USDRIVE

DRIVING RESEARCH AND INNOVATION FOR
VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

# Advanced Combustion and Emission Control Roadmap

March 2018

*This roadmap is a document of the U.S. DRIVE Partnership. U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability) is a voluntary, non-binding, and non-legal partnership among the U.S. Department of Energy; USCAR, representing Fiat Chrysler Automobiles, Ford Motor Company, and General Motors; five energy companies – BP America, Chevron Corporation, Phillips 66 Company, ExxonMobil Corporation, and Shell Oil Products US; two utilities – Southern California Edison and DTE Energy; and the Electric Power Research Institute (EPRI).*

*The Advanced Combustion and Emission Control (ACEC) Tech Team is one of 13 U.S. DRIVE technical teams whose mission is to accelerate the development of pre-competitive and innovative technologies to enable a full range of efficient and clean advanced light-duty vehicles, as well as related energy infrastructure.*

*For more information about U.S. DRIVE, please see the U.S. DRIVE Partnership Plan, www.vehicles.energy.gov/about/partnerships/usdrive.html or www.uscar.org.*

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# Overview and Approach

The Advanced Combustion and Emission Control (ACEC) Technical Team is focused on removing technical barriers to the commercialization of advanced, high-efficiency, emission-compliant internal combustion (IC) engines for light-duty vehicle powertrains (i.e., passenger car, minivan, SUV, and pickup trucks)[1]. Elimination of the technical barriers will enable light-duty engines with significantly higher fuel efficiency than current conventional engines. This document describes the current state of light-duty engine technology and industry trends, establishes research targets, and identifies pathways and barriers to those targets. This roadmap was developed through a collaborative process to ensure it represents the vision of both industry and government stakeholders.

Increasing the efficiency of internal combustion engines is a technologically-proven and cost-effective approach to dramatically improving the fuel economy of the nation's fleet of vehicles in the near- to mid-term, with the corresponding benefits of reducing our dependence on foreign oil and reducing carbon emissions. Efficiency can be increased by improving combustion processes, minimizing engine losses such as friction, reducing the energy penalty of the emission control system, and using recovered waste energy in propulsion. Compliance with exhaust emission regulations will be mandated and requires aftertreatment technologies integrated with the engine combustion approaches. Because of their relatively low cost, high performance, and ability to utilize renewable fuels, internal combustion engines, including those in hybrid vehicles, will continue to be critical to our transportation infrastructure for decades.

In the last few years, there has been a rapid growth in the development of autonomous and connected vehicles. There is discussion that traditional cars and trucks as we know them today will be replaced by “mobility solutions.” What is the most suitable powertrain for future transportation solutions: a pure IC engine, a pure battery-electric, or a hybrid powertrain? For now, the ACEC Technical Team believes that traditional and hybrid-electric powertrains are fully compatible with future transportation solutions and that our objective of improved engine efficiency is necessary for these solutions.

The ACEC Technical Team efforts support the U.S.DRIVE Partnership goal to “significantly improve the efficiency of vehicles powered by advanced internal combustion powertrains (including hybrids) and vehicle fuel systems while protecting the environment.”[2] As will be discussed, the ACEC 2020 and 2025 U.S.DRIVE research targets are as follows:

- 2020: A 20% improvement in engine efficiency, compared to a 2010 baseline. Engine concepts shall be commercially viable and meet 2020 emissions standards.
- 2025: A 25% improvement in part-load engine efficiency and a 20% improvement in maximum efficiency compared to a 2010 baseline. Relative to the updated 2017 baseline, these goals represent a range of 13% to 27% improvement depending on the engine pathway. Engine concepts shall be commercially viable and meet 2025 emission standards.

The ACEC Tech Team has identified multiple combustion strategies that require further research and development (R&D) to achieve these goals. In order of priority, as identified by the United States Council for Automotive Research (USCAR) team members, the combustion strategies are:

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[1] In this roadmap, light-duty vehicles are defined as vehicles with gross vehicle weights less than 14,000 lbs.

[2] Ref: U.S. DRIVE Partnership Plan, November 2016, https://energy.gov/eere/vehicles/us-drive-partnership-plan-roadmaps-and-accomplishments

1. **Dilute Gasoline Combustion**: This strategy involves advanced, efficient combustion of gasoline fuel, which is dominated by the propagation of a flame through fuel and air that is largely premixed. Dilution is accomplished with exhaust gas recirculation (EGR) or excess air. The efficiency gain is achieved through reduced heat loss and greater work extraction associated with combustion of dilute gasoline-air mixtures. The primary engine platform for this technology will be downsized, boosted engines, but work on hybrid-optimized platforms (both naturally aspirated and boosted) is also highly relevant. Even though engines employing flame-propagation combustion have been produced for more than a century, they still have significant potential to contribute to fuel efficiency gains through elimination of part-load efficiency losses. A key attraction of this strategy is its relatively small increase in complexity and cost. Market analysts forecast that gasoline-fueled engines will continue to be the most-used option in the passenger car market in the U.S. for several decades, and as a result, will account for the largest fraction of fuel consumption. In this roadmap, ethanol (as E85) and natural gas combustion are included in this strategy because many physical properties of combustion are similar although fuel infrastructure and some hydrocarbon fuel specific emission challenges exist. The research areas of highest priority for dilute gasoline combustion and emission control are:
    a. Knock mitigation, including low-speed pre-ignition
    b. Low-temperature emissions aftertreatment
    c. Reduced cold start emissions
    d. Low-cost, lean-$NO_x$ aftertreatment
    e. Thermal management (efficient, low-cost waste heat recovery and thermal barrier materials)
    f. Increase EGR and air dilution tolerance
    g. Research that reduces the content, complexity, and cost of engines while increasing efficiency to enable a higher penetration of hybrid electric vehicles
2. **Clean Diesel Combustion**: This strategy involves techniques for the clean, advanced combustion of diesel fuel, where burning predominantly takes place simultaneously with the mixing of fuel and air, known as diffusion-flame or mixing-controlled combustion. Automotive diesel combustion enables a very efficient engine design with the highest proven thermal efficiency. Clean diesel engines reduce emissions via advanced diesel combustion and advanced aftertreatment systems. This combustion strategy will be focused on engines for medium-duty pickup trucks, where this technology is already popular. On-going clean diesel R&D will have applicability to heavy-duty engine manufacturers for maximum impact. The research areas of highest priority for clean diesel combustion are:
    a. Reduced engine-out $NO_x$ and particulate emissions
    b. Reduced cold start emissions
    c. Efficient, low-cost, low-temperature emissions aftertreatment
3. **Low-Temperature Combustion (LTC)**: This novel strategy involves the flameless, staged burning of the fuel in the combustion chamber at low temperatures. LTC offers potential for achieving efficiencies as high as, or higher than, diesel engine combustion approaches. Moreover, a major attraction of LTC is its simultaneous potential for dramatically lower engine-out nitrogen oxides (NOx) and particulate (PM) emissions and hence lower aftertreatment costs. The LTC strategy has many variants, e.g., Homogeneous

Charge Compression Ignitions (HCCI), Partially Premixed Charge Compression Ignition (PCCI), and others that are characterized by the degree of fuel-air mixing prior to the start of combustion and extent of flameless combustion. Although these technologies offer low engine-out NOx and PM emissions, they create significant aftertreatment challenges due to reduced exhaust gas temperatures, and may produce higher engine-out hydrocarbon (HC) and carbon monoxide (CO) as well as higher cold-start emissions.

In recognition of the trend towards downsized engines with high specific power in light-duty vehicles, LTC research will focus on barriers related to a multi-mode combustion strategy. A likely multi-mode combustion strategy is to use SI flame-propagation combustion at high loads and wide-open throttle to achieve suitable power density, while employing LTC at low to mid loads for higher efficiency. The research areas of highest priority for low-temperature combustion are:

a. Expanded speed and load range
b. Reduced engine-out HC and CO emissions
c. Lower combustion noise
d. Simpler transient control/combustion mode switching
e. Improved cold operation
f. Increase tolerance to changes in ambient temperature and humidity, and market fuel variability
g. Reduce cost of lean-NOx aftertreatment system
h. Research that reduces the content, complexity, and cost of engines while increasing efficiency to enable a higher penetration of hybrid electric vehicles

These advanced combustion strategies will result in lower exhaust temperatures that are not compatible with conventional aftertreatment systems. Therefore, R&D on appropriate advanced aftertreatment technology is an integral part of the roadmap. In addition, waste heat recovery strategies to improve efficiency are included. An extensive list of barriers and technical strategies to both advanced combustion and emission control are listed in Appendix A.

The ACEC powertrain R&D roadmap is intended to be compatible with current and future liquid (petroleum and non-petroleum derived hydrocarbons with some oxygenated components such as alcohols and biodiesel) and gaseous (hydrogen and natural gas) fuels. A greater understanding of how new fuels impact advanced combustion strategies and aftertreatment systems could provide pathways for further engine efficiency improvements, in addition to identifying practical, economic fuels and fuel-blending components with potential to directly displace significant amounts of petroleum. Fuel properties play a critical role in increasing engine efficiency as well as influencing exhaust aftertreatment architecture and catalyst composition. Appendix B discusses fuel property recommendations made by ACEC for gasoline and diesel fuels, and includes results of a survey on low-temperature-combustion fuel properties. Hydrogen as a fuel for enabling high-efficiency, clean engines has also been considered. Appendix C discusses the current state of the art of hydrogen internal-combustion engine technology.

# Current Baseline Production Powertrain Technology

Since 2000, the annual sales volume of light-duty vehicles ranged from 10 to 17 million, with economic conditions strongly influencing the annual sales. Table 1 shows the light-duty vehicle types in the U.S. market in 2010 and 2015, with preliminary data for 2017. Internal combustion engines (ICEs) power nearly all vehicles. The ACEC Tech Team considers the ICE as the dominant propulsion system for many decades into the future. ICE's are used in vehicles with manual and automatic transmissions, hybrid, plug-in hybrids, and range-extended electric vehicles. The only vehicles without an ICE are battery electric vehicles (BEV) and fuel cell vehicles (FCV). In 2010, an extremely limited number of BEV and FCV powered vehicles were available and were concentrated in regions with charging or hydrogen fueling infrastructure. The market penetration of these non-ICE vehicles increased in 2015 and could increase in the future depending on customer demand, infrastructure development, cost of fuel, and alternative vehicle cost compared to an ICE vehicle.

The ICEs in light-duty vehicles are either spark ignited (SI) or compression ignited (CI), also known as diesel. SI engine technology has more than 93% of the market and dominates in the U.S. The market penetration of diesel powered light-duty cars and trucks was approximately 3 and 4% in 2010 and 2015, respectively, but decreased significantly in the preliminary data for 2017. Light-duty diesel engine use is concentrated in larger pickups and vans designed mainly for commercial use with gross vehicle weight (GVW) greater than 10,000 lbs. Due to the higher market penetration and importance for personal transportation, the ACEC baseline is focused on vehicles using an SI engine.

*Table 1. US Light-Duty Vehicle Types and Percent Market Penetration*[3]

| | 2010 | 2015 | 2017 (prelim) |
|---|---|---|---|
| Gasoline | 93.6 | 93.3 | 94.5 |
| Gasoline Hybrid | 3.7 | 2.0 | 3.3 |
| Diesel | 2.7 | 4.0 | 0.3 |
| Plug-In Electric Hybrid | 0.0 | 0.3 | 0.9 |
| Electric | 0.0 | 0.4 | 1.0 |

Table 2 shows the market penetration of key technologies in SI ICE’s in 2010, 2015, and 2017. In 2010, the most common SI ICE configuration in the US was the multi-valve, port fuel injection (PFI), stoichiometric, gasoline-fueled, engine with Variable Valve Timing (VVT) and Three-Way Catalyst (TWC) aftertreatment technology.[4] Based on its popularity, the ACEC team chose this as the baseline engine configuration. Multi-valve refers to 3- or 4-valves per cylinder to increase airflow and thus engine torque. The VVT strategies change the phasing of intake and/or exhaust valves relative to the crankshaft to increase internal EGR, reduce pumping work, and optimize combustion for improved performance and efficiency. In 2010, 84% of vehicles had engines with

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[3] Environmental Protection Agency, Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2017, EPA-420-R-18-001, January 2018, Table 5.1 Data from 2017 is projected from automakers.

[4] If properly designed, this engine can operate with blends of ethanol and gasoline up to 85% ethanol.

some form of VVT (also referred to as cam phasing) technology. By 2015, nearly all engines had VVT. Port fuel injection refers to injection of fuel into the intake port in a manner that a stoichiometric mixture of fuel and air is inducted into the cylinder during the intake stroke. In 2010, 91% of vehicles used PFI engines. The use of PFI has decreased significantly and is being replaced by direct injection (DI) of fuel into the cylinder, which was featured in more than half the vehicles in 2017. Table 2 also shows the penetration of turbocharging which increased significantly since 2010, with approximately one quarter of vehicles using turbocharging according to 2017 data. This trend is consistent with the downsized and boosted pathway that will be discussed.

*Table 2. U.S. Light-Duty Gasoline Engine Technologies and Percent Market Penetration*[5]

| | 2010 | 2015 | 2017 (prelim) |
|---|---|---|---|
| Multi-valve | 86.1 | 92.5 | 92.4 |
| Port Fuel Injection | 91.6 | 57.5 | 48.2 |
| Variable Valve Timing | 84.4 | 98.7 | 98.8 |
| Stoichiometric 3-Way | 100 | 100 | 100 |
| Direct Injection | 8.4 | 42.5 | 51.5 |
| Turbocharger | 3.3 | 16.0 | 25.2 |

All stoichiometric engines, regardless of fueling strategies, require TWC aftertreatment closely coordinated with engine operation. The engine/TWC control system uses heated oxygen ($O_2$) sensors and sequential fuel injection to achieve high catalyst efficiency. These stoichiometric powertrains will be required to meet U.S. EPA Tier 3 emission regulations. Potential technologies to attain this level of emission control include additional Platinum Group Metal (PGM) content, reduced engine-out emissions (especially HC and NOx) and exhaust particulate filters (for both gasoline and diesel DI engines).

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[5] Environmental Protection Agency, Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2017, EPA-420-R-18-001, January 2018 Table 5.3.1

# Fuel Economy and Emission Regulations and Trends

Light-duty-vehicle corporate average fuel economy (CAFE) regulations are now in place to 2025. The current regulations require a US fleet average of 250-g $CO_2$ per mile in 2016 (equivalent to 35.5 miles per gallon) and 163-g $CO_2$ per mile in 2025 (equivalent to 54.5 miles per gallon). These requirements for 2016 and 2025 are a 1.4-times and more than a 2-times increase in miles per gallon versus a 2008 baseline of 25 miles per gallon, respectively. Each manufacturer has a different fuel economy target depending on the vehicle mix and volume sold, and each vehicle has a fuel economy target based on the vehicle footprint.[6]

Manufacturers do not assume that the engine alone will provide the necessary fuel economy improvements. Instead, a combination of technologies at a vehicle level will be used to meet the regulation. Customer demand will play a role in technology selection. Technology areas that will improve CAFE include:

- Engine (dilute gasoline, clean diesel, LTC, boosting and downsizing, and other advanced fuel injection and combustion approaches)
- Transmission (automatic, manual, dual clutch, …)
- Vehicle (mass, tires, aerodynamics, …)
- Hybrid (strong, mild, …)

Specific CAFE plans and technology selections for each manufacturer are confidential. However, achieving the goals of the ACEC Tech Team is likely critical for all OEMs to meet fuel economy mandates after 2016.

The U.S. EPA Tier 3 emissions regulations apply to vehicles entering the U.S. fleet today, although the emission level requirements are phased in from 2017 through 2025, with each year requiring lower fleet-average tailpipe emissions. Additionally, emission-system warranty requirements increased from 120,000 miles to 150,000 miles and 15 years. Somewhat easing the burden of these requirements on the aftertreatment system is the introduction of the Tier 3 fuel regulation that reduces the average sulfur content in gasoline fuel to 10 ppm. However, addressing sulfur poisoning of catalysts will remain a challenge even with the lower sulfur content of market fuel. Another important difference in the Tier 3 emission regulation, as compared to the previous Tier 2 regulation, is that $NO_x$ and non-methane organic gases (NMOG) were combined into one emission bin ($NO_x$+NMOG). This change, together with the lower Tier 3 tailpipe emissions, represents 80% lower emissions than the previous Tier 2 Bin 5 emissions requirement.[7]

Although methane ($CH_4$) is excluded from the NMOG regulation, $CH_4$ and $N_2O$ are now both regulated as greenhouse gas emissions due to the disproportionately higher impact they have on global warming compared to $CO_2$. Specifically, $CH_4$ has a factor of 25 greater global warming potential than $CO_2$. Even more impactful, the $N_2O$ global warming potential is 298 times that of $CO_2$.[8][9] Thus, although not necessarily emitted by combustion processes at significant levels, the generation of $N_2O$ by the emission control system must still be minimized. Note that $CH_4$ and $N_2O$

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[6] Credits for other $CO_2$ reduction technologies and business decisions can reduce the CAFE target. Examples of these credit and incentive opportunities are: reduced refrigerant leakage from air conditioner; flex fuel (credit declines to zero in 2016); BEV, PHEV and fuel cell vehicles; natural gas vehicles; credit transfer between car/truck fleets or future/previous model years; credits purchased from other OEM's.

[7] Tier 2 Bin 5: 90 mg/mi NMOG and 70 mg/mi NOx. Tier 3: 30 mg/mi NMOG plus $NO_x$.

[8] www.epa.gov/climateleadership/documents/emission-factors.pdf

[9] Note: global warming potential based on 100-year period

greenhouse-gas emission standards are implemented on a cap basis, with caps of 30 mg/mile and 10 mg/mile, respectively. Emissions above the cap are counted against the rated fuel economy of the vehicle as $CO_2$ equivalent greenhouse gas.

Automakers that sell vehicles in section 177 states[10] must meet California Air Resource Board (CARB) emission standards. These LEVIII regulations, like the EPA Tier 3 standards, are also stringent. Today, California vehicles are certified to emission levels ranging from LEV to SULEV emissions standards. LEVII PZEV vehicles had SULEV emissions, but defined HC and $NO_x$ levels separately within the standard and required additional evaporative emission control, while maintaining a 150,000-mile warranty. The Federal Tier 3 2025 fleet average requirement of Bin 30 NMOG+$NO_x$ FTP cycle emissions is similar to California's LEVIII SULEV30 for NMOG+$NO_x$ level[11]. This regulation "harmonization" is beneficial as it reduces the need for development of multiple emissions variants of a specific vehicle model.

