High Efficiency Clean Combustion in Multi-Cylinder Light-Duty Engines (ACE 17)

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Overview

Activity direction evolves with the DOE *needs* and is currently focused on milestones associated with Vehicle Technologies emissions objectives.

Duration

- Consistent with VT MYPP
- Activity scope changes with DOE *needs*

Barriers

- Efficiency/combustion
- Emission control
- Engine management

Budget

- FY 2006 $350k (milestone met)
- FY 2007 $350k (milestone met)
- FY 2008 $400k (milestone met)
- FY 2009 $400k (in progress)
- FY 2010 $400k (anticipated)

Interactions / Collaborations

- Industry technical teams
- DOE working groups
- One-on-one interactions with industry
- Common engine geometry between Sandia, UW, and ORNL.

Objective is to further development, implementation and integration of advanced combustion for optimal efficiency and lowest possible emissions

➡ *In progress*

Characteristics	FY 2006	FY 2007	FY 2008	FY 2009	FY 2010
Peak Brake Thermal Efficiency (HC Fuel)	41%	42%	43%	44%	45%
Part–Load Brake Thermal Efficiency (2 bar BMEP @ 1500 rpm)	27%	27%	27%	29%	31%
Emissions	Tier 2 Bin 5	Tier 2 Bin 5	Tier 2 Bin 5	Tier 2 Bin 5	Tier 2 Bin 5
Thermal efficiency penalty due to emission control devices	< 2%	< 2%	< 2%	< 1%	< 1%

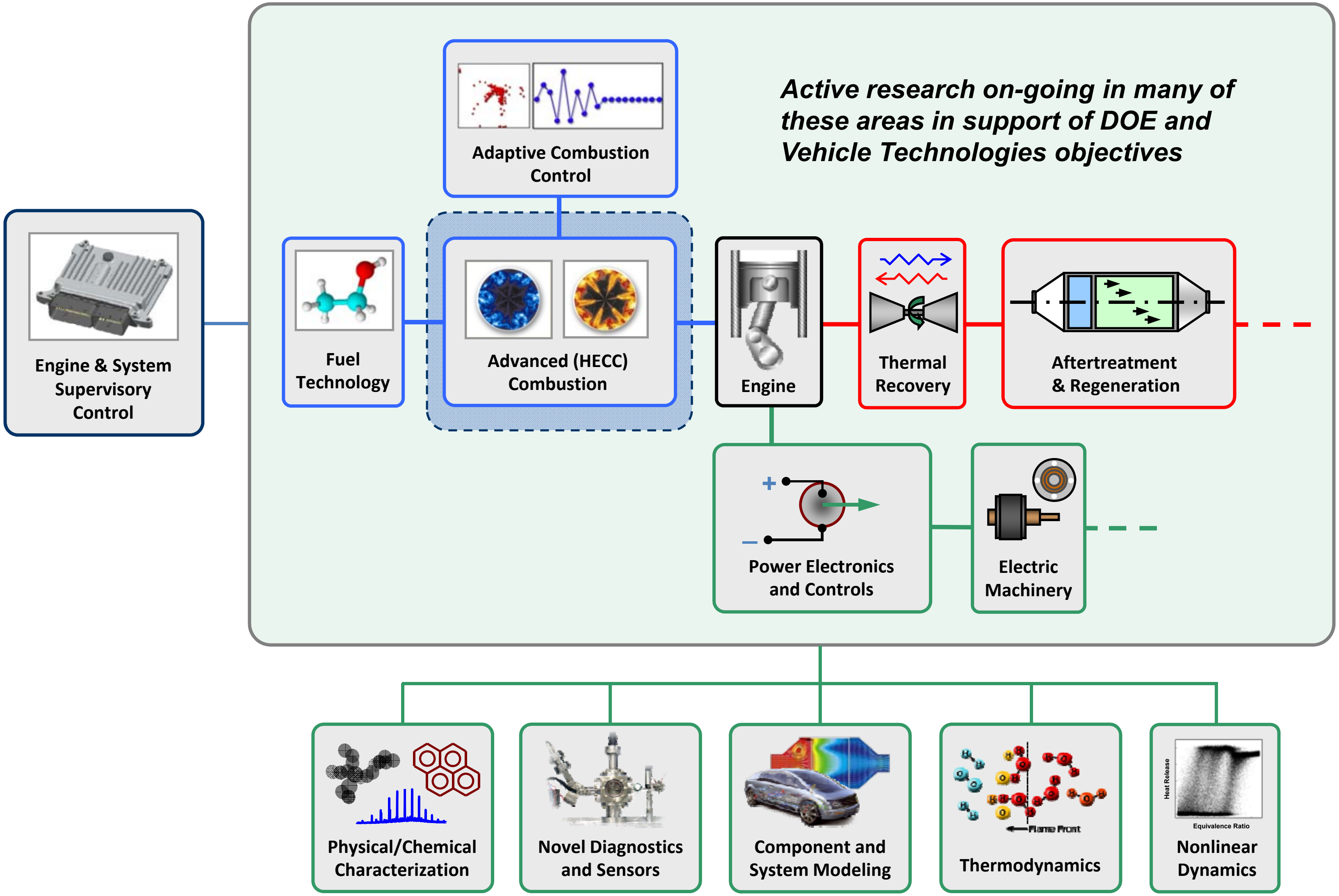
FY 2008 Milestone ➡ *complete*

Explore HECC operation and EGR/air mixture temperature effects to better understand implementation of low temperature combustion processes on multi-cylinder engines (September 30, 2008).

FY 2009 Milestone ➡ *in progress*

Characterize cylinder/cyclic dispersion of HECC operation for modal conditions which are consistent with LD diesel operation (September 30, 2009).

