High Efficiency Clean Combustion in Multi-Cylinder Light-Duty Engines

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Project overview

This project addresses current DOE VT objectives. The present focus is on high efficiency stratified combustion approaches that can achieve diesel-equivalent efficiency with substantially reduced emissions.

Timeline

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

Barriers

- **Efficiency/emissions**
- **Combustion control**
- ➡ **VT performance milestones**

Budget

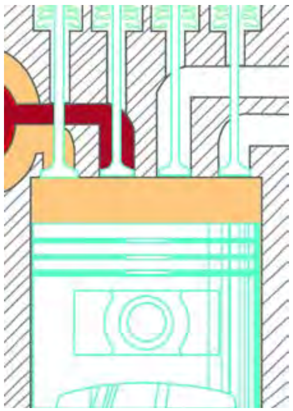
- **FY 2010 – \$300k (High Efficiency Clean Combustion) + \$300k (High Dilution Stoichiometric GDI Combustion)**
- **FY 2011 – \$300k (High Efficiency Clean Combustion) + \$350k (High Dilututión Stoichiometric GDI Combustion)**

Partners / Interactions

- **Regular status reports to DOE**
- **University of Wisconsin – Madison: RCCI modeling and single-cylinder engine experiments**
- **University of Michigan: Predictive GDI modeling for cycle simulation**
- **BorgWarner: Advanced turbocharging and EGR systems**
- **Robert Bosch LLC: GDI engine controls and hardware**

Relevance & Milestones

Objective is to develop and assess advanced combustion approaches on multicylinder engines for achieving diesel-like efficiency with low engine-out emissions



- **FY 2010 Q3 – Met**

  Demonstrated efficiency & emissions potential of dual-fuel advanced combustion on a multicylinder light-duty engine

- **FY 2011 Q4 – In Progress**

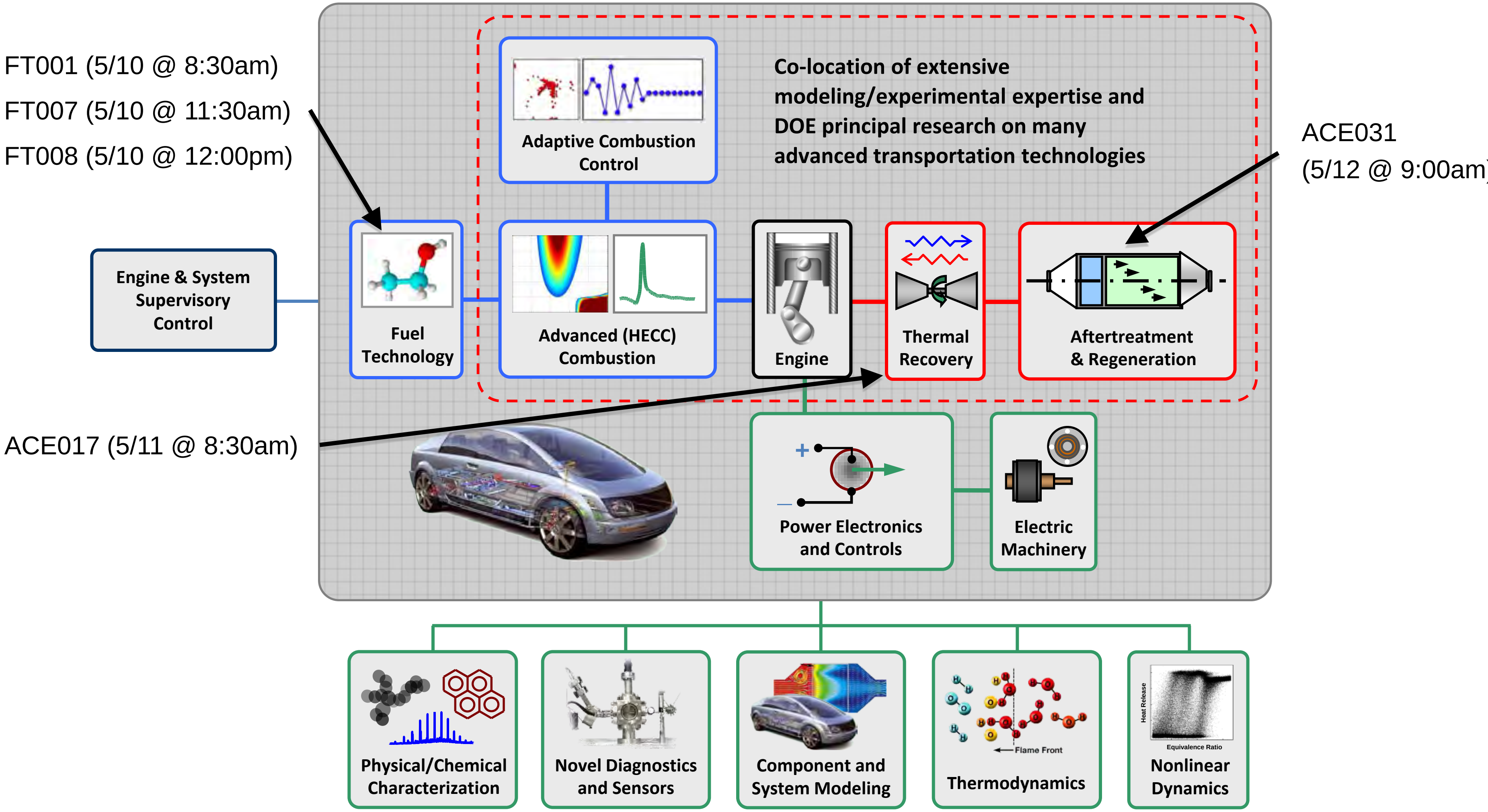
  Demonstrate high-dilution GDI combustion with low engine-out emissions

