DAY 1: SESSION 1

Technology Enablers/Drivers (TED)

Asim Iqbal, FCA
John Mengwasser, Shell
Paul Miles, Sandia
Leah Webster, Nissan
WHERE THERE IS A “WILL” THERE IS A WAY

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There are many factors that go into introducing new technology into the marketplace: Investment into new research, technology breakthroughs, the development of those technologies for a market application, capital investment, production capability, lead time, value and economic benefit to consumers, marketing, etc. To many people’s surprise, EPA’s regulatory process cannot circumvent any of these factors. However, we can and have leveraged it to great benefit for air quality in the U.S. in large part to the little word “will” and a similar little phrase “necessary to permit the development and application.”

This little word allows us to be “technology forcing”, and not merely follow the market. We still need to and do take into consideration all the other factors necessary to introduce a new technology into the marketplace; and we can’t base standards on projected breakthroughs in technology. But we can project the application of technologies that have been developed and bring them to market.

By leveraging new technology in our standard setting, emissions from mobile sources are a small fraction of what they once were. Along with similar progress in stationary source emissions, violations of the CO national ambient air quality standard (NAAQS) has been eliminated, levels and exceedances of the ozone and PM NAAQS have been dramatically reduced. Much of the U.S. population today has no memory of what a smoggy sky looks like, or how it feels in their lungs.

In recent years, we have begun leveraging this same technology forcing authority to the new challenging frontier of greenhouse gas emissions. We’ve put in place two round of standards for light-duty vehicles and trucks, and heavy-duty vehicles through 2025 and 2027. Similarly, we’ve implemented the RFS program to require ever increasing use of lower GHG emitting transportation fuels. But we’re nowhere near the finish line in order to achieve the goal of 80% reduction in GHG emissions. Over the coming years we will need to leverage our authorities to push the market not only further in these areas, but also expand to other portions of the mobile source market – just as we have done over the recent decades for health-related pollutants. Technologies WILL continue to be developed, and by working with our stakeholders, we WILL continue to leverage their use to improve air quality for all our citizens.
CAFE STANDARDS BEYOND 2021 – LATEST ANALYSIS AND NEXT STEPS

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In 2012, the Department of Transportation’s (DOT’s) National Highway Traffic Safety Administration (NHTSA) announced final Corporate Average Fuel Economy (CAFE) standards applicable to manufacturers’ passenger car and light truck production for the U.S. market during model years 2017 through 2021, as well as augural standards that could eventually be formally proposed for model years 2022 through 2025. In the same action, the Environmental Protection Agency (EPA) announced harmonized greenhouse gas (GHG) emissions standards spanning model years 2017-2025, and committed to revisit those standards for model years 2022-2025. In parallel, the California Air Resources Board (CARB) committed itself to accept manufacturers’ compliance with federal standards as constituting compliance with related CARB GHG standards.

On July 18, 2016, NHTSA, EPA, and CARB completed the first step in the mid-term evaluation process for CAFE and GHG emissions standards for model years 2022-2025 by issuing a Draft Technical Assessment Report (TAR). The Draft TAR evaluates fuel economy improvements made in response to CAFE and GHG emissions standards so far, and how auto manufacturers could potentially improve their fleets to meet more stringent standards in the future.

Relative to its 2012 analysis, DOT’s latest analysis reflects significant updates to relevant methodologies, data, and assumptions. This presentation will provide an overview of DOT’s analysis, reviewing key updates and results, and discussing similarities and differences relative to past analyses. The presentation will also discuss the process for proposing and finalizing CAFE standards for model years beyond 2021.
FUEL-ENGINE CO-OPTIMIZATION: A NOT-SO-NEW IDEA FOR THE FUTURE

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The DOE Vehicle Technologies Office supports research, development and deployment (RD&D) related to on-road vehicles with the objective of reducing the use of petroleum and lower greenhouse gas (GHG) emissions. While the largest focus is on electrification of light-duty vehicles, it is well-recognized that engines and fuels will continue to power most vehicles for many years to come. As such, improvements in drivetrain efficiency and reduction in carbon intensity of fuels remain the strongest levers to achieve these goals and are appropriate subjects for near- and mid-term RD&D. The engine, emissions control and fuel and lubricants R&D elements of the program are a well-integrated and critical element of the work of VTO, comprising approximately 25% of the budget of the Office. (Other elements – electric motors and batteries, vehicle systems integration and testing, materials research, and technology deployment – comprise the balance of the budget of about $280M annually, at present.) This presentation will describe the objectives and goals of the engines, emission control, fuels and lubricants portions of the R&D program of VTO, discuss our modes of interaction with industry, university and national laboratory partners, and provide select examples of projects in the engine-fuel space, with a particular focus on the fuels program. In addition, the general outlook for the future research program will be discussed.

Significant improvements in the greenhouse gas (GHG) profile of light and heavy duty vehicles can be achieved through the judicious exploitation of fuel properties in combination with engine design improvements relative to considering fuel characteristics and engines independently. Additional dramatic GHG reductions can be attained when desirable fuel properties are achieved through low-GHG fuel routes. The Co-Optimization of Fuels and Engines (“Co-Optima”) initiative at the Department of Energy is a systematic effort to identify and fully exploit these synergies in order to achieve deep GHG reductions in light-, medium- and heavy-duty vehicles with both conventional and hybrid electric drive trains. The effort is conceived as an end-to-end project which is intended to lead to commercial introduction of co-optimized fuels and engines through collaboration with a diverse collection of stakeholders. In addition to a focus on improving efficiency, providing desired properties via low-carbon blendstocks (presumably bio-derived) is a major focus. To this end, the Bioenergy Technology Office (BETO) is a co-equal sponsor of the Co-Optima program along with VTO.