An important trend in worldwide emission regulations is the increased emphasis on testing emission compliance through Real Driving Emissions (RDE) certification procedures using Portable Emissions Measurement Systems (PEMS).[12] Although not currently mandated in the United States, RDE type testing is an important consideration for aftertreatment technology development.

A new challenge of the Tier 3 emissions standards for light duty vehicles is the inclusion of increasingly strict particulate matter emissions levels, which are based on mass measurements of particulate matter (PM) as opposed to particulate number (PN) regulated by other countries. With a Tier 3 Bin 30 limit of 3 mg/mile, this PM regulation is 70% less than the previous Tier 2 Bin 5 level of 10 mg/mile. The diesel particulate filter (DPF) has been shown to be highly successful at controlling PM emissions from clean diesel combustion engines, but DPFs increase the cost and complexity of the aftertreatment system. For advanced low temperature combustion and dilute gasoline engine technologies, the size, chemical composition, morphology, and quantity of PM emissions are substantially different from diesel engines and are highly dependent on combustion specifics. This requires filter technologies, where needed, to be tailored to combustion strategies to effectively control PM emissions. To support particulate filter development, additional sophisticated analytical techniques, such as particle-size distribution analyzers, are necessary to characterize properly complex PM emissions and filtration efficiencies of aftertreatment devices. Such analytical capabilities are essential in light of the upcoming particulate number requirement in European emissions regulations.

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[10] The term "section 177 states" refers to states that adopt California emission standards (www.epa.gov/state-and-local-transportation/vehicle-emissions-california-waivers-and-authorizations)

[11] California Low Emission Vehicle Regulation – LEV III (Proposed for model years 2017 -2025)

[12] Ref: ec.europa.eu/info/law/better-regulation/initiatives/ares-2016-6339064_en

# Current State of Advanced Combustion Strategies

This section describes the current status of the advanced combustion strategies prioritized in this roadmap. The improvements from advanced combustion strategies will be combined with efficiency gains from reducing parasitic losses and by converting wasted energy to propulsion. Current engines have reduced friction due to lower viscosity oils, roller rather than sliding elements in the valve train, preferential heating of the oil to reduce viscosity after startup and variable-capacity oil pumps that deliver only the volume of oil required. Turbocharged engines recover energy from the exhaust and use it to compress the air entering the engine. With the new emphasis on engine downsizing, turbocharged engines are offered in an increasing volume of vehicles.

## Dilute Gasoline Combustion:

Dilute combustion in advanced gasoline SI engines offer the greatest potential for decreasing fossil fuel use, since gasoline is the most widely produced and used fuel in the U.S. — a trend expected to continue for the foreseeable future. Moreover, the incremental cost of the added technology for a dilute gasoline combustion engine over the baseline PFI engine is potentially less than half the incremental cost of an emission compliant diesel relative to the same baseline PFI engine. Recent technology improvements in engine fuel systems, combustion system design, controls, and aftertreatment systems are further improving the potential for this engine-type. A particularly significant development during the last decade has been the increasing use of direct fuel injection, which is showing signs of displacing PFI systems. Direct fuel injection is also a significant enabler for several dilute-combustion gasoline-engine designs described below.

Dilute combustion of gasoline and its benefits can be achieved in two major ways. The first is the use of excess air (lean-burn) as the diluent. The other is the use of EGR. The current state of dilute combustion of gasoline engine/aftertreatment technology can be summarized as follows:

### *Advanced lean-burn gasoline SI engines*

Advanced lean-burn gasoline SI engines have been shown to offer efficiency gains at part load via improved gas properties, decreased throttling losses, and decreased heat losses. Over the past 15 years, several original equipment manufacturers (OEMs) have attempted to introduce lean-burn gasoline engines into production in Europe and Asia, with limited success. Examples are Mitsubishi (1996), and Toyota and Nissan (1997) in Japan. These products were terminated within a few short years due to the lack of significant fuel economy benefit to the customer and shortcomings of the exhaust aftertreatment system. Later attempts by Mercedes-Benz and BMW in Europe in 2006 met Euro 4 standards and achieved fuel economy improvements in the 12% to 20% range on the new European driving cycle (NEDC) relative to their counterpart stoichiometric baseline engine. These latter introductions utilized improvements in combustion system design, fuel systems (the piezo injector) engine-control systems, and relied on increased availability of low-sulfur gasoline (less than 10 ppm) required by lean-$NO_x$ trap (LNT) aftertreatment systems.

Basic strategies for control, *e.g.*, cold-start, warm-up, and mode switching between lean and stoichiometric engine operation have been developed over the last 15 years and are now standard. Control schemes to improve the $NO_x$ performance of LNT aftertreatment systems are now becoming standard as well. Many combustion system designs for enabling spark-ignited gasoline engines to operate lean have been attempted. The combinations of port configurations, air-motions, and fuel-spray characteristics, mixing characteristics, ignition and combustion characteristics investigated have been large. Through these efforts, significant improvements in combustion system performance and reductions in engine-out emissions have been achieved. At this time, the most promising combustion system approach is the spray-guided direct injection combustion system, like that employed in Mercedes-Benz and BMW lean-burn engines introduced in Europe in 2006. Coupled with an LNT aftertreatment system these engines have now been able to meet Euro 5 standards.

### *Advanced EGR-diluted gasoline SI engines*

Like lean-burn, dilution with EGR also offers improvements in efficiency via improvements in gas properties, decreased throttling losses, and decreased heat losses. Generally, dilution with EGR offers slightly less maximum fuel economy improvement than dilution with excess air, but more $NO_x$ reduction. Typically, EGR dilution is used with stoichiometric fuel-air mixtures, and therefore conventional TWC aftertreatment technology can be used. EGR admitted into the intake manifold via an external EGR valve or via VVT/VVL techniques offers lower complexity, but lower efficiency improvement. Since cooled EGR mitigates knock, advanced techniques using cooled EGR in downsized boosted applications could enable high degrees of downsizing and the full dilute-burn fuel efficiency potential.

### *Fuels for dilute/lean-burn SI engines*

Dilute SI engines can operate with the typical range of gasoline and ethanol blends sold today as gasoline, and do not need special gasoline or any special fuel other than lower sulfur content fuels if lean-NOx traps (LNTs) are to be used. In fact, some of the more sophisticated designs have boasted the potential for multi-fuel capability. Most of the technical paths to dilute SI engines are also applicable to fuel blends with high alcohol content, with some potential additional advantages provide by the alcohol. In experimental studies with E85, ethanol's higher octane number and latent heat of vaporization have shown the potential to enable higher thermal efficiency, and thereby, overcome some or all of the miles per gallon (MPG) reduction when using ethanol. While the research has been largely conducted in PFI-type engines, the potential advantages should extend to dilute Fuel Flexible Vehicle (FFV) engines as well, giving the consumer additional incentives to use these fuels.

Dilute SI Engines can also operate with natural gas. Today's light-duty natural gas engines are either dedicated (only natural gas) or bi-fuel (gasoline and natural gas). Engines in these vehicles have port or manifold injected natural gas, spark ignition of well-mixed fuel and air, and a three-way exhaust catalyst. The changes to the engine to enable natural gas use are known and consist of modified valve seats, an injection system for both fuels, and aftertreatment system with improved methane ($CH_4$) oxidation at lower temperatures. However, $CH_4$ emissions from natural gas engines are problematic, since the catalytic oxidation of $CH_4$ is difficult and $CH_4$ GHG emissions above the 30 mg/mi light duty vehicle cap, as measured over the Federal Test Procedure (FTP) drive cycle, count against fuel economy.

Natural gas vehicles leverage a fueling infrastructure in which the number of natural gas filling stations has doubled in the last 5 years. On-board natural gas storage requirements affect vehicle packaging (unless the storage is well integrated into the vehicle). The energy density of the fuel either limits vehicle range or requires a large fuel storage tank. On-board fuel storage is generally compressed gas for light duty vehicles. Whereas, liquefied natural gas is a potential for heavy-duty applications.

## **Clean Diesel Combustion:**

In 2015, more than twenty models of passenger-car and light-truck vehicles with a diesel engine were marketed in the US. Approximately 70% of these models were trucks and SUV's. Overall, these state-of-the-art diesel engines and emissions control systems provide the highest proven vehicle fuel economy for vehicles with only internal combustion engines. In addition, these vehicles have dramatically lower NOx and particulate matter (PM) emissions compared with diesel vehicles from a decade ago and meet current emission regulations. The dramatic decrease in emissions resulted from the combined advances in combustion and aftertreatment technologies.

Diesel aftertreatment system components typically include a diesel particulate filter (DPF) for PM control, an SCR for $NO_x$ control, and a diesel oxidation catalyst (DOC) to aid in CO and hydrocarbon emission control. Thermal management of the catalyst system and active regeneration of the DPF are also integral aspects of design. Lean-NOx traps (LNT) technologies for $NO_x$ control have been commercialized, but selective catalytic reduction (SCR) has become the dominant clean diesel catalyst for controlling $NO_x$ to levels required by Tier 3 standards in the U.S. Essential to the introduction of the diesel catalyst based aftertreatment technologies was the mandated introduction of low-sulfur diesel fuel (maximum 15 ppm) in

2006. Sulfur is a poison for catalyst technologies, and although not completely eliminated, the lower diesel-fuel sulfur level provided the opportunity for implementing less costly and more effective catalytic aftertreatment systems.

Additional details on the state of diesel/aftertreatment system technology can be summarized as follows:

- Diesel engines provide improved engine thermal efficiency from part load to high load. Diesel engine has a cost premium driven by aftertreatment, fuel injection system, and engine structure to accommodate higher cylinder pressure.
- Light-duty diesel engines typically employ a swirl-supported, direct-injection (DI) diesel combustion. Dramatic engine-out emissions reductions have been achieved through improvements in intake air handling; introduction of four valves per cylinder; increased intake pressure boosting; electronically controlled, high-pressure fuel injection; combustion chamber design and advanced controls.
- Traditional diesel deficiencies such as exhaust odor; poor acceleration; poor starting; and noise, vibration and harshness have been greatly reduced.
- Urea-based SCR $NO_x$ aftertreatment has realized improved performance and durability via the introduction of small pore zeolite materials and size reductions through integration of the SCR and DPF functions into a single device.
- Virtually all diesel vehicles sold for on-road applications utilize catalyst-based diesel particulate filter (DPF) technology to reduce PM by more than 95%.
- *Diesel Fuels:* Low sulfur diesel fuel, mandated in 2006, has successfully enabled catalyst-based aftertreatment for diesel. In addition, oxygenated fuel has been shown to provide the potential for dramatically reducing PM emissions while minimally affecting $NO_x$ levels. However, other than biodiesel, no other oxygenated diesel fuels have yet to be developed or proven. Other diesel fuel improvements for emissions reduction *(e.g.*, modified composition, blending agents that also minimize petroleum use, and fuel composition tailored for optimal $NO_x$-adsorber performance) continue to be investigated for future direction.

## Low-Temperature Combustion:

Research and development is being aggressively conducted worldwide on engines employing low-temperature combustion (LTC) because of the simultaneous potential for fuel efficiency and low emissions (i.e., reduced aftertreatment) that LTC offers. Several different LTC strategies are being developed. These strategies range from Homogeneous Charge Compression Ignition (HCCI), most applicable for gasoline-like fuels, to Premixed Charge Compression Ignition (PCCI), often used for diesel-like fuels, to dual fuel approaches like Reactivity Controlled Compression Ignition (RCCI) using a diesel-like and a gasoline-like fuel in combination.[13]

Laboratory research to-date has suggested that LTC is capable of enabling engines with diesel-like and potentially even higher fuel efficiency, coupled with ultra-low PM and $NO_x$ emissions. The lower engine-out emissions suggest the potential for less costly $NO_x$ and PM aftertreatment relative to the advanced diesel option. However, research also shows that effective engine control over a full load-speed range is difficult and needs further development. In addition, the combination of higher HC and CO emissions combined with lower exhaust temperatures (resulting from greater efficiency of fuel energy conversion to work) creates challenging conditions for emission control.

Two companies (GM and Daimler) built demonstration engines/vehicles employing HCCI in a mixed-mode approach: HCCI at light-to-moderate loads and SI at high loads. These engines showed improved fuel economy largely through reduced pumping losses, reduced heat transfer, and faster-burning better-phased

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[13] Ref: Dempsey, Curran and Wagner, International J of Engine Research, 17, 897-917, 2016

combustion under light-load conditions where the engine spends much of its duty cycle. Mazda has announced plans to introduce a mixed-mode, spark-assisted HCCI engine in 2019, with goals of improved efficiency as much as 20 to 30% compared to the current Mazda SkyActiv-G engine.

No light-duty engines employing LTC are marketed yet, although advances in diesel engine combustion, such as higher injection pressure, multi-pulse injection, and increased use of EGR are pushing larger fractions of the reacting fuel-air mixtures in a diesel toward fuel-air mixtures characteristic of PCCI-type LTC. This trend is helping reduce the burden on aftertreatment systems. In the heavy-duty sector, early mixed-mode diesel-LTC approaches included two commercial diesel fueled engines: the late-injection MK system by Nissan and the early-injection UNIBUS system by Toyota.

Additional details on the state of LTC technology can be summarized as follows:

- Significant progress has been made understanding the fundamentals of LTC combustion processes for various applications (e.g., fuel-air mixture preparation, ignition, progress of combustion, and emissions formation).
- Gasoline- and diesel-fueled LTC strategies under naturally aspirated conditions have been shown to work at light-to-moderate loads.
- Boosting, EGR, retarded combustion timing, and thermal and/or fuel stratification have been shown in the lab to enable very high load HCCI on pump grade gasoline, opening the possibility for full time HCCI. In the lab, peak indicated thermal efficiencies of 48% and loads up to 19 bar IMEP were demonstrated in a single-cylinder engine representative of a Cummins B-series, pickup-size engine.
- LTC achieved by dual fueling with gasoline and diesel fuel (RCCI) has been shown in the lab to exhibit diesel-like efficiency or better over a wide operating range, with low engine-out nitrogen oxide and soot emissions[14]. RCCI has also shown efficiencies greater than diesel in a single-cylinder heavy-duty engine, up to full-loads, when using natural gas as the low-reactivity fuel[15]. However, these techniques are still in the early stage of research.
- Techniques for overcoming idle and very light load CO and HC emissions noted in early research on HCCI have been developed. One approach is to induce partial fuel stratification through timing of the fuel injection. Research is also suggesting that the operating range of LTC may be improved with an advanced fuel that has ignition and vaporization characteristics specifically tailored for LTC operation. Research suggests a low-octane, low-cetane fuel with volatility similar to gasoline (e.g., naphtha) may provide a better fuel for LTC, but further research is required. Such a fuel could also potentially improve energy efficiency at refineries, providing additional reductions in oil use.
- Approaches for controlling LTC and for switching between LTC and SI or diesel combustion modes are progressing as indicated by the development of the GM and Daimler demonstration HCCI engines. Control technologies being explored include advanced fuel-injection strategies, VVT, variable intake temperature, controlled EGR, and variable compression ratio (VCR).
- The engine/aftertreatment systems must function effectively as a system. Some LTC relevant systems integration has been done as part of the development of current technology diesel engines. Initial efforts are represented by the HCCI demonstration vehicles built by GM and Daimler.
- *LTC Fuels:* At present, LTC regimes are mostly constrained by the use of gasoline or diesel fuel. However, there is currently inadequate understanding of which fuel properties are needed to better enable LTC.

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[14] S. J. Curran, R. M. Wagner, and R. M. Hanson, "Reactivity Controlled Compression Ignition (RCCI) Combustion on a Multi-Cylinder Light-Duty Diesel Engine", International Journal of Engine Research, Vol. 13, No. 3, pp. 216-225 (2012).

[15] Nieman, D., Dempsey, A. and Reitz, R., "Heavy-Duty RCCI Operation Using Natural Gas and Diesel," SAE Int. J. Engines 5(2):2012, doi:10.4271/2012-01-0379.

# Engine Goals to Achieve Brake Thermal Efficiency Targets

Engine efficiency improvement can be achieved by the application of technologies to a system (engine or aftertreatment) to reduce the fuel consumption, improve the torque, or improve reduction of a pollutant. Efficiency improvement is measured at a specific test condition or multiple test conditions. For an engine, efficiency is measured at a specific speed and torque and reported using measures such as brake thermal efficiency (BTE) or brake specific fuel consumption (BSFC). For an aftertreatment system, the emissions reduction efficiency is measured at a specified flowrate, temperature and gas composition.

An alternative approach to specify the ACEC goals is an improvement in vehicle fuel economy[16]. This approach involves two steps. First, the efficiency of the engine is improved and studied at specific test conditions. Second, the improved engine is integrated into a specific vehicle, optimized for the vehicle application, and the system is tested on a drive cycle. Many vehicle specific assumptions including vehicle size, aerodynamics, transmission, tires, drive schedule and control system are required for a fuel economy test. A poor integration or technology mismatched for the vehicle application may lead to little or no fuel economy improvement with the improved engine.

Given the engine and aftertreatment focus of the ACEC Tech Team and no significant focus on the overall vehicle, we elected to express our goals in terms of engine efficiency improvement. This choice avoids specification of the many vehicle related assumptions and integration required as part of a vehicle fuel economy goal. In addition, since most companies consider fuel economy work as competitive technology, our focus continues to be pre-competitive in nature.

Prior to 2010, the ACEC efficiency goal was expressed as an improvement in engine peak brake thermal efficiency (BTE) at a test point. Our goal was to improve maximum brake thermal efficiency from 30%, representative of PFI engines in 2000, to a 45% peak thermal efficiency, representative of the potential of an advanced diesel engine.

After 2010, the ACEC team changed the efficiency goal from a single efficiency point for a diesel engine to three pathways that represented both SI and diesel engines and their duty cycles.[17] In addition, the technical challenges and merit of approaches related to enabling the emissions goals for these advanced engines were identified. Subsequent sections cover these topics.

## Technological Pathways to increases in engine efficiency

There are several pathways to increase engine efficiency that are typically determined by technology. Technological pathways are also closely synonymous with megatrends or directions that a majority of the automotive industry is pursuing. For example, one megatrend is the greater incorporation of stop- start technology. Here the trend is to shut off the engine at idle and thus save fuel and increase vehicle fuel efficiency. If this technology pathway or direction proves sustainable, then engine efficiency at idle conditions will become moot. The team accepted that stop-start technology is on a sustainable pathway and so idle was not included in any efficiency deliberations.

Upon surveying the directions (or megatrends) that the automotive industry seems to be taking, the team chose the following three pathways to increased engine efficiency that look credible, robust and sustainable.

