High Efficiency Clean Combustion Engine Designs for Gasoline and Diesel Engines

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Overview – Gasoline Engines

Timeline

- **Start – April 2005**
- **End – October 2009**
- **85% complete**

Budget

- **Total project funding**
  - **DOE share $6.25M**
  - **GM share $6.25M**
- **Funding received in FY08 and FY09**
  - **GM $0.44M**

Barriers Addressed

- HCCI operating range
- Mixed mode operation
- Lack of cyl press sensor
- System cost

Partners

- GM is project lead
- Subcontractors are Sturman Industries (gas – FFVA)
- Several suppliers involved at component level

Objectives – Gasoline HCCI Engines

- **Enabling System – demonstrate engine on dyno and in vehicle; quantify benefits; reduce cost and risk; identify areas of deficiency**

- **Fully-flexible System – demonstrate engine on spin rig, dyno, and in vehicle; quantify effects on HCCI operating range; reduce cost and risk; identify areas of deficiency**

Milestones – Gasoline HCCI Engines

- **2008: fuel consumption benefit of enabling system quantified**
- **2008: multicylinder fully-flexible system design released**
- **2009: multicylinder fully-flexible system spin rig testing initiated**

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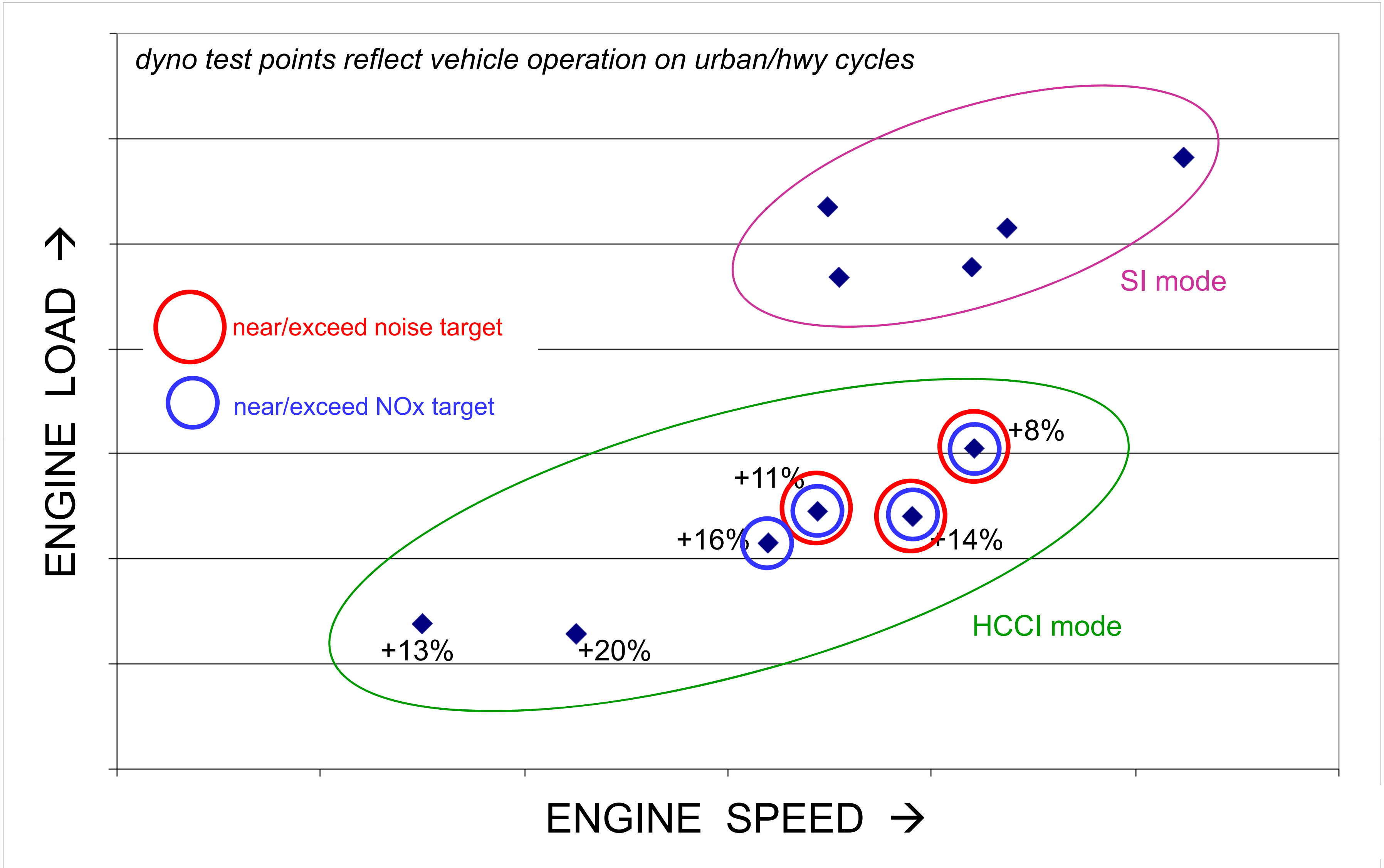
- **2009: multicylinder fully-flexible system spin rig, firing engine testing completed**
- **2009: fully-flexible vehicle build completed**

