A. Introduction

On February 24-26, 2014, the Coordinating Research Council (CRC) hosted a workshop at Hyatt Regency Baltimore, which focused on advanced fuel and engine efficiency. The workshop was co-sponsored by American Petroleum Institute (API) and U.S. Department of Energy (DOE). The main goal of the workshop was to understand the state of the art and identify gaps in current research efforts towards understanding fuel and engine efficiency effects. The workshop included two introductory sessions and five themed sessions: Spark Ignition – Octane, Spark Ignition – Systems, Compression Ignition, Alternative Fuels, and Advanced Combustion. Breakout sessions were also included on both days in order to capture key learnings, identify potential gaps in understanding, and brainstorm new research ideas. The workshop involved two introductory sessions and five themed sessions: Spark Ignition – Octane, Spark Ignition – Systems, Compression Ignition, Alternative Fuels, and Advanced Combustion.

B. Overall Workshop Highlights

Opening Session: Day One

Three speakers gave presentations on fuel economy targets, various strategies for improving engine efficiency, and technology roadmaps.

Edward Nam from EPA (U.S. Environmental Protection Agency) introduced EPA’s fuel economy and GHG (greenhouse gas) standards, their meanings and misconceptions. He also discussed projections of available technologies, costs for consumers and manufacturers, and an evaluation of how current vehicles can meet future targets. John Heywood from Massachusetts Institute of Technology discussed two major options to improve efficiency of the internal combustion engine: improve the performance of conventional technology and make the transition to new energy sources. Projections of available technology were provided with implications of increasing fuel octane on engine efficiency. John Kasab from Ricardo Inc. argued that two ways to move from conventional to low–carbon vehicles are to improve efficiency and to use low carbon fuels. The effectiveness of different engine and vehicle technologies were discussed.
**Session One: Spark Ignition – Octane**

Three speakers gave presentations on the implications of fuel octane, compression ratio, knock, and cooled EGR on gasoline engine efficiency.

*Jim Simnick* from BP (British Petroleum) presented conclusions from a literature review completed by the CRC Octane Group. The relationships between octane and engine efficiency were defined, and suggestions for research topics were made. *Henning Kleeberg* from FEV presented the efficiency and emissions benefits of a two-stage variable compression ratio engine system. *Terry Alger* introduced news developments in the use of cooled EGR (Exhaust Gas Recirculation) for high efficiency gasoline engines. Knock suppression characteristics and emissions benefits were quantified.

**Session Two: Spark Ignition – Systems**

Four speakers gave presentations on the Spark Ignition systems including hybrid vehicle (HV) applications, fuel injection technology, knock simulation methodology, and GDI (gasoline direct injection).

*Koichi Nakata* from Toyota Motor Corporation emphasized the important role of HV systems in reducing CO₂ emissions. A combination of technologies such as higher CR (compression ratio), Atkinson cycle, lean boost, DI (direct injection) and high RON (research octane number) fuels could be combined to achieve thermal efficiencies higher than 40%. *Edwin Rivera* from Delphi Automotive presented challenges and achievements on fuel injector developments. Various factors such as precise fuel mass delivery, laser drilling of injector holes, high fuel injection pressures, and multiple injection strategies are currently being considered. *James Peyton-Jones* from Villanova University introduced a novel statistical method to simulate, analyze, and control knock. Benefits of this knock control approach over traditional methods were discussed. *Cary Henry* from Southwest Research Institute discussed future emissions standards and approaches to achieve them. The importance of both PM (particulate matter) and PN (particle number) emissions were discussed, and different technologies for reducing these emissions were presented.

**Session Three: Compression Ignition**

Three speakers presented strategies for improving emissions and performance of compression ignition engines.

*Harsha Nanjundaswamy* from FEV Inc emphasized the importance of advanced control systems for emission, complex hardware, and calibration measures. *Stuart Johnson* from Volkswagen (VW) introduced the history of VW’s diesel engine and discussed features of their new diesel engine. *Tom Livingston* from Bosch LLC emphasized that a systems integration approach is key for improving emissions and performance of the diesel engine. The effect of injection strategies on emissions and performance was discussed.