### *Engines for Hybrid application*

Various kinds of hybrid electric vehicles have appeared for almost two decades now and although they have had a slow start, all indications are that they will see increased popularity. The vehicle fuel-economy gain is significant with hybrid technology. The engine contribution to the vehicle fuel efficiency gain results

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[16] For example in 2008, DOE issued a project solicitation with goals to improve the fuel economy of a light-duty vehicle with a gasoline-fueled engine by 25% and a diesel-fueled engine by 40% relative to a current vehicle with a gasoline port injected engine by 2020. Tier 2 Bin 2 emissions were required

[17] USDRIVE ACEC Tech Team, “A Methodology to Determine Engine Efficiency Goals and Baselines,’ 2012

from the engine operating in a narrower speed and load range. Thus, the engine better lends itself to be optimized for peak efficiency in that narrow range, although its power density may be lower than conventional engines.

### *Conventional Naturally Aspirated Engines*

This technology pathway has been around for decades, and captures a very large collection of technologies aimed at reducing various part-load engine efficiency losses without boosting. The most common part-load loss is due to throttling. This pathway simultaneously addresses other losses such as heat transfer and losses associated with working fluid properties. Thus, this pathway would include technologies such as external EGR, lean homogeneous-charge combustion, lean stratified-charge combustion, HCCI combustion, etc. It would also include all forms of cam phasing, variable-lift valve control, and fully variable-valve actuation, as well as cylinder deactivation. Since no boosting is employed, the power density of such engines is at conventional levels.

### *Down-sized Boosted Engines*

This technology has found favor in the last ten years as a pathway to higher engine efficiency and vehicle fuel economy. Like the conventional naturally aspirated engine, this technology also addresses part-load losses, not by reducing the losses directly, but by increasing the load factor of the engine. Further gains in efficiency are made by decreasing mechanical friction by replacing larger engines and higher cylinder counts with smaller engines and fewer cylinders. The power densities of such engines are typically high.

## Engine speeds and loads for efficiency testing and reporting

Engines operate over a wide range of speeds and loads. To completely characterize the engine requires testing and reporting of an efficiency map over the entire operating regime. Generation of an engine map requires a large amount of time and expense and usually is not warranted during research and development of a concept. On the contrary, a single number like the peak efficiency of an engine may not capture the practical in-use behavior of the engine. Choosing the above three technology pathways as a first step allows for easier assessment of engine efficiency.

One aim of the team was to keep the testing brief and concise, preferably having only a handful of operating conditions to test. By having defined technology pathways as mentioned above, the task of choosing operating conditions was greatly simplified. For each of the three technology pathways, one operating condition stands out that is of greatest consequence, as illustrated in Figure 1.

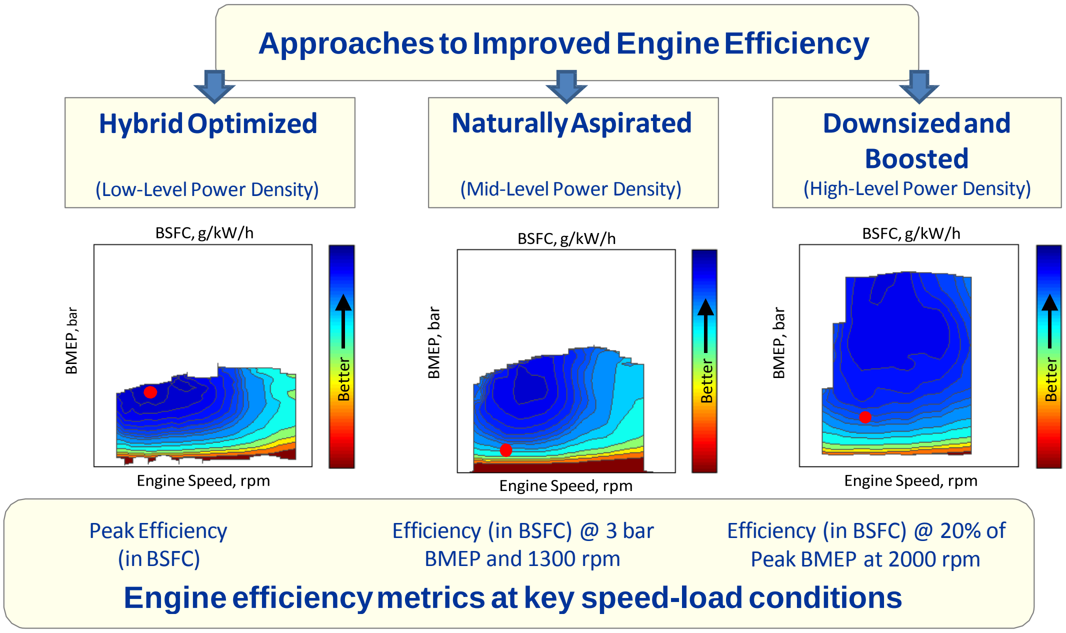

Figure 1. Technology pathways to improving engine efficiency and the selected operating conditions for evaluating efficiency improvements. Red dot is the representative speed-load point for each pathway.

In a parallel hybrid electric vehicle configuration, the engine can be augmented by battery power, while for series hybrids, the engine provides electricity for propulsion or simply charges the batteries and the electric machine propels the vehicle. For these reasons, the engine operating range can be very narrow and the engine can be designed to be very efficient in the narrow range of operation. What matters most is that the engine achieves its maximum efficiency in that narrow range. Therefore, for the hybrid pathway, the peak efficiency point was chosen.

An engine that is on the conventional, naturally aspirated pathway operates a large fraction of the time under part-load conditions. Under these part-load conditions, throttling losses are especially significant. Most research and development is aimed at reducing these part-load losses. This is illustrated in the middle part of Figure 1. This operating condition represents typical part-load operation for many engine-vehicle combinations. What matters most for this technology pathway is the efficiency gain achieved at or around this part-load operating condition. Originally in 2010, for this technological pathway, an engine speed of 2000 RPM and engine load of 2.0 bar BMEP was chosen.  However, industry trends show newer 9 and 10-speed transmission technology has made this point less relevant.  Transmissions with more gears allow the engine to be operated at a lower engine speed and higher engine load.  Furthermore, advances in engine design technology have increased specific power and torque and allowed naturally aspirated engines also to undergo some degree of downsizing.  Therefore, in 2017, the team chose an engine speed of 1300 RPM and 3 bar BMEP as the new part-load operating condition.

For the downsized boosted pathway, which seeks to operate at heavier loads by downsizing the engine, an engine speed of 2000 RPM and 20% of peak BMEP was chosen. This is illustrated in the right-hand part of Figure 1. While engines of this type do not operate routinely at peak torque, their design is such that a greater fraction of their duty cycle moves closer to the peak torque point. Further, since the degree of downsizing achievable depends on the extent of boost or low-speed torque obtained, the peak torque was thought to be a good figure of merit for this concept. The efficiency at 20% of peak torque (or BMEP) is used for our baseline purposes. Very often, this point for a typical boosted gasoline engine is around 4.0 bar BMEP at 2000 RPM.

Finally, it is understood that in all discussions of engine efficiency, emissions requirements, whether tailpipe or targeted engine-out values, are always met.

## Baseline Engine Efficiencies

Baseline engine efficiencies at the points chosen for each technology pathway are needed in order to set the amount of increase over the baseline as a goal. It was decided that baseline efficiencies should be drawn from production engines, and not from a development engine or concept engine in a laboratory situation. It is usually very difficult to get robust efficiency values for laboratory engines because of proprietary reasons, and further, such engines usually do not have all the emissions, production, assembly, and cost considerations and compromises that affect the final thermodynamic efficiency of the engine. Therefore, the state-of-the art baseline efficiency was chosen to be from a vehicle that can be purchased in a vehicle showroom. For our 2013 roadmap, it was decided that the baseline engine should be model year 2010 multi-valve, port-fuel injected, equipped with variable valve timing, operating stoichiometric on regular fuel with a 3-way catalyst. Further, the engines chosen as baselines were to be high-volume engines and not a niche or special one-of-a-kind engine.

Obviously, one would choose the engine with the highest efficiency in production to establish the baseline. This will mean that many existing engines will have to be tested and the one with the highest efficiency chosen. This is a monumental task in itself; so, the possibility of using existing databases was pursued. The team decided to use USCAR Engine Benchmarking Team's database for this purpose. For each Technology Pathway, engines from the USCAR database were chosen subject to the constraints described above. Values for engine efficiency and/or peak load were determined from the database and Table 3 was populated with the baseline efficiency values. The efficiencies highlighted in Table 3 are at the same key speed/load conditions presented in Figure 1. In the 2013 edition of the ACEC Roadmap document, engines in the 2010 timeframe were used for determining the baseline. These baseline engines have been replaced with engines representative of 2017 in this edition of the Roadmap document. Engines used to benchmark both the hybrid-optimized and the naturally aspirated pathways used port-fuel injection, while the downsized boosted pathway baseline engine used a combination of port and direct injection.

## Goals for Engine Efficiency Increases

Armed with baseline efficiencies, the final task is to set the increment over the baseline as a goal for future engine research and development. This task is equally challenging since there can be a variety of investigations, conclusions, and/or opinions on how much improvement in efficiency is possible with a given technology. One reason for the varied opinions is the fact that baselines are varied. The improvement in efficiency that can be possible is typically directly dependent on how low the baseline efficiency is. Hence, the importance of choosing a single, relevant, and highest possible baseline, as described earlier.

A second reason for the varied opinions is the varied maturity of the same technology among the different OEMs and R&D institutions. As a development program on any technology progresses, the estimated efficiency gain can increase because the concept is being tapped for its maximum potential. On the other hand, the estimated efficiency gain can also decrease with program progress as more of the real world, practical limitations and compromises of the concept are recognized. The more mature a development program, the more robust the estimate for the efficiency gain. Therefore, if only technology status sets the goals, the goals will be continuously changing as work is completed.

The ACEC team used two methods to set future goals. For the 2020 goals, the team used an analytical process to study the goals. The approach was a second-law analysis, performed by Oak Ridge National Laboratory to determine the upper bound in efficiency by identifying and minimizing losses. The study determined the upper bound in efficiency. These values were degraded by team member opinion because only a fraction of the losses was recoverable based on practical considerations.

To set the 2025 goals, the ACEC team monitored improvements in efficiency published in technical papers and in production vehicles. This activity checked progress toward the 2020 goals and ensured that the 2025 goals were still stretch targets.

Based on the results of this study and the opinions of team members, the 2020 and 2025 team goals shown in Table 3 were selected. These goals are stretch goals to drive engine research and represent improvements beyond current engines. For 2020, the goal is a 20% improvement in engine efficiency compared to the original 2010 baseline at all conditions. For 2025, the goal is a 25% engine efficiency improvement at the 3-bar and 20%-load points, corresponding to the naturally aspirated and downsized boosted pathways, pathways. Based on analysis of the current trajectory for peak efficiency, the 2025 peak efficiency goals are kept the same as 2020.  Relative to the 2017 baseline, these goals represent a range of 13% to 27% improvement depending on the engine pathway.  In recognition that measured efficiency is not meaningful unless an engine meets system constraints, additional targets are in development by the team to guide meaningful single-cylinder dynamometer-based research commensurate with an early technology readiness level focus. These targets will be published in a later version.

*Table 3. .  Engine efficiency baselines and goals for multi-cylinder engines. The engine operating condition most important for the overall efficiency of each technology pathway is represented by the highlighted cells.*

| | | **2010 Baseline** | | | | **2020 Stretch Goals** | | | |
|---|---|---|---|---|---|---|---|---|---|
| Technology Pathway | Fuel | Peak Efficiency[a] | Efficiency[a] at 2 bar BMEP, 2000 RPM | Efficiency[a] at 20% of Peak Load, 2000 RPM | Peak Load[b] at 2000 RPM | Peak Efficiency[a] | Efficiency[a] at 2 bar BMEP, 2000 RPM | Efficiency[a] at 3 bar BMEP, 1300 RPM† | Efficiency[a] at 20% of Peak Load, 2000 RPM |
| Hybrid Application | Gasoline | 38 | 25 | 24 | 9.3 | 46 | 30 | 33 | 29 |
| Naturally Aspirated | Gasoline | 36 | 24 | 24 | 10.9 | 43 | 29 | 33 | 29 |
| Downsized Boosted | Gasoline* | 36 | 22 | 29 | 19 | 43 | 26 | 35 | 35 |
| | Diesel | 42 | 26 | 34 | 22 | 50 | 31 | 36 | 40 |

| | | **2017 Updated Baseline** | | | | **2025 Stretch Goals** | | |
|---|---|---|---|---|---|---|---|---|
| Technology Pathway | Fuel | Peak Efficiency[a] | Efficiency[a] at 3 bar BMEP, 1300 RPM | Efficiency[a] at 20% of Peak Load, 2000 RPM | Peak Load[b] at 2000 RPM | Peak Efficiency[a] | Efficiency[a] at 3 bar BMEP, 1300 RPM† | Efficiency[a] at 20% of Peak Load, 2000 RPM |
| Hybrid Application | Gasoline | 39 | 29 | 27 | 9.9 | 46 | 35 | 30 |
| Naturally Aspirated | Gasoline | 36 | 29 | 26 | 11.5 | 43 | 35 | 30 |
| Downsized Boosted | Gasoline* | 38 | 31 | 32 | 20.8 | 43 | 38 | 36 |
| | Diesel | 40 | 32 | 33 | 24.4 | 50 | 39 | 42 |

[a]:Brake Thermal Efficiency (BTE) expressed as [%]

[b]: Brake Mean Effective Pressure (BMEP) expressed as [bar]

† Updated speed/load point for 2017 baseline and 2025 stretch goals reflects advances in transmissions and downsizing

*: Downsized boosted gasoline efficiencies based on engine with direct injection, using premium fuel

## Aftertreatment Goals to Achieve Advanced Combustion Emissions Compliance

The overarching emissions goal for the powertrain technologies shown in Table 3 is the U.S. EPA Tier 3 Bin 30 emission standard, which represents a greater than 80% reduction in combined $NO_x$ and NMOG emissions compared with the previous Tier 2 Bin 5 standard. In addition, the PM emissions of less than 3 mg/mile represent a 70% reduction of the Tier 2 Bin 5 standard. In order to achieve these extremely low criteria emission levels along with newly enacted greenhouse gas requirements, future catalyst and emission control systems must adapt to operating with higher efficiency in low temperature regimes not previously experienced. The triple challenge of more stringent emissions standards, greenhouse gas control, and required low temperature catalyst performance will significantly challenge current catalyst technologies and force the introduction of new aftertreatment approaches. Therefore, a principal goal of future low temperature aftertreatment technologies, embraced by the ACEC Technical Team, is to achieve greater than 90% conversion of criteria pollutants ($NO_x$, CO, HCs) at 150°C for the full useful life of the vehicle (defined as the longer of 150,000 miles or 15 years). Additionally, these technologies must optimize or replace precious metal usage to control cost and minimize the production of $N_2O$ and $CH_4$ to avoid potential negative adjustments to fuel economy ratings. This requirement of a lower conversion temperature will reduce the time needed to achieve catalyst lightoff and thus lower cold start emissions, which is a significant contributor to overall tailpipe emissions.

The catalyst sub-team of the ACEC Technical Team, the Low Temperature Aftertreatment (LTAT) group, hosted a workshop in November 2012 to specifically focus on the "150ºC Challenge" identified above. A report from the workshop entitled "Future Automotive Aftertreatment Solutions: The 150°C Challenge Workshop Report" serves as a technical roadmap for research and development activities that facilitate and provide aftertreatment solutions for the advanced combustion strategies identified by the ACEC Technical Team. In addition to the emission- related barriers and technical strategies shown below, the workshop roadmap report serves as a reference for additional relevant technical challenges and approaches. Four main areas of research and development that are addressed in the report are captured in the four breakout sessions conducted at the workshop[18]:

- **Modeling:** development of models and simulation tools ranging from the molecular level to the system level to predict performance and better understand catalytic processes
- **Materials:** research and development of new and novel material combinations that will enable lower temperature catalytic performance, increased selectivity to inert species, and optimal storage of pollutant and reductant species
- **Industry and Supplier Needs:** definition of critical performance and durability specific requirements and boundary conditions for auto industries to commercialize advanced emission control systems
- **System Integration:** research and development of non-catalytic emission control components (e.g. thermal management, reductant supply, advanced substrates) and integrated systems to enable Tier 3 Bin 30 emissions

In addition to the needs identified by the "150ºC Challenge" workshop, a survey of emission-control research activities of interest to industry is conducted on a bi-annual basis by the Crosscut Lean Exhaust Emissions Reduction Simulations (CLEERS) working group[19], an R&D focus group of the DOE Advanced Engine Crosscut Team that consists of members from both light-duty (U.S.DRIVE) and heavy- duty (21st Century Truck Partnership) government-industry partnerships. Industry input from the most recent survey is incorporated into the barriers and technical strategies sections below.

A significant portion of the research addressing emission challenges entails the evaluation of new catalyst

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[18] USDRIVE Workshop, "Future Automotive Aftertreatment Solutions: The 150°C Challenge", 2012, available at www.cleers.org.

[19] "2015 CLEERS Industry Priorities Survey Final Report", available at www.cleers.org/reports.php

and storage materials. In order to accelerate the process of advancing the development of promising inception-stage catalyst technologies, the ACEC Technical Team LTAT subgroup created protocols for evaluating catalytic and storage/release performance on a bench-reactor scale. These protocols are specific to a catalyst function (e.g. oxidation, storage, TWC) and provide specific guidelines to characterize materials, including details of the simulated gas mixtures representative of the combustion strategies that are the focus of ACEC. These protocols also provide a means to compare performance of emissions control technologies across multiple research teams. The protocols have been promulgated to the research community via the CLEERS R&D Focus Group and associated website (www.cleers.org). Table 4 shows specific simulated exhaust composition data given in the Low-Temperature Oxidation Catalyst Test Protocol.[20] Each column in Table 4 represents a combination of combustion and fuel technologies that represent the three combustion strategies in this roadmap. “LTC-G” and “LTC-D” represent Low Temperature Combustion with gasoline and diesel fuels, respectively. “S-GDI” and “L-GDI” represent Dilute Gasoline Combustion with gasoline direct injection (GDI) at stoichiometric and lean air-to-fuel ratios, respectively. “CDC” represents Clean Diesel Combustion. Research needs for emissions control vary because pollutant concentrations and exhaust compositions depend on the combustion strategy. In the “Barriers/Technical Strategies” section below, descriptions of research needs are given for each combustion strategy. Table 5 shows which emission control technologies are relevant to each combustion strategy as a guide to understanding the complete array of research needs (as discussed in Appendix A).

