Development of High-Efficiency Clean Combustion Engines Designs for SI and CI Engines

Kenneth J. Patton & Manuel A. Gonzalez D.

GM Powertrain Advanced Engineering

June 11, 2010

ACE036

Overview

Timeline

- Start: April 2005
- End: May 2010
- Project is complete

Budget

- Total project funding
  - DOE share $6.25M
  - GM share $6.25M
- All funding received by FY09

Barriers

- Barriers addressed
  - HCCI operating range
  - Mixed mode operation
  - Readiness of cylinder pressure sensor technology
  - System cost

Partners

- GM is project lead
- Subcontractor is 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 ✓ complete
- Fully-flexible system – demonstrate engine on spin rig, on dyno, and under vehicle conditions; quantify effects on HCCI operating range; reduce cost and risk; identify areas of deficiency ✓ complete
- Influence future production gas engine designs ✓ complete

Milestones – Gasoline HCCI Engines

- 2008: enabling system fuel consumption benefit quantified
- 2008: multicylinder fully-flexible system design released
- 2009: multicylinder fully-flexible system spin rig testing completed
- 2010: multicylinder fully-flexible system dyno testing completed
- 2010: fully-flexible system fuel consumption benefit quantified

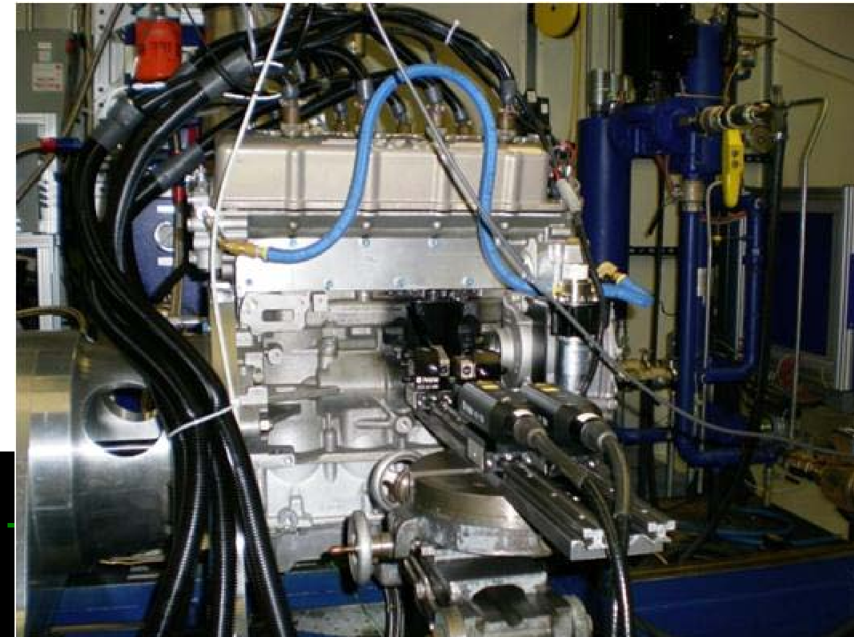
Approach – Gasoline HCCI Engines

- 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 and implement this technical content in future production engine designs

Technical Accomplishments

Spin-Rig Testing of Fully-Flexible Multicylinder Engine

- Spin-rig testing demonstrated acceptable control of valvetrain functions (lift, duration, timing)
- Significant reduction of occurrences of piston-to-valve collisions
- Adequate control of valve closing velocity
- Steady-state and transient operation successfully demo'd



Technical Accomplishments

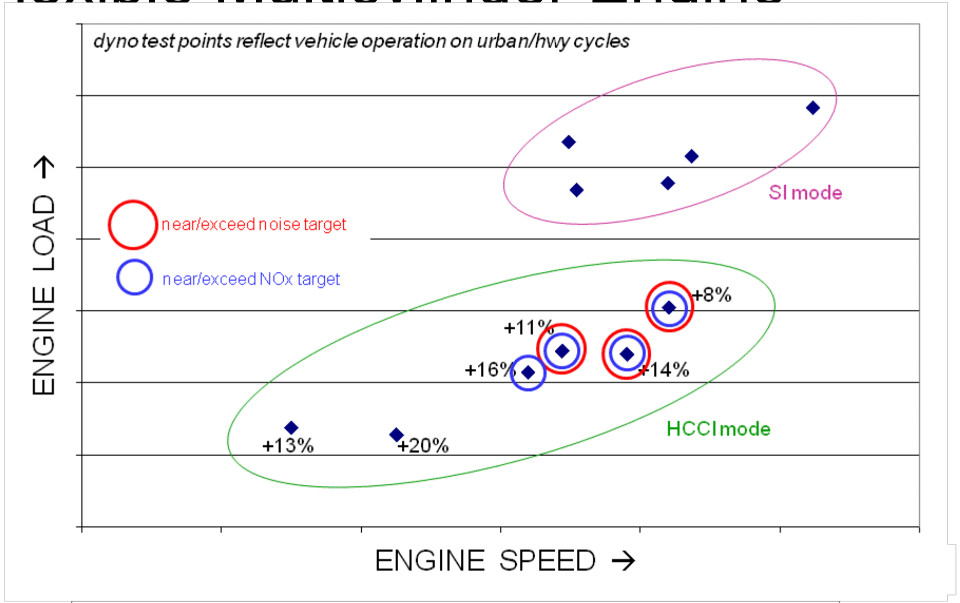
Dyno Testing of Fully-Flexible Multicylinder Engine

