher KLSA than other fuels of similar RON.
- Higher aromatics contribute to higher NOx emissions.

5. Milpied et al., IFP, SAE 2009-01-0324

Impact of Fuel Properties on the Performances and Knock Behavior of a Downsized Turbocharged DI SI Engine – Focus on Octane Numbers and Latent Heat of Vaporization

Engine: 0.3L 1 cylinder, 4 valve, DI, no VVT, CR = 9.5, ”sonic throttle” turbo
Fuels: 7 fuels with RON from 91.6 to 100.4.MON from 81.6 to 90
6 fuels with 100 RON, 87.6 to 90 MON, and different LH-Vaporization
Test conditions: Engine dyno, steady state, 1200 RPM, WOT, lambda = 0.8; 3 part load points at 1200 and 2400 RPM.
Measured: IMEP at KLSA
Important figures: 5, 8, and 10

Major findings

- RON increase allowed max knock limited load to increase at all RPM.
- MON increase did not have consistent effects.
- A 2 to 8 kJ/kg increase of “cooling power” has the same impact as the increase of 1 point of RON value.
- The high LHV and RON of ethanol together provide a large increase in IMEP. An E30 blend with a 95.6 RON gasoline allows 2000 RPM IMEP to increase by7.5 bar.

6. Akihama et al., Toyota-Exxon, SAE 2004-01-1950

Fuel Octane and Composition Effects on Efficiency and Emissions in a High Compression Ratio SIDI Engine

Engine: 2L 4 cylinder, 4valve, DI, no VVT?, CR = 13, stratified charge at light load
Fuels: 5 fuels, Japanese regular 91.7 RON, Japanese premium 99.6 RON, primary blends of octane, heptanes, and toluene with 83.8, 103.1 and 100 RON.

Test conditions: Engine dyno, steady state, 1200 RPM, light load, lambda = 0.52, 2 low RON fuels- WOT at 2000 and 4000 RPM, lambda = 1.15, 3 high RON fuels.
Measured: IMEP at KLSA
Important figures: 4, 11, and 19

Major findings

- Low octane (RON=84, comprised of toluene, iso-octane, and n-heptane) yielded 5.5% higher brake thermal efficiency and significantly lower hydrocarbon emissions than a base gasoline (RON=91) at low load operation.
- High RON fuel, in particular one that is high in aromatics, yields significant torque benefits under high load.
- Higher efficiency under low load stratified conditions can be obtained with lower octane fuels that undergo SICI (Spark Induced Compression Ignition) combustion. The brake efficiency is about 7% higher than that of a base engine (CR =9.8) because of its higher compression ratio and the occurrence of SICI combustion which yields lower HC emissions.
- Under WOT condition, a high RON and high aromatic model fuel (RON=103, comprised of toluene, iso-octane, and n-heptane) exhibited significant torque/efficiency benefits compared to pure iso-octane
- RON is a better predictor of knock resistance, while lower MON gives better knock resistance at higher CR.

7. **Brusstar et al., EPA Publication (undated)**

Economical, High-Efficiency Engine Technologies for Alcohol Fuels

Engine: 1.9L 4 cylinder, 2-valve, PFI, no VVT, CR = 19.5, turbocharged, cooled EGR at all loads
Fuels: M100, E100, M50 to 90 blends and E10 to 85 blends
Test conditions: Engine dyno, steady state, complete engine map
Measured: BMEP, efficiency
Important figures: 4 and 5

- Tests used turbo-diesel converted to SI with no change to CR.
- High EGR was used to prevent knock enabling near MBT spark timing for all loads at stoichiometric AF.
- Over 40% brake thermal efficiency can be obtained in a high compression ratio, PFI SI engine using neat methanol and ethanol fuels.
- Decreasing the fuel alcohol content generally gives lower brake thermal efficiency and somewhat decreased load range.
- The efficiency gain for E30 should yield an estimated 10% to 12% gain in fuel economy, and thus more than compensate for the approximately 8% loss in fuel energy density compared to gasoline.

8. Szybist et al., ORNL- Delphi SAE 2010-01-0619
Investigation of Knock Limited Compression Ratio of Ethanol Gasoline Blends

Engine: 2L, 1 cylinder, 4valve, DI, Sturman hydraulic valve actuation, geometric CR varied from 9.2.to 12.9
Fuels: 5 fuels, regular 90.8 RON, premium 96.1 RON, E10 at 95.7 RON, E50 at 101.6 RON and E85 at 101.5 RON
Test conditions: Engine dyno, steady state, 1500/2000/2500 RPM WOT, 1500 RPM/90kPa MAP throttled/ with LIVC/ with EIVC and at 1500 RPM/80kPA MAP
Measured: IMEP at KLSA, ISFC and indicated efficiency
Important figures: Table 3, Figures 7, 8, and 11

Major findings
- With increasing ethanol content, both power and efficiency increase simultaneously.
- The increase is due to the increased air flow from evaporative cooling, the higher energy flow per unit air mass and the mole multiplier effect (N of products is higher than N of reactants with alcohols).
- Both EIVC and LIVC strategies improve thermal efficiency relative to throttling,
- The fuel consumption penalty associated with E85 can be reduced by 20% by operating at a high mechanical CR and utilizing the EIVC (Early Intake Valve Closing) and LIVC (Late Intake Valve Closing) control strategies to maintain compatibility with gasoline at WOT.

9. Kalghatgi , Shell, SAE 2001-01-3584
Fuel Anti-Knock Quality – Part I. Engine Studies

Engines: 0.5L 1 cylinder and 0.344L 1 cylinder, 4valve, PFI? , geometric CR of 10.5 (some tests conducted at 8 CR)
Fuels: 22 fuels, RON range from 85 to 102, MON from 78 to 100
Test conditions: Engine dyno, steady state, 1200/2000/3000 RPM WOT
Measured: Knock intensity and peak cylinder pressure as a function of ignition timing
Important figures: Table 3, Figures 9 and 10

Major findings
- In equation OI=RON-K*S, K decreases as the engine becomes more prone to knock; i.e., as its octane requirement increases.
- K is negative at lower speeds but becomes positive at higher RPM as ONR decreases with speed.
- End gas temperatures of high CR engines are lower than those of RON test.

