Advanced Combustion and Emission Control Technical Roadmap for Light-Duty Powertrains

Introduction

The Advanced Combustion and Emission Control Technical Team is focused on removing critical technical barriers to the commercialization of advanced, high efficiency, emission-compliant internal combustion (IC) engines for light-duty vehicles (passenger cars, minivans, SUV's, and pickup trucks). Fuels under consideration include clean, hydrocarbon-based fuels (petroleum- and non-petroleum-based) and hydrogen. Elimination of the technical barriers will enable light-duty vehicles with dramatically higher fuel economies than current light-duty vehicles powered by conventional port-fuel-injected (PFI) engines. The engine technologies under consideration are also applicable to both conventional and hybrid-electric vehicle (HEV) powertrains.

Overall, the Technical Team supports the *FreedomCAR and Fuel* goals of enabling (a) clean, energy-efficient vehicles operating on clean, hydrocarbon-based fuels powered by IC engine powertrains, (b) clean, energy-efficient hydrogen-fueled vehicles operating on IC engine powertrains that provide a bridge to hydrogen fuel cell powered vehicles and that help enable a transition to a hydrogen economy, and (c) HEVs that are durable and affordable. Achieving these goals will promote more efficient use of petroleum-based fuels, and concurrently, reductions in the emission of CO_2 greenhouse gases per vehicle mile traveled, while at the same time enabling emission compliant light-duty vehicles.

Over the past several years, R&D efforts have been focused on light-duty compression-ignition, direct-injection (CIDI) engine technology utilizing a conventional, swirl-supported diesel combustion system coupled with aftertreatment systems for removing nitrogen oxides (NOx) and particulate matter (PM) from the exhaust stream. Powertrains using this CIDI engine technology in either a conventional or an HEV mode offer the potential for impressive vehicle fuel economy gains over powertrains using conventional gasoline-fueled PFI engines. The R&D efforts have contributed to significant improvements in CIDI engine performance and significant reductions in the emission of NOx and PM. The emissions reductions in commercial CIDI technology to date have largely been achieved through modification of the swirl-supported diesel combustion system and the use of EGR for in-cylinder NOx control. Aftertreatment systems for removing NOx and PM from diesel exhaust also have been developed and have shown significant potential for reducing NOx and PM emissions even further. However, in spite of the impressive gains in engine and aftertreatment systems, compliance with EPA Tier 2 emissions standards has not been demonstrated in a production viable manner with conventional CIDI engine technology. Further significant reductions in CIDI engine-out NOx and PM emissions and improvements in the effectiveness of aftertreatment systems, especially at the low and high ends of the exhaust temperature range, are required to enable the commercialization of engines with the fuel economy advantages of the CIDI engine.

To address these needs, the Team will continue its focus on the development of more effective, commercially viable NOx and PM aftertreatment systems. In addition, the Team will transition the combustion R&D focus to support the development of advanced low-temperature combustion (LTC) strategies for use in CIDI engines. LTC strategies offer potential for achieving the high efficiencies typical of CIDI engines while providing dramatically lower engine-out emissions over part or all of the engine load range. LTC thus offers the potential to significantly reduce the burden on exhaust aftertreatment systems and thereby reduce the efficiency penalty and the cost of emission control.

For engines operating on hydrocarbon-based fuels, the LTC regimes to be focused on involve low-temperature, compression-ignition combustion. This form of low-temperature combustion occurs under dilute conditions without significant flame propagation and can enable engines with high, diesel-like thermal efficiencies and ultra low NOx and PM emissions. The engines technologies being investigated include engines operating solely on LTC modes, such as the homogeneous charge compression-ignition engine (HCCI), to engines that will utilize conventional CIDI or spark-ignited (SI) combustion modes at higher loads and LTC modes at moderate to light loads (referred to here as “mixed-mode” operation). Mixed-mode options offer the potential to couple the strengths of both conventional and advanced combustion modes to overcome many of the deficiencies in each. Mixed-mode operation using conventional CIDI combustion at high loads combines the high-efficiency, high-load capabilities of CIDI with the high-efficiency, low-emission capabilities of the LTC to overcome deficiencies in CIDI aftertreatment systems at light loads while dealing with the limited operating range of LTC. Similarly, coupling SI at high loads with LTC at more moderate loads provides a gasoline-fueled engine with CIDI-like engine efficiency capabilities and low emissions. High efficiencies are achieved with the SI-LTC option through higher compression ratios at part load and elimination of part-load throttling losses inherent with PFI engines. Emissions for the SI-LTC option are controlled by the proven three-way catalyst at high loads and the low-emission nature of LTC combustion at lighter loads.

The advanced engine options employing LTC that are being considered have the potential to be more efficient and less expensive than the conventional CIDI/aftertreatment option. Therefore, the use of LTC could help overcome two key challenges that are inhibiting the introduction of highly-efficient CIDI engines, emissions and cost. Moreover, the advanced engine technologies offer longer term potential for even further fuel efficiency gains by adding engine design advancements (*e.g.*, increased expansion ratio, variable valve timing (VVT), reduced friction, improved exhaust heat recovery, *etc.*) and by further reducing the emission-control fuel economy penalty.

The Team's hydrogen-fueled IC engine (H_2ICE) efforts are focused on utilizing the unique combustion characteristics of hydrogen to achieve an advanced SI-based engine that has a high efficiency (comparable to a CIDI engine), performance characteristics comparable to a conventional PFI 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 NOx production. High dilution also enables efficient part-load operation (*i.e*., operation without the throttling losses of conventional PFI engines). Hydrogen engines operating under lean conditions have already been demonstrated in a laboratory environment with peak brake thermal efficiencies of 38% and near-zero emissions (well below Tier 2 requirements, bin 5). With design advancements such as higher boost pressure with intercooling, efficiencies approaching that of a CIDI engine may be possible along with PFI power densities. These engines will provide an interim hydrogen-based powertrain technology that promotes the longer term *FreedomCAR* goal of transitioning to a hydrogen economy with a hydrogen fuel-cell powered transportation system.