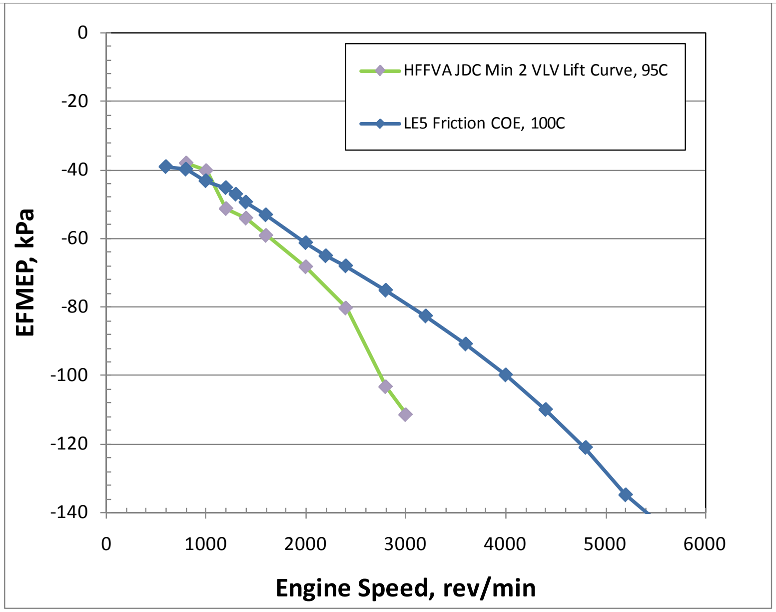
- Actuators capable of adequate control of exhaust valve opening under firing conditions
- Initial assessment of cylinder-to-cylinder and cycle-to-cycle variability is encouraging (much more to learn)
- Performance of fully-flexible valve actuation system is sufficient for dyno assessment of SI and HCCI combustion system characteristics and performance.

Technical Accomplishments

Dyno Testing of Fully-Flexible Multicylinder Engine

- Steady-state fuel consumption improvement
- Initial measurements of parasitic loss behavior of system are as predicted via early analyses





Collaboration/Coordination

- Close collaboration on analysis, design, and development of electrohydraulic fully-flexible valve actuation systems with Sturman Industries (Woodland Park, CO)
- Significant collaboration with suppliers of engine components and subsystems as part of normal engine design/development activity

Future Work – Gasoline HCCI Engines

- This project is complete as of May 28, 2010
- Several areas of continued GM internal work are directly related to this project
  - extensive HCCI program
  - efforts to productionize "building block" elements which were specifically from this project include:
    - combustion system design
    - variable valvetrain systems
    - cylinder pressure sensing
    - increased speed/accuracy/authority cam phasing systems
    - advanced fuel and combustion systems
- While not part of DoE program, major efforts in place and ongoing
- Where success was limited
  - cylinder pressure sensor robustness & supply base
  - transient operation of FFVA system needs improvement

Summary – Gasoline HCCI Engines

- Successful demonstration of gasoline HCCI enabling technology using valvetrain with limited complexity
- Successful demonstration of fully-flexible VVA technology which increased the capability of the gasoline HCCI engine
- Significant key engine design elements directly resulting from this project are being used in the design of future GM products
- Still need more improvement of robustness of cylinder pressure sensors and development of supply base
- Still need significant improvement of transient operation and NVH characteristics of FFVA system

Overview – Diesel Engines

Timeline

- Start: 2005 – Single cylinder engine (SCE) – Fully Flexible Variable Valve Actuation
- End: 1Q2010 – SCE and Multi-cylinder engine (MCE)
- Percent complete: 100%