Important to consider interactions/compatibility of combustion strategy with other efficiency enabling technologies



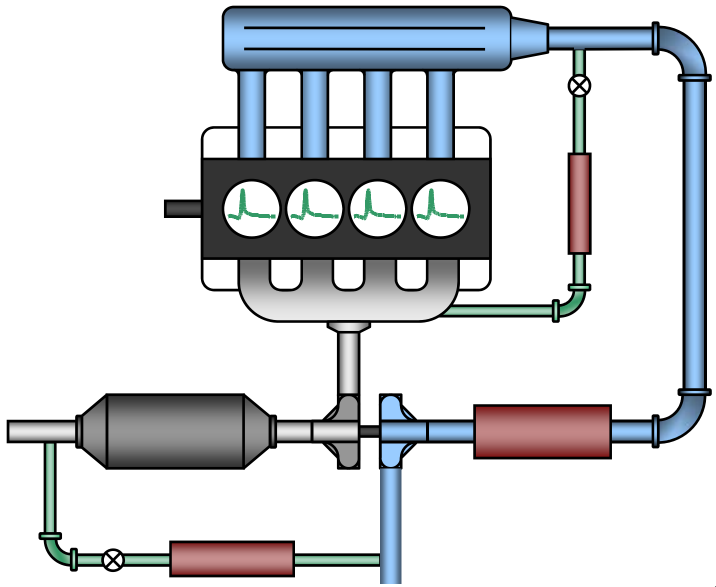
Comprehensive approach necessary for successful implementation of *robust* HECC operation

ORNL *toolbox* for multi-cylinder combustion research

Intake Charge Preparation
LP+HP EGR systems for manipulating intake charge conditions.

Flexible Engine Control
Unconstrained control and integration of custom algorithms.

Exhaust Speciation
Improved understanding of particulate and gaseous emissions and matching with emission controls.



Thermodynamics
Identification of efficiency opportunities and synergies with thermal energy recovery.

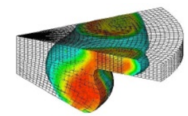
Combustion Stability
Characterization and control of cyclic/cylinder dispersion for more robust HECC operation.

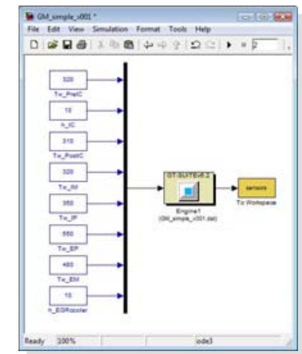
Combustion Noise
Phenomenological models and combustion characterization methods.

Modeling
Guidance for experiments as well as interpretation of experimental data.

Simulation + Experiment + Collaboration

Simulation to characterize and evaluate HECC operation from engine to vehicle level.



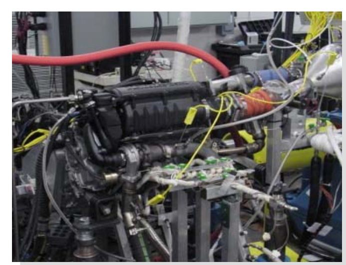


- **Combustion modeling (In-house multi-zone models)**
  - » Guide experiments and interpret experimental data.
- **Engine-system modeling (GT-Power & WAVE)**
  - » Evaluate combustion management strategies, design/evaluate auxiliary systems such as low-pressure EGR, etc.
- **Vehicle System modeling (PSAT & GT-Drive)**
  - » Evaluate integration of technologies (e.g., HECC, thermal energy recovery, aftertreatment, etc.) and operational strategies across simulated drive cycles.

Experiments for development and demonstration of methods in multi-cylinder environment.

GM 1.9-L Engine (2005, 2007)

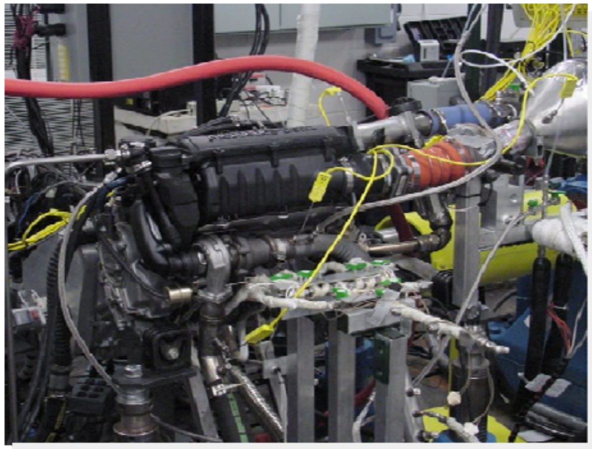
Number Cylinders	4
Bore, mm	82.0
Stroke, mm	90.4
Compression Ratio	17.5
Rated Power, kW	110
Rated Torque, Nm	315



MB 1.7-L Engine (1999)

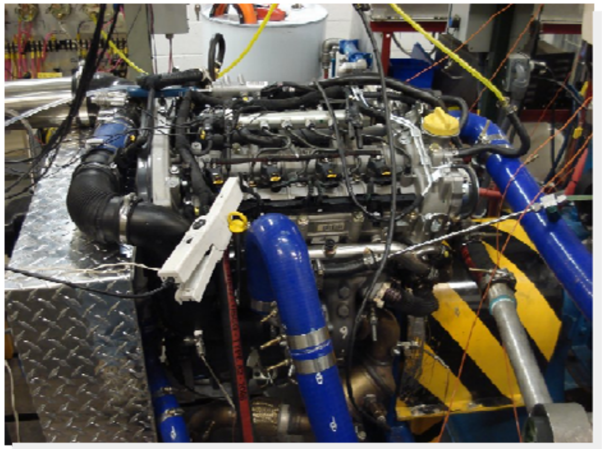
Number Cylinders	4
Bore, mm	80.0
Stroke, mm	84.0
Compression Ratio	19.0
Rated Power, kW	66
Rated Torque, Nm	180

More details on multi-cylinder engine platform



MB 1.7-L Engine (1999)

