U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Overview of the VTO Advanced Combustion Engine R&D Program

June 6, 2016

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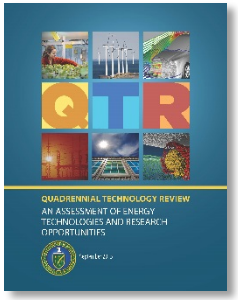
Outline

- State of technology today for ICE.
- Overview of the Advanced Combustion Engine R&D Program.
- Combustion and Emission Control:
  - Engine Combustion R&D.
  - Emission Control R&D.
  - High Efficiency Engine Technologies R&D.
- Summary.

Increasing Engine Efficiency

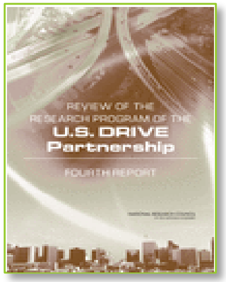
Increasing the internal combustion engine (ICE) efficiency is one of the most promising and cost-effective approaches to improving the fuel economy of the U.S. vehicle fleet for decades to come.

"Significant opportunities exist for improving internal combustion engines, which dominate today's vehicle fleet. Improving internal combustion engines requires research in simulation, sensors, controls, materials, and engine waste heat recovery, as well as new combustion strategies." DOE QTR 2015[1]



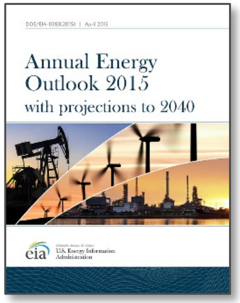
DOE 2015

"…better understanding of the combustion process and emissions production can help to overcome a major barrier to more advanced ICEs, this work is important to the country. …" NRC Report 2013[2]



NRC 2013

EIA *AEO 2015*[3] reference case scenario - even by 2040, ***over 99% of vehicles sold will have ICEs***.



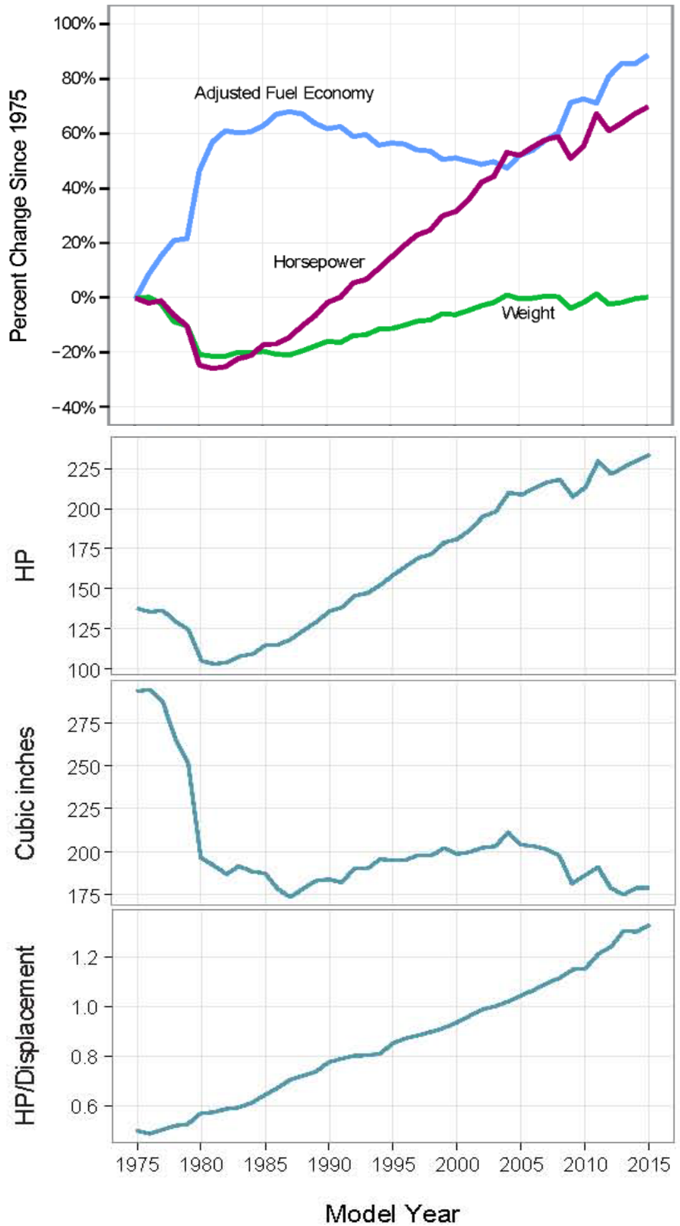
DOE 2015

[1] Quadrennial Technology Review, DOE 2015

[2] *Review of the Research Program of the U.S.DRIVE Partnership: 4th Report,* NRC 2013

[3] *Annual Energy Outlook 2015*, April 2015.

Passenger Vehicle Fuel Economy Trends



Increase in internal combustion engine performance has been largely responsible for significant fuel economy increases (in spite of increases in vehicle size and weight).

Engine Displacement and Power

Horsepower

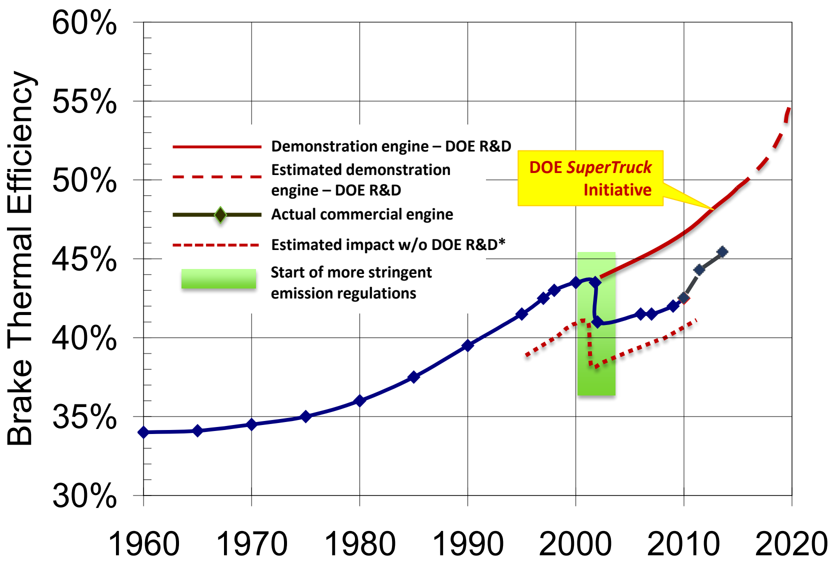
Displacement

Average Specific Power

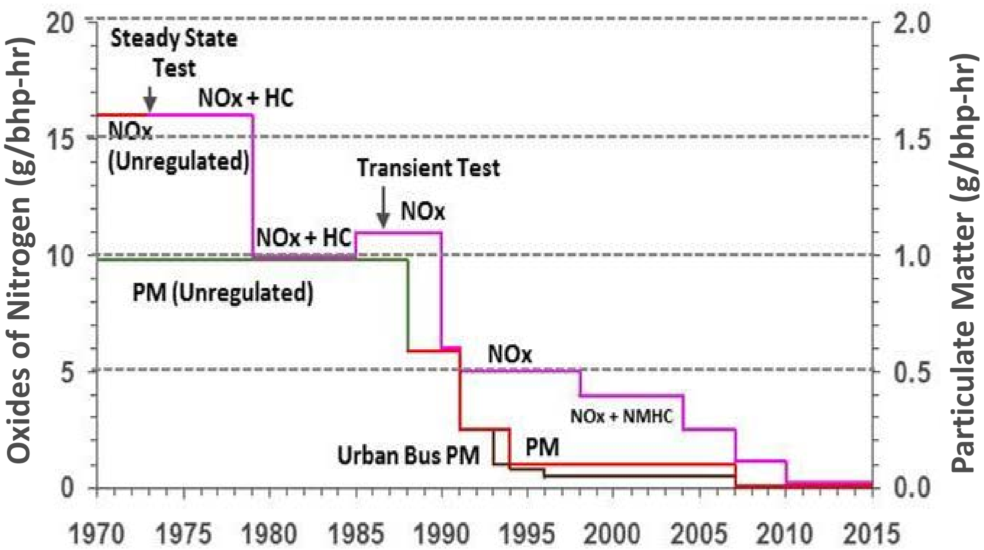
Source: EPA, Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2015, December 2015. EPA-420-R-15-016.

Progress In Heavy-Duty Diesel Engine Efficiency and Emissions

Historical progress in heavy-duty engine efficiency and the challenge of simultaneous emissions reduction, illustrate positive impact from DOE R&D support.