Budget

- **Total project funding**
  - **DOE share $6.25M**
  - **GM share $6.25M**

(All funding received)

Barriers

- Barriers addressed
  - To operate at Low Temperature Combustion (LTC) conditions 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

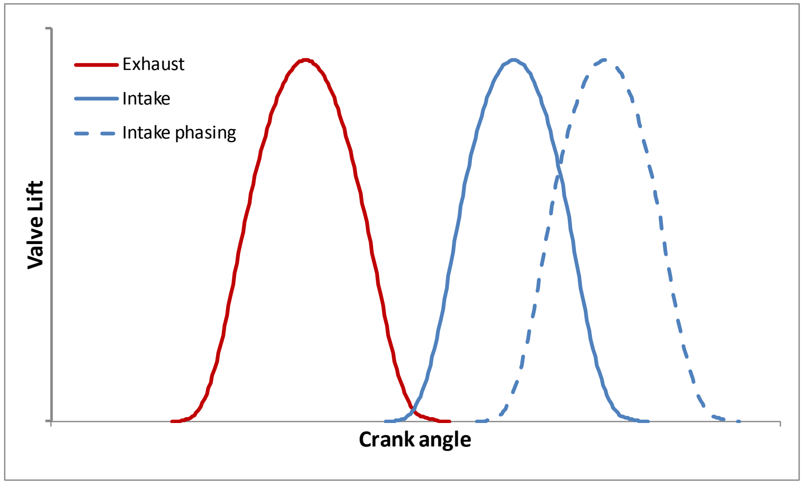
  - Task 1 - Single cylinder engine testing using a fully flexible electro-hydraulic VVA system (FFVVA) – Tier 2 Bin 5 NOx engine-out (EO) targets

  - **Task 2 - Multi-cylinder engine testing using a "simple mechanism" VVA system – steady state engine-out emission targets combined with aftertreatment technology for beyond Tier 2 Bin 5 tailpipe targets and enhanced fuel economy**

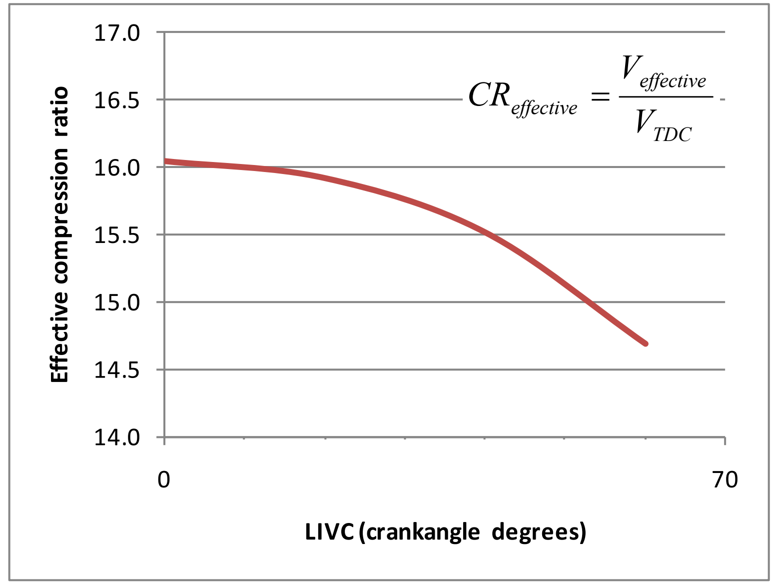
Milestones – Diesel Engines

- 2007: Late Intake Valve Closing investigation completed in SCE
- 2008: Internal EGR investigation completed in SCE
- 3Q 2009 – 1Q 2010: Multicylinder testbed with baseline prototype engine
- 2009: Modifications to Multi-cylinder engine <u>completed</u>:
  - Concentric intake camshaft and phaser
  - Two stage series sequential turbocharging
  - 2-profile exhaust camshafts
- 2010: Multi-cylinder engine testing <u>completed</u>:
  - Late Intake Valve Closing: Effective Compression Ratio Study
  - Secondary Opening of Exhaust Valves - Exhaust Rebreathing: Internal EGR Study