Transition to more modern engine platform <u>complete</u>



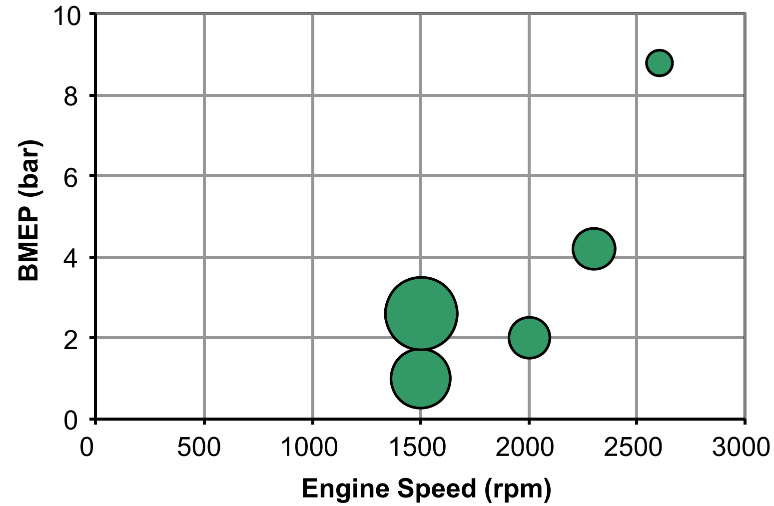
GM 1.9-L Engine (2005, 2007)

- **Bosch Gen 1 fuel system**
- **Modifications include VGT, HP & LP EGR, throttle, etc.**
- **Flexible micro-processor based controls**
- **WAVE model**

- **Bosch Gen 2 fuel system**
- **OEM version includes VGT, EGR cooler, throttle, etc.**
- **Geometry common to ORNL, UW, and SNL (optical)**
- **Open ECU and flexible micro-processor based controls**
- **GT Power model**

Engine conditions consistent with LD drive cycles and consistent with those used in related activities at ORNL

- **Used to estimate drive-cycle emissions and efficiency for technology comparisons.**
- **Considered representative speed-load points for light-duty diesel engines.**
- **Method does not account for cold-start, transient phenomena, aftertreatment regeneration, etc.**



Point	Speed / Load	Weight Factor	Description
1	1500 rpm / 1.0 bar	400	Catalyst transition temperature
-	1500 rpm / 2.0 bar	NA	VT milestone condition (not included in FTP estimate)
2	1500 rpm / 2.6 bar	600	Low speed cruise
3	2000 rpm / 2.0 bar	200	Low speed cruise with slight acceleration
4	2300 rpm / 4.2 bar	200	Moderate acceleration
5	2600 rpm / 8.8 bar	75	Hard acceleration

Road-load condition defined for milestones in VT MYPP

For more information on modal conditions see

SAE 1999-01-3475, 2001-01-0151, 2002-01-2884, 2006-01-3311 (ORNL)

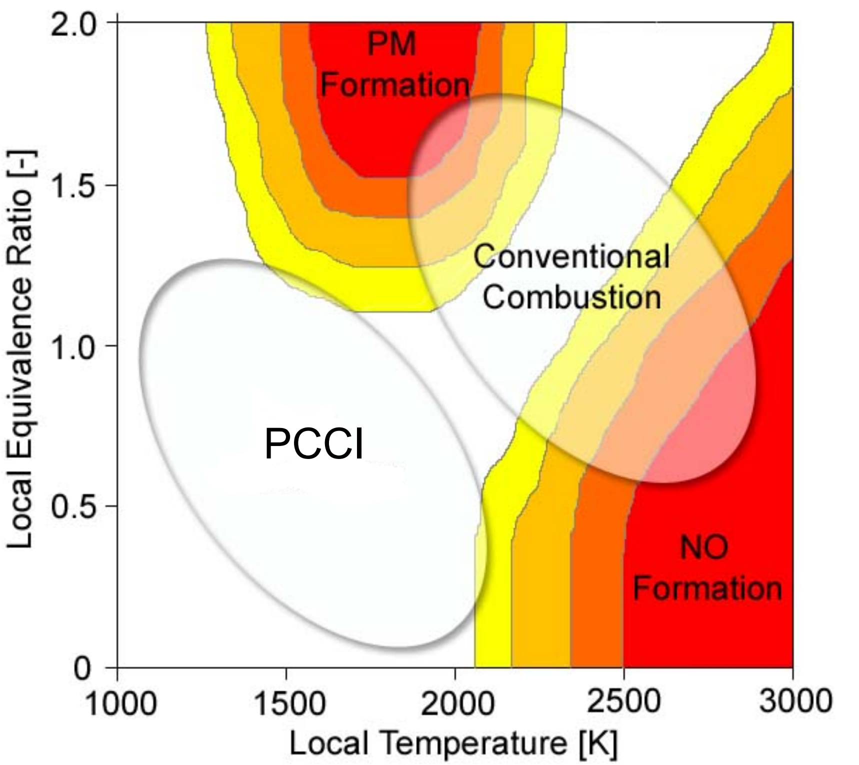
Technical Accomplishments/Progress (since February 2008)

- Established and compared HECC methods for optimal efficiency, emissions, and combustion noise (MB and GM engines).
- Explored load expansion and thermal influences with additional emphasis on higher load operation more consistent with engine downsizing (GM engine).
- Performed drive-cycle simulations based on experimental HECC maps to characterize potential of conventional and advanced powertrains.
- Evaluated fuel properties effects on HECC operation (Fuels Technologies activity)
- *In progress* characterizing cylinder/cyclic dispersion sensitivity to HECC method and EGR/air maldistribution (not shown).

FY 2009 experiments scheduled for Spring 2009 (now) and are on-going.

