Overview of the DOE Advanced Combustion Engine R&D

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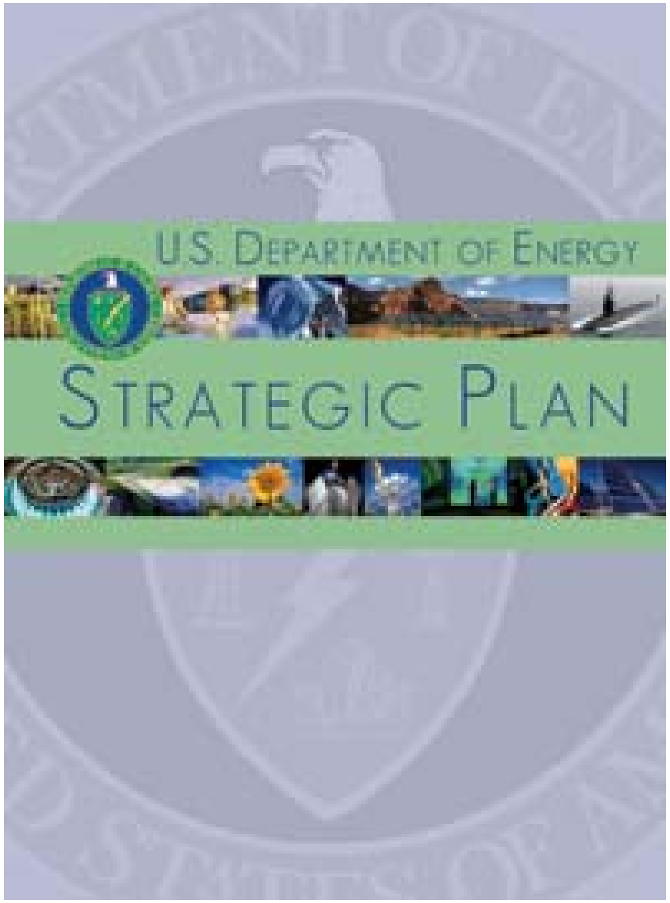
Supports DOE's Energy Security Strategic Goal

Energy Security Strategic Goal

- **Goal 1.1 – Energy Diversity**
  - Reduce dependence on energy imports, particularly oil in the transportation sector…
  - Collaborate globally with governments and scientists to expedite the development and deployment of unconventional energy resources…
- **Goal 1.2 – Environmental Impacts of Energy**
  - Develop technologies to reduce vehicle emissions by improving efficiency and greatly expanding the use of clean fuels…



Our Oil Situation

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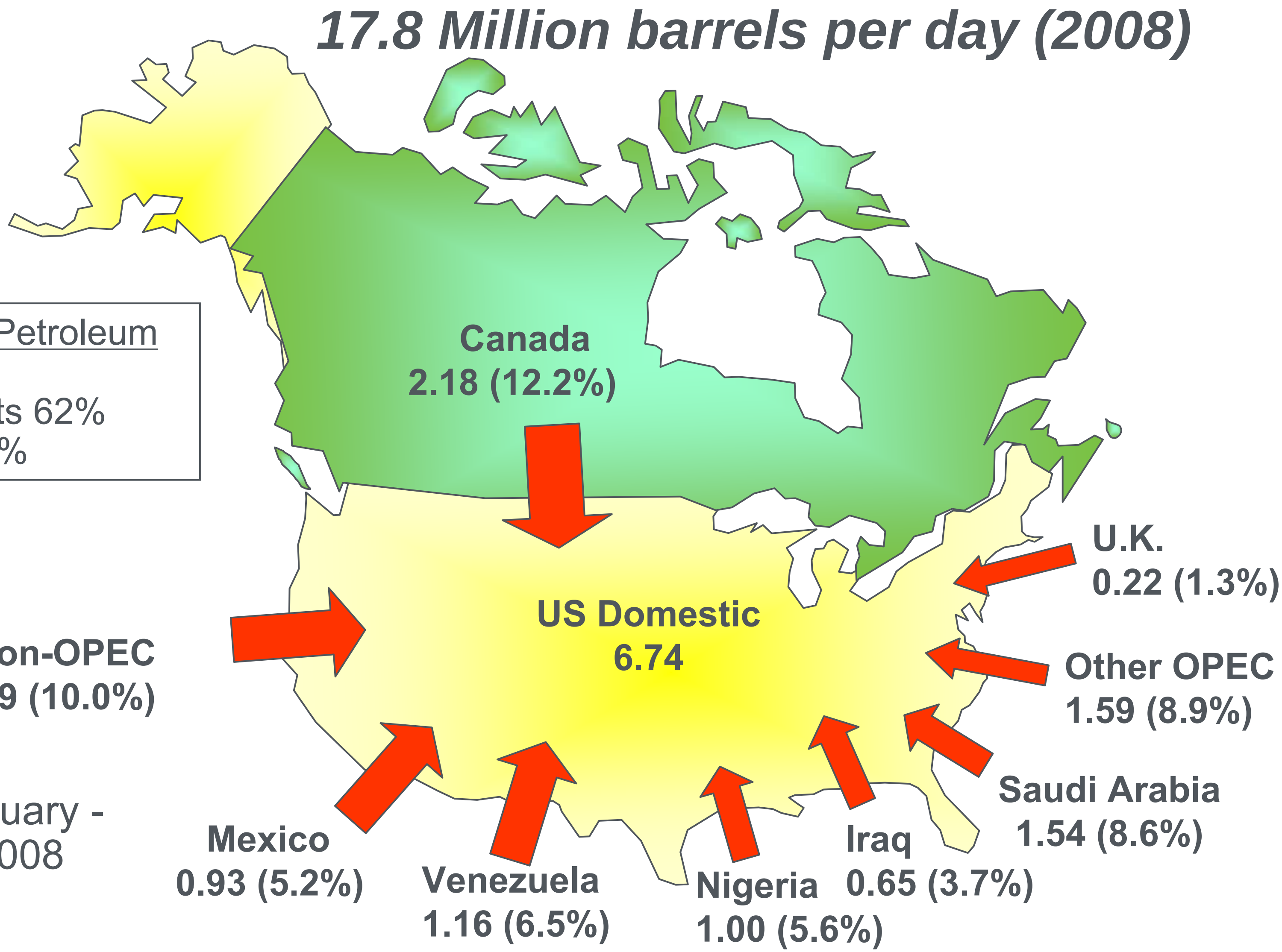
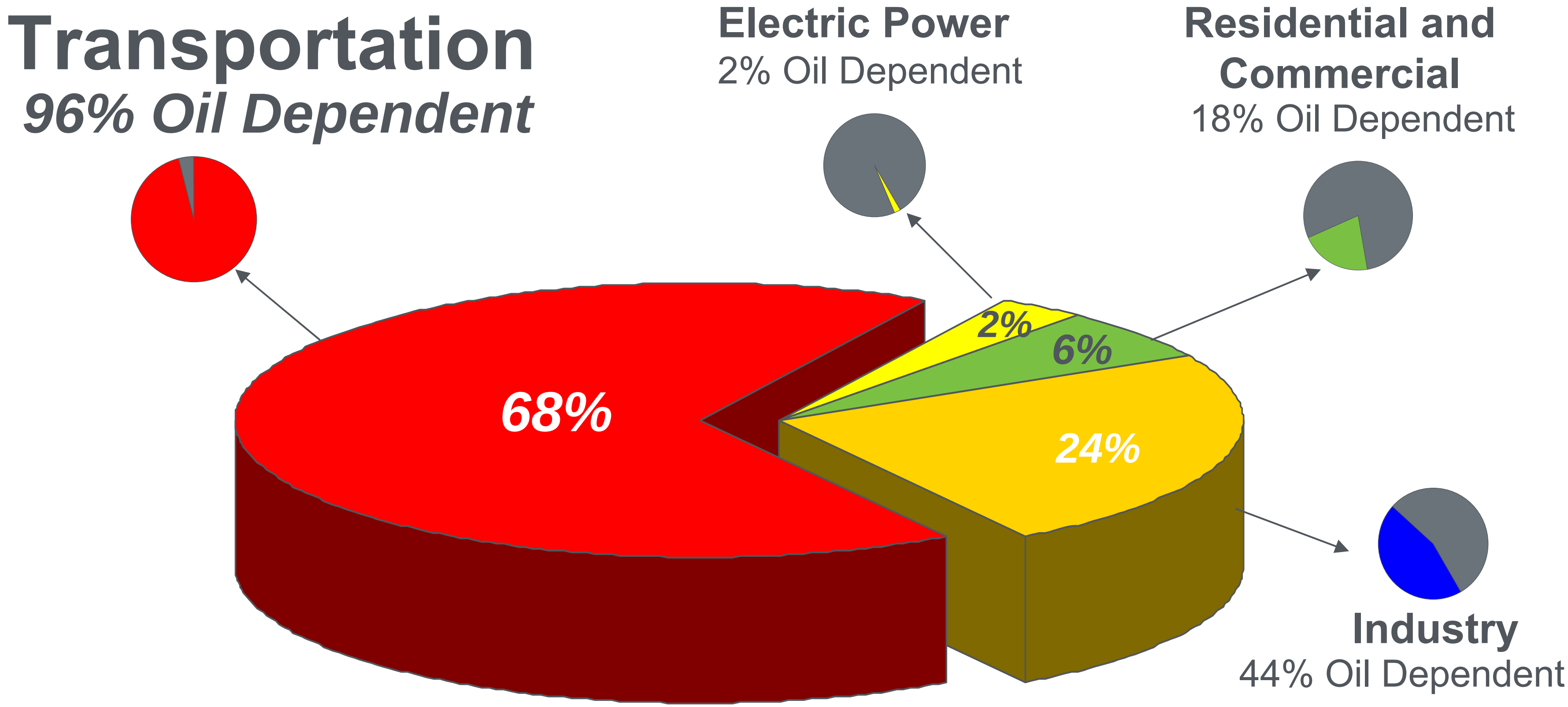
Crude Oil & Petroleum Products
Gross Imports 62%
Domestic 38%