Approach: Address implementation of advanced combustion on production-like engine hardware

Develop and demonstrate technologies through modeling, experiments, and analysis

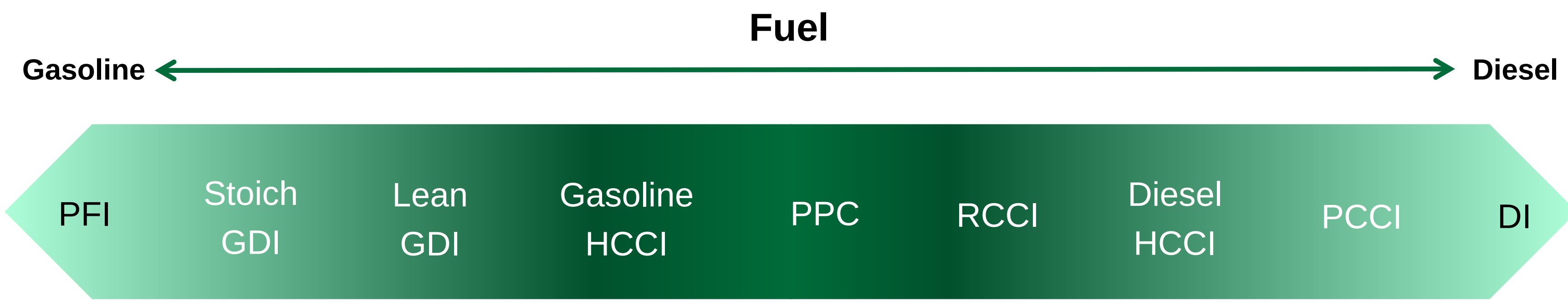
- **Modeling**
  - » Combustion modeling to guide experiments & provide insight into results – collaborations with University of Wisconsin & University of Michigan
  - » Dynamic modeling to understand processes at the edge of combustion stability – use to develop real time controls and feedback metrics
  - » Engine-system modeling to understand efficiency opportunities – determine where losses are, guide work towards technologies that will reduce them
  - » Vehicle system modeling to estimate real-world fuel economy potential – indicate the ultimate value of advanced combustion
- **Experiments**
  - » Extend existing success on single-cylinder engines to multi-cylinder engines with real turbomachinery, EGR imbalances, and limited degrees-of-freedom for controls
- **Analysis**
  - » Second-law thermodynamic analysis to quantify fuel availability distribution and destruction
  - » Detailed emissions analysis to understand details of combustion and guide the matching of aftertreatment systems

Comprehensive approach to system efficiency opportunities and challenges builds upon on-going activities at ORNL and elsewhere



Approach: Moving to a fuel-neutral combustion world

- **Advanced combustion strategies are increasingly using engine hardware that looks similar**
- **These strategies also blur the lines between fuel selection and combustion propagation mechanisms**

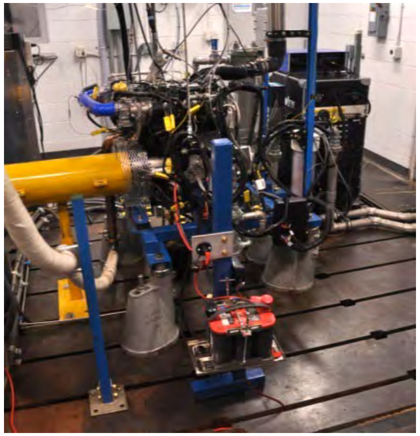


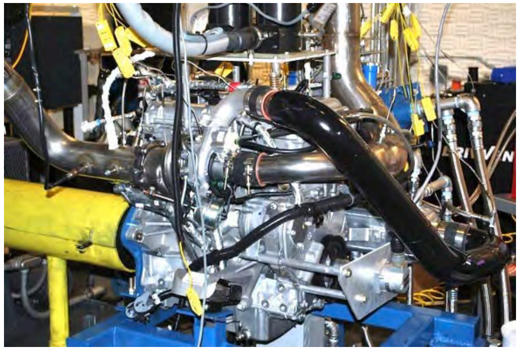
Two engine platforms are in use for this work

- **GM EU 1.9-L diesel**
- **Multiple ECU systems**
  - » dSpace MABX/Ricardo VEMPS
  - » GM-supplied "open" ECU
  - » Drivven controller
- **Updated hardware**
  - » Closed-loop thermal control on coolant, oil, intake, EGR, fuel
  - » PFI fuel system
  - » Low pressure EGR (in progress)