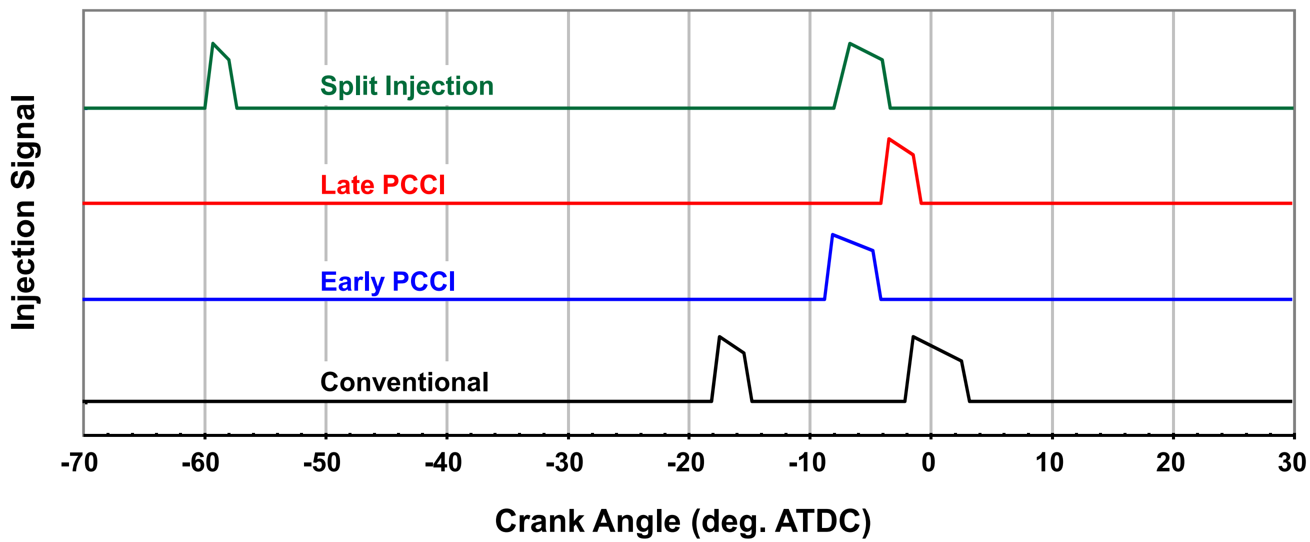
Premixed Charge Compression Ignition (PCCI) combustion is primary path for this activity

- **Most compatible with current and near-term engine technologies.**
- **Purpose is to reduce in-cylinder emissions formation with minimal impact on brake thermal efficiency.**
- **Driven by high intake charge dilution and high fuel injection pressures to increase premixed combustion.**
- **Sensitive to thermal boundary conditions and transients.**
- **Many acronyms but collectively referred to as High Efficiency Clean Combustion (HECC).**

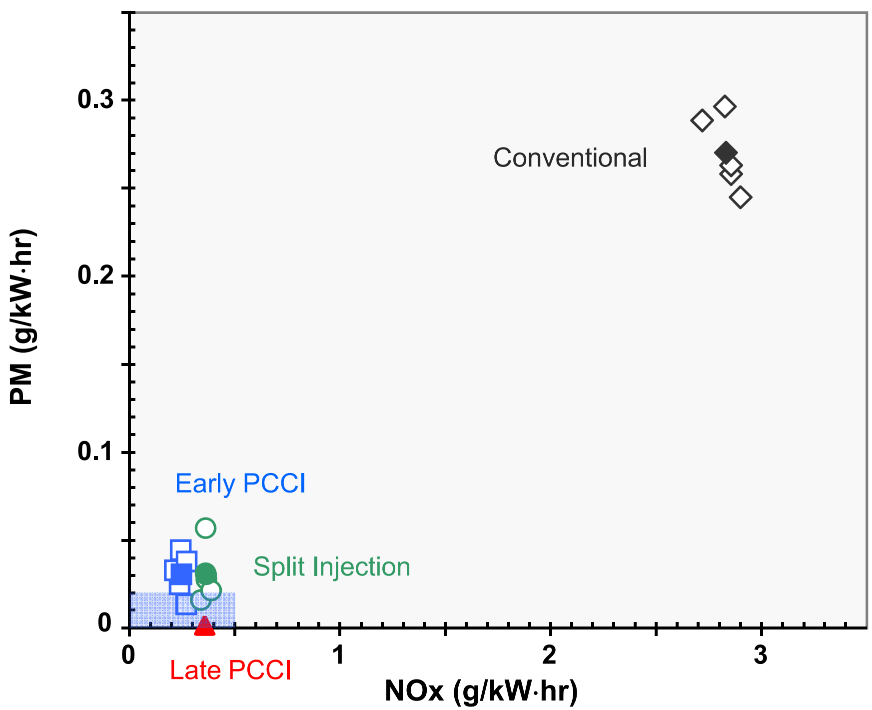


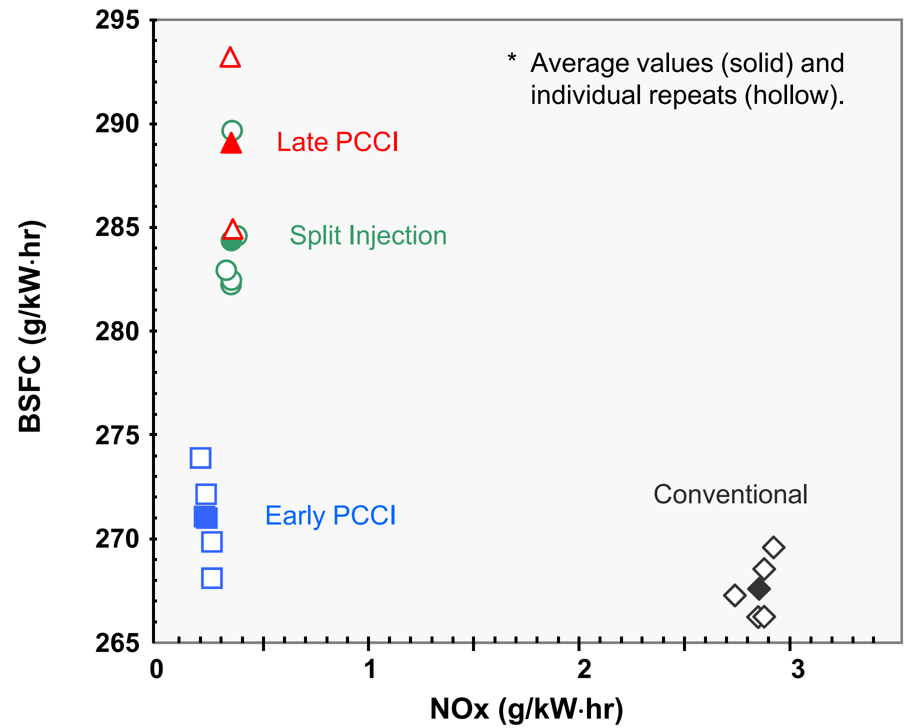
Several PCCI approaches explored on the MB and GM engines from an efficiency and systems integration perspective