Data for January - October 2008



Source: Crude Oil and Petroleum Products, *EIA Petroleum Supply Monthly, December 2008*.

Oil Consumption by End-Use Sector, 2007
20.7 Million Barrels per Day (39.8 Quads)



Source: *DOE/EIA Annual Energy Review 2007*, July 2008 *(Next Update: June 2009)*

U.S. Oil Dependence Is Driven By Transportation

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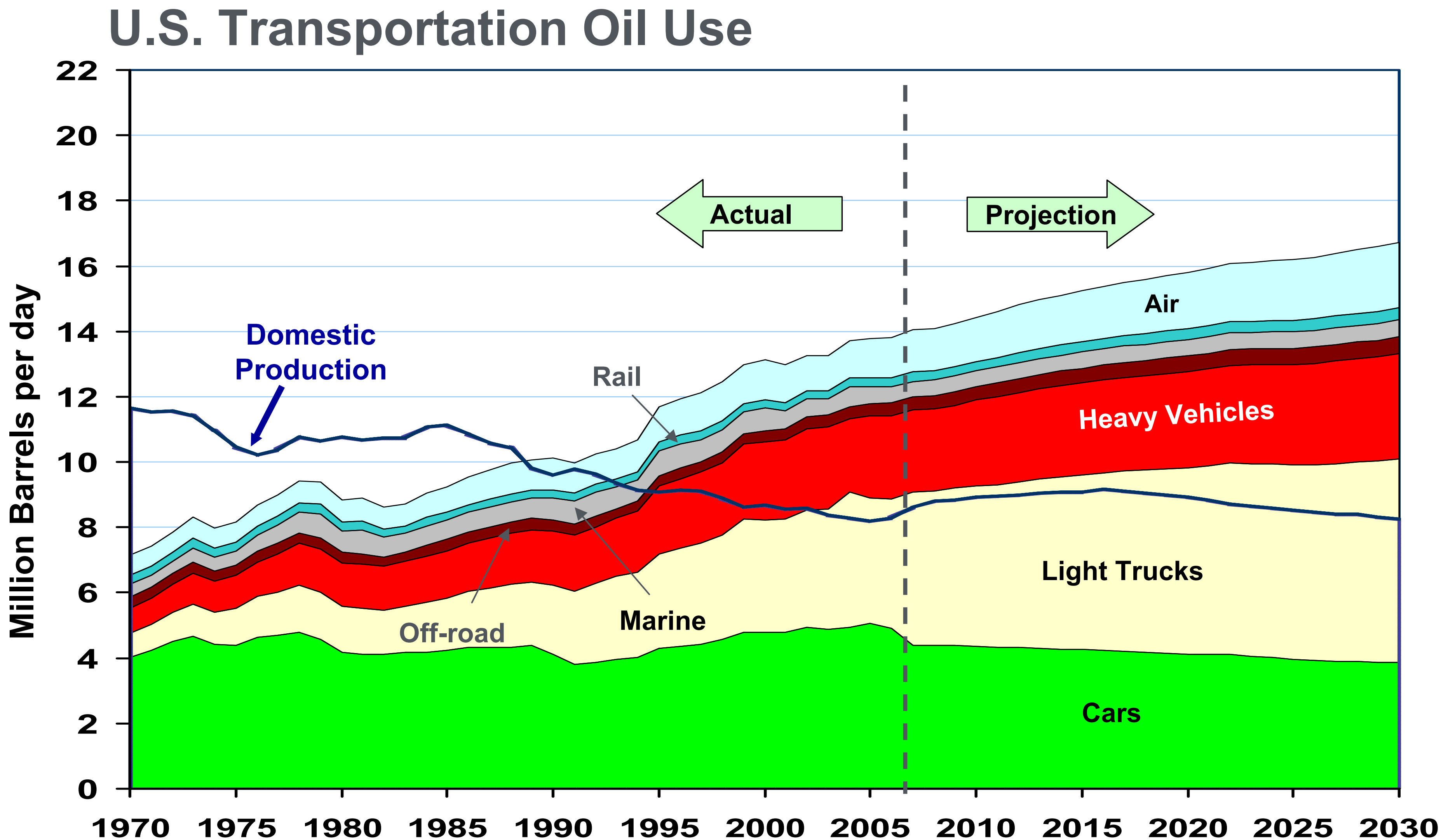

Sources: Actual: *Transportation Energy Data Book, Edition 27*, ORNL, 2008.
Projection 2007-2030: *EIA Annual Energy Outlook 2008*, February 2008. (includes CAFE increase per EISA)

Vehicle Technologies Program Vision and Mission

Vision: *Transportation energy security will be achieved through a U.S. highway vehicle fleet of affordable, full-function cars and trucks that are free from petroleum dependence and harmful emissions without sacrificing mobility, safety, and vehicle choice*.

Mission: *Develop more energy-efficient and environmentally friendly highway transportation technologies that enable America to use less petroleum*.

