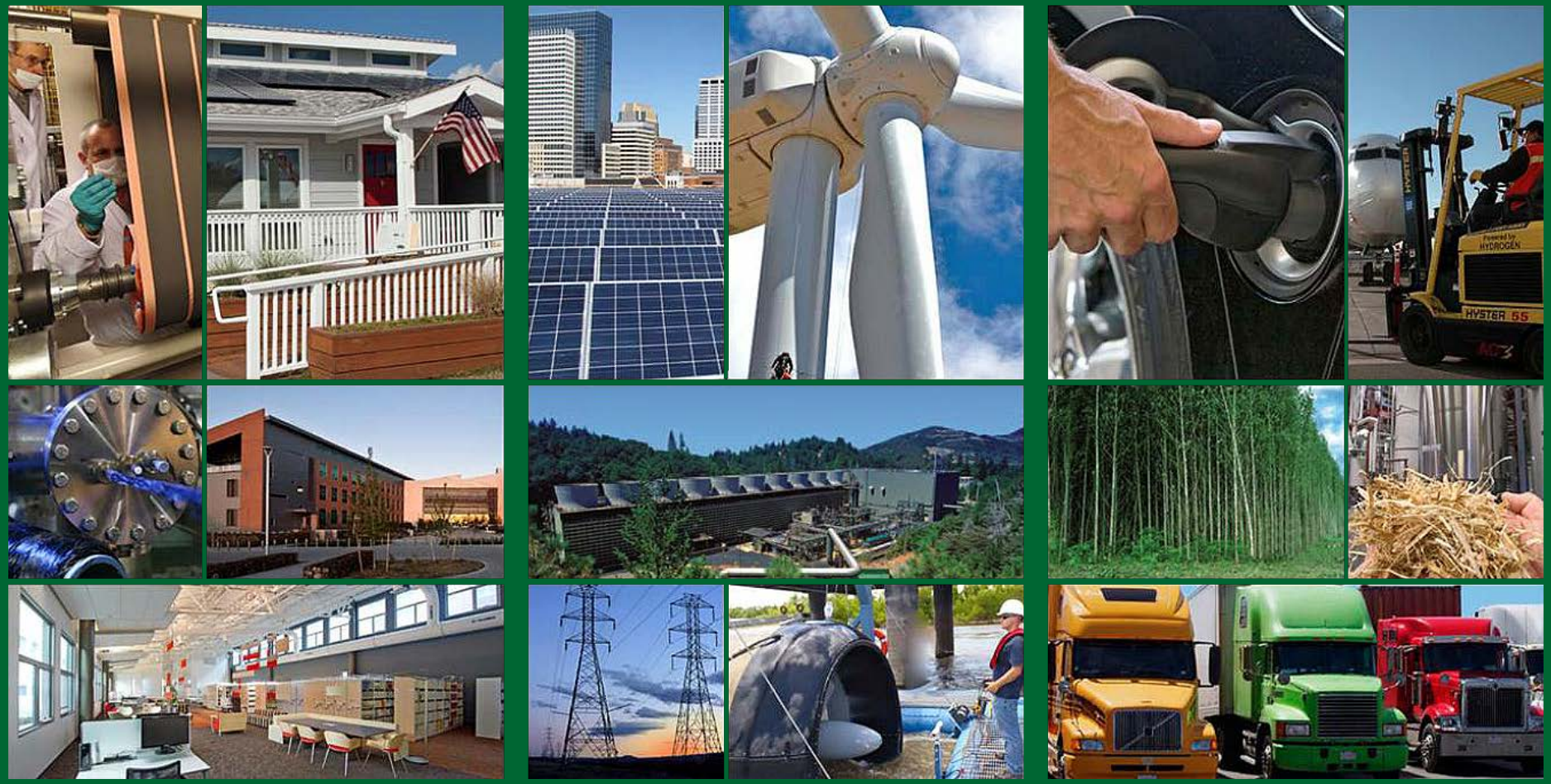
DOE's Vehicle Technologies Office

ADVANCED COMBUSTION SYSTEMS PROGRAM



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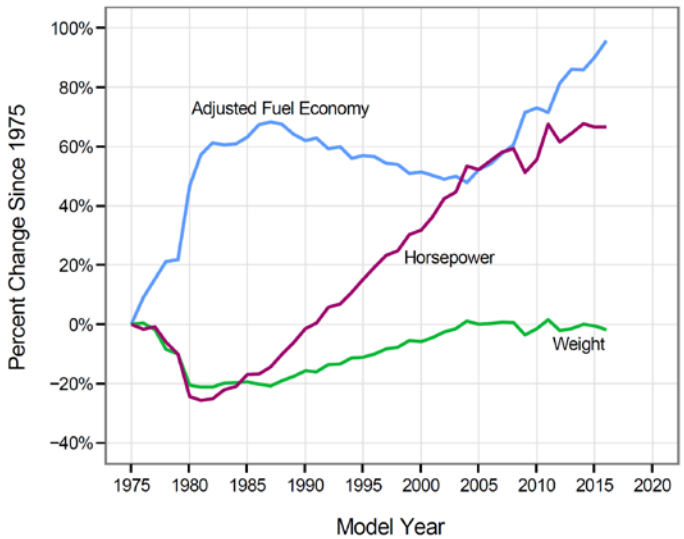
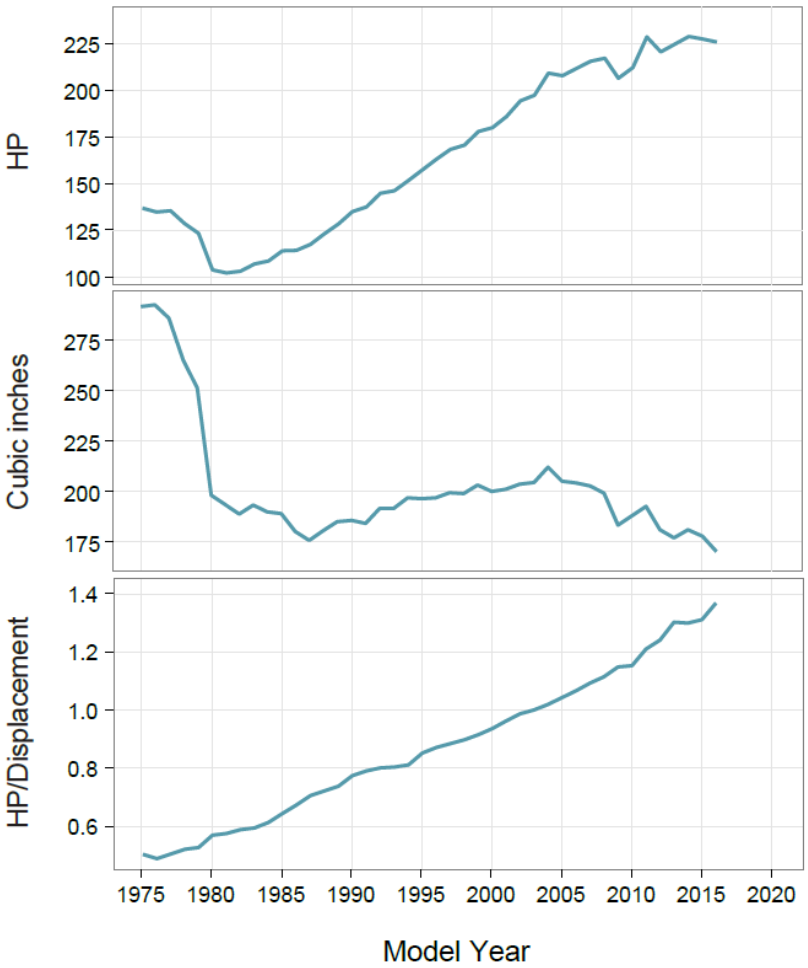
Gurpreet Singh
PROGRAM MANAGER
Office of Energy Efficiency and Renewable Energy

Vehicle Fuel Economy Trends



Increases in engine efficiency have improved fuel economy and performance while vehicle size and weight have continued to increase.



Engine Power and Displacement

Source: Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2016, EPA-420-R-16-010, November 2016.