10. Kalghatgi, Shell, SAE 2001-01-3585
Fuel Anti-Knock Quality- Part II: Vehicle Studies – How Relevant is MON in Modern Engines?

Vehicles: 23 cars MY 1994 to 2001, 15 European, 8 Japanese, 5 DI, 3 PFI-Turbo, 15 MPFI
Fuels: 19 special gasoline blends, RON range from 86.3 to 101.1, MON from 81 to 97.6
Test conditions: All chassis dyno tests (?) Acceleration time from 1500 to 3500 RPM in 4th gear at WOT and 75% throttle, and from 1200 to 3000 RPM in 5th gear at 75% throttle, Torque measured at steady state at 1500/2500/3500 RPM for manual transmission vehicles only
Measured: Acceleration time, Vehicle Tractive effort
Important figures: Table 1, Figures 4, 6, and 7.

Major findings
- (RON+MON)/2 is inappropriate in modern engines.
- Acceleration time can be represented as a quadratic function of OI.
- Torque can be represented as a quadratic function of OI.
- Most K values are negative and positive values are close to zero.
- Lack of correlation between K values from acceleration test and torque test not noted by author.

11. Kalghatgi et al., Shell Toyota, SAE 2005-01-0244
Octane Appetite Studies in Direct Injection Spark Ignition (DISI) Engines

Engines: Prototype DISI, no details given, CR of 11 and 12.5
Vehicles: 2 Toyota Avensis cars with 2L DISI engines
Fuels: 15 fuels, RON range from 86.4 to 105, MON from 80.3 to 98.2 for engine tests
10 fuels with RON from 86.3 to 101.1, MON from 81 to 97.6 for vehicle tests
Test conditions: Engine dyno tests at WOT and 1200/2000/4000/ 6000 RPM, lambda at 0.85
Vehicle tests on chassis dyno, acceleration from 1200 to 3000 RPM in 4th gear at 75% throttle and WOT, and from 1200 to 3500 RPM in 5th gear at WOT.
Measured: Vehicle: Acceleration time, Vehicle Tractive effort
Engine: KLSA, torque at KLSA (analyzed in paper)
Important figures: Table 1, Table 3, Figure 2c, 5, 7, and 9.

Major findings
- At low and moderate engine speeds, commonly used on the road, for a given RON, a lower MON fuel had better anti-knock quality.
- KLSA and torque increase with increasing OI.
- K increases with engine speed.
- There is a rough correlation between K and engine octane requirement, with K decreasing as ONR increases.

- Paper generally confirms findings of earlier Kalghatgi papers for vehicle acceleration time.

12. Kalghatgi, Shell, SAE 2005-01-0239
Auto-Ignition Quality of Practical Fuels and Implications for Fuel Requirements of Future SI and HCCI Engines

Review of previous papers and data, appears to use the vehicle data from 2001-01-3585 plus data on 14 additional cars.
Important figures: Figure 7 and 8

Major Findings

- Modern SI engines will be less likely to knock with higher sensitivity fuels. For a given RON, they will prefer lower MON fuels. They might also require higher RON.
- It is very likely that changes in specifications to the fuel could be implemented without undue penalty on tailpipe emissions because of improvements in engine and after-treatment technology and with other fuel specifications such as on sulfur, benzene, and volatility in place.
- Future engines will have lower K as increasing CR decreases volume of hot residuals in cylinder, DI reduces temperature from evaporative cooling, while turbo/downsize increases pressure at start of compression.
- Increased aromatic content will increase CO2 per MJ of fuel energy and increases combustion chamber deposits.

13. Bradley and Kalghatgi, Shell, SAE 962105 1996
Fuel Blend and Mixture Strength Effects on Auto-ignition heat release rates and knock intensity in SI engines

Engine: 0.5 L 2 valve Ricardo E6 PFI, CR = 10.18
Fuels: Regular gasoline, E10 and E85 Fuel spec not provided
Test conditions: Engine Dyno, steady state, 1200 RPM WOT, Lambda=0.88, 1 and 1.1
Measured: IMEP, Peak Pressure Location, knock intensity, unburned end gas temperature
Important figures: 5, 7 and 9

Major Findings

- Unburned end gas temperatures were higher than estimated from compression heating due to pre-flame reactions.
- Heat release rates from the Arrhenius equation plotted against the inverse of end gas temperature + constant agree with measurements.
- For similar temperatures, auto-ignition heat release rates for paraffinic fuels are higher than those for aromatic fuel.
- For the same temperature and pressure, fuel blends with lower octane number give a higher volumetric heat release rate.
- There is a similar but less marked trend for heat release to increase with lower A/F ratios.

14. Nakata et al., Toyota, SAE 2006-01-3380
The Effect of Ethanol Fuel on a Spark Ignition Engine

Engine: 1.5L 4 cylinder, 4-valve, PFI, no VVT, CR = 13
Fuels: US regular with 91.5 RON and 83 MON, Japanese premium with 99.6 RON and 87.1 MON, and ethanol blended with US regular in varying quantities.
Test conditions: Engine Dyno, steady state, at 0.2 MPa BMEP and at WOT
Measured: Torque, fuel consumption and emissions
Important figures: 2, 3, and 4

Major Findings

- By blending ethanol with gasoline as E10 or E20 to increase octane number, ethanol allows compression ratio to be raised which can result in improved engine torque and reduced CO_2.
- With E100, torque increases 20% at 2800 RPM relative to US regular and 5% relative to Japanese premium. This is due to ignition timing retard from MBT for both gasolines.
- Torque effect saturates at E50 when MBT is achieved. Higher levels of ethanol decrease volumetric efficiency, up to 2% decrease for E100.
- CO_2 reduction is due to the 3% higher thermal efficiency than gasoline and from ethanol's higher H/C ratio.
- Valve timing optimization has the potential to improve startability for ethanol under cold conditions.