Historical Trend in Heavy-Duty Diesel Engine Efficiency



Historical Trend in Emissions from New Diesel Engines

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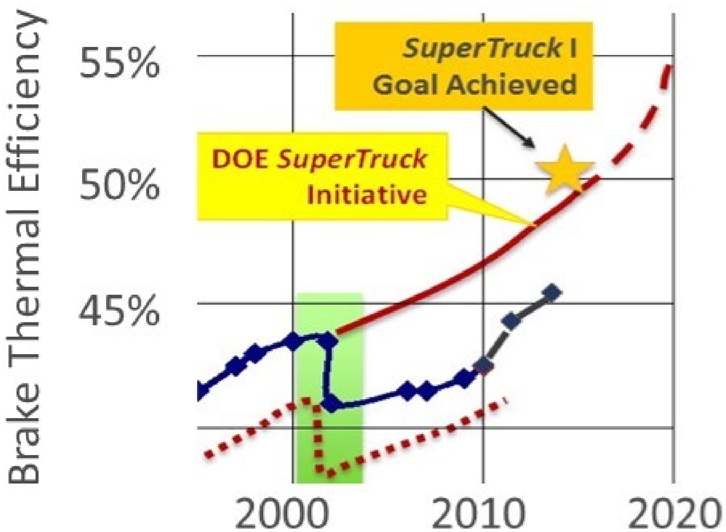
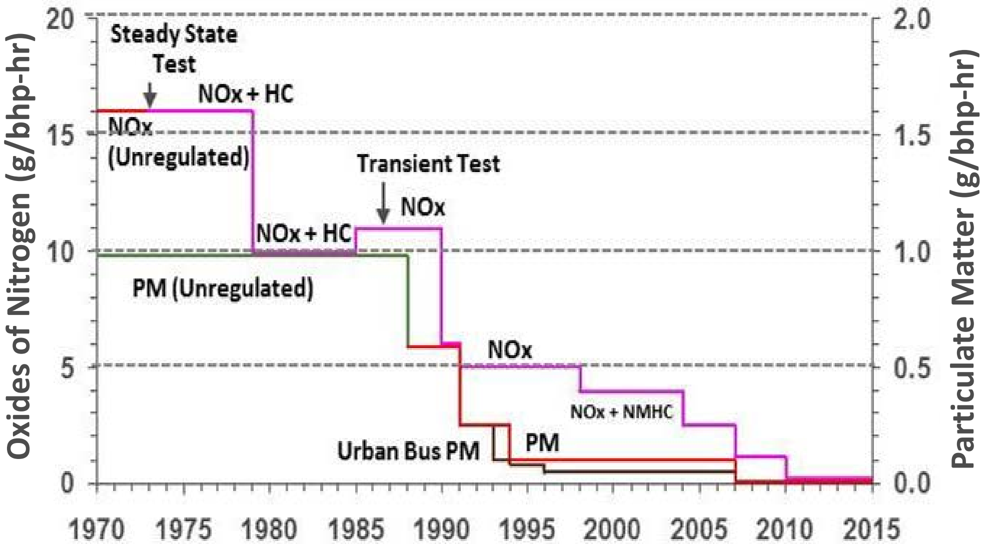


Historical Trend in Heavy-Duty Diesel Engine Efficiency



Historical Trend in Emissions from New Diesel Engines

"By incorporating a mix of available technologies with future innovations, we were able to use the SuperTruck program to take the first steps in seeing what may be technically possible and commercially viable." *Derek Rotz, DTNA PI for SuperTruck, DTNA Press Release, March 21, 2015,*

"The DOE's support, together with the skill of our powertrain engineers working on the SuperTruck program, helped generate significant powertrain innovations." *- Göran Nyberg, President of Volvo Trucks North America, Volvo Truck Press Release, April 14, 2016.*

Advanced Combustion Engine R&D

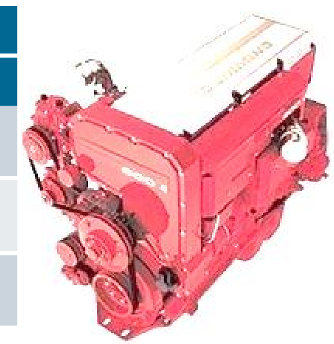
Strategic Goal: Reduce petroleum dependence by removing critical technical barriers to mass commercialization of high-efficiency, emissions-compliant internal combustion engine (ICE) powertrains in passenger and commercial vehicles.

Primary Directions

- Improve ICE efficiency through advanced combustion strategies.
- Develop efficient aftertreatment technologies.
- Reduce losses and recover waste energy.

Performance Targets*

	Light-Duty 2020	Heavy-Duty 2020
Engine brake thermal efficiency	--	55%
Fuel economy improvement*	35 – 50%	30%
NOx & PM emissions	Tier 3, LEV III	EPA Standards



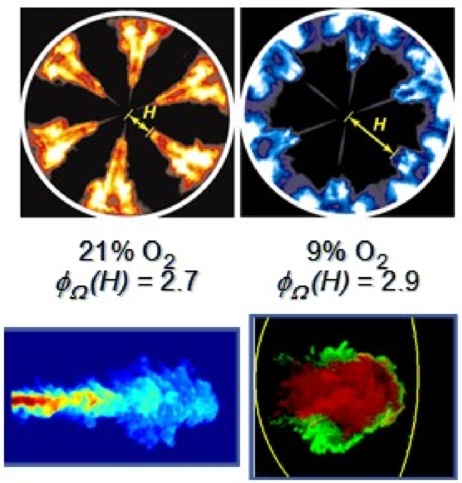
*compared to 2009 model year baseline

Advanced Combustion Engine R&D Program Budget

Major Activities	FY 2015 Enacted	FY 2016 Enacted
Advanced Combustion Engine R&D	**$49,000K**	**$37,141K**
Combustion and Emission Control	49,000	37,141

Advanced Combustion Engines: Major R&D Areas

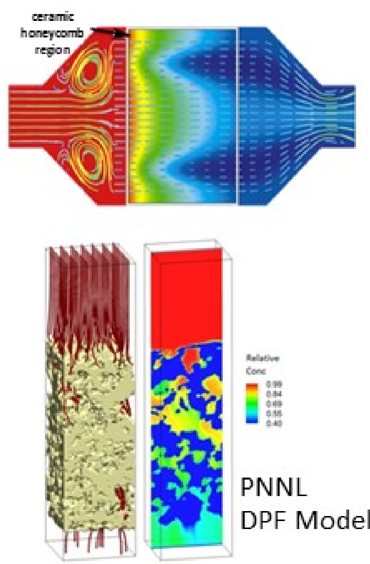
Strategic Goal: Remove critical technical barriers to mass commercialization of high-efficiency, emissions-compliant ICE powertrains in passenger and commercial vehicles.



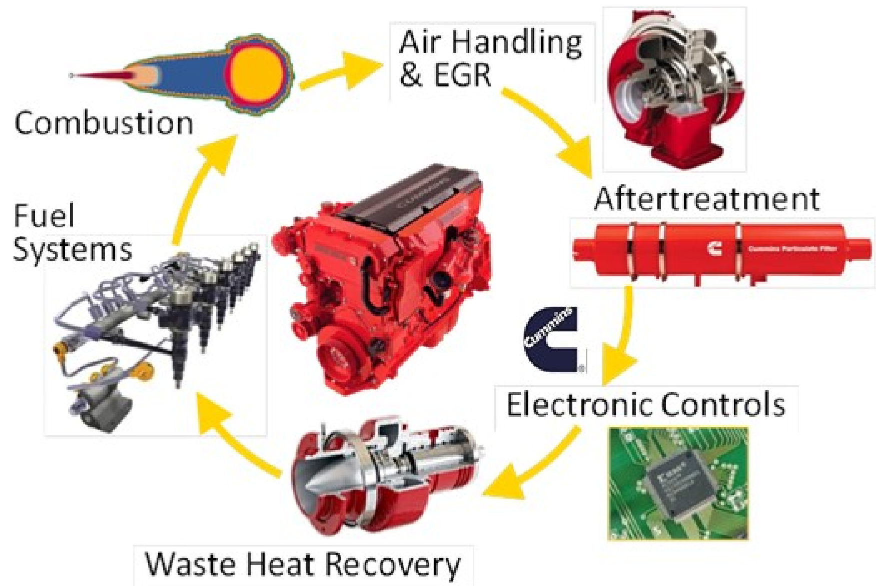
Fuel concentration

Soot (red) and OH (green)