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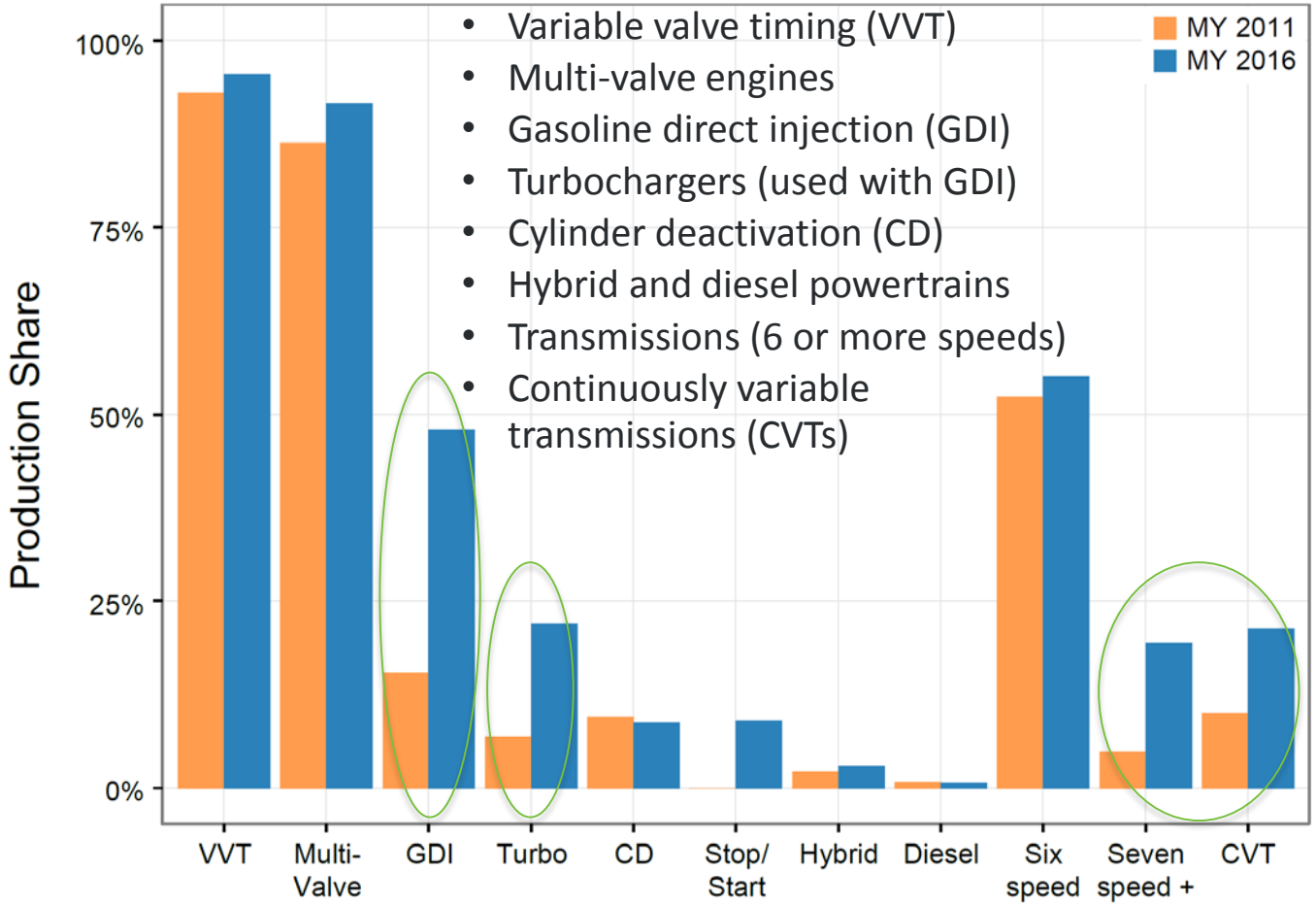
Engine Technologies in Production Vehicles

Technology Production Share for MY 2011 and MY 2016



- Variable valve timing (VVT)
- Multi-valve engines
- Gasoline direct injection (GDI)
- Turbochargers (used with GDI)
- Cylinder deactivation (CD)
- Hybrid and diesel powertrains
- Transmissions (6 or more speeds)
- Continuously variable transmissions (CVTs)

Source: *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2016*, EPA-420-R-16-010, November 2016.

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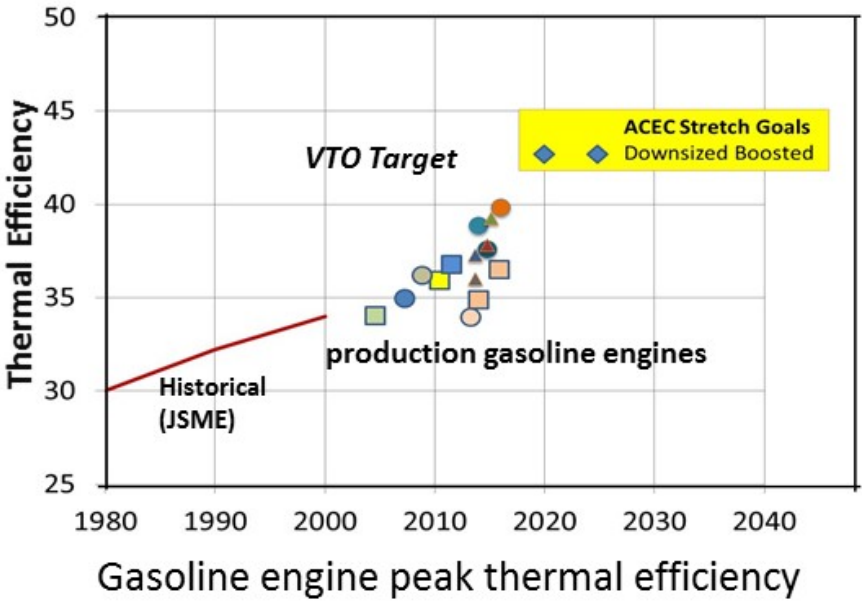
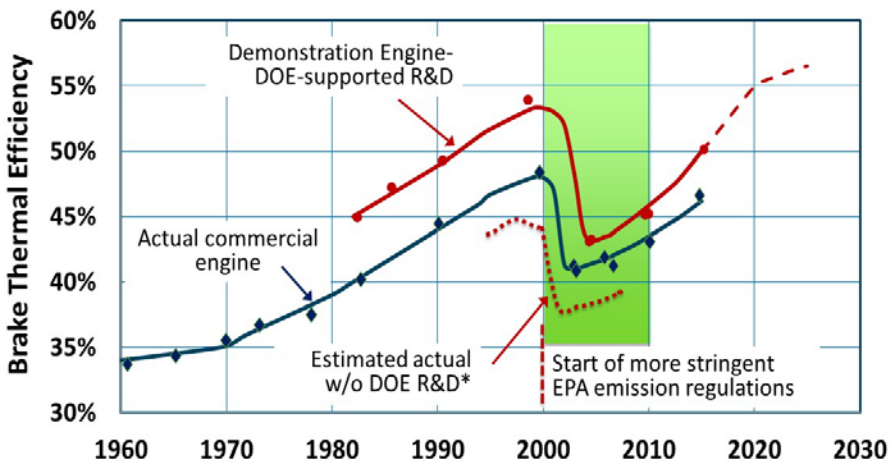
VTO Advanced Combustion Systems R&D – Increase Engine Efficiency

More efficient engines will improve fuel economy of over 99% of new passenger and commercial vehicles in the near- to mid-term.





Historical Trend in Heavy-Duty Diesel Engine Efficiency

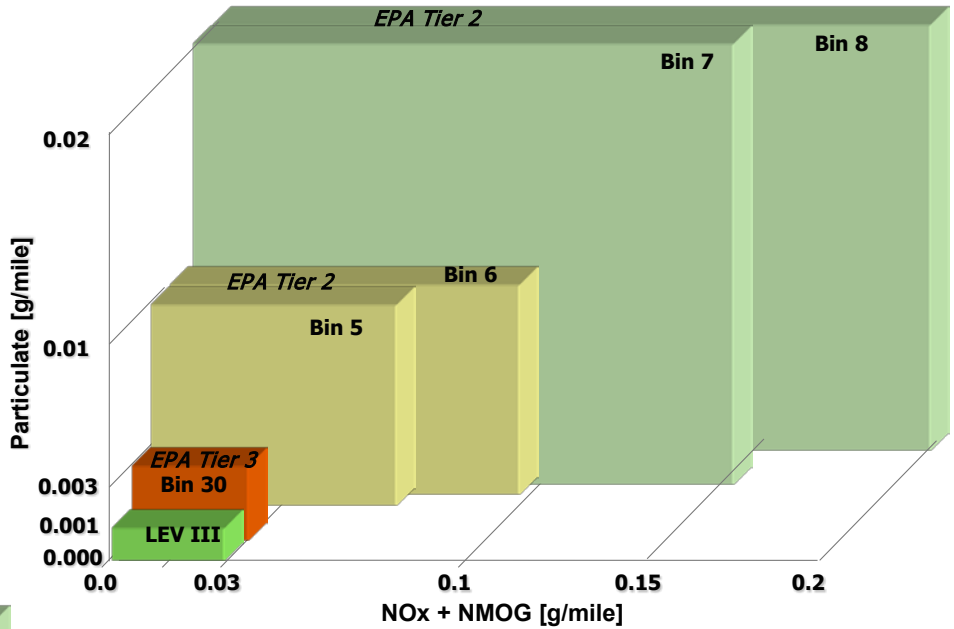
Potential consumer savings of over $315 million per day (over 135 million gallons of fuel <u>per day</u> saved) based on meeting Program goals