15. Nakata et al., Toyota, SAE 2007-01-2007
The Impact of RON on SI Engine Thermal Efficiency

Engine: 1.5L 4 cylinder, 4-valve, PFI, VVT, CR = 10 and 13
1.5L 4 cylinder, 4-valve, PFI, VVT, CR = 13 Atkinson cycle
2.0L 4 cylinder, 4-valve, PFI, VVT, CR = 9.3 Turbo
1.8L 4 cylinder, 4-valve, DI+PFI, VVT, CR = 13 Turbo
1.58L 4 cylinder, 4-valve, PFI, VVT, CR = 13
Fuels: US regular with 91.5 RON and 83 MON, Japanese premium with 99.6 RON and 87.1 MON, and ethanol blended with US regular in varying quantities.
Test conditions: Engine Dyno, steady state, 2800 RPM, Lambda=1
Measured: KLSA, Thermal efficiency
Important figures: 5, 6, 7 and 9

Major findings

- For high compression ratio engines, turbocharged engines and lean boosted engines, high RON fuels are effective to improve thermal efficiency.
- Ethanol results in improvement of thermal efficiency due to high anti-knock quality and the effect of decrease in cooling heat loss.

- Lean boosted engine has larger potential to increase the thermal efficiency compared with NA engine by raising RON.
- Low concentration of ethanol like 10% with various hydrocarbon fuels leads to an increase in RON and contributes to reduce HC, NOx, and CO2. The negative effect of ethanol on volumetric fuel economy can be improved by using ethanol as an octane booster.

16. Nakata et al., Toyota, International Journal of Engine Research, Oct 2010
The effect of fuel properties on thermal efficiency of advanced spark-ignition engines

Engine: 1.5L 4 cylinder, 4-valve, PFI, VVT, CR = 13 Atkinson cycle
1.8L 4 cylinder, 4-valve, PFI, VVT, CR = 13, Turbo, lean burn
Fuels: 15 fuels with RON varying from 90 to 107, MON from 81 to 93.9, 6 fuels containing butanol and/or ethanol for engine 1; subset used for engine 2, also fueled with E100 and neat iso-butanol.
Test conditions: Engine Dyno, steady state, 1300 and 2800 RPM WOT, Lambda=1, spark timing at MBT or KLSA.
Measured: KLSA, Thermal efficiency for engine 1 and BMEP, MAP and efficiency for engine 2
Important figures: 6, 9 and 10

Major findings
- The Atkinson cycle engine showed a 10% improvement in thermal efficiency for fuel RON increasing from 90 to 100 with no additional improvement for higher RON at 1300 RPM and 5% at 2800 RPM.
- The lean boosted engine could operate at much higher BMEP with higher RON fuels and efficiency increased by 7.4% for fuel RON increasing from 90 to 100 at 2800 RPM. With 109 RON ethanol, efficiency increased by 12.8%. Highest thermal efficiency for butanol and 100 RON gasoline occurs at 1MPa BMEP and with E100 at 1.4 Mpa (could be higher but against cylinder pressure limits).
- The combination of high-RON fuels and the lean boosted engine significantly improved engine thermal efficiency. Thermal efficiency of 44% can be obtained with neat ethanol having a RON of 109, exceeding levels offered by diesel. Therefore, the impact on CO2 reduction is large.
- Alcohol fuels have high RON and expand the lean limit under the engine warmed-up condition but under cold conditions present difficulties because alcohol does not include volatile components.

17. Williams, Nakata, et al., BP-Toyota, SAE 2009-01-1908
Impact of Butanol and Other-Bio-Components on the Thermal Efficiency of Prototype and Conventional Engines

Engine: 1.5L 4 cylinder, 4-valve, PFI, VVT, CR = 13 Atkinson cycle
1.8L 4 cylinder, 4-valve, PFI, VVT, CR = 13, Turbo, lean burn

Fuels: 14 fuels with RON varying from 91.4 to 108, MON from 80.2 to 94.3, 6 fuels containing butanol and/or ethanol for engine 1; subset used for engine 2, also fueled with E100 and neat iso-butanol
Test conditions: Engine Dyno, steady state, 1300 and 2800 RPM WOT, Lambda=1
Measured: KLSA, Thermal efficiency for engine 1 and BMEP, MAP and efficiency for engine 2
Important figures: 1,5 and 8 (many items repeated from IJER paper by Nakata, Ref. 16)

Major findings
- The use of fuels containing high octane bio-components together with technologies like downsized lean-boosting will enable a reduction in CO2 emissions.
- RON had the greatest influence on engine performance of all the fuel properties studied.
- Thermal efficiency, combustion, and emissions were not adversely affected as a result of adding any butanol to gasoline.
- Further CO2 savings can be achieved by increasing the H/C ratio of the fuel.
- Thermal efficiency increases sharply as RON is increased from 90 to 100. The 10% increase in thermal efficiency can be explained by the advanced ignition timing facilitated by the use of the higher octane fuels. Thermal efficiency levels out at around 38% with fuels in excess of 100 RON as the engine can be run at its optimum, MBT, timing. A maximum thermal efficiency of 42.9 was achieved with 108RON gasoline.
- A near linear relationship between thermal efficiency and fuel RON existed from 98 to 102 RON, beyond which further thermal efficiency gains are constrained by high cylinder pressures under lean conditions, and by exhaust gas temperatures under stoichiometric operation.
- Since the Atkinson cycle decreases intake air volume by late intake valve closing, the thermal efficiency peaks before full advantage can be taken of very high octane fuels. This would suggest that turbo-charging has the potential to improve thermal efficiency further with high RON fuels since higher RON can increase thermal efficiency.