- **GM NA 2.0-L gasoline "LNF"**
- **Bosch-supplied "open" ECU**
- **Hardware updates**
  - » Closed-loop thermal control on coolant, oil, intake, EGR, fuel
  - » Low pressure EGR (in progress)
- **Developing relationship with Bosch**
  - » Planning on supplying a flex fuel version of the LNF developed through a DOE-funded program

2007 MY GM 1.9-L engine installed in the test cell





2009 MY GM 2.0-L LNF engine installed in the test cell

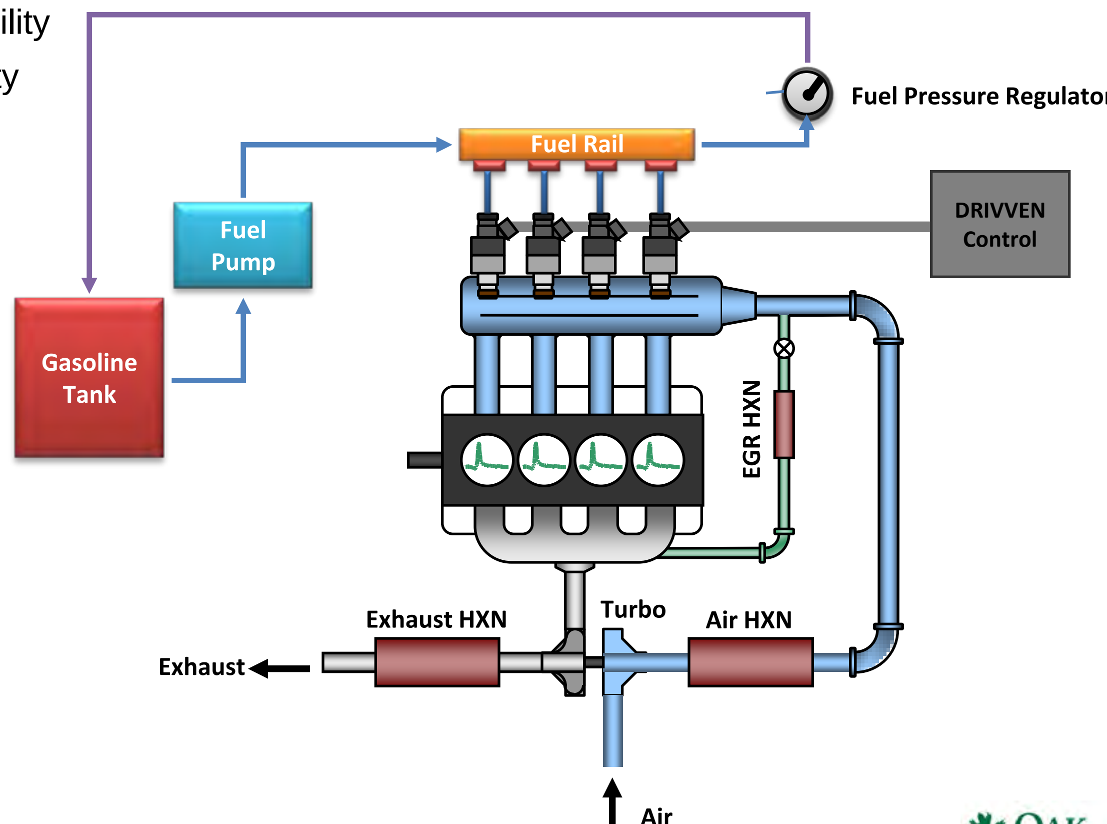
Technical Accomplishments Summary

- **Continued development of RCCI capability**
  - » ORNL is running RCCI at both modeled and non-modeled points
  - » Exploring steady-state modal points to enable estimation of FTP fuel economy & emissions
  - » Demonstrating load expansion beyond PCCI operating range without using EGR
  - » Demonstrating simultaneous emissions and efficiency benefit at low speed operation
- **Significant modifications and upgrades to support high efficiency advanced combustion research**
  - » Installed new 2007 MY version of the GM 1.9-L engine
  - » Commissioned new Drivven engine controller with integrated DAQ & next-cycle feedback control
  - » Increased EGR cooling capacity for high-dilution operation, including closed-loop thermal controls

- **Added new GDI combustion research capability**
  - » Installed production version of the GM 2.0-L LNF GDI engine
  - » Bosch is planning to provide an open ECU for this engine
  - » Upgraded emissions analysis to support GDI particulate measurement

RCCI operation is realized on a modified production GM diesel engine

- **Engine uses stock turbocharger and diesel fuel system**
- **EGR cooler has been upsized for increased EGR cooling capacity**
- **A PFI fuel system has been added to enable RCCI**
- **Control is via a Drivven engine control system**
  - » Full control of diesel & gasoline fuel systems
  - » Cylinder-to-cylinder balancing capability
  - » Next-cycle feedback control capability
- **Engine thermal boundary conditions are in closed-loop control**
  - » Coolant
  - » Oil
  - » Fuel
  - » EGR
  - » Intake charge