Co-Optima comprises two parallel thrusts: advanced spark ignition (SI) engines and appropriate fuels; and, advanced compression ignition (CI) engines and fuels. Spark ignition engines and fuels (“Thrust I”) are relatively well-understood and the technology development trajectory for these engines over the next decade is likely to be towards downsized, boosted, and possibly downspeeded, engines paired with suitable fuels. Such engines can be optimized using a fuel with a high research octane number (RON), possibly in combination with other properties which are less well-defined at present (such as flame speed and heat of vaporization). Because the hardware trajectory is fairly well-understood, Thrust I of Co-Optima is focused primarily on defining the
fuel properties which enable high efficiency and identifying routes to those properties that can be achieved using low-GHG (likely bio-based) blendstocks. Because SI engines are present in almost all LDVs in the U.S., it is expected that the Thrust I approach will target that market. The Co-Optima initiative is targeting 2025 for the market introduction of Thrust I engines and fuels.

Thrust II, or advanced CI engines, are far less well-defined than Thrust I engines at present. In general, Thrust II engines operate in a lean/dilute combustion environment and operate with lower peak temperatures and pressures than traditional diesel CI engines. Many approaches to Thrust II combustion are “kinetically controlled”, in the sense that ignition occurs as a result of the formation of free radicals, or combustion precursors. What all approaches share is that the raw, engine-out criteria pollutant emissions can be very low. Each approach to Thrust II combustion has differences that affect what fuel properties are required for optimal operation and it is far from clear which approach or approaches will ultimately succeed in the market. Due to the relative immaturity of Thrust II technology, there is more white space for innovation and a longer anticipated time horizon for its introduction. Because CI engines are dominant in the heavy-duty market, it is likely that the first Thrust II vehicles and fuels will appear in that market. The Co-Optima initiative is targeting 2030 for the introduction of Thrust II engines and fuels.

Because the Co-Optima program has become in recent years the largest single element of the fuels program (and a significant portion of the engines program), this presentation will include a substantial focus on it. It will describe the objectives and goals of the Co-Optima program and provide examples of technology projects in both the Thrust I and Thrust II space. The structure of the program will be described. Technical and market obstacles to implementation will be discussed.
DRIVING TOWARD A LOWER CARBON TRANSPORTATION FUTURE

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Significant transformation of the power generation sector is underway in the United States. Rapid growth in the renewable sector, combined with declining economics for coal, is resulting in a grid that will become significantly less carbon intensive over the next 15 years. Is the transportation sector keeping pace and making an equal contribution in the effort to prevent climate change? Diesel and gasoline consumption in the United States has been on the rise for the past four years. Are current policies and efforts sufficient to reverse this course or is more needed? Boesel will review current trends and opportunities in the light-duty vehicle and fuel sectors in both California and the nation as a whole.
Gasoline-Fueled Engine Technologies: Spark Ignition (GSI)

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Greg Lilik, ExxonMobil
Scott Sluder, ORNL
Marie Valentine, Toyota
OCTANE-ON-DEMAND: MEETING THE TIME-VARYING GASOLINE ENGINE’S OCTANE REQUIREMENT THROUGH ON-BOARD FUEL BLENDING

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The octane requirement of a gasoline engine varies with load and speed. For example, at a brake mean effective pressure of 5 bar it is about 60 RON, at 10 bar some 90 RON, and at 20 bar over 100 RON. Our current operating mode is to use a single fuel, with a high enough octane rating so that knock never occurs. However, producing high-enough octane fuel to avoid knock while maximizing engine power, torque, and efficiency has proved to be too expensive, so in practice engine compression ratio and boost levels, especially in turbocharged engines, are constrained: gasoline spark-ignition engines are not as powerful or efficient as they could be.

There are strong pressures to improve engine efficiency, and raise the maximum output, which through engine downsizing further increases efficiency, by suppressing this knock limit. Also, moderate amounts of ethanol, which has an octane rating well over 100, are available and already extensively used in 10 percent blends to augment gasoline octane quality. The potential to realize significantly higher-octane fuel with higher ethanol content blends is well documented. Octane-on-demand thus becomes feasible if the available ethanol is used to create a high-octane fuel stream, which is used in the engine only when needed to upgrade a lower-octane base fuel stream through on-board fuel blending.

Examples of on-board fuel blending approaches that will be discussed are the dual-fuel approach with two tanks, separately filled, the larger with a standard base gasoline and the smaller with a high ethanol content blend. The second approach utilizes an on-board membrane-based fuel separator that separates out the ethanol component of the standard gasoline (along with some of the high octane hydrocarbons) to provide two fuel streams: one (some 15% by volume) that has a high octane rating (above 100 RON); the other a lower-octane stream (RON in the 80s). With octane-on-demand, to meet the time-varying octane requirement of the engine, the appropriate amounts of these two fuels are blended together and then injected into the engine cylinder. Thus, knock is always avoided, enabling increased compression ratio, higher boost levels, and significant engine downsizing, and the fuel’s octane is fully utilized.

The quantitative background of this octane-on-demand approach will be explored, as will the engine efficiency and engine-in-vehicle fuel economy benefits. These do depend on the engine’s calibration (especially, the amount of spark retard) and type of driving, but are substantial: e.g., 20 to 25% better mpg relative to a standard naturally-aspirated gasoline engine, and about half that benefit relative to a typical turbocharged gasoline engine. Octane-on-demand is a significant practical opportunity to reduce vehicle fuel consumption and greenhouse gas emissions.
EVALUATION OF CURRENT AND FUTURE ATKINSON ENGINE TECHNOLOGIES

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As part of the U.S. Environmental Protection Agency (U.S. EPA) “Midterm Evaluation of Light-duty Vehicle Standards for Model Years 2022-2025”, the U.S. EPA is evaluating engines and assessing the effectiveness of future engine technologies for reducing CO₂ emissions. Current engines, transmissions, and vehicles are benchmarked and then modeled in ALPHA. The fuel economy improvement potential of new technologies such as cooled EGR (cEGR) are being evaluated in models and hardware.