- **Advanced combustion approaches use similar intake charge dilution and fuel injection pressure *for each engine*.**
- **Mass of fuel delivery is the same for all strategies *for each engine*.**
- **Experiments performed for FTP modal conditions described earlier.**



MB efficiency and emissions comparison for several strategies under road load conditions

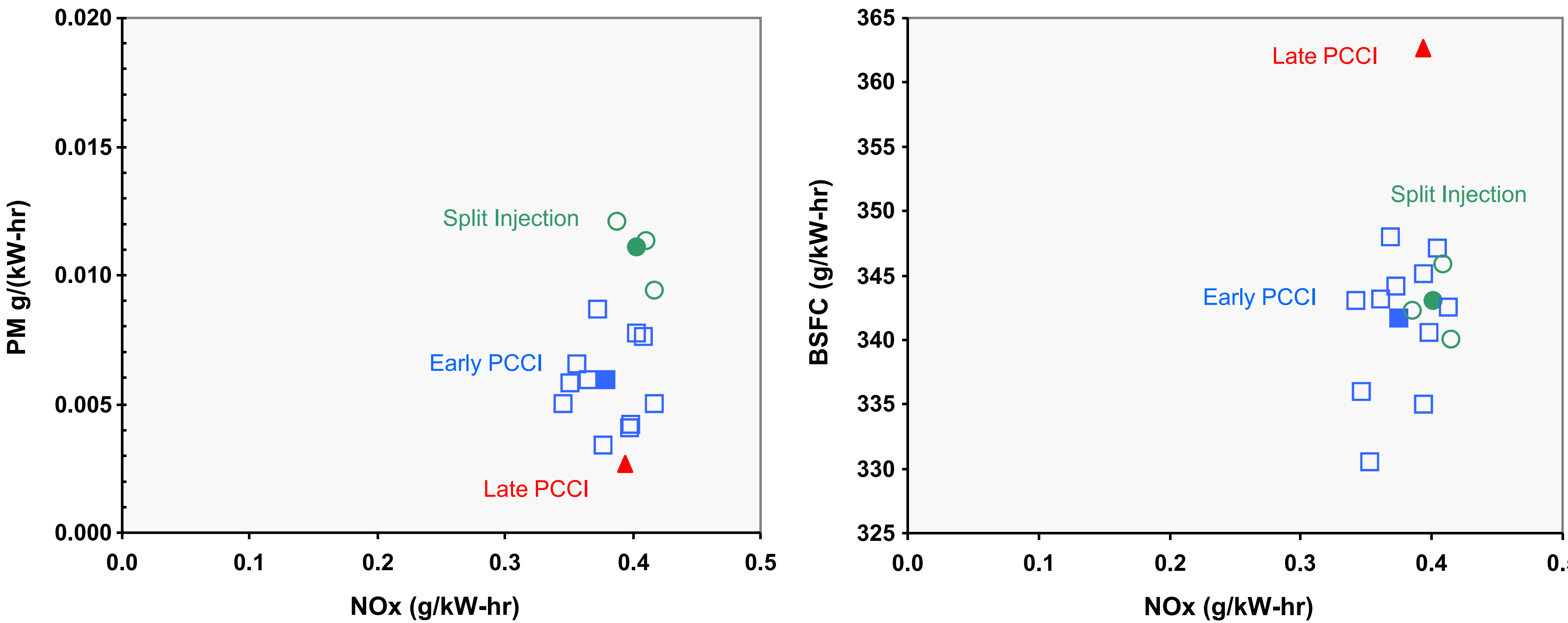




- **Early PCCI appears most effective for HECC operation.**
- **Combustion noise higher for HECC (88-90 dB range)**
- **Similar trends observed for moderate acceleration conditions.**

Data source: **MB Engine**, 1500 rpm, 2.6 bar BMEP

Similar trends for GM engine but with much lower PM emissions

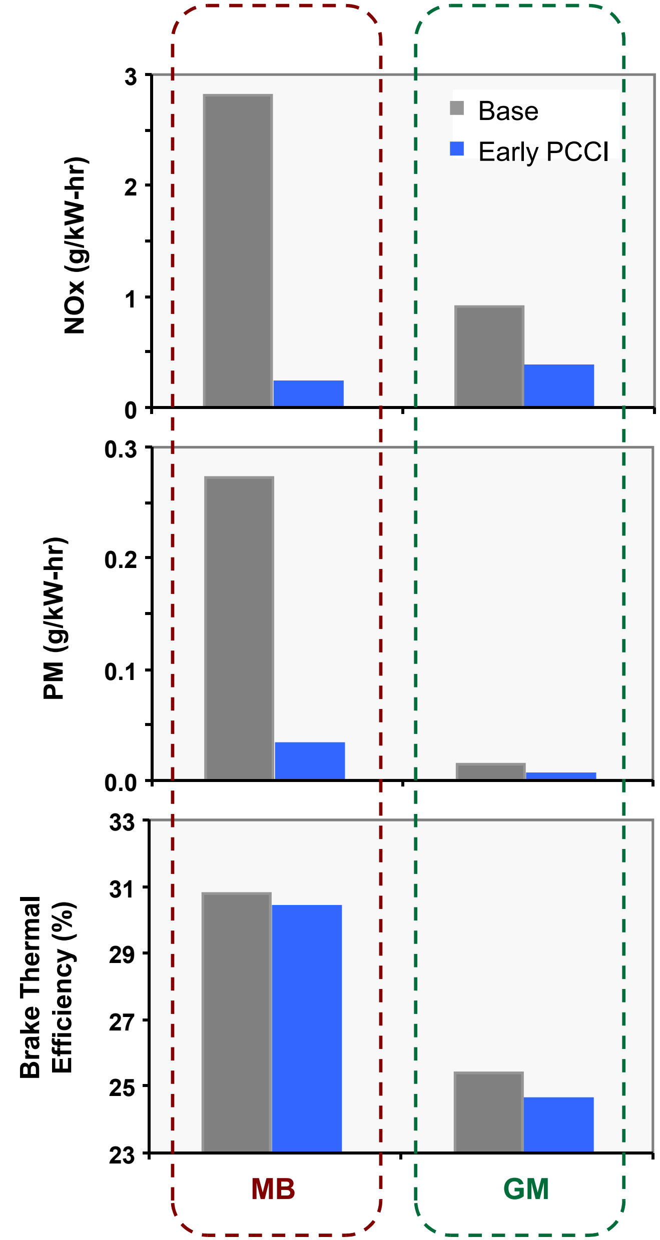


- **Similar trends observed for moderate acceleration conditions.**
- **Note significant difference in scales as compared to MB data on previous slide.**
- **CO/HC emissions also much higher for these experiments.**

