DAY 1:

Introduction

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2012-2025 LIGHT-DUTY VEHICLE STANDARDS AND THE MID-TERM EVALUATION

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The U.S. Environmental Protection Agency (EPA) and the Department of Transportation’s National Highway Traffic Safety Administration (NHTSA) issued final rules to reduce greenhouse gas (GHG) emissions and improve fuel economy for model years (MYs) 2017-2025 light-duty vehicles. EPA’s standards apply to LDVs (passenger cars, light-duty trucks, and medium-duty passenger vehicles). The final standards are projected to result in an average industry fleetwide level of 163 g/mile of carbon dioxide (CO2) in model year 2025, which is equivalent to 54.5 mpg if achieved exclusively through fuel economy improvements.

This broadly supported national program conserves billions of barrels of oil, cuts carbon pollution, protects consumer choice, saves consumer thousands of dollars, and enables long-term planning for automakers. This program builds on the success of the first phase of the National Program for MYs 2012-2016 vehicles, which is projected to result in an average LDV tailpipe CO2 level of 250 g/mile by MY 2016, equivalent to 35.5 mpg (if achieved exclusively through fuel economy). Combined, the two programs result in MY 2025 vehicles emitting one-half of the GHG emissions of a MY 2010 vehicle, representing the most significant federal action ever taken to reduce GHG emissions and improve fuel economy.

These standards are based on CO2 emissions-footprint curves, where each vehicle has a different CO2 emissions compliance target depending on its footprint value. Manufacturers are not compelled to build vehicles of any particular size or type, and no single vehicle is required to meet its individual target. Each manufacturer will have its own fleet-wide standard that reflects the vehicles it chooses to produce, and the GHG program provides a wide range of credit programs and flexibilities for manufacturers to meet the standards.

EPA projects that manufacturers will comply with the standards by using a wide range of technologies, including continual advances in gasoline engines and transmissions, vehicle weight reduction, lower tire rolling resistance, vehicle aerodynamics, and more efficient vehicle accessories. EPA expects that the majority of improvements will come from advancements in internal combustion engines, although we also expect to see some increased electrification of the fleet through the expanded production of stop/start, hybrid vehicles, plugin hybrid electric vehicles, and electric vehicles.

Given the long time frame at issue in setting standards for MYs 2022-2025, and given NHTSA’s obligation to conduct a separate rulemaking in order to establish final standards for vehicles for those model years, EPA and NHTSA will conduct a comprehensive mid-term evaluation. As part of this undertaking, EPA and NHTSA will develop and compile up-to-date information for the evaluation, through a collaborative, robust and transparent process, including public notice and comment. EPA and NHTSA fully expect to conduct this mid-term evaluation in coordination with the California Air Resources Board (CARB). The comprehensive evaluation process will lead to final agency action by both agencies.
OPPORTUNITIES FOR IMPROVING ENGINE EFFICIENCY AND FUELS

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There are strong regulatory and market pressures to reduce vehicle fuel consumption thereby reducing the cost of driving and greenhouse gas emissions. Doing this by improving the efficiency of mainstream engine technology and improving the transportation fuels these engine use have the greatest impact in the nearer- to mid-term since such improvements can be implemented relatively rapidly on a large scale. The focus of this Workshop is thus an important one. The opportunities for improving engine efficiency are well known, though the implementability of the options available is less clear. And many of these engine opportunities are constrained by the available fuels, especially their octane rating or resistance to knock.

Important areas for improving engine efficiency are: (1) reducing friction and its relative importance (increasing mechanical efficiency); (2) increasing compression ratio (increases indicated fuel conversion efficiency); (3) boosting the engine usually by turbocharging (increases the mechanical efficiency); (4) uses of variable valve control to modify engine operation in several ways; (5) downsizing the engine displacement in a specific vehicle context when changes are made that increase the engine’s maximum bmep (normalized torque).

Fuels currently constrain compression ratio increases and turbocharger boost levels to about 11:1 in naturally-aspirated gasoline engines, and 10:1 in TC engines at boost levels of about 2 bar absolute. We have recently completed a study of compression ratio effects on engine efficiency. This shows considerable variability between different studies. Also raising compression ratio from 10:1 to 11:5:1 has double the increase in efficiency than from 11.5 to 13.