This presentation reviews the results of EPA’s benchmarking of a Mazda 2.0L 13:1 CR SkyActiv engine. The engine was then tested in an HIL test bed to represent chassis testing of an advanced vehicle configuration, which includes assumptions for a future high-efficiency transmission and reduced vehicle road loads. The engine was operated over simulated EPA city and highway test cycles to assess the greenhouse gas (GHG) emissions performance in the context of EPA’s LD GHG standards through year 2025.

The benchmarking data from the 13:1 engine were then used to develop a GT Power model. The model was used to predict the potential fuel consumption performance of increased compression ratio, cEGR, and cylinder deactivation.
EFFICIENCY AND EMISSIONS BENEFITS OF ULTRA-LEAN ENGINE OPERATION AS ENABLED BY JET IGNITION

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Stringent global fuel economy and greenhouse gas emissions legislation for light duty passenger cars has created an interest in non-traditional operating modes. One such mode in spark ignition (SI) gasoline engines is lean combustion. While lean operation in SI engines has previously demonstrated the ability to reduce fuel consumption, the degree of enleanment capability of the system is limited by increasingly unstable combustion in the lean region, particularly for homogeneous lean approaches. MAHLE Jet Ignition® (MJI) is a pre-chamber-based combustion system that extends this lean limit beyond the capabilities of modern SI engines by increasing the ignition energy present in the system. This allows the engine to exploit the benefits of homogeneous ultra-lean ($\lambda > \sim 1.6$) combustion, namely reduced fuel consumption and reduced emissions of nitrogen oxides ($\text{NO}_x$).

Pre-chamber combustors such as that utilized in MJI have been studied extensively for decades. Pre-chamber-based jet ignition concepts have unique features such as flame quenching and ignition site targeting that enable further system optimization. In this presentation, the engine performance improvement pathways of the system are explored through an examination of experimental results from engines incorporating the jet igniter. A minimum brake specific fuel consumption (BSFC) value of 200 g/kWh and a peak brake thermal efficiency (BTE) value of greater than 42% are analyzed and discussed, as are emissions data. Performance across the engine operating map and relevant system limitations are also presented. Accurate understanding of the potential performance of the jet ignition system throughout a typical engine operating envelope can lead to further system optimization, enable concept scalability, and inform system cost-benefit analyses.
A PRAGMATIC APPROACH TO REDUCING THE CO2 FOOTPRINT OF THE INTERNAL COMBUSTION ENGINE

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As industry at large works to reduce the CO2 footprint of the internal combustion engine, it is paramount to synergistically develop engine technologies and the fuels necessary to support them. From a pragmatic perspective, minimizing engine generated CO2 means synergistically minimizing all loss mechanisms. To minimize parasitic losses, we need to continue the industry-wide trend to downsize boosted engines without sacrificing compression ratio. To minimize heat losses and maximize work extraction, without sacrificing our ability to meet future criteria emissions legislation, we must pursue advanced lean, low temperature combustion. As such, to minimize engine generated CO2, at a vehicle level, we must aggressively implement high compression ratio downsize boosted engine technology and synergistically integrate advanced lean, low temperature combustion processes. And, to support both the near-term migration to high compression ratio, downsize boosted engine and the long-term integration of lean, low temperature combustion, it will be necessary for gasoline-based fuels to evolve. To support this migration of engine technologies, gasoline-based fuels will have to simultaneously become more knock resistant under high load, boosted engine operation and easier to autoignite under low load, lean operating conditions. Fortunately, through proper formulation, both goals can be met with a single gasoline-based fuel. By increasing both the RON and Sensitivity of the fuel, we can enhance high load knock resistance in support of the industry wide trend to high compression ratio downsize boosted engine, while enabling next generation lean, low temperature combustion. By migrating to fuels with increased alcohol, olefin, and cyclo-paraffin content, we can enable the implementation of high efficiency downsize boosted engine and a new generation of lean, low CO2 internal combustion engines.
DAY 2: SESSION 3

Gasoline-Fueled Engine Technologies: Compression Ignition (GCI)

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Steve Ciatti, ANL
Steve McConnell, Marathon Petroleum
GASOLINE COMPRESSION IGNITION – A PROMISING TECHNOLOGY TO MEET FUTURE ENGINE EFFICIENCY AND EMISSIONS TARGETS

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For GCI applications, light naphtha and alkane rich gasolines are of interest because they make ideal fuels for GCI engine applications and may need far less refining if used in a GCI application instead of a conventional SI or GTDI application. To support the development of fuels and engines for GCI applications, work with model fuels and surrogate fuels is of interest to explore the sensitivities of these combustion processes to specific fuel properties, which has been one of the missions of the Fuels for Advanced Combustion Engines (FACE) program. Through the FACE program, a variety of standardized gasoline formulations are available for research purposes, and a number of research groups have been exploring the formulation of surrogate fuel mixtures, which, by simplifying the composition of the fuel to where the combustion of the surrogate fuel can be described with a tractable chemical kinetic mechanism, can enable predictive simulation of combustion processes. In one portion of the work being presented, we seek to compare the combustion behavior of a set of reference gasolines, a set of FACE gasolines and surrogate mixtures that have been proposed to represent those FACE gasolines (specifically FACE A, C, I and J).
FUNDAMENTAL COMBUSTION CHARACTERISTICS OF GCI FUELS