Pathways to Energy Security for Future Transportation

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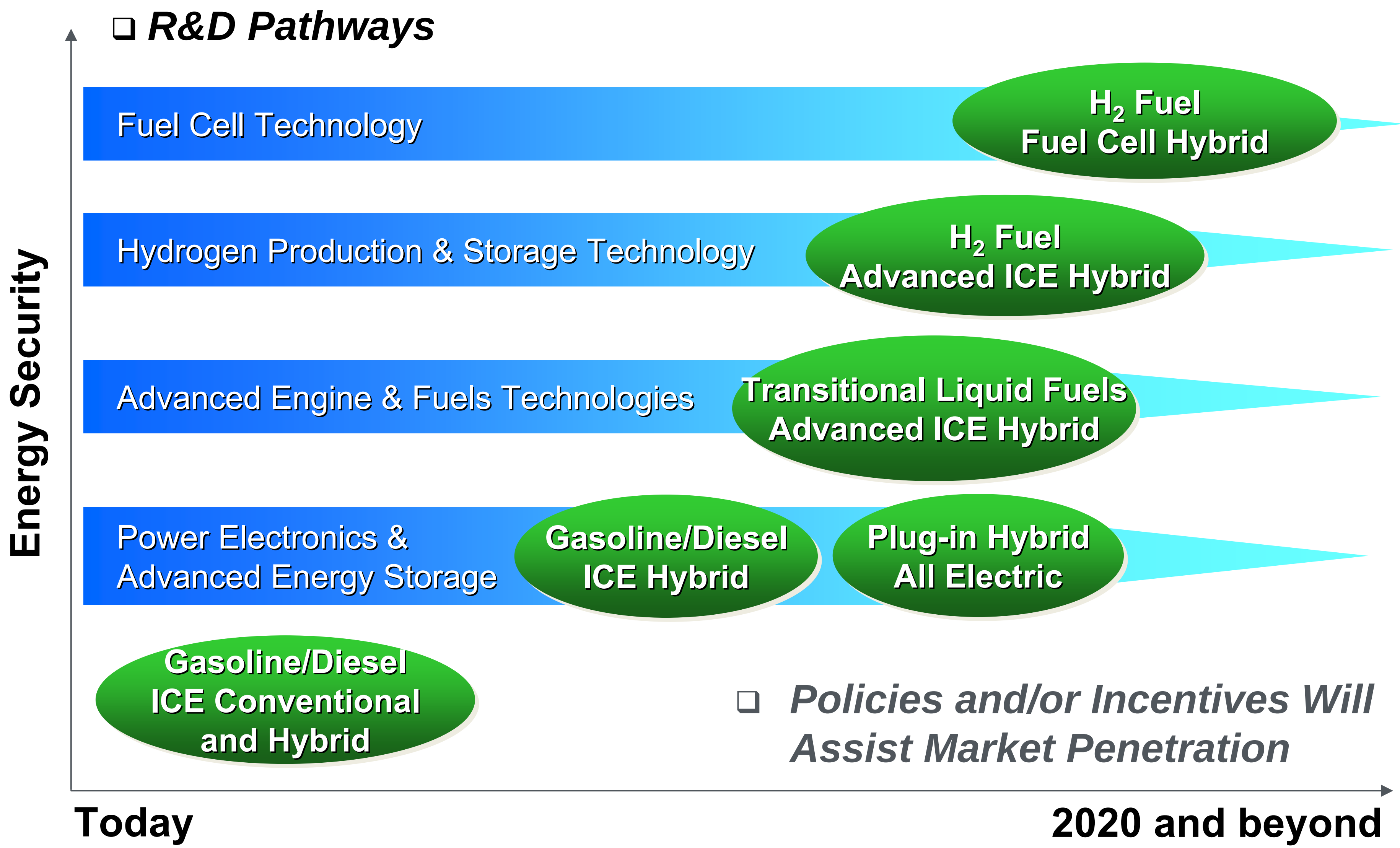

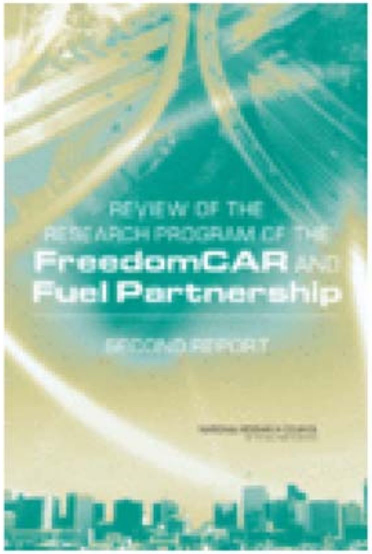

The National Research Council fully supports advanced combustion engines research:

"***Internal combustion engines (ICEs) will be the mainstay of the nation's automotive fleet for a very long time***, even if the goals of the fuel cell program and the hydrogen infrastructure program are met, enabling fuel cell vehicles to be introduced in large numbers by 2020."

"This kind of ***research has provided understanding*** that allows ICE engines ***to meet emission constraints and efficiency goals simultaneously***. …would have an immediate, significant effect on petroleum use. … new findings are quickly translated into large-scale development activities and, if these are successful, ***will be rapidly deployed by industry***. …"

Source: *Review of the Research Program of the FreedomCAR and Fuel Partnership: Second Report,* Committee on Review of the FreedomCAR and Fuel Research Program, Phase 2, National Research Council, 2008.

Advanced Combustion Engine R&D

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Strategic Goal: Reduce petroleum dependence by removing critical technical barriers to mass commercialization of high-efficiency, emissions-compliant internal combustion engine (ICE) powertrains in passenger and commercial vehicles

Primary Directions

- ICE efficiency improvements for cars, light- and heavy-duty trucks through low-temperature combustion and minimization of thermal and parasitic losses
- Aftertreatment development integrated with combustion strategies for emissions compliance and minimization of efficiency penalty
- Waste energy recovery with thermoelectric and mechanical systems
- Coordination with fuels R&D to enable clean, high-efficiency engines using hydrocarbon-based (petroleum and non-petroleum) fuels and hydrogen

Performance Targets

	2010 (light-duty)	2018 (heavy-duty)
Engine brake thermal efficiency	45%	55%
Powertrain cost	< $30/kW	
NOx & PM emissions	Tier 2, Bin5	EPA Standards

Advanced Engine R&D Budget by Activities

Major Activities	FY 2008 Appropriation	FY 2009 Appropriation	FY 2010 Request
Advanced Combustion Engine R&D	**$44,591K**	**$40,800K**	**$57,600K**
Combustion and Emission Control	38,815	35,089	47,239
Combustion Research at National Labs	10,700	14,400	↘
Combustion R&D with Industry	8,500	7,600	↑
Combustion Research with Universities	2,100	1,400	↑
TOTAL	$21,200	$23,400	↑

Basic Energy Sciences Budget: $35M
Vehicle Technology Fuels: $8M
Industrial Technology Program: $10M
Others

Overall R&D Approach

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Advanced Combustion Engine R&D → **Industry**

Fundamental Research → **Applied Research** → **Technology Maturation & Deployment**

Fundamental R&D

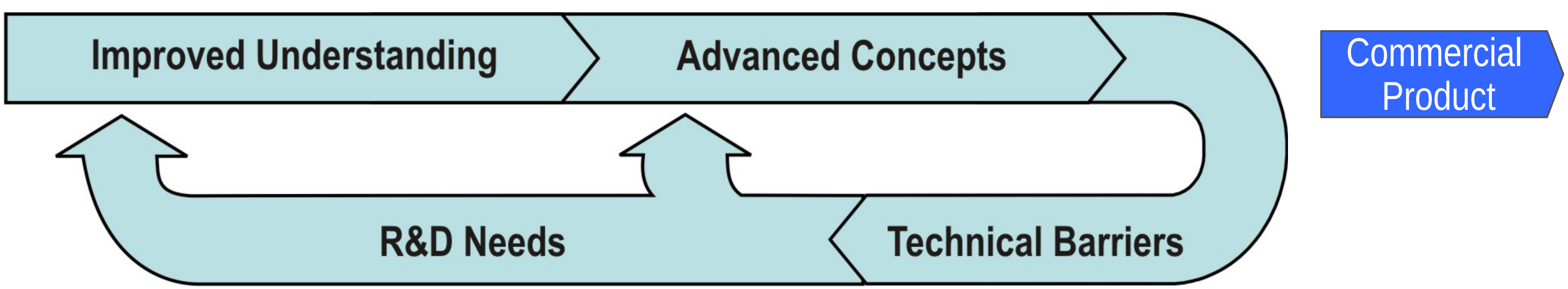
- SNL – Advanced Combustion Strategies (lean-burn, LTC, advanced DI)
- PNNL – Catalyst Characterization (NOx and PM Control)
- ANL – X-ray fuel spray characterization
- LLNL – Chemical kinetics models (LTC and emissions)
- LANL – CFD modeling of combustion
- Universities (U. of WI, Texas A&M, U. of MI, MIT, others) – Complementary research

Fundamental to Applied Bridging R&D

- ORNL – Experiments and simulation of engines and emission control systems (bench-scale to fully integrated systems)
- ANL – H_2-fueled ICE; fuel injector design

Competitively Awarded Cost-shared Industry R&D

- Auto and engine companies – engine systems
- Suppliers – enabling technologies (sensors, VVA, WHR)



Fundamental Combustion Research

- **Strategic Goal**: To provide the science base on combustion and emission processes needed to develop more efficient, cleaner engines for transportation.
  - Supports FreedomCAR mid-term program goals
    - light-duty - peak efficiency of 45%, emission compliant, by 2010
  - Supports 21st Century Truck Program goal
    - heavy-duty - peak efficiency of 50%, emission compliant, by 2015

- Key customers: the U.S. vehicle and engine industry.

- Strong interactions and collaborations between industry, suppliers, universities, and national labs.