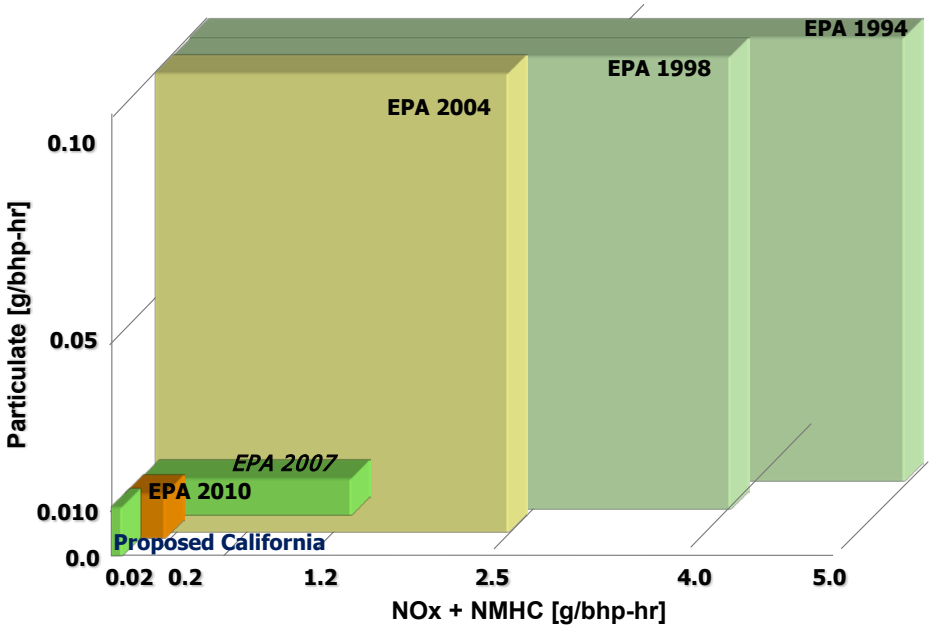
Engine efficiency improvements can increase passenger and commercial vehicle fuel economy by over 50% and 40%, respectively[1]

[1]*Quadrennial Technology Review 2015*, Chapter 8: Advancing Clean Transportation and Vehicle Systems and Technologies. DOE 2015.

More Stringent Emissions Standards

Federal and California Light-Duty Vehicle Emissions Standards





Federal and California Heavy-Duty Engine Emissions Standards

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Technical Challenges

- Develop combustion strategies that maximize engine efficiency while:
  - Operating over the full load-range
  - Improving transient response, and noise, vibration, and harshness (NVH)
  - Reducing in-cylinder emissions formation
- Develop effective aftertreatment technologies for lean, low temperature exhaust emissions while:
  - Reducing cost and energy penalty
  - Reduce volume and weight
- Reduce overall cost of engine system
  - Maintain performance, mobility, fuel economy and affordability

Market Challenges

- Fuel Economy ↑
- Emissions (more stringent regulations) ↓
- Cost to Consumer ↓

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Advanced Combustion Systems Budget – Past & Present

Funding in millions	**FY 2016** Enacted	**FY 2017** Enacted
Advanced Combustion Engine R&D	$37.1	$38.8

Advanced Combustion Systems R&D

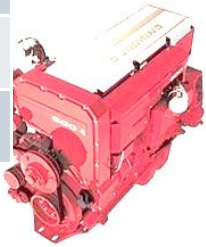
Strategic Goal: Reduce petroleum dependence by removing critical technical barriers to mass commercialization of high-efficiency, emissions-compliant internal combustion engine (ICE) powertrains in passenger and commercial vehicles.

Primary Directions

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

Program Goals

	Light-Duty			Heavy-Duty		
	2015	2020	2025	2015	2020	2025
Engine brake thermal efficiency	--	--	--	50%	55%	57%
Fuel economy improvement*	25%	35%	40 %	20%	30%	35%
NOx & PM emissions	Tier 2, Bin 2	Tier 3/ LEV III	Tier 3/ LEV III	EPA Standards	EPA Standards	EPA Standards



*Compared to: LD baseline is 2009 port fuel injected gasoline vehicle
HD baseline is 2009 HD diesel engine

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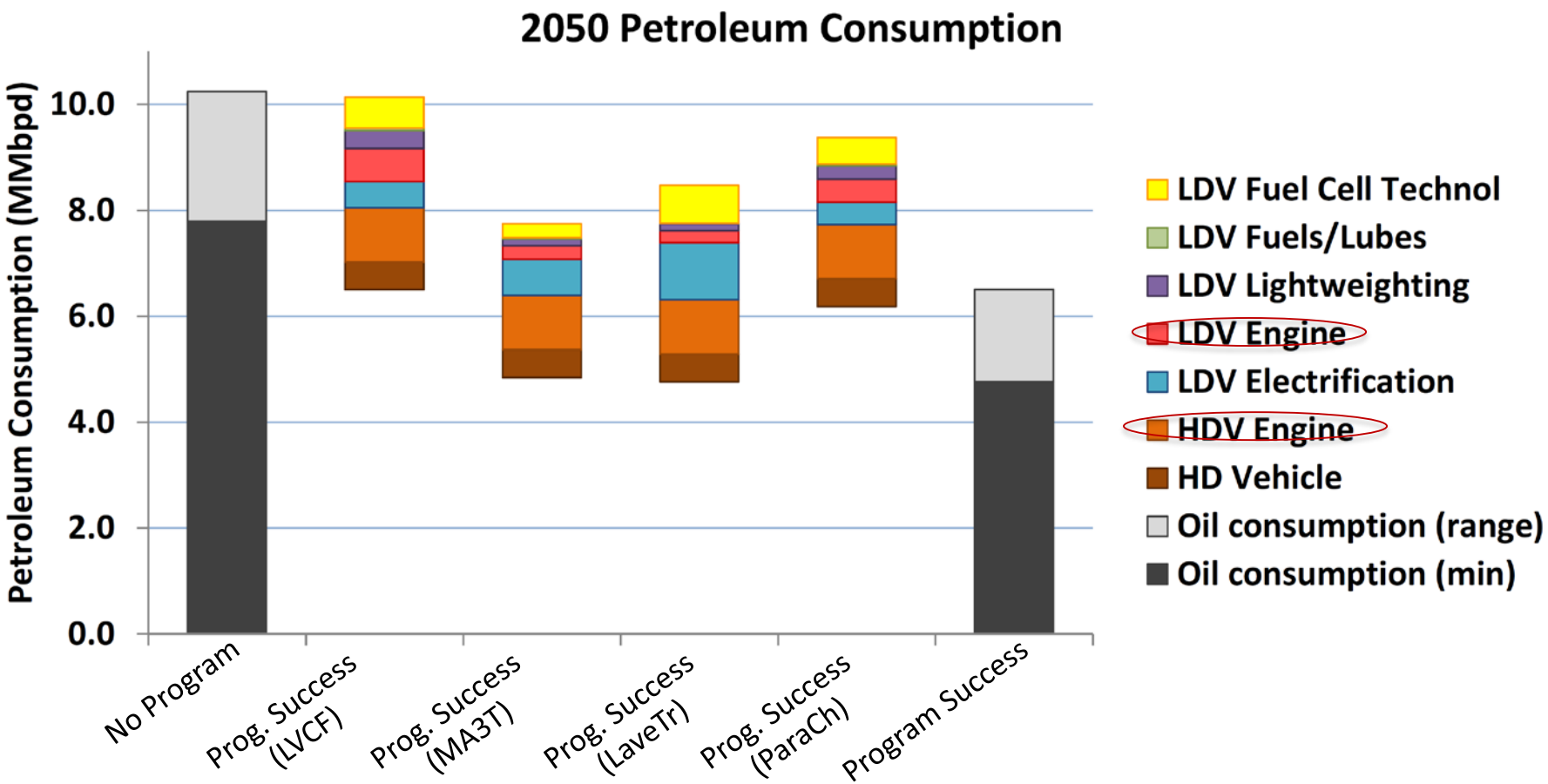
Significant ICE Contribution to Quantified VTO Benefits



Applied analysis aggregates subprograms to estimate VTO program benefits.
Petroleum reduction: 2.9–3.7 mbpd (~26–31 billion barrels cumulatively)
(Models use different assumptions and slightly different light-duty vehicle market representation)

Source: Stephens et al (2016). http://www.anl.gov/energy-systems/publication/vehicle-technologies-and-fuel-cell-technologies-program-prospective

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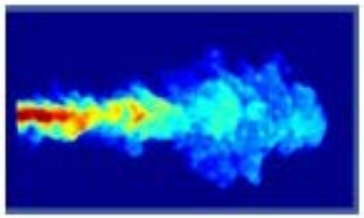
VTO Advanced Combustion Systems Program - R&D Strategy and Portfolio