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A difficult question to answer is “what is the ideal fuel for GCI engines?” The combustion performance and pollutant emissions of a particular fuel are dictated by the physical and chemical properties of its constituent molecules, as well as the engine operating conditions. Our goal is to enable simulation driven fuel design by developing a fuel formulation strategy based on first-principles of combustion science. We show that a broad scientific methodology can be applied to better understand the combustion of real word fuels in GCI applications. Gasoline fuels with a range of properties (e.g., octane ratings physical properties, etc.) are tested in various fundamental and applied combustion systems. Strategies for surrogate fuel formulation are created to understand the relationships between fuel properties and combustion performance. Detailed chemical kinetic models are then used to predict the various fundamental combustion properties (e.g., ignition delay, flame speed, intermediate species, etc.), and reacting flow simulations are used to provide insights. Computational fluid dynamic (CFD) simulations are also utilized to understand the coupling between physics and chemistry under realistic GCI engine conditions. Finally, the fundamental science is used to provide design targets for GCI engine fuels.
GASOLINE COMPRESSION IGNITION – A PROMISING TECHNOLOGY TO MEET FUTURE ENGINE EFFICIENCY AND EMISSIONS TARGETS

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The use of gasoline in compression ignition engines offers significant advantages in terms of increased efficiency and reduced emissions compared to either conventional diesel compression ignition or gasoline spark ignition engines. Diesel fueled compression ignition engines offer the advantage of higher efficiency than conventional gasoline spark ignition engines due to their ability to operate lean and at higher compression ratios. But gasoline spark ignition engines have the advantage of much lower emissions of particulate matter (PM) and oxides of nitrogen (NOx) than diesel compression ignition engines due to the significantly longer premixing time available to reduce the local richness of the fuel-air mixture before combustion.

For several years there has been a great deal of effort made in researching ways to run a compression ignition engine with simultaneously high efficiency and low emissions. Recently much of this focus has been dedicated to using gasoline-like fuels that are more volatile and less reactive than conventional diesel fuel to allow the combustion to be more premixed. One of the key challenges to using fuels with such properties in a compression ignition engine is stable engine operation at low loads. This work provides an analysis of how stable gasoline compression ignition (GCI) engine operation was achieved down to idle speed and load on a multi-cylinder compression ignition engine using only 87 anti-knock index (AKI) E10 gasoline – ie, regular pump gasoline in the United States.

The variables explored to extend stable engine operation to idle included: uncooled exhaust gas recirculation (EGR), injection timing, injection pressure, and injector nozzle geometry. The results of three-dimensional computational fluid dynamics engine combustion simulations revealed the importance of retaining sufficient local richness and stratification of the fuel-air mixture centered in the piston bowl for stable ignition and combustion at idle operation. By updating the low speed and load engine fuel consumption data, Autonomie vehicle simulations predicted an improved advantage of GCI engine operation compared to baseline port fuel injection gasoline engine operation from 25% to 28.7%.

Where the challenge of load expansion for HCCI has typically been to loads higher than approximately 5 bar IMEPg, the challenge of load expansion for stratified GCI engines using conventional gasoline blends has been to loads lower than 5 bar IMEPg and down to idle. The use of several advanced engine management technologies have been investigated, including intake heating, unconventional levels of low load intake boosting (typically higher than possible with a standard turbocharger), negative valve overlap (NVO) for significantly increased exhaust gas residual, fuel injection during the NVO period for reforming to increase its reactivity, or exhaust rebreathing via re-opening the exhaust valve during the intake stroke. Previous work by the current authors has been focused on extending the stable lower load limit of GCI using a production multi-cylinder diesel engine at 1500 revolutions per minute (RPM) and 850 RPM with an 87 AKI gasoline fuel that has already been successfully operated on this engine from 4 to 20 bar brake mean effective pressure (BMEP).
Advanced internal combustion piston engines are forced to operate in regimes in which combustion is no longer fully transport limited, and instead is at least partially governed by chemical kinetics of combusting mixtures, in order to enhance efficiency while simultaneously reducing the formation of traditional pollutants. Kinetically-controlled combustion allows the operation of piston engines at high compression ratios, with partially-premixed dilute charges; these operating conditions simultaneously provide high thermodynamic efficiency and low NOx and particulate matter (PM) emissions. Similarly, modern Spark Ignition engines are not kinetically controlled, but are often kinetically limited (by end-gas auto-ignition), and future lean-burn Spark Ignition engines may rely on end-gas auto-ignition to improve combustion efficiency.

The investigations shown in this presentation study the effect of ethanol addition to gasoline, as well as gasoline composition, on the low-temperature chemistry of gasoline type fuels auto-ignited in engines. These investigations are primarily carried out in a simplified, fundamental engine experiment, named Homogeneous Charge Compression Ignition, but are supported by representative data from more applied engine systems, such as Gasoline Compression Ignition engines and Spark Ignition engines. These experimental investigations, and the accompanying modeling work, show that ethanol is an effective scavenger of radicals at “low” temperatures (below 900 K), and this radical scavenging inhibits the low temperature oxidation pathways of gasoline auto-ignition. Further, the investigations measure the sensitivity of gasoline auto-ignition to system pressure at conditions that are relevant to modern engines. It is shown that at high intake pressure conditions in an HCCI engine, gasoline begins to exhibit Low-Temperature Heat Release. However, the addition of ethanol significantly delays the onset of Low-Temperature Heat Release with pressure, which in turn significantly reduces the system reactivity. This behavior is shown to impact both Gasoline Compression Ignition and Spark Ignition engines by limiting the range of operation of combustion regimes.

These findings have major implications for a range of modern engines. Low-Temperature Heat Release significantly enhances the auto-ignition process, which limits the conditions under which advanced combustion strategies may operate. As these advanced combustion strategies are required to meet emissions and fuel-economy regulations, the findings shown in this presentation may benefit and be incorporated into future engine design toolkits, such as detailed chemical kinetic mechanisms.
DAY 3: SESSION 4

Diesel-Fueled Engine Technologies (DF)

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Greg Lilik, ExxonMobil
Chuck Mueller, Sandia
THE INFLUENCE OF FUEL CETANE NUMBER ON CATALYST LIGHT-OFF
OPERATION IN A MODERN DIESEL ENGINE

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Design of modern diesel engine vehicles involves a collective optimization and balancing of trade-offs for fuel efficiency, emissions, and noise. To meet increasingly stringent emission regulations, diesel engines employ aftertreatment devices to control NOx, HC, CO and PM emissions and use active exhaust warm-up strategies to ensure those devices are active as quickly as possible. A typical strategy for exhaust warm-up is to operate with retarded combustion phasing, limited by combustion stability and HC emissions. The amount of exhaust enthalpy available to light-off catalyst is limited by the extent to which combustion phasing can be retarded.