**Opening Session: Day Two: Introduction**

Four speakers gave presentations on future projects and plausible technologies for meeting regulatory actions.
Steve Przesmitski discussed DOE’s (U.S. Department of Energy) fuel and lubricant technologies subprogram, including previous achievements and possible future projects. Scott Sluder from Oak Ridge National Laboratory emphasized the importance of understanding regulatory actions when planning R&D activities. Possible changes in future emissions regulations were discussed. Gopal Duleep from HD Systems discussed new technologies for fuel economy improvements and major strategies adopted by different companies. Bob McCormick from National Renewable Energy Laboratory discussed benefits of biofuels for SI (spark ignition) and CI (compression ignition) engines. Requirements of future biofuels for SI and CI engines were also discussed.

Session Four: Alternative Fuels

Five speakers discussed alternative fuels including both liquid fuels and natural gas.

John Kasab from Ricardo Inc. described increasing interest in ethanol as an anti-knock additive. Different ethanol contents and biodiesel blends were tested to evaluate the impact of biofuel on fuel economy and emissions. Magnus Sjoberg from Sandia National Laboratory presented experimental results using DISI (direct injection spark ignition) with gasoline-ethanol blends. High ethanol blends showed opportunities for clean and efficient stratified operation. Heather Hamje from CONCAWE showed the impact of FAME (fatty acid methyl ester) content on soot formation, DPF (diesel particulate filter) regeneration frequency, and fuel consumption. Hugh Blaxill from Mahle Powertrain LLC discussed the development of a pre-chamber ignition system for lean combustion of liquid and gaseous fuels. Jeff Jetter from Honda R&D Americas showed the potential of using natural gas for light-duty vehicles.

Session Five: Advanced Combustion

Five speakers discussed fundamentals of different advanced combustion concepts.

Dave Foster from University of Wisconsin discussed fundamental understanding of engine efficiency and engine loss mechanisms and pointed out that irreversibility losses are the main problem. A major way to overcome these problems and improve engine efficiency is to use low temperature combustion to increase gamma. John Dec from Sandia National Laboratory discussed the potential for higher efficiencies with low emissions utilizing LTGC (low temperature gasoline combustion). Various strategies for increasing the maximum load limitations of HCCI (homogeneous charge compression ignition) engines and achieve efficiency improvements using HCCI were demonstrated. Jerry Caton from Texas A&M University presented a comparison between a conventional engine model and a high efficiency engine model. The effects of changing compression ratio, burn duration, mixture composition, EGR, boost level, and heat transfer on thermal efficiency were discussed. Scott Curran from Oak Ridge National Laboratory discussed fuel effects on RCCI (reactivity controlled compression ignition) combustion. Drive cycle analysis and the potential benefits of biofuels on RCCI range expansion were discussed. Martin Tuner from Lund University discussed fuel flexibility, efficiency, and challenges of PPC (partially premixed combustion). Engine tests and simulations results were shown to assess the efficiency and emissions benefits using PPC.
C. Summary of Session Presentations

Opening Session: Day One
Session leaders: Krystal Wrigley (ExxonMobil) and Marie Valentine (Toyota)

Workshop Introduction
The session leaders thanked the Workshop co-sponsors U.S. Department of Energy and the American Petroleum Institute, CRC staff, the presenters, and the participants. Reminders on safety evacuation and on antitrust issues were presented.

2012-2025 Light-Duty Vehicle Standards and the Mid-Term Evaluation
by Edward Nam, U.S. Environmental Protection Agency

Vehicle greenhouse gas and fuel economy targets for 2025 are 54.5 MPG (miles per gallon) and 163 g/mile (grams per mile) CO₂ over the standard driving cycle. Real-world GHG is expected to be closer to 223 g/mile including on-road adjustment factors such as road grade, tire pressure, wind, road surface, fuel, temperature, etc. The manufacturers’ average new sales fleet is expected to meet the target, although every vehicle in the fleet does not have to meet the target. A cost increase of approximately $1,800 for these technology developments is anticipated, but significant fuel savings to consumers at the pump are also expected. There are many available technologies to meet the new standards. Mild HEVs (hybrid electric vehicles) sales are projected to increase to over 25% by 2025. Because technology penetration rates may vary by manufacturers, a specific technology may be quickly adopted by one manufacturer, even though its adoption in the overall fleet may be slow to develop. More than 25% of MY2013 (model year 2013) vehicles meet 2016 year targets, but less than 5% of vehicles meet 2025 targets. There will be a mid-term evaluation to determine if the targets should be changed.