R&D Strategy

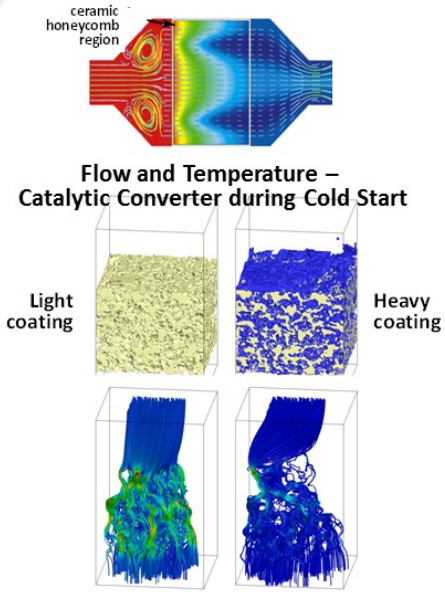
- **Utilize unique national lab capabilities (experimental and modeling/computational) to develop fundamental knowledge of engine combustion and emissions formation/mitigation.**
- **Work collaboratively with academia and industry.**

Diesel Combustion

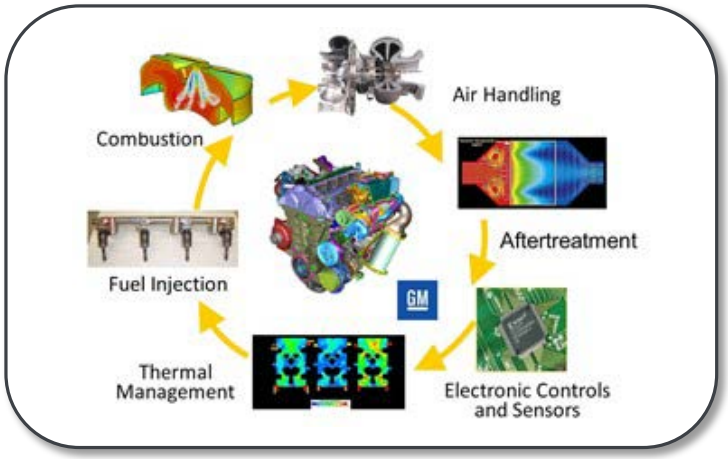


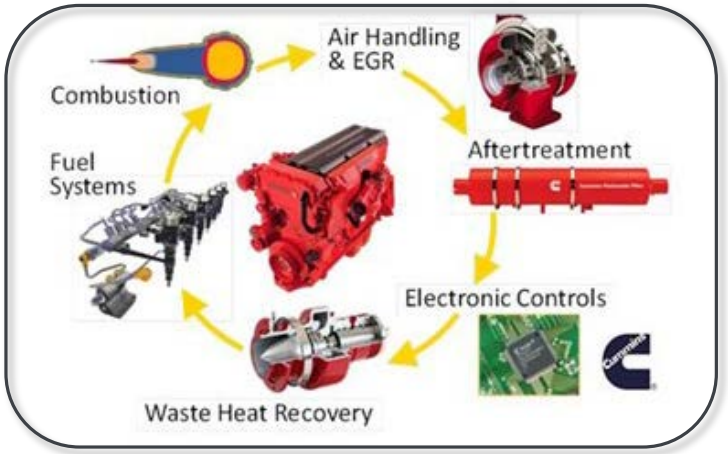
Fuel Spray

Combustion R&D



Emission Control R&D





High Efficiency Engine Technologies R&D

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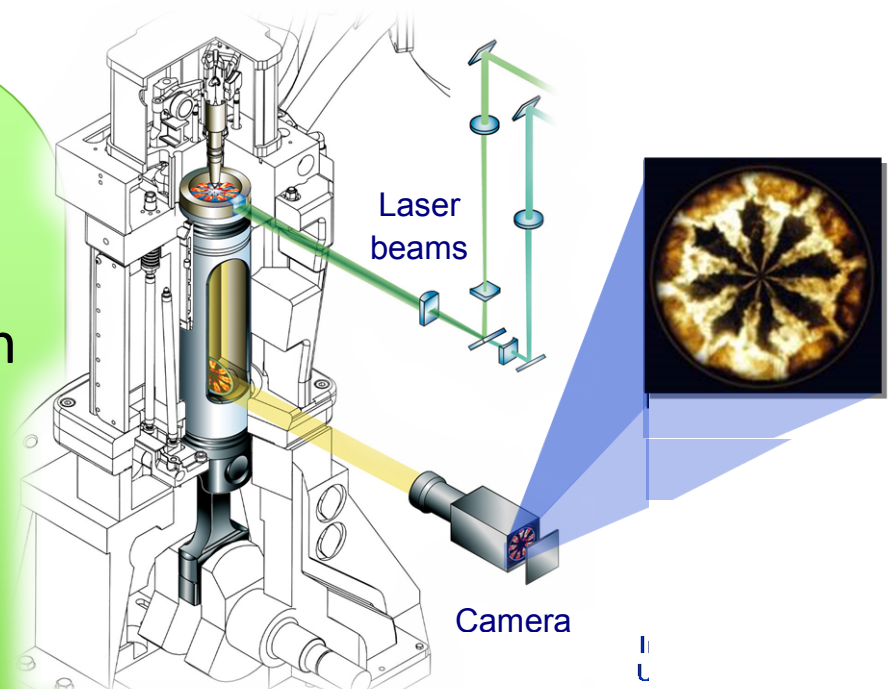
Combustion R&D

- 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 industry to design advanced engine.



Engine Simulation

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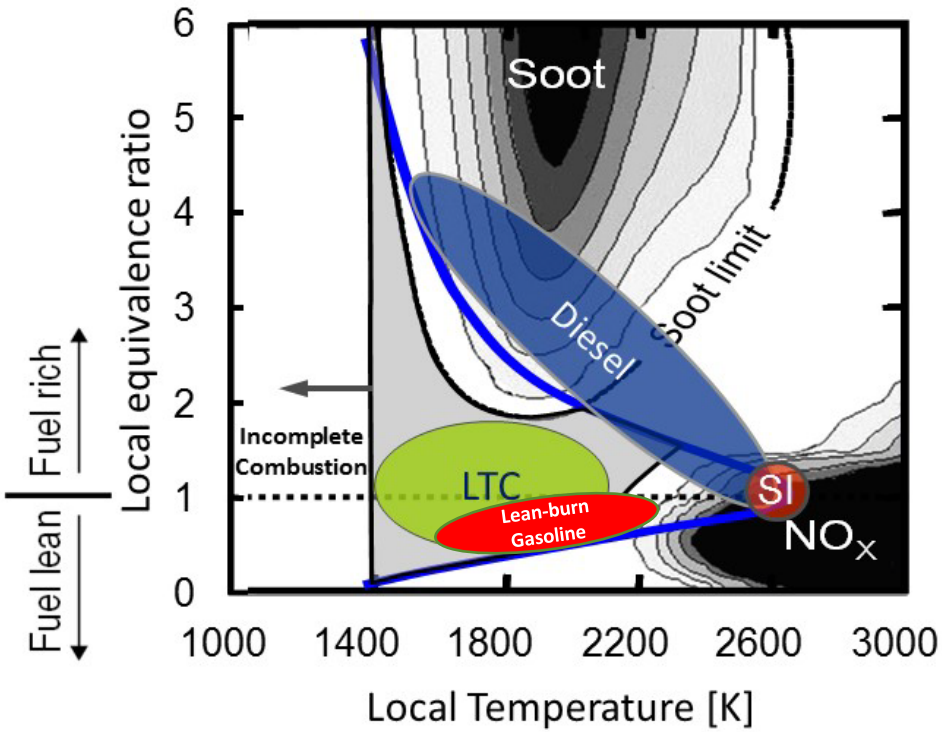
Efficient Clean Advanced Combustion Engines

Combustion Strategies Enabling Improved Efficiency and Very-Low Emissions

- Low-Temperature Combustion (LTC)
- Lean-burn Gasoline Combustion
- Clean Diesel Combustion

Challenges:

- Combustion phasing
- Load range
- Heat release rate
- Transient control
- HC and CO emissions
- Fuel characteristics



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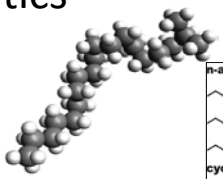
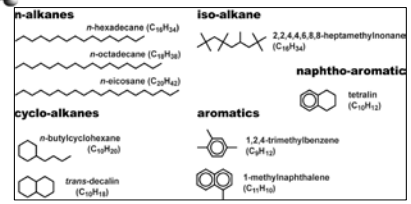
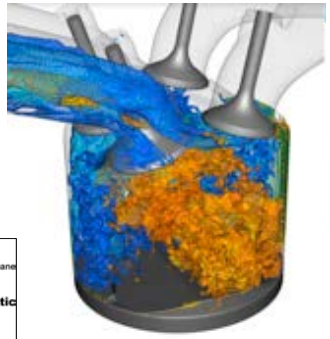
Approach – Use Unique DOE Lab Capabilities to Develop Science-Based Knowledge and Tools Applied to Engine Design

- Close coupled modeling and experiments:
  - Advanced diagnostics (e.g., optical, laser, x-ray, and neutron based techniques)
  - Multi-dimensional computational models and combustion simulators.
  - Fuel kinetics