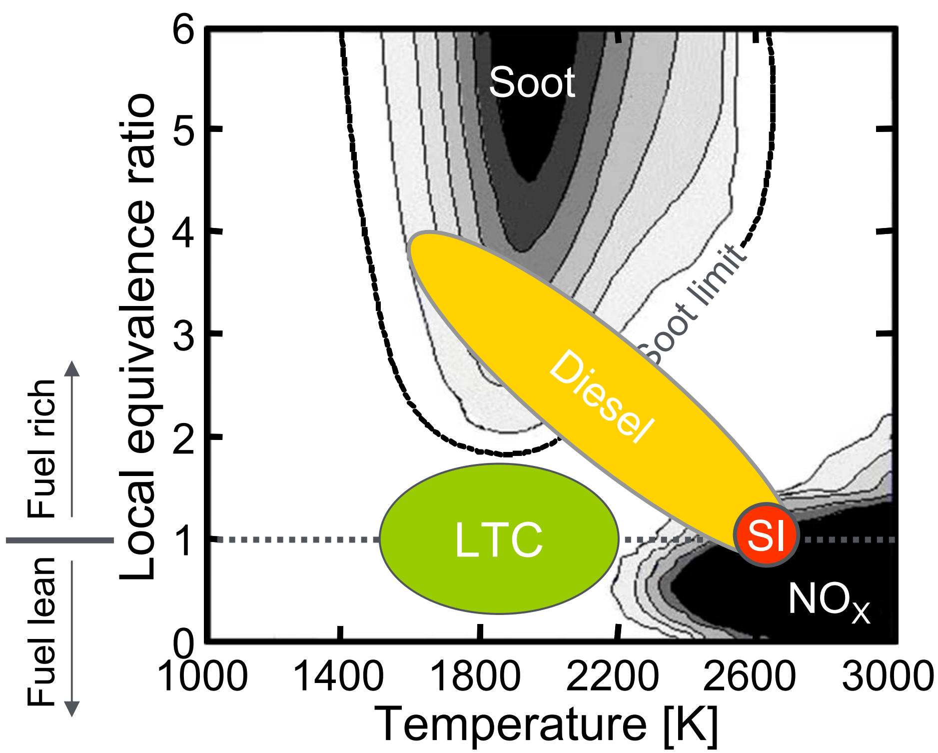
Advanced Combustion MOU

Goal: To develop the knowledge base for low-temperature combustion (LTC) strategies and carry research results to products.

- Combustion work coordinated under a Memorandum of Understanding (MOU) – Recently renewed through 2013
- Five energy companies joined MOU in 2006
  - Added perspectives for production of potential fuels or fuel blends

Focus On Low-Temperature Combustion (LTC) Strategies

Potential to enable high-efficiency and low-emission operation



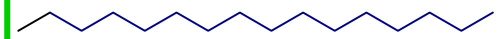
- LTC used generically to represent many processes
  - Homogeneous-Charge Compression-Ignition (HCCI)
  - Premixed-Charge Compression-Ignition (PCCI), SCCI, HECC, MK, UNIBUS, …
- Challenges
  - Combustion phasing
  - Load range
  - Heat release rate
  - Transient control
  - HC and CO emissions
  - Fuel characteristics

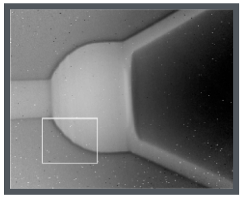
Fundamental Research Tools Improve Combustion Models, Engine Simulations, and Support Industry R&D

- Close coupled modeling and experiments
  - Advanced diagnostics
    - Optical-, laser-, and x-ray- based techniques
  - Multi-/single-cylinder engines
  - Combustion simulators
  - Multi-dimensional computational models
  - Fuel kinetics
- Close collaboration between industry, national labs and universities

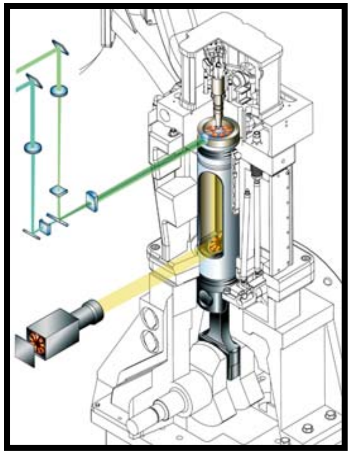
<u>Recent key accomplishments in following slides</u>

n-hexadecane

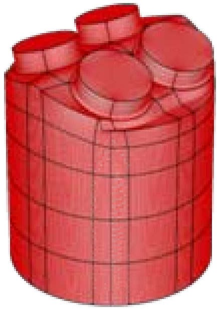




Nozzle Sac X-Ray Image

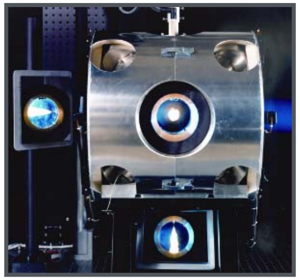


Optical Engines

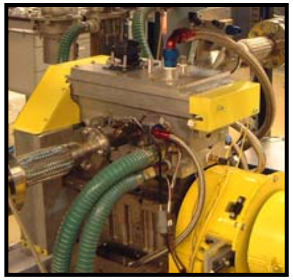


3-Million Cell LES Grid

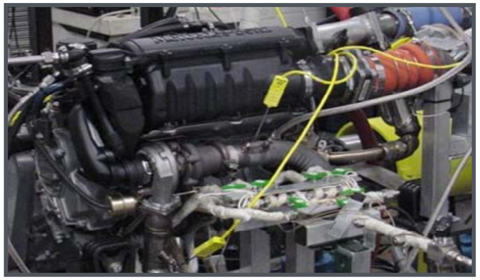
HCCI & Lean-burn Gasoline



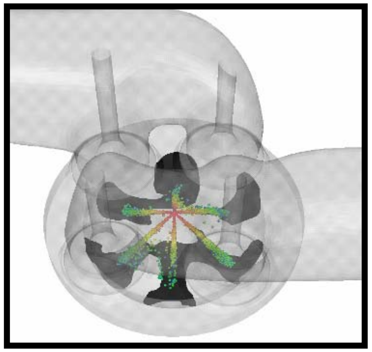
LTC Simulator



H2 Engine



Multi-Cylinder Diesel, LTC and Lean-burn Gasoline



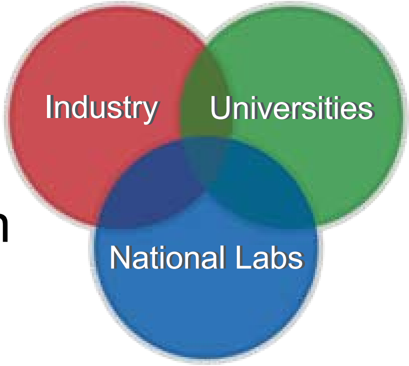
Engine Simulation

Leading to engine CFD modeling tools widely used in industry

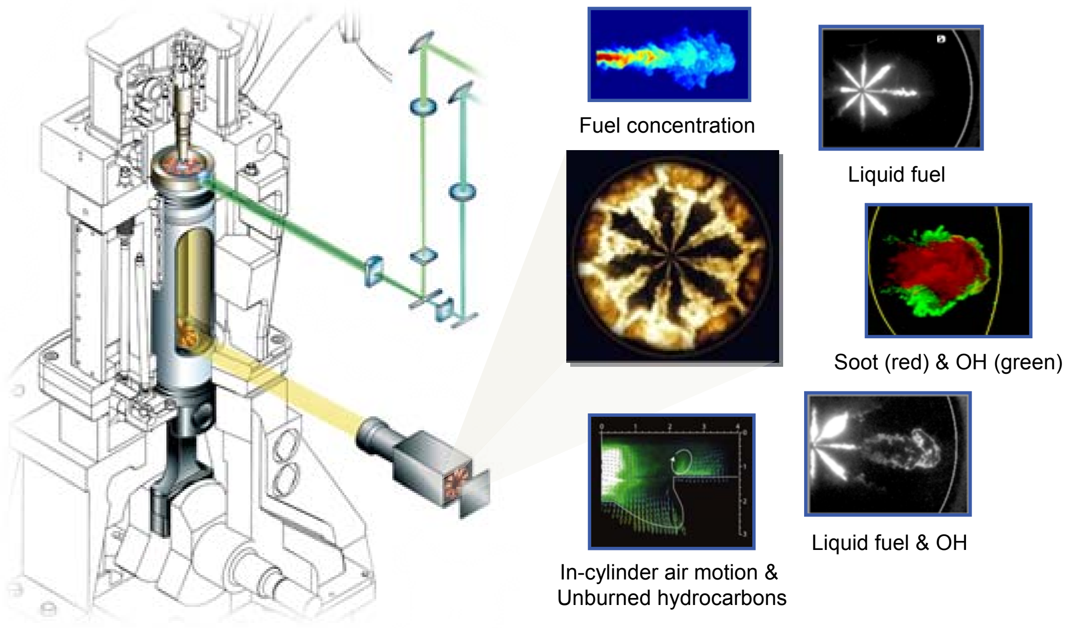
A "Science-Based Engineering" Milestone

Cummins 2007 ISB 6.7 liter diesel

- The science and technology foundation was provided by a DOE-supported multi-institution collaboration.