A group of us at MIT has recently examined the impact of increasing the octane rating of the gasoline used by the majority of U.S. light-duty vehicles, with parallel increases in compression ratio and TC engine boost levels. This study involved engine-in-vehicle assessments, in-use vehicle fleet projections, and analysis of fuel production in the refinery. The overall result of transitioning the standard dominant gasoline from today’s regular (RON of 92) to premium (RON 98 was examined). Overall, U.S. fleet fuel consumption decreases over time leading to about a 5 percent reduction by 2040, and the refinery impacts with effective uses of available ethanol are small. Such a transition effected by the petroleum and automotive industries in partnership seems worthwhile.
TECHNOLOGY ROADMAP FOR LIGHT-DUTY VEHICLE CAFE/GHG EMISSIONS

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With the 2011 issuance of the MY 2017–2025 corporate average fuel economy (CAFE) rules from the National Highway Traffic Safety Administration (NHTSA) and corresponding and coordinated rules on greenhouse gas emissions from the Environmental Protection Agency (EPA) and California Air Resource Board (ARB), light-duty vehicle manufacturers have visibility to these regulatory requirements for the next decade. Ricardo provided technical input to EPA for these rules (Kasab, et al., 2011) by developing a technology roadmap and evaluating future vehicle performance. In addition, Ricardo has been conducting internal research programs to demonstrate future engine technologies and performance. In this presentation, Ricardo will review the technology roadmap for MY2025, discuss how manufacturers are already progressing along the roadmap, and provide an overview of relevant research results.

DAY 1: Session 1

Spark Ignition: Octane

Jim Simnick
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CRC STUDY ON OCTANE NUMBER AND ENGINE EFFICIENCY – LITERATURE REVIEW: REPORT CM-137-11-1, -1B

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The Coordinating Research Council (CRC) conducted a program to investigate the relationship between octane number and engine efficiency. This study, conducted by Dr. K. G. Duleep of H-D Systems, gathered 250 technical papers and then refined these to 45. Ten papers directly examined the relationship between engine efficiency and octane number of the fuel. He also interviewed several OEM’s to gain perspective and their non-confidential input.

The analyses of the technical papers indicated that there is no simple relationship linking compression ratio (CR) and engine efficiency. Advice from the OEM’s suggested to focus on engine rather than vehicle studies, and divide the analyses into naturally aspirated versus turbocharged/boosted air management. Subdivisions were also made for port fuel injection versus direct injection.

H-D Systems developed a model to link engine thermal efficiency to CR, and then link CR to fuel octane, sensitivity (i.e. RON – MON), and latent heat of combustion of the fuel. Analyses of the data in the studies using the model indicated trends. The trends were shown for several variables: the effect of cylinder bore size on indicated efficiency, the effect of CR and RON level on torque, effect of octane number on knock limited spark advance (KLSA), spark timing on net indicated mean pressure (NIMEP), torque vs. RPM for various levels of RON in a turbocharged engine, and the charge cooling and chemical octane effects of ethanol.

Conclusions (i.e. findings) were given for the naturally aspirated and turbo/boosted engines. The analyses indicated several gaps in our knowledge of this area and the report described areas for future research.
OCTANE RATING AND VEHICLE EFFICIENCY

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A well-to-wheels analysis of CO₂ emissions, petroleum consumption, and cost was conducted for combinations of hypothetical future national octane rating standard (92 to 102 RON), ethanol content (E10, E20, E30), and blending approach (midlevel blend or E10+E85). A regional refinery model was used to estimate effects on the US refining sector, with the results then integrated with other relevant well-to-tank data from the GREET model. Using the resulting fuel properties, tank-to-wheel impacts were estimated for engines with and without re-optimization for each fuel.
IMPACT OF FUEL KNOCK RESISTANCE ON ENGINE EFFICIENCY

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In order to meet the aggressive Corporate Average Fuel Economy (CAFE) regulations, which require an almost 2 fold increase in fuel economy by MY 2025, automotive OEMs are exploring a wide range of engine technologies and fuel properties to boost engine efficiency. Improving the fuel knock resistance (octane number) is a key enabler for increasing the compression ratio, improving thermodynamic efficiency of spark ignition engines, and meeting CAFE requirements. However, customer acceptance requires that vehicles operate adequately on all available pump gasolines. This inherent requirement to operate on lower octave fuel constrains the compression ratio of production engines, thereby limiting the benefit of various fuel efficient technologies including turbocharging with downsizing, cooled-EGR, and gasoline direct injection. Thus, availability of lower octave fuel in the market is detrimental to SI engine efficiency and is in fact a liability for achieving the CAFE targets.
RECENT DEVELOPMENTS IN THE USE OF COOLED EGR IN HIGH EFFICIENCY GASOLINE ENGINES