Diesel cetane number (CN), a measure of fuel ignition quality, has an influence on combustion stability at retarded combustion phasing. Diesel fuel in the United States tends to have a lower cetane number (both minimum allowed and average in market) than other countries. It is unclear to what extent low cetane number influences the ability to retard combustion phasing while controlling feed gas HC emissions during the catalyst light-off phase.

To begin to address this question, a single-cylinder engine study was conducted to compare the ability to generate exhaust temperature and enthalpy with low emissions with fuels of 46 and 53 CN. The calibration was optimized for each fuel to maximize exhaust temperature and exhaust enthalpy while controlling emissions at or below a target level. The fuels were found to produce comparable exhaust temperature, enthalpy and emissions when the engine was operated at the same calibration. However, when the calibrations where optimized for each fuel, the higher cetane number fuel tolerated significantly greater post injection retard within hydrocarbon and PM emissions constraints, thus enabling increased exhaust enthalpy and temperature.

This study suggests that while a change in market cetane would have little impact on catalyst light-off and tailpipe emissions in legacy vehicles, future vehicles may be limited by low cetane fuel in their ability to achieve ultra-low emissions such as LEV III. The study also highlights the importance of assessment methodology when making conclusions about the effect of fuels on legacy and future vehicles.
THE ROLE OF LIGHT-DUTY DIESEL IN MEETING 2025 CAFE REQUIREMENTS

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The 2025 CAFE requirements present a great opportunity for advanced diesel engine powertrains; at the same time the 2025 SULEV 30 fleet average (NOx+NMOG) of 0.03 g/mile at 150k mile full useful life requirement presents a significant challenge. The presentation will outline the advancements in diesel engine, aftertreatment hardware, and manufacturability of critical components which is advancing many new diesel powertrains. These new diesel powertrains are exemplified by higher ranked performance and efficiency while covering emissions and fuel economy at optimum levels with superior drivability. Furthermore, the presentation will go over upcoming engine hardware enhancements, introduction of mild-hybridization and advanced compact aftertreatment system configurations to enhance the opportunity to further improve fuel economy while achieving a significant emissions reduction. The presentation will also shed light on how the new diesel engine as a powerhouse shall be integrated with rest of the powertrain such as transmission including the role of controls to meet the highest efficiency. The presentation will conclude with a note on optimum mix of technologies that enable light-duty diesel applications to address the 2025 GHG levels with in-use LEV III emissions compliance without compromising drivability at a competitive cost vs. gain margin compared to other powertrain options available on the market.
THE ROLE OF LATE-CYCLE OXIDATION FOR PM EMISSIONS AND ENGINE EFFICIENCY

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Even with modern aftertreatment systems, PM emissions remain an important challenge for diesel engine developers. During recent decades, optical diagnostics have been extensively used to study soot processes both in optically accessible engines and spray vessels. These studies have typically focused on the formation of soot. Concepts like $\phi$-$T$ diagrams and the quasi-steady lift off length have aided our understanding of what governs soot formation. The lift off length is a particularly attractive concept for experimentalists since it is relatively easy to measure and offers explanatory power.

A number of studies have shown, however, that trends in soot formation often fail to predict trends in engine-out emissions of soot. The exception is conditions where either fuel-air premixing or decreased flame temperature more or less completely suppresses soot formation, but such conditions are rare under real-world operating conditions.

This presentation compiles results from a number of experiments, comparing the relative importance of soot formation and soot oxidation. An initial challenge was to find suitable experimental methods to study soot oxidation in the cylinder. For this reason, the earliest studies relied on indirect evidence to show that soot oxidation was the limiting process for the emissions. Lately, direct measurements of soot oxidation rates have been performed in an optical engine using laser extinction. These studies systematically screened the influence of various factors that were suspected to influence the in-cylinder soot oxidation, including gas density, inlet temperature, intake oxygen concentration and injection pressure.

The results indicate that intake oxygen concentration by far has the largest influence on the late-cycle soot oxidation rate. The effect seems to be due to reduced local temperature in the mixing controlled reaction zone where the soot is oxidized, which in turn limits the production of the dominant oxidizing species, OH. Apart from this factor the injection pressure and the nozzle orifice diameter turn out to be the most dominant factors. This indicates that the injection process influences the soot oxidation long after the end of injection. Supposedly, this influence is due to bulk flow structures set up by the spray, which survive long enough to generate turbulence during the late cycle.