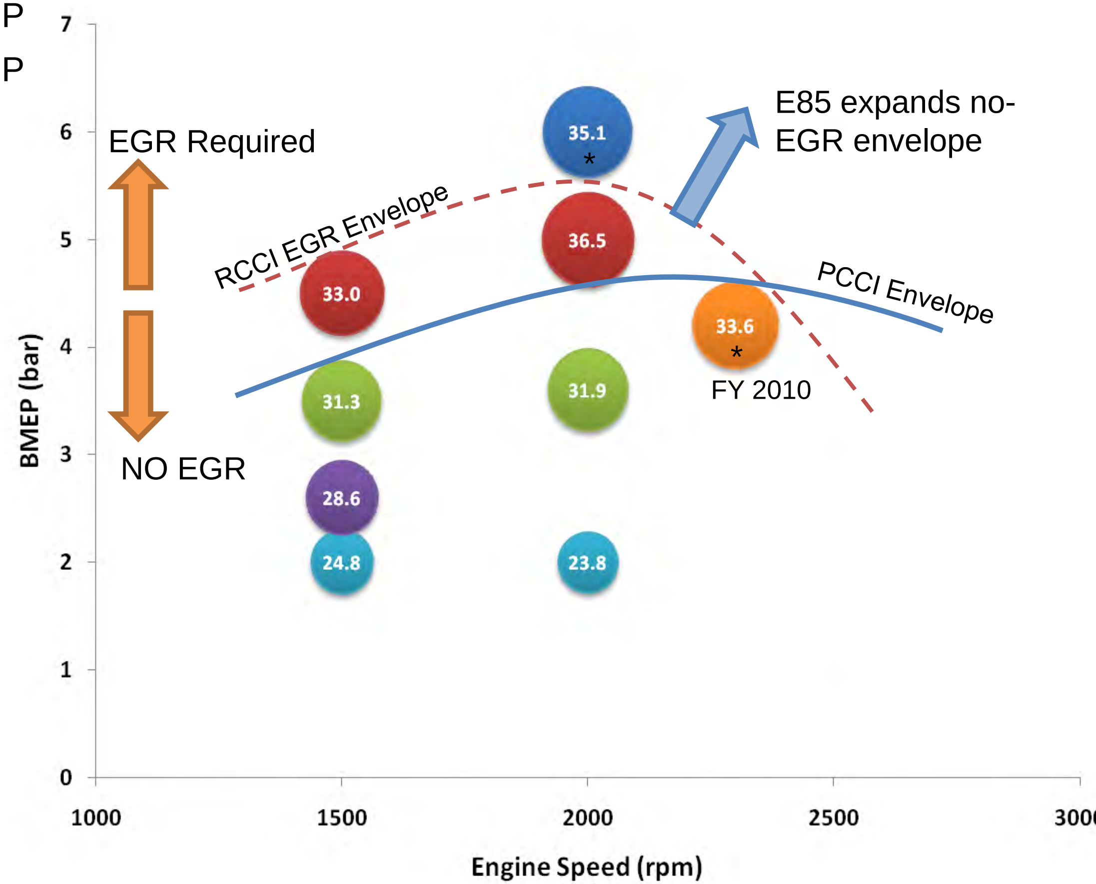


Current RCCI focus is on drive cycle estimation and load expansion

- **One experimental point based off modeling at UW: 2000 rpm, 6 bar BMEP**
  - » Limited to single-pulse diesel injection by injector orifice size
- **Road-load mapping process started**
  - » 1500 rpm; 2.0, 2.6, 3.5, 4.5 bar BMEP
  - » 2000 rpm; 2.0, 3.6, 4.0, 5.0 bar BMEP

Observations:

- » RCCI without EGR provides a useful load expansion over previous PCCI work
- » Load range for RCCI with EGR is expected to cover most of engine envelope
- » Addition of ethanol to the gasoline extends the no-EGR envelope – will explore this FY in conjunction with fuel technology activities



* These points were guided by CFD modeling at UW-Madison

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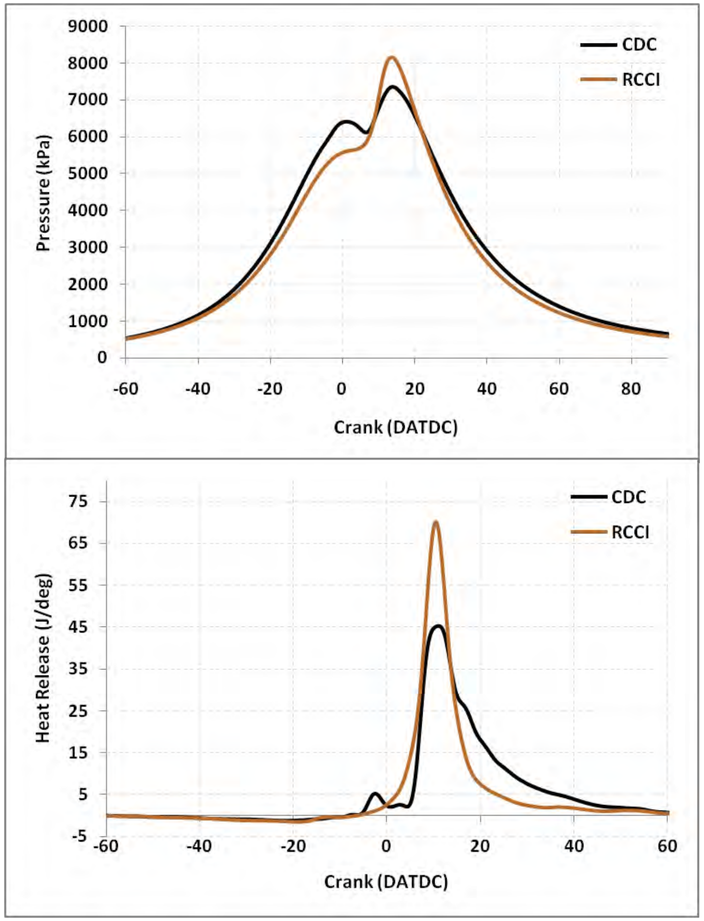
2000 rpm, 6 bar BMEP operating point details