- Sandia's Combustion Research Facility provided a key enabler – the fundamental understanding of the physical and chemical processes driving diesel combustion.



GM with DOE Support Takes New Combustion Technology Out of the Lab and Onto the Road

FOR RELEASE: 2007-08-24

PONTIAC, Mich – Engine experts have dreamt about it, talked about it and lectured about it, and today – for the first time – General Motors is letting outside parties drive the "most awaited advanced combustion technology" of the past 30 years.

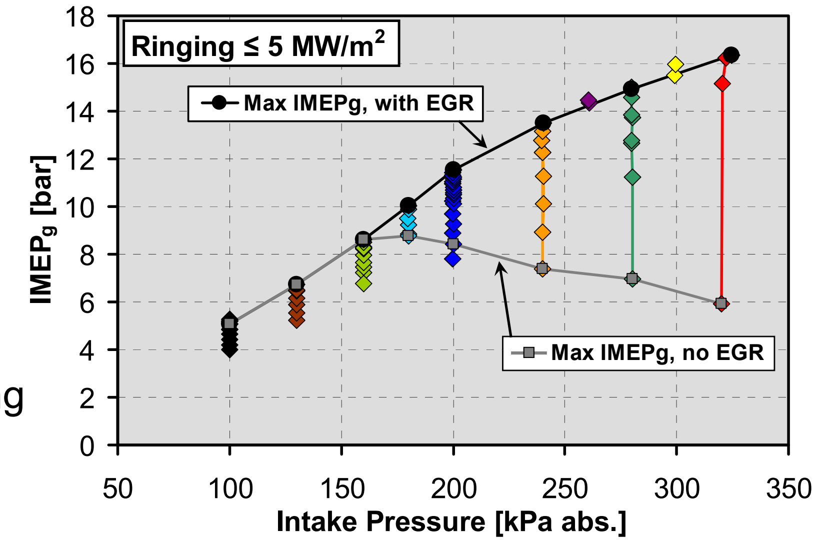
GM demonstrated the combustion process, known formally as homogeneous charge compression ignition, or HCCI, for the first time in two driveable concept vehicles, a 2007 Saturn Aura and Opel Vectra. When combined with the enabling advanced technologies such as direct injection, electric cam phasing, variable valve lift and cylinder pressure sensing, HCCI provides up to a 15-percent fuel savings, while meeting current emissions standards.

Motivation:

- Increase the high-load limit of HCCI
  - Allow use over a much more of the operating map
  - Offer potential for full-time HCCI.

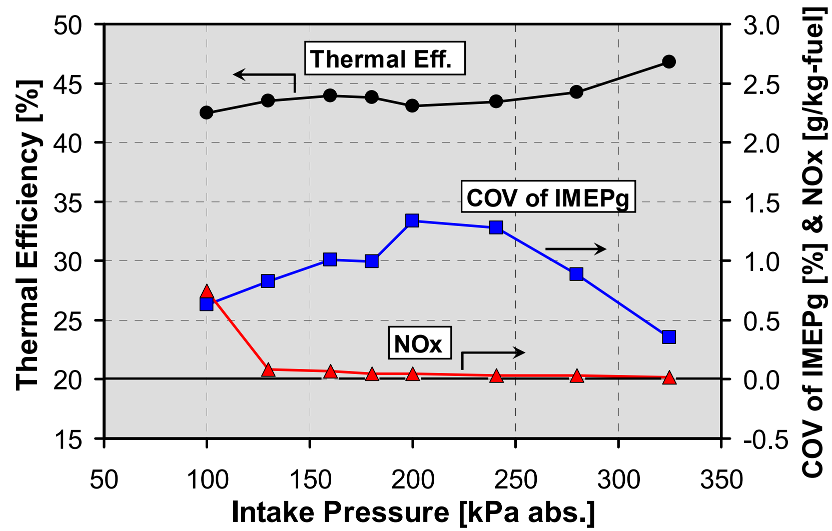
Method:

- Boosting combined with cooled EGR and intake temperature adjustment are used to:
  - Control the autoignition enhancement from boosting
  - Prevent knock by retarding combustion timing
- Fuel: Conventional 87-octane gasoline.



Findings:

- Boosted HCCI achieves loads comparable a turbo-charged diesel ⇒ **$IMEP_g$ of 16.3 bar**
  (1200 rpm, P_{boost} = 324 kPa, T_{in} = 60°C combined with EGR)
  - **Stability** ⇒ COV of $IMEP_g$ < 1.5%.
  - **No engine knock** ⇒ Ringing ≤ 5 MW/m²
  - **High efficiency** ⇒ Indicated thermal eff. = 47%,
  - **Ultra-low NOx** ⇒ 0.015 g/kg-fuel



Currently investigating robustness of the high-load operation over a broader parameter range.

Dual-fuel (gasoline/diesel) LTC achieves 53% efficiency and EPA 2010 emissions without aftertreatment (UW)

Motivation:

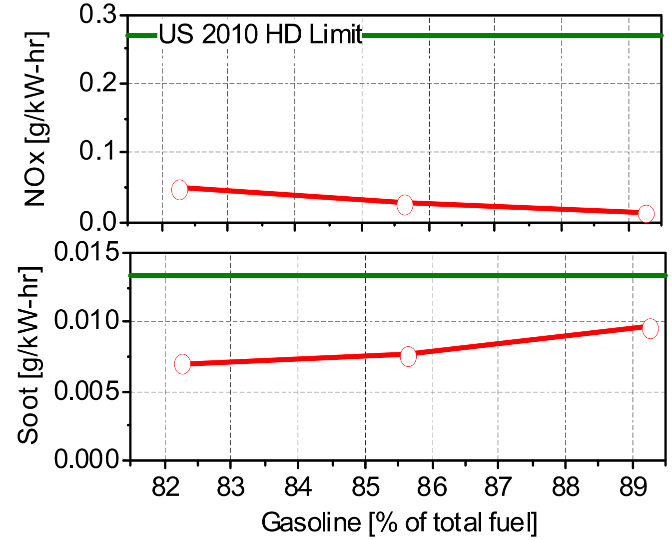
- Low emission HCCI has high load limits caused by uncontrolled high pressure rise rates (PRR) and timing. Optimized fuel reactivity can provide control.

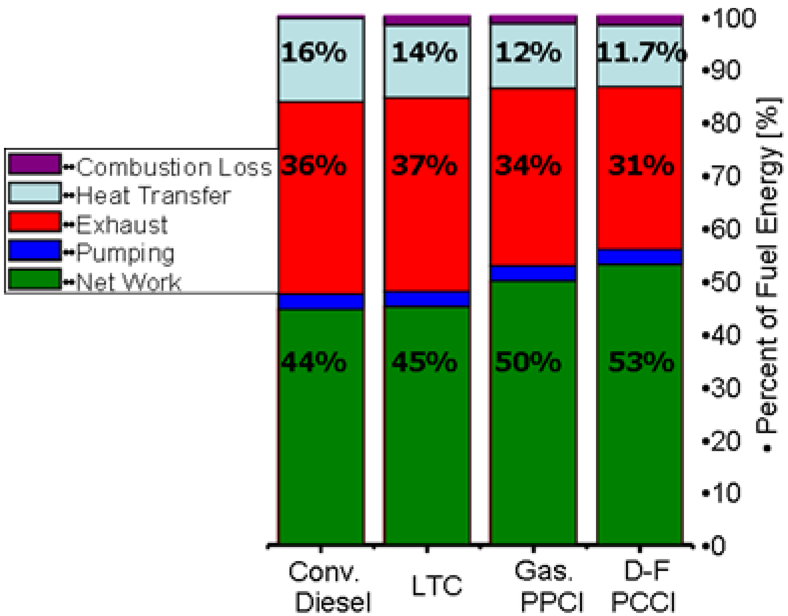
Method:

- Dual-fuel PCCI concept used to control fuel reactivity.
  - Port fuel injection of low reactivity gasoline
  - Blended in-cylinder with high reactivity diesel using low pressure multiple injections*.
- Experiments conducted in Caterpillar 3401 HD diesel.
- Guided by CFD with Genetic Algorithm optimization.
- Lower EGR rates needed than for single fuel LTC.