VVA - Late Intake Valve Closing

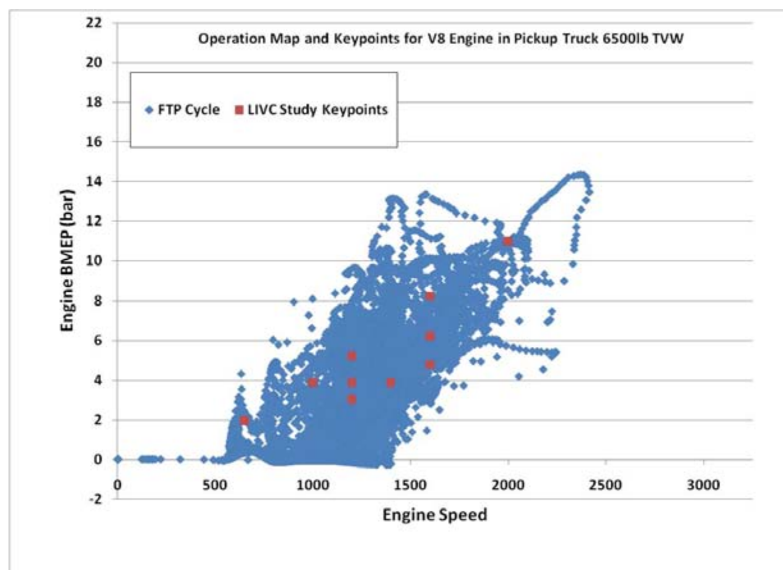


LIVC phasing capability up to 90 ca degrees



Effective compression ratio in LIVC operating range with potential applicability

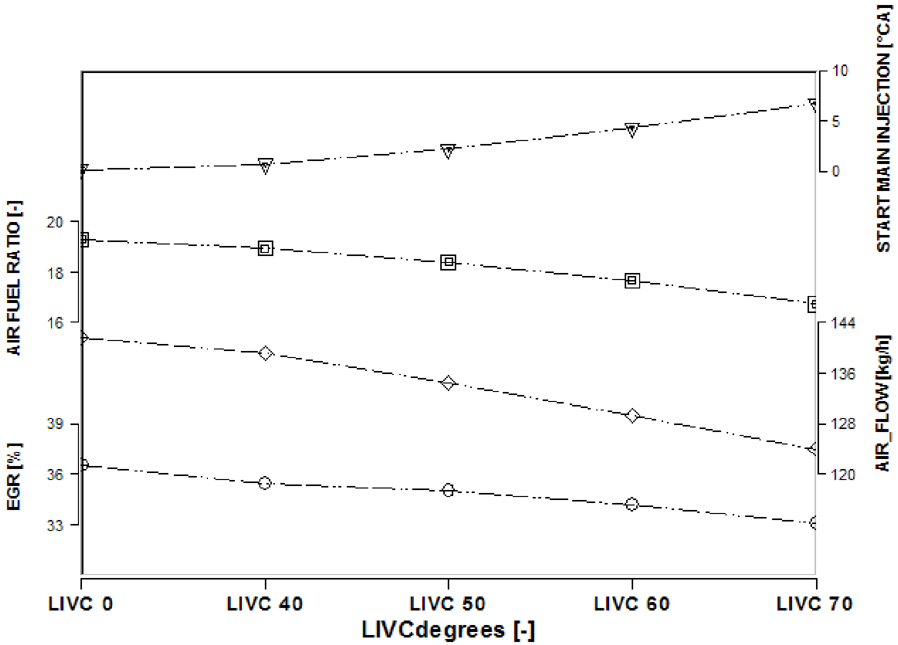
Two stage system, concentric camshaft and phaser. Installation in multi-cylinder engine head