Opportunities for Improving Engine Efficiency and Fuels
by John B. Heywood, Massachusetts Institute of Technology

Professor Heywood said that there are two main methods to improve vehicle efficiency: improve conventional vehicle technology and make the transition to new energy sources. Among new energy sources, natural gas is inconvenient for light-duty vehicles, and hydrogen as a fuel still has many barriers. Through improvements in technology, steady improvement in fuel consumption from many different propulsion systems is expected. There is a potential for a reduction of up to 50% in vehicle fuel consumption by 2050. HEVs present a significantly more promising path because they have more flexibility than BEVs (battery electric vehicles), which have many barriers. By 2030, GHG reduction may not be very large due to fleet turnover, but by 2050, about 30–40% reduction in fuel consumption on a fleet average basis is expected. Professor Heywood said that more time will be needed for broad penetration of some technologies, noting that even TC (turbocharged) engines took more than 15 years to have a real impact. By increasing f 92 RON to 98 RON gasoline and introducing engine technology that can benefit from higher octane, about a 5% improvement in fuel consumption can be expected, according to a study done at MIT. Although this may not seem like a large number, a 5% improvement is an important gain that would result in a substantial reduction in fuel demand.
Technology Roadmap for Light-Duty Vehicle CADE/GHG Emissions
by John Kasab, Ricardo Inc

There are many technological options to reduce GHG emissions. Improved efficiency and low-carbon fuels are two ways to move from conventional to low-carbon vehicles. In the long term, electrification of the powertrain is key to the future efficiency improvement of light-duty vehicles. Hybrid vehicles provide more opportunities for improvement, but they carry large cost penalties. Through reduction in rolling resistance and aerodynamic drag, the 2025 target of 264 g CO₂/mile can be met. A 40% improvement in fuel consumption compared to a conventional NA (naturally aspirated) engine was achieved by a lean-boosted engine system. Ricardo’s HyBoost vehicle used an electric supercharger for transient low speed torque, along with a turbocharger. John concluded that there are many ways to achieve low-carbon vehicles, but market interest is important.

Questions / Answers

Q: What is the major area to consider other than fuels and technology (infrastructure, policies, etc.)?
  • John Kasab: marketing and comprehensive energy policy
  • John Heywood: “clean” alternative energy sources.
  • Edward Nam: fuel price and consumer behavior

Q: Separating the vehicle from the engine, how is the TC engine more efficient than the NA engine?
  • John Heywood: lower half of the speed/load map of a TC engine is more efficient than in an NA engine. Reduced impact of friction gives the efficiency benefits.

Session One: Spark Ignition - Octane
Session leader: Jim Simnick (BP)

Introduction
The session leader introduced the themes for Session One: knock control is critical to performance and new and novel technologies are here and on the horizon.

CRC Study on Octane Number and Engine Efficiency – Literature Review
by Jim Simnick, BP and CRC Octane Group

Some selected results from the comprehensive CRC study on Octane Number and Engine Efficiency were presented. SI (spark ignition) octane research in combustion research and development is garnering a lot of interest. The relationship between octane and engine efficiency was defined, using 45 relevant papers. Engine octane requirement is affected by many different factors. The keys for knock resistance and OEM (original equipment manufacturers) recommendations were studied. Due to the many relevant variables, such as engine type/fuels/ operating conditions, statistical analysis was not possible. DI and higher RON fuels give higher torque output at KLSA (knock limited spark advance) than PFI (port fuel injection).
using lower RON fuels. Outstanding torque output could be attained with high RON fuel over the ranges of 1000 RPM to 5000 RPM (revolutions per minute). Octane effects on NA engines and TC engines were discussed in terms of thermal efficiency. Research suggestions were made based on the literature survey.

**Two-Stage Variable Compression Ratio (VCR) System to Increase Efficiency in Gasoline Powertrains**

*by Henning Kleeberg, FEV*

Lower CR resists knock at high loads while higher CR improves efficiency at low loads. Henning introduced three different ways to vary the piston’s TDC (top dead center) positions to achieve VCR (variable compression ratio). A variable length connecting rod with eccentric piston wrist pin suspension was used for two-stage VCR. Transition time of the CR was fast enough to meet the ideal CR trace versus time. Various two-stage VCR combinations were compared in terms of CO₂ reduction over the FTP (Federal test procedure) 75 cycle. The potential improvement in CO₂ emissions over different driving cycles using a combination of 10 and 14 CR was demonstrated. Using the two stage VCR, a 12% reduction in CO₂ emissions was attained, while only 4% reduction was attained using a fixed CR.