Combustion R&D



Emission Control R&D



High Efficiency Engine Technologies R&D

Overall R&D Approach

Advanced Combustion Engine R&D | Industry

Fundamental Research | Applied Research | Technology Maturation & Deployment

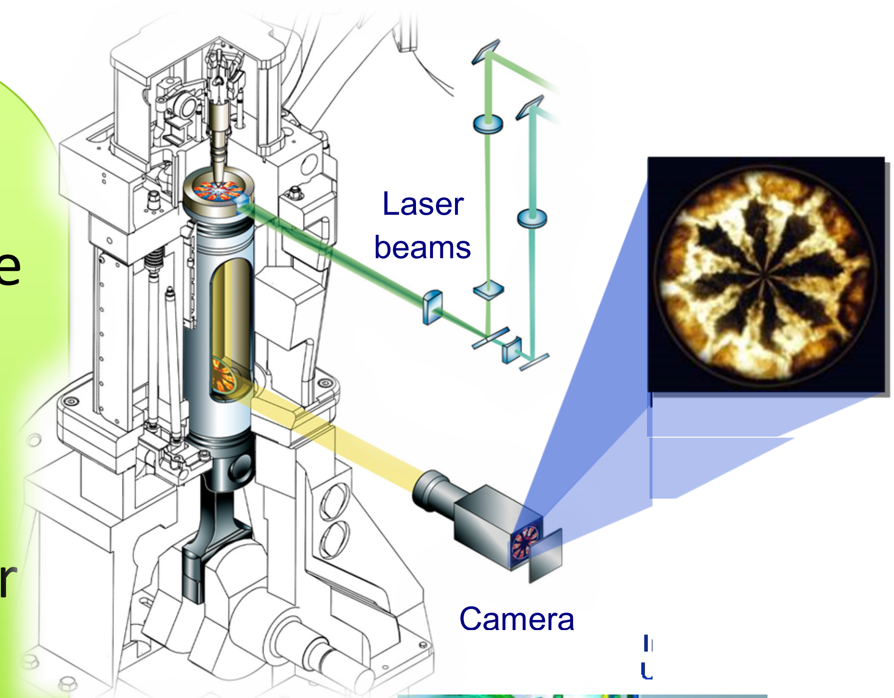
Fundamental R&D
- SNL – Advanced combustion strategies (LTC, lean-burn gasoline, advanced diesel).
- LLNL – Chemical kinetics models (combustion, fuels and emissions).
- LANL – CFD modeling of combustion.
- ANL – X-ray fuel spray characterization and modeling.
- PNNL – Catalyst characterization (NO_x and PM control).
- Universities – Complementary research.

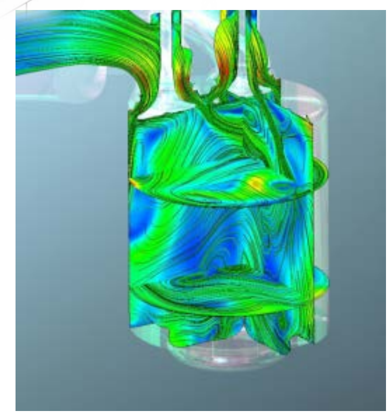
Fundamental to Applied Bridging R&D
- ORNL – Experiments and simulation of engines and emission control systems (bench-scale to fully integrated systems).
- ANL – Fuel injector design, LTC engine experiments.

Competitively Awarded Cost-shared Industry R&D
- Automotive and engine companies – engine systems.
- Suppliers – enabling technologies (sensors, ignition, VVA, WHR).

Combustion R&D

- ❑ Explore advanced combustion strategies to achieve higher engine efficiencies with near-zero emission of NO_x and PM.
- ❑ Develop greater understanding of engine combustion and in-cylinder emissions formation processes.
- ❑ Develop science-based, truly predictive simulation tools for engine design.



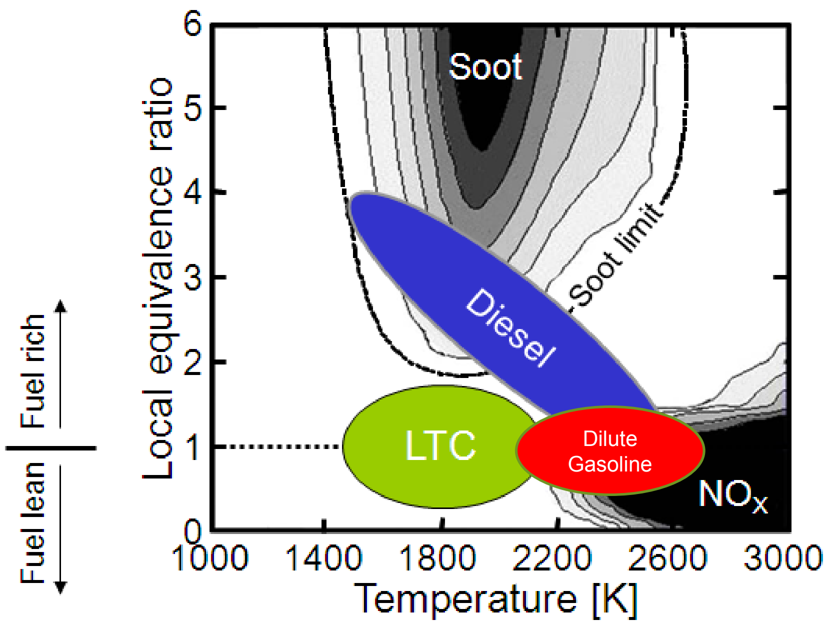


Engine Simulation

Combustion R&D - *Directions and Challenges*

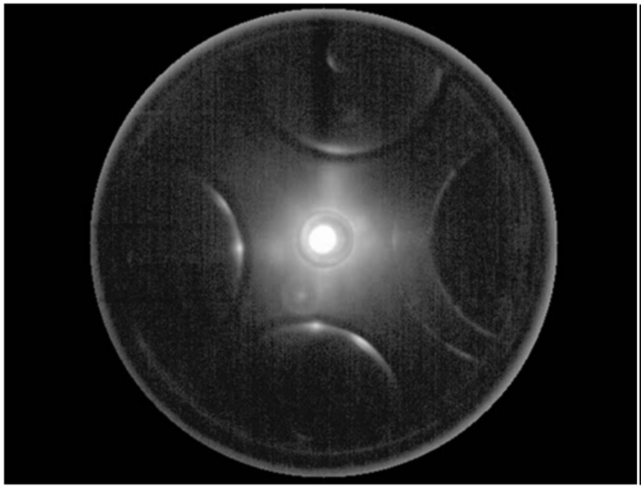
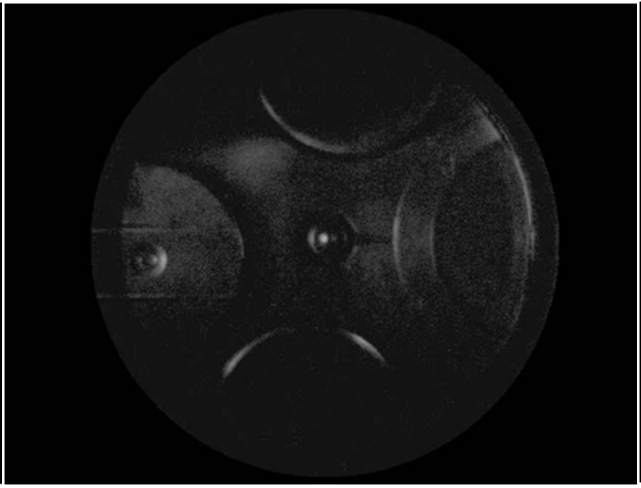
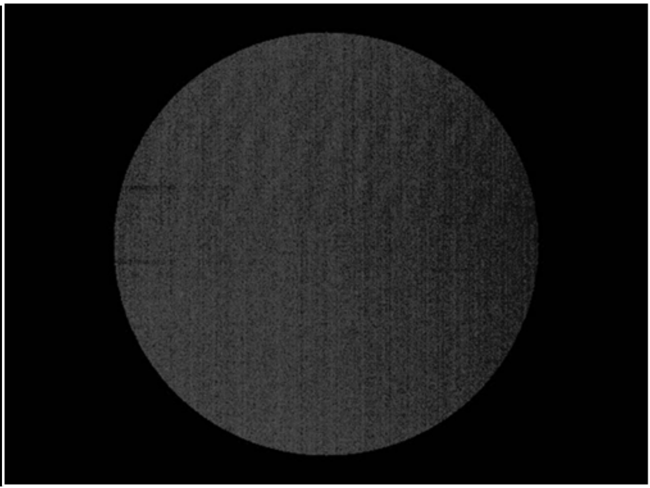
Combustion Strategies Enabling Improved Efficiency and Very-Low Emissions

- ❑ Low-Temperature Combustion (LTC):
  - Premixed-Charge Compression-Ignition (PCCI), PPCI, PCI, MK, … – “mixed enough”.
  - Homogeneous-Charge Compression-Ignition (HCCI) – “heterogeneous enough”.
  - Reactivity Controlled Compression Ignition (RCCI) – “dual fuel” combustion.
- ❑ Dilute Gasoline Combustion: Fuel-air mixing, ignition and flame propagation in stratified mixtures, stochastic misfire and knock challenges, fuels, emissions…
- ❑ Clean Diesel Combustion: EGR, high-pressure and multi-pulse injection, lifted-flame combustion, post injections for in-cylinder and aftertreatment emission control....