DOE fuel research efforts are conducted in coordination with the Advanced Combustion and Emission Control Technical Team. Fuels research has two overall goals. One goal is to determine fuel characteristics that will enable emissions compliant, high efficiency engine options. Advances in fuel formulation have the potential to enable more effective use of LTC combustion strategies over a wider operating range, enabling greater benefits from the use of LTC. Fuel composition changes, oxygenate addition, and additives have also been shown to impact engine-out emissions. Understanding these fuel effects will be critical to achieving program goals. The second goal of the fuels research will be to provide non-petroleum-based fuel options that can reduce our nation's dependence on petroleum for transportation. Non-petroleum diesel fuels can be produced from renewable resources such as seed oils as well as synthesized from natural gas, tar (oil) sands, coal, etc. The production of diesel fuel from these sources is well developed, yet none of these are in significant use in the United States because of their cost. Moreover, their effect on advanced combustion strategies and aftertreatment systems is largely unknown.

State of High Efficiency Powertrain Technology

<u>CIDI Engine/Aftertreatment Technology:</u> Conventional CIDI engine technology using swirl-supported diesel combustion provides an efficiency benchmark for the advanced, high-efficiency powertrain R&D for light-duty vehicles to be undertaken as part of the Advanced Combustion and Emission Control Technical Team. Impressive gains have been made in CIDI engines in recent years through technical advances in areas such as intake pressure boosting and air handling, four valves, fuel injection, combustion chamber design and electronic

control. Major advances have also been made in exhaust aftertreatment systems for reducing NOx and PM. However, CIDI engine/aftertreatment system compliance with EPA Tier 2 emission regulations is still not commercially viable.

The current state of CIDI engine/aftertreatment technology can be summarized as follows:

- CIDI engines have the highest efficiency of proven engine concepts for light-duty vehicles with peak brake thermal efficiencies (BTE) of 41% and part-load BTE (at 2 bar BMEP and 1500 rpm) of 27%. These efficiencies can translate to more than 20% higher fuel economy relative to current PFI, gasoline engine-powered, light-duty vehicles, and as a result, proportionally lower emission of CO_2 greenhouse gases. (The exact vehicle fuel economy improvement over PFI engines will depend on vehicle weight, size, drive cycle, and aftertreatment fuel economy penalties.)
- Traditional CIDI deficiencies such as exhaust odor, smoke, poor acceleration, poor starting, and noise, vibration and harshness have been greatly reduced.
- The cost of CIDI engines is greater than the cost of naturally aspirated PFI engines due largely to costs associated with the high pressure fuel injection system, higher compression ratios, and intake pressure boosting which are needed to provide PFI engine-like drivability.
- The associated infrastructure for CIDI engines (*e.g.*, design capabilities, production, maintenance, and fuel supply) exists in a well developed state.
- *Combustion:* The conventional light-duty CIDI engine employs a swirl-supported, direct-injection (DI) diesel combustion system and a high pressure fuel injection system. Dramatic engine-out emissions reductions have been achieved through improvements in the air intake, fuel injection and combustion chamber design. Some vehicles with CIDI engines (with less than three liter displacement) can now meet Euro 4 emissions standards (0.25 g/km NOx and 0.025 g/km PM) with only limited use of oxidation catalysts for aftertreatment. Light trucks have also been demonstrated at close to Tier 2, Bin 9 levels with only a passive aftertreatment system (0.3 g/mile NOx and 0.06 g/mile PM). However, the engine-out emissions from CIDI engines employing swirl-supported, direct-injection (DI) diesel combustion have not come close to meeting EPA Tier 2 emission regulations in a durable and cost effective manner. Advances in the effectiveness and durability along with reductions in the cost of NOx and PM aftertreatment systems or advances in low-emission combustion technology are required.
- *NOx aftertreatment:* NOx aftertreatment systems for further reducing NOx emissions from CIDI engines have emerged through heavy-vehicle research, but none of the NOx reduction technologies are commercially viable at this time, even with low-sulfur (<15 ppm) diesel fuel. Three technologies that have potential are NOx adsorber-catalysts, selective catalytic reduction (SCR) systems using urea, and lean NOx catalysts (*i.e.*,

SCR with hydrocarbon reductants). Full scale laboratory prototype demonstrations suggest that meeting future NOx regulations with these systems may be feasible, but there are many unresolved issues. These issues include the following: the durability of the NOx adsorbers are not proven and the temperature window of high conversion is too narrow, the urea SCR system requires significant infrastructure development, and the lean NOx system requires catalysts with higher catalytic activity over a broader temperature window.

- *PM aftertreatment:* PM aftertreatment systems for further reducing CIDI engine-out PM emissions have emerged to the point of limited commercial operation. For some specialized heavy-duty applications, catalyst-based diesel particulate filters (DPFs) have been developed. These systems must operate with low-sulfur diesel fuel (<15 ppm) and well controlled application duty cycles, and are not yet applicable for general deployment. Nevertheless, they can achieve PM reduction in excess of 90%. A system has also been released in Europe which employs fuel-borne catalysis, an oxidation catalyst (for exhaust gas heating) and sophisticated engine controls to initiate regeneration. However, a fuel-borne catalyst approach is unlikely to be acceptable in the United States.
- *Fuels:* Future fuel regulations lower the diesel fuel sulfur to the 15 ppm level starting in 2006 based on R&D showing the impact of sulfur on catalyst-based aftertreatment systems. This will improve the viability of some NOx aftertreatment strategies such as a lean-NOx trap and will lead to modest reductions in engine-out PM emission. Also, fuel oxygenation has been shown to provide the potential for dramatically reducing PM emissions with little effect on NOx; however, the cost effectiveness of methods for oxygenation needs to be demonstrated. Other fuel improvements for emissions reduction (*e.g.*, modified composition, blending agents that also minimize petroleum use, and fuel composition tailored for optimal NOx-adsorber performance) are being investigated.