*Table 4. Simulated exhaust parameters: Oxidation catalysis* (a)

| **Constant components** | **S-GDI** | **CDC** | | **L-GDI** | **LTC-G** | **LTC-D** |
|---|---|---|---|---|---|---|
| [$O_2$] | 0.74% | 12% | | 9% | 12% | 12% |
| [$H_2O$] | 13% | 6% | | 8% | 6% | 6% |
| [$CO_2$] | 13% | 6% | | 8% | 6% | 6% |
| **Variable components** | all in [ppm] | | | | | |
| [CO] | 5000 | 500 | | 2000 | 2000 | 2000 |
| [$H_2$] **(b)** | 1670 | 100 | | 670 | 670 | 400 |
| [NO] | 1000 | 200 | | 500 | 100 | 100 |
| | Hydrocarbon – [ppm] on $C_1$ basis **(c)** | | | | | |
| Total [HC] | 3000 | 1400 | | 3000 | 3000 | 3000 |
| [$C_2H_4$] | 700 (1050) | 500 (778) | | 700 (1050) | 700 (1050) | 500 (1667) |
| [$C_3H_6$] | 1000 (1500) | 300 (467) | | 1000 (1500) | 1000 (1500) | 300 (1000) |
| [$C_3H_8$] | 300 (450) | 100 (155) | | 300 (450) | 300 (450) | 100 (333) |
| [i-$C_8H_{18}$] | 1000 (0) | - | | 1000 (0) | 1000 (0) | - |
| [n-$C_{12}H_{26}$] | - | 500 (0) | | - | - | 2100 (0) |

(a) Balance $N_2$

(b) Held at constant percentage of [CO]

(c) The HC $C_1$ concentrations in parenthesis to be used if the user chooses to omit the liquid HC species

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[20] “Aftertreatment Protocols for Catalyst Characterization and Performance Evaluation: Low-Temperature Oxidation Catalyst Test Protocol”, USDRIVE, available at www.cleers.org/acec- lowt

*Table 5. Emission control technology research needs for combustion strategies. (✓=need for emission-control technology,* **?** *=further research required to determine applicability)*

| | **Low Temperature Combustion** | | **Dilute Gasoline Combustion** | | **Clean Diesel Combustion** |
|---|---|---|---|---|---|
| | **LTC-G** (Gasoline Fuel) | **LTC-D** (Diesel Fuel) | **S-GDI** (Stoichiometric) | **L-GDI** (Lean) | |
| Lean NOx Catalysts | ✓ | ✓ | | ✓ | ✓ |
| Three-Way Catalyst | | | ✓ | ✓ | |
| CO/HC Oxidation Catalysts | ✓ | ✓ | | | ✓ |
| HC Traps | ✓ | ✓ | **?** | **?** | **?** |
| Passive NOx Adsorbers | ✓ | ✓ | **?** | **?** | ✓ |
| Particulate Filters | ✓ | ✓ | ✓ | ✓ | ✓ |
| Multifunction Devices/Systems | ✓ | ✓ | | ✓ | ✓ |

# Research Leveraging with Other DOE Activities

**Vehicle Technologies Office (VTO):** Significant leveraging of research in support of the ACEC Tech Team roadmap and goals occurs with DOE VTO R&D program activities.

*Medium- and Heavy-duty Engine R&D Projects:* There are substantial research activities on engine technology, combustion, aftertreatment, and related enabling technologies for the special requirements of the medium- and heavy-duty engine applications. This research is aligned well with the roadmap of the 21st Century Truck (21CT) Partnership. The potential cross-cutting application to passenger car vehicles is a key basis for creating the Advanced Engine Crosscut Team that helps guide the research for maximum leveraged benefit. The Advanced Engine Crosscut team includes the ACEC Tech team members and major truck engine OEMs. Most of the efforts in the medium-duty and heavy-duty engine research are conducted via cooperative research and development agreements or CRADAs with industry. As an example, the SuperTruck programs have been performed in close collaboration between DOE, industry, and the national laboratories. However, fundamental research into heavy-duty combustion is also sponsor at the national laboratories.

*Fuel Technologies Research:* There are two significant thrusts in this area: (1) determining fuels characteristics that can help enable high-efficiency, low-emission engine technologies, and (2) research that will stimulate or enable use of non-petroleum fuels, emphasizing renewable fuels such as ethanol, biodiesel, and renewable diesel. In particular, the initiative to co-optimize fuels and engine technologies offers an opportunity to combine fuel diversification with improving engine efficiency and performance. Co-optimization of higher-efficiency engines and high performance fuels utilizing the fundamental knowledge and new understanding created by this effort has the potential for an additional light-duty vehicle fuel economy improvement. Cutting-edge research at the national laboratories, in close collaboration with academia and industry, will strengthen the knowledge base of high-efficiency, advanced combustion engines and fuels.

*Propulsion Materials Program:* This research area Program is addressing materials needs for catalytic aftertreatment systems, sensors, EGR components, fuel systems, and particle filter media that have direct application to emissions barriers for all engine technologies. Also supported are materials R&D for lightweight valve trains, low-inertia turbochargers, and components for high BMEP engines, all being significant for higher efficiency. Materials requirements for less friction yet adequate cylinder sealing are addressed as well.

**Office of Science, Basic Energy Sciences (BES) Activities:** The BES activities provide the combustion and catalysis science underpinnings necessary for supporting the VTO applied combustion and aftertreatment R&D activities.

*Gas-Phase Chemical Physics Activity:* Research on gas-phase combustion chemistry, complex reacting flows, and laser diagnostics for investigating complex reacting flows are critical research areas that are helping form a foundation for engine combustion research. In addition, the BES activities are developing high- fidelity modeling tools such as Direct Numerical Simulation and Large Eddy Simulation (LES) tools. VTO is now directly leveraging LES. VTO activities are funding efforts to extend and apply LES in close coordination with critical engine combustion experiments to provide new understanding about advanced engine combustion strategies not obtainable through experiments alone. Moreover, the high-fidelity computational tools being developed and applied will help improve engineering CFD tools and will lead to a new generation of engine simulation tools required for simulating stochastic challenges that face engine designers (*e.g.*, misfire for stratified charge DISI engines and low-speed preignition for downsized boosted engines.) Recently, BES and VTO jointly funded a Combustion Research and Computational Visualization facility at the Combustion Research Facility for jointly developing and applying the new high-fidelity simulation tools in close coordination with fundamental and applied

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experimental combustion research.

*Catalysis Science Activity:* This program office within BES funds the largest fraction of basic research in catalysis in the Federal government, and produces research outcomes of relevance to programs of the Office of Energy Efficiency and Renewable Energy, including the VTO programs, and of the Office of Fossil Energy. This activity develops the fundamental scientific principles enabling rational catalyst design and chemical transformation control. Research includes the identification of the elementary steps of catalytic reaction mechanisms and their kinetics, and the construction and determination of active catalytic sites at the atomic level. The Advanced Combustion and Emission Control activities are leveraged with the BES/Catalysis Science (BES/CS) program in two important ways. First, recent BES/CS funded studies have identified novel catalyst materials and structures that provide for significantly lower temperature reactivity. For example, BES/CS research identified a unique catalyst composed of a mixture of Cu, Ce, and Co oxides with low temperature CO oxidation performance that was further investigated in the VTO program where low temperature oxidation performance benefits for HCs were discovered. Such collaboration is enabling great progress toward the “150ºC Challenge” of the VTO program. Secondly, the BES/CS program continues to invest considerable resources aimed at the development of theory, modeling, and simulation of catalyst materials and catalytic pathways. These developments are directly applicable to the VTO-funded Crosscut Lean Exhaust Emissions Reduction Simulations (CLEERS) activity.

# Cost Strategy Discussions

The ACEC technical team objective is to find commercially viable technology solutions that achieve the efficiency and emissions objectives. Cost assessments and strategies for engine technologies are a challenge for three reasons. (1) The technology content necessary to achieve the efficiency and emission objectives is not defined. (2) The actual cost data is proprietary for each manufacturer and not publically disclosed. And, (3) the price of platinum group metals (PGMs) which are required for aftertreatment systems is extremely volatile which greatly complicates predicting future PGM-based catalyst costs.

Since the technology content required to achieve the objectives is not defined and the costs cannot be quantified, the ACEC technology development roadmap does not include specific cost targets, but rather considers strategies that favor cost reduction. One strategy is to increase volume to reduce unit cost. Unfortunately, most of the added technologies cited for the systems considered are in high volume production and are in the second or later generation of production. Some exceptions in their first generation are lean $NO_x$ aftertreatment for gasoline and diesel, piezoelectric injectors for gasoline, and on-board diagnostics for diesel. A second strategy is to eliminate or reduce content in one of the key systems: aftertreatment, boosting, and fuel injection. Some examples cited previously in this document are:

- Use LTC strategies with high efficiency to lower engine-out emissions and reduce aftertreatment content and cost vs. diesel
- Develop and improve efficiency of lean-burn DISI which has lower cost fuel injection components vs. diesel
- Develop new catalyst materials for $NO_x$ and PM reduction to improve the cost effectiveness of aftertreatment systems vs. today's lean systems
- Combine discrete aftertreatment elements into one component that accomplishes multiple aftertreatment functions
- Focus on either naturally aspirated or slightly boosted engines to reduce the requirements for the boosting device vs. diesel or multiple stage turbocharged engine

A major element of the aftertreatment cost is the amount and price of PGMs. PGM market volatility is greatly affected by mining and processing operations in foreign (and often less stable) countries. Figure 2 shows PGM market costs since 1992; large cost fluctuations are evident for all three PGMs. Critical material supplies are subject to worldwide government stability and, in general, form a national point of economic concern. Optimization of catalyst PGM is included in the research for different aftertreatment systems. PGM usage needs to be minimized while meeting Tier 3 emission standards, and research is needed to discover and develop PGM alternatives for catalysis.

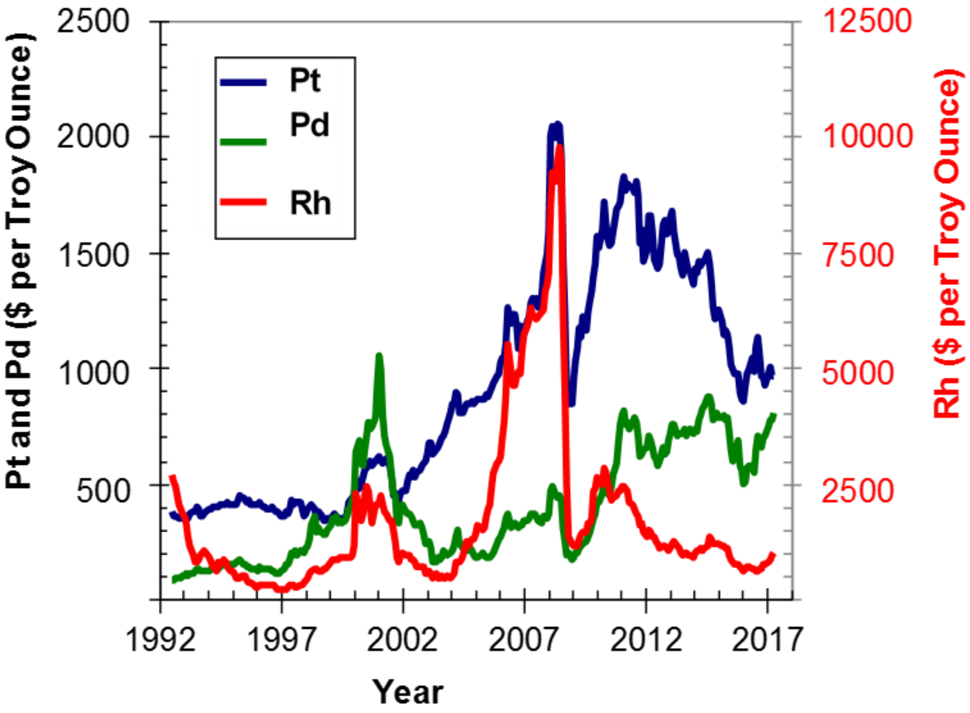


Figure 2. Monthly average cost of Platinum Group Metals Pt, Pd, and Rh from July 1992 to April 2017. Note that the Rh scale is 2.5 times the magnitude of the Pt and Pd scale. [*Source: www.platinum.matthey.com (JohnsonMatthey)]*

# Appendix A: Barriers/Technical Strategies

Significant progress has been made on the various advanced engine technologies, as discussed in the State of the Advanced Powertrain Technologies Section, but barriers remain. In the following, the barriers and strategies for overcoming the barriers are discussed. The discussions are organized by first stating specific strategies, which are followed by further details and discussion of the specific barrier(s) addressed.

**Dilute Gasoline Combustion:** While the efficiency potential is not as high as the LTC and clean diesel combustion strategies, dilute gasoline combustion strategies provide an option for lower cost fuel-efficiency improvement on a broad scale, providing the potential for a major reduction in oil usage through large market penetration. An overall strategy for developing dilute-burn engines has to capitalize on the benefits of the technology, be cognizant of the technology trends, and address the barriers that have prevented the technology from being successful thus far. The overall barriers inhibiting the introduction of high-efficiency, dilute gasoline engine technology are: (a) robust lean-burn and EGR-diluted combustion technology and controls, especially relevant to the growing trend of boosting and down-sizing engines, (b) the lack of cost-effective, commercially viable aftertreatment technologies for lean-burn systems and controls that allow compliance with EPA Tier 3 emissions regulations, and (c) lack of understanding of the impact of ethanol/gasoline blends. Detailed strategies and barrier discussions can be summarized as follows:

*Combustion technology for advanced dilute combustion gasoline engines:* The three important combustion challenges are combustion robustness (stochastic, cycle-to-cycle combustion variations, partial burns and misfires), operating lean or EGR-diluted over a wide speed and load range, and controlling engine-out emissions of hydrocarbons (HCs) at light loads and nitrogen oxides ($NO_X$) at heavy load.

- A comprehensive understanding of intake airflows, fuel sprays, combustion and emissions formation, as well as their interaction with chamber/piston geometry and fuel injection strategies over a wide operating range is needed to develop optimal combustion system designs. The knowledge base must be embodied in robust modeling tools.
    - Understanding and robust modeling tools for rapidly screening proposed designs based on sound metrics are lacking. The number of proposed combustion system designs (e.g., port configurations, air-motions, fuel-spray characteristics, mixing characteristics, ignition and combustion characteristics) for enabling gasoline engines to operate lean is large, making the field fertile for research and development.
    - A significant barrier is an incomplete understanding of the dynamics of fuel- air mixture preparation that result in stochastic combustion problems (partial burns, misfire, and cycle-to-cycle variations). Consistently creating optimal combustible mixtures near the spark plug and away from walls in an overall lean environment is a challenge. Generating appropriate turbulence for enhancement of flame speed is a further complexity. Research to provide a comprehensive understanding of intake airflows and fuel sprays over a wide operating range is best undertaken with significant support from optical diagnostics and advanced high-fidelity modeling tools.
- New ignition systems should be systematically investigated.
    - In addition to proper fuel-air mixture preparation and control at the sparkplug, more robust ignition systems for lean and EGR, as well as boosted conditions that reduce combustion variability are needed. Several new ignition systems have been proposed (high-energy inductive systems, plasma, corona, laser, etc.) and should be investigated.

- Expand efforts to broaden the lean and EGR-diluted operating range.
  - At high loads and speeds, knock is a limiting condition that needs to be addressed through combustion chamber design, ignition strategies, and fuel composition tailoring. At low loads, combustion variability, misfire and HC emissions are primary obstacles that can be addressed via mixing control and robust ignition systems.
- Understand and improve dilute combustion strategies during cold start and cold operation to reduce emissions.
  - It is generally more difficult to tap into the high efficiency potential of dilute combustion during cold operation. Combustion efficiency suffers and emissions increase when lean or EGR-diluted engines are operated under cold conditions.
- Improve $NO_x$ emission control at medium and heavy load operation, for boosted as well as non-boosted engines.
  - Cooled EGR for reducing in-cylinder $NO_x$ has potential but its integration with the stratified combustion system is not well developed.
  - Optimal exhaust temperature and conditions for optimal integration with aftertreatment need to be explored.
- An advanced control system to manage transient operation needs to be developed. The control system should be capable of handling intake boost, on-board diagnostics (OBD), and aftertreatment management.
  - Dilute combustion gasoline engines will have significant variation in operating conditions over their speed-load range. Requirements for control will be expanded when pressure boost is added. Sensors such as misfire detectors may need to be incorporated into predictive model-based control.
- For longer term, higher efficiency goals, developing VVT and VCR strategies for dilute combustion gasoline engines could provide further benefits.
  - Direct injection spark ignition (DISI) operation with VVT and VCR and the detailed impacts on combustion and emissions are relatively unknown.
- DISI engine combustion modes and regimes enabled with the use of multiple pulsing injection techniques that deliver higher thermodynamic efficiency should be investigated.
  - The use of multiple pulsing and multiple fuels in the same combustion cycle is a new field that is currently not well understood.

*Lean Gasoline Combustion Aftertreatment Technology*: The efficiency, durability, sulfur tolerance and cost-effectiveness of the catalyst-based aftertreatment systems for lean-burn DISI have not been proven to Tier 3 Bin 30 emission levels. In addition, PM emissions from lean DISI engines in urban drive cycles can be higher than from PFI engines with three-way catalysts (TWCs), or from diesels equipped with DPFs, necessitating PM control. For the stoichiometric variant of dilute gasoline combustion (S-GDI), emission control challenges are fewer due to the mature three- way catalyst technology that is highly effective at stoichiometric exhaust conditions. Thus, the aftertreatment challenges of focus here, including research needs for TWC technology, are specific to the lean-burn variant of dilute gasoline combustion (L- GDI). Of course, some research for lean emission control is relevant to stoichiometric applications. The research and development challenges for emission control technologies of interest for L-GDI combustion (as listed in Table 5) are presented here.