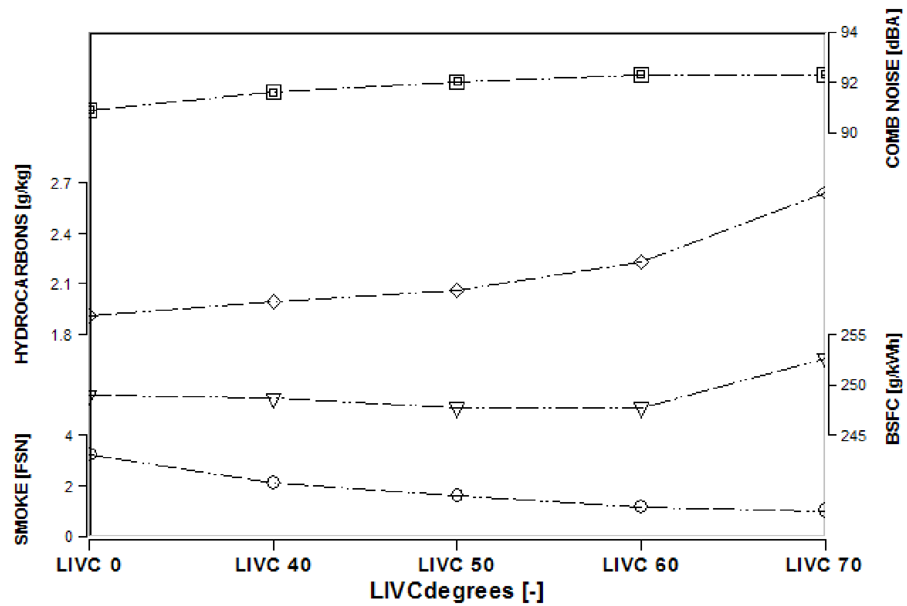
Engine operating map for LIVC study

Variation of main engine parameters at different LIVC phasing and constant NOx emissions

1600 rpm/4.8 bar BMEP
Normal combustion
Coolant @ 88C, Bypass OFF
70% reduction EINOx
Ca50 12 atdc fix
Fix VNT position



- Advanced SOI for constant combustion phasing
- Volumetric efficiency and AFR drops with less efficient charging
- Less EGR is required at constant NOx by lower temperature profile in the cycle



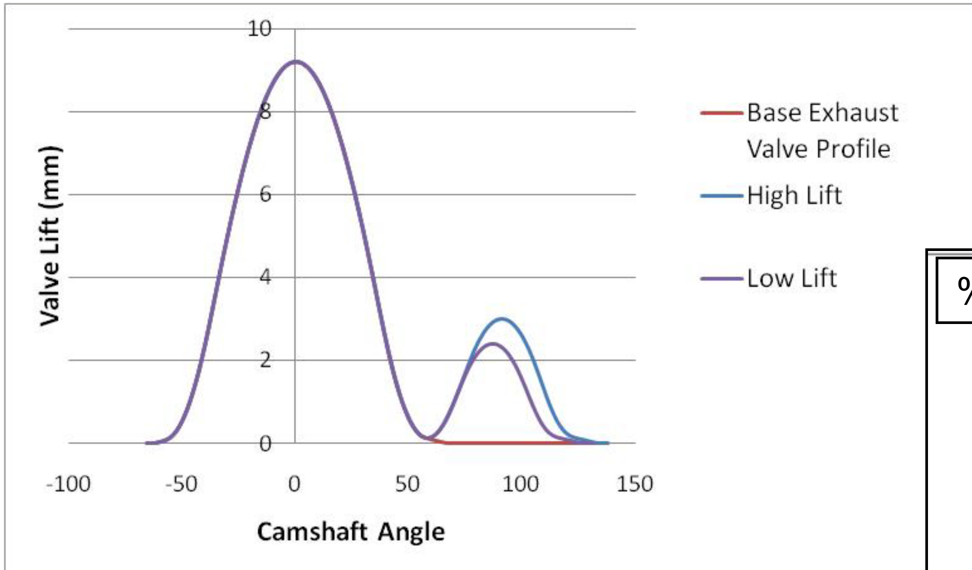
- Longer ignition delay and mixing with higher noise
- Lower temperature profile for higher HCs
- Optimum BSFC can be achieved for different phasing with balance of combustion efficiency and engine friction
- Higher mixing and oxygen accesibility by lower effective compression ratio with lower soot emissions