Advanced Low-Temperature Combustion (LTC) Regimes: R&D is being conducted on high efficiency engines operating with low-temperature combustion (LTC) regimes, but these engines are in a very early state of development relative to the more conventional, light-duty CIDI engine discussed in the previous section. Research has shown that LTC is capable of providing CIDI–like high efficiencies with ultra-low PM and NOx emissions. However, operation with LTC when using gasoline or diesel fuel is limited to moderate to light loads and carbon monoxide (CO) and hydrocarbon (HC) emissions become significant at the lightest loads. Moreover, control over the phasing of the combustion is challenging. Based on research to date, LTC is likely be used at moderate to light loads with conventional SI or CIDI combustion being used at high loads when using gasoline or diesel fuel, respectively. This mixed-mode approach avoids the difficulty of extending LTC operation to high loads while still providing the same power densities and full-load capabilities of SI or CIDI engines. Since automotive engines spend the majority of their time at less than two-thirds load in the test schedules used for fuel-economy testing, the benefits of LTC are still realized over a major portion of the typical engine duty cycle. The current state of LTC technology for use in advanced, high efficiency IC engines can be summarized as follows:

- No light-duty engines operating on HCCI (the most elementary form of LTC) are commercially available. The engine load capabilities of HCCI are limited to less than approximately half load when using conventional gasoline or diesel fuel. However, research suggests that the operating range may be improved with an advanced fuel that has ignition and vaporization characteristics designed specifically for HCCI operation. Such an advanced fuel may enable operation purely on ultra-low-emission HCCI combustion, potentially significantly reducing fuel injection and aftertreatment system costs relative to a CIDI engine.
- Mixed-mode engine technology is commercially available in two diesel-fueled engines and one gasoline-fueled engine. These include the diesel fueled MK and UNIBUS systems, and a gasoline fueled two-stroke motorcycle engine.
- The brake thermal efficiency of engines operating in LTC modes has been established as being at least equal to CIDI combustion, but strategies to exploit LTC operation to meet the efficiency goals in Table 1 are not fully determined.
- The total engine/aftertreatment system cost when using LTC modes is likely to be greater than conventional PFI engine/aftertreatment system costs and could approach or exceed the higher cost CIDI engine/after-treatment system. The cost of an engine/aftertreatment system using LTC will depend primarily on the fuel injection system, intake air pressure boosting, aftertreatment, and engine/aftertreatment control system requirements.
- Development of strategies for controlling LTC and strategies for switching between LTC and SI or CIDI combustion modes has begun. The control strategies are needed to control combustion timing and switching between combustion modes, and to optimize engine/aftertreatment performance over the load/speed map. Control technologies being explored include advanced fuel-injection strategies, VVT, variable intake temperature, controlled EGR, and variable compression ratio (VCR).
- Research indicates that incomplete combustion at very light loads is an issue for operation with LTC. Methods for improving combustion efficiency at very light loads must be found to maintain fuel economy and control HC and CO emissions. This may also mean that oxidation catalysts capable of operating in low-temperature exhaust streams will be required to control HC and CO emissions at light loads.
- The associated infrastructure for LTC engines (*e.g.*, design capabilities, production, maintenance and fuel supply) is similar to that of SI or CIDI engines and is well developed.
- Fuel effects on LTC are inadequately understood.

Powertrain systems integration: The engine/aftertreatment systems must function effectively as a system. Some systems integration has been done as part of the development of current technology CIDI engines, but much more remains to be done regarding packaging of aftertreatment systems, development of sensors for control of the engine/aftertreatment system, and development of system control strategies. The integration of LTC modes with matching aftertreatment systems is relatively undeveloped. At present, there are no durable, cost-effective NOx sensors or NH_3 sensors (for urea based SCR NOx reduction systems) and there are no PM sensors available.

Hydrogen IC engines: Hydrogen IC engines based on SI combustion technology are under development. The very low lower-flammability limit and the high flame speed of hydrogen allow combustion of hydrogen in SI engines under very dilute, low temperature conditions that produce very low NOx emissions and that enable high thermal efficiency operation at part-load. Hydrocarbon, CO, and CO_2 emissions are also limited to trace amounts resulting from lubricating oil. The current state of hydrogen-fueled IC engine technology can be summarized as follows:

- Gen-sets powered by a 6.8 liter, V-10, turbo-charged, hydrogen-fueled engine are commercially available (Ballard Power Systems).
- Full-scale prototype H_2-fueled vehicles have been produced. Examples include: a 2.0 liter naturally-aspirated IC engine in a light-weight, 3300 pound, 5 passenger vehicle; a 2.3 liter, super-charged, IC engine in a small wagon vehicle; and a 2.3 liter, super-charged, IC engine-based hybrid-electric-vehicle (ICE-HEV) powertrain for a small wagon vehicle.
- H_2ICE technology operating under lean conditions with intake air pressure boosting to produce power densities approaching conventional PFI technology have been demonstrated under research conditions with peak brake thermal efficiencies of 38%.
- H_2ICE technology using high exhaust gas recirculation (EGR) and no aftertreatment has been demonstrated with California SULEV emissions capabilities under research conditions at several speed and load conditions.
- Infrastructure associated with IC engine design, production, and maintenance is well developed. However, the same as for fuel cells, commercially viable hydrogen production, distribution, and storage infrastructure must be developed.
- Results from hydrogen engine demonstrations to date suggest that vehicles powered by hydrogen IC engines operating with lean combustion can deliver many of the benefits of a fuel-cell powered vehicle at a cost comparable to that of a vehicle powered by a conventional PFI engine. Hydrogen fueled IC engines, therefore, present a bridging opportunity to the implementation of fuel cell technology that can be mass-marketed in the near-term and that will stimulate the hydrogen infrastructure, storage, dispensing and safety technologies in advance of the introduction of hydrogen fuel cell powered vehicles.

Goals

The Advanced Combustion and Emission Control Technical Team goals for advanced, high-efficiency, IC engine are given in Table 1. Table 1a applies to hydrocarbon-fueled engines and Table 1b to hydrogen-fueled engines. The widely used conventional gasoline PFI engine is shown as a benchmark. The best CIDI engine to date is also shown for reference, but this engine does not meet EPA Tier 2, Bin 5 emissions requirements.