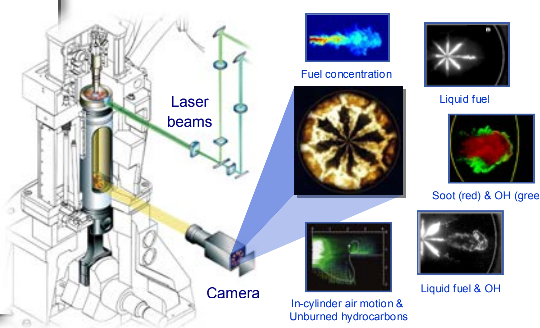
- ❑ LTC Challenges:
  - Combustion phasing.
  - Load range.
  - Heat release rate.
  - Transient control.
  - HC and CO emissions.
  - Fuel characteristics.

Comparison of Engine Combustion Processes

Spark ignition (gasoline)	Kinetically controlled combustion	Compression ignition (diesel)
		

Advanced Engine Combustion R&D

- **Goal:** To develop the knowledge base for advanced combustion strategies and carry research results to products.
  - Science-base for advanced combustion strategies.
  - Computational tools for combustion system design and optimization.
  - Identify potential pathways for efficiency improvement and emission compliance.
- Close collaboration with industry through the <u>Advanced Engine Combustion MOU</u> led by Sandia National Labs ***carries research to products.***



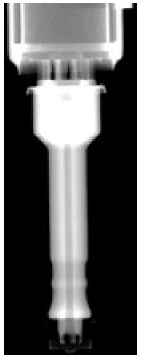
- **Cross cuts light-duty and heavy-duty engine R&D.**
- **University research integrated with MOU.**

Research Tools Bridge Fundamentals to Application

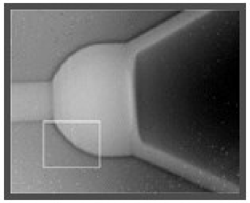
- ❑ Close coupled modeling and experiments:
  - Advanced diagnostics including optical, laser, x-ray, and neutron based techniques.
  - Multi-dimensional computational models and combustion simulators.
  - Fuel kinetics.
  - Multi- and single-cylinder engines.

Optical Engine

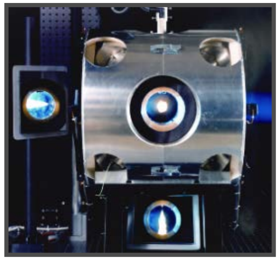
HCCI & Lean-burn Gasoline



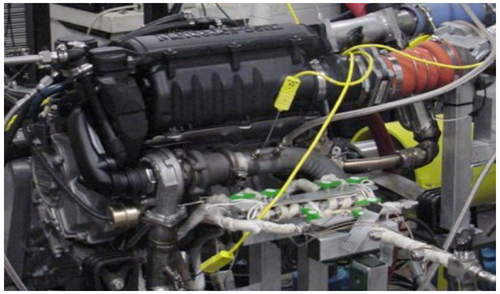
Neutron Imaging-GDI Injector



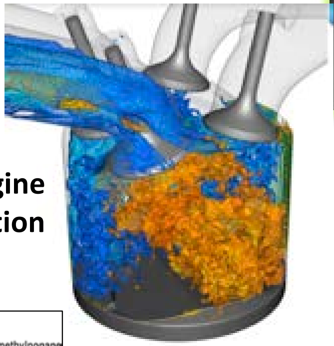
Nozzle Sac X-Ray Image



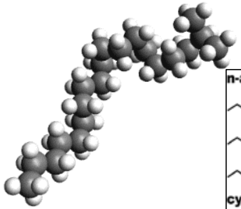
LTC Simulator

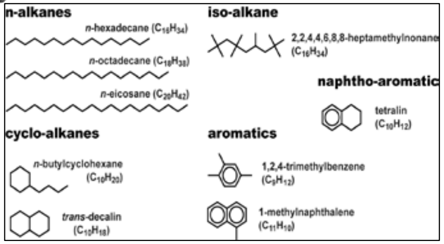


Multi-cylinder Engine Test Cell



Engine Simulation





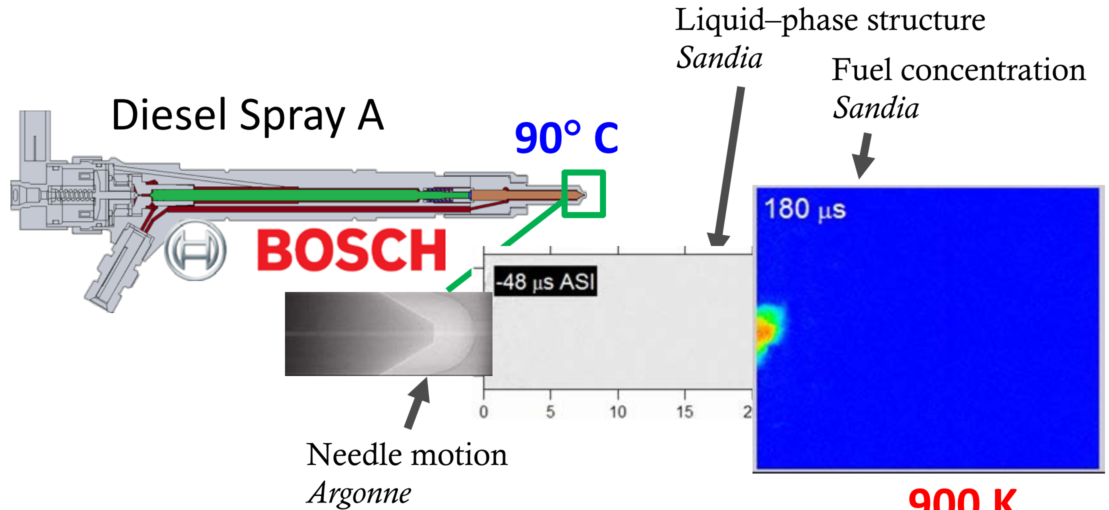
- ❑ Close collaboration between industry, national labs and universities.
- ❑ Cross-cuts light- and heavy-duty engine R&D.

Leading to engine modeling tools widely used in industry

Collaborative Research through the Engine Combustion Network Accelerates CFD Model Development

Goal: Develop diesel and gasoline target conditions with emphasis on CFD modeling shortcomings.

- Over 40 different measurements, more than 10 institutions
- Over 15 years of research performed in about 3 years
- Comprehensive experimental and modeling contributions.
- Engine datasets using these injectors are now available.

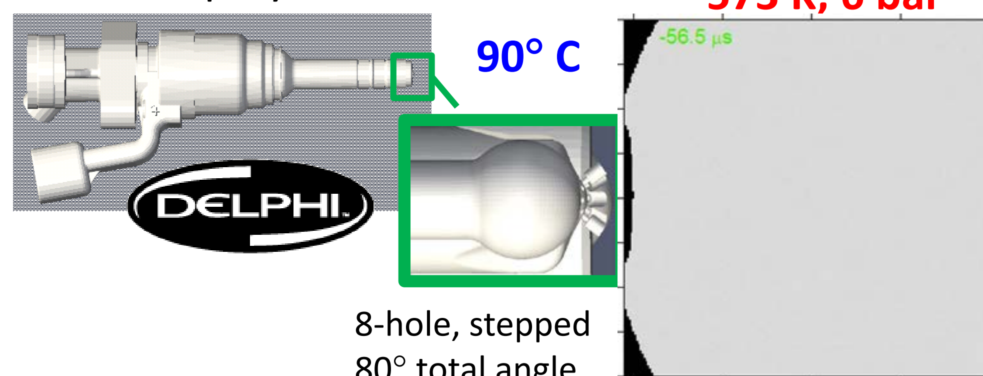


900 K
60 bar

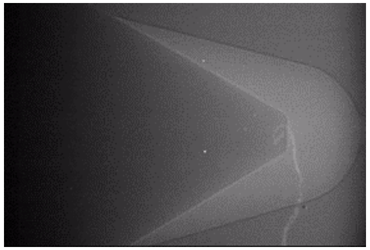
>60 measurements/diagnostics contributed from >15 institutions