**Impact of Fuel Knock Resistance on Engine Efficiency**

*by Ken Hardman, Fiat Chrysler Automobiles*

Propulsion system efficiency improvement is the key to meet the EPA vehicle efficiency target. DI boosted engines, improvements in accessory efficiency, and electrification are strategies to improve vehicle efficiency. Manufacturers and their suppliers are exploring many different possibilities to improve engine efficiency. An ideal operating region is where the engine is knock limited. Elevated operating temperatures hurt combustion stability with knock, even with premium gasolines. At elevated temperatures, the compression ratio has to be reduced to achieve an acceptable combustion stability using regular gasolines. Changing fuel RON from 91 to 100 gives about a 4% increase in fuel economy. Fuel knock resistance is expected to be an important factor to meet fuel economy goals.

**Recent Developments in the Use of Cooled EGR in High Efficiency Gasoline Engines**

*by Terry Alger, Southwest Research Institute*

There are significant challenges to using downsizing and boosting: low CR, large enrichment region, and significant thermal efficiency. Cooled EGR (exhaust gas recirculation) reduces knock, emissions, and cycle efficiency, and exhaust temperatures. Ten per cent EGR gives about a 5 point AKI (anti-knock index) increase. NOₓ, CO, and particulate emissions all decrease with increasing EGR. D-EGR (Dedicated EGR) dedicates one cylinder for generating EGR and gives benefits of both 25% EGR and reformate. The faster burn rate from the introduced hydrogen helps combustion stability and improves knock tolerance. Implementation onto the vehicle showed over 10% improvement in MPG.
Questions / Answers

Q: Are there chemical factors other than RON and octane sensitivity that have to be considered?

- Terry Alger: identical octane rating fuels can result in different engine responses. Modernizing the grade of fuel is required.
- Jim Simnick: Making the octane test more relevant to today’s engines is also important, but this would involve a massive efforts.

Q: How do fuel changes add to engine efficiency improvements?

- Ken Hardman: Compression ratio can change
- Terry Alger: Distillation curves and other fuel properties are also important

Q: How was the RON of D-EGR estimated?

- Terry Alger: Mass averaged. The net octane of the fuel can be improved using a reformer.

Session Two: Spark Ignition - System

Session leader: Scott Jorgensen (GM)

Introduction

This session focused on hardware aspects. The session leader suggested that the audience constantly think about what are the next steps as they listen.

Effect of HVs and Future Fuels on CO\textsubscript{2} Reduction

by Koichi Nakata, Toyota Motor Corporation

Hybrid systems can reduce CO\textsubscript{2} by approximately 50%, and hybrid vehicle sales will play an important role in meeting emissions goals. The maximum thermal efficiency target is above 40%, and is currently around 36%. This target is met by using a higher CR, Atkinson cycle, lean boost, DI, and high RON fuel. Higher RON fuel is needed for good performance at slow engine speeds. Thermal efficiency using a lean boost engine results in efficiencies over 40%, and a maximum of 44% using ethanol. Combining lean boost and high RON fuel would result in significant reductions in CO\textsubscript{2} emissions.

Fuel Injection Technology Trends

by Edwin Rivera, Delphi Automotive

A dramatic increase in the number of GDI engines is projected in the next ten years. DI engines have particulate mass and particulate number challenges. The speaker described various trends in injector technologies. Precise fuel mass delivery is accomplished by controlling individual injector pulse width to balance the fuel delivery. Another trend is to use laser drilling to create the injector holes which improves coking resistance. Fuel pressures as high as 400 bar will be available for MY2018 vehicles. Multiple injections can be used to reduce particulate emissions. There are advanced injector technologies available for alternative fuels. CNG (compressed natural gas) direct injection improves volumetric efficiency as GDI does for gasoline engines.
For ethanol, such as for ethanol fuels in Brazil, the injector tip can be heated to enhance vaporization of low volatility fuel.