Indications that the late-cycle oxidation is the driving mechanism behind trends in soot emissions are welcome since they provide practical means to decrease PM emissions independently of NOx. This is because NOx predominantly is coupled to the early combustion phases. The findings also imply that a reduction in PM is conducive to increasing the thermodynamic efficiency of diesel engines, since efficient late-cycle oxidation simultaneously decreases PM and reduces the mixing-controlled tail of the heat release.
LEANER LIFTED-FLAME COMBUSTION ENABLED BY THE USE OF AN OXYGENATED FUEL OR A NOVEL MIXING-ENHANCEMENT TECHNIQUE

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Leaner lifted-flame combustion (LLFC) is a mixing-controlled combustion strategy for compression-ignition (CI) engines that does not produce soot because the equivalence ratio in reacting regions is less than or equal to approximately two. In addition to preventing soot formation, LLFC can simultaneously control emissions of nitrogen oxides because it is tolerant to the use of exhaust-gas recirculation for lowering in-cylinder temperatures. Experiments were conducted to study whether LLFC is facilitated by an oxygenated fuel blend (T50) comprising a 1:1 mixture by volume of tri-propylene glycol mono-methyl ether with an ultra-low-sulfur #2 diesel emissions-certification fuel (CFA). Results from the T50 experiments are compared against baseline results using the CFA fuel without the oxygenate. Dilution effects were studied by adding nitrogen and carbon dioxide to the intake charge. Initial experiments with a 2-hole fuel-injector tip achieved LLFC at low loads with the T50 fuel, and elucidated the most important operating parameters necessary to achieve LLFC. The strategy was then extended to more moderate loads by employing a 6-hole injector tip, where lowering the intake-manifold temperature, reducing the coolant temperature, and retarding the start-of-combustion timing resulted in sustained LLFC at both 21% and 16% intake-oxygen mole fractions at loads greater than 5 bar gross indicated mean effective pressure. In contrast to the results with T50, LLFC was not achieved under any of the test conditions with CFA. In order to achieve LLFC at higher temperatures, higher loads, and without requiring an oxygenated fuel, a novel approach for in-cylinder mixing enhancement called ducted fuel injection (DFI) is proposed. Imaging experiments in a constant-volume combustion vessel confirmed that significantly lower soot luminosity is observed when DFI is employed, relative to traditional free-spray combustion.
DAY 3: SESSION 5

Alternative/Emerging Fuels (AF)

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MARKET FEASIBILITY OF ADVANCED FUELS AND VEHICLES

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As the fuels and vehicles industries evaluate the technical capabilities of advanced fuels and engine design, a critical factor that must be considered is the feasibility of the market to accommodate and accept these products in a sustainable manner. Influencing the outcome of a market introduction will be consumer behavior relative to vehicle purchase decisions and fuel buying patterns and retailer interest in new fuel products determined by the cost of introduction and expected return on investment.

Each of these factors can be addressed in a strategic manner to increase the potential for market success, but they must be evaluated carefully and incorporated into the overall strategic decisions associated with product development and introduction. The ideal fuel and engine combination may in fact fail in the market place if it is not consistent with consumer and retailer interests. Consequently, to achieve the greatest desired results, it may be more advisable to proceed with alternate scenarios that are determined to have a greater likelihood for successful market introduction and adoption.

This presentation will evaluate consumer behavior and interests, examine retailer constraints that must be overcome to ensure the successful introduction of a new fuel and vehicle combination and consider emerging trends that are affecting the direction of the market.
Development of advanced spark-ignition (SI) and compression ignition (CI) engines with improved efficiency is needed to achieve greenhouse gas (GHG) emission reduction goals. There are significant opportunities to leverage fuel properties to create more optimal engine designs. The fact that low-net-carbon biofuel blendstocks offer additional GHG emission reductions leads to the idea of optimizing the entire fuel production-utilization value chain as a system from the standpoint of life cycle GHG emissions. This is a difficult challenge that has yet to be realized.

Biomass contains nominally 50 wt% oxygen. Oxygenate bioblendstocks can be produced with lower energy input and life-cycle GHG emissions, and lower cost than hydrocarbon bioblendstocks. Certain oxygenates exhibit unique properties that can be exploited for improved engine performance. This presentation will discuss critical fuel properties for more efficient combustion, survey the properties of a range of biofuels that may be produced in the future, and describe the ongoing challenges of fuel-engine co-optimization.

For SI engine fuels a high resistance to autoignition is critical. For direct injection (DI), highly boosted engines operating at low rpm it has been shown that at constant RON, fuels with a lower MON provide better autoignition resistance. Additionally, fuel properties such as heat of vaporization (HoV), flame speed, and dilution tolerance may prove critical for enabling high efficiency engine design. Particle emissions and how they are affected by fuel chemistry are also of concern. The effects of RON, MON, and HoV will be illustrated with experimental data. We show that high HoV fuels allow increased load under knock limited conditions for intake air temperatures higher than used for the RON test. The results of screening several hundred proposed bioblendstocks (mainly oxygenates) for critical SI engine fuel properties, with selection of the most promising are described. Blending properties including blending octane numbers are discussed. Fuel chemistry effects on DISI engine particle emissions will also be reviewed.

Advanced CI has the potential for achieving both high efficiency and low emissions (leading to reduced aftertreatment cost). Engine concepts range from fully premixed (homogenous charge compression ignition) to mixing controlled (spray combustion) and in all cases fuel ignition is controlled by reaction kinetics. Fuels with gasoline-like and diesel-like volatility can be used. The major challenges include achieving a wide speed-load range, controlling combustion over transients, and low-exhaust temperatures requiring more active catalysts. Fuel effects on achievable load range and transient operation have not been widely investigated, although there are data showing that load range may be increased with a fuel having optimal vaporization, ignition, and combustion properties. Fuel reactivity, octane sensitivity, HoV, flame speed, dilution tolerance, and $\phi$ sensitivity are all important factors. Fuel volatility may impact particulate matter emissions via the degree of fuel-air stratification. A discussion of status and data needs in this area will be presented.
Today, carbon-rich fossil fuels, primarily oil, coal and natural gas, provide 85% of the energy consumed in the United States. Fossil fuel use increases CO2 emissions, increasing the concentration of greenhouse gases and raising the risk of global warming. The high energy content of liquid hydrocarbon fuels makes them the preferred energy source for all modes of transportation. In the US alone, transportation consumes around 13.8 million barrels of oil per day and generates over 0.5 gigatons of carbon per year. This has spurred intense research into alternative, non-fossil energy sources. The DOE-funded Joint BioEnergy Institute (JBEI) is a partnership between seven leading research institutions (Lawrence Berkeley Lab, Sandia Labs, Lawrence Livermore Lab, Pacific Northwest National Lab, UC-Berkeley, UC-Davis, and the Carnegie Institute for Science) that is focused on the production of infrastructure compatible biofuels derived from non-food lignocellulosic biomass. Biomass is a renewable resource that is potentially carbon-neutral. Plant-derived biomass contains cellulose, which is more difficult to convert to sugars. The development of cost-effective and energy-efficient processes to transform cellulose and hemicellulose in biomass into fuels is hampered by significant roadblocks, including the lack of specifically developed energy crops, the difficulty in separating biomass components, low activity of enzymes used to hydrolyze polysaccharides, and the inhibitory effect of fuels and processing byproducts on the organisms responsible for producing fuels from monomeric sugars. This presentation will highlight the research efforts underway at JBEI to overcome these obstacles, with a particular focus on the development of an ionic liquid pretreatment technology for the efficient production of monomeric sugars from biomass that is compatible with downstream microbes for the production of advanced biofuels.
OPTIMISED NATURAL GAS ENGINES FOR PHASE II GHG COMPLIANCE