18. Caton et al., US Naval Academy, SAE 2007-01-0473
An Experimental and Modeling Investigation into the Comparative Knock and Performance Characteristics of E85, Gasohol [E10] and Regular Unleaded Gasoline [87 (R+M)/2]

Engine: CFR engine with CR variable from 8 to 17, PFI retrofit
Fuels: Regular gasoline, E10 and E85 Fuel spec not provided
Test conditions: Engine Dyno, steady state, 900 RPM WOT, Lambda=0.9
Measured: IMEP, Peak Pressure Location, thermal efficiency
Important figures: 5, 7, 12, 15, and 20

Major findings
- Engine torque and thermal efficiency increase with fueling on E10 and E85 as compared to gasoline. This is due to more ideal pressure phasing with the higher octane quality of ethanol at this high load low speed condition.

- To maintain knock limit from CR=8 requires 5 deg. Spark retard per I CR increase for gasoline and E10 up to CR=11, 2 degrees per 1 CR for E85 up to CR= 16.5.
- Thermal efficiency is flat from CR= 8 to 11 for gasoline and E10, but increases at 2% per CR for E85 from 10.5 to 16.5.
- All thermal efficiency values appear very low relative to modern engines and to Otto cycle theoretical efficiency.

19. Brewster, Orbital Corp., SAE 2007-01-3625
Initial Development of a Turbo-charged Direct Injection E100 Combustion System

Engine: 2L 4 cylinder, 4 valve, no VVT, DI (air assisted), CR = 10.4, Turbo
Fuels: E100, premium gasoline 98 RON, MON not specified
Test conditions: Engine Dyno, steady state, 2000 RPM, lambda = 1, WOT, "moderate" boost
Measured: Torque, MAP, Turbine inlet temp, spark timing
Important figures: 5 and 12

Major findings

- Ethanol required lower airflow and boost pressure, and delivered lower exhaust temperature, higher brake efficiency and lower emissions of CO2 compared to gasoline at the same torque.
- The fuel flow rate for ethanol is significantly higher due to lower energy density. When expressed in terms of fuel energy flow, it is apparent that ethanol requires a lower input to achieve the same engine output, which is reflected in the higher brake efficiency. In consequence, the level of CO2 emitted at a given condition is seen to fall by approximately 4%. For operation of ethanol, the resultant efficiency and CO2 emissions at MBT will be more favorable than those observed for gasoline at KLSA or later ignition timings.
- Emissions of CO2 are reduced by between 7% and 13% by E100 relative to premium gasoline.

20. Moore et al., Delphi, SAE 2011-01-0900
Engine Efficiency Improvements Enabled by Ethanol Fuel Blends in a GDi VVA Flex Fuel Engine

Engine: 2L 4 cylinder, 4 valve, VVT, 2 step VVL, DI, CR = 11.85, Turbo
Fuels: E85, regular gasoline 90.8 RON, MON not specified, splash blended E10, E20 and E50
Test conditions: Engine Dyno, steady state, 2250 RPM, lambda = 1, 6 bar BMEP, no boost
Also load sweeps at 2000 RPM 6 bar BMEP, and knock limited torque at 1000 to 4000 RPM
Measured: Torque, MAP, Turbine inlet temp, spark timing
Important figures: 22, 23, 27, 29, 31, and 34

Major findings

- Cam phasing and injection timing were optimized for E85 to minimize fuel consumption and emissions.
- Engine out HC, NOx, and soot emissions were reduced with increasing ethanol content.
- Resistance to EGR induced knock enabled reduced NOx emissions for higher ethanol blends, using high valve overlap for internal EGR.
- Lower NOx should result from reduced combustion temperatures due to charge cooling and a lower adiabatic flame temperature.
- The use of spark retard was used to keep knock at an acceptable level. The use of spark retard also results in a reduction in NOx but both combustion stability (COV) and BSFC deteriorate.
- The effect of increasing load via effective compression ratio resulted in an increase in hydrocarbons, NOx, and FSN. The emissions however were strongly related to ethanol content with higher ethanol blends reducing emissions.

21. Boretti, University of Ballarat, SAE 2010-01-2154
Performances of a Turbocharged E100 Engine with Direct Injection and Variable Valve Actuation

Simulation study of efficiency map of 4L NA engine 10.5 CR, and 1.6L turbo DISI engine with 9 CR for gasoline and 13CR for E100
Fuels: 95 RON gasoline and 129 RON E100, MON not specified.
Complete engine map computed using WAVE model for lambda =1
Important figures: 8 a,b,c, 11 a,b, and Table 4

Major findings

- Direct fuel injection and turbo charging are the two key features for pure ethanol engines to take full advantage of ethanol’s higher research octane number and heat of vaporization.
- Paper implies a 4 CR increase is possible with E100 relative to 95 RON gasoline in turbo engine.
- E100 allowed torque increase of 20% to 28% over range of engine speed.
- Thermal efficiency increases by 5.7 to 6.25%.
- Comparisons with 4L NA and between turbo engines are not at same rated power or torque.

22. Bromberg and Cohn, MIT Paper LFEE 2008-01RP, 2008
Effective Octane and Efficiency Advantages of Direct Injection Alcohol Engines

CFR PFI engine simulation with base characteristics set to 85 ON primary reference fuel.
Effective blending octane number of ethanol is determined.
Important figures: Tables 4, 5, and 6.

Major findings

- The effective blending octane number of ethanol was found to be ~160 RON+MON/2 for DI engines and about 180 for methanol.
- Paper asserts the combination of high compression ratio and downsizing provided by direct methanol injection together with reformer enabled ultra lean operation at light loads could provide an efficiency improvement of 40-45% relative to a conventional port fuel injected gasoline engine. (No computations shown.)