Table 1a The status of conventional PFI engines and the best CIDI engines to date and the Combustion and Emission Control program technical goals for advanced, high-efficiency, hydrocarbon-fueled IC engines.

Characteristics	Units	Current Status		Goals by Fiscal Year		
		PFI [a]	CIDI [b]	2007	2010	2013
Engine peak brake thermal efficiency	%	30	41	43	45	46
Engine part-load brake thermal efficiency (2 bar BMEP at 1500 rpm)	%	20	27	29	31	32
Emission control fuel economy penalty [c, d]	%	--	--	<5	<4	<3
Powertrain cost [e, f]	$/kW	20	30	35	30	30
Projected vehicle emissions [g]	Tier 2	<Bin 10	Bin 10	Bin 5	Bin 5	Bin 5

[a] Based on current production port-fuel-injected (PFI) engines.
[b] Values representative of current CIDI engines with passive emission control.
[c] Fuel economy penalty over the combined Federal Test Procedure drive cycle resulting from emission control achieved either by use of LTC combustion strategies or aftertreatment systems. The fuel economy penalty is relative to CIDI engines that meet the 2003 emissions standards.
[d] The "fuel economy penalties" are given in terms of a percentage loss in fuel economy (*e.g.*, a percent reduction in miles per gallon). (If expressed in terms of a cycle average thermal efficiency loss, a 3 to 5% fuel economy loss is equivalent to a 1 to 2% thermal efficiency loss.)
[e] High-volume production: 500,000 units per year.
[f] Constant out-year cost reflect the goal of maintaining powertrain (engine, transmission, and emission control) system cost as the system complexity increases with time.
[g] Projected full-useful-life emissions for a passenger car/light truck using advanced petroleum-based fuels as measured over the Federal Test Procedure and other supplemental test procedures used for certification in those years.

Table 1b The status of hydrogen-fueled SI engines under development and the Combustion and Emission Control program technical goals for advanced, high-efficiency, hydrogen-fueled IC engines.

Characteristics	Units	Current Status	Goals by Fiscal Year	
			2010	2015
Engine peak brake thermal efficiency	%	38	45	45
Powertrain cost [a, b]	\$/kW		45	30
Projected vehicle emissions [c]	Tier 2	< Bin 5	Bin 5	Bin 5

[a] High-volume production: 500,000 units per year.
[b] Constant out-year cost reflect the goal of maintaining powertrain (engine, transmission, and emission control) system cost as the system complexity increases with time.
[c] Projected full-useful-life emissions for a passenger car/light truck using advanced petroleum-based fuels as measured over the Federal Test Procedure and other supplemental test procedures used for certification in those years.

Major Barriers

<u>*High-Efficiency Engines - Hydrocarbon-fueled:*</u> Overall barriers that have blocked the introduction of current high-efficiency CIDI engine technology using conventional diesel combustion are: (a) the lack of effective, commercially viable emission control technologies that allow compliance with EPA Tier 2 emissions regulations and (b) the cost disadvantages of the conventional CIDI engine air handling, high-pressure fuel injection, and emission control equipment relative to PFI technology. Finding a pathway to overcoming the emissions barrier is the major initial challenge facing engine designers. Providing the pathway will require further improvements in NOx and PM aftertreatment systems and/or the utilization of advanced, ultra low-emission, low-temperature combustion strategies, *i.e.*, changes in the mode of combustion currently used in CIDI engines. Such improvements will enable the majority of the leap forward in fuel efficiency over the conventional PFI engines targeted in Table 1a. Achieving, the remaining portion of efficiency improvement goals will require technology advances in the base engine as well as reductions in the fuel economy penalties associated with PM and NOx aftertreatment systems and LTC strategies. Overcoming the cost barrier will require optimization of the overall powertrain system and its subsystems and technical improvements in engine, fuel injection, combustion, and emission control systems that maximize their effectiveness and durability, and reduce costs.

Detailed barriers:

Aftertreatment Systems:

- The durability and sulfur tolerance of the catalyst-based aftertreatment systems under development have not been proven, even with the 15 ppm, low-sulfur fuel that will start becoming available in 2006. Aftertreatment system desulfurization strategies or fuel sulfur traps may be required to overcome sulfur degradation problems. Deactivation of catalyst-based systems also occurs as a result of other poisons, coking, and surface morphologic changes. To compensate for the gradual loss of effectiveness, regeneration and desulfation must be conducted more frequently, thus lowering fuel efficiency.
- Most catalysts-based systems require relatively high exhaust gas temperatures to light-off the catalysts, to achieve high emission reduction efficiency, or to regenerate. However, the high efficiency of CIDI engines results in low exhaust gas temperatures during much of typical light-duty vehicle driving cycle. As a result, energy must be added to raise exhaust gas temperatures, especially during regeneration or at lighter loads, resulting in increased vehicle fuel consumption.
- Development and optimization of catalyst-based aftertreatment systems are inhibited by the lack of understanding of catalyst fundamentals (*e.g.*, surface chemistry, deactivation mechanisms, particulate capture and oxidation) and catalysts modeling capabilities.
- Sensor technology for control and OBD for aftertreatment systems is inadequate. Sensitivity and response times do not meet requirements, interferences exist, and current prototypes are expensive and unreliable.
- <u>NOx Emissions:</u> Cost effective catalyst-based NO_x reduction systems with sufficient conversion efficiency to meet NO_x emissions goals are not yet available. Space (volume) requirements for NOx systems are also large and need to be reduced. Comments on specific systems follow:
  - NO_x adsorbers are a promising NO_x reduction system for light-duty vehicles, but they have a limited temperature window for high NOx conversion efficiency, a significant fuel economy penalty during regeneration, an unknown durability even with low sulfur fuel, and a strong sensitivity to sulfur (*i.e.*, they degrade rapidly with exposure to fuel sulfur) and other contaminants (*e.g.*, ash). The sensitivity to sulfur requires that they be desulfated periodically, requiring temperature excursions that can degrade the catalyst.
  - Urea-based selective catalytic reduction (SCR) systems have validated good NOx reduction efficiency and durability on heavy-duty vehicles, a reasonable temperature window for effective NOx reduction, and a relatively high level of sulfur tolerance. Significant drawbacks to urea-SCR include the lack of a urea refueling infrastructure, the need to carry urea, enforcement hurdles presented by urea as a reductant, and the potential for ammonia break-through.