Approach – Gasoline HCCI Engines

- **Use extensive analysis, production-level design practices, build, and test to generate production-feasible properties which deliver acceptable HCCI operation under expected operating conditions**
- **Use the opportunity to generate and use hardware to encourage supply base to develop and produce needed components such as cylinder pressure sensors, valve actuation mechanisms**
- **During design/analysis phases, focus on reducing cost and technical risk of subsystems and components**
- **Use results of program to protect for this technical content in future production engine designs**

Technical Accomplishments

Quantified Efficiency Benefit Due to HCCI



Technical Accomplishments

Multicylinder Fully-Flexible Engine Design Completed

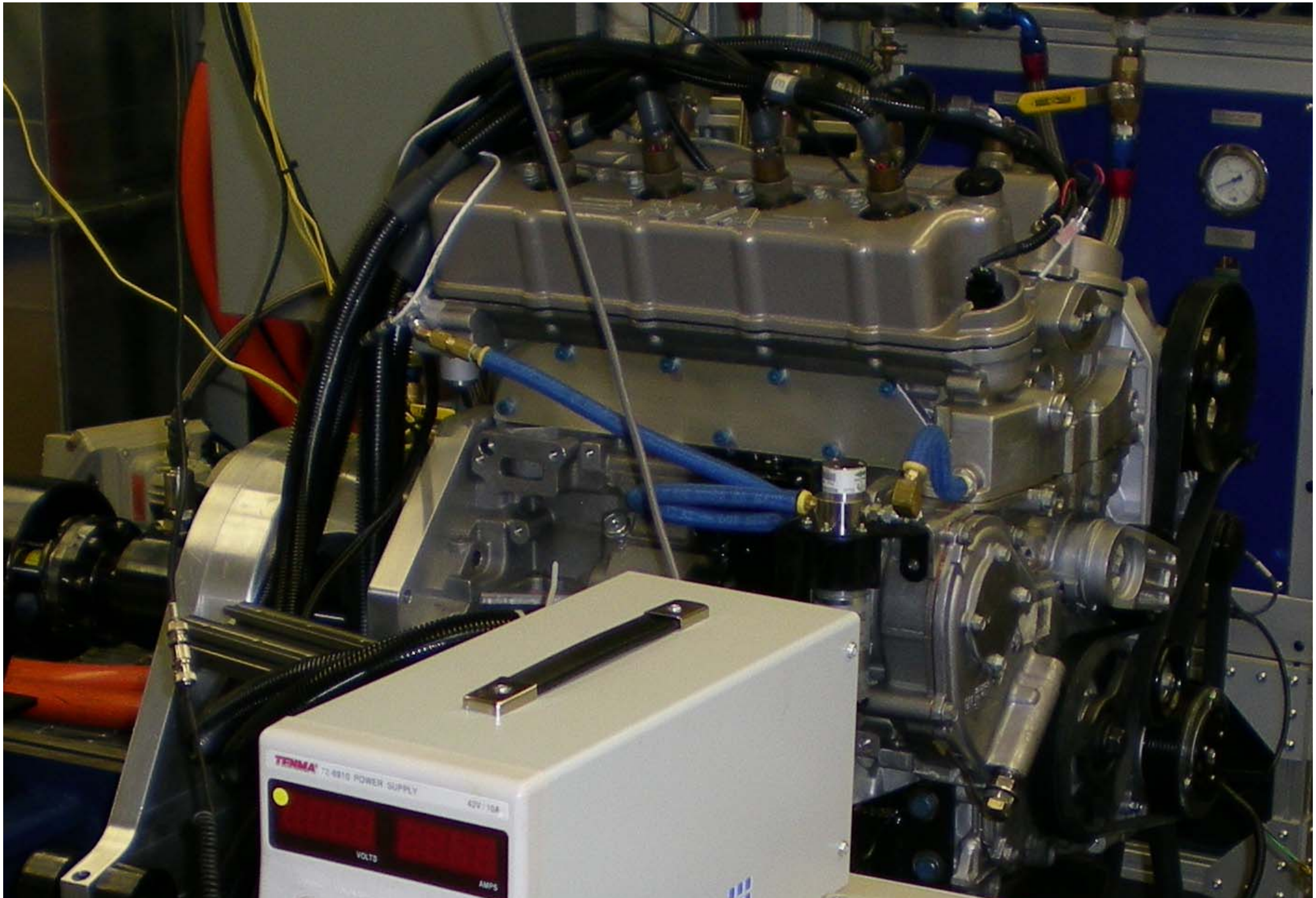
GM Ecotec L4-based

Fuel system, combustion chamber layout, and cylinder pressure system from enabling engine design

Electrohydraulic fully-flexible valve actuation (GM+Sturman design) on each intake and exhaust valve