Data source: **GM Engine,** 1500 rpm, 2.6 bar BMEP

Advanced combustion is trade-off between NOx, PM, and BTE

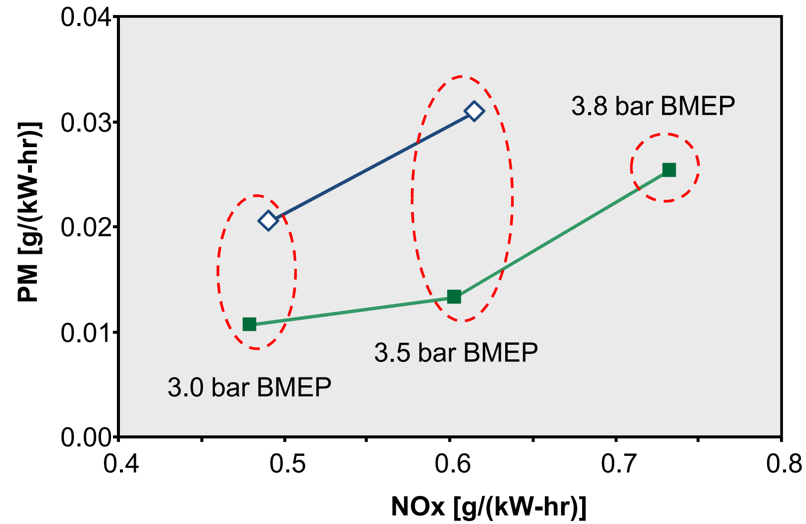
- **Explored for several strategies on both engines for FTP modal conditions.**
  - » For comparison shown, high BTE is accompanied by higher PM.
  - » As an example, BTE of 29% with reasonable NOx and PM has also been demonstrated on GM for 1500 rpm, 2.0 bar BMEP.
- **Influenced by thermal conditions such as encountered during cold-start and transients.**
  - » Thermal effects of intake mixture, EGR, coolant, and lubrication currently under investigation.
- **Controllable to better match aftertreatment, thermal energy recovery, or other technologies.**
  - » "Characterization of LNTs for LD diesel engines"
  - » "Emissions controls for multimode LD diesel engines"
  - » "Vehicle Technologies efficiency engine milestones"

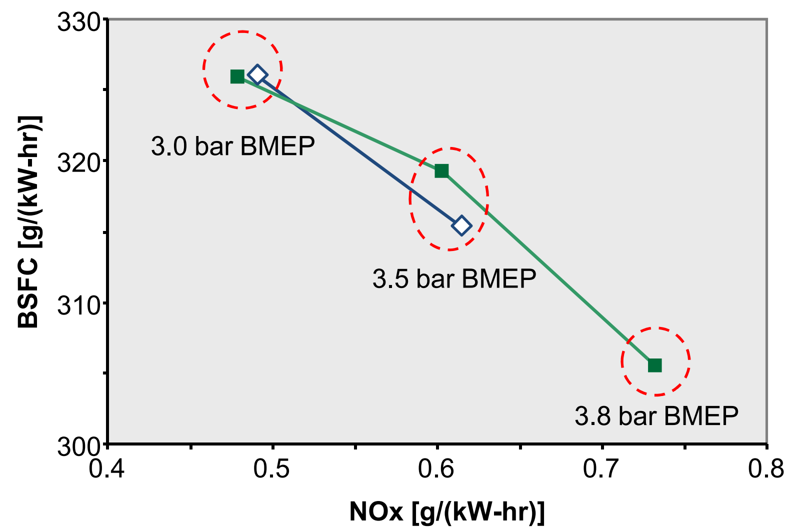


Data source: 1500 rpm, 2.6 bar BMEP (road load)

Thermal conditions affect ability to achieve good efficiency with low emissions

- **Lower intake air-EGR mixture temperatures enable expanded HECC operation.**
- **Most significant impact was on PM formation.**
- **Lower intake temperature was necessary to achieve HECC at 3.8 bar BMEP, 1500 rpm.**