23. Bromberg and Cohn, MIT Paper 3/15/07, 2007
Effect of CR and Manifold Pressure on Ethanol Utilization in Gasoline/Ethanol Engines

Simulated engine with CR at 10 and 12, and PFI and DI
Fuels: gasoline (87 ON, research or motor unspecified, possibly R+M/2) and E100
Entire speed/load map simulated.
Important figures: 1, 2, and 3

Major findings

- Direct injection of ethanol was used with either PFI gasoline or DI gasoline to counter knock.
- Ethanol injection used at MAP over 0.7 bar with CR=12 and PFI gasoline, and at higher MAP for other conditions.
- Ethanol fraction increased with MAP and decreased with RPM.
- For most driving cycles, the ethanol fraction can be kept below 5%, except for US06 cycle. High torque situations like towing might be a problem as well.

24. Bromberg et al., MIT Paper 2/23/06, 2006
Calculations of Knock Suppression in Highly Turbocharged Gasoline/Ethanol Engines Using Direct Ethanol Injection

Engine: Turbocharged DI ethanol+ gasoline engine with E100 DI
Fuels; gasoline and E100 used together
Important figures – superseded by paper 22 above

Major findings

- Use direct ethanol injection in spark ignition gasoline/ethanol engines.
- Evaporative cooling from direct ethanol injection, coupled with the high octane rating of ethanol, can be highly effective in inhibiting knock, thereby allowing the use of small turbocharged engines with substantially increased efficiency.
- Less than 1 gallon of ethanol for 20 gallons of gasoline could be sufficient to allow engine downsizing.
- Engine could be downsized by a factor of 2 and the drive cycle efficiency could thereby be increased by approximately 30%.

25. Cairns et al., Mahle BP, SAE 2009-01-0138
A Study of Gasoline-Alcohol Blended Fuels in an Advanced Turbocharged DISI Engine

Engine: 2L 4 cylinder, 4 valve, VVT, 2 step VVL, DI, CR = 9, Turbo
Fuels: regular (95/86 RON/MON), midgrade (98/88), premium (102/91), E10 (98/88), E22 (102/88) E85 (108/90), and Butanol 22%
Test conditions: Engine Dyno, steady state, 2000 RPM/ 2 bar and 4 bar BMEP, and 4000 RPM /2 bar
Injection timing sweeps and EGR sweep.
Measured: IMEP and BSFC, efficiency computed
Important figures: 9 and 10

Major findings

- Under part-load conditions, when alcohol was added, fuel consumption over the drive cycle increased in direct proportion to the reduction in calorific value of the fuel. For example, with E85 the calorific value was 32% lower than 98 RON fuel while the fuel consumption was 33% higher.
- Fuel RON and MON had almost no effect as engine was not knock limited with any fuel at 2 bar and 4 bar BMEP.
- Concluded that SI engine downsizing and fuel containing low-to-moderate amounts of alcohol significantly improved fuel economy over the drive cycle, but same effect with gasoline shown.

26. Caton, Texas A&M University, SAE 2009-01-2621
A Thermodynamic Evaluation of the Use of Alcohol Fuels in a Spark-Ignition Engine

Simulated 5.7L V-8, 8.1 CR, 2 valve MPFI engine
Simulated load and speed: 325 kPa BMEP and WOT at 2000 RPM. (MAP= 50 kPa)
Fuels: Iso-octane, methanol and ethanol
Important figures: 8, 9, 10, and 16

Major findings

- No change in efficiency at constant part load due to decreased intake temperature, but increases about 0.5% for a -25K drop at WOT with a BMEP increase of 8.5%
- Alcohol fuels require more throttle opening for a given BMEP to compensate for lower air-fuel mixture energy density.
- Second law analysis shows higher fuel energy destruction with isooctane than ethanol and methanol.
- NOx concentrations for iso-octane were higher than for the alcohol fuels due to the slightly higher gas temperatures during combustion.

27. Stein et al., Ford, SAE 2009-01-1490
Optimal Use of E85 in a Turbocharged Direct Injection Engine

Engine: 3.5L 6 cylinder, 4 valve, VVT, DI for E85 and PFI for gasoline, CR = 12, Turbo
Fuels: E85 with unknown RON/MON, + regular gasoline 91RON, 83 MON
Test conditions: Engine Dyno, steady state, 2500 RPM, lambda = 1 up to 20 bar BMEP, load sweeps
Measured: Torque, Peak pressure, Turbine inlet temp, spark timing, efficiency, E85% of total fuel
Important figures: 3 and 4

Major findings

- By enabling higher CR and engine downsizing, the use of E85 DI + gasoline PFI makes the engine more efficient in its use of gasoline.
- At 12 CR no E85 is required up to 6 bar BMEP, increasing to 40% at 10 bar.
- E85 consumption is only 1% of fuel mass on FTP cycle and 16% on US06 cycle.
- When no E85 is being injected, injector tip cooling may be required.

28. Mittal and Heywood, MIT, SAE 2008-01-2414
Relevance of Fuel RON and MON to Knock Onset in Modern SI Engines

Engine: 0.5L one cylinder Ricardo, 4 valve, fixed valve timing, CR = 9.8, 11.6, 13.4
Fuels: 96 and 91 RON primary reference fuel, 3 heptane-toluene-octane mix with 96 RON and MON of 79 to 89, an ethanol heptanes blend with 96 RON and 70MON, 3 fuels with 91 RON and MON of 79.3, 83.6 and 86.4, unleaded regular (91/83) and premium (96.1/ 87) gasoline.
Test conditions: Engine Dyno, steady state, 1500 RPM, lambda = 1, WOT (MAP = 1 bar), intake air temperature varied and AF varied from 0.7 to 1.6 for some tests.
Measured: KLSA, cylinder pressure, accelerometer and microphone for knock.
Important figures: 2, 5, 6, 7, 8, and 9

Major findings

- With 25 degree intake temp and CR = 9.8, the octane index increases with fuel sensitivity at both 91 and 96 RON with a K of -0.22
- K is only weakly dependent on spark plug location and CR from 9.8 to 13.4
- K is moderately dependent on AF ratio and is highest at lambda = 1
- K increases strongly with engine speed.
- K increases strongly with intake air temperature.
- K decreases with increasing boost pressure
- Response surface developed from all data

29. Mittal and Heywood, MIT, SAE 2009-01-2622
The Shift in Relevance of Fuel RON and MON to Knock Onset in Modern SI Engines Over the Last 70 Years

Review paper of historic CRC data on vehicle fuel octane sensitivity.
Important figures: 6, 7, and 8

Major findings

- K is a parameter in Octane Index = K MON + (1-K) RON.
- It shows the relevancy of the RON and MON tests. K has decreased primarily due to better engine cooling, better engine breathing, and the usage of fuel injection that eliminated intake air pre-heat.
- WAVE model predictions of knock limited octane number are inline with decreasing K values over time.
- When K<0, the MON is no longer relevant.