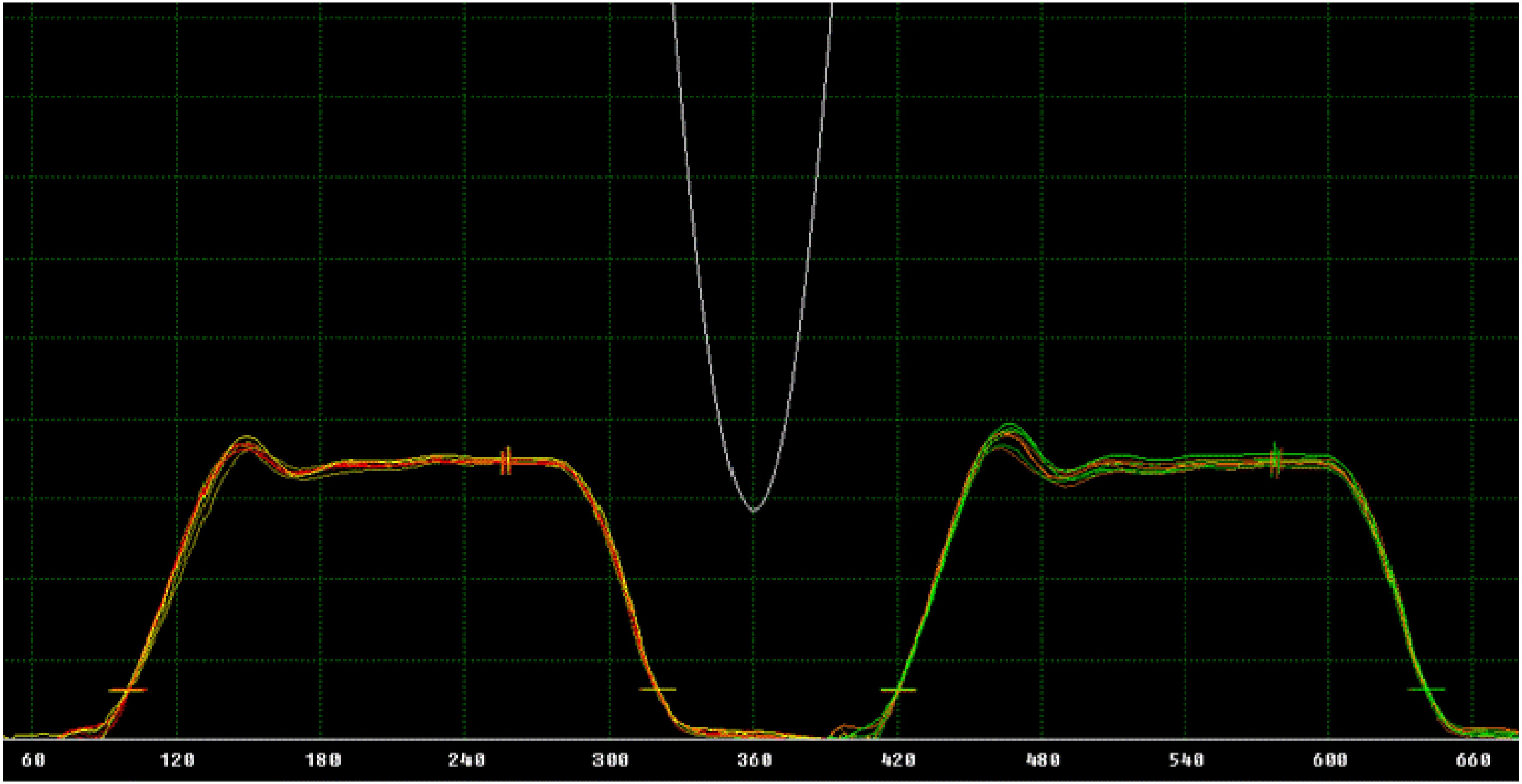
Technical Accomplishments

Multicylinder Fully-Flexible Spin Rig Testing Initiated



Technical Accomplishments

Multicylinder Fully-Flexible Spin Rig Test Results



representative results from multicylinder spin rig showing all valves operating at a fixed speed/load condition

Future Work – Gasoline HCCI Engines

- Closeout of enabling system testing (vehicle data)
- Completion of multicylinder fully-flexible spin rig and dyno testing (includes steady-state and transient performance characterization)
- Completion of fully-flexible system vehicle demonstration and testing
- Major known issues/concerns at this time:
  - Operating range of HCCI mode
  - Mode-switching performance
  - Cylinder pressure sensor supplier/hardware viability

Summary – Gasoline HCCI Engines

- This program will result in, and was a major contributor to, successful demonstrations of both enabling and fully-flexible design solutions
- This program has had and will continue to have a significant impact on GM production engine designs
- Guidance from this merit review will influence the remaining work

Overview – Diesel Engines

Timeline

- Start: 2005 – Single cylinder engine (SCE) – Fully Flexible Variable Valve Actuation
- End: 3Q2009 – SCE and Multi-cylinder engine (MCE)
- Percent complete: 80%

Budget

- **Total project funding**
  - **DOE share $6.25M**
  - **GM share $6.25M**
- **Funding received in FY08 and FY09**
  - **GM $0.44M**

Barriers

- Barriers addressed
  - To operate smoothly between Low Temperature Combustion (LTC) with extended limits and conventional CIDI using "VVA simple mechanisms" for control of effective compression ratio and internal EGR
  - Expand the useful range of the Early Premixed Charge Compression Ignition (PCCI) LTC mode in order to reduce fuel consumption
  - To reduce engine out emissions
  - To minimize the fuel energy required to raise exhaust gas temperature for catalyst efficiency and regeneration

Partners

- FEV
- TEAM Corporation
- Mechadyne International
- Eaton Corporation
- Mitsubishi Engine NA
- Project lead: GM R&D and Powertrain