*Lean NOx Catalysts:*

*Selective Catalytic Reduction (SCR):*

- General R&D challenges for SCR are described in the “LTC Aftertreatment Technology” section above. Specific additional R&D challenges for L-GDI combustion are presented here.
- Optimize control of $NO_x$ and temperature for lean-burn gasoline combustion
  - Spark-ignited lean-burn gasoline engine combustion results in higher NOx emission concentrations as compared with LTC and diesel combustion. Optimizing SCR performance for the higher engine out $NO_x$ levels will be necessary to minimize fuel penalty and catalyst volume. The range of exhaust flows and temperatures in gasoline-based engines are also challenges.
- Determine the potential of hydrocarbon- selective catalytic reduction (HC-SCR) and how fuel ethanol content affects performance (also see discussion for diesel aftertreatment)
  - Effects of gasoline as a reductant and various levels of ethanol in gasoline are required for optimizing the performance of HC-SCR. The ethanol content of gasoline may provide unique opportunities for optimizing HC-SCR.
- Stoichiometric operation effects
  - During stoichiometric operation, the state of the catalyst, such as $NH_3$ storage on SCR catalysts or oxidation state of catalyst active sites, may be affected. Such changes may have a dramatic effect on $NO_x$ reduction when lean operation occurs; thus, studies of these issues are needed.
- Optimize NO:$NO_2$ control (See discussion for LTC aftertreatment also.)
  - Lean-burn gasoline-engine exhaust temperatures are higher than diesel exhaust, where most lean aftertreatment has been developed. Modern TWC uses Pd, which is far less active than Pt for producing $NO_2$; therefore, SCR catalysts insensitive to NO:$NO_2$ ratio will be ideal. Higher $NO_2$ in the feed often leads to higher $N_2O$ emissions. Selectivity to $N_2$ is needed.
- Minimize $NH_3$ oxidation for passive SCR approaches
  - Passive SCR is one approach of interest for lean NOx control for lean gasoline applications. In passive SCR aftertreatment, $NH_3$ is produced on-board via rich engine operation and conversion of engine out NOx to $NH_3$ over the three-way catalyst. Since on-board $NH_3$ production entails a fuel penalty, SCR formulations with low $NH_3$ oxidation during lean operation over temperatures corresponding with lean gasoline engine exhaust are of interest.

- *Lean $NO_x$ Trap (LNT):*

- General R&D challenges for LNTs are described in the “LTC Aftertreatment Technology” section above. Specific additional R&D challenges for L-GDI combustion are presented here.
- Improve durable NOx storage capacity with low fuel penalty
  - The applicability of LNTs for the lean-burn gasoline engine application is not well established. The higher $NO_x$ emissions from lean-burn gasoline engines (relative to

    diesel engines) will challenge LNT technology. However, relative to diesel combustion, higher exhaust temperatures and reduced emission control during cold start (assuming stoichiometric control) will be beneficial for LNT. Increases in NOx storage capacity at appropriate L-GDI exhaust temperatures are needed to minimize fuel penalty from LNT regeneration.

  - New catalyst materials and regeneration strategies may be needed to maintain high efficiency and low fuel penalty over a wide exhaust temperature range typical of gasoline-based engines.

- Increase durability at high exhaust temperatures
  - Most likely, lean gasoline engines will also operate at stoichiometric and rich conditions for portions of the engine load and speed operating map. Consequently, the LNT catalyst will be exposed to high temperatures (significantly higher than diesel exhaust temperatures where a large portion of LNT R&D has been performed). Thus, research into hydrothermal durability of LNTs at those higher temperatures is needed, particularly under stoichiometric conditions.
- Fuel sulfur effects and mitigation
  - Even with reductions in gasoline sulfur content mandated by Tier 3 regulations, sulfur remains a catalyst poison of concern. Sulfur is a well- known barrier to LNT technology. Impacts from the sulfur levels must be determined, and potential mitigation strategies need to be analyzed.
  - Improving LNT sulfur tolerance and reducing fuel usage for sulfur regeneration (“desulfation”) strategies should also be pursued.

### *Three-Way Catalyst (TWC):*

- Improve oxidation of CO and HCs during lean operation
  - TWC technology has traditionally been developed for stoichiometric exhaust conditions with some R&D devoted to rich operation utilized during transient operation and for catalyst thermal protection. TWCs for lean gasoline applications must maintain similar performance during stoichiometric and rich conditions, but during lean operation, control of CO and HCs is needed. Thus, optimization of TWC CO and HC oxidation under oxygen-containing exhaust is needed.
- Generate $NH_3$ during rich engine operation for the passive SCR approach
  - In lean NOx control approaches such as “passive SCR”, TWCs are used to produce $NH_3$ on-board during rich operation of the engine. The efficiency of $NH_3$ production is critical to system-level fuel efficiency as the goal is to minimize rich operation to achieve the highest fuel economy gain from lean operation.
  - The impacts of hydrothermal aging, S exposure, and other degradation mechanisms on TWC $NH_3$ production need to be understood and mitigated.
  - Materials and methods to maintain high selectivity to $N_2$ at low temperature are needed.

### *HC Traps:*

- General R&D challenges for HC Traps are described in the “LTC Aftertreatment Technology” section above. Specific additional R&D challenges for L-GDI combustion are presented here. As noted in Table 5, the need for HC Traps for dilute gasoline combustion is likely application specific. Therefore, a primary benefit to the R&D is to aid in the decisions on HC Trap commercial viability under application-specific cases. Note that in some cases, if HC emissions increase from lean NOx control methods, HC Trap HC emission reductions during the cold start of regulatory drive cycles may make up for lean HC emission increases to enable overall vehicle compliance and, thereby, lean gasoline vehicle commercialization.

- Customize storage and release temperatures for gasoline engine exhaust conditions
  - Since the temperature range of gasoline engine exhaust is very different from LTC and diesel engine exhaust, HC Traps must be designed for appropriate HC storage and release at temperatures suitable for the gasoline engine temperature ranges and corresponding downstream catalysts that would oxidize the HCs.
- Customize HC Traps for HC species in gasoline exhaust
  - Similar to design of HC Traps for gasoline exhaust temperature ranges, HC Traps must be designed for effective control of specific HC species that are present in gasoline engine exhaust. Note that ethanol is a significant component of gasoline fuel for both real-world driving and certification drive cycle testing.

### *Passive NOx Adsorbers (PNAs):*

- General R&D challenges for PNAs are described in the "LTC Aftertreatment Technology" section above. Specific additional R&D challenges for L-GDI combustion are presented here. As noted in Table 5, the need for PNAs for dilute gasoline combustion is likely application specific. Therefore, a primary benefit to the R&D is to aid in the decisions on PNA commercial viability under application-specific cases. Note that, in some cases, PNA NOx emission reductions during the cold start of regulatory drive cycles may make up for imperfect lean NOx emission control to enable overall vehicle compliance and, thereby, lean gasoline vehicle commercialization.
- Customize storage and release temperatures for gasoline engine exhaust conditions
  - Similar to needs for HC Traps for lean gasoline applications, since the temperature range of gasoline engine exhaust is very different from LTC and diesel engine exhaust, PNAs must be designed for appropriate NOx storage and release at temperatures suitable for the gasoline engine temperature ranges and corresponding downstream catalysts that would reduce the NOx.
  - Engine out NOx emissions are generally higher for L-GDI engines in comparison to LTC and diesel engines; thus, the feasibility of PNAs for L- GDI may depend on increasing PNA NOx storage capacity. PNA formulations with higher NOx storage capacity are needed.

### *Particulate Filters:*

- General R&D challenges for particulate filters are described in the "LTC Aftertreatment Technology" section above. Specific additional R&D challenges for L-GDI combustion are presented here.
- Characterize and improve understanding of particulate emission from L-GDI combustion
  - Particulate matter (PM) emission from dilute combustion gasoline engines is not fully understood. These particulates are generally smaller in diameter and are emitted at higher levels than those produced by diesel engines. The morphology and chemical composition of the particulates is also affected by combustion.

  - Worldwide, regulations for particulate matter are both mass- and number-based. Therefore, both the engine-out and filter-out particulate mass and number need to be characterized. In addition, the filtration efficiency on both a mass- and number-basis needs to be understood.

- Determine effect of ethanol and fuel chemistry on particulate formation

Increasing levels of ethanol in gasoline have been shown to reduce in- cylinder formation of PM for L-GDI combustion, but the gasoline blend octane level also impacts PM formation. Understanding the effects of ethanol and fuel chemistry is needed for certification and real world fuels.

- Develop durable filter substrates for smaller diameter particles with low regeneration fuel economy penalty
  - Feasibility for meeting U.S. mass-based regulations is unconfirmed, while implications for Euro particle number regulations needs to be understood.
  - PM aftertreatment causes reduced engine efficiency through increased backpressure and fuel economy penalties associated with regeneration. Thus, low backpressure filters are needed.
  - PM aftertreatment effectiveness can be sensitive to fuel contaminants (*e.g.*, ash); extended durability and backpressure implications need to be established.
  - R&D is needed to address the effects of catalyst coatings on particulate filter filtration efficiency and backpressure.

### *Multifunction Devices/Systems:*

- General R&D challenges for multifunction devices and systems are described in the "LTC Aftertreatment Technology" section above. Specific additional R&D challenges for L-GDI combustion are presented here.
- Reduce cost, size, and complexity of emission control system with multifunction catalysts that combine multiple components onto one substrate
  - Example combined multifunction components of interest for L-GDI applications include (but are not limited to): combining TWC and particulate filter functions onto one (filter) substrate, combining lean NOx control and particulate filter functions onto one (filter) substrate, combining TWC and LNT functions, combining LNT and SCR catalysts for greater overall lean NOx control, and utilizing TWC $NH_3$ formation for on-board $NH_3$ reductant supply to downstream SCR catalysts (passive SCR).
- Optimize control of engine and emission control system for transient performance
  - Mixed-mode operation is likely for lean gasoline engines where portions of the operating load-speed map require stoichiometric operation. Thus, studies related to optimizing the engine and emission control system under mixed-mode operation are needed.
- Active thermal management of the exhaust aftertreatment system to maximize lean-$NO_x$ conversion, HC oxidation, and possibly particulate filter regeneration with minimal fuel economy penalty is required.
  - Thermal management of the overall exhaust aftertreatment system is a challenge that will become more complex if particulate filter regeneration becomes necessary.

  - An overall greenhouse-gas emission assessment will be needed to account for any system interactions.

### *Fuel Technology*:

Combustion and emission control management strategies to enable efficient and clean operation over the range of gasoline to E85 under dilute-burn conditions must be developed. E85's specific fuel properties (e.g., higher octane number, higher latent heat of vaporization, and greater lean-limit and flame speed) should be exploited for maximum fuel efficiency with E85.

  - The knowledge base must be extended to include ethanol/gasoline blend effects to design effectively optimal engines for E85 use. Cold start is an increased concern with E85.

- Exploit ethanol's exceptional NOx reductant properties for lean NOx control.
  - Further understanding of ethanol's interaction with NOx reduction catalysts is required.
- The aging and deactivation processes for lean-NOx aftertreatment control technologies for lean-burn gasoline are not fully established.
  - The impact of sulfur at Tier 3 mandated levels needs to be understood.
- Establish the compatibility of aftertreatment systems with ethanol.
  - Alcohols are excellent catalyst reductants and have been effectively used to reduce NOx over hydrocarbon-SCR catalysts in lean engine exhaust.
  - Ethanol may reduce PM formation in gasoline DISI engines (see "Particulate Filtration" above)
- Barriers for use of natural gas are infrastructure and on-board storage. With more natural gas fueling stations, interest from customers and demand for this technology may increase. Current light-duty natural gas vehicles are mainly intended for commercial applications with dedicated fuel stations. Future heavy-duty applications for Class 8 vehicles will require new fueling stations along the main truck routes. Lack of infrastructure forces manufacturers to offer bi-fuel vehicles and prevents engine optimization (such as higher compression ratio) for natural gas. Natural gas has a lower energy storage density than current liquid fuels and causes either compromised vehicle packaging (fuel tank decreases space in the vehicle) or reduced vehicle range on a fuel fill. Increased fuel storage density is necessary. In addition, it is widely accepted that the state-of-art TWC technology is not capable of removing $CH_4$ at temperatures below 400°C under normal conditions.

**Clean Diesel Combustion** Clean, high-efficiency diesels compliant with current emissions regulations have been introduced into the market. However, cost remains an overall challenge for the widespread adoption of these high-efficiency engines. Moreover, further improvement in fuel efficiency is required to achieve the targets outlined in the previous section. The higher cost of diesels relative to gasoline PFI technology is primarily attributable to the cost of air handling, high-pressure fuel injection, higher-pressure engine operation, and emission control equipment. Reducing costs and achieving the fuel efficiency targets will require overcoming barriers in combustion system technology (e.g., air handling, fuel injection, combustion strategy) and emission control technology. Overcoming the barriers will help maximize fuel economy, improve aftertreatment system effectiveness and durability, and reduce overall costs. In addition, understanding the impacts of emerging fuel changes dictated by mandates to blend biodiesel with diesel is critical. Specific technical strategies to address major barriers are:

### Combustion System Technology for Advanced Diesels:

- Improve the fundamental knowledge base for combustion and emissions processes and develop more robust, computationally efficient models for combustion system design for improved efficiency and reduced $CO_2$ emission. The knowledge base and modeling tools are required to design combustion systems for maximum fuel economy and minimum emissions. Areas of weakness include:
    - Inadequate understanding of the fundamentals of the effects of fuel injection, air motion (e.g., swirl, turbulence), thermodynamic state and composition, and combustion chamber geometry on fuel-air mixing, combustion and emission formation processes over the full load range inhibits progress.
    - Poor understanding of fuel spray fundamentals and accurate fuel spray submodels. This includes inadequate understanding of fuel injector parameters (*e.g.*, timing, spray-type, orifice geometry, injection pressure, single pulse *versus* multi-pulse, *etc*.,) on diesel spray, combustion development and spray interaction with walls. Research on spray development, including the development of spray flows inside the injector, and entrainment process and the effects of injection rate (ramp-up and ramp- down) on combustion/emissions/efficiency are required.
    - Lack of quantitative databases on the engine combustion system and the various combustion sub processes for model verification and validation. Use of advanced diagnostics tools will be critical in developing these. New collaborative/leveraged approaches for developing vetted databases such as the Engine Combustion Network are essential.
    - Robust and accurate soot models are lacking, especially that capture the impacts of EGR and boost. Soot formation and oxidation processes under diesel conditions are not well enough understood to develop robust soot models for computational fluid dynamics (CFD).
    - Radiant heat transfer is largely ignored or modeled in very rudimentary ways for diesels, yet it is an important mechanism for heat transfer, with changes in combustion strategies dramatically affecting radiation heat transfer through the amount of soot formed. It is especially important for determining local temperatures that control NO formation.
    - Tailoring of combustion for exhaust aftertreatment devices to allow better control of engine/aftertreatment system performance for both emissions and fuel consumption.
- Develop improved engine-out $NO_x$ control using higher levels of EGR
    - Technology for delivery of cooled high EGR levels needs to be further developed. Back pressure and fouling problems must be overcome.
    - Technology for increased boosting to improve EGR tolerance and mitigate soot formation associated with EGR $NO_x$ control is needed.
    - The effects of high EGR on diesel combustion and emissions ($NO_x$ and soot) are not well enough understood.
    - Fouling of cooler systems with particulate is problematic and needs to be addressed.

- Provide the understanding and air handling equipment required to further downsize diesel engine technology and better enable higher EGR operation.
  - Understanding of diesel combustion under very challenging highly boosted conditions is largely unknown and must be developed.
  - Significant challenges exist with developing low cost durable multi-stage turbochargers.
- Stoichiometric diesel combustion offers a pathway for using a conventional TWC on a diesel for $NO_x$, CO and UHC emission control. Some heavy-duty engine R&D is occurring but further research is required.
  - Combustion system requirements for stoichiometric diesel combustion for light-duty engine are largely unknown.

*Clean Diesel Combustion Aftertreatment Technology*: Clean diesel aftertreatment systems have been commercialized and proven effective for both heavy-duty and light-duty applications. However, the lower Tier 3 Bin 30 emission levels will challenge these systems even further. In addition, the cost and complexity of aftertreatment systems remain primary barriers for clean diesel commercialization in the light-duty market. The research and development challenges for emission control technologies of interest for clean diesel combustion (as listed in Table 5) are presented here.

### *Lean NOx Catalysts:*

#### *Selective Catalytic Reduction (SCR):*

- General R&D challenges for SCR are described in the "LTC Aftertreatment Technology" section above. Specific additional R&D challenges for diesel combustion are presented here.
- Develop SCR approaches directly utilizing $NH_3$ stored on solid state materials
  - Urea-SCR requires extra cost for urea storage and injection systems. Utilizing $NH_3$ directly as the $NO_x$ reductant could reduce costs associated with urea handling, eliminate urea deposit formation, and improve low temperature $NO_x$ reduction performance. Some companies are marketing solid-state $NH_3$ storage devices to enable $NH_3$-SCR, but further research is needed to implement solid-state $NH_3$ storage for the highly transient diesel engine application. Understanding the temperature dependence of $NH_3$ release rates will be critical to this approach. Light-off temperatures of SCR catalysts need to be lowered from state-of-the art Cu-based SCR catalyst at 200°C to 150°C or lower to take advantage of non-urea based ammonia reductants. $N_2$ selectivity of any new materials should be measured, and $NO_2$ dependency should be minimized as discussed in previous sections.
- Improve $N_2$ selectivity (minimize $N_2O$ formation)
  - The low temperatures and significant engine out NOx emissions from diesel engines results in potential for $N_2O$ formation over catalysts in the

emission control system. Since $N_2O$ is a greenhouse gas that contributes to regulated greenhouse gas emissions, formation of $N_2O$ must be mitigated.

- Further develop hydrocarbon SCR approaches
  - Hydrocarbon-SCR (HC-SCR also known as "Lean $NO_x$ Catalysis") has been examined as an alternative to urea- and $NH_3$-SCR. While previous attempts demonstrated narrow temperature ranges and comparatively low $NO_x$ reduction efficiency and $N_2$ selectivity, recent research has shown promise by combining HC-SCR and $NH_3$-SCR catalysts where $NH_3$ is produced by the upstream HC-SCR catalyst. The "dual SCR" approach is further advanced with the assistance of $H_2$ that increases overall $NO_x$ reduction performance. Greenhouse gas production, especially $N_2O$, should be carefully monitored as early HC-SCR technology was often 90% selective to $N_2O$

### *Lean $NO_X$ Trap (LNT):*

- General R&D challenges for LNTs are described in the "LTC Aftertreatment Technology" section above. Specific additional R&D challenges for diesel combustion are presented here.
- Reduce the Platinum Group Metal (PGM) content to reduce commercial risk due to PGM market volatility
  - LNTs contain platinum group metals (PGMs) which substantially contribute to the cost of the LNT approach. In addition to the magnitude of cost, large fluctuations in PGM market pricing have made technology selection processes difficult for companies since development timeframes span years. Thus, a major barrier to address for LNTs is reducing PGM content. Novel formulations for LNT PGM reduction need to be investigated (such as Perovskite-based LNTs).
- Expand the operation temperature window
  - Another formulation dependent area of LNT to address is the temperature window for $NO_x$ reduction. Expansion (particularly to lower temperatures) would reduce both overall LNT size requirements and cost.
  - Lowering the temperature required for desulfation will reduce the fuel penalty associated with these events. New materials will focus on achieving this capability
- Improve $N_2$ selectivity (minimize $N_2O$ formation)
  - The low temperatures and significant engine out NOx emissions from diesel engines results in potential for $N_2O$ formation over catalysts in the emission control system. Since $N_2O$ is a greenhouse gas that contributes to regulated greenhouse gas emissions, formation of $N_2O$ must be mitigated.