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The use of cooled EGR in gasoline engines has been shown to improve engine efficiency through a variety of mechanisms. The presentation will focus on advanced activities in the industry in methods to improve SI engine efficiency in general and using cooled EGR in particular. The mechanism of efficiency improvement, along with recent results from SwRI’s HEDGE II program, will be presented to detail some of the most promising configurations for high efficiency. Finally, the next generation of cooled EGR engines, using Dedicated EGR technology, will be presented and discussed with respect to the level of fuel economy improvement potential. Both test cell and vehicle level results will be shown.
DAY 1: Session 2

Spark Ignition: Systems

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Reducing CO₂ is strongly required due to energy security and climate change. To respond the issue, Toyota has been modifying THS (Toyota Hybrid System) since the first generation Prius. In regard to the engine development for THS, enhancing the maximum engine thermal efficiency is essential. Therefore Toyota has developed Atkinson cycle engine and cooled EGR technology.

In this presentation, the future engine technology such as lean boosted concept for enhancing the engine thermal efficiency is described. In addition to the engine technology, the effect of high RON fuels on the engine thermal efficiency is also described. Some results show that turbocharged engine has higher effect to enhance the engine thermal efficiency with high RON fuels.

Ethanol is well known for its high RON characteristics. Therefore the case where ethanol is blended as splash blend is studied from the viewpoint of the engine thermal efficiency and driving range. The result shows that less than 20% ethanol concentration seems to be the most practical for consumers.
Fuel economy and CO₂ global mandates are driving the need for a substantial increase in vehicle fuel efficiency over the next several years. This is driving innovation in gasoline fuel injection systems as well as the use of alternative fuels. Gasoline direct injection (GDi) engines are a key technology for improved fuel economy and engine performance. As a result, the number of GDi vehicles worldwide will continue to markedly increase in the coming years with added emphasis on downsized, turbocharged engines and increased dilution levels for improved engine efficiency with very low emissions.

The presentation will describe technology trends focused on improving the efficiency of spark ignition engines. Fuel systems are being developed focused on meeting the needs of future GDi engines. Key fuel system requirements for these engines include precise fuel metering combined with excellent atomization and spray control capability. Specific activities focused on meeting these requirements are discussed including: increased fuel system pressure; advanced laser manufacturing methods offering improved manufacturing precision and alternative injector spray hole shapes; and control algorithms offering multiple injection capability and precise control of small injection quantities over the lifetime of the injector.
ADVANCES IN KNOCK AND COMBUSTION CONTROL SYSTEMS:
A STOCHASTIC APPROACH.

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Cyclic variations in combustion mean that few cycles burn according to the design intent even under nominally steady state conditions. The extreme cycles typically degrade overall efficiency, emissions and driveability, and result in knock at one extreme and misfire at the other. The literature on knock sensors and signal processing is very extensive, but relatively little work has been done optimizing knock detection, or designing knock controllers in a way that explicitly addresses and exploits the stochastic nature of knock. Recent work shows that adopting a stochastic framework gives new insights which can significantly improve conventional controller performance, and also lead to novel advanced knock control designs. These improvements provide tighter control, and enable operation closer to the knock limit without sacrificing the fast transient response that is necessary when knock does occur.
Recently enacted legislation for particulate emissions from light duty automotive applications are requiring drastic reductions from today’s levels. In the United States, the California Air Resource Board is requiring particulate mass emissions to be less than 1 mg/mi, while the European Union is requiring particulate number emissions to be less than $6 \times 10^{11}$ #/km for spark-ignited engines. Historically, spark ignited engines have required no emission control devices to meet the regulated particulate emission levels due to the good mixing associated with port fuel injected combustion. However, with the advent of direct-injected gasoline engines as a strategy for reducing fuel consumption, the charge feed is less homogeneous and results in a notable increase in the formation of solid particulates. This presentation will provide a discussion of potential strategies for managing particulate emissions both with engine based hardware and controls, as well as exhaust treatment methods. A discussion of the impact of advanced combustion strategies on particulate emissions will also be included.
DAY 1: Session 3

Compression Ignition

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INTRODUCTION TO NEAR TERM TECHNOLOGIES FOR LD DIESEL EFFICIENCY

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The upcoming LEV III and Tier 3 emissions legislation along with the parallel introduction of stringent CAFE standards are extreme challenges for passenger cars. As the need for emission minimization towards near zero emissions for NOx, HC and particulates is implemented these standards create a very challenging framework for highly fuel-efficient diesel engines. On the other hand, due to the stringent GHG legislation, the diesel engine generates an increased interest in the North American market allowing the manufacturers a cost-effective approach to meet aggressive future fleet-average CO2 standards without using mass electrification.