Gasoline Spray G

573 K, 6 bar



X-ray and Neutron Imaging of Fuel Injector



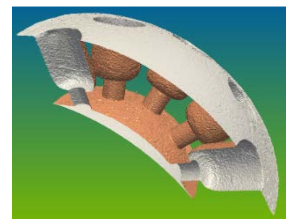
Needle Motion

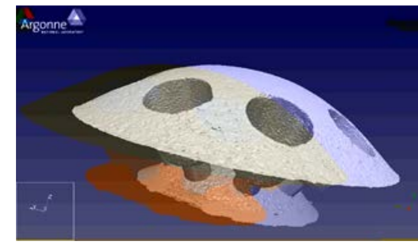
Near-Nozzle Fuel Density

X-rays enable unique capabilities, both *inside* and *outside* the nozzle

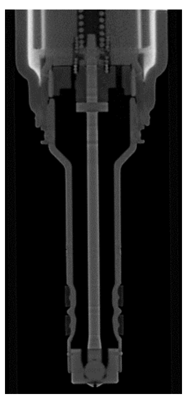
Argonne NATIONAL LABORATORY

High Precision Nozzle Geometry

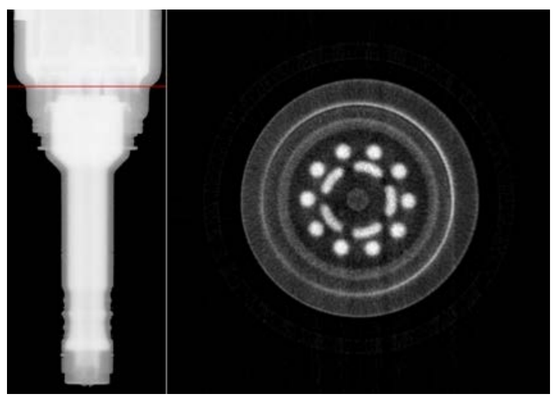




3d model of ECN Spray G nozzle



Empty



Fuel-filled

Samples can be analyzed at one cross-section or a complete reconstruction can provide a cross-section of the entire sample

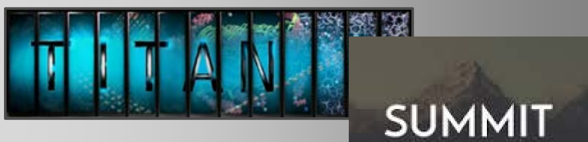
- Neutron imaging of GDI injector with fuel inside

OAK RIDGE National Laboratory

Predictive Simulation and HPC to Accelerate Engine Design

Basic Science

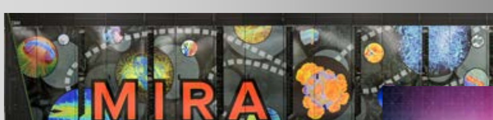
<u>DOE Office of Science</u>
Advanced Scientific Computing Research (ASCR) basic science tools and high performance computing (HPC) resources.



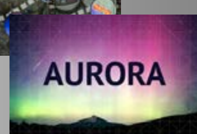
DAKOTA
TASMANIAN

<u>ORNL allocations on Titan:</u>
2015 – 32.5 Mhrs (2 ALCC)
2016 – 13 Mhrs (1 ALCC, 1 DD)
2017 – 20+ Mhrs proposed

Oak Ridge National Laboratory

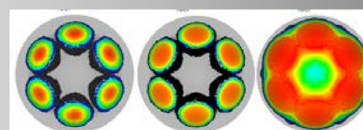


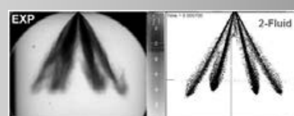
Argonne NATIONAL LABORATORY

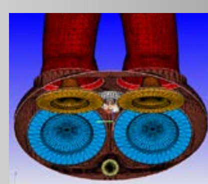


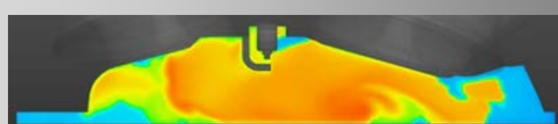
Applied R&D

<u>DOE/EERE/VTO</u>
Developing and expanding capabilities to gain new insight and understanding and improve engine design process.









Manufacturing/ Commercialization

<u>OEMs and ISV</u>
Close collaboration with industry quickly transitions next generation of high efficiency clean engines ti the vehicle market.

GM

Ford

12 mpg
Daimler Trucks North America

Making use of unique world class resources to address real-world challenges

Defining DOE/VTO Role in CFD Modeling

- **General consensus on DOE Role**: Support science-based model development and refinement using High Performance Computing (HPC) resources at the national labs (DOE/SC/ASCR).
- FOA university awards in Area of Interest "Physics-based CFD Sub-model Development and Validation."

FY 2015 - 2018

- The Pennsylvania State University - $0.684M
- University of Illinois - $0.698M
- Michigan Technological University – $0.750M
- University of Wisconsin - $0.542M
- University of Alabama - $0.595M
- Ohio State University - $0.716M
- Boston University - $0.833M
- Georgia Institute of Technology - $0.829M


Sustainable TRANSPORTATION

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Defining the Future Role of the Vehicle Technologies Office in Supporting Development of Computational Fluid Dynamics Simulation Capabilities for Internal Combustion Engines

August 18, 2014 Workshop Draft Report

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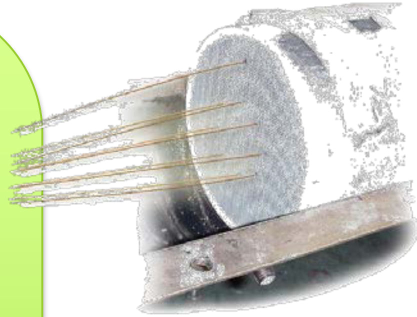
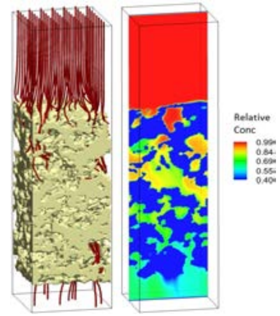
Matthew McNenly, LLNL
Doug Longman, ANL

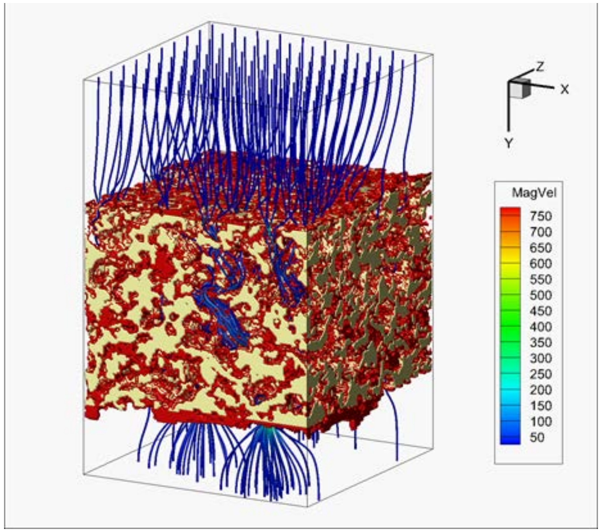
Workshop Report - Defining DOE/VTO Role in Supporting Development of Advanced Engineering CFD Codes IC Engines, August 18, 2014.

Emission Control R&D

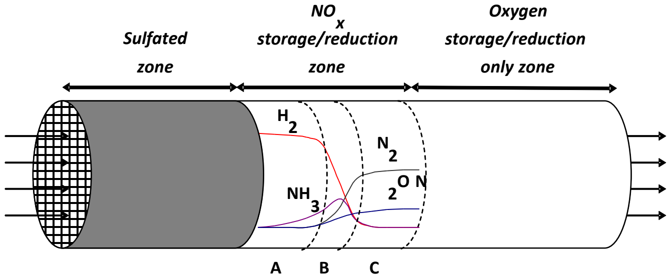
- Develop more efficient approaches for reducing NO_x, and oxidizing PM, HC, and CO in low temperature exhaust ($150^{O}C$).
- Reduce energy penalty and cost of emission control systems.