Lawrence Livermore National Laboratory



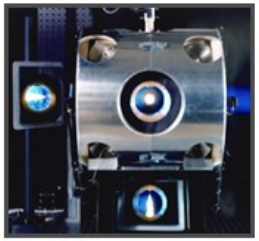
Engine Simulation

Los Alamos NATIONAL LABORATORY

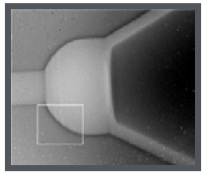
Sandia National Laboratories

Optical Engine

HCCI & Lean-burn Gasoline

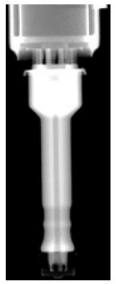


LTC Simulator



Nozzle Sac X-Ray Image

Argonne NATIONAL LABORATORY

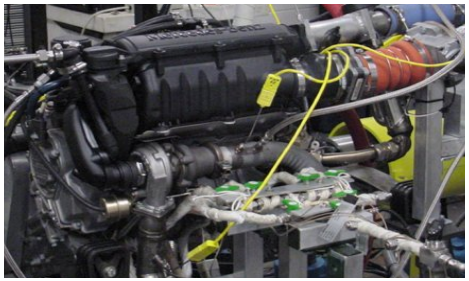


Neutron Imaging-GDI Injector

OAK RIDGE National Laboratory

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

ACS R&D Program develops science-based knowledge and modeling/computational tools for use by industry to improve engine efficiency



Multi-cylinder Engine Test Cell

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Close collaboration with industry *carries research to products*

Advanced Engine Combustion MOU

- Identify potential pathways for efficiency improvement and emission reduction.

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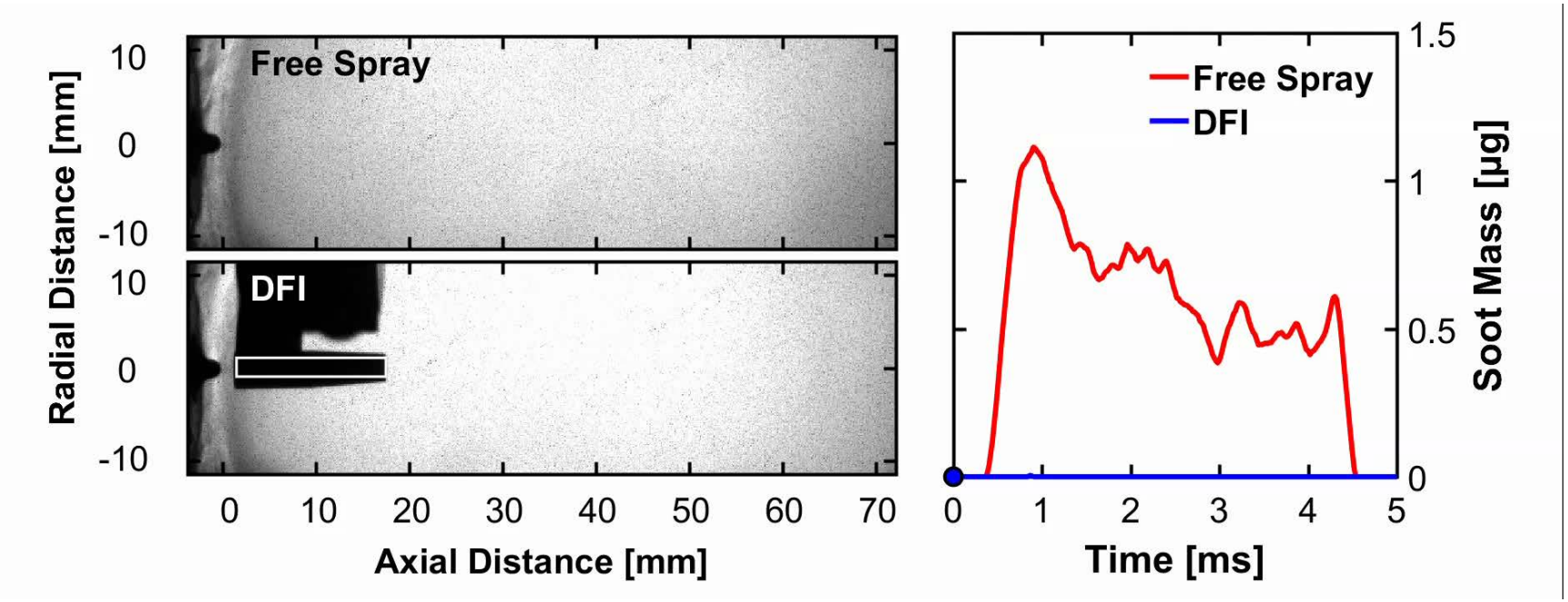
Ducted Fuel Injection (DFI): A New Combustion Concept for High-Efficiency Internal Combustion Engines

- Innovation: Inject fuel through a tube downstream of the fuel-injector orifice to increase turbulent mixing prior to combustion to prevent soot formation

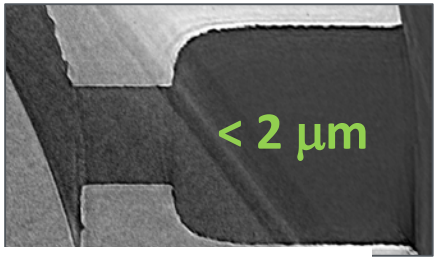


- Addresses key barrier of elevated emissions of soot and NO_x from high-efficiency, mixing-controlled combustion strategies with renewable fuels
- Could be a key technology for future engines
  - A simple, mechanical approach which is very effective for lowering soot
  - Tolerant to fuel variability

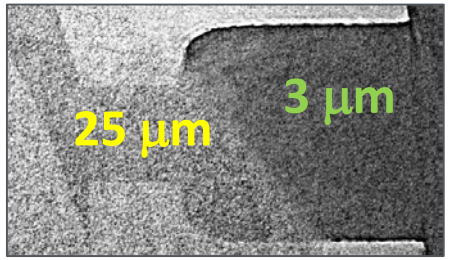
Sandia National Laboratories
U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy

High Precision has been Achieved in Nozzle Geometry Visualization

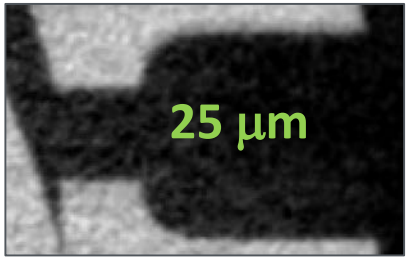
Comparison of Fuel Spray Nozzle Geometry from Different Sources



Argonne

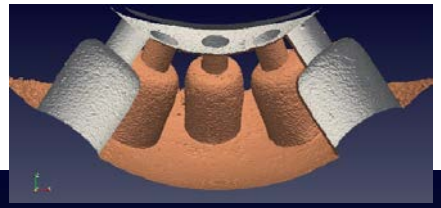


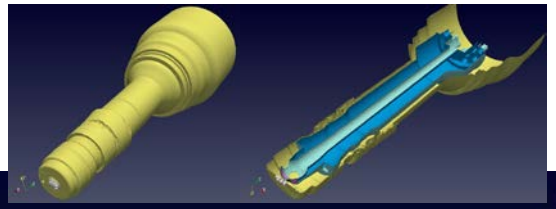
European Synchrotron



Commercial Service

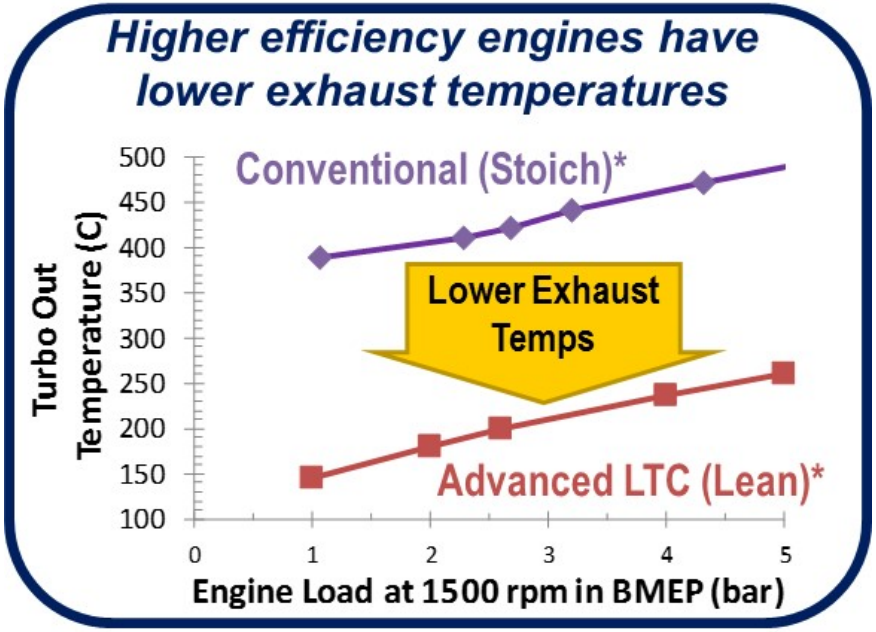
- Nozzle geometries are available from other sources, but limited resolution
- World-class spatial resolution with optimized X-Ray and neutron tomographies