In this event, the FEV Group presents advanced technology concepts to ensure robust series production realization under the upcoming legislative standards. The system approach, concept description and results obtained are the content of this paper which focuses on an engine with a displacement of 3.0L, covering various vehicle applications up to 5500 lbs. An integrated control concept is presented, which optimizes the balance between efficient combustion and exhaust energy supply, providing a permanently tailored NOX raw emission level for the entire cycle. According to the test cycle details it is mandatory to raise the exhaust gas temperatures by combining efficient measures like VVT and tailored, minimized in-cylinder post injection sequences. These efficient measures are necessary since the efficiency-optimized engine concepts lack exhaust gas enthalpy. Refined catalyst specifications and close-coupled aftertreatment arrangements in conjunction with optimized urea injection systems deliver the appropriate platform for a successful fulfillment of the upcoming standards. During this study, three different NOX raw emission levels and an additional VVT strategy have been analyzed in combination with three different exhaust aftertreatment configurations, realizing the targeted tailpipe emissions with specific advantages for each configuration.
DIESEL EFFICIENCY AND ASSOCIATED FUEL EFFECTS

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This presentation will explain how the Volkswagen Group is improving the efficiency of diesel engines while still maintaining LEV III/Tier 3 emission levels. Engine efficiency and emissions performance have historically been a trade-off with regards to diesel engine development. This discussion will center on how to break the compromise between emissions and efficiency with improvements in both engine hardware and control strategies. In addition to hardware and strategy developments, the presentation will consider how fuel properties also impact engine efficiency and emissions performance and how fuel properties must be considered during development. To summarize, three main aspects will be considered: 1) engine developments to improve efficiency 2) engine developments to improve emissions 3) fuel influences on the balance between efficiency and emissions.
Reciprocating Internal Combustion engines will remain dominate transportation prime mover for decades. The need to reduce fuel consumption and exhaust emissions both highlights and challenges Diesel engine use in light-duty vehicles.

Discussed are Diesel Systems approaches for achieving performance goals, focusing on Fuel Injection System aspects.

Advanced fuel injection systems and control techniques discussed for optimization of the combustion event:

- Multiple injections per combustion cycle
- Injection rate shaping
- Nozzle design
- Control algorithms

While some control techniques may provide limited compensation for fuel quality variation; consistent state-of-the-art Diesel fuel quality is necessary to assure system performance and durability expectations are met.
DAY 2:

Introduction

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DOE FUELS AND LUBRICANTS PROGRAM

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The presentation by Dr. Przesmitzki will discuss the U.S. Department of Energy’s end-use transportation fuels and lubricants research program. The research is coordinated within the Vehicle Technologies Program in the Office of Energy Efficiency and Renewable Energy and supported by National Laboratories, universities, and industrial partners. The fuels and lubricants program is designed to support the major R&D programs in transportation research, including the U.S. DRIVE Initiative and the 21st Century Truck Partnership. This program has been undertaken to enable current and emerging advanced combustion engines and emission control systems to be as efficient as possible while meeting future emission standards. The program also addresses petroleum displacement and efficiency improvements through the use of advanced petroleum and non-petroleum fuels and blending components, and improved lubricants.
An understanding of near-term and possible future emissions regulations is important to attempts to identify research needs in support of technological progress. The auto manufacturers and energy companies produce products that are increasingly globalized, causing regulatory action (or inaction) in some areas to impact product designs in ways that affect other countries as well. US and EU regulations have become dominant global regulatory benchmarks for emissions control standards. An overview of the proposed Tier 3 standard is provided and compared with the current Tier 2 standard. Euro VI, the upcoming standard in Europe, has similar regulatory directions compared with Tier 3. Fuel formulations are just as important. The EU has led the world in reducing sulfur and eliminating lead in gasoline. Worldwide sulfur levels are trending downwards, with 10 PPM sulfur gasoline expected in China, the US, and Russia by 2017. Other countries are also reducing sulfur and most have now eliminated lead. Biofuel mandates are also on the rise. Possible future regulatory directions derived from these trends are presented.
FUTURE OF ENGINE EFFICIENCY AND FUEL EFFECTS TO 2025

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Fuel economy standards to 2025 have been promulgated recently and are popularly referred to as the 54.5 mpg standard. The standards are challenging and will dictate the requirements for new drivetrain technology to 2025 and beyond. The value of 54.5 mpg is misleading since the standards allow credits for many technologies not directly associated with fuel economy, and it is widely accepted that these alternative technologies will be adopted due to their relatively low cost. The analysis derives the likely actual fuel economy of the new light vehicle fleet required to comply with 2025 standards if all credits are utilized, and forecasts of new drivetrain technology required to comply are developed based on the actual requirements.