**New Approaches to Knock Simulation, Analysis, and Control**  
*by James Peyton Jones, Villanova University*

Knock remains a major problem for engines. Knock is an uncorrelated random process, but the probability of damaging knock events can be controlled. Traditional knock control is more conservative than a “likelihood control” approach, because “likelihood control” only responds when measurement indicates that there is a need for control. By utilizing optimized knock control, the probability distribution function is more narrowly distributed. To predict knock events in a reliable and repeatable way, a stochastic simulation is needed.

**Meeting Future Global Particulate Emission Standards**  
*by Cary Henry, Southwest Research Institute*

The LEV-III emission standard requires a 90% reduction in PM emissions. PM and PN regulation is a controversial topic, as many different organizations require different standards. For example, GDI engines produce high UFP (ultra fine particle) PN emissions but are also low in total particle mass emission production. Particulate emissions from GDI engines vary with the different phases of the FTP-75; PM is higher in the first phase under cold start conditions. Due to changing particulate emissions over the driving cycle, many strategies are being proposed, such as dual PFI/GDI fuel systems and multiple injections per cycle GDI. Cooled EGR can reduce PM and PN utilizing low temperature combustion strategies. Another approach is to use gasoline particulate filters which reduce PN by 90%.

**Questions / Answers**

Q: Are more specified fuels required as hardware technologies develop?
   - Edwin Rivera: Technologies will be more tolerant of different fuels.
   - Cary Henry: Yes, but it also depends on the type of technologies.
   - James Peyton-Jones: Much more complex control system would be required for the technologies to be more tolerant of different fuels.

Q: How large is the efficiency improvement from a Miller cycle?
   - Koichi Nakata: Cannot confirm the exact number, but new engines are being developed.

Q: What are the applications of advanced injector technologies?
   - Edwin Rivera: There are several applications, but these are not working actively.

Q: What technology that is not standard today will be mainstream in the future?
   - Cary Henry: Cooled EGR is one strong possibility.
Session Three: Compression Ignition
Session leader: Chuck Mueller (Sandia National Laboratory)

Introduction
The session leader introduced the speakers and their topics in this compression ignition engine session and briefly introduced their topics.

Introduction to Near Term Technologies for LD Diesel Efficiency
by Harsha Nanjundaswamy, FEV Inc.

To meet SULEV (super ultra-low emission vehicle) regulations, significant engine-out emission reduction is required. Advanced emission-based control concepts for complex hardware and tailored calibration measures are key points to meet the target. A sweet spot for the best BSFC (brake specific fuel consumption) and NOx tradeoff was found. Optimizing air management for the improved process is the key for efficient combustion control. Combustion system performance was optimized using both high pressure and low pressure EGR. Low pressure EGR offers improved distribution with a low thermal footprint, while high pressure EGR offers faster response time with high capacity. The combination of LNT (lean NOx trap) and SCR (selective catalytic reduction) provides a good compromise.

Diesel Efficiency and Associated Fuel Effects
by Stuart Johnson, Volkswagen of America

Diesel is an important platform in the Volkswagen group’s portfolio. In the U.S. and around the world, governments are applying new regulations on GHG and fuel economy, and diesel engines offer significant potential to help meet these regulations. The speaker described the history of diesel engines in VW. Features of the new diesel engine were discussed, including injector, cooling system, exhaust gas aftertreatment system, etc. A range of cetane numbers were tested, from 47 to 77 with various test points. Both fuel and load point affect engine HC, NOx, and CO emissions. Energy density, volatility, fuel density, and biofuel compositions are other fuel properties that are important. Volatility might be more important than previously considered.

Light-Duty Diesel Fuel Injection Systems
by Tom Livingston, Bosch LLC

Projections show that ICEs (internal combustion engines) will remain a dominant technology at least for the near- to medium-term future. Systems integration is key to improving emissions and performance of the diesel engine. Fuel injection pressure has a large impact on power output, emissions, and CO2. Benefits of advanced injection strategies such as multiple injections are being evaluated. Nozzle volume must be minimized to result in significant reduction in HC (hydrocarbon) emissions. Fueling accuracy, improved system control, drift, and temperature compensation are parameters to be controlled using advanced control algorithms. Fuel quality affects fuel system components, so consistent diesel fuel quality is required for optimum performance and durability.
Questions / Answers

Q: If you could magically change one thing, what would it be?
   - Tom Livingston: Consistency of fuel properties.