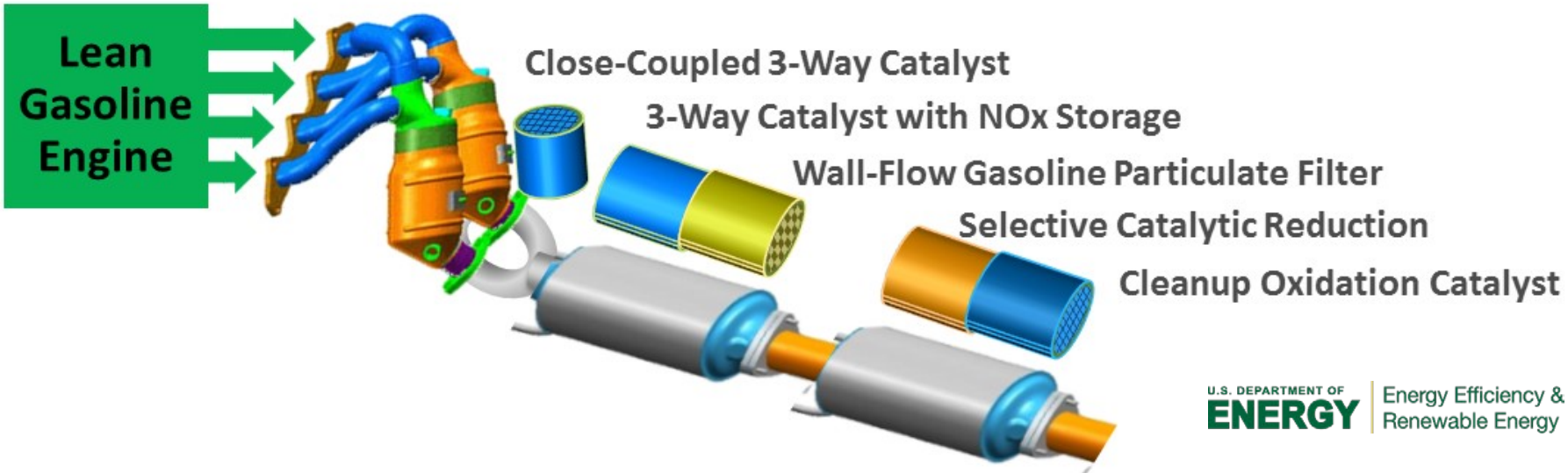




Emission Control R&D

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





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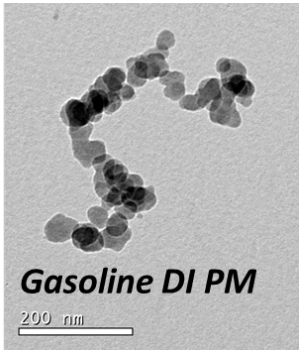
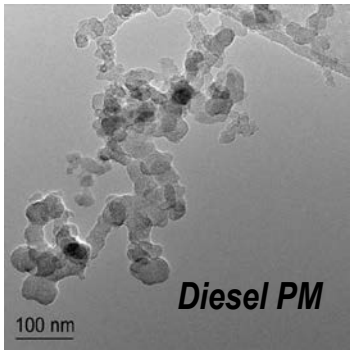
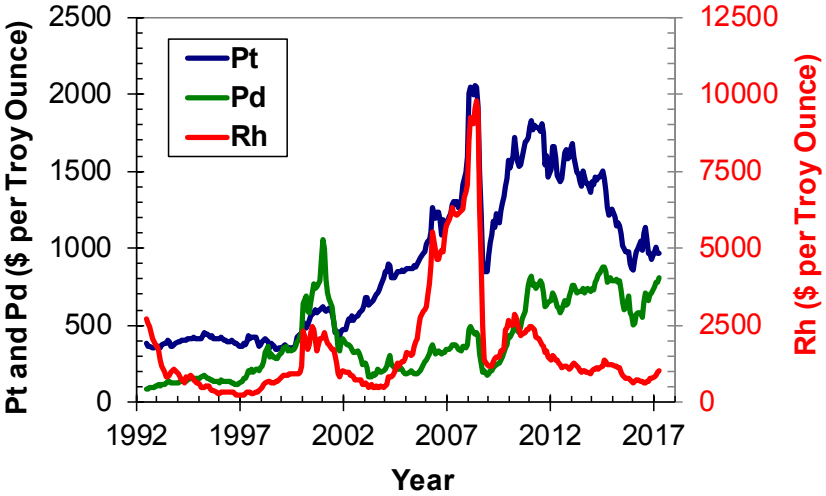
Emissions Challenges

- Low Exhaust Temperatures due to Efficient Combustion
  - Cold start emissions
  - Tier 3 regulation
- Lean NOx reduction
  - Cost of lean-NOx aftertreatment
- Particulate matter (PM) emissions
  - PM characteristics from DI gasoline and diesel engines are different
- Energy Penalty of emission control systems
- Cost
  - Increasing aftertreatment system complexity
  - Highly volatile PGM costs







PGM Cost

Source: www.platinum.matthey.com (JohnsonMatthey)

Close Collaboration and Coordination for Joint Research and Development of Emission Control Data and Models

- Cross-cut Lean Engine Emission Reduction Simulations, CLEERS (www.cleers.org) - industry, national labs, and universities collaborate to develop functional models for lean emission control devices and systems.

CLEERS Technology Focus Group

Adv. Eng. Crosscut

ACEC TT

DOE VTO

LD OEMs:
FCA
Ford
GM

EPA
TARDEC

HD OEMs:
Caterpillar
Cummins
Daimler
Navistar
Paccar
Volvo

Suppliers:
BASF
Johnson-Matthey
Umicore
Corning
Delphi
Haldor Topsoe

CLEERS Industry Survey Recipients

Industry:
John Deere
Bosch
Tenneco
IAV
N2Kinetics
Emissol

Nat'l Labs:
ORNL
PNNL
ANL
LANL

Universities:
Chalmers Univ.
Michigan Tech. Univ.
Pennsylvania State Univ.
Politecnico di Milano
Purdue Univ.
Texas A&M Univ.
UCT Prague
Univ. of Houston
Univ. of Kentucky
Univ. of Notre Dame
Univ. of Michigan
Univ. of Virginia
Univ. of Wisconsin

Denso	Aramco	CPERI/CERTH	Hannam Univ.	Univ. of Connecticut
Eaton	AVL	NREL	Karlsruhe Inst. of Tech.	Univ. of Kansas
GE	CD Adapco	PSI	Mass. Inst. of Tech.	Univ. of New Mexico
Hyundai	Converge	SwRI	Michigan State Univ.	Univ. Pierre & Marie Curie
Hino	Exothermia	NRCan	Ohio State Univ.	Univ. of Tennessee
NGK	Gamma	TNO	Queens Univ. Belfast	West Virginia Univ.
Toyota	Ricardo		Seoul National Univ.	Wayne State Univ.

CLEERS Participants

- Fundamental surface-reaction-based to component models.
- Increasingly relied on by industry in product development and optimization.

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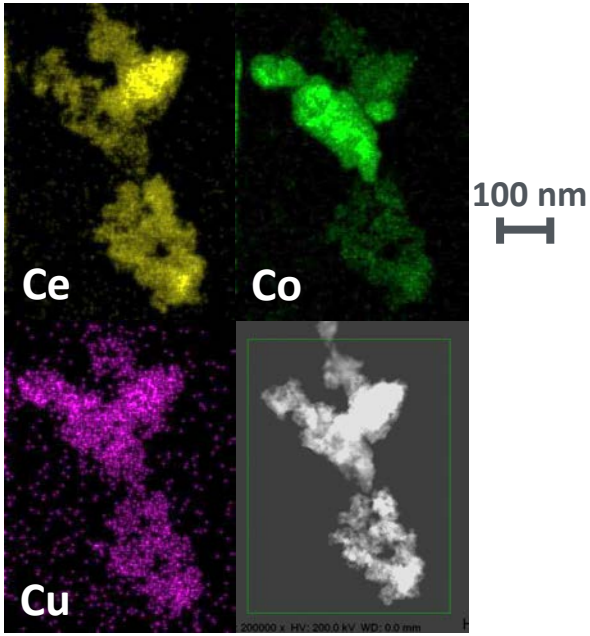
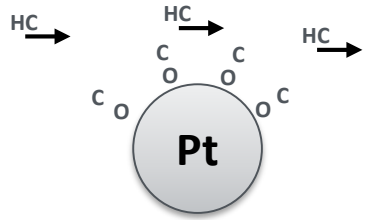
BES and EERE Collaboration Overcomes Inhibition Problem for CO and HC Control at Low Temperatures