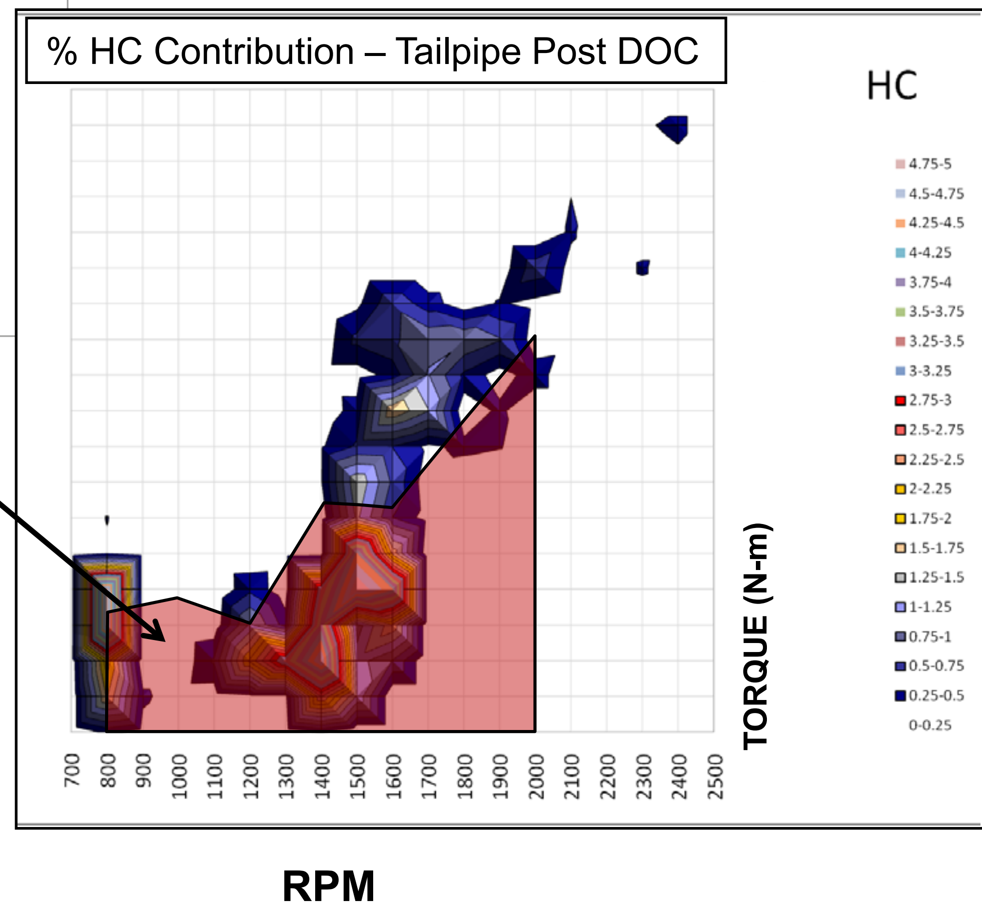
LIVC - VVA Functions

- **Benefits of LIVC**
  - Alternative for variable compression ratio
  - Shows benefits within the load range of 2 to 7 bar BMEP when at Tier 2 Bin 5 NOx levels with aftertreatment, potential for further NOx reductions
  - Impact in fuel consumption up to ~ -1% in FTP keypoints
  - Simultaneous smoke-NOx reduction can be higher than 50% in FTP keypoints
  - Expands early PCCI range beyond current limitations
  - Reduction in EGR required at constant NOx up to ~10%

- **Limitations/Challenges of LIVC**
  - Reduction in volumetric efficiency
    - Imposes a critical requirement for the turbocharging system
    - High load not achievable due to lower volumetric
    - Combustion variability at low AFRs with high LIVC
    - Higher boost pressure needed to offset lower volumetric efficiency to achieve lower fuel consumption and operation at high enough Air-Fuel Ratio
  - LIVC generally causes an increase in the HC and CO emissions, impacts area of application in engine map

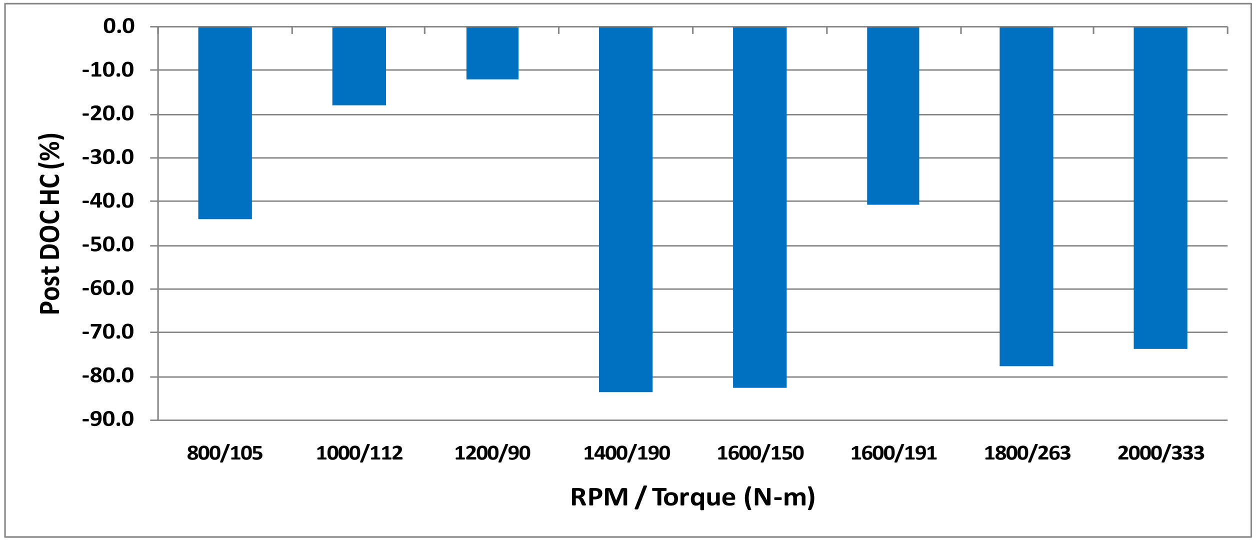
Exhaust rebreathing camshafts and ports implementation