Q: What is important in terms of the fuel’s volatility characteristics?
   - Stuart Johnson: T10 volatility is more important than T90.

Q: Is there any chance that automakers will allow more than B5?
   - Stuart Johnson: Volkswagen is looking at the potential of higher biodiesel contents.
   - Tom Livingston: It’s not about how much biodiesel but what kind of biodiesel.

Opening Session: Day Two

Session leaders: Krystal Wrigley (ExxonMobil) and Marie Valentine (Toyota)

Introduction
Krystal Wrigley thanked the Workshop’s co-sponsors (U.S. Department of Energy and the American Petroleum Institute), the CRC staff, and presenters. The Day Two sessions will consider efficiency gains in the longer term and alternative fuels.

Keynote Address: Fuel and Lubricant Technologies Subprogram
by Steve Przesmitzki, U.S. Department of Energy

Gasoline, diesel, and many other fuels all come from crude oil, so other fuels have to be considered for the longer-term. Removal of lead, reformulated gasoline, and reduced sulfur in diesel and gasoline are all successful achievements from the DOE’s program. E15 fuel has been studied extensively and is now legal for vehicles newer than MY2001. The new emphasis in the program is on drop-in biofuels, and many different pathways are being researched. High octane fuel projects are investigating GHG and infrastructure aspects of a renewable super premium fuel. The potential of many other alternative fuels such as natural gas, methanol, butanol, biobutanol, and GTLs (gas-to-liquids) are also being investigated. DOE’s lubricant research focuses on friction reduction, combustion, and emissions.

Relentless Progress: Emissions Regulations and the Road Ahead
by Scott Sluder, Oak Ridge National Laboratory

Understanding where we are now and where we are moving in terms of regulatory actions is important to plan research and development activities. Emissions regulations have a great impact on fuel formulation. Globally increasing biofuel targets indicate that vehicle certification fuels should include biofuel components. Additional emissions such as CH₄, NO₂, and N₂O might be measured for Euro 7. As the U.S. Tier 3 regulation has just been finalized, it is hard to anticipate future regulations. The likelihood of adoption of the WLTP (Worldwide Harmonized Light Vehicles Test Procedure), more attention on PM and air toxics such as acetaldehyde, and further reduction in CH₄, N₂O, and NOₓ are being debated.
**New Technologies to Meet 2025 CAFE Standards and their Impact on Fuels**

*by Gopal Duleep, HD Systems*

Europe is firmly focusing on GDI, turbocharging, and a downsizing path. VW and BMW have already changed a majority of their engines. Currently fuel economy benefits using GDI-turbo are on the order of 10% compared to roughly equally performing NA engines. Mercedes is showing significant benefits from stratified charge in light load. While Europe and the U.S. are focusing on turbo-GDI, Japanese markets are moving towards higher CR in combination with the Miller or Atkinson cycles. The Prius type 2 electric motor system has been successful in U.S. markets. As engine efficiency improves in the low load region, motor requirements will change for hybrids.

**Emerging and Future Biofuels – Implications for Engine Efficiency**

*by Bob McCormick, National Renewable Energy Laboratory*

For SI engines, higher CR is desirable using higher knock resistant fuel, while CI engines have motivations to lower the CR. Ethanol enables efficient engine technologies due to its high RON with HoV (heat of evaporation) benefits. Some potential oxygenate products derived from cellulose have high octane numbers and low heats of vaporization. New biofuels include appropriate fuels for highly efficient SI engines. Emerging renewable diesel fuels include both high CN (cetane number) paraffins and low CN aromatic streams.

**Session Four: Alternative Fuel**

*Session leader: Craig Fairbridge of Natural Resources Canada*

**Introduction**

The session leader went through the definitions of an alternative fuel. The first three presentations focused on liquid fuels while the last two talks focused on natural gas.

**Biofuels for Efficient Engines**

*by John Kasab, Ricardo Inc.*

Three key automotive inventors expressed hopes for alternative fuels commenting on ethanol as an anti-knock additive. Higher octane fuels allow engines to run at a higher CR with a positive property of latent heat of vaporization. Ricardo is investigating an extreme boosted direct injection engine with BMEP (brake mean effective pressure) as high as 35 PSI (pounds per square inch) with E85 and 30 PSI with E0 gasoline. Different diesel fuels including B0, B15, and B30 have been tested, and all fuels met Euro 4 emissions limits. Future SI engines will need higher octane fuels; a closed-loop combustion control helps reduce fuel consumption penalties, but more work needs to be done.