1. BES research on Co-Cu-Ce catalyst
2. EERE applied research under automotive conditions shows Co-Cu-Ce overcomes inhibition
3. Co-Cu-Ce catalyst improves low temperature oxidation at lower Pt loading



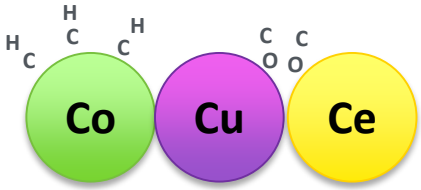
Conventional Pt Catalyst:

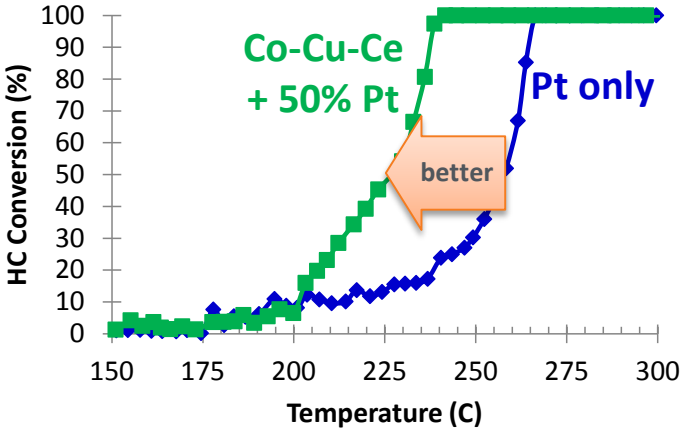
CO and HCs compete for active site; CO inhibition limits HC oxidation



New Co-Cu-Ce Catalyst:

Separate active sites for CO and HCs prevent inhibition





Note: the Co-Cu-Ce+Pt catalyst has 50% less Pt than the Pt only catalyst

Z.-G. Liu, S.-H. Chai, A. Binder, Y.-Y. Li, L.-T. Ji, S. Dai, *Appl. Catal. A-Gen.* **2013**, *451*, 282–288.

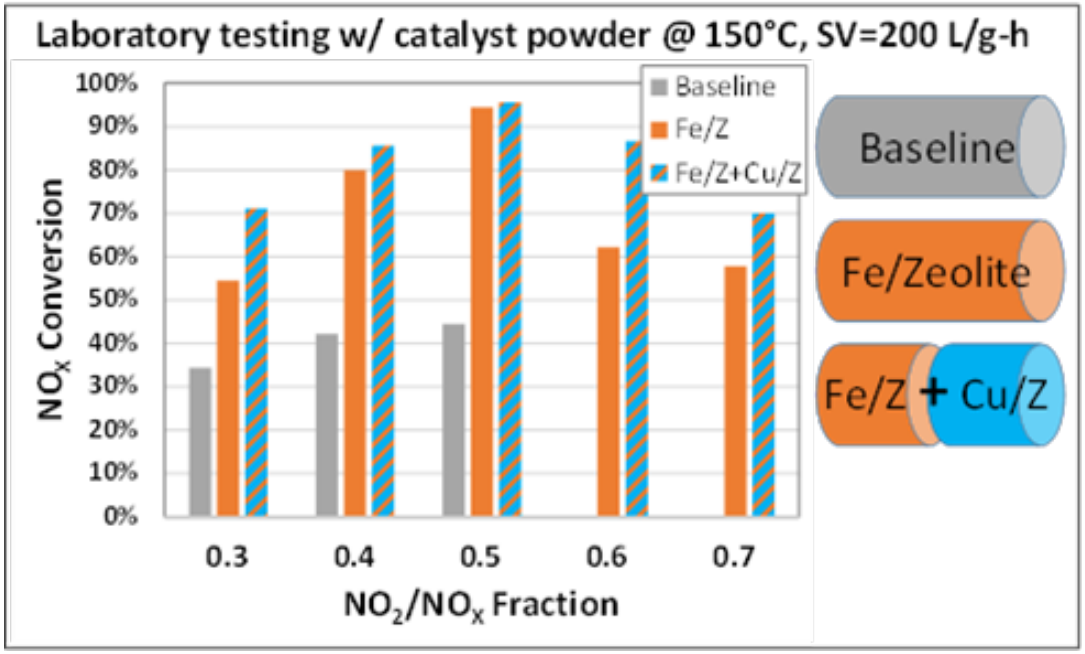
A. J. Binder, T. J. Toops, R. R. Unocic, J. E. Parks II, S. Dai, *Angewandte Chemie Intl. Ed.* **54**, 13263 –13267 (2015).

OAK RIDGE National Laboratory

Co-Cu-Ce catalyst gives lower temperature CO & HC control at 50% less cost

New SCR Catalyst Demonstrates Improved, Sustainable Low Temperature Performance (PNNL, Cummins, Johnson Matthey)

- Fast-SCR reaction (consumes NO and NO_2 in equimolar amounts) is efficient for low-temperature NOx conversion but impeded by ammonium nitrate which forms as a solid poison at typical fast-SCR conditions below 180°C
- PNNL-developed novel iron-exchanged zeolite SCR catalyst eliminates ammonium nitrate deposition under fast-SCR conditions at a temperature as low as 150°C.
- Cummins and Johnson Matthey will conduct full scale demonstration for exhaust aftertreatment.



Steady-state NOx conversion of a commercial baseline SCR catalyst, PNNL's Fe/zeolite, and the dual bed Fe/zeolite + Cu/zeolite concept.

Pacific Northwest NATIONAL LABORATORY

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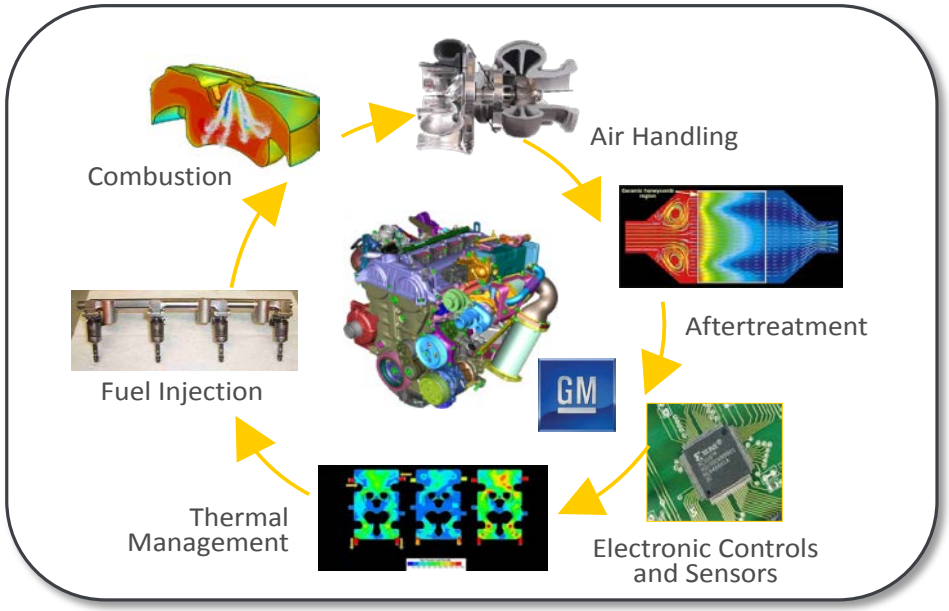
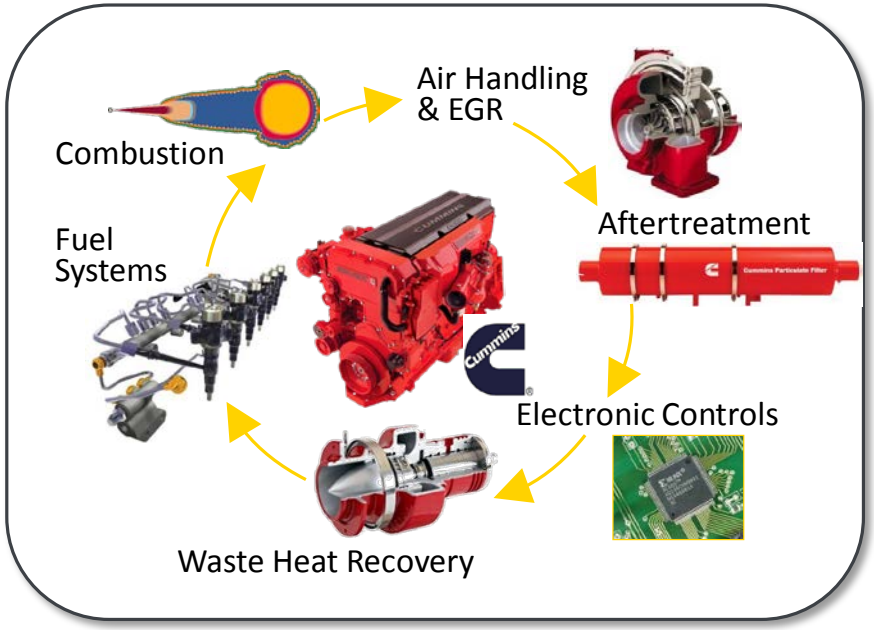
High-Efficiency Engine Technologies R&D

- Research, 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.