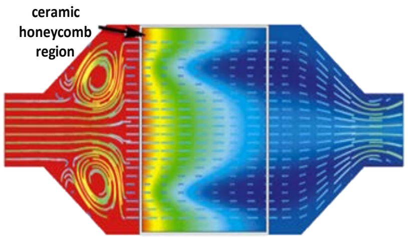






PNNL DPF Model

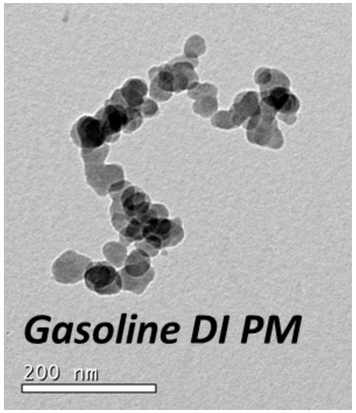


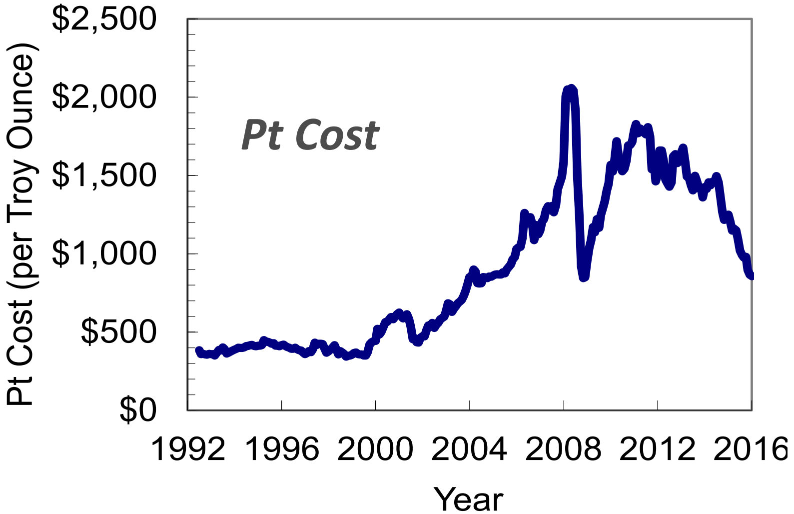


Flow and Temperature Computations during Cold-start of a Catalytic Converter

Emissions Challenges

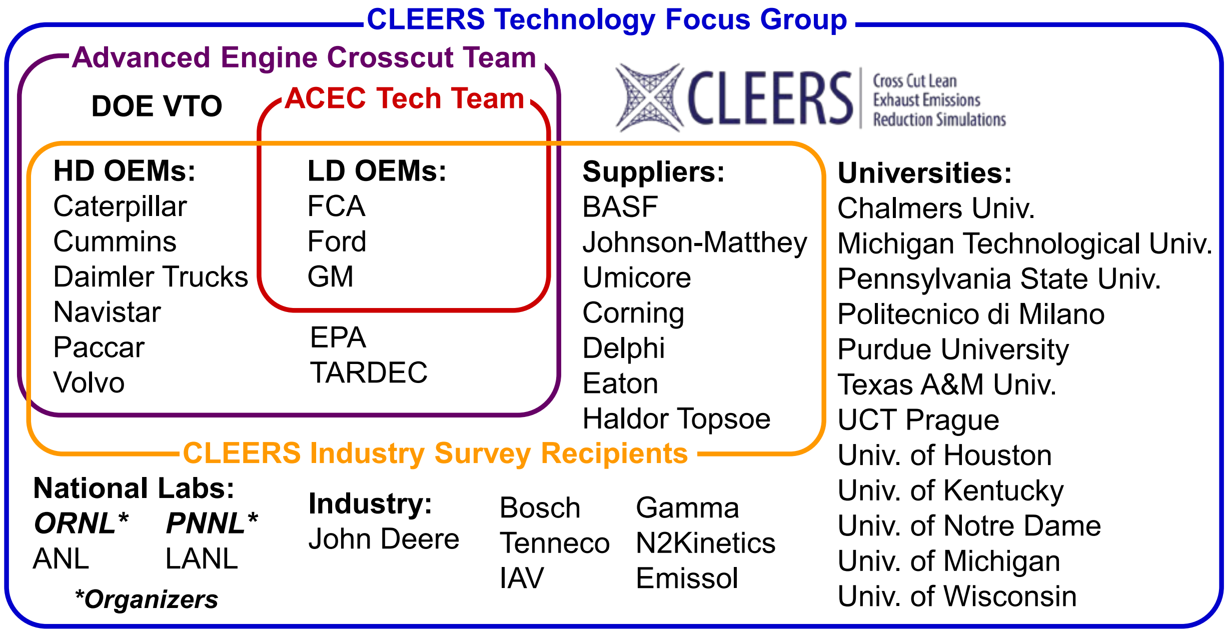
- Low exhaust temperatures due to efficient combustion:
  - Cold start emissions.
  - Tier 3/LEV III regulations.
- Particulate matter (PM) emissions:
  - PM characteristics from DI gasoline and diesel engines are different.
  - New lower regulations on particulate mass.
  - Particle number standard will be more challenging for DI gasoline.
- Lean-NO_x reduction:
  - Barrier is cost-effective lean-NO_x aftertreatment.
- Energy penalty of emission control systems.
- Cost
  - Aftertreatment system complexity is increasing.
  - PGM costs are highly volatile.





CLEERS* Enables Joint Coordination and Development of Emission Control Data and Models

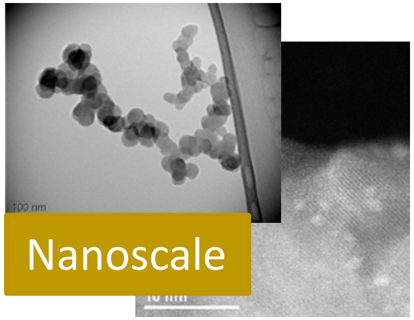
- *Cross-cut Lean Engine Emission Reduction Simulations (www.cleers.org) promotes collaboration and interactions among industry, national labs, and universities to achieve functional models for lean emission control devices and systems.



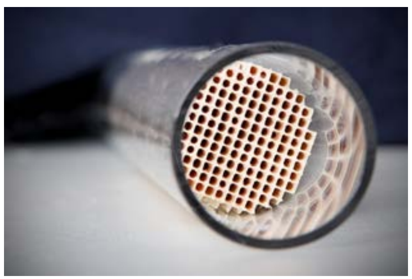
- Key activities include: an annual workshop, monthly teleconferences, and a website (www.cleers.org) with an active database of models and experimental data.
- Simulations range from fundamental surface-reaction based to component level models.
- Models are increasingly relied on by industry in product development and optimization.

EERE VTO Catalysis Research for Vehicles Spans from Nanoscale to Full Scale

TEM images of PM and PGM dispersed on support



Monolith supported catalyst core



Engine-catalyst system

Full Scale

Research Areas

Surface Chemistry
Defining surface moieties and intermediates with DRIFTS and other tools

PGM Characterization
Defining Platinum Group Metal (PGM) roles and understanding sintering processes

Poison Effects
Understanding effect of fuel- and oil-borne poisons/fouling agents on aging processes

Reaction Mechanisms
Characterizing reaction processes and measuring kinetics

Characterizing Formulation-Specific Chemistry
Understanding role of components of complex heterogeneous catalyst formulation

Performance and Selectivity
Measuring formulation affect on performance and selectivity (including differentiating regulated vs. unregulated products)

Controlling Unique Advanced Combustion Emissions
Studying combination of advanced catalysts with advanced combustion to achieve overall gains in fuel economy and cost-effective emission compliance

Minimizing Fuel Penalty during Active Regeneration
On-engine studies to minimize fuel use and optimize emission control

Characterizing Combustion-Specific PM and MSATs
Defining morphology, size distribution, and chemical composition of Particulate Matter (PM) and Mobile Source Air Toxics (MSATs)

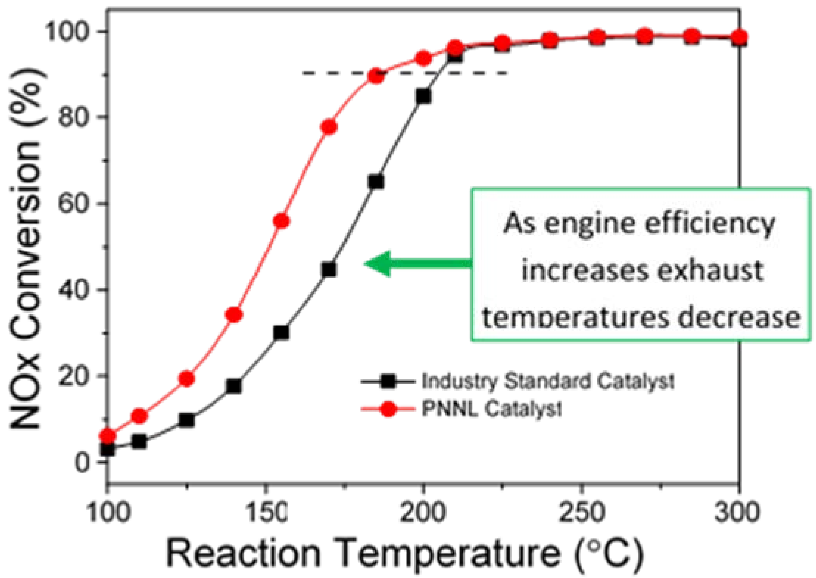
Particulate Filter-Based Control of PM
Studying oxidation kinetics, thermal issues, and fuel penalty for particulate filters

Industry Benefits

- Understanding Catalyst Fundamentals
- Predicting Degradation and Defining Mitigation Strategies
- Developing and Validating Models for Product Design, Controls, and OBD Optimization
- Achieving Cost-Effective Emissions Compliance while Maximizing Fuel Efficiency

Promising Automotive Catalyst Provides NO_x Control at Temperatures Approaching 150°C (PNNL)

- PNNL researchers developed new SCR catalyst that shows 90% NO_x conversion at temperatures significantly lower than current technology.
- Also, the new class of catalysts has potential to be durable for over 150,000 miles of use, a requirement for commercialization.
- This new material is being further improved to meet industry needs for conversion efficiencies of greater than 90% at 150°C, while also maintaining sufficient durability to meet regulatory requirements.