**DISI with Gasoline/Ethanol Blends**

*by Magnus Sjoberg, Sandia National Laboratory*

Lean stratified combustion can improve fuel economy by increasing high gamma (specific heat ratio \(c_p/c_v\)) no pumping losses, and reduced heat transfer. A research engine with optical access
was used for testing. Soot emissions depend strongly on load and fuel composition. Acceptable maximum load with a threshold soot limit was determined for each fuel. Head ignition (spark timing when head of fuel spray arrives at spark gap) is not suitable for gasoline as it leads to extremely high smoke number, so the spark timing has to be retarded appropriately. E85 operation shows 3% higher thermal efficiency at stoichiometric operation, but efficiency improvement with stratified combustion is lower with E85. E85 vaporization uses valuable energy near TDC, which hurts the thermal efficiency. High ethanol blends offer opportunities for clean and efficient stratified operation, but more engine calibration work for flex fuel vehicles is required.

**Impact of FAME Content on the Regeneration Frequency of Diesel Particulate Filters**
*by Heather Hamje, CONCAWE*

A repeatable multi-cylinder engine test protocol was developed to evaluate the impact of FAME content on DPF regeneration frequency. Engine testing was done to measure PM, CO, CO₂, HC, NOₓ, and DPF accumulated soot. The measurements indicate that the time between DPF regeneration is lengthened while PM emissions decrease with increasing FAME content. A fuel economy penalty comes from two sources: from DPF regeneration and from higher back pressure as soot accumulates on the DPF. The average penalty from back pressure was calculated from BMEP and was found to be less than 1%. The total FEP (fuel economy penalty) depended primarily on the DPF regeneration frequency and decreased as the FAME content increased.

**Questions / Answers (Speakers 1-3)**

Q: The test results from E35 were odd compared to the other fuels. Did you test any fuels with lower ethanol content?

- Magnus Sjoberg: It might be due to the combination of wall wetting and aromatics composition.

Q: What do you think we can do as an industry to close information gaps and develop better understanding?

- Gopal Duleep: More studies to be done on well to wheel analysis. More work should be done understanding the quality of fuels.

**The Development of a Pre-chamber Ignition System for Lean Combustion of Liquid and Gaseous Fuels**
*by Hugh Blaxill, Mahle Powertrain LLC*

Lean combustion approaches can be applied to homogeneous SI, stratified SI, and homogeneous turbulent jet ignition (TJI). Natural gas can be used in many different applications including dual-fuel and HPDI (high pressure direct injection), LNG (liquefied natural gas), etc. The objective of the project described in the presentation was to cost-effectively achieve 45% efficiency and 30% drive cycle fuel economy improvements. Optical engine test results show the jet penetration prior to ignition is correlated to jet velocity. Thermodynamic engine test results show significant thermal efficiency gains. TJI is an effective technology for ultra lean combustion with high thermal efficiency and low NOₓ emissions.
Natural Gas for Light-Duty Vehicles
by Jeff Jetter, Honda R&D Americas

Natural gas vehicles (NGV) are getting attention due to energy security, environmental benefits, and consumer benefits. Multiple natural gas vehicle models are already available in U.S. markets. Dedicated natural gas vehicles have more incentives available than bi-fuel vehicles. In California, people purchase NGVs mostly due to carpool lane access and fuel prices. There are no fuel quality specifications for NGVs or shale gas. Water content in different NG sources was surveyed, and was found to be over the limit in from some of the pipelines. Infrastructure is a major challenge, and the availability of home refueling is a must.

Session Five: Advanced Combustion
Session leaders: Bill Cannella (Chevron) and Robert Wagner (Oak Ridge National Laboratory)

Introduction
Advanced combustion for higher engine efficiency and low emissions (NOx and PM) was discussed in this session.