The analysis finds that European manufacturers and Ford are following one possible evolutionary path for new technology while most Japanese manufacturers are following a different path, and GM and Chrysler may adopt elements of both paths. The European approach relies on direct fuel injection, downsizing and turbo-charging with increased levels of boost and aggressive downsizing for the post-2020 time frame. In contrast, the Japanese manufacturers are developing high compression ratio naturally aspirated engines with Miller or Atkinson cycles, but are likely to maintain or even potentially increase engine displacement. Possible impacts on fuels are examined for these paths.
EMERGING AND FUTURE BIOFUELS – IMPLICATIONS FOR ENGINE EFFICIENCY

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The past decade has seen a high level of innovation in production of biofuels from sugar, lipid, and lignocellulose feedstocks. As discussed in several talks at this workshop, ethanol blends in the E25 to E50 range could enable more highly efficient spark-ignited (SI) engines. This is because of their knock resistance properties that include not only high research octane number (RON), but also charge cooling from high heat of vaporization, and high flame speed. Emerging alcohol fuels such as isobutanol or mixed alcohols have desirable properties such as reduced gasoline blend vapor pressure, but also have lower RON than ethanol. These fuels may be able to achieve the same knock resistance benefits, but likely will require higher blend levels or higher RON hydrocarbon blendstocks. A group of very high RON (>150) oxygenates such as dimethyl furan, methyl anisole, and related compounds are also produced from biomass. While providing no increase in charge cooling, their very high octane numbers may provide adequate knock resistance for future highly efficient SI engines. Given this range of options for highly knock resistant fuels there appears to be a critical need for a fuel knock resistance metric that includes effects of octane number, heat of vaporization, and potentially flame speed. Emerging diesel fuels include highly branched long-chain alkanes from hydroprocessing of fats and oils, as well as sugar-derived terpenoids. These have relatively high cetane number (CN), which may have some benefits in designing more efficient CI engines. Fast pyrolysis of biomass can produce diesel boiling range streams that are high in aromatic, oxygen and acid contents. Hydroprocessing can be applied to remove oxygen and consequently reduce acidity, however there are strong economic incentives to leave up to 2 wt% oxygen in the product. This oxygen will primarily be present as low CN alkyl phenols and aryl ethers. While these have high heating value, their presence in diesel fuel at significant volume percentage will require higher CN blendstocks or the use of cetane improving additives.
DAY 2: Session 4

Alternative Fuels

Craig Fairbridge
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BIOFUELS FOR EFFICIENT ENGINES

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Biofuels will have an important role to play in meeting future greenhouse gas emissions requirements, as they help reduce lifecycle carbon emissions from vehicles. The challenge is that current biofuels are not simple drop-in replacements for today's distillate fuels. Ricardo will discuss the role of ethanol and biodiesel in supporting energy policy needs, and share relevant results from internal research and publicly available programs on how these fuels interact with current and future engines.
STRATIFIED DISI USING GASOLINE-ETHANOL BLENDS

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The lean-burn stratified-charge DISI engine has a strong potential for increased thermal efficiency compared to the traditional throttled SI engine. However, in order to minimize the cost of the exhaust aftertreatment system, it is imperative to achieve low engine-out emissions of both soot and NOx. This experimental study of a spray-guided stratified-charge combustion system highlights differences in exhaust smoke level depending on fuel type, load level, and spark-timing strategy. Gasoline, ethanol and blends thereof are studied using a single-cylinder optically accessible research engine.

For a given load and spark-timing strategy, high-ethanol blends like E85 show a beneficial reduction of soot emissions compared to gasoline. The oxygen content of ethanol can explain most of the soot reduction. Because of the soot-abating properties of ethanol, high-ethanol blends like E85 can be operated with a high degree of fuel stratification, offering both high efficiency and low soot and NO emissions. On the other hand, gasoline has a much higher tendency to form soot for operation with a stratified charge. Hence, gasoline must be operated with a lower degree of fuel stratification, using a later spark relative to the injection event to provide more time for fuel/air mixing.

Special engine operation is used to quantify the effects of vaporization cooling on the thermal efficiency of the engine. The results show that the high latent heat of vaporization of E85 contributes to a 3% relative loss of thermal efficiency for stratified operation. This is attributed to the use of high-quality heat (exergy) of the compressed and heated gases to accomplish the phase change from liquid to gaseous fuel. On the other hand, the strong vaporization cooling of E85 improves the thermal efficiency for well-mixed stoichiometric operation that utilizes fuel injection during the compression stroke. This happens because of a general reduction of gas temperatures during the compression and expansion strokes, leading to both higher work-extraction efficiency and lower heat-transfer losses.