- Keypoints operating area selected by HC contribution to cold start FTP cycle
- High/Low Lift and duration profiles
- Valvetrain exhaust implementations opposite to intake helical and tangential ports

IEGR VVA Functions



- **Benefits of Internal EGR**
  - ➡ Emissions reduction during cold start conditions
    - CO reduction ~30% (first 200 sec of FTP cycle), HC reduction ~50%
  - ➡ Mitigate external EGR cooler fouling
  - ➡ Alternative to intake throttling and losses, alternative to retard timing strategy
  - ➡ Increase in exhaust temperature (with increase in fuel consumption)
  - ➡ Higher low load/speed combustion stability
  - ➡ Can be noise neutral

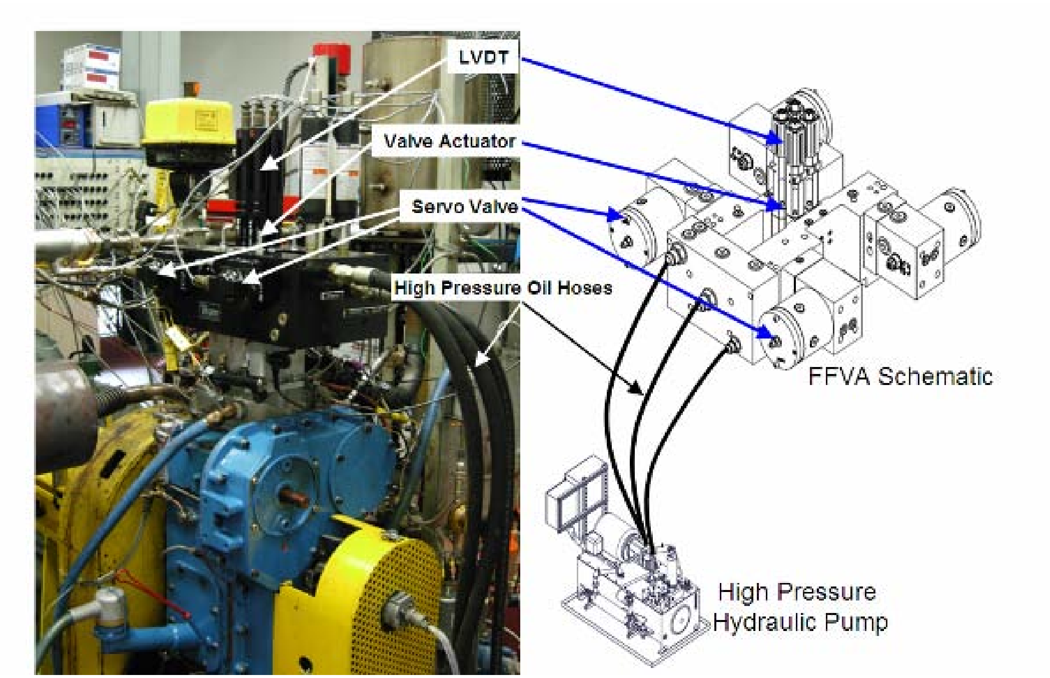
- **Limitations/Challenges of Internal EGR**
  - ➡ Estimated FC potential penalty ~0.3% (overall FTP cycle)
  - ➡ Limited to smoke trade-off loads and speeds
  - ➡ Difficult to measure actual quantity of internal EGR for calibration purposes
  - ➡ Compiting with 2-stage charging system energy balance

- Tailpipe emissions performance during FTP, (as HC % of reduction) is favored by less engine out emissions plus faster light-off and higher conversion by higher operating temperature
- Internal EGR relative to retarded SOI for 40 C increase in exhaust temperature (implementations in each of both exhaust ports – 800 rpm/105 N-m)
  - ✓ ~5-8% lower BSFC
  - ✓ ~45% lower HC emissions
- For matching exhaust temperature, IEGR by exhaust rebreathing shows promising results for a competitive strategy to retarded injection timing at idle