Objectives – Diesel Engines

- Investigate the use of variable valve actuation (VVA) as a means to improve the efficiency of a light duty diesel engine approaching and exceeding Tier 2 Bin 5 NOx emission levels
  - Task 1 - Single cylinder engine testing using a fully flexible electro-hydraulic VVA system (FFVVA) – Tier 2 Bin 5 NOx engine-out (EO) targets
  - Task 2 - Multi-cylinder engine testing using a “simple mechanism” VVA system – EO emission targets for potential vehicle demo using a “simple mechanism” VVA system combined with aftertreatment technology for beyond Tier 2 Bin 5 tailpipe targets

- The fully flexible VVA work helps to understand the upper bound efficiency/emissions potential of VVA on a diesel engine

- The multi-cylinder engine work will aid in understanding the requirements and performance capability towards a production viable VVA system

- Focus on developing enabler technologies for tailpipe emission levels beyond Tier 2 Bin 5 that also enhance fuel economy

Milestones – Diesel Engines

- **2007: Late Intake Valve Closing investigation completed in SCE**
- **2008: Internal EGR investigation completed in SCE**
- **2009: Multicylinder testbed with baseline prototype engine testing initiated**

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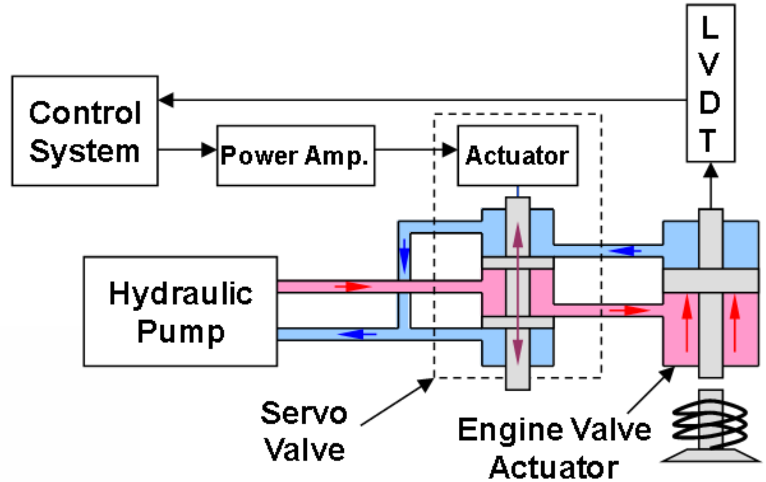
- **2009: Design of "FFVVA system" for upgraded SCE in-progress**
- **2009: 1D Modeling and 3D design for "VVA simple mechanisms" and charging/EGR in-progress**
- **2009: Modifications to MCE build with intake valves phasing, 2-step exhaust valves and upgraded series sequential charging system initiated**