Findings:

- Dual-fuel operation at 6, 9, and 11 bar net IMEP achieved with near zero NOx and soot and reasonable PRR (<10 bar/degree) with ~160 g/kW-hr net ISFC.
- Start-of-Combustion timing controlled by diesel; heat release duration controlled by gasoline fraction.
- Compared to conventional diesel, achieved about a 20% improvement in indicated thermal efficiency.





* Patent application in progress - 8/09

In-cylinder sources of UHC and CO identified in light-duty, diesel low-temperature combustion (SNL & UW)

Motivation:

- Fuel efficiency of Low-Temperature Combustion (LTC) systems can be improved and load ranges extended by identifying and minimizing sources of UHC and CO emissions

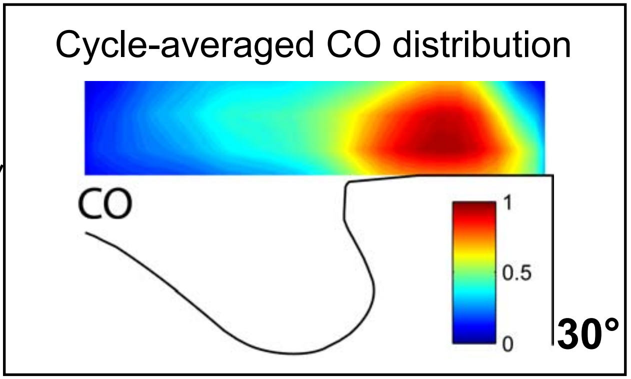
Method:

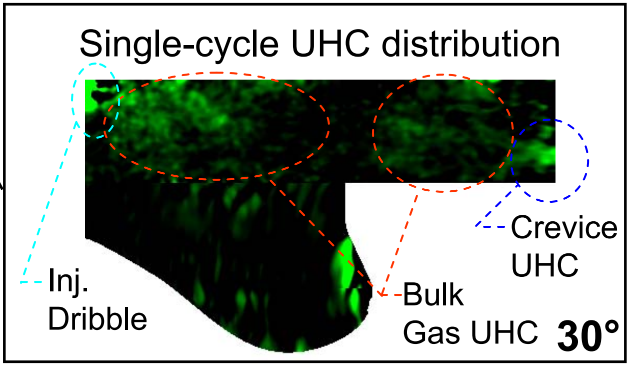
- In-cylinder distributions of UHC and CO (unique capability) are obtained with laser-induced fluorescence
- Measured distributions are used to improve and validate computer models used for engine optimization

Findings:

- CO emissions from both early- and late-injection (PCI- and MK-like) LTC stem primarily from the squish volume
- UHC primarily stems from bulk gases in the central cylinder and squish volume, but also comes from injector dribble and crevice flows.
- Squish height and spray targeting studies show that a small squish height and optimal spray targeting are critical.

Findings are providing engine design guidance. Comparisons of measured CO & UHC distributions with predictions show need for improved models for fuel/air mixing and lead to 50% improvement in UHC predictions.





Data for road-load condition with MBT timing and EGR levels resulting in 10% oxygen

Eccentric motion of a DI diesel needle linked to fluctuations in spray density using *x*-ray imaging (ANL)

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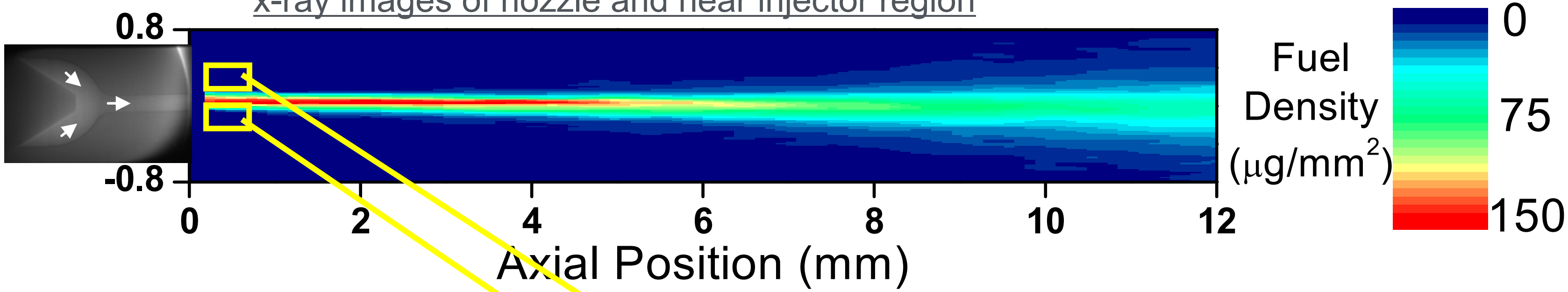
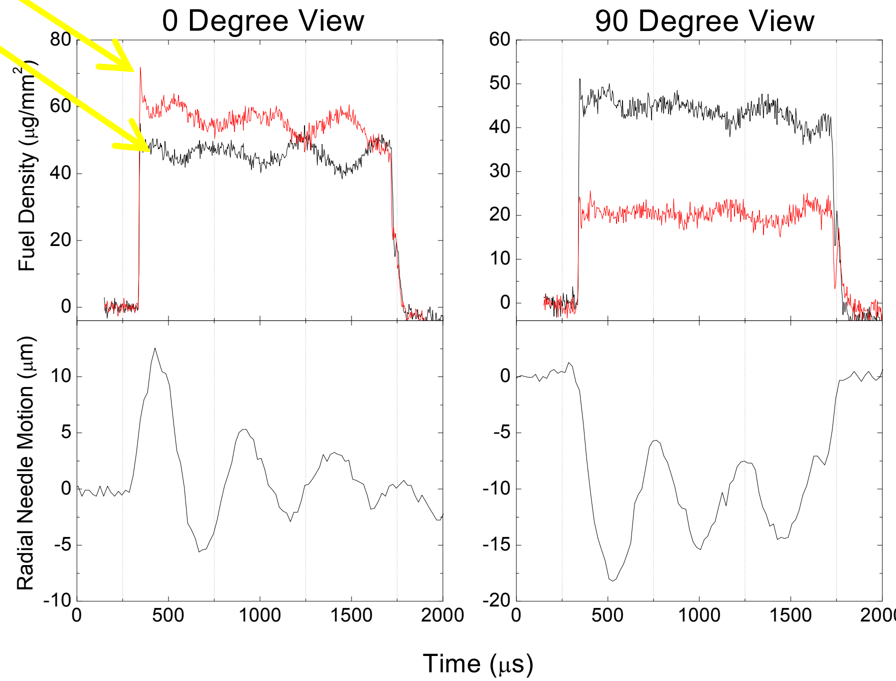
x-ray images of nozzle and near injector region



- Used unique x-ray measurements of fuel spray density combined with new measurements of injector valve motion
- Oscillations in the fuel density are observed as the fuel first emerges.
  - These correlate perfectly with measured eccentric needle motion.
  - First demonstration of link between injector motion and fuel density.
- CFD being performed to help understand the correlation.



KIVA-4 codes advanced (LANL)

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Motivation: Provide KIVA-4 parallel version to OSTI to supply the engine modeling community an efficient internal combustion engine solver and source code.