Technical Accomplishments

Single Cylinder FFVVA Engine – VVA Study

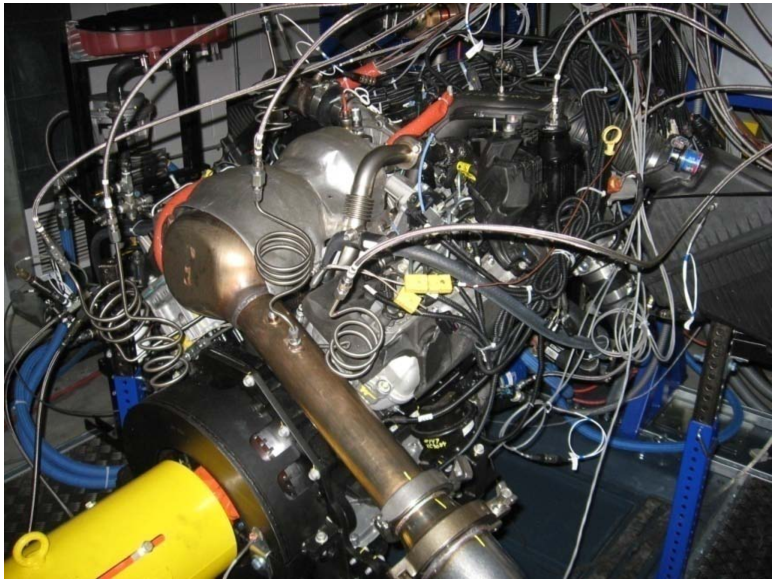
- *Late Intake Valve Closing*
- *Exhaust Recompression*
- *Intake Rebreathing*
- *Exhaust Rebreathing*
- *Early Exhaust Valve Opening*



Multi Cylinder Engine – VVA Study

- *Late Intake Valve Closing (one valve) with two stage turbocharging*
- *Exhaust Rebreathing (one valve) with single and two stage turbocharging*





Base
4.5L V8 Diesel
Engine Testbed

Patent application - Diesel engine with switching roller finger followers for internal EGR control

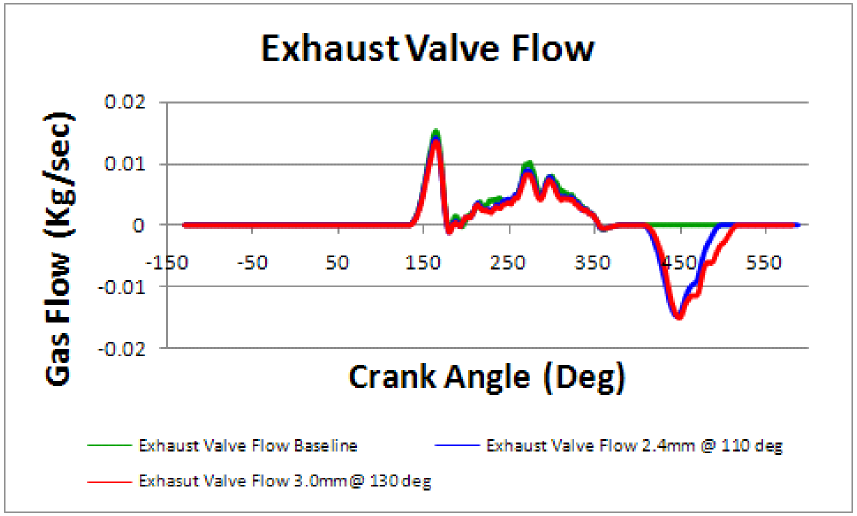
- ***The application of switching roller finger followers on the exhaust valvetrain of multi-cylinder diesel engines for selectively producing the re-opening of exhaust valves for internal EGR control***

EGR Level	Exh Valve #1	Exh Valve #2
0	Off	Off
1	On	Off
2	Off	On
3	On	On

V8 Diesel Engine
1-D Simulation
Actuation of one exh. valve
650 rpm/2.2 bar BMEP
Internal EGR up to 40%

Ways to apply the system:

- Single Exhaust valve per cylinder - allows one discrete rebreathing profile to be used, switchable
- Both exhaust valves per cylinder - single actuator, allows a higher amount of EGR to be introduced based on a single actuator
- Both exhaust valves per cylinder - dual actuator circuit, allow combinations of internal EGR rate to be achieved (zero, low and high)
- Both Exhaust valves per cylinder - dual actuator circuit, dual lift profiles, flexible control with 3 levels of internal EGR possible (additional control achieved with back pressure regulation)



Summary – Diesel Engines

- **This program has been a major contributor to a successful understanding of the technical merit and impact of VVA strategies on fuel efficiency and emissions**
- **Program results has provided technical input for future GM production engine designs**