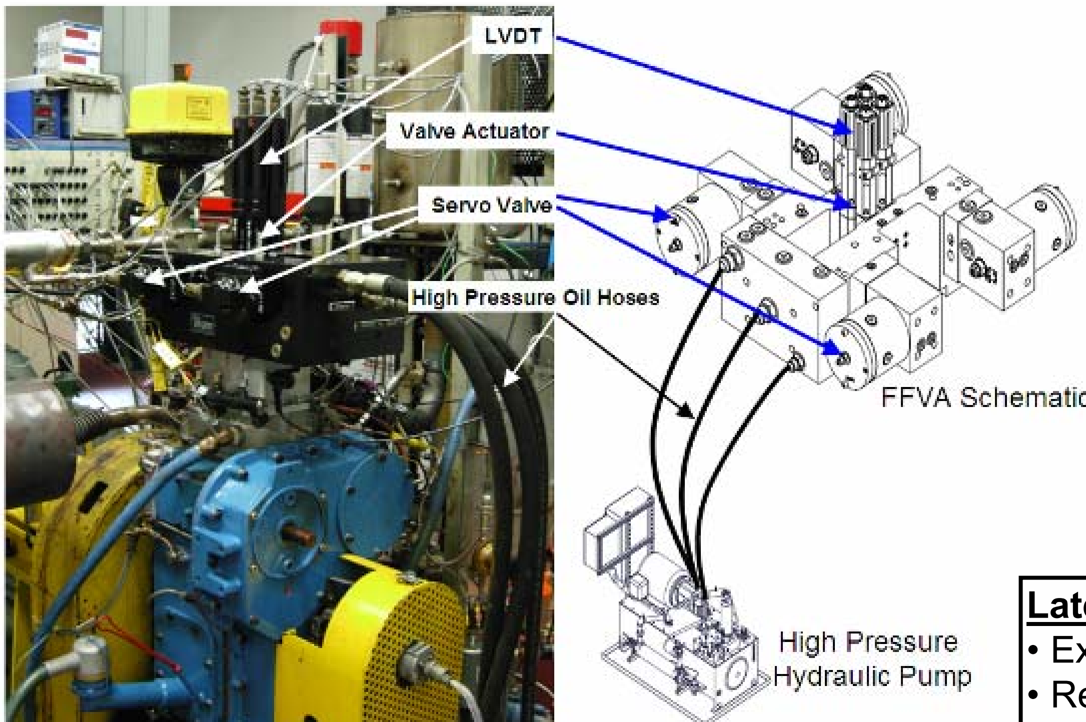
Approach – Diesel Engines

- **Use extensive analysis, production-level design practices, build, and test to generate production-feasible properties which deliver acceptable Low Temperature Combustion (LTC) operation under expected operating conditions**
- **Use the opportunity to generate and use hardware to encourage supply base to develop and produce needed components such as variable valve actuation mechanisms and charging systems**
- **During design/analysis phases, focus on reducing cost and technical risk of subsystems and components**
- **Use results of program to protect for this technical content in future production engine designs**

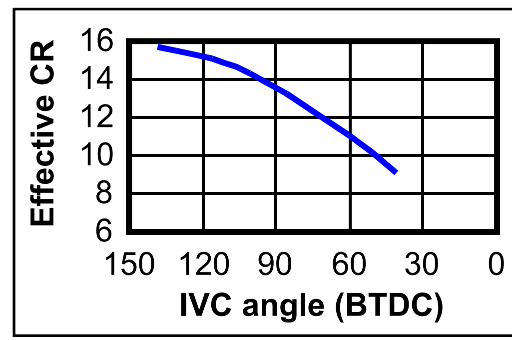
Approach – Single Cylinder Engine

- A research oriented VVA system using independent electro-hydraulic actuators for each valve
- Designed to achieve a very high level of control and flexibility
- Not a production intent system





SCE FFVVA

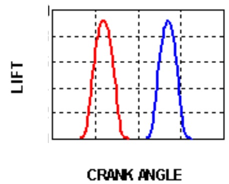
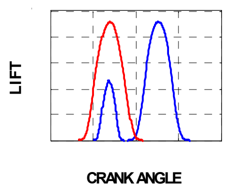
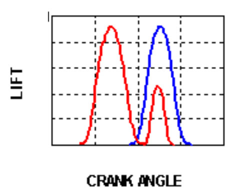


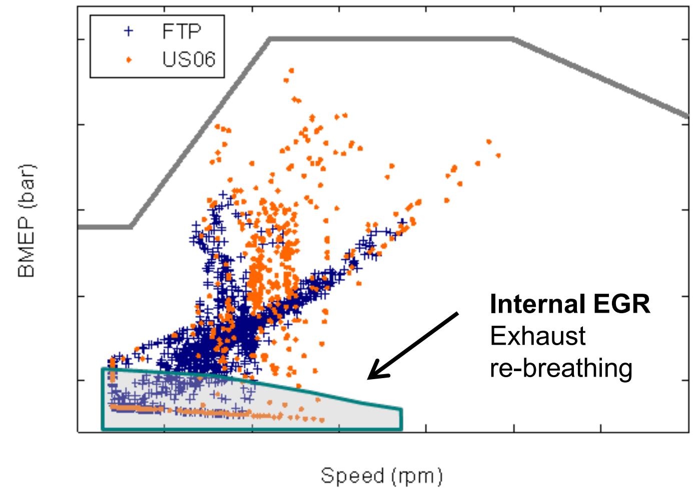
Late Intake Valve Closing (SCE 2007):

- Expand Early PCCI operating range
- Reduce smoke emissions
- Improve fuel economy due to improved combustion phasing