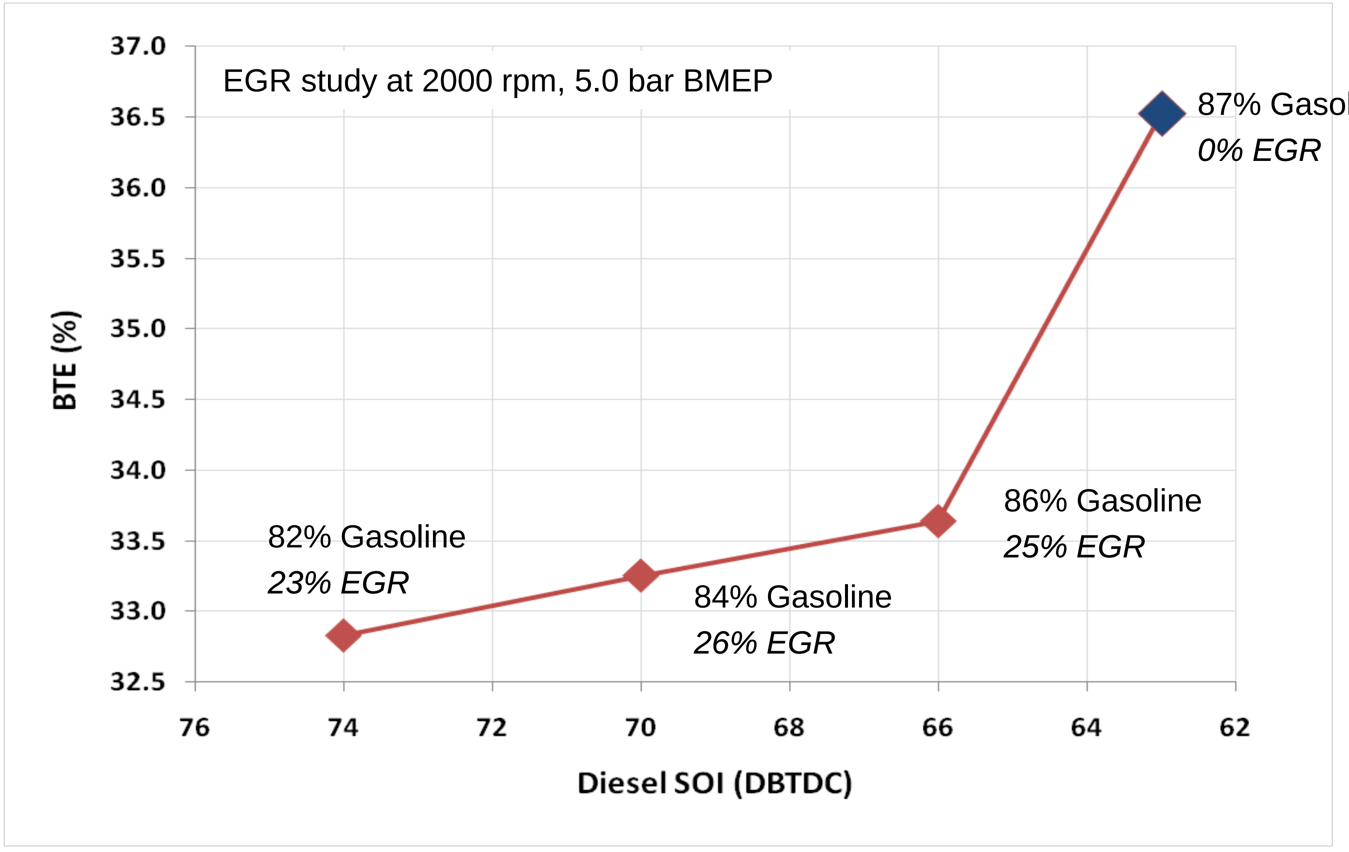
- **Conventional operation based on 2007 Opel maps (courtesy GM Europe)**
- **RCCI experiments carried out with single diesel pulse, 81% gasoline**
  - » Current injector turndown not suitable for split injection of diesel fuel