Light-Duty



Heavy-Duty

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Advanced Technology Powertrain for Light-Duty Vehicles

Goal: 35% improvement in fuel economy (MPG) by 2020, compared to 2009 baseline vehicles (Chevy Malibu, Hyundai Sonata).

GM

DELPHI

- *Increased engine efficiency and demonstrated over 25% fuel economy improvement in 2015.*
- *Developing advanced combustion technologies to further increase engine efficiency.*
- *Pathways to meet fuel economy goal also includes meeting Tier 3 emission standards.*

SuperTruck II

Engine Goal: 30% improvement in engine efficiency by 2020, compared to a 2009 baseline SuperTruck engine.

- *Increased engine efficiency by 20% in 2015.*
- *Advanced combustion technologies will further increase engine efficiency to 55 percent.*
- *Pathway to meet fuel economy goal also includes meeting prevailing EPA emission standards.*
- *Tractor-trailer freight efficiency improvements of over 104%, 88%, 86%, and 115%, for Navistar, Volvo, Cummins/Peterbilt, and Daimler, respectively.*

SuperTrucks by Navistar, Volvo, Cummins/Peterbilt, and Daimler.

Vehicle Systems Projects

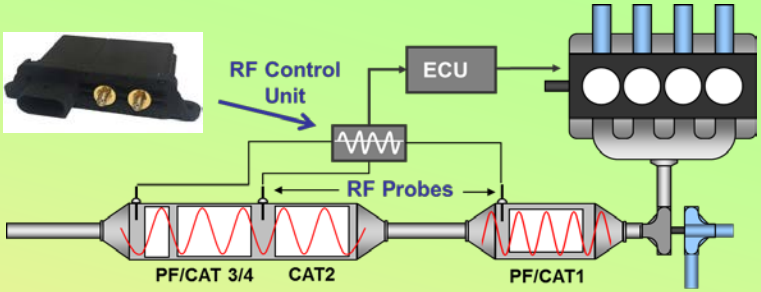
Developed truck and bus radial tire material with 16% better rolling resistance with improved tear strength and treadwear over the state of the art carbon black-filled natural rubber-based tread compound. Processing of tread compound similar to carbon black control.

Truck and bus radial tire surface-modified with novel silica technology.

Validated Navistar SuperTruck aerodynamic performance in full-scale wind tunnel tests; evaluated performance of aero devices and integrated design for tractor-trailers and tankers; and achieved major reduction in aerodynamic drag for tanker trailers through geometry modifications

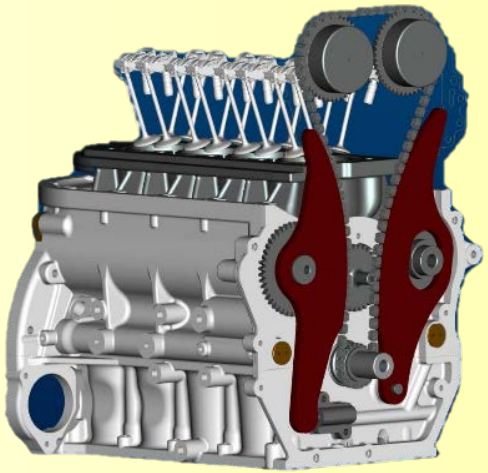
Enabling Technologies for Engine and Powertrain System

CTS demonstrated the feasibility to directly measure stored ammonia on SCR and oxygen on three-way catalyst using unique radio frequency (RF) sensors.



CTS Your Partner in Smart Solutions

Multi-function radio-frequency (RF) sensing platform for more efficient and robust emission controls of advanced combustion engines.



Envera LLC has designed and built the Variable Compression Ratio engine using an Eaton VVL with a high-speed clutch and completed round of engine testing to demonstrate light load efficiency.

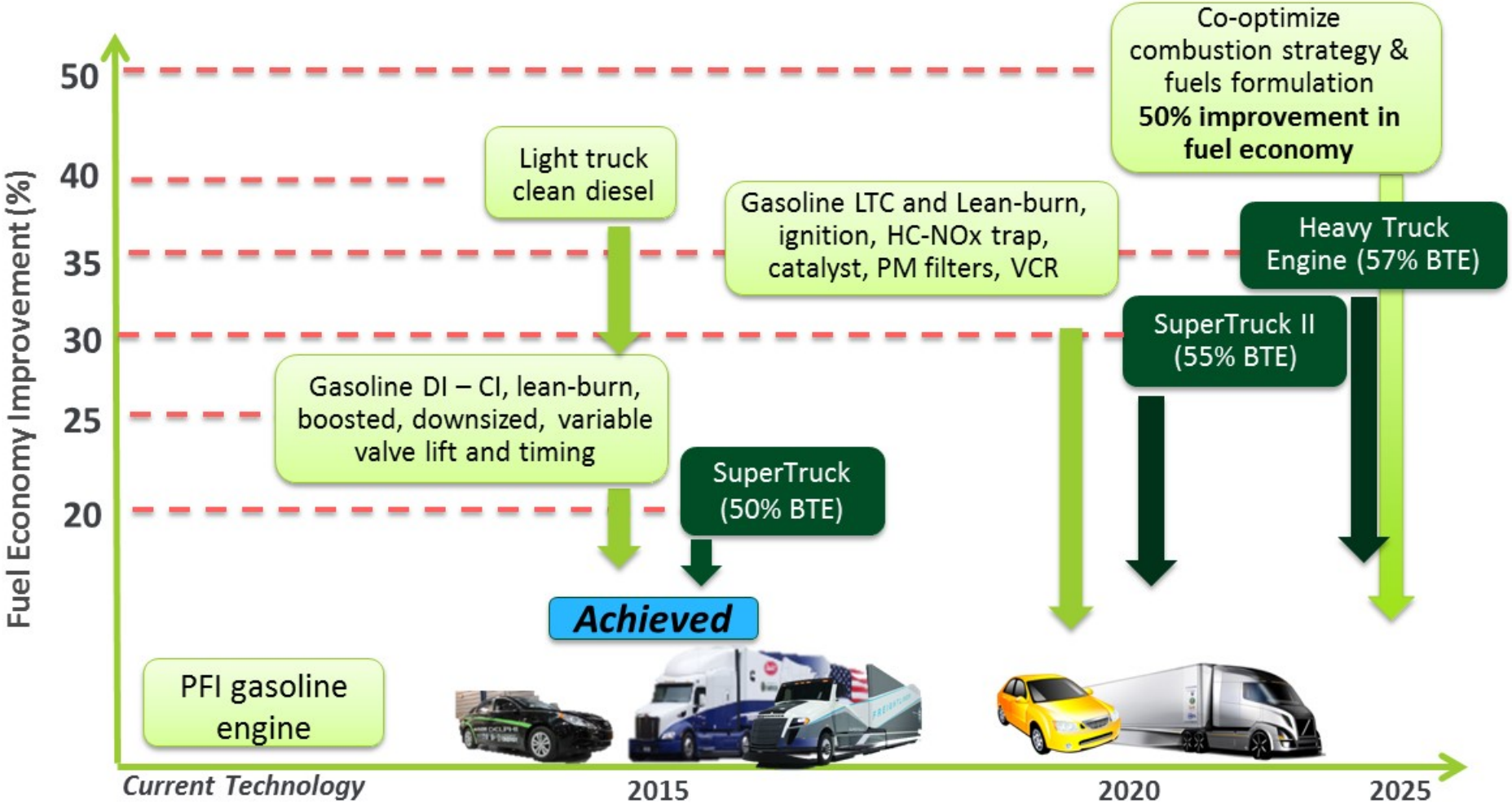
Compression Ratios:

Maximum: 17.5:1

Minimum: 8.2:1

R&D Roadmap – *Addressing Critical Barriers for Commercializing Advanced Combustion Engines in Vehicles*

Increase Engine Efficiency to Improve Fuel Economy



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Conclusion

- Increasing the efficiency of internal combustion engines 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 impact.
- EERE VTO Advanced Combustion Systems R&D Program, in collaboration with industry and academia, and using unique DOE national laboratory expertise and facilities, contributes to increasing engine efficiency and performance leading to improvements in vehicle fuel economy and reduction in emissions.
- There is still significant potential to improve internal combustion engine efficiency using advanced combustion strategies, engine-fuel co-optimization and efficient emission controls; potential for 50% and over 35% fuel economy improvement for passenger and commercial vehicles, respectively.

Contact

Gurpreet Singh

gurpreet.singh@ee.doe.gov

Web site:

Vehicle Technologies Office

www.vehicles.energy.gov

http://energy.gov/eere/vehicles/vehicle-technologies-office