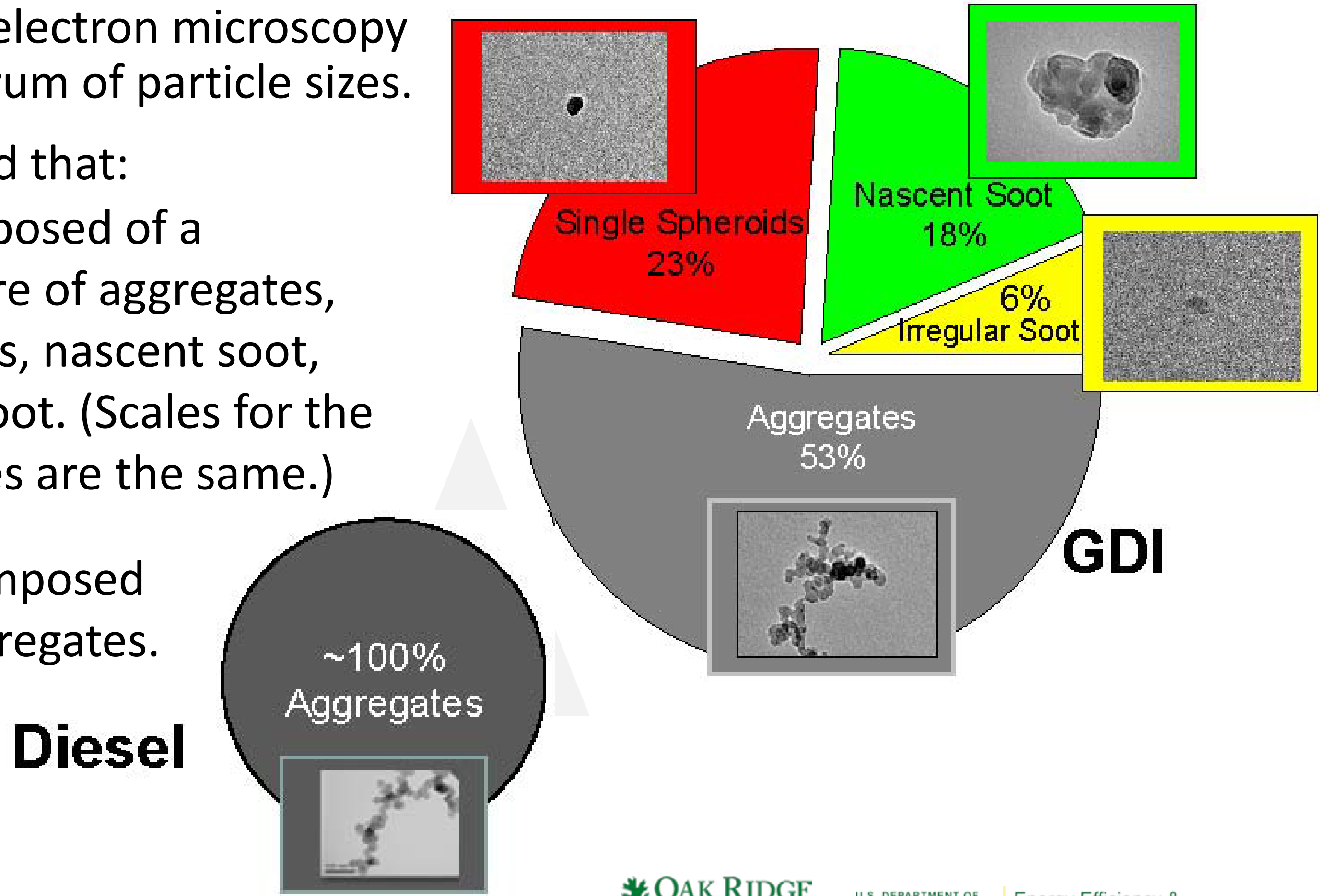
NO_x conversion efficiency during NH_3 selective catalytic reduction (SCR) with a novel catalyst formulation (PNNL).

Increased NO_x conversion efficiency SCR catalysts will enable vehicles powered by higher-efficiency engines with typically lower exhaust temperatures to meet U.S.EPA Tier 3 and LEV III emissions standards.

GDI PM Size, Shape, and Composition Highlights Control Challenges that Differ from Diesels (ORNL)

Elevated particulate matter (PM) emissions have become a challenge as direct-injection replaces port-fuel injection in gasoline engines to boost fuel economy.

- A representative PM sample from a 2.0 L turbocharged GDI engine was collected for a transmission electron microscopy (TEM) of full spectrum of particle sizes.
- TEM images showed that:
  - GDI PM is composed of a complex mixture of aggregates, single spheroids, nascent soot, and irregular soot. (Scales for the GDI TEM images are the same.)
  - Diesel PM is composed of nearly all aggregates.



University Projects in Emission Control R&D

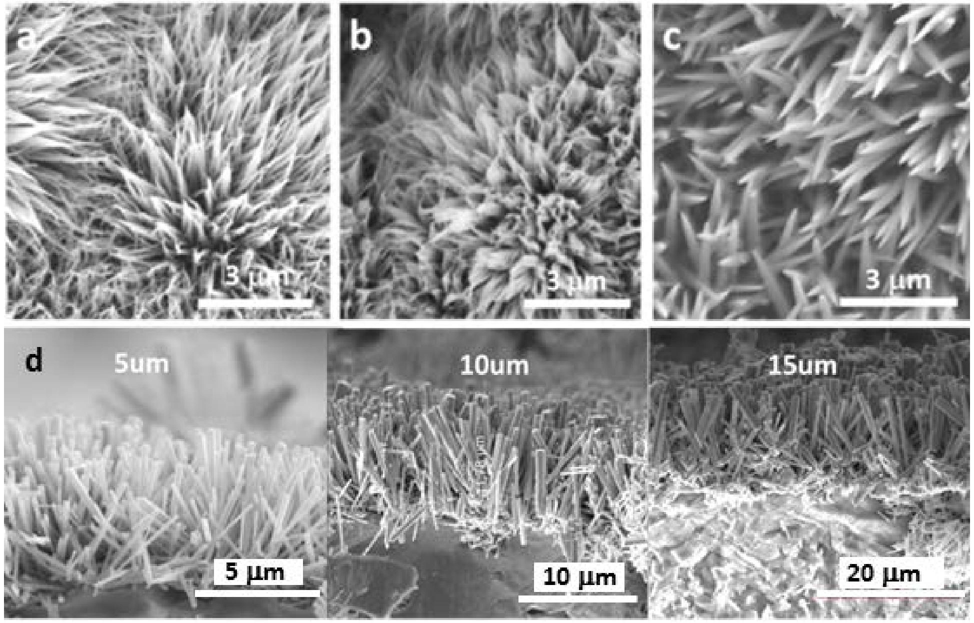
FY 2012-2015
DOE-NSF Grants

- University of Kentucky - \$0.90M
- University of Houston - \$1.20M
- Purdue University - \$1.50M