30. Mittal et al., MIT, SAE 2010-01-0617
The Underlying Physics and Chemistry behind Fuel Sensitivity

Simulation using chemical kinetic models of auto-ignition
Fuels simulated: blends of iso-octane, n-heptane and toluene
Important figures: Figure 5

Major findings

- Non-sensitive fuels are paraffin while higher sensitivity fuels tend to be aromatics and olefins
- No clear relationship between chemical structure and sensitivity
- Fuels with a higher octane sensitivity have a stronger temperature dependence of the auto-ignition time.
- Paraffins tended to have lower octane sensitivity relative to olefins, aromatics and ethers

31. Morikawa et al., Fuji. SAE 2005-01-0240
A Study on New Combustion Method of High Compression Ratio Spark Ignition Engine

Engine: 0.6L 1 cylinder, 4 valve, PFI, CR = 10 and 12, existing crank and special elliptic and leaf shaped crank drive to provide higher piston speed at TDC
Fuels: gasoline, 91 RON and 100 RON
Test conditions: Engine Dyno, steady state, 600 RPM, lambda=1, load sweep
Measured: IMEP and efficiency
Important figures: 3, 16, and 17

Major findings

- They realized a high compression ratio engine by concentrating on the crank mechanism where the crank speed varies to provide higher speed at TDC.
- With a leaf shaped gear and turbulence enhancing port, a CR of 12 was possible with 91 RON fuel without knock at MBT spark.
- Efficiency was improved by 12% over base engine using 91 RON fuel at CR of 10.
- HC and NOx exhaust gas emissions were improved.

32. Fukui et al., Cosmo Research Institute, SAE 2001-01-1964
Effects of Octane Number on Stratified Charge Combustion in a Direct Injection Gasoline System

Engine: 0.46L 1 cylinder, 4 valve, DI , CR = 12
Fuels: 4 single component fuels: benzene, cyclo-hexane, iso-octane and methyl-cyclo-hexane
5 primary reference fuels: RON of 70, 75, 80, 90, 94
4 refinery feedstock based fuels: naptha (67.5/64.5), isomerate (79.7/77.8), FCC(88.5/77.4) and reformate (102.2/91)
Test conditions: Engine Dyno, steady state, 1200 RPM, lambda=1, homogenous,73 kPa MAP
Steady state, 1200 RPM, lambda = 2, stratified charge, 87 kPa MAP
Measured: IMEP and efficiency vs. octane at MBT spark
Important figures: 2, 3, 7, and 8

Major Findings
- Low RON fuels provide higher efficiency for stratified charge lean combustion.
- This is potentially explained by the possibility that very lean mixture near the cylinder wall auto-ignites with low octane fuel.
- Unburned HC emissions for stratified charge combustion decreases as octane number decreases.
- The effect of MON is not clear, but it may have some effect.

33. Hashimoto et al., JOMO Research, SAE 2000-01-0253
Effects of Fuel Properties on the Combustion and Emission of Direct-Injection Gasoline Engine

Engine: 0.5L 1 cylinder, 4 valve, DI, 10 CR (Toyota D-4 engine), variable swirl
Fuels: 13 single component fuels: see Table 2 in paper
4 refinery feedstock based fuels: alkylate, light distillate of FCC (79.7/77.8), FCC (88. reformate (102.2/91), and Japanese premium gasoline as base fuel.
Test conditions: Engine Dyno, steady state, 1200 RPM, lambda= 2 and 3, stratified charge
Steady state, 1200 RPM, lambda = 1, homogenous charge, no swirl
Measured: IMEP and efficiency vs. octane at MBT spark
Important figures : 2, 3, 4, 5, 23, and 29
Major findings

- Under stratified charge combustion conditions, and lambda = 2, IMEP with paraffins, olefins, and ethers were higher than with the base fuel, but aromatics were lower. Paraffins had lower IMEP than ethers and olefins.
- At lambda = 3, IMEP with paraffins was equal to IMEP with base fuel, olefins and ethers were higher, and aromatics except toluene were lower.
- Relationship to burning velocities established.
- Olefins had lower HC and higher NOx emissions than other substances.

34. Ayala et al., MIT, SAE 2006-01-0229
Effects of Combustion Phasing, Relative Air-fuel Ratio, Compression Ratio, and Load on SI Engine Efficiency

Engine: 0.5L one cylinder Ricardo, 4 valve, fixed valve timing, CR = 9.8, 11.6, 13.4
Fuels: TSF with 120 RON, AF sweeps with unleaded premium 96.1 RON /87 MON
Test conditions: Engine Dyno, steady state, 1500 RPM, lambda = 1, 1.3, 1.6, target loads of 8 to 15 bar attained with hydrogen enhancement and intake boost, spark sweep. Some AF sweeps also performed at MBT spark and 3.5 bar NIMEP.
Important figures: 1, 4, 5, 25, and 26

Main findings
- Changes in NIMEP with spark retard are well correlated to the change in 50% mass burn duration relative to the duration at MBT spark.
- Peak efficiency as found to occur at a burn duration of 30 CAD across a variety of operating conditions.
- At constant load, higher CR leads to higher pumping loss and higher heat transfer, but improves with the expansion ratio effect.
- Fuel effects only indirectly addressed with burn duration.