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A second phase of US Federal on-road Heavy Duty Green House Gas (GHG) regulations were proposed in 2015 and are expected to be implemented from 2021 to 2027 (Federal Register, 2015). These regulations impact on-road vehicles from Class 2b to Class 8, encompassing pickup trucks, vans, vocational trucks and tractor-trailers. Compliance with these new regulations will require the application of a broad range of powertrain and vehicle technologies. In some categories, compliance with the regulations using gasoline and diesel engines will require the introduction of hybridization for the first time. Hybridization has been implemented in light duty vehicles for some years and in certain heavy duty applications such as transit buses. However, implementation across a broad range of heavy duty vehicle types will require significant advances in component technologies and integration (California Air Resources Board, November 2015).

Natural gas is a low carbon fuel (California Air Resources Board, September 2015) and has been successfully implemented in certain segments of the heavy duty space such as refuse trucks (US Department Of Energy, 2015) and transit buses (National Petroleum Council, 2012). However, current engines are still not fully optimised for natural gas which limits the potential of the option in some categories. When natural gas engines are fully optimised for the fuel, they can provide new opportunities to meet customer needs, reduce fuel costs and address the regulations while avoiding hybridization or electrification.

This paper focusses the application of Compressed Natural Gas (CNG) and Liquefied Natural Gas (LNG) engines of two types: Enhanced Spark Ignited (ESI) CNG engines and 2nd generation High Pressure Direct Injection (HPDI 2.0) LNG engines in 3 applications: Heavy Duty Pickup Trucks (ESI, Class 2b/3), Medium and Heavy Duty Vocational vehicles (ESI, Class 6/7) and Heavy Duty Tractor Trailers (HPDI 2.0, Class 8). The principles and challenges of the combustion approaches and system design are discussed and the potential of the applications to address the Phase II GHG regulations are presented.

References
Supplemental Written-Only Abstracts
CO-OPTIMIZATION OF FUELS AND ENGINES

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This talk presents an overview of the U.S. Department of Energy (DOE) "Co-Optima" research effort – which focuses on the Co-Optimization of Fuels and Engines. This is a collaborative effort involving nine national laboratories, funded by both the Office of Bioenergy Technologies and the Vehicle Technologies office, focused on answering the following three questions:

1. What fuel properties maximize engine performance?
2. How do engine parameters affect efficiency?
3. What fuel and engine combinations are sustainable, affordable, and scalable?

This talk reviews progress made in the first year of this project in all three of these areas, as well as details regarding the methodology used to down select from numerous candidate fuels. In addition, the portfolio of engine and fuel property research projects is reviewed, including plans for future research in 2017.
EFFECT OF FUEL COMPONENTS ON ABNORMAL COMBUSTION OF THE SI ENGINE - KNOCKING UNDER LOW SPEED TO HIGH SPEED WITH HIGH COMPRESSION RATIO ENGINE

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In these days, improving fuel economy of SI engine is required in the world due to energy securities and environmental issues such as climate change. Under this situation, new engine technologies are being developed and researched all over the world. In addition to the development of automotive industry, Cross-ministerial Strategic Innovation Promotion Program (SIP) started in 2015 in Japan (JSAE 20165267, paper in press).

In an effort to meet the CO2 reduction of the vehicle, hybrid vehicle technology, which combines electric motors and gasoline engines, has been introduced into the market. For hybrid vehicle, natural aspirated (NA) gasoline engines with high compression ratio are mainly adopted. In addition to popularize hybrid vehicles, improving fuel economy of conventional vehicles is also essential. For this aim, turbocharged engines have been introduced into the market (SAE 2016-01-0684, SAE2015-01-1268).

One common point across these technologies is that the pressure and temperature of the air-fuel mixture in the combustion chamber become higher compared to conventional engines. These high pressures and temperatures lead to abnormal combustion such as knocking, auto-ignition, and pre-ignition at low and high engine speeds. Authors have studied about the RON and MON effect on abnormal combustion. In many cases, RON has higher correlation with abnormal combustion characteristics than that with MON other than the case of high speed pre-ignition (SAE 2012-01-1276, 2011-01-1984).

To understand the effect of fuel components on abnormal combustion, it is essential to clarify chemical reaction. In this paper, knocking phenomena is described as below.