- Hydrocarbon-SCR has been found to have inadequate NOx conversion over a wide temperature range, although certain strategically matched catalysts and reductants have shown potential. The methods for producing the highly effective reductants are not developed, but LTC modes may be a path in that the HC emissions can be relatively high and include partially oxidized species.
- Plasma-assisted SCR NOx aftertreatment systems attempt to generate more reactive hydrocarbon reductants from fuel using catalysts and an electric discharge. The system has a large fuel economy penalty.
- In general, optimized methods for injecting reductants and controlling the regeneration processes involved in most NOx reduction systems are needed. Some reductant strategies need partial fuel reformation to achieve reasonable catalytic activity, but the reformation systems are not well developed.

• <u>PM Emissions:</u> PM aftertreatment systems are more developed than NOx aftertreatment systems. However, the most effective PM aftertreatment technologies cause reductions in engine efficiency through increased back pressure and fuel economy penalties associated with heating during regeneration. Improved regeneration strategies that minimize engine efficiency losses due to back-pressure increases and regeneration energy requirements are needed. Effective regeneration strategies are especially needed when subjected to extended light-load, low exhaust temperature operation. In addition, PM aftertreatment system effectiveness can be sensitive to fuel-borne sulfur or other contaminants (*e.g.*, ash); the long term durability of PM aftertreatment systems has not been proven; and there is a need for more cost effective filter materials.

Advanced Low-Temperature Combustion Technology:

• Inadequate understanding of the fundamentals of the effects of fuel injection, air motion (*e.g.*, swirl), and combustion chamber geometry on fuel-air mixing, combustion and emission formation processes for a range of LTC regimes, as well as an inadequate capability to accurately simulate these processes. This includes inadequate understanding of fuel injector parameters (*e.g.*, timing, spray-type, orifice geometry, injection pressure, single pulse *versus* multi-pulse, *etc*.,) on LTC regimes.
• Mechanisms for controlling the ignition timing of LTC modes are not well developed. Ignition timing is determined by the chemical-kinetic reaction rates, which are controlled by temperature and mixture composition histories during the ignition period. Since ignition timing is most sensitive to temperature, methods using temperature to control ignition timing need to be investigated and developed.
• The heat transfer characteristics during LTC are likely to be very different than for SI and DI diesel combustion. Because of the sensitivity of the LTC processes to temperature, improved understanding of wall heat transfer under LTC operation is needed to develop engines that operate

effectively and to develop control strategies. The need for improved understanding of heat transfer is especially true during thermal transients, since thermal transients will affect ignition timing and combustion phasing. Because of the transients and the thermal inertia of cylinder walls, wall temperatures during transients will not match those during steady state operation, especially during transitions between modes.

- Methods for controlling the LTC process during rapid engine transients experienced in automotive applications have not been devised yet.
- LTC operation is typically limited to moderate to low-load operation due to excessive combustion rates at higher loads which can induce unacceptable noise, and eventually, engine damage. The effects of engine speed on LTC strategies are also largely unknown.
- HC and CO emissions and associated combustion inefficiencies occur at low loads, especially for pure HCCI combustion.
- Either conventional spark or CIDI ignition technologies must be used for cold start or methods for effective cold starting when using LTC need to be devised. 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.
- <u>Mixed-mode operation:</u> Mixed-mode operation offers the potential to achieve power densities comparable to conventional PFI engines, but there are many challenges to mixed-mode operation:
  - Inadequate understanding of the fundamentals of fuel injection, fuel-air mixing and in-cylinder combustion/emission formation processes needed to optimize a mixed-mode combustion system over the entire speed load range of an engine. This includes the use of multiple injection strategies.
  - Control mechanisms that allow the engine to operate smoothly in both LTC and conventional CIDI or SI combustion modes, and that allow the engine to switch smoothly between LTC and conventional combustion modes are needed.
  - Barriers relevant to high load operation of the NO_X and PM aftertreatment systems (see *Aftertreatment Technology* barriers) and very low-load emissions HC and CO emissions problems associated with LTC combustion apply.

Additional barriers to thermal efficiency goals
Resolving the barriers in aftertreatment and combustion described above are critical to achieving the efficiency, emissions compliance, and fuel penalty goals presented in Tables 1a and 1b. However, additional barriers also exist that need to be addressed to help reach the efficiency goals,

- Inadequate baseline for energy balance and availability (exergy) losses in modern CIDI and LTC mode engines. Understanding the losses in engines is key to determining effective strategies for achieving higher efficiency. Precompetitive data for the major loss mechanisms, especially for engines in LTC modes, is very limited.

- Low-quality of exhaust energy in already-efficient CIDI engines equipped with coolers for EGR and compressors. The greater fidelity of second law analysis reveals very low exergy in the exhaust of a modern CIDI engine, especially at part load. This limits the effectiveness of many waste heat recovery strategies. New approaches will be needed.
- Mature friction-control technology. Having been the focus of substantial private sector research, efficiency gains by further reductions in mechanical friction appear to be small.
- Need for high fuel injection pressure. The trend in CIDI engines has been use of increased fuel injection pressures for emission controls. This carries a notable parasitic loss, especially seen at part load.
- Efficiency challenge of small turbomachines. It is generally accepted that the efficiency of boosting systems affects overall engine efficiency. Small turbochargers have inherent efficiency disadvantage.
- Inherent exergy losses in conventional combustion processes. Among the largest losses in internal combustion engines, the availability destruction in rapid flame propagation combustion may be only offset to a limited extent by LTC modes.
- Heat transfer losses from combustion. Extensively addressed in "low-heat rejection engine" R&D, this loss mechanism appears to remain large.