### *CO/HC Oxidation Catalysts:*

- General R&D challenges for CO/HC oxidation catalysts are described in the "LTC Aftertreatment Technology" section above. Specific additional R&D challenges for diesel combustion are presented here.
- Lower HC light-off temperature with reduced PGM
  - Tier 3 emission standards require nearly zero HC emissions while efforts are underway to reduce the use of high cost precious metals such as Pt. Pd is a good substitute for Pt while it also stabilizes Pt dispersions. Materials/strategies to improve

low temperature performance will necessitate further investigations.

- Monitor greenhouse gas emissions from new DOC formulations
  - Pt is well known to produce large amounts of $N_2O$ at lower exhaust gas temperatures, especially at higher HC/$NO_x$ ratios experienced during rapid warm-up of the catalyst system during cold start and initiation of filter regeneration. Current DOCs are also relatively ineffective at burning methane. Formulations that minimize $N_2O$ and $CH_4$ emissions are needed.

### *HC Traps:*

- General R&D challenges for HC Traps are described in the "LTC Aftertreatment Technology" section above. Specific additional R&D challenges for diesel combustion are presented here. As noted in Table 5 the need for HC Traps for clean diesel combustion is likely application specific. Therefore, a primary benefit to the R&D is to aid in the decisions on HC Trap commercial viability under application-specific cases.
- Utilize HC Trap technologies to improve low temperature and cold start emission control performance
  - Diesel engines have relatively low temperature exhaust, and the cold start portion of the certification drive cycle is significant in length. HC Traps can be utilized to trap HC emissions during low temperature operation for subsequent release and control at higher temperatures where downstream control catalysts can effectively oxidize the HCs.

### *Passive NOx Adsorbers (PNAs):*

- General R&D challenges for PNAs are described in the "LTC Aftertreatment Technology" section above. Specific additional R&D challenges for diesel combustion are presented here.
- Utilize PNAs to improve low temperature and cold start NOx control
  - Diesel engines have relatively low temperature exhaust, and the cold start portion of the certification drive cycle is significant in length. PNAs can be utilized to trap NOx during low temperature operation for subsequent release and control at higher temperatures where downstream control catalysts can effectively reduce the NOx.

### *Particulate Filters:*

- General R&D challenges for particulate filters are described in the "LTC Aftertreatment Technology" section above. Specific additional R&D challenges for diesel combustion are presented here.
- Optimize substrate material for lower weight and improved thermal durability
  - Filter substrates made of cordierite and SiC materials have demonstrated reliable performance in field use, but newer materials may offer improvements in thermal durability, PM trapping efficiency, and weight reduction. Implementation of such materials will be investigated.
  - Worldwide, regulations for particulate are both mass- and number-based. Thus, for new substrates, both the engine-out and filter-out particulate mass and number needs to be characterized, and the filtration efficiency on both a mass- and number-basis needs to be understood.
- Reduce fuel efficiency penalty

- A significant barrier is the fuel penalty required for regeneration or soot oxidation of the diesel particulate filter, which results from heating the filter to elevated temperatures (>550ºC). Control and filter-based strategies for fuel penalty reduction need to be improved.

- Develop and improve on-board diagnostics to reduce the fuel penalty associated with regeneration and enable cost-effective emission compliance
  - Currently, back pressure sensors are employed in conjunction with control maps to identify when regeneration (soot oxidation) is needed, but more advanced sensors may enable reducing the regeneration frequency and/or shortening the length of the process (both of which will reduce fuel penalty). These sensors may also be required by regulations for on-board diagnostics.

### *Multifunction Devices/Systems:*

- General R&D challenges for multifunction devices and systems are described in the "LTC Aftertreatment Technology" section above. Specific additional R&D challenges for diesel combustion are presented here.
- Reduce cost, size, and complexity of emission control system with multifunction catalysts that combine multiple components onto one substrate
  - Example combined multifunction components of interest for diesel applications include (but are not limited to): combining HC Trap and oxidation catalysts, combining PNA and NOx control components, combining LNT and SCR NOx control catalysts, and combining SCR on particulate filter.

### *Fuel Technology:*

- Determine the effects of biodiesel on the combustion system and aftertreatment operation and performance.
  - Fundamental understanding of the impact of biodiesels on combustion and emission processes and systems and emission control technology is lacking.

**Low-Temperature Combustion:** Critical barriers remain that are inhibiting the commercial viability and wide spread implementation of LTC. Barriers include the need for: (a) improved understanding and further development of LTC technology for operation with either gasoline or diesel fuel, including control methodologies and technologies, especially for mixed-mode operation; and (b) aftertreatment technologies compatible with LTC, including control methodologies and technologies that will integrate with overall engine operation, and (c) understanding of the impact of likely future fuels on LTC and whether LTC can be more fully enabled by fuel specifications different from gasoline and diesel fuel. Within these barrier topics are barriers that overlap with those for diesel technology, including the need for improvements in air handling and fuel injection systems.

Specific technical strategies for overcoming the technical barriers and more detailed discussions of the barriers include:

### *Combustion Technology:*

- Improve the fundamental knowledge base for gasoline- and diesel-fueled LTC processes. An expanded knowledge base is required to tailor LTC processes for maximum fuel economy and emission compliance.

  - Inadequate understanding of LTC fundamentals for a range of conditions continues to inhibit development of LTC. The expanded knowledge base should include the effects of chamber geometry, air motion, fuel injection, and chemical kinetic processes on fuel-air mixing, auto-ignition and combustion, and emission formation processes. Effects of advanced fuel injection strategies (e.g., multiple fuel injections, higher injection pressure, smaller orifices, orifice geometry and patterns, etc.) should be included. Both experimental and advanced high-fidelity modeling tools are required to develop the knowledge base.

- Use the knowledge base to support the development of advanced engine simulation tools required to speed the development and optimization of LTC.
  - Inadequate simulation tools for accurately and robustly simulating advanced LTC processes are a barrier to engine development.

- Determine the factors limiting the upper load and/or speed ranges over which various types of LTC work and develop methods for extending the limits.
  - Initial research has shown that the highest load operation for LTC operation is typically limited to moderate loads under naturally aspirated conditions due to excessive combustion rates at higher loads. The high combustion rates induce unacceptable noise, and eventually, engine damage. Recent research is revealing pathways for extending the load range capability by staging auto ignition and heat release. Examples include intake pressure boosting coupled with EGR, tailored thermal stratification, tailored fuel-air stratification for two-stage ignition fuels (e.g., diesel fuel), and dual-fuel injection using high and low reactivity fuels.

- Develop methods for controlling combustion inefficiencies and the associated hydrocarbon (HC) and carbon monoxide (CO) emissions at low loads, near idle, especially for operation in an HCCI mode.
  - Highly premixed HCCI-type combustion near idle conditions results in very low temperatures and as a result, combustion inefficiency with high CO and HC emissions. Research has shown that use of controlled charge stratification, negative-valve-overlap fueling, and spark-assist are approaches that can significantly improve combustion efficiency at lower loads, but further development is needed.

- Improve fundamental understanding of stochastic and deterministic phenomena that may limit LTC operation.
  - Many LTC strategies are very sensitive to boundary conditions and operate near the edge of stability. The ability to operate near this edge for maximum efficiency and lowest emissions is strongly influenced by stochastic phenomena associated with mixing and other physical processes as well as deterministic impacts from prior engine cycles.

- Improve cold starting technologies for LTC.
  - During cold start with LTC, the fuel/air charge receives no preheating from warm intake manifolds and ports, resulting in low compressed-gas temperatures and misfiring. Solutions to ignition challenges could include promoting compression ignition by increasing the compression ratio with a VVT or VCR system during cold start or use of spark-ignition or glow plug ignition until the engine warms up.

- Develop full time LTC operation.
  - Using LTC combustion over the entire speed, load range could eliminate the need for

exhaust gas PM and $NO_x$ aftertreatment systems, providing a lower cost option for high efficiency engines. Some of technologies for load range extension already described suggest that full-load LTC operation with gasoline or gasoline/diesel fuel combinations is possible in the laboratory. Cold start solutions, transient operation and all the other facets of LTC already described are also critical. Additionally, a new fuel tailored for optimal LTC operation offers longer-range potential.

- Characterize wall heat transfer during LTC operation, especially during transients such as load/speed changes, for effectively designing engine performance and developing control strategies.
  - The heat transfer characteristics for LTC are very different than for SI and DI diesel combustion. They are lower, and therefore, potentially afford an important efficiency advantage for LTC. However, because of the sensitivity of the LTC processes to temperature, there is a strong need for improved understanding of heat transfer, especially during transients. Because of the transients and the thermal inertia of cylinder walls, wall temperatures and heat transfer during transients will not match those during steady state operation
- Develop technologies for rapid control of ignition timing and engine operation, especially during engine transients.
  - Methods for rapidly controlling LTC combustion timing are not well developed. Ignition timing is heavily dependent on chemical-kinetic reaction rates, which are controlled by temperature and mixture composition histories during the ignition period. Examples of potential technologies for rapidly controlling combustion timing and engine operation include VVT to control hot residuals and effective compression ratio, VCR, hot EGR, multi-pulse fuel injection, fuel injection during negative-valve-overlap for HCCI, and as recently shown, independent dual fuel injection using low and high reactivity fuels (*e.g.*, gasoline and diesel or gasoline plus gasoline with ignition enhancer). Spark-assisted-ignition is another path to improved ignition timing control, as well as wider operating ranges for LTC. Combustion and emissions sensor technology for feedback control will also be essential.
- Mixed-mode operation can utilize the higher efficiency and reduced emission potential of LTC at light to moderate loads to both achieve fuel efficiency improvement and reduce the aftertreatment system requirements relative to conventional engine technologies, and thereby cost. However, there are many challenges to mixed-mode operation. Development of combustion systems that are effective across conventional and LTC modes of operation and control strategies/technologies that allow the engine to transition and operate smoothly in either LTC and conventional diesel or SI combustion modes are needed.
  - The knowledge-base and modeling capabilities for both conventional and LTC combustion modes are inadequate to develop and design combustion systems that operate effectively on different modes of combustion over the entire speed-load range. Research on all aspects of optimal mixed-mode combustion systems is required. It is critical that use of conventional diesel combustion at high loads in a mixed-mode combustion system produce emissions that are as low or lower than current diesel engines. Development of effective fuel injection and fuel-air mixing strategies (*e.g.*, multiple injections) will be especially critical to achieving optimal operation over entire speed-load range.
  - Strategies and technologies for controlling mixed-mode operation with smooth transitions need continued improvement. These might include strategies and technologies already discussed for LTC control like use of VVT, VCR, multi-pulse fuel

injection, or spark-assisted combustion. These technologies will be essential for improving and optimizing efficiency and emissions control without compromising the power density under conventional engine combustion modes at high loads.

*LTC Aftertreatment Technology*: Although $NO_x$ and particulate emissions are dramatically reduced for LTC, $NO_x$ and perhaps particulate emissions may still need to be controlled to achieve regulation compliance. The burden on $NO_x$ aftertreatment in particular is reduced, but operating conditions such as cold start and high-load operation where advanced combustion becomes difficult to control will force additional catalytic control. The consensus is that conventional aftertreatment systems are likely not suitable for lower exhaust temperatures (i.e. lower than 150°C). Furthermore, CO and hydrocarbon emissions can be higher during advanced combustion modes while exhaust temperature will likely be lower. Thus, CO and HC emission control becomes more of a challenge, and there is an increased risk for higher greenhouse gas emissions (i.e. $N_2O$, $CH_4$). Optimal performance of the engine could also involve utilizing both advanced and conventional combustion modes in mixed-mode operation. While advanced LTC combustion modes provide unique opportunities for reducing engine out $NO_x$ and PM emissions and improved fuel economy, emission control and system integration issues continue to require investigation so that synergistic LTC and mixed-mode combustion and effective aftertreatment can be developed. The research and development challenges for emission control technologies of interest for LTC combustion (as listed in Table 5) are presented here.

### *Lean NOx Catalysts:*

- *Selective Catalytic Reduction (SCR):*

- Improve low temperature $NO_x$ reduction
  - Lower $NO_x$ emissions resulting from advanced LTC combustion will still require $NO_x$ reduction to meet future regulations. Improving SCR performance for low temperature exhaust will be needed. A high selectivity to $N_2$ over $N_2O$ is required.
- Mitigate hydrocarbon fouling
  - Hydrocarbon emissions can increase during advanced combustion, and the chemistry of the hydrocarbon emissions can differ significantly. Improved Cu-zeolite SCR catalysts have minimized the impact of hydrocarbon fouling, but further research will be required to understand and mitigate the potential impact of higher HC concentrations and HC composition resulting from advanced combustion.
- Optimize $NO:NO_2$ control
  - Varying the $NO:NO_2$ ratio under LTC conditions will affect SCR performance. Therefore, formulations insensitive to the $NO:NO_2$ ratio are favored. High $NO_2$ in the SCR catalyst feed often results in increased $N_2O$ emissions and should be avoided.
- Enable low-temperature reductant ($NH_3$) performance
  - Aqueous urea used on current diesel truck systems requires at least 200°C exhaust to decompose urea into ammonia ($NH_3$) for reducing $NO_x$ on the catalyst. Thus, enabling lower temperature NOx control will require new methods of introducing and utilizing $NH_3$.
- Minimize $N_2O$ formation

    - $N_2O$ formation from SCR can increase in the lower operating temperatures associated with SCR; thus, SCR formulations to minimize $N_2O$ formation are of interest.

- *Lean $NO_x$ Trap (LNT):*
  - Reduce precious metal loading and volume
    - Lower $NO_x$ emissions from advanced combustion strategies offer an excellent opportunity for reducing the size of LNT catalysts since the $NO_x$ storage capacity of the LNT is proportional to catalyst size. Reduction in Platinum Group Metal (PGM) content and/or reduction in catalyst volume will be favored for advanced aftertreatment system development.
  - Improve temperature-dependent optimization for transient operation
    - Changes in exhaust temperature during advanced LTC combustion and the related variation in $NO_x$ provide new challenges and opportunities for managing the engine-LNT synergistic operation. These control strategies must be effective for transient operation that will likely involve mixed-mode combustion.
  - Improve sulfur tolerance
    - LNT catalysts are very sensitive to poisoning by S (sulfur) since the active NOx storage component, typically alkali and alkaline earth metals that form nitrates, also forms sulfates that are thermodynamically very stable. Minimizing the negative effects of S on LNT performance is needed.
    - On-board desulfation procedures are commonly used to control S poisoning effects for LNT catalysts. Typically, desulfation occurs at high temperatures in reducing environments since these conditions are required to reduce the sulfate species on the catalyst. Due to lower overall exhaust temperatures, low temperature desulfation catalysts and procedures may need to be developed to minimize fuel penalties and durability impacts from high temperature desulfation events.

### *CO/HC Oxidation Catalysts (OC):*

- Improve low temperature control of CO and hydrocarbon emissions
  - Advanced combustion techniques have been shown to produce higher CO and hydrocarbon emissions that are difficult to control at low temperatures. Improved OC catalyst formulations are required. Of importance, formaldehyde emissions from LTC can be higher and need to be controlled, as well as methane.
  - Lower exhaust gas temperatures coupled with the higher HC/$NO_x$ engine- out ratios may exacerbate $N_2O$ creation due to HC + $NO_x$ reactions on the OC.
- Optimize NO:$NO_2$ control
  - Optimal SCR performance and/or passive soot oxidation depends on balancing the ratio of NO to $NO_2$ species. Varying HC and $NO_x$ emissions and exhaust temperatures with LTC will alter the OC $NO_2$ production and make this a greater challenge. Effective control of NO:$NO_2$ by the OC is favorable and must be understood for LTC conditions.
- Enable exotherm generation for thermal management
  - In exhaust systems, the OC often generates extra heat to manage the performance in

downstream components (i.e. soot oxidation in filter). LTC may result in lower exhaust gas temperatures that will make it difficult to ignite the large amounts of fuel required for efficient filter regeneration.

### *HC Traps:*

- Improve materials for low temperature HC storage, thermal release and reaction at active OC temperatures
  - HC Traps have been demonstrated that trap HCs at low temperatures where OCs cannot effectively oxidize the HCs. Subsequently, the HCs are thermally released at higher temperatures (above OC "light-off") when OCs can effectively oxidize the HCs. Research into materials with suitable temperature for HC trapping and release at appropriate temperatures is needed. In addition, increasing the HC storage capacity is desired.
- Design HC Traps for wide range of HC species
  - Various zeolite materials have been utilized to trap HCs, but the trapping efficiency varies greatly depending on the different HC species in the exhaust stream. Material selection and combinations are needed to enable suitable trapping efficiency over the broad range of HCs in LTC exhaust.
  - The type and quantity of partial reaction products resulting from incomplete oxidation of the incoming engine out HC species requires research to determine how to optimize both the trap and downstream HC control.
- Characterize and understand HC Trap durability
  - The durability of HC Traps must be studied and characterized. Since HC Traps are a new class of catalysts with little on-road experience, research of HC Trap durability and degradation rates is important to understand for the various materials likely to be employed for HC Traps.
  - The hydrothermal stability of HC Trap materials requires additional understanding.
  - The effects of S and other poisons on HC Traps need to be understood, and any negative impacts need to be minimized or mitigated.
  - The potential of fouling and pore occlusion from heavy HCs and particulate matter or coke needs to be researched, understood, and mitigated if occurring.
- Understand state of HC Trap for shutdown/restart and optimize restart/cold start performance
  - For effective adsorption of HCs during cold start and low temperature exhaust conditions, the state of the HC Trap must be prepared for HC adsorption. For example, if shutdown of the engine occurs when the HC Trap is heavily loaded with HCs, the HC Trap will be substantially less effective in adsorbing HCs during the subsequent cold start or warm start. Thus, an understanding of HC Trap state as a function of operating condition history, via models or diagnostics, is needed.
  - Methods for controlling HC Trap state during operation are of interest.
  - The impact of $H_2O$ and other condensable species on HC Trap performance during shutdown and restart needs to be understood and mitigation strategies defined.