In summary, stratified charge operation can be implemented for flex-fuel vehicles. In particular high-ethanol blends offer opportunities to achieve clean and efficient stratified operation. However, taking full advantage of the ethanol content comes at the price of more engine calibration work for flex-fuel vehicles.
IMPACT OF FAME CONTENT ON THE REGENERATION FREQUENCY OF DIESEL PARTICULATE FILTERS

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Modern diesel vehicles utilize two technologies that have been motivated by recent European legislation: diesel fuel blends containing Fatty Acid Methyl Esters (FAME) and Diesel Particulate Filters (DPF). Oxygenates like FAME, are known to reduce particulate matter (PM) formation in the combustion chamber and reduce the amount of PM that must be filtered from the engine exhaust by the DPF. This effect is also expected to lengthen the time between DPF regenerations and reduce the fuel consumption penalty that is associated with PM loading and regeneration.

This study investigated the effect of FAME content, up to 50% v/v (B50), in diesel fuel on the DPF regeneration interval by repeatedly running a Euro 5 multi-cylinder bench engine over the New European Driving Cycle (NEDC) until a specified PM loading limit had been reached. The fuel economy penalties due to DPF backpressure and regeneration were calculated from the data and were compared with values found in the literature.

The results verify the expected reduction of engine-out PM emissions and corresponding increase in regeneration interval with increasing FAME content. DPF regeneration intervals were greater for higher FAME levels than for lower levels while the B10 fuel gave similar results to the B0 fuel. The fuel consumption penalty associated with reducing the frequency of DPF regeneration was generally smaller as the FAME content and regeneration interval increased, although again little difference was observed between the B0 and B10 fuels. The fuel consumption penalties associated with DPF backpressure were much lower than those due to DPF regeneration and were essentially constant for all fuels.
THE DEVELOPMENT OF A PRE CHAMBER COMBUSTION SYSTEM FOR LEAN COMBUSTION OF LIQUID AND GASEOUS FUELS

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Increasingly stringent US fuel economy regulation has emphasized the need for automotive engines to achieve greater levels of efficiency. In conjunction with this, the potential benefits of gaseous fuels is a strong driver in some sectors of the market. Current spark ignition engines, whether fueled by gasoline or gaseous fuels have potential for improvement in efficiency and, therefore, fuel economy. Lean operation in spark ignition engines has demonstrated the ability to increase thermal efficiency, but this is typically accompanied by increased NOx emissions. Ultra-lean operation ($\lambda > 2$), however, has demonstrated increased thermal efficiency and the potential for significant reductions in NOx. Turbulent Jet Ignition (TJI) enables ultra-lean operation by utilizing a pre-chamber combustor as the ignition source for main chamber combustion in a spark ignition engine. This presentation seeks to demonstrate the interaction between the pre-chamber and main chamber combustion events, specifically the effect of particular TJI hardware parameters. The potential of the TJI pre-chamber ignition system will be shown on efficiency and other engine parameters for liquid and gaseous fuels showing the respective future application opportunities.
NATURAL GAS FOR LIGHT DUTY VEHICLES

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In recent years, natural gas has gained prominence as an energy source in the US market. Domestic resource estimates have increased dramatically, as production technology advancements have made “new” resources available. A minimum 100-year supply is available at the current rate of consumption, and some estimates are much higher. Natural gas prices have decreased accordingly, and are expected to remain stable into the foreseeable future. In addition to the benefits of low price and energy security, natural gas use as a vehicle fuel is generally considered to have CO$_2$ benefits from a WTW (well-to-wheel) perspective, when compared to gasoline and diesel fuel.