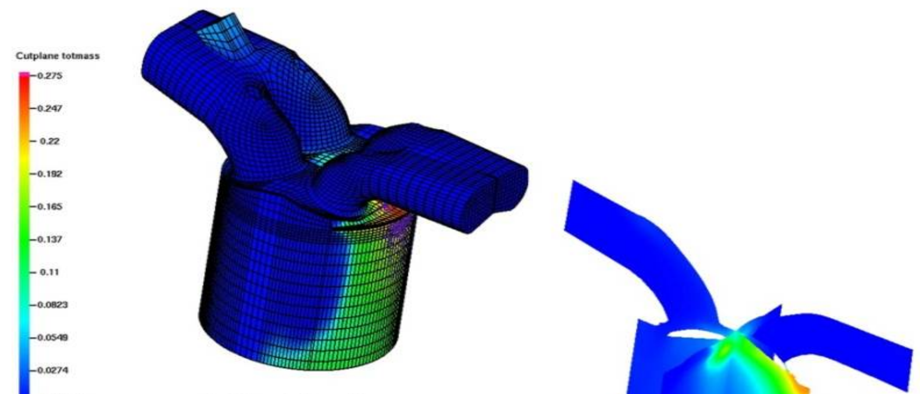
Method: Develop compatible coding in KIVA-4 to form software capable of handling the engines in the KIVA test suites – domains representative of various engine types as developed by various grid generators.

Results: Full version release in late fall with an <u>Alpha version for early fall</u>

Other advances and directions:

- Wall heat conduction capability
- Improved wall film model
- Cut-cell method for complex grid generation in hours, instead of days
- Increase accessibility of KIVA-4 with state-of-the-art unstructured grid generation capability – Cubit
- Advancing the speed, accuracy and robustness of KIVA using 2nd and higher-order spatial accuracy algorithms with minimal additional computational effort.

Parallel four-valve engine simulation with KIVA-4



Fuel Concentration and Spray

Colors show fuel concentration.

Fuel Concentration Cross Section

Developed chemical kinetic model for n-hexadecane, a primary reference fuel for diesel engines (LLNL)

Motivation:

- Detailed chemical kinetic models are critical for evaluating and predicting low-temperature combustion ignition and emissions, and are used for improving simplified models for CFD engine simulations.
- *n*-Hexadecane is a recommended component in a diesel fuel surrogate model (Farrell et. al. SAE 2007)

Accomplishments:

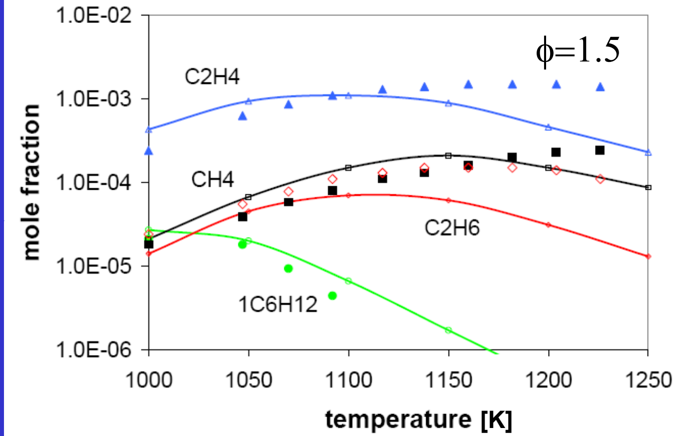
- First-ever complete set of high and low temperature kinetic mechanisms for all C8 - C16 n-alkanes
- Ignition of C8-C16 n-alkanes similar ⇒ can use smaller n-alkane model to treat larger n-alkane (Also, enables better treatment of distillation curve)

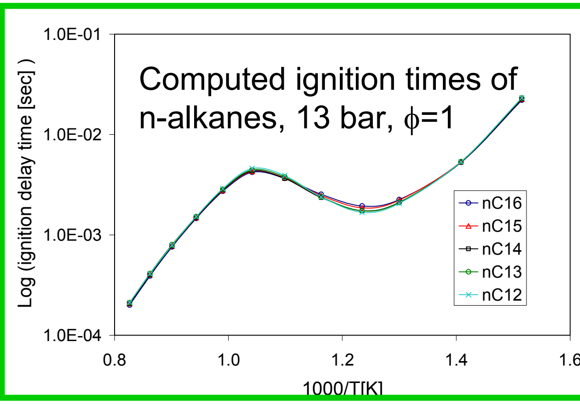
Future:

- Develop and validate mechanisms for primary reference fuels, and gasoline and diesel surrogate model fuels.

n-hexadecane

n-hexadecane model agrees well experiments at 1 atm: (stirred reactor)



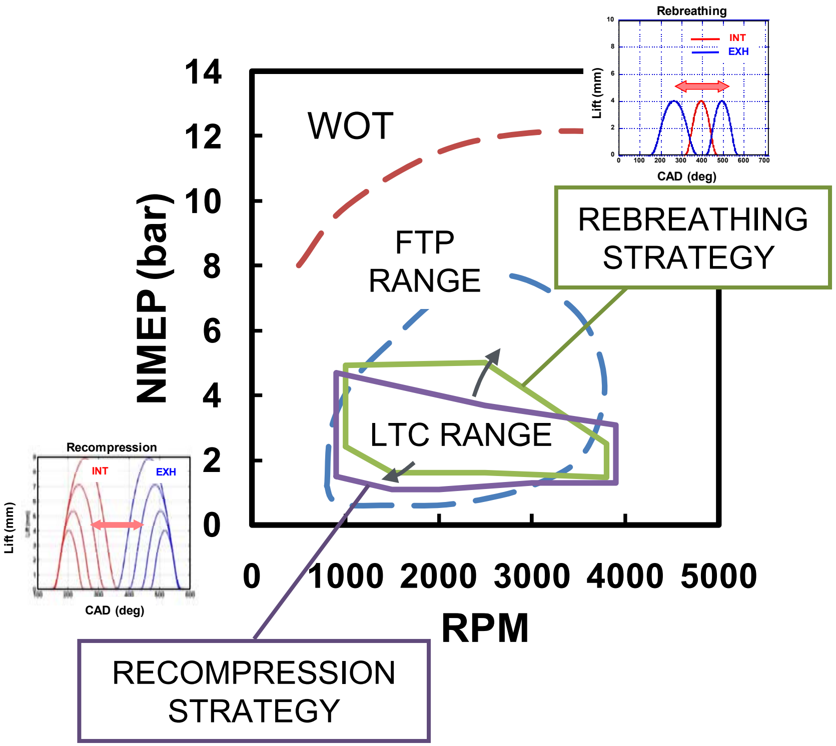


Motivation:

- Optimizing the many complex strategies for extending the HCCI range requires an accurate engine system model.
- The key to this development is a full featured combustion model.

Accomplishment:

- Developed a fundamentally based HCCI combustion model for use with GT-Power®
  - Model predicts ignition, burn rate and combustion efficiency.
- Model was used to compare rebreathing and recompression valve strategies for a naturally aspirated HCCI engine subject to NOx, knock and misfire constraints.
- Model predictions show significant differences in high-and low-load limits for rebreathing and recompression strategies with fuel economy gains of 8% and 11%, respectively.



Will examine intake boosting effects in future.

A collaboration and website to share research on direct-injection engine fuel sprays and combustion (SNL)

- The Engine Combustion Network (ECN) (**http://www.ca.sandia.gov/ECN/**) will provide an open forum for collaboration among experimental and computational researchers. The ECN will:
  - **Establish an internet library of well-documented experiments** appropriate for model validation and the advancement of understanding of engine fuel injection and combustion.
  - **Provide a framework for collaborative comparisons** of measured and modeled results.
  - **Identify priorities** for further experimental and computational research.
- Maintained by Sandia National Laboratories.
- Progress:
  - Website is operational and receiving very positive feedback.
  - Initial standardized fuel injection conditions and 8 collaborators identified for developing comprehensive database utilizing the unique capabilities of participating organizations.
  - Bosch donated 10 diesel fuel injectors to be used by selected ECN collaborators.

DI H_2 engines offer path to sustainable, clean, high-efficiency transportation, with near zero CO_2 emissions.

- Control of fuel/air mixture for optimal combustion phasing and minimal heat transfer losses are a challenge.
- Research providing key insight into the fuel/air mixing and combustion processes.
- Ford demonstrates over 45% BTE on a single-cylinder research engine.
  - Hybridization can offer efficiency comparable to fuel cell powertrains.