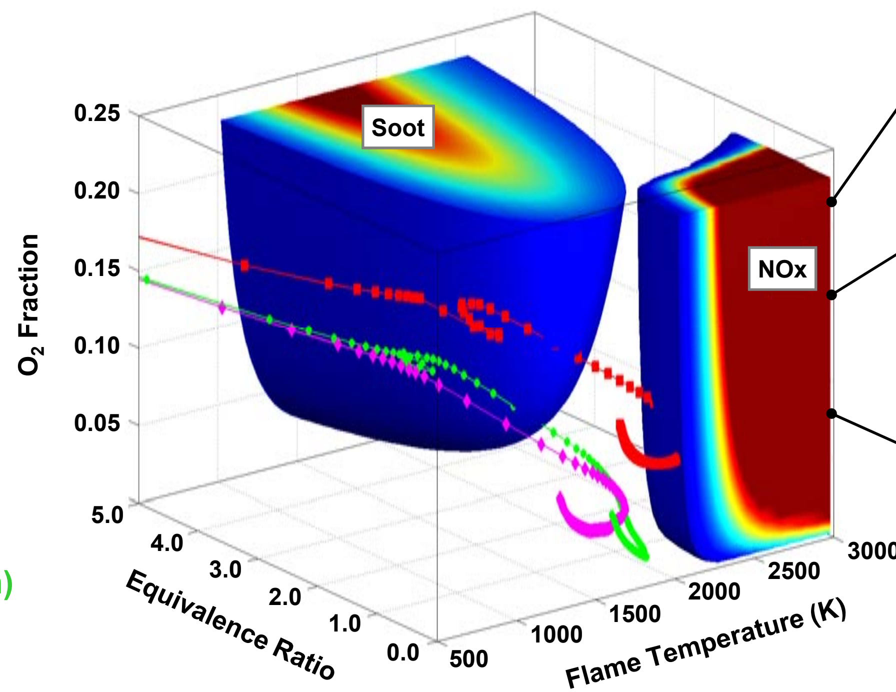


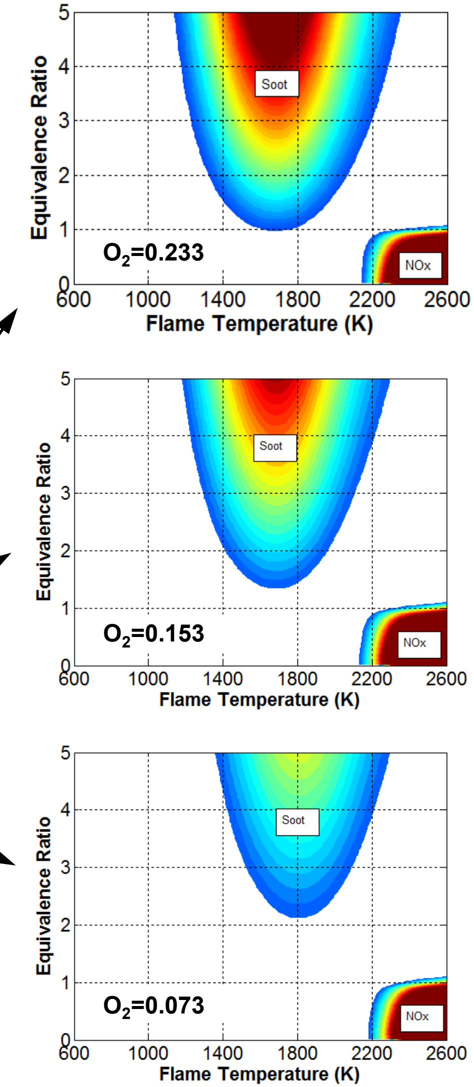


ΔT 8-10 °C { ◇ higher intake temperature; ■ lower intake temperature }

Analysis/modeling provides guidance on pathways and thermal effects on emissions formation

- **Experimental heat release profiles with phenomenological model are used to construct the combustion path across the 3-D map of soot and NOx as a function of ϕ-T-O_2.**
- **3D Soot-NOx map demonstrates : (a) soot zone is shrunken at low oxygen concentration; (b) high dilution has potential to avoid the rich soot zone.**

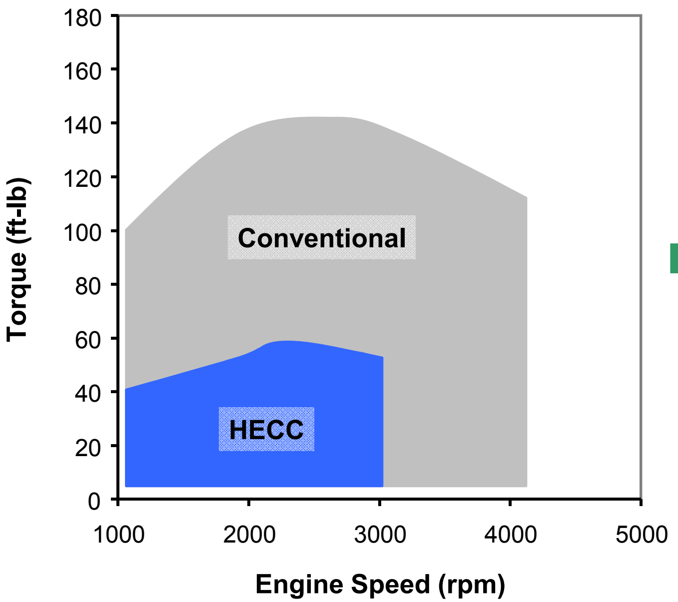


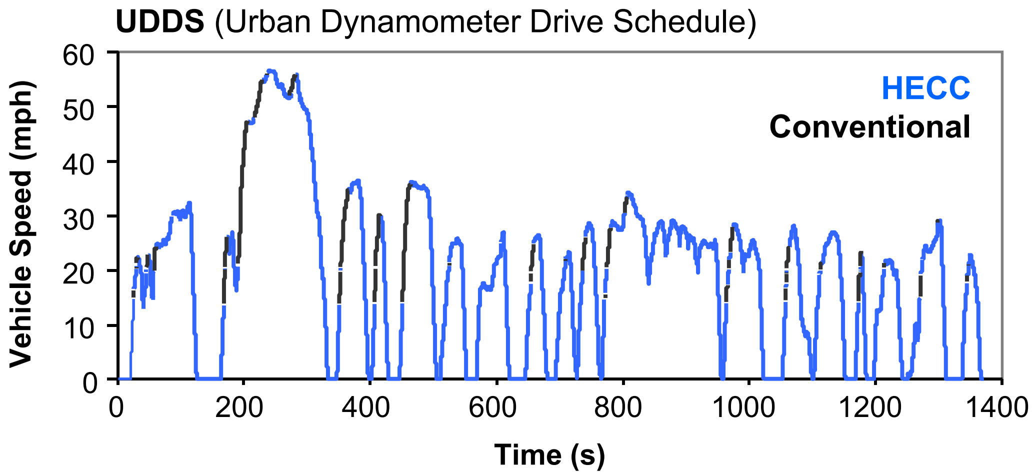


Analysis/model validated with KIVA and performance and engine-out emissions data.

Mixed-mode HECC operation investigated over drive cycles with experimental maps and PSAT

- **Uses mixed-mode simulation with HECC operation when appropriate as dictated by speed-load requirement.**
- **Vehicle configuration based on MB 1.7-L diesel engine and Honda Civic chassis.**
- **Simulations include cold- and warm-start with (shown) and without aftertreatment.**





Vehicle in HECC mode 91% of UDDS.