	CDC (OEM DRIVVEN)	**RCCI** (81%gas, SOI 70DBTDC)
BTE (%)	35.9	35.1
BSFC (g/kw-hr)	233	238
MPRR (bar/deg)	2.7	7.3
NOx (ppm)	216	18.5
HC (ppm)	136	3783
CO (ppm)	119	1458
FSN (-)	1.23	0.00
EGR Rate (%)	17.2	32.2
Boost (bar)	1.38	1.27
Swirl Intensity	2.3	2.9
Mass Air Flow (g/s)	36.2	29.5
Exhaust Temp (C)	424	395

Expansion of the no-EGR operating range is significant for efficiency

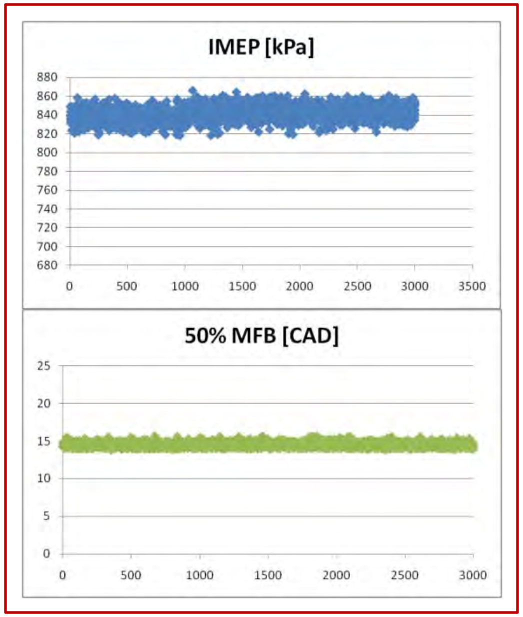
- **EGR enables RCCI at higher loads, but with a penalty due to pumping losses**
- **The turbocharger is limited on how much EGR can be delivered using the production high pressure loop system**
- **For edge cases, adjusting the fuel split allows a comparison of EGR & no-EGR operation**



Combustion stability will add challenges to closed-loop control

- **Comparison of 3000 cycles of conventional vs. RCCI**
  - » Optimization is expected to reduce the COV of RCCI from its present level

CDC

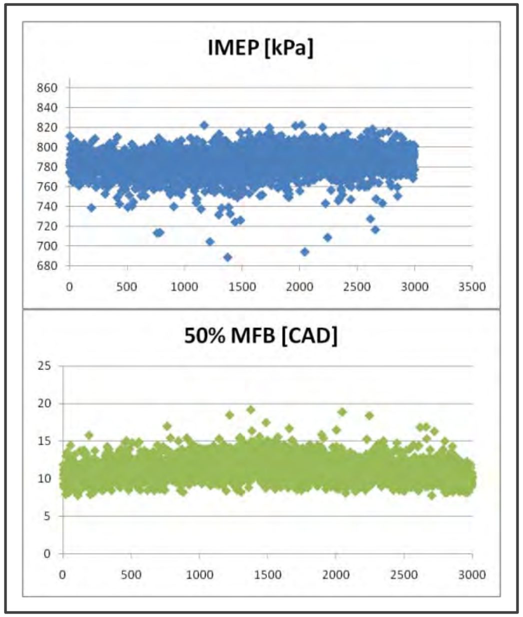


	CDC	RCCI
IMEP COV	0.8	1.8
MFB50 COV	2.0	15.0

Stability dependent on:

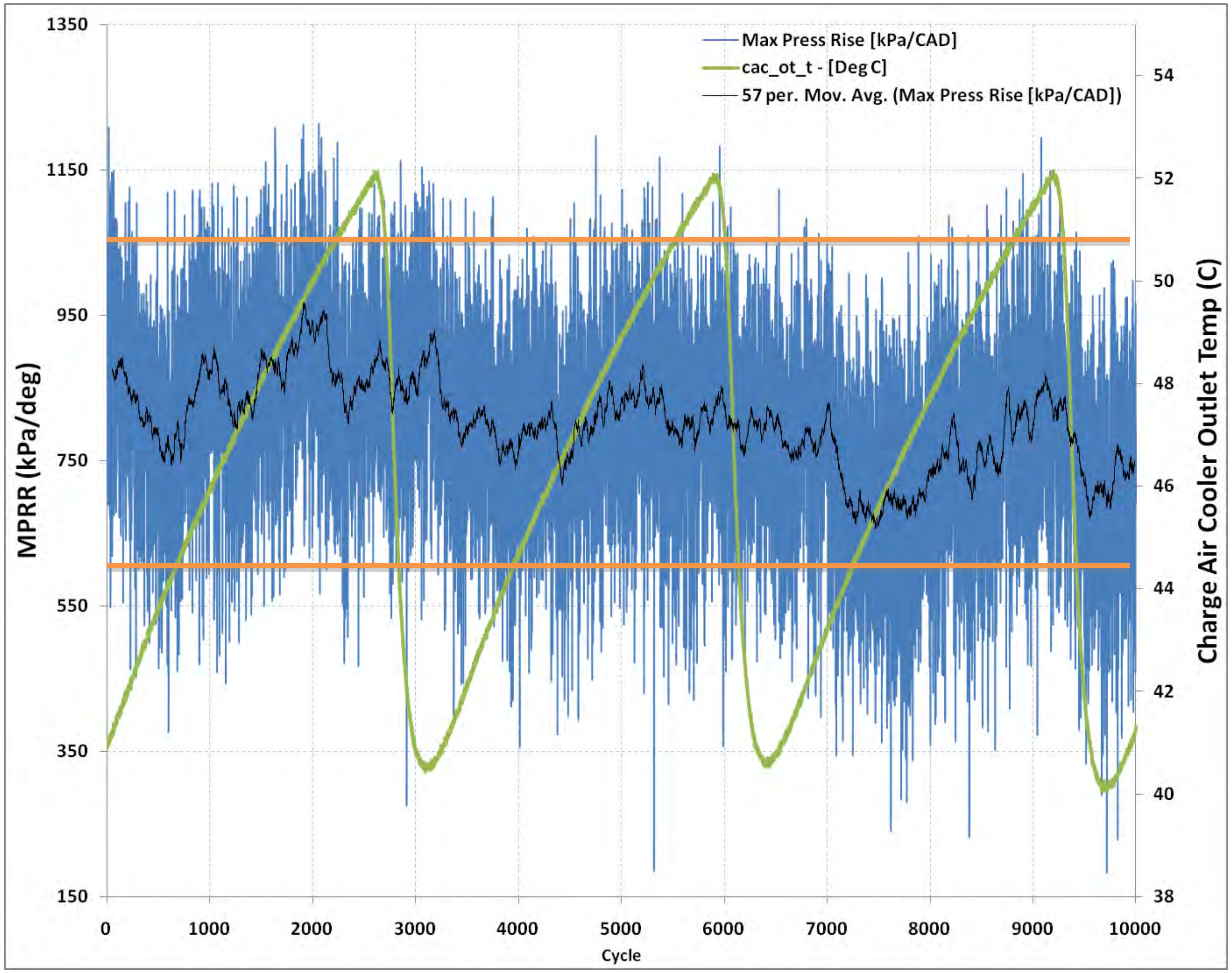
- Intake charge temp
- Cylinder balance

RCCI



Combustion stability is very sensitive to intake charge temperature

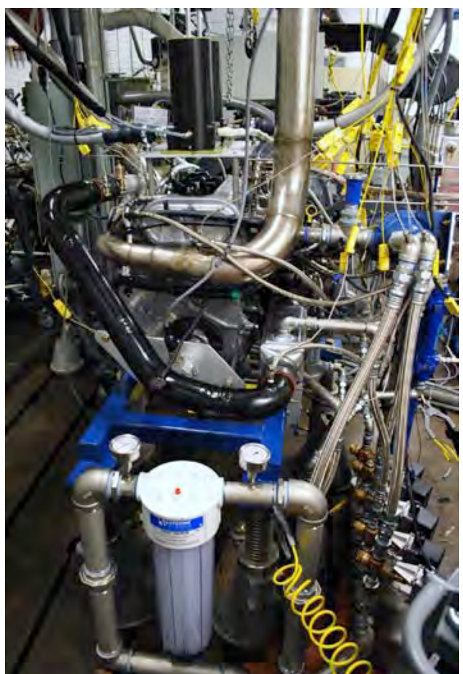
Impact of intake temperature on peak pressure rise rate



- **Intake charge cycles with EGR & charge air cooler control valve swings**
- **MPRR shows signs of following intake charge trend**
- **Improving combustion control for compatibility with production thermal conditions is needed**
- **Modeling and single-cylinder experiments suggest that lower compression ratio leads to reduced sensitivity to intake temperature**

New GDI engine installation expands combustion research capability

- **Current engine is the production GM LNF engine**
  - Turbocharged, 260 hp rated power
- **Enables exploration of SI-based combustion strategies**
- **Initial plans are to extend the stoichiometric operating range to high EGR levels**
  - Targeting low engine-out NO_x while maintaining compatibility with three-way catalyst
- **Industry-expressed interest in sharing advanced ignition system technology**
  - Necessary enabler for high-boost, high-dilution combustion



Front view of engine in test cell

AVL Micro Soot Sensor to enable measurement of particulate concentration in GDI exhaust

Collaborations and Interactions

- **University of Wisconsin - Madison**
  - » Ongoing iteration between modeling, single-cylinder engine, multi-cylinder engine to quantify differences in results and understand tradeoffs
  - » Visiting student at ORNL for 6 months to incorporate multi-cylinder work into thesis
- **BorgWarner**
  - » Technical input for improving turbocharging efficiency
  - » Guidance on optimizing EGR systems
- **University of Michigan**
  - » Submodel development for GT-Power to enable predictive combustion modeling of highly dilute GDI operation
- **Robert Bosch LLC**
  - » Supplying open ECU for GM 2.0-L LNF engine
  - » Supplying flex-fuel version of LNF engine to extend experimental capability
- **Other ORNL-DOE Activities**
  - » Detailed characterization of regulated and unregulated emissions
  - » Health effects impact of RCCI particulate emissions
  - » Study of aftertreatment system matching to RCCI operation