35. Bradley et al., Shell, SAE 2004-01-1970
Relevance of Research and Motor Octane Numbers to the Prediction of Engine Auto-ignition

Simulation study of auto-ignition integral for 4 conditions:
- MON conditions in CFR test
- RON conditions on CFR test
- MAP = 0.1 MPa, T intake = 393°K, lambda = 3.5, 900 RPM
- MAP = 0.2 MPa. T intake = 313°K, lambda = 4.0, 900 RPM

Fuel: Low Octane fuel with MON of 73.2 and RON of 83.9 (from Kalghatghi HCCI paper)
Important Figures; 7, 8, 9

Major findings

- Auto-ignition integral of delay time as a function of T and P derived from experimental data.
- Polynomial fits to experimental data were used for PRF.
- Polynomials were estimated for a non-PRF fuel to fit the observed MON and RON values.
- Evaluations at non CFR test conditions provided a good match to observed K values in Kalghatgi paper.
- Main reason for low K value is the lower assumed pressure exponent for non-PRF fuels at 1.3 versus 1.7 for PRF.

36. Muranaka et al., Nissan, SAE 870548
Factors limiting the improvement of thermal efficiency of S. I. Engine at higher compression ratio

Engine: Simulation model, no engine or fuels specified
Test Conditions: Indicated efficiency calculated as a function of displacement, CR, combustion chamber shape, speed and load.
Important figures: 8, 9, 16, 17, and 18

Major findings
Analysis considers 1) fuel air cycle composition effects, 2) cooling loss, 3) time loss from combustion duration, and 4) unburned fuel effect.
- Fuel air cycle has higher efficiency increase per unit CR change then air cycle but lower absolute efficiency.
- The smaller the swept volume, the lower the efficiency due to cooling loss and S/V at TDC is a good indicator of cooling loss.
- The higher the engine speed, the higher the indicated efficiency.
- The higher the load, the higher the efficiency.
- Combustion duration effects are small over a wide range. (~0.5%) but optimum value is around 30° crank angle..
- Comparison to measured values shows computations to over-predict by 4 to 5% possibly due to error in heat transfer computations and unburned crevice HC.

37. Jaaskelainen and Wallace, University of Toronto, SAE 932746
Effect of increasing CR in a light-duty natural gas-fueled engine on efficiency and emissions

Engine : 2L 4 cylinder, 4 valve, no VVT, PFI, CR = 10 and 11.5
Test conditions: engine dyno, steady state, 1200/ 2000/ 2800 RPM, load sweep, lambda = 1
Fuel : Natural Gas, 95.3% methane
Important figures: 8, 9, 10, and 20

Major findings

- Increasing CR from 10 to 11.5 increased WOT torque by 3.2% with NG fuel but the base torque was 13 to 15 % lower than with gasoline
- Increasing CR improved BSFC by 2 to 3% over entire load range indicating ISFC increased more than the pumping loss increase at constant load.
- HC emissions increased by 30 to 50% with increased CR but NOx emissions were comparable.

38. Munoz et al., Ford, SAE 2005 -01 -0100
Effect of CR on stratified charge DI Gasoline Combustion

Engine: 0.5L single cylinder, 4 valve, PFI and DI, CR = 8.5, 10, 11, and 12, staggered intake valve timing
Fuel: unspecified, fuel effects not examined
Test conditions: engine dyno, steady state, 1500 RPM/1bar, 1500 RPM/ 2.62 bar and 2000 RPM/ 2 bar, lambda on DI optimized for minimum consumption
Measured: NMEP, fuel consumption, thermal efficiency and combustion efficiency
Important figures: 5 and 9

Major findings
- Effect of increasing MAP and using leaner AF in stratified charge DI engine provides almost no benefit to NSFC.
- Increasing CR from 10 to 12 increases thermal efficiency by 2.6% at 1bar and 2.5% at 2bar.
- Relative to PFI, fuel conversion efficiency is about 5.5% better at 1bar and 4.5% at 2.62 bar.
- Combustion loss is greater for lean SIDI but pumping loss is lower than for stoichiometric MPI.

39. McNally, et al., CRC, SAE 912394
The effects of gasoline octane quality on vehicle acceleration performance

Vehicles: study on 155 1989 passenger cars and 27 light trucks
Fuels: FBRU fuels with 80 to 104 RON in one RON increments from 84 to 104
Test conditions: Acceleration tests to determine vehicle ONR. Vehicles retested with ONR+8, ONR+4 and ONR-4 fuels.
Measured: Acceleration time for 0-30, 0-60, 0-70 mph at WOT and 40-70mph at maximum throttle
Important figures: 2, 3, 4, and 5

Major findings

- Knock sensor equipped vehicles showed a ~1.5% increase in acceleration time with (ONR-4) fuel and a small decrease with (ONR + 8) fuel in the 0-60 and 0-70 acceleration test. In contrast, vehicles without knock sensors were unaffected by fuel octane on average.
- Even with KS vehicles only 30% of the vehicles showed a significant effect of fuel octane.

40. Beck, et al., Shell, SAE 2006-01-3407
The Impact of Gasoline Octane on Fuel Economy in Modern vehicles

Vehicles: 5 European models (~MYR 1995- 2000), 3 DI and 2 MPFI no details given
Fuels: 14 fuels from the Kalghatgi paper SAE 2001-01-3585 varying from 88 to 99.4 RON and sensitivity from 1.4 to 11.
Test conditions; 3 vehicles and 10 fuels on chassis dyno, Shell drive cycle, Artemis drive cycle and US06 and 3 vehicles on 2 fuel pairs on same cycles.
Important figures: 4, 5, 6, and Table 3

Major findings
- Fuel consumption could be fitted to a curve FC = A + B exp C*OI and curve explains 80 to 90% of fuel related FC variability for each car.
- Paired comparisons indicate statistically significant FC improvements for all 3 vehicles between 91 and 95 RON fuels but improvement is a function of both drive cycle and vehicle.