Technical Accomplishments

Identified Effects of Internal EGR in SCE

Strategy	SCE Fully Flexible Variable Valve Actuation	Observations
Recompression (Early exhaust valve closing + late intake valve opening)		• Pumping losses • Needs to change the lift profiles of all four valves
Intake Re-breathing (Intake valve re-opening during exhaust stroke)		• Higher heat losses than exhaust re-breathing • More difficult to open than exhaust valve
Exhaust Re-breathing (Exhaust valve re-opening during intake stroke)		• Only one exhaust valve lift profile need to be changed • Multiple profiles possible and combined with intake - exhaust pressure control • Lower pumping losses than recompression • Easier to be opened than intake valve • Less heat losses than intake re-breathing



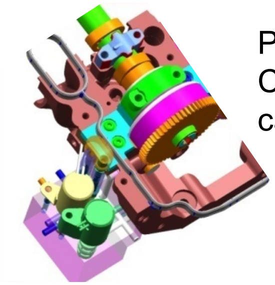
- **Benefits of Internal EGR**
  - Emissions reduction of CO and HC during cold start conditions and at idle
  - Potential to mitigate external EGR cooler fouling
  - Alternative to intake throttling and losses
  - Increase in exhaust temperature
  - Improved low load/speed combustion stability

- **Limitations/Challenges of Internal EGR**
  - Potential fuel consumption penalty with compensation by reduced post injection quantity
  - Limited to very light loads and speeds
  - Difficult to measure actual quantity of internal EGR for calibration purposes

Technical Accomplishments

Single Cylinder FFVVA Engine with updated MCE head and fuel system – In progress

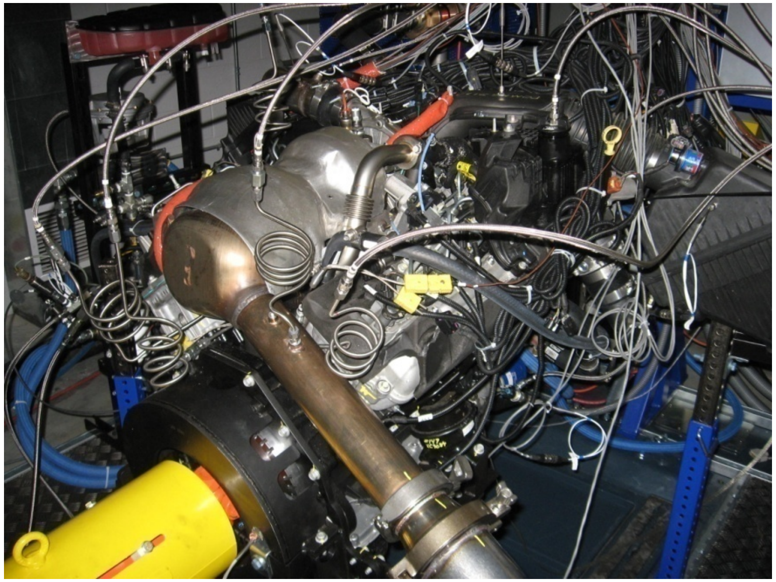
Multicylinder Engine with VVA Mechanisms Design/Integration In-progress



Phaser – Concentric camshafts

Two-step Roller Finger Followers

Two-stage series sequential turbochargers (concept)



4.5L V8 Diesel Engine Testbed

Future Work – Diesel Engines

- **Completion of updated fully-flexible valve actuation in SCE and testing for further understanding of thermodynamics**
- **Multicylinder with "VVA simple mechanism" and dyno testing (includes steady-state and initial transient performance characterization)**
- **Major known issues/concerns at this time:**
  - **VVA transient response**
  - **Charging response**
  - **Operating range of LTC mode**
  - **Warm-up performance**

Summary – Diesel Engines

- This program will result in, and was a major contributor to, successful understanding of the technical merit and impact of VVA strategies on fuel efficiency and emissions
- This program will have an impact on future GM production engine designs
- Guidance from this merit review will influence the remaining work