System Cost:

- The aftertreatment emissions control devices currently available and the use of high pressure fuel injection, high compression ratio operation, and air handling equipment for pressure boosting all increase the cost of high efficiency CIDI technology relative to conventional PFI engine-based powertrains. LTC modes offer the potential to the reduce formation of emissions in-cylinder, and therefore, the potential to reduce aftertreatment system requirements and cost. Moreover, mixed-mode operation using LTC at moderate loads and conventional SI combustion at high loads may utilize lower compression ratios, less intake pressure boosting, and lower pressure fuel injection equipment than CIDI engines, thus minimizing cost increases relative to conventional PFI engines

Enabling technologies:

- Lack of real-time sensors and measurement tools for exhaust NOx and PM needed for both engine/aftertreatment development and closed-loop control of production systems. Sensitive, real-time PM measurement and sensor development are especially needed for PM aftertreatment system development and for on-board control. NH_3 sensors for urea SCR NOx control systems will also be needed. Oxygen sensors being used for air-fuel ratio monitoring are being found to have interference from hydrogen during fuel-rich excursions during LNT regeneration.

- Lack of on-board sulfur trap technology in the event that 15 ppm fuel sulfur levels still prove too high.
- Lack of a sensor for determining the mode of combustion that an engine is operating under. A combustion mode sensor may be needed for controlling an engine using mixed-mode combustion.

Powertrain systems integration:

- Simultaneous attainment of future required emission-reduction and thermal-efficiency goals requires unprecedented attention to the effective integration of multiple, new system technologies. This can be effectively accomplished only with a combination of experimental and simulation tools. The current state of modeling in aftertreatment systems is improving, but needs continued attention for another two years. Similarly, relatively low-order modeling of advanced combustion regimes and their emissions will be needed for control, augmented by experimental data where prediction is impractical (such as predicting engine-out HC species).
- Inadequate systems control technology for effectively controlling and optimizing engine operation over a full load-speed map when using advanced low-temperature or mixed-mode combustion options. This includes control of: a) ignition timing across the load-speed map; b) the rate of heat release; and c) transients and cold starts. Either virtual or direct sensors for determining the mode of combustion and its boundary are needed.
- Inadequate systems control technology for integration and optimization of engine operation and multiple emission reduction systems.

High-Efficiency Engines - Hydrogen-fueled: The major IC engine related barriers to achieving advanced, hydrogen-fueled, spark-ignited IC engines meeting the thermal efficiency and emissions goals in Table 1b are:

- A hydrogen-fueled engine requires the use of technologies to increase engine power density, especially when dilute, low-temperature combustion of hydrogen is implemented for NOx emission control. These include the use of turbo/super charging, intercooling, and/or high compression ratios. The resulting dilute, high-pressure, high-temperature in-cylinder conditions push combustion into a parameter space where hydrogen combustion stability, combustion duration, and pre-ignition phenomena are not well understood.
- Use of EGR provides one method of intake charge dilution to control NOx formation. EGR levels of 50% and higher may provide emissions reduction benefits, but the tolerance of combustion to the high EGR levels is not understood and components to deliver high EGR levels without throttling of the engine do not exist.
- Several fueling strategies can be used: throttle-body, port fuel injection, and direct injection. Direct injection offers the highest engine power density, as well as improved safety by eliminating the possibility for

flashback. By timing the direct injection after intake-valve closure, 20-30% improvements in power density can be achieved. However, a lean or dilute and nearly homogeneous mixture must be created by the hydrogen jet and in-cylinder gas motion before combustion of mixtures rich enough to form significant NOx can occur. Improved understanding of direct-injection hydrogen mixing processes is needed to optimize direct injection systems.
- The high diffusivity and small molecular size of hydrogen makes injector leakage an issue. Also, fuel injectors and other components typically rely on the fuel for lubrication, but hydrogen has no lubricity making durability a potential problem.
- Hydrogen embrittles many materials.

Technical Strategy

High-Efficiency Engines - Hydrocarbon-Fueled: The ACEC Technical Team will focus on supporting the development of emission control technologies and combustion technologies needed to enable engines with high, CIDI-like engine efficiencies that meet EPA Tier 2 standards in a cost effective durable manner, thus providing a major efficiency gain over conventional PFI engines. For additional fuel economy improvements, a systematic approach will be pursued to further minimize losses associated with emission controls, friction, and other parasitics, and thermodynamic losses during combustion, and heat transfer.

Aftertreatment Systems:
- Develop improved understanding and modeling capabilities for catalyst-based aftertreatment system fundamentals (*e.g.*, surface chemistry) needed to further develop and optimize PM and NOx aftertreatment systems, reduce their fuel economy penalties, expand their temperature window, increase their effectiveness especially at low temperatures, and make them more cost effective and less susceptible to catalyst deactivation (*e.g.*, by sulfur and other poisons, coking, and surface morphologic changes).
- Continue to develop the adsorber and SCR/reductant NOx aftertreatment strategies and any associated reductant delivery systems and regeneration processes. The goals are to reduce costs and any fuel economy penalties, while simultaneously improving the temperature operating window, NOx reduction effectiveness, durability, space (volume) requirements, and control during transients as needed for each system. Also, strategies using partially reformed fuel as a reductant to increase catalyst activity will require the development of effective fuel reformers.
- Fuel sulfur levels of 15 ppm or less will be phased-in between 2006 and 2010, however, the durability of aftertreatment systems even at these sulfur levels needs to be established (except for urea-SCR). Desulfurization strategies (*e.g.*, for NOx adsorbers) will be needed during

the transition period, and maybe permanently if sulfur poisoning still proves to be a durability problem with 15 ppm sulfur fuels.