FY 2014 FOA Incubator Award

- University of Connecticut - \$1.450M

Metal Oxide-Based Nano-Array Catalysts for Low Temperature Diesel Oxidation

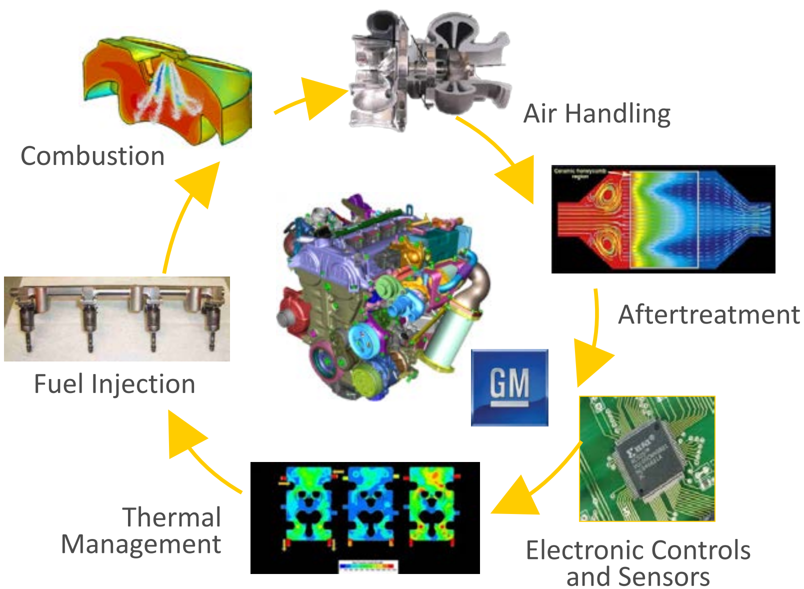


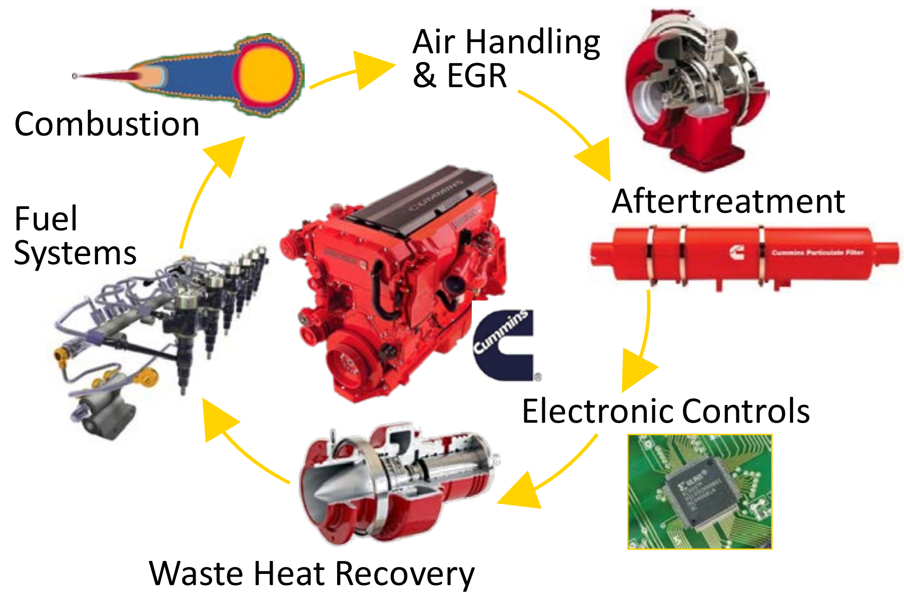
SEM images of the as-prepared nanowire array catalysts

- Demonstrated on a range of scales, in-situ solution-based growth of (nanostructure array) nano-array on monolith:
  - **Reduced PGM.**
  - **Improved efficiency due to size, shape, and structure.**

High-Efficiency Engine Technologies R&D

- Develop and demonstrate system level technologies to improve vehicle fuel economy through combination of combustion strategies, emission control, fuel injection, air handling, waste heat recovery, and control systems.





Integration of Component Technologies

ACE R&D 2020 Goals

- Increase engine efficiency to improve gasoline and diesel passenger vehicle fuel economy by 35% and 50%, respectively.*
- Increase fuel economy of heavy-duty vehicles by 30%.*

*compared to 2009 baseline

Advanced Technology Powertrain for Light-Duty Vehicles – Phase 2 (ATP-2)

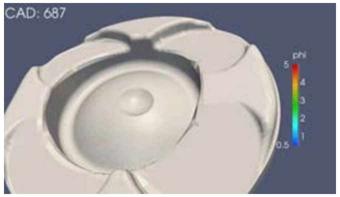
Goal: By 2020, develop and demonstrate system level technologies to achieve 35% fuel economy improvement for gasoline vehicles over the baseline 2009 gasoline vehicle.

Status

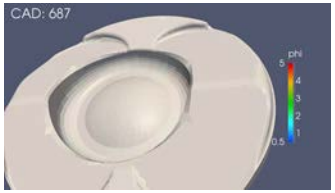
- **General Motors** is developing a Lean Miller Cycle Gasoline Engine including various other technologies for integration in a Chevrolet Malibu.
  - Identified key features of fuel injection, stratification and mixing process using CFD and designed ports, piston bowls and sprays to optimize across the speed-load range.
- **Delphi is** developing a Gasoline Direct-injection Compression Ignition (GDCI) engir for integration in a passenger vehicle.
  - Characterized Gen 2 GDCI multi-cylinder engine and refined engine controls and calibration for vehicle with Gen 1 level hardware.
  - Completed design and initial build of Ger 3 GDCI hardware.

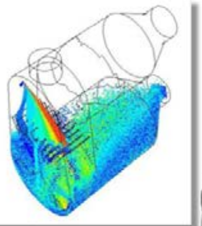
GM

Initial Design



Improved Design





New aftertreatment system

DELPHI

Gen 2 GDCI Engine

Cylinder head with compact, integral exhaust manifold with pre-turbo catalyst

SuperTruck Initiative

SuperTruck 1

- **Class 8 tractor-trailer systems freight efficiency Improvement**
  - Cummins and Daimler have demonstrated 86% and 115% on-road freight efficiency improvements, respectively. Volvo and Navistar on track to meet 50% efficiency target.
- **Engine efficiency**
  - Cummins and Daimler have demonstrated over 50% engine efficiency. Navistar and Volvo on track to achieve the 50% target.

12 mpg

Total project funding:

DOE + Industry = $284 Million

SuperTruck 2

- **Class 8 tractor-trailer to demonstrate:**
  - Greater than 100% freight efficiency improvement (2009 baseline).
  - 55% engine efficiency – Waste heat recovery.
  - Cost effectiveness with 18-36 month payback period.
  - Comparable acceleration and gradeability.
- **Technologies expected to be included:**
  - Engine efficiency, emission control and waste heat recovery.
  - Advanced transmission and hybridization.
  - Aerodynamic drag reduction of tractor and trailer.
  - Auxiliary power unit to reduce idling.
  - Low rolling resistance tires.
  - Lightweight materials.
  - Others….

DOE SuperTruck Initiative Helped Generate Powertrain Innovations

Volvo Trucks

Volvo Uses Knowledge Gained from SuperTruck to Increase Efficiency, Performance in 2017 Powertrain Lineup

"The DOE's support, together with the skill of our powertrain engineers working on the SuperTruck program, helped generate significant powertrain innovations." - Göran Nyberg, President of Volvo Trucks North America.

The development of several new features, such as the wave piston, turbo compounding and a common rail fuel injection system, were supported directly by the program, sponsored by the U.S. Department of Energy.

MID- TO LONG-TERM: Dual clutch transmissions, controllable or electrified auxiliaries, mild hybridization, waste heat recovery, 55% efficient engine, increased peak cylinder pressure

Cab forward designs, further weight reduction (aluminum, carbon fiber), novel tire compounds, solar energy harvesting etc…

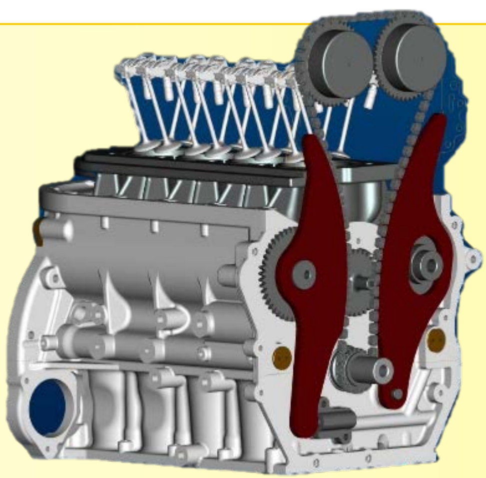

Courtesy of Volvo

Enabling Technologies for Engine and Powertrain System

Eaton Corporation continues development of Roots expander based Rankine cycle waste heat recovery system (using 50/50 glycol water mixture as working fluid) to demonstrate baseline PACCAR heavy duty diesel engine fuel economy improvement.

Roots Expander

PACCAR MX13 (I-6) 360kW @ 1700 rpm
24.3bar peak BMEP with #2 diesel



Envera LLC is developing a Variable Compression Ratio engine using an Eaton VVL with a high-speed clutch which will improve fuel economy while delivering needed torque and power with down-sized engine.

Compression Ratios:

Maximum: 17.5:1

Minimum: 8.2:1

Summary

- Internal combustion engines are forecasted to remain the dominant power source for vehicles in the next several decades, hence increasing their efficiency is one of the most promising and cost-effective approaches to improve the fuel economy of the U.S. vehicle fleet and reduce transportation's energy and climate change impacts.
- EERE Advanced Combustion Engine R&D, in collaboration with industry and academia, using unique DOE national laboratory expertise and facilities, significantly contributes to increases in engine efficiency and performance leading to improvements in vehicle fuel economy and reduction in emissions.
- There is still significant potential to further improve internal combustion engine efficiency using advanced combustion strategies, engine optimization and efficient emission controls; potential for 50% and over 30% fuel economy improvement for passenger and commercial vehicles, respectively.

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