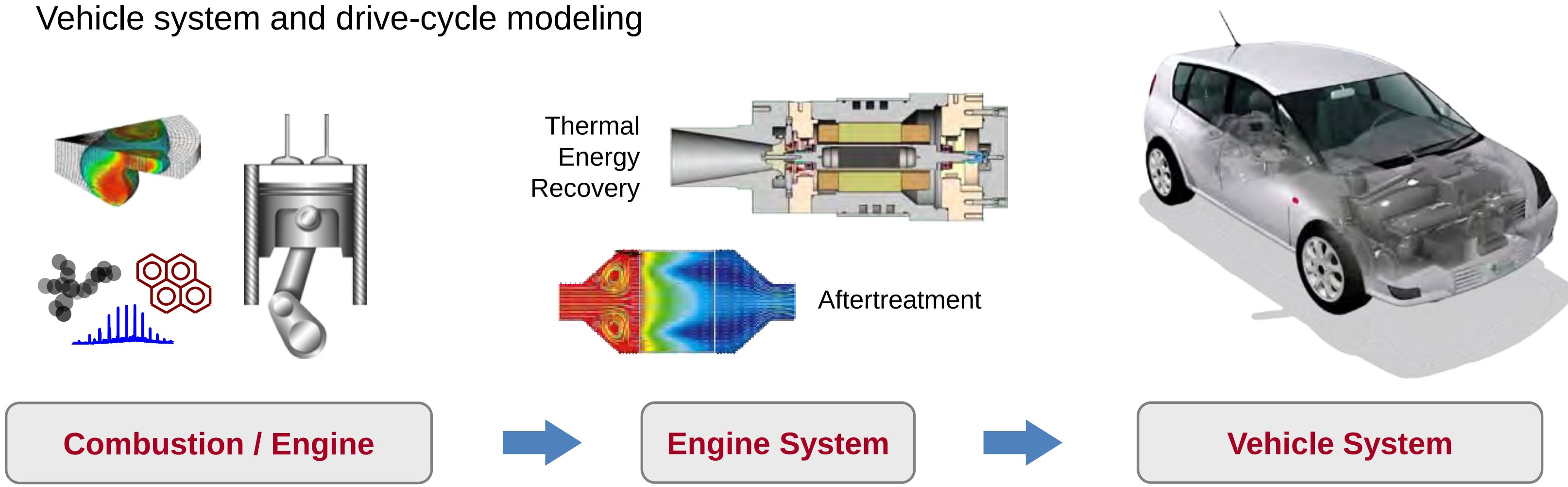
Next Steps FY 2011

- **Optimize RCCI performance on a multicylinder engine**
  - » Steady-state modal points for FTP emissions estimation
  - » Map full operating range of RCCI (with and without EGR)
  - » Determine optimum compression ratio for RCCI operation
- **Evaluate RCCI fuel effects**
  - » Performance with E10, E20, E85 fuels
- **Data analysis for deeper understanding of RCCI combustion**
  - » Combustion stability issues for feedback control systems
  - » Loss analysis via second-law thermodynamic analysis
  - » Vehicle system modeling to predict real-world benefit of RCCI
- **Add low pressure EGR system to improve thermal stability of intake charge**

- **Perform baseline mapping of production LNF engine**
- **Install Bosch-supplied flex-fuel LNF engine**
- **Complete installation of low-pressure EGR system**
- **Demonstrate high-dilution GDI combustion approach on a multicylinder engine**

Future FY 2012

- **Continue to develop and assess potential of high efficiency concepts on multicylinder engines**
  - » Many approaches suggest good performance and emissions on single-cylinder engines
  - » Integration with turbomachinery, heat rejection limitations, and other production-hardware restrictions must be addressed to identify technical barriers to implementation
  - » Feedback control strategies to enable stable operation must be developed for robust systems
- **Leverage with fundamental expertise and on-going activities to better understand systems integration issues and fuel economy potential**
  - » Detailed emissions characterization
  - » Health effects issues
  - » Aftertreatment integration
  - » Vehicle system and drive-cycle modeling



Summary

On track to meet FY 2011 milestones

- **Relevance**
  - » Demonstrating advanced combustion on production-like multicylinder engines
- **Approach**
  - » Comprehensive approach including Modeling + Experiments + Analysis + Collaboration
- **Technical Accomplishments**
  - » Operating RCCI on-engine at modeled & non-modeled points
  - » Demonstrating load expansion relative to PCCI with no-EGR RCCI operation
  - » Demonstrating efficiency tradeoff between EGR & no-EGR cases
  - » Installed new GDI engine to expand advanced combustion capability to SI-based systems
- **Collaborations**
  - » Regular communication to DOE, industry, and others through technical meetings and one-on-one interactions
  - » University of Wisconsin and University of Michigan on combustion modeling
  - » Robert Bosch LLC on engine controls and engine hardware
- **Future**
  - » Continue to demonstrate advanced combustion technologies on multicylinder engines
  - » Address combustion stability and control challenges inherent in advanced combustion
  - » Address emissions and health effects of advanced combustion strategies

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