- Improve catalyst-based PM trap regeneration methods and reduce their fuel economy penalties. Current regeneration strategies include raising engine exhaust temperatures by injection of fuel late in the engine cycle, use of EGR, intake or exhaust throttling, lowering the effective expansion ratio via split, post or retarded injection, microwave heating (which offers wide load range regeneration capability, especially at loads where fuel injection methods do not work well), and multi-canister sequential regeneration via electrical heating. Methods for handling ash buildup also need development.

Advanced Low-Temperature Combustion Technology:

- Conduct research using gasoline and diesel fuel to develop the fundamental knowledge-base for low-temperature combustion and emissions processes and their dependencies on fuel injection, air motion (*e.g.*, swirl), fuel-air mixing, combustion chamber geometry, and chemical kinetic processes through both experimental and modeling approaches. Use the knowledge-base to support the development of advanced, high efficiency engines and the engine simulation tools used to aid the rapid development and optimization of engines.
- Determine the injection strategies (*e.g.*, multiple fuel injections, higher injection pressures, smaller orifices, orifice geometry, *etc.*) needed to tailor fuel-air mixing processes to optimize the LTC combustion process for maximum fuel economy while meeting prevailing emissions standards.
- Develop technologies to effectively control ignition timing across the load-speed map with rapid response. Since ignition timing is most sensitive to temperature and since temperature can be influenced by a number of parameters, potential control technologies include VVT (low-cost cam phasers to electro-hydraulic systems) to control hot residuals and effective compression ratio, intake air blending with air heated with an exhaust stream heat exchanger, VCR, and hot exhaust gas recirculation.
- Determine the factors limiting the load and/or speed ranges over which various types of LTC work and develop methods for extending the limits. Potential methods include intake pressure boosting, tailored thermal stratification of the charge to produce sequential autoignition and a slower overall heat release rate, and tailored mixture stratification for fuels with two-stage ignition chemistry (*e.g.*, diesel fuel) to distribute “cool-flame” heat release rate. Mixture stratification can be achieved by fuel injection strategies and/or by in-cylinder flows and combustion chamber geometry. Fuel composition changes are also an option for extending the limits of operation of LTC regimes.
- Technologies for controlling the engine during rapid transients must be devised that are sufficiently fast to accommodate the rapid transients experienced in automotive applications. This may involve combining rapid

controls that have a limited control range, such as intake air blending, with slower controls such as VCR or a low-cost VVT system that combined can provide a greater range of control.

- Develop methods for controlling hydrocarbon (HC) and carbon monoxide (CO) emissions and the associated combustion inefficiencies at low loads, especially for operation in an HCCI mode. At the very low temperatures experienced near idle conditions, oxidation catalysts lose effectiveness and the combustion inefficiency results in a significant fuel-economy penalty. Initial results suggest that effective use of charge stratification at low loads can significantly improve combustion efficiency at the lower loads and reduce HC and CO emissions, but further development is needed. Other options that need to be examined include heating of the intake air or throttling of the intake allowing a higher overall equivalence ratio and higher combustion temperatures (at the expense of reduced thermal efficiency).
- Determine the characteristics of wall heat transfer during LTC operation and during transients, especially transients during changes in mode of operation.
- Operating an engine using LTC combustion over the entire speed, load range could eliminate the need for exhaust gas PM and NOx aftertreatment systems, providing a lower cost option for high efficiency engines. Achieving this goal will require increasing the LTC load range capabilities (as already discussed), plus providing LTC cold start capabilities. Solutions to the ignition problem (aside from using conventional CIDI or SI engine ignition strategies which could introduce PM and NOx emissions) include promoting compression ignition by increasing the compression ratio with a VVT or VCR system during cold start, use of ignition assists such as a glow plug until the engine warms up, or use of a small burner to heat intake air initially.
- <u>Mixed-mode operation:</u>
    - Improvements in the knowledge-base and modeling capabilities for both conventional and LTC combustion modes will be needed to design combustion systems that operate effectively on different modes of combustion over the entire speed-load range. It is especially critical that mixed-mode operation at high loads with conventional CIDI combustion produce emissions that are as low or lower than current CIDI 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.
    - Develop technologies and control mechanisms that allow an engine to operate smoothly in both LTC and conventional CIDI or SI combustion modes, and to switch smoothly between LTC and conventional operation. Fuel-injection strategies, in-cylinder mixing techniques, and combustion chamber geometries must be developed that can produce the required fuel/air mixture for effective LTC combustion, yet be capable of operating in an SI or CIDI mode using only adjustments that

can be readily made during engine operation. This might include adjustments to the effective compression ratio using VVT or developing operating regimes where the engine can operate in either LTC or SI mode. The development of a practical VCR system would also be beneficial for improving the efficiency and range of LTC-mode operation without compromising the power density under SI operation.

Strategies specific to 2007-2013 brake thermal efficiency: Many of the elements of the previous section on Advanced Low-Temperature Combustion are important to reaching the brake efficiency targets. Additional necessary approaches are presented as follows

- Using models and experiments, update the baseline energy and exergy distributions and losses in modern CIDI and LTC mode operations. This will aid in identifying the areas for improvement and R&D priorities.
- Using the resulting baseline data, develop and validate systematic strategies to mitigate the quantified losses, such as:
    - Using models and experiments, determine the extent that LTC can be exploited to mitigate availability losses in combustion and heat transfer.
    - Develop and validate effective approaches to utilizing low-temperature energy from exhaust and EGR coolers.
    - Develop and validate novel approaches to reducing parasitic losses associated with accessories, fueling systems, and friction.
    - Examine improvements to the base engine thermodynamic operation through greater expansion ratio, recuperation, reduced heat transfer, and combustion phasing. Improvements in boosting and exhaust utilization efficiency should be examined.
    - Give high priority to the part load efficiency goal, since this is where more gain in over-the-road fuel economy can be achieved.
- Track progress toward efficiency goals and progress in mitigating individual loss mechanisms in modern engine platforms at lab sites, but in very close cooperation with industry, such as through the ACEC team or Combustion MOU.

Cost: Minimize the cost increases of engine/aftertreatment system relative to a conventional PFI engine to provide a favorable trade-off between the increased engine/aftertreatment system costs and the reduced operating costs resulting from a higher fuel economy.