Predictions of the knocking occurrence timing with various RON fuels with low and high engine speed is needed for improvement in the engine performance and its thermal efficiency. However, it is well understood that there are complicated chemical reaction such as Low Temperature Oxidation reaction (LTO), and Negative Temperature region (NTC). These reactions make knocking estimation difficult. Therefore, in this presentation the influencing factor on the knocking is discussed with experimental data and chemical reaction calculation results with high compression ratio engine (CR12~14), low and high RON fuel (75~100RON), low and high engine speed (1300~5200rpm) case.
It is generally agreed that overall lean operation is required for achieving the upper bounds of thermal efficiency that is possible with SI engines. Spray-guided stratified-charge operation is one promising approach to lean operation. However, due to the fuel stratification present in this combustion system, it can be challenging to ensure low engine-out smoke levels. There are several operational parameters that affect the smoke emissions. Considered here are changes to engine load, engine speed, intake pressure, and injection- and spark-timing strategy. This includes operation with either single or double injection.

By examining wide ranges of fuels and operating strategies, it becomes clear that the effect of fuel properties on smoke emissions varies greatly with operating point. A combination of all-metal exhaust-emissions engine testing and optical-engine diagnostics shows that the dominating soot-production pathway changes with operating point. This explains why the role of fuel properties varies between operating conditions.

For non-boosted operation at a low engine speed of 1000 rpm, wall-wetting due to spray impact onto the piston-bowl appears to be an important pathway for soot formation. Here, mid-level ethanol-gasoline blends (E30 and E35) show elevated smoke emissions relative to their E0 counterparts. This indicates that enhanced vaporization cooling associated with ethanol content promotes wall-affected soot formation. Here, the NOx / PM trade-off with EGR suggests that engine-out smoke is limited by soot-formation rates.

For slightly boosted operation at a moderate engine speed of 2000 rpm, bulk-gas soot formation appears to be the dominating pathway for exhaust smoke. Here, smoke emission decreases strongly with ethanol addition, even in the E30 to E35 range. This indicates that for soot formation, fuel chemistry dominates over physical properties like vaporization cooling. Furthermore, the NOx / PM trade-off with EGR suggests that engine-out soot is controlled by oxidation rates, similarly to that observed for diesel engines.

Overall, stratified-charge SI engine operation shows strong potential for high engine efficiency. However, smoke emissions can be highly dependent on both aromatic and ethanol content of the fuel, depending on operating conditions. Therefore, practical implementation may require that engine-operating strategies adapt to the properties and composition of the fuel being used.
SPLIT CYCLE CONCEPTS

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In the history of the diesel engine several attempts have been made to introduce game changing designs. So far they have mostly failed. Striving for very high efficiencies has been described as a “whack a mole” game. If you solve one problem you inevitably create a new one.

This presentation focus on a few major issues with present engine layouts that split cycle concepts address. We can identify a few major losses: Friction, heat losses in the combustion chamber and unrestrained expansion from start of exhaust valve opening. It is not uncommon that the exhaust valve starts to open while there are still 10 bar of pressure or more in the combustion cylinder. The turbo is only able to recover a fraction of the remaining potential expansion work. By using very dilute combustion or overexpansion from a Miller cycle it is possible to improve the indicated efficiency significantly. But this will reduce power density and thus increase friction.

By adopting a dual compression expansion engine (DCEE) split cycle concept it is possible to create an over-expanded cycle that also has better volume/area ratio. It allows for dedicated low pressure and high pressure components which potentially reduce both friction and heat loss. But the split cycle introduce a number of engineering challenges.

Maintaining a low heat loss from the combustion is essential. The suggested method is stratification and a more or less quiescent combustion system. This is important also to control heat load considering that the high pressure part of the cycle on its own will have a BMEP above 50 bar. Even more critical is the gas exchange between the high pressure combustion cylinder and the low pressure cylinder where the next step of the expansion takes place. This gas exchange needs to take place without excessive heat losses, pressure drop or unrestrained expansion. The next expansion step creates a further potential heat loss. But insulation is not too difficult when there is no combustion present.

Most of those engineering challenges have previously been encountered in engine projects. The Hyperbar engine use very extreme boost levels and the adiabatic engine research is also a valuable asset.
The cost of biomass feedstock is a primary contributor to the overall cost of producing renewable liquid transportation fuels. Biomass costs typically contribute between 25-50% of the total fuel cost. Waste streams represent low cost and, in many cases, carbon rich resources which could serve as economical feedstocks for the sustainable production of liquid fuels. Furthermore, many waste streams such as municipal solid waste already have collection and sorting infrastructures in place. This talk will focus on the conversion of two waste streams to liquid fuels. First, the fermentation of syngas (a mixture of CO + H₂) to ethanol will be discussed. Syngas is present in steel mill stack gas or can be generated from a variety of waste resources, such as municipal solid waste gasification. Similar to corn ethanol, syngas ethanol can be concentrated and applied directly for use in gasoline engines. Alternatively, we have developed a process to convert ethanol to non-oxygenated hydrocarbon fuels. The first step of the process is to dehydrate ethanol to ethylene. Thus, the process can be employed for any light olefin (C₂-C₄) stream, including non-renewable sources such as the unsaturated portion of alkylate feeds. The hydrocarbon fuels are 95+% isoalkanes with a low concentration of aromatics. The fuel properties of the diesel and gasoline fractions will be discussed. The second waste conversion process discussed will be the conversion of municipal wastewater sludge via hydrothermal liquefaction (HTL). HTL is a wet conversion process. Feeds are typically 10-20% solids and 80-90% water. The process employs high temperature water (350°C) at sufficiently high pressure to maintain the feed in the condensed phase. Hence, no water is vaporized, avoiding significant energy costs. Primary sludge from municipal wastewater treatment plants contains about 50% cellulose and 50% bio-solids. Of the bio-solids, a large fraction consists of fats, oils and greases. The HTL process produces a biocrude containing a wide range of gasoline boiling range cyclic compounds from cellulose conversion and free fatty acids from lipid conversion. Hydroprocessing of the biocrude to increase the H/C ratio and decrease the O and N heteroatom content results in a naphthenic rich gasoline fraction and n-alkane rich diesel fraction. Fuel properties of these fractions will also be discussed. Finally, the economics of each waste conversion process will be discussed.