### *Passive NOx Adsorbers (PNAs):*

- Improve low temperature NOx storage for thermal release at active lean NOx catalyst temperatures
  - A relatively new technology known as the Passive NOx Adsorber (PNA) traps NOx at low temperatures for subsequent thermally induced release at higher temperatures where the NOx is reduced by a downstream NOx control catalyst (SCR, LNT). Research into materials with suitable temperatures for NOx adsorption and desorption at appropriate temperatures is needed. Control of the temperature at which NOx is desorbed by the PNA is critical since release at temperatures too low for downstream NOx reduction negates the benefit of the PNA technology. Thus, research into the temperature and rate of release of NOx as a function of PNA material composition is needed to optimize NOx release temperatures.
  - In addition, increasing the NOx storage capacity of a PNA may be needed to trap the required NOx influx.
- Minimize effect of CO and HCs on PNA function
  - Due to high CO and HC levels for LTC, the function of PNAs must be impacted minimally by CO and HCs.
- Characterize and understand PNA durability
  - The durability of PNAs must be studied and characterized. Since PNAs are a new class of catalysts with little on-road experience, research of PNA durability and degradation rates is important to understand for the various materials likely to be employed for PNAs.
  - The hydrothermal stability of PNA materials requires additional research efforts.
  - The effects of S and other fuel- and lubricant-borne poisons on PNAs is not fully characterized. Negative impacts need to be minimized or mitigated.
- Understand the state of the PNA for shutdown/restart and optimize restart/cold start performance
  - For effective adsorption of NOx during cold start and low temperature exhaust conditions, the state of the PNA must be prepared for NOx adsorption. Similar to the case for HC Traps (above), an understanding of PNA state as a function of operating condition history, via models or diagnostics, is needed.
  - Methods for controlling PNA state during operation are required.
  - The impact of $H_2O$ and other condensable species on PNA performance during shutdown and restart need to be understood and mitigation strategies defined.

### *Particulate Filters:*

- Characterize particulate from advanced LTC combustion techniques and its impact on particulate filter performance
  - LTC combustion can generate a different level and type of particulate than particulate from conventional diesel combustion. Specifically, particulate from LTC combustion is smaller in size and has higher organic content. Characterizing the particulate from various combustion techniques at different engine operating conditions is critical to optimizing filter-based emission control.

  - Worldwide, regulations for particulate are both mass- and number-based. Thus, both the engine-out and filter-out particulate mass and number need to be characterized, and the filtration efficiency on both a mass- and number-basis must be determined.

- Determine potential of catalytic oxidation for particulate control
  - The high organic content of LTC particulate may facilitate particulate emission control via catalysis as opposed to filtration. Such approaches are of interest for research.

### *Multifunction Devices/Systems:*

- Reduce cost, size, and complexity of emission control system with multifunction catalysts that combine multiple components onto one substrate
  - If multiple catalysts are needed to control LTC emissions, then cost, size, and complexity are risks to commercialization. Combining catalyst functions on a single monolith multifunction catalyst can mitigate the risk. In particular, combining components like HC Traps with oxidation catalysts can potentially achieve high HC conversion efficiency with lower overall cost, but R&D is needed to optimize the combination of technologies.
  - Examples of combined multifunction components of interest for research include (but are not limited to): combining HC Trap and oxidation catalysts, combining SCR and particulate filter functions onto one (filter) substrate, combining NOx trapping and NOx reduction functions (via combining PNAs with SCR or LNT with SCR).
- Determine methods for diagnosing and monitoring emission control functionality in multifunction devices/systems
  - As multiple emission control functions and components are combined onto single devices, the difficulty in assessing the status of the specific control functionality becomes much more challenging. Thus, methods, either model-based or device-based, for assessing the state of various catalytic and other functions of multifunction devices require further research and development.
  - New on-board diagnostic methods to diagnose the “health” of multifunctional devices based on the device functionality/chemistry are required.
- Optimize control of engine and emission control system for transient performance
  - Mixed-mode operation is likely for commercial vehicles that employ advanced LTC combustion techniques, but controlling when the engine operates in conventional or advanced LTC combustion modes becomes more complicated when considering various states of the emission control system. Thus, studies related to optimizing the engine and emission control system under mixed-mode operation are needed.
- Develop robust simulation tools for individual catalyst aftertreatment and particulate filter components/systems
  - While significant progress has been made in developing models of aftertreatment components and systems, more progress is needed in this important area, as engine/aftertreatment manufacturers have become increasingly reliant on simulation for design and development of products.
- Validate models with experimental approaches that further fundamental understanding

    - A highly interactive CLEERS (Crosscut Lean Exhaust Emissions Reduction Simulations) consortium of industry, national labs, and universities is already working effectively to advance simulation capabilities. These activities will be continued and will include experimental validation of models and other experimental tasks that provide the underlying fundamental understanding needed to build detailed catalyst models.

*Fuel Technology*: As refinery feedstock continues to trend away from light-sweet crude and biofuel use and blending in gasoline and diesel fuel grows, opportunities may exist to adjust some fuel properties if they are proven highly advantageous for LTC operation.

- An improved understanding and coupling of fuel formulation with LTC strategy will both enable development of more robust LTC approaches and potentially broader usage of LTC in the market place.
    - Optimal LTC operation over the full speed/load range remains a barrier. Fuel formulation offers one pathway and opportunity to expand LTC. The understanding of fuel property effects on LTC processes must be improved for a range of formulations spanning gasoline to diesel, and current to next- generation bio-fuels, as well as blending of conventional and biofuels. DOE and CRC are sponsoring research on Fuels for Advanced Combustion Engines (FACE) to make available a common set of petroleum-based fuels with controlled parameter variations for LTC research. The use of these fuels across many institutions will serve to accelerate the understanding of fuel formulation effects on LTC and enable expanded advanced combustion regimes of operation. Additional efforts regarding biofuels are needed. For example, the use of ethanol has been shown to reduce exhaust dilution requirements for enabling expanded high load operation.
- Fully explore dual-fuel injection using two fuels (a low-reactivity gasoline-like fuel and a high reactivity diesel-like fuel) for enabling full load/speed range LTC operation.
    - The use of two fuels of differing reactivity to foster controlled heat release through reactivity stratification shows promise for high efficiency clean operation through simulation and single-cylinder/multi-cylinder engine experiments in the laboratory. Understanding of the modes of combustion progress and the fuel reactivity and other requirements are not understood. Transient operation and emission control requirements remain to be evaluated.
- Low-cost, efficient onboard means of tailoring fuel properties may be a desirable path for generating optimal LTC fuel properties or for enabling the duel-fuel, reactivity controlled LTC combustion.
    - However, technologies for onboard reforming have not been developed.

**Parasitic Loss Reduction and Waste Heat Recovery:** Parasitic loss reduction and waste heat recovery are potential technologies to study provided the loss reduction results in improved propulsion efficiency. Reduction in parasitic losses is needed provided the efficiency improvement is achieved at a reasonable cost. New oil formulations are one example of possible research.

- An increasing volume of engines will use turbocharger systems to increase the torque and power from a small engine. This is the downsized engine trend discussed previously. Improvements in the efficiency of the turbine and compressor and surge/choke limits are beneficial and improve the capabilities and boosting of the system.
- Other mechanical exhaust-energy recovery systems including Rankine Cycle systems are

feasible. However, the packaging and cost of this system for a light-duty vehicle are not proven.

- Exhaust waste energy can be recovered electrically with a thermoelectric device. Challenges for these devices are to identify materials with high efficiency in the temperature range of the exhaust. Current material property changes with potential to increase efficiency include a ball-milling process to increase grain boundaries and skutterudites to improve thermal conductivity. Other materials with better efficiency are required. A thermoelectric system also consists of many thermal and electrical junctions. Decreasing the contact resistance between junctions will improve efficiency. Waste heat recovery from the exhaust of a light-duty vehicle is challenging since the urban drive cycle used for fuel-economy evaluation is a relatively low-load, highly transient cycle and exhaust heat availability is limited.

- An alternate waste-heat recovery strategy is to use a thermoelectric device to cool the passenger compartment. This strategy has potential to remove the refrigerant that is a greenhouse gas and eliminate the mechanically driven HVAC compressor.

**Cross-Cutting Technologies/Approaches for Enabling Goals**: High-value cross- cutting technologies and approaches for helping enable the full emission compliant efficiency potential of engine technologies discussed in the prior sections include both hardware (e.g., sensors for monitoring and closed loop feedback, Variable Valve Timing (VVT) and Variable Compression Ratio (VCR)) and thermodynamic analyses to identify promising directions for meeting targets.

- Develop and/or improve $NH_3$, $NO_x$ and PM sensors for closed-loop control of engine/aftertreatment system and for determining aftertreatment breakthrough or poor performance. Closed-loop control will provide the ability to optimize the engine/aftertreatment system for performance and minimize aftertreatment fuel-economy penalties. Urea SCR systems will need an $NH_3$ sensor insensitive to $NO_x$ for optimizing operation.
  - Real-time sensors and measurement tools for exhaust $NO_x$ and PM and for $NH_3$ are lacking. Sensitive, real-time PM measurement and sensor development are especially needed. Moreover, conventional oxygen sensors used for air-fuel ratio monitoring have demonstrated a biased response in the presence of high hydrogen levels during fuel-rich operation, such as LNT regeneration or passive SCR $NH_3$ generation.

Develop combustion sensors that can be used for feedback and control of combustion and for determining the combustion mode. Such capabilities will be needed for fully implementing and controlling advanced combustion approaches, especially mixed-mode engine operation, and integration of engine/aftertreatment systems.

  - Combustion sensor technologies (e.g., pressure measurement) are under development, but improved durability and cost effectiveness are critical.

- VCR technologies for enabling full utilization of LTC combustion strategies and for maximizing engine efficiency.
  - Highly flexible, durable, robust, low-cost technologies are not ready for market implementation.

- Update the baseline energy and exergy distribution and loss data for modern diesel, LTC, lean burn DISI, and hydrogen engines using models and experiments. Understanding these data for various engine technologies is key to determining effective strategies for achieving higher efficiency.

\- Baselines analysis of energy balances and availability (exergy) losses for modern engines are inadequate. Precompetitive data for such analyses, especially for engines in LTC and stratified lean-burn gasoline modes, is very limited.

- Develop and validate systematic strategies for mitigating the quantified losses using the resulting baseline energy and exergy data, and track progress against strategies. Place high priority on part-load efficiency improvements, since this is where more gain in over-the-road fuel economy can be achieved. Specific examples include:
    - Determine the extent that advanced combustion can be exploited to mitigate inherent exergy losses in combustion and heat transfer. The inherent exergy losses in conventional combustion processes are among the largest losses in internal combustion engines.
    - Examine improvements to the base engine thermodynamic operation through greater expansion ratio, recuperation, reduced heat transfer, combustion phasing, downsizing and down speeding. Most strategies for efficiency improvement lack guidance from coupled energy/exergy balance analyses. Heat transfer and the impact on efficiency have been extensively addressed in "low-heat rejection engine" R&D, but it remains a challenge.
    - Develop and validate new effective approaches to utilizing low-temperature energy from exhaust and EGR coolers. Exhaust energy in high-efficiency engines, especially diesel engines with coolers for EGR, is of low quality, making effective heat recovery challenging.
    - Develop and validate novel approaches to reduce parasitic losses associated with accessories, fueling systems, and friction. Friction reduction is a mature technology. It has been the focus of substantial private sector research, making further efficiency gains challenging. Down speeding is one approach. Diesel engine fuel injection has trended to higher injection pressure for emission controls. This carries a notable parasitic loss, especially at part load, but also potential for optimization.

Improvements in boosting and exhaust-energy utilization efficiency should be examined. It is generally accepted that the efficiency of boosting systems affects overall engine efficiency. Small turbochargers have inherent efficiency disadvantage.

**Powertrain Systems Integration for Enabling Goals:** Integration is the process of combining all the elements of the vehicle into a working system that meets customer requirements such as durability, quality, and performance and meets regulatory requirements such as emissions, safety, and efficiency. Complete vehicle systems integration is beyond the scope for the ACEC technical team. Each OEM performs this work during the design, engineering and manufacture of a vehicle.

The ACEC technical team can, however, address a subset of vehicle systems integration; namely, engine, aftertreatment, and fuel systems integration. Effective integration of these systems with a focus on reducing the size/mass of components, increasing robustness of the system over a wide range of inputs, and discovering enablers such as sensors for control and diagnostics can further enable overall fuel economy, emission compliance, performance, and durability requirements. Some examples of ways in which we can improve the potential for integration of these systems into a vehicle follow.

- Develop and validate robust mathematical models for each technology. These models can be combined in a total vehicle model during the OEM integration.
- Use system level modeling for the engine, transmission, vehicle and fuel systems to identify the optimal powertrain, engine map, and fuel characteristics for different vehicle scenario assumptions. This modeling gives direction to the technology development to ensure the result has potential for vehicle applications.

- Implement sensors for diagnostics and controls. Suitable sensors and their control code should be developed as a part of a technology study. Sensors are needed for combustion performance, to detect specific species in the aftertreatment system, and measure the fuel quality.

- Integrate multifunction catalysts into aftertreatment systems that involve multiple catalyst devices (DOC, LNT, SCR, and DPF). If a single catalyst can perform multiple aftertreatment functions, then fewer devices require packaging and integration improves. Reductions in aftertreatment system mass and volume also reduce the time required to achieve operating temperatures during cold start, improving emissions performance.

- Optimize thermal management of aftertreatment. Catalysts in aftertreatment systems require specific temperatures for maximum efficiency. Improvement in the catalyst conversion efficiency at lower temperatures improves potential for vehicle use. In addition, system-level approaches to manage heat flow in the aftertreatment system can potentially improve performance at low exhaust temperatures, while improving catalyst durability by reducing high temperature excursions.

Achievement of Tier 3 standards implies that aftertreatment systems must be capable of handling emissions immediately after engine startup for all varieties of combustion strategies. In addition, alternative fuel economy approaches employing hybrid powertrains, that use intermittent engine operation, will deprive downstream aftertreatment systems of heat. Therefore, in general engine strategies and aftertreatment technologies that reduce the catalyst light- off time and temperature (e.g. 150°C) and increase exhaust energy are important areas of research and development.

# Appendix B: ACEC Fuel Property Recommendations

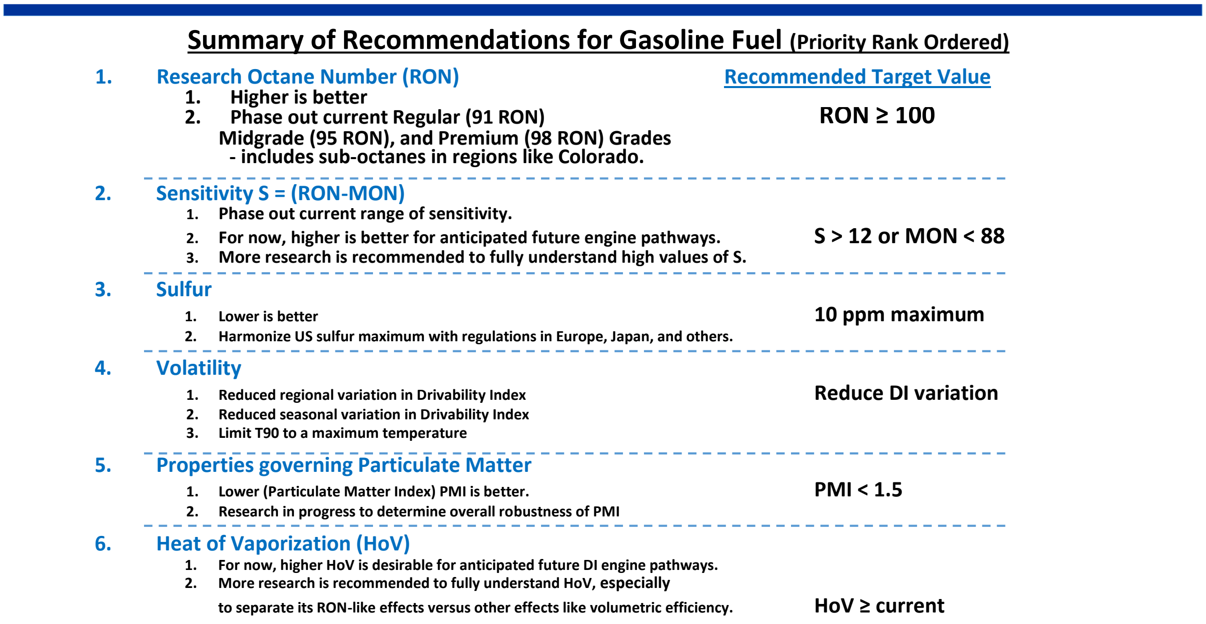
## Introduction

A sub team of the ACEC consisting of several members from FCA, Ford, GM, ANL, ORNL, PNNL, and SNL worked on the fuel property recommendations described in this section. The team conducted an exhaustive review of the published literature on fuel property effects on IC engine efficiency and emissions. In many cases, extensive consultation occurred with experts within each member organization. Only engine combustion and thermodynamic effects were considered, with no regard for fuel sources, refinery, or distribution issues. Further, fuels were only regarded for their properties and not the molecular components that might result in those properties.

For gasoline and diesel fuel, properties were rank ordered based on their relative influence on engine efficiency and emissions, as well as on aftertreatment performance. Based on the published evidence, new fuel property values were recommended relative to typical present-day values. In each case, the direction of change (increase or decrease) and, if applicable, the numerical value or range for the fuel property was recommended.

The team decided on a different process for fuels for low-temperature-combustion (LTC). Because of the relative infancy of this mode of combustion, the number of variants in approach, and the lack of sufficient published literature with conclusive engine data, it was decided to conduct a survey of several principal investigators presently active in this area of research as to their desired fuel properties for specific low-temperature-combustion approaches.

The final recommendations for each fuel (gasoline, diesel, and low-temperature- combustion) are presented below.



**Summary of Recommendations for Gasoline Fuel** (Priority Rank Ordered)

1. **Research Octane Number (RON)** — Recommended Target Value
   1. Higher is better
   2. Phase out current Regular (91 RON) Midgrade (95 RON), and Premium (98 RON) Grades - includes sub-octanes in regions like Colorado.

   RON ≥ 100
2. **Sensitivity S = (RON-MON)**
   1. Phase out current range of sensitivity.
   2. For now, higher is better for anticipated future engine pathways.
   3. More research is recommended to fully understand high values of S.

   S > 12 or MON < 88
3. **Sulfur**
   1. Lower is better
   2. Harmonize US sulfur maximum with regulations in Europe, Japan, and others.