State of the Art of Advanced Combustion
by Dave Foster, University of Wisconsin

Advanced combustion can be defined as strategies beyond standard SI and CI combustion. Maximum theoretical work from an ideal engine equals the Gibbs free energy, and theoretically the efficiency should be close to 100%. However, irreversibilities and engine process losses are two major loss mechanisms that deteriorate the engine efficiency. Availability tracking shows several loss mechanisms that can be improved, but combustion loss due to irreversibility cannot be improved. Lean combustion increases indicated efficiency by use of a higher gamma gas combined with relatively low combustion temperature. Low temperature combustion is the key for long term efficiency improvement of the ICE.

Achieving High-Loads with HCCI and Partially Stratifies Low-Temperature Gasoline Combustion (LTGC)
by John Dec, Sandia National Laboratory

LTGC has the potential for high efficiencies with very low NOx and PM emissions. Maximum load has been the major limitation to the implementation of LTGC. By using EGR, the maximum load of the HCCI engine could be increased up to 16 bar with high boost. The ability to substantially retard combustion phasing makes this possible. Increasing ethanol helped to increase boost by reducing the EGR requirement and allowing more air instead. Early DI PFS (partial fuel stratification) allows a substantial increase in thermal efficiency and maximum load for higher intake pressure.
Designing Efficient Engines: Strategies Based on Thermodynamics
by Jerry Caton, Texas A&M University

Conventional and high efficiency engine models have been simulated using a three zone combustion model. Moving towards the high efficiency case, each combustion parameter was changed one by one, resulting in an efficiency improvement from 37% to 54%, a 46% increase. The benefit comes mainly from reductions in heat transfer losses. Thermodynamics is an important tool to understand efficiency improvement strategies. Increased CR, lean operation and EGR are important factors for higher efficiencies.

Fuel Effects on RCCI Combustion: Performance and Drive Cycle Considerations
by Scott Curran, Oak Ridge National Laboratory

Combustion is an important part of the solution to maximize efficiency with low emissions. The range of operation must be optimized to improve the drive cycle fuel economy. The drive cycle simulation tool Autonomie was used to analyze potential fuel economy benefits. Biofuels can enable RCCI range expansion; ethanol allows for load expansion, and biodiesel allows for increased PFI without decreasing combustion stability. RCCI offered over 20% fuel economy improvement, comparing different 2009 PFI engines. Advanced combustion techniques like RCCI can benefit from many renewable fuels which have unique properties enabling higher efficiency and better performance.

State of the Art of PPC
by Martin Tuner, Lund University

Fuel flexibility, efficiency, and challenges of PPC (partially premixed combustion) were discussed. Engine tests show that the stable operational load is relatively wide with different fuels, demonstrating fuel flexibility. An excellent efficiency of 48% could be achieved in a simulation of a PPC engine. It is interesting to note that the in-cylinder heat transfer losses of the PPC engine were about half that of a conventional diesel engine. Benefits of PPC include fuel flexibility, high efficiency, high load, and low emissions, while challenges are transient emissions, combustion noise, idle, and high RON operations.
### D. Abbreviations

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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>AKI</td>
<td>Anti-Knock Index</td>
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<tr>
<td>API</td>
<td>American Petroleum Institute</td>
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<td>BEV</td>
<td>Battery Electric Vehicle</td>
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<td>BMEP</td>
<td>Brake Mean Effective Pressure</td>
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<td>BP</td>
<td>British Petroleum</td>
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<td>BSFC</td>
<td>Brake Specific Fuel Conversion</td>
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<tr>
<td>CAFE</td>
<td>U.S. Corporate Average Fuel Economy Standard</td>
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<tr>
<td>CN</td>
<td>Cetane Number</td>
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<tr>
<td>CNG</td>
<td>Compressed Natural Gas</td>
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<td>CRC</td>
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<td>DI</td>
<td>Direct Injection</td>
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<tr>
<td>DISI</td>
<td>Direct Injected Spark Ignition</td>
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<td>DOE</td>
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<tr>
<td>DPF</td>
<td>Diesel Particulate Filter</td>
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<td>EGR</td>
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<td>FAME</td>
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<td>GAMMA</td>
<td>Specific heat ratio $c_p/c_v$</td>
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<td>GDI</td>
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<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
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<tr>
<td>g/mile</td>
<td>Grams per mile</td>
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<td>GTL</td>
<td>Gas-to-Liquid</td>
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<td>HC</td>
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<td>MPG</td>
<td>Miles per Gallon</td>
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