41. Russ, Ford, SAE 960497
Review of the effect of engine operating conditions on borderline knock

Engine: 0.676L single cylinder FEV engine, 4 valve and 2 valve heads, CR = 9, 10
Fuels: 91 RON and 97 RON gasoline, other specification not provided.
Test conditions: Engine dyno, load, RPM sweep at MAP of 99 kPa and coolant temp= 90° C
Measured: Cylinder pressure, KLSA
Important figures: 2, 3, 4, 5, 6, 7

Major findings:
- Spark advance can increase by 1 deg per 1 ON
- Intake air temp increase by 7 deg requires 1 ON
- ONR is highest at lambda = 0.95 and decreases by 2 ON per 1 AF
- ONR increases by 3 to 4 ON per 10kPa MAP
- ONR increases by 5 ON per 1CR
- ONR increases by 1ON per 30kPa back pressure increase
- ONR increases by 1 ON per 10°K, equal effect of cylinder head and block temperature

42. Millo, et al., Marzano Polytechnic – Fiat, SAE 941862
Effect of unleaded gasoline formulation on antiknock performance

Engine: 1.6L 4 cylinder, 2 valves, no VVT, PFI, CR = 9.3
Fuels: 3 fuels with ~ 95 RON/ 85 MON (2 with high aromatics/olefins)
3 fuels with 15% MTBE, 15% methanol and 15% ethanol, respectively, blended into regular gas with about 101 RON / 87.5 MON, PRFs with RON of 86 to 100 in steps of 2.
Test Conditions: engine dyno, MAP at 0.96 bar (WOT), 2000 to 5000 RPM, AF ~ 13, inlet air at 20° C.
Measured: Knock intensity, KLSA with different fuels at 2000, 3000, 4000 and 5000 RPM.
Important figures: 4 and 5

Major findings
- ON of fuel decreases with RPM for all fuels; i.e., K increases from about 0 at 2000 RPM to about 0.67 at 5000 RPM
- K for high olefins fuels was higher at all RPM
- The OI for MTBE fuels indicates larger change in K with speed than for regular gasoline
- The OI for methanol and ethanol blends show very sharp increase in K with speed rising to 0.91 and 0.93, respectively, at 5000 RPM from 0.23 and 0.21 at 2000 RPM

43. Bell, Sasol, SAE 2010-01-1454
Modern SI engine control parameter responses and altitude effects with fuels of varying octane number

Vehicles: 4 identical DI Turbo models with 2L engine, 1 PFI Turbo with 1.8L engine and 2 PFI models with 1.4L and 1.6L engines
Fuels: 5 fuels total - 1 PRF with 93 RON, toluene standard fuel with 93 RON and S = 11, 3 full boiling range fuels with 93/83, 93.6/81.8 and 94.9/83.3 RON/MON
Test conditions: vehicle acceleration from 40 to 120 km/hr in appropriate gear at sea level and at 1535m altitude site
Measured: acceleration time at 10 km/hr intervals with GPS data, ignition timing and boost pressure (MAP)
Important figures: 9, 14, and 15

Major findings:
- Naturally aspirated PFI vehicles were not knock limited at altitude
- DI Turbo engines produced very different responses between vehicles of the same model
- Boost pressure came up more slowly at altitude due to slightly more timing retard at sea level, and higher ambient pressure
- DISI vehicles seem to have an increase in K with altitude from -0.76 to -0.36, but responses from other cars varied due to simultaneous control of boost and timing.

44. Taniguchi, et al., Toyota, SAE 2007-01-2037
Feasibility study of Ethanol Applications to a DI Gasoline engine

Engine: 3L V-6, 4valve, DI, VVT not stated, CR = 11.5, 13
Fuels: premium gasoline 96.4 RON, MON not given, E20 (102 RON), E50 (105 RON) and E100 (111 RON) with only E100 tested at 13 CR.
Test conditions: engine dyno, WOT, lambda = 0.85, spark at KLSA or MBT, RPM sweep; load sweep at 3200 RPM, lambda = 1; injector flow rates increased to keep injection timing constant.
Measured: Torque, ignition timing, volumetric efficiency, 0-90% combustion period
Important figures: 2, 6, 8, and 9

Major findings:
- E100 with 13 CR engine showed 7.6% improvement in maximum torque over gasoline with 11.5 CR. At RPM below 2400, ignition had to be retarded for gasoline at 11.5 CR but E100 was able to use MBT spark at all RPM with 13 CR.
- E100 had only slightly better volumetric efficiency, mostly over 2800 RPM, since E100 vaporizes faster than gasoline.
- In spite of improved torque, E100 full load efficiency improvement is small below 5000 RPM. Authors believe that this is due to higher fuel loss to crankcase (blow-by gas is not recycled) and longer combustion period for ethanol. Over 5200 RPM, gasoline requires very rich AF to suppress exhaust gas temperature to allowable level.
- 1 to 1.5% improvement in part load efficiency observed at part load 3200 RPM. Explanation is not clear.

45. Haghgooie, Ford, SAE 902134
Effect of fuel octane and inlet air temperature on knock characteristics of a single cylinder engine

Engine; 0.5L Ricardo hydra 1 cylinder, 4 valve, no VVT, CR = 8.7
Fuels: 91 RON and 97 RON gasoline, no other properties given
Test conditions: engine dyno, RPM = 1500, lambda = 1, MAP = 1bar, spark advance varied at 3 different intake air temperatures of 306°, 338° and 366° Kelvin,
Measured: Cylinder pressure, Knock frequency
Important figures: 7, 8, and 10

Major findings:
- As intake air temperature increases, knock occurs at more retarded spark timing.
- The crank angle of knock is linearly proportional to spark advance at almost 1 to 1.
- Knock intensity stays almost constant, independent of air temperature and fuel octane, up to the point where over 95 percent of cycles are knocking.
- The knock frequency is inversely proportional to the bore diameter.