This presentation will focus on issues unique to NGVs and their fuel:
- Current light-duty NGV landscape; available vehicles and production strategies.
- Dedicated CNG vehicles vs. CNG-gasoline bi-fuel vehicles.
- NGV advantages from the customers’ perspective.
- Challenges to NGV market expansion, and the importance of home refueling.
- CRC activity related to NGV fuel quality.
- Latest WTW CO$_2$ estimates for NGVs, from the CRC Life Cycle Analysis Workshop.
DAY 2: Session 5

Advanced Combustion

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STATE OF THE ART OF ADVANCED COMBUSTION

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With the understanding that the internal combustion engine is a chemical process, and not a heat engine, it is possible to identify what are the constraints that limit the maximization of its efficiency. Thermodynamic analyses performed from this framework can be used to identify, and quantify the magnitudes of, the losses within the mechanical cycle which facilitates the thermodynamic processes that embody the generation of power from the combustion of fuel. In this presentation the governing relationship which describes the maximum work of the engine will be given. Then the quantification of the losses that occur in the engine will be presented. This allows assessment of where gains can be made and what the technical challenges will be of achieving them. This thermodynamic reasoning leads one to conclude that to maximize efficiency and minimize emissions the temperatures in the cylinder should be kept as low as possible. To achieve the ultimate in lower temperatures one needs to achieve combustion via auto-ignition processes which yield a more volumetric energy release, as opposed to the highly localized discreet energy release of a flame front. This results in challenges of controlling combustion phasing, achieving higher loads, and manipulating the trade-offs between in-cylinder work extraction, heat transfer and energy in the exhaust. These challenges will be addressed in a more quantitative way in the presentations within this session.
ACHIEVING HIGH-LOADS WITH HCCI AND PARTIALLY STRATIFIED LOW-TEMPERATURE GASOLINE COMBUSTION (LTGC)

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Improved efficiency of internal combustion engines is critical for reducing petroleum consumption and CO₂ emissions. Engines using low-temperature gasoline combustion (LTGC), based on the compression ignition of a premixed or partially premixed dilute charge, have a strong potential for contributing to these goals since they have high efficiencies and provide ultra-low engine-out NOₓ and particulate emissions. Most investigations of LTGC have focused on premixed operation, which is commonly referred to as homogeneous charge compression ignition (HCCI), but advantages to various forms of charge stratification have recently been demonstrated as outlined below. Despite the significant potential of HCCI/LTGC, the relatively low power output of these engines has historically limited their practical application.

However, recent research has shown that intake-pressure boosting can be applied to LTGC to achieve loads comparable to those of turbo-charged diesel engines with similar cylinder-head pressure limits to that of the engine used for the reported LTGC studies (155 bar). For LTGC, as intake boost was increased, a combination of reduced intake temperature and cooled EGR was used to compensate for the pressure-induced enhancement of autoignition and to provide sufficient combustion-phasing retard to prevent knock. For fully premixed operation (i.e. HCCI), a load of 16.3 bar IMEPg was achieved using a conventional, (R+M)/2 = 87-octane gasoline, and loads of 18.1 and 20.0 bar IMEPg were obtained using E10 and E20 (blends of 10 and 20% ethanol with this gasoline), respectively. Ethanol blending significantly reduces the autoignition reactivity under boosted conditions, thereby reducing the required EGR. This leaves more air available for combustion, so higher loads can be attained. Central to achieving these results was the ability to retard CA50 as late as 19° after TDC with good stability, to prevent knock. Detailed examination of the heat release rates shows that this substantial CA50 retard was possible because intake boosting significantly enhances the early autoignition reactions of the gasoline, keeping the charge temperature rising toward the hot-ignition point despite the high rate of expansion at these late crank angles.

Further studies show that this pressure-induced enhancement of the early autoignition reactions also makes the rate of autoignition sensitive to the local equivalence ratio within the cylinder. Therefore, with sufficient boost, partial fuel stratification (PFS) can be applied to create a distribution of fuel/air mixtures that autoignite sequentially, substantially reducing the peak pressure-rise rate, and therefore, the knocking propensity. Exploiting this effect, LTGC with PFS was found to allow significantly higher loads and/or higher efficiencies for a given boost level than premixed fueling, without engine knock, and while maintaining engine-out NOₓ and particulate emissions far below US-2010 standards. For example, at an intake pressure of 3.0 bar absolute, PFS allowed a load of 19.4 bar IMEPg, compared to only 17.2 bar IMEPg for premixed fueling, which would significantly ease turbo-charger design requirements. Additionally, PFS gives higher indicated thermal efficiencies than premixed fueling, mainly because less CA50 retard is required to control knock. These efficiencies are similar to, or exceed, those of diesel engines with a similar displacement (0.98 liters/cylinder). Overall, boosted LTGC shows strong potential for providing a high-efficiency gasoline engine that can achieve power levels comparable to those of turbo-charged diesel engines.
Thermodynamics is the key discipline for determining and quantifying the elements of advanced engine designs which lead to high efficiency. In spite of its importance, thermodynamics is often not given full consideration in understanding engine operation for high efficiency. By fully utilizing the first and second laws of thermodynamics, detailed understanding of the engine features that provide for high efficiency may be determined. Of all the possible features that contribute to high efficiency, the results of this study show that highly diluted engines with high compression ratios provide the greatest impact for high efficiencies. Other important improvements which increase the efficiency include reduced heat losses, optimal combustion phasing, reduced friction, and reduced combustion duration. Thermodynamic quantification of these concepts is provided.