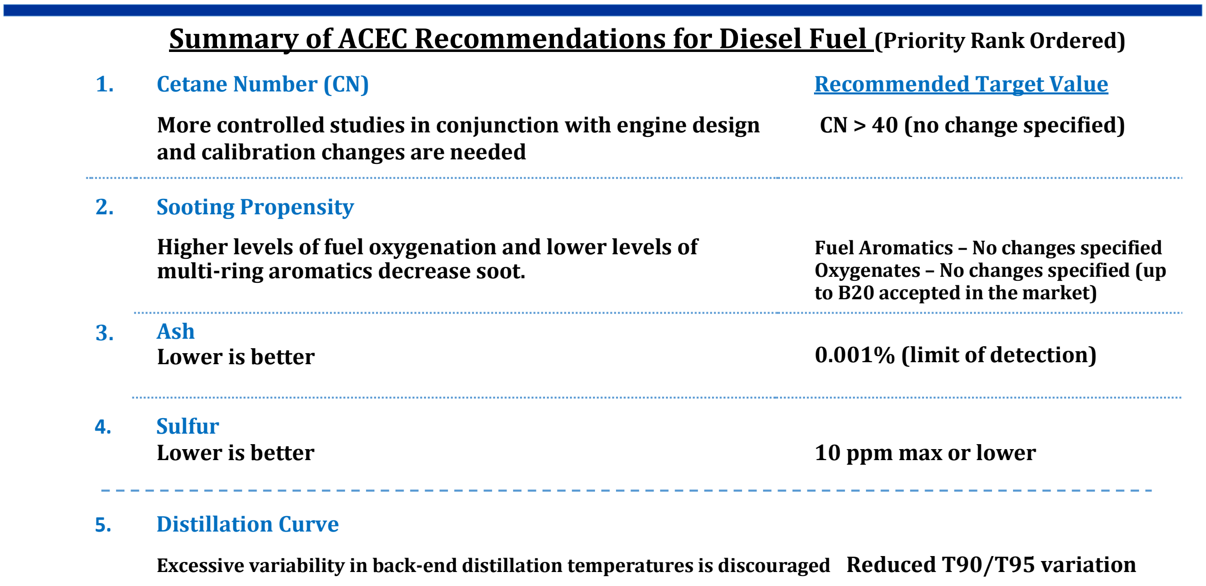
   10 ppm maximum
4. **Volatility**
   1. Reduced regional variation in Drivability Index
   2. Reduced seasonal variation in Drivability Index
   3. Limit T90 to a maximum temperature

   Reduce DI variation
5. **Properties governing Particulate Matter**
   1. Lower (Particulate Matter Index) PMI is better.
   2. Research in progress to determine overall robustness of PMI

   PMI < 1.5
6. **Heat of Vaporization (HoV)**
   1. For now, higher HoV is desirable for anticipated future DI engine pathways.
   2. More research is recommended to fully understand HoV, especially to separate its RON-like effects versus other effects like volumetric efficiency.

   HoV ≥ current

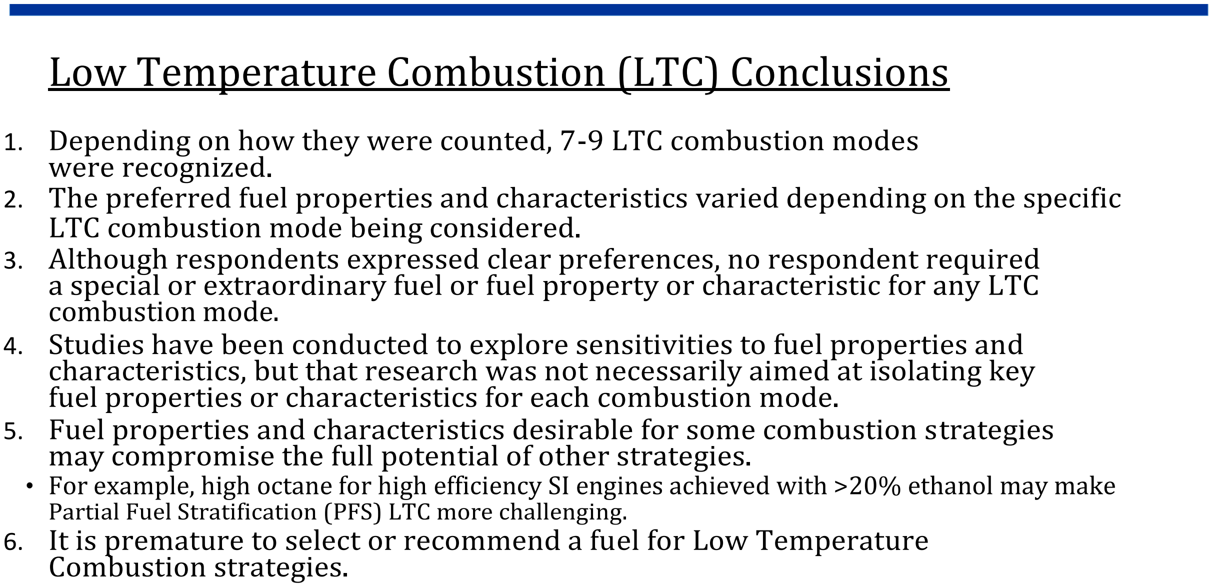
Figure A.1 Summary of Gasoline fuel property recommendations.



## Summary of ACEC Recommendations for Diesel Fuel (Priority Rank Ordered)

| | | Recommended Target Value |
|---|---|---|
| 1. | **Cetane Number (CN)**<br>More controlled studies in conjunction with engine design and calibration changes are needed | CN > 40 (no change specified) |
| 2. | **Sooting Propensity**<br>Higher levels of fuel oxygenation and lower levels of multi-ring aromatics decrease soot. | Fuel Aromatics – No changes specified<br>Oxygenates – No changes specified (up to B20 accepted in the market) |
| 3. | **Ash**<br>Lower is better | 0.001% (limit of detection) |
| 4. | **Sulfur**<br>Lower is better | 10 ppm max or lower |
| 5. | **Distillation Curve**<br>Excessive variability in back-end distillation temperatures is discouraged | Reduced T90/T95 variation |

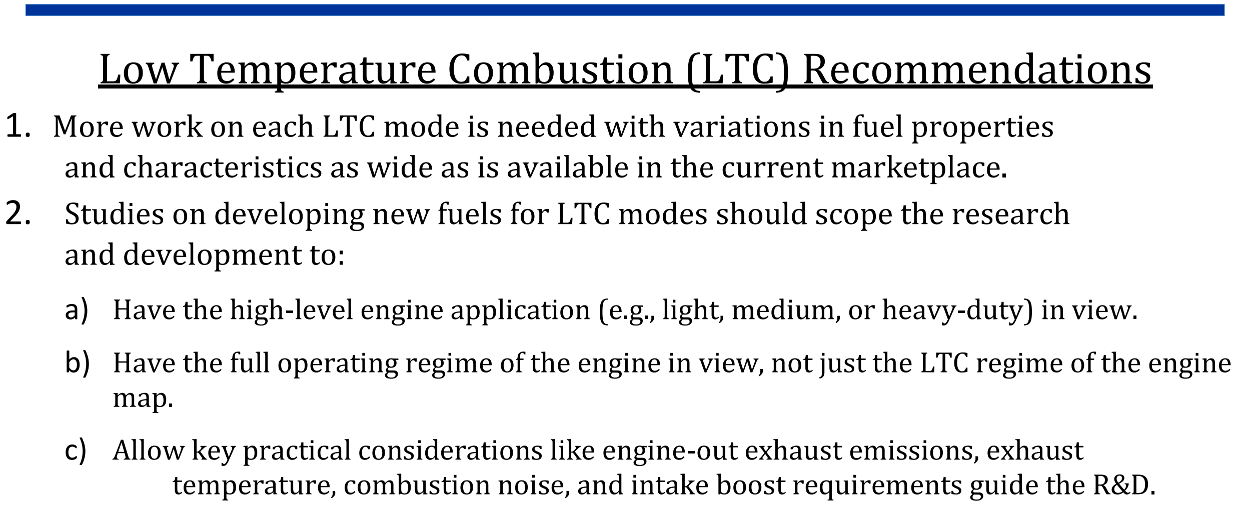
Figure A.2 Summary of Diesel fuel property recommendations.



## Low Temperature Combustion (LTC) Conclusions

1. Depending on how they were counted, 7-9 LTC combustion modes were recognized.
2. The preferred fuel properties and characteristics varied depending on the specific LTC combustion mode being considered.
3. Although respondents expressed clear preferences, no respondent required a special or extraordinary fuel or fuel property or characteristic for any LTC combustion mode.
4. Studies have been conducted to explore sensitivities to fuel properties and characteristics, but that research was not necessarily aimed at isolating key fuel properties or characteristics for each combustion mode.
5. Fuel properties and characteristics desirable for some combustion strategies may compromise the full potential of other strategies.
   - For example, high octane for high efficiency SI engines achieved with >20% ethanol may make Partial Fuel Stratification (PFS) LTC more challenging.
6. It is premature to select or recommend a fuel for Low Temperature Combustion strategies.

Figure A.3 Conclusions for low-temperature-combustion (LTC) fuels.



## Low Temperature Combustion (LTC) Recommendations

1. More work on each LTC mode is needed with variations in fuel properties and characteristics as wide as is available in the current marketplace.
2. Studies on developing new fuels for LTC modes should scope the research and development to:
   a) Have the high-level engine application (e.g., light, medium, or heavy-duty) in view.
   b) Have the full operating regime of the engine in view, not just the LTC regime of the engine map.
   c) Allow key practical considerations like engine-out exhaust emissions, exhaust temperature, combustion noise, and intake boost requirements guide the R&D.

Figure A.4 Recommendations for low-temperature-combustion (LTC) fuels.

# Appendix C: Hydrogen-Fueled Engines

The ACEC Technical Team has been considering hydrogen as a fuel for enabling high-efficiency, clean engines. Hydrogen has a high flame speed, very lean ignitability limits, and contains no carbon, giving it the potential for diesel engine like efficiencies, conventional spark-ignition control of combustion timing, and very low engine-out emissions, including $CO_2$ emissions.[21] Hydrogen ICEs offer a bridging opportunity to hydrogen fuel cells. If these engines were mass-marketed in the near-term, they could stimulate the hydrogen infrastructure, storage, dispensing, and safety technologies, thus promoting the longer-term U.S.DRIVE goal of transitioning to a hydrogen economy.

Significant progress has been made on hydrogen-fueled ICEs. While technical barriers remain, the potential for direct-injection hydrogen ICEs with 45% brake thermal efficiency and low emissions was demonstrated in the lab. This fuel efficiency potential is close to that of fuel cells. However, due to changes in research funding priorities, the lack of an emerging hydrogen-fueling infrastructure, research on hydrogen-fueled ICEs has been tabled. The following discussion in this appendix documents the current state of hydrogen ICE technology and the remaining research barriers.

## Technology Development History

The Hydrogen-fueled Internal Combustion Engine ($H_2$ICE) efforts have been focused on utilizing the unique combustion characteristics of hydrogen to achieve an advanced SI-based engine that has a high efficiency (comparable to a diesel engine), performance characteristics comparable to a conventional PFI gasoline engine, and emissions that are effectively zero. The unique combustion characteristics of hydrogen include a very low lower-flammability limit and a high flame speed. These characteristics allow very dilute (*i.e.*, very low- temperature), stable SI combustion with drastically reduced $NO_x$ production. High dilution also enables efficient part-load operation (*i.e.*, operation without the throttling losses of conventional PFI engines). Engine-out hydrocarbon, CO, and $CO_2$ emissions are also limited to trace amounts resulting from lubricating oil. Design advancements such as higher boost pressure and downsizing offer even higher efficiencies and power densities, possibly exceeding those of hydrocarbon-fueled engines.

The current state of hydrogen-fueled IC engine technology is summarized as follows. Ford, BMW, Mazda, Quantum and others built and tested demonstration and commercial PFI H2ICE vehicles using premixed SI engine technology. Recent examples that include light-duty and some heavy-duty engines, all in very small quantities, include:

- BMW Hydrogen 7 demonstration vehicle (~100 vehicles) with emissions well below SULEV standards;
- Quantum/Ford Escape and Prius H2ICE hybrid vehicles
- Silverado H2ICE conversion by Electric Transportation Energy Corporation
- Commercially sold Ford E-450 shuttle bus (30 vehicles) with premixed, supercharged hydrogen SI engine technology meeting Phase II heavy-duty 2010 emission standards, with over 99.7% reduction of CO, CO and NMHC
- Mazda is leasing RX8 vehicles with rotary gasoline/H2 and mono H2 fueling in Japan

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[21] While tail-pipe $CO_2$ emissions may be zero, $CO_2$ emissions incurred by the generation of hydrogen must be considered.

  - In Europe, H2ICE activity includes MAN with the HyFleet: Cute Program described at http://www.global-hydrogen-bus-platform.com/Technology/HydrogenInternalCombustionEngines)
  - Gen-sets powered by hydrogen-fueled engines are commercially available in low volume (Hydrogen Engine Company, others)
- Premixed H2ICE technology operating under lean conditions with intake air pressure boosting to produce power densities approaching conventional gasoline PFI technology have been demonstrated under research conditions with peak brake thermal efficiencies of over 40% by Ford, with emissions below SULEV.
- Turbo-charged, direct-injection (DI) H2ICE technology with power density greater than a comparable naturally aspirated gasoline engine has been demonstrated in the lab with peak brake thermal efficiencies of 45.5% (based on single-cylinder research engine data). Vehicle level simulations based on these results suggest a potential for meeting 2016 CAFE targets and Tier 2 Bin 2 (SULEV) emissions without aftertreatment. Further fuel-economy improvement potential through engine downsizing is also a possibility.
- Costs for H2 engines are comparable to conventional gasoline fueled SI engine.[22][21]
- When hybridized, advanced H2ICE powertrains are projected to offer driving cycle efficiency comparable to advanced fuel cell vehicles, with acceptable performance and all weather capability. Current Hybrid H2ICE's in demonstration fleets have shown similar fuel economy to current fuel cells (South Coast Air Quality Management District fleet usage reports).

## Barriers/Technical Strategies

The primary path to high efficiency use of hydrogen in ICEs is direct-injection (DI), spark-ignited (SI), H2ICEs. DI-H2ICE offers the potential for fuel efficiency approaching or exceeding that of current high-efficiency diesel engines, power densities comparable to or greater than conventional PFI gasoline engines, and emissions compliant with EPA Tier 3, all in a cost effective durable manner. DI-H2ICE also has the potential to overcome largely the pre-ignition and flashback challenges for PFI-type H2ICEs. Major barriers related to DI-H2ICE engines include (a) developing a robust, durable, cost-effective DI hydrogen combustion system, including hydrogen fuel injectors and boosting technologies, and (b) hydrogen compatible emission control technologies that are also robust and cost effective. Specific technical strategies with associated barrier discussion are as follows:

### *Combustion Technology:*

- Develop the fundamental knowledge base and simulation tools for DI-H2ICE SI combustion and $NO_x$ emission processes. This includes ultra-lean (for idle) to stoichiometric conditions and use of boosted, high EGR at stoichiometric conditions as a potential $NO_x$ control strategy, including both premixed and stratified conditions.
  - The knowledge base for supporting the development of DI-H2ICEs and the simulation tools for designing and optimizing them is limited. The required lean or dilute, high-pressure and high-temperature in-cylinder conditions push combustion

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[22] It should be noted that the same as for fuel cells, commercially viable on-board hydrogen storage and hydrogen production, distribution, and fueling infrastructure must be developed and add to vehicle cost.

into a parameter space where hydrogen combustion stability, combustion duration, and pre-ignition phenomena are not well understood. Improved understanding of hydrogen SI combustion progress and stability, pre-ignition phenomena, and $NO_X$ emission formation over the expected range engine speeds and loads, combustion chamber geometries and in-cylinder air motions (*e.g.*, swirl) is required.

- Improve the understanding of DI hydrogen injection and hydrogen-air mixing processes and models for simulation.
    - DI offers the highest engine power density, as well as reduced pre-ignition problems and improved safety by eliminating the possibility for flashback. By timing the direct injection after intake-valve closure, 20-30% improvement in power density can be achieved relative to injection before intake-valve closure. However, the hydrogen jet must create a lean or dilute and nearly homogeneous mixture and in-cylinder gas motion before spark ignition and combustion of mixtures rich enough to form significant $NO_X$ occurs.
- Aggressive use of EGR (levels up to 50%) and boosting to achieve dilute stoichiometric combustion at high-loads, coupled with low-$NO_X$, lean combustion at light to moderate loads has potential as an H2ICE strategy. Another strategy is stoichiometric combustion coupled with a more conventional TWC for high loads and low-$NO_X$, lean combustion at light to moderate loads.
    - The load range capabilities for these options are unknown and must be determined.

Develop hydrogen compatible technologies for high power density, high- efficiency SI H2ICE, *e.g*., turbo/super-chargers, intercoolers, high compression ratios, high EGR delivery components, hydrogen injectors for DI operation, pistons and rings, spark plugs, and lubricant technology.

- Commercially viable DI hydrogen injectors do not exist. Reliability, durability, and lubrication (hydrogen has no lubricity) are significant challenges. Additionally, the high diffusivity and small molecular size of hydrogen makes injector leakage an issue. Electronic actuation/control will be essential for integration into modern engine control systems.
- Compatibility with hydrogen and effectiveness for DI H2ICE conditions are largely unknown. Hydrogen embrittles many materials.
- Components to deliver high EGR levels without throttling do not exist.
- Lubricants will be the only source of hydrocarbon emissions; additionally, very effective lubricant control is needed to minimize deposits in the combustion chamber that can lead to preignition problems and deposits on valve heads that can affect breathing, performance and emissions.

*Aftertreatment Technology for Hydrogen Engines*: The primary pollutant from H2ICEs is $NO_X$ if undiluted fuel-air mixture equivalence ratios from about 0.6 to stoichiometric are present in the combustion strategy. Envisioned strategies try to avoid equivalence ratios in the 0.6 to 1.0 range. If stoichiometric combustion is used to achieve high loads, a conventional-type TWC is currently the envisioned aftertreatment technology. If combustion in the 0.6 to close to stoichiometric range is required, lean combustion aftertreatment like the LNT may be required.

- Determine optimal TWC catalyst composition requirements for operation with stoichiometric hydrogen-combustion exhaust streams.
    - Integration of TWC with stoichiometric hydrogen for optimal low cost performance has not been done.

- If EGR-dilution is not used, lean SI combustion in approximately the 0.6 to 1.0 range is required for an effective combustion system; other lean burn $NO_x$ technologies must be pursued: e.g., SCRs, LNTs, hybrid LNT and SCR systems.
    - The performance of these technologies in a hydrogen-fueled ICE system is not understood and development for the application is required. Compatibility with hydrogen is unknown. Development associated with other engine technologies must be extended to include hydrogen ICE conditions to achieve optimal cost effective operation. An example is determining LNT performance with $H_2$ as the reductant during regeneration and optimal LNT catalyst formulations. Another would be exploring a hybrid LNT/SCR system using rich hydrogen exhaust gas to generate $NH_3$ for the SCR.