Drive cycle simulations show benefits of mixed-mode HECC operation on NOx and soot emissions and challenges associated with HC/CO

HECC and conventional

FTP CYCLE	UDDS	US06	ECE
NOx, g/mi	0.348	1.076	0.248
Soot, g/mi	0.038	0.089	0.028
HC, g/mi	0.668	0.304	1.033
CO, g/mi	3.422	1.942	4.900
HECC time, %	90.9	57.6	96.2

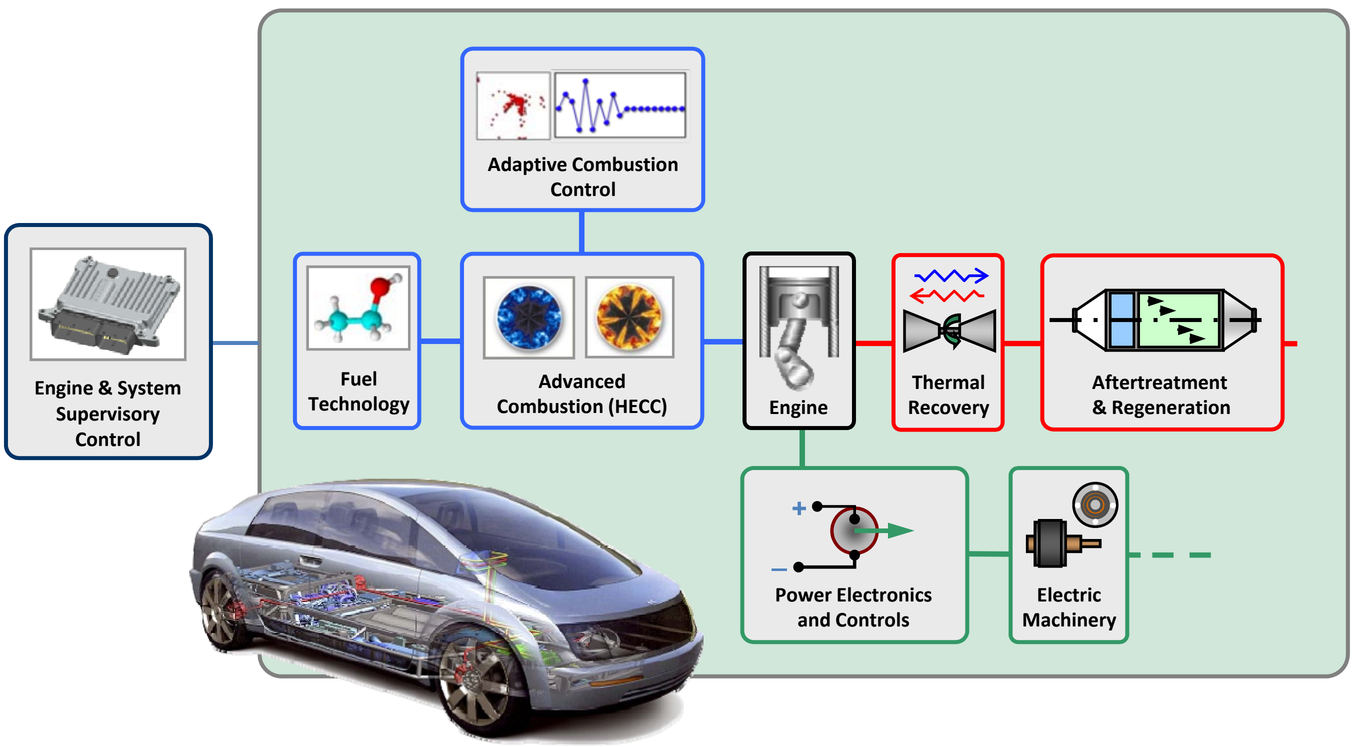
Conventional only

FTP CYCLE	UDDS	US06	ECE
NOx, g/mi	0.897	1.325	1.072
Soot, g/mi	0.065	0.096	0.079
HC, g/mi	0.418	0.295	0.639
CO, g/mi	1.554	1.535	2.027
HECC time, %	na	na	na

- **Simulations also complete with NOx and PM aftertreatment models.**
  - » Different regeneration strategies and combustion modes.
  - » Evaluation with advanced powertrains such as HEV and PHEV.
  - » See VSS06, Daw, “PHEV Engine and Emissions Models” for more information.
- **Models in development with GT-Drive to evaluate bottoming cycle potential on light-duty drive cycles.**

Path Forward

- Continued integration with other advanced technologies and fuels research in support of 2010 and beyond Vehicle Technologies objectives.
- Continued load expansion efforts to improve use with engine downsizing.
- Continued exploration of sensitivity to engine thermal conditions for improved integration with other advanced technologies.
- ➡ Transient and systems integration issues are becoming more and more important AND are focus points of the next phase of ORNL advanced combustion research.



Summary or *take away points*

- **Objective / Approach**
  - » To further development, implementation and integration of advanced combustion for optimal efficiency AND lowest possible emissions
  - » Comprehensive approach including modeling, analysis, and experiment.
- **Technology Path & Demonstration**
  - » Development and demonstration of advanced combustion strategies with combined emphasis on efficiency, emissions, and integration with other technologies including aftertreatment.
  - » Load expansion for improved in-cylinder emissions reduction across conventional speed-load maps with additional emphasis on higher load operation more consistent with engine downsizing.
  - » Drive-cycle simulations based on experimental advanced combustion maps are being used to characterize potential of HECC operation for conventional and advanced powertrains.
- **Technology Transfer**
  - » Aspects of this activity are regularly communicated either directly or indirectly to DOE, industry, and others through government working groups, technical meetings, and one-on-one interactions.
- **Longer Term**
  - » *Transient* issues are becoming more and more important. *Need* for more emphasis on the development, integration, and evaluation of advanced transportation technologies to better understand synergies and/or operational issues for optimal efficiency AND lowest emissions.

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