- Reduce the cost of engines with CIDI-like fuel efficiencies through effective use of the ultra low-emission potential of LTC modes to lower engine-out emissions, thus reducing aftertreatment system costs.

- Reduce aftertreatment system costs and develop new catalyst materials for NOx and PM reduction that improve the cost effectiveness of aftertreatment systems (*e.g.*, eliminate the use of precious metals).
- Reduce the cost of sensor technology.
- Optimize engine/aftertreatment system performance.

Enabling technologies:

- Develop and/or improve sensors for NOx and PM needed 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 NOx.
- Develop combustion feedback sensors that can be used for determining the combustion mode an engine is operating on. Such capabilities will be needed to control mixed-mode engine operation and the engine/after-treatment system.
- Develop on-board fuel sulfur traps if sulfur poisoning still proves to be a durability problem with 15 ppm sulfur fuels.
- Develop new sensitive, real-time PM measurements diagnostics for developing engines with ultra low-PM emissions, especially during rapid engine transients, and for providing the engine out emissions characterization needed for design optimization and life-cycle analysis of PM aftertreatment systems.
- Develop variable valve actuation and variable compression ratio technologies for enabling maximum utilization of LTC combustion strategies and for maximizing engine efficiency.

Powertrain systems integration:

- Demonstrate progress toward goals in thermal efficiency, aftertreatment, and LTC technologies using modern engine platforms and prototype systems. In some cases, mule vehicle (not expensive show cars) demonstrations may be invoked to validate what can be achieved and to observe transient effects.
- Develop and utilize models of engine, combustion and aftertreatment systems to help demonstrate complete integrated systems.
- Develop the sensors and control technologies (See *Enabling Technologies*) needed to control integrated powertrain systems.

<u>*High-Efficiency Engines - Hydrogen-Fueled*</u>*:* The hydrogen IC engine efforts within DOE's Combustion and Emission Control Program will focus on R&D that supports the development of advanced, hydrogen-fueled IC engines with efficiencies that approach those of high-efficiency CIDI engines, power densities that are comparable to conventional PFI engines, and emissions that at minimum comply with EPA Tier 2 standards, bin 5, all in a cost effective durable manner.

- Develop hydrogen engine technology that couples lean, low-temperature combustion of hydrogen, which has very low NOx emission capabilities, with technologies such as turbo/super-charging, intercooling, high compression ratios, and/or direct injection of hydrogen to provide engine power densities comparable with current PFI gasoline engines.
- Conduct research to develop the fundamental knowledge-base on very lean, low-temperature hydrogen combustion under high-pressure in-cylinder conditions. The knowledge-base is needed to support both the development of advanced hydrogen-fueled engines and the simulation tools used to aid the development and the optimization of engines. This will require improved understanding of hydrogen injection and fuel-air mixing processes; combustion stability, combustion duration and pre-ignition phenomena; and the effects of engine speed and load, combustion chamber geometry and in-cylinder air motion (*e.g.*, swirl) on hydrogen combustion and emissions processes.
- Aggressive EGR and stoichiometric combustion coupled with conventional aftertreatment to control NOx emissions and pressure boosting also has potential as a hydrogen IC engine strategy. Combustion tolerance to the high EGR levels and systems for delivering high EGR levels must be developed. The load range capabilities for this option must be determined.
- Determine the optimal hydrogen injection strategy. Hydrogen injection strategies include throttle-body, port fuel injection, and direct injection, with the latter providing significant safety and power density advantages.
- Develop hydrogen compatible components (fuel injector, ignition system, spark plugs, pistons, valves, rings, *etc.*).
- Develop improved lubricant control technology. 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.
- Determine the options for lean-NOx aftertreatment in the event that they will be required, and conduct R&D to provide that option.

<u>Leveraged Research from other DOE FCVT programs</u>:

- *Light truck and heavy truck diesel R&D programs.* DOE R&D programs in these areas include substantial activity on engine technology, combustion, aftertreatment, and related enabling technologies for the special requirements of these applications. The potential cross-cutting application to passenger car vehicles was a key basis for creating the Diesel Crosscut team that helps guide the research for maximum leveraged benefit. Most of the effort in this program is conducted via cooperative agreements with the engine OEMs or through CRADAs.
- *Propulsion Materials Program.* The DOE Propulsion Materials Program is addressing certain materials needs for catalytic and plasma aftertreatment, sensors, EGR components, fuel systems, and particle filter

media that have direct application to emissions barriers. Furthermore, the program supports 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. A survey of industry and study regarding materials issues for HCCI engines was started in early CY 2005.

- *Fuels Technology Program.* This program conducts R&D in two significant thrusts: (1) determine fuels characteristics that can help enable high-efficiency, low-emission engine technologies, and (2) conduct research that will stimulate or enable use of non-petroleum fuels, including stimulating progress toward hydrogen-fueled transportation.
  - With respect to fuels as enablers, the program has supported extensive studies of diesel fuel sulfur effects on emission control devices and systems. These efforts were cited in the EPA rules requiring low sulfur diesel fuel and have resulted in several complete test beds for fuel and emission control aging studies, including a passenger car and a light-truck each equipped with NOx adsorber systems. Methods are also being developed to study the fate of phosphorous compounds in aftertreatment systems. Depending on future budgets, this phase of the program may be extended to determine the effects of other fuel parameters besides sulfur and phosphorous.
  - Research capabilities for determining the fundamental effects of fuel composition (including oxygenation) on combustion and emission processes in-cylinder have been developed and research is underway to determine fuel composition effects on CIDI combustion and is planned for LTC regimes.
  - Renewable fuel options are also being examined as part of the program to determine their emissions characteristics and general compatibility with CIDI and LTC strategies.
  - Research on how to tailor fuel composition to create optimal NOx adsorber reductants is underway.
  - Health effects studies of exhaust from diesel and spark ignition engines have also been conducted under the auspices of the Fuels Program. These efforts have resulted in an overall improvement in perspective concerning the environmental impacts of diesel engine exhaust.