An automotive engine (5.7 liter) which included some of the features mentioned above (e.g., high compression ratios, lean mixtures, and high EGR) was evaluated using a thermodynamic cycle simulation. These features were examined for a moderate load (bmep = 900 kPa), moderate speed (2000 rpm) condition. By the use of lean operation, high EGR levels, high compression ratio and other features, the net indicated thermal efficiency increased from 37.0% to 53.9%. These increases are explained in a step-by-step fashion. The major reasons for these improvements include the higher compression ratio and the dilute charge (lean mixture, high EGR). The dilute charge resulted in lower temperatures which in turn resulted in lower heat loss. In addition, the lower temperatures resulted in higher ratios of the specific heats which account for a more effective conversion of thermal energy to work. The importance of the specific heats towards efficiency is quantified in this work. In addition, these design features often result in low emissions due to the low combustion temperatures.
MULTI-CYLINDER RCCI: FUEL EFFECTS

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In-cylinder blending of gasoline and diesel to achieve Reactivity Controlled Compression Ignition (RCCI) has been shown to reduce NOx and PM emissions while maintaining or improving brake thermal efficiency as compared to conventional diesel combustion (CDC). The RCCI concept has an advantage over many advanced combustion strategies in that by varying both the percent of premixed gasoline and EGR rate, stable combustion can be extended over more of the light-duty drive cycle load range. Changing the percent premixed gasoline changes the fuel reactivity stratification in the cylinder providing further control of combustion phasing and pressure rise rate than the use of EGR alone.

However, the current range of the multi-cylinder light-duty experimental RCCI engine map investigated to date does not allow for RCCI operation over the entirety of some drive cycles and may require a multi-mode strategy where the engine switches from RCCI to CDC when speed and load fall outside of the RCCI range. The potential for RCCI to reduce drive cycle fuel economy and emissions is explored here by simulating the fuel economy and emissions for a multi-mode RCCI-enabled vehicle operating over a variety of U.S. drive cycles using experimental engine maps for multi-mode RCCI. The role that unique properties of alternative fuels can have on drive cycle coverage are explored. RCCI fuel economy simulation results are compared to the same vehicle powered by a representative 2009 PFI gasoline engine over multiple drive cycles. Engine-out drive cycle emissions are compared to CDC and observations regarding relative gasoline and diesel tank sizes needed for the various drive cycles are also summarized. This drive cycle analysis using vehicle systems simulations with experimentally derived engine maps also allows investigation of the wells-to-wheels implications of multi-mode RCCI on a light duty vehicle with conventional and renewable fuels.
STATE OF THE ART PPC

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Future engines need to be both cleaner and more efficient to meet coming legislation and consumer demand. Partially premixed combustion (PPC) is one concept that by being fuel flexible, efficient and low emitting could have potential influence on the future combustion engine. The research has so far demonstrated that PPC has an impressive fuel flexibility that cannot be matched by either Otto or diesel combustion principles. With the same engine hardware, fuels ranging from high cetane numbers such as diesel to high octane numbers such as gasoline and ethanol can all be operated singularly in PPC. The different fuels offer similar peak efficiencies in PPC operation but with substantial differences in emissions and load range performance. The underlying reasons for the differences are understood to some extent, but several aspects are less well understood and require further research. On-going research employs surrogate fuels and design of experiments (DoE) methodology to quantify the influence from each single fuel component and operating parameter as well as all the interactions.

Recent investigations that combine experiments and simulations indicate that it is possible to operate a HD-PPC engine on commercial gasoline with a production two-stage boost system over the European Stationary Cycle (ESC) while likely meeting Euro VI and US10 emissions. Peak brake efficiency reached above 48% and a large operating window covering the majority of the ESC can likely be operated with brake efficiency above the peak efficiency for current state of the art HD-diesel engines. The loss sources were quantified and it could be demonstrated that the reduced in-cylinder heat transfer losses is a dominant factor for the high efficiency of PPC. Sensitivity analysis was used to quantify the relative merits of -reducing heat losses in the cylinders -reducing heat losses the exhaust piping network -reducing engine friction.

The main research targets are to improve the understanding of how PPC actually works and how to further expand the operating range and efficiency, especially for light-duty PPC.