<u>Test Results:</u>

Date:	**17-Jan-2008**
Engine Speed:	**3000 RPM**
Injection Pressure: *(Consistent with FreedomCAR Specification)*	**98 atm**
Net IMEP (720): *(Boost Assumptions Based on H2 Multi-cylinder)*	**14.56 bar**
FMEP: *(Consistent with published multi-cylinder data)*	**0.70 bar**
Resulting BMEP:	**13.86 bar**

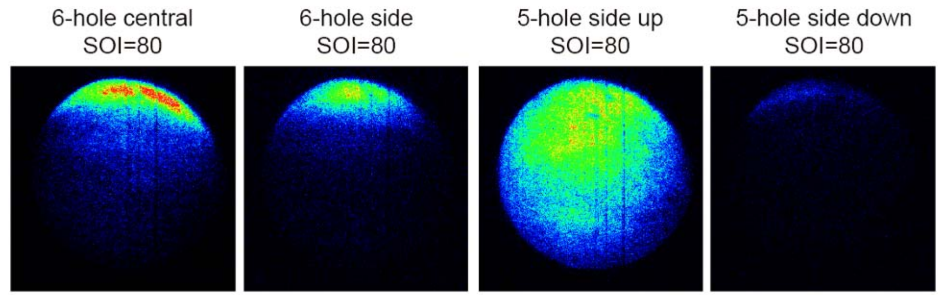


Figure 1: ANL: Endoscopic OH* intensity measurements, an indicator for air/fuel ratio and ultimately NOx emission,

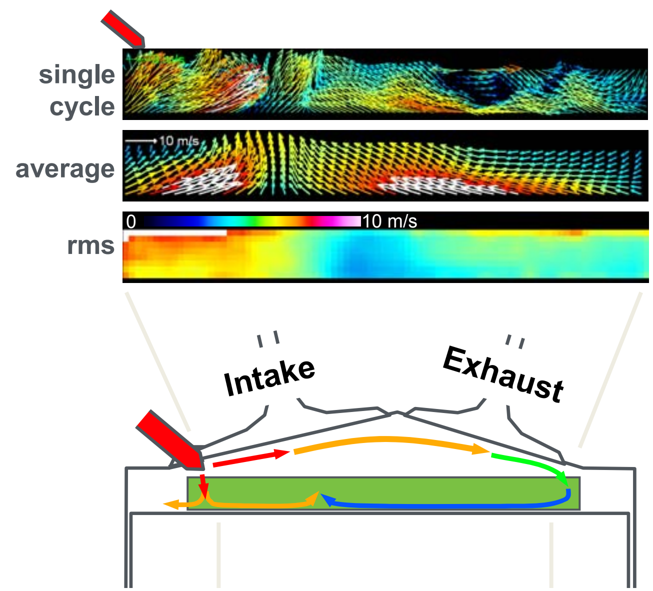
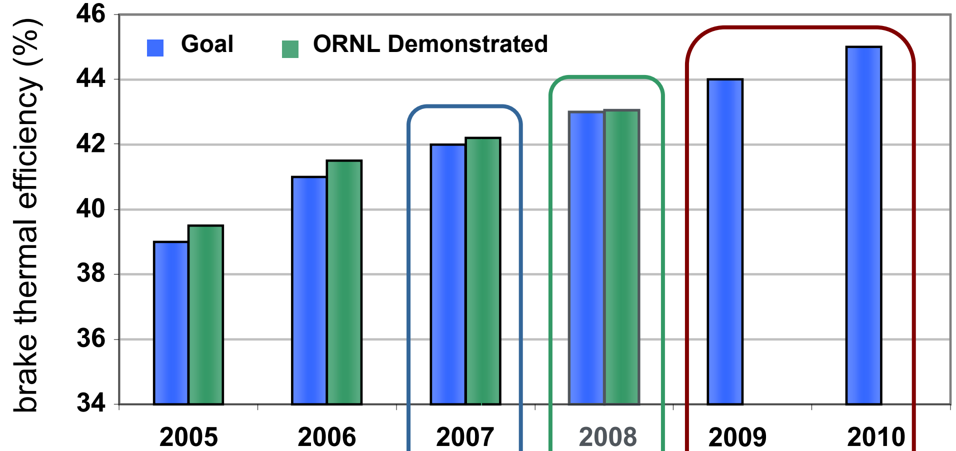


Figure 2: SNL: Velocity fields (top 3 images) measured with PIV.

Light-duty engine efficiency progress (ORNL)

Path to 45% peak Brake Thermal Efficiency (BTE) includes

- **Modern base engine**
- **Enabling technologies demonstrated in FY 2008**
- **The recovery of thermal energy from the exhaust and EGR systems**



Base engine upgraded in FY 2007 to more advanced GM 1.9-L engine; increase in peak BTE for the base engine from 39% to 41%.

\+

Re-optimization of Engine Operation
Turbo-machinery and fuel parameters.

Fuel Properties
High cetane within range US market fuels.

Electrification of Auxiliaries
Engine coolant pump.

Advanced Lubricants
Low viscosity oils.

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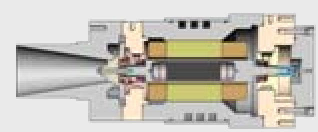
Thermal Energy Recovery
Modeling complete and experiments in progress.

Turbine expander under development with an organic Rankine system to recover thermal exhaust/EGR energy and convert to electricity to improve peak BTE from 43% to 45%.



Questions?

Mixed-mode diesel/LTC operation over light-duty drive cycles evaluated with vehicle simulation tools (ORNL)

Motivation

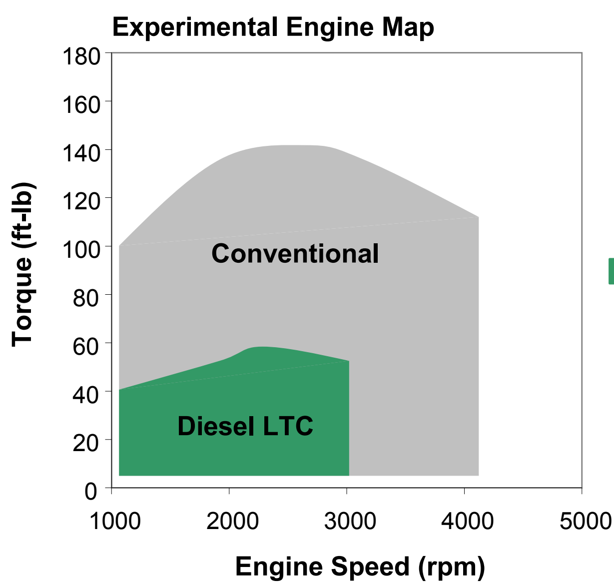
- Speed/load coverage of light-duty (LD) drive cycle is likely to require a combination of LTC & conventional combustion.

Strategy

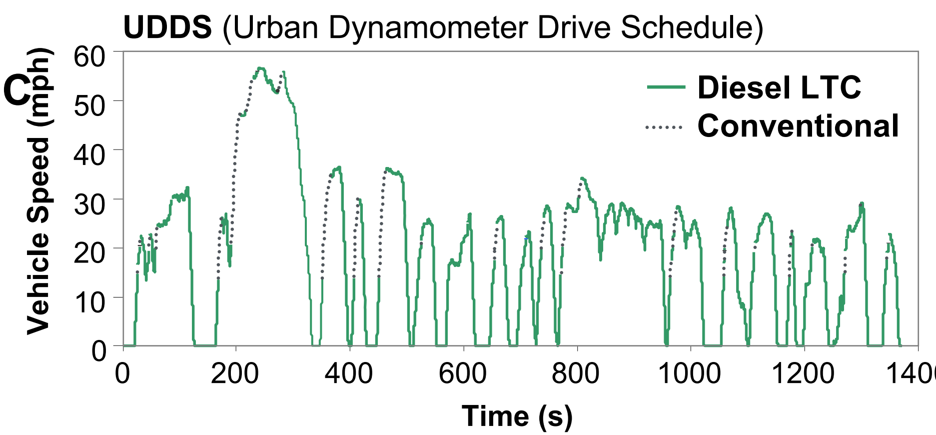
- Use LTC operation when appropriate as dictated by speed-load requirement.
- Vehicle configuration based on LD diesel engine and Honda Civic chassis.

Accomplishments

- Showed benefit and challenges of mixed-mode LTC operation on emissions (60% NOx reduction, 40% PM reduction, 60% HC increase, 120% CO increase).
- Demonstrates importance of expanding LTC operating range.
- Developed simulations with PM and NOx aftertreatment models as well as advanced HEV/PHEV powertrains.



HECC



Vehicle in HECC mode 91% of UDDS. Simulation shows 60% reduction in NOx and 40% reduction in PM over the UDDS cycle.