DEER Conference 2010

Late Intake Valve Closing and Exhaust Rebreathing in a V8 Diesel Engine for High Efficiency Clean Combustion

High-Efficiency Clean Combustion Engine Designs for Compression Ignition Engines
GM-DOE AGREEMENT No. DE-FC26-05NT42415

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September 29, 2010

Outline

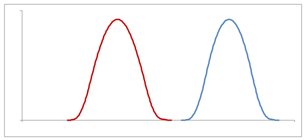
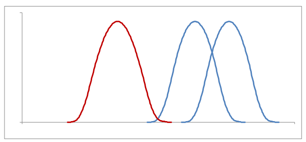
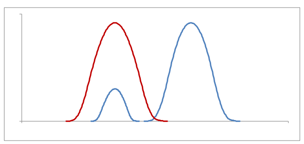
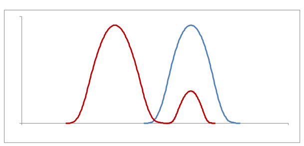
- Objectives
- Technical Approach & Hardware
- Discussion of Variable Compression Ratio - Late Intake Valve Closing & Two Stage Turbo Charging
- Discussion of Internal EGR - Exhaust Rebreathing
- Estimated overall driving cycle impacts
- Summary
- Acknowledgements

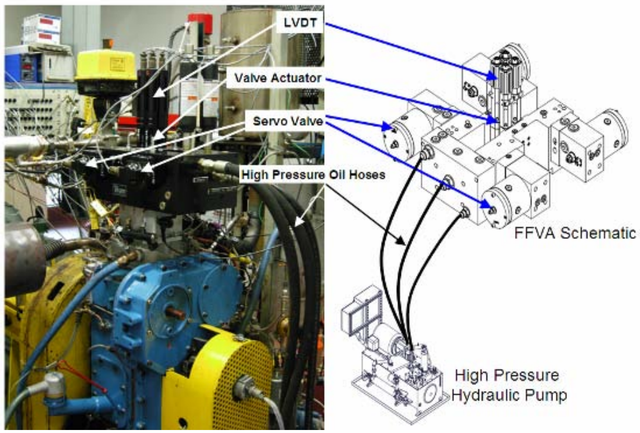
Objectives

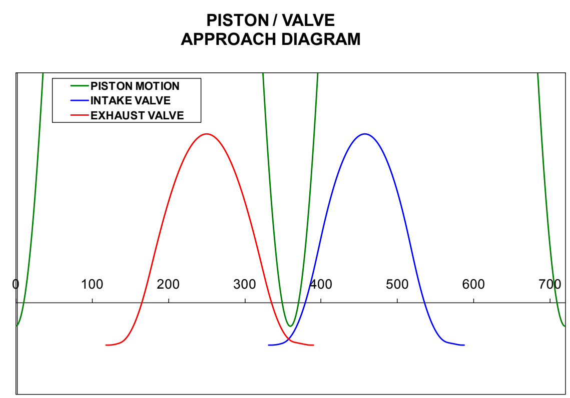
- Investigate the use of variable valve actuation (VVA) as a means to improve the efficiency of a light duty diesel engine approaching and exceeding Tier 2 Bin 5 NOx emission levels
  - Multi-cylinder engine testing using a “simple mechanism” VVA system – steady state engine-out emission targets combined with aftertreatment technology for beyond Tier 2 Bin 5 tailpipe targets and enhanced fuel economy
    - Late Intake Valve Closing (LIVC) Study
    - Exhaust Rebreating Study

- Barriers addressed
  - To operate at Low Temperature Combustion (LTC) conditions using “VVA simple mechanisms” for control of effective compression ratio and internal EGR (IEGR)
  - 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

VVA Strategies

Strategy	Valve profiles	Observations
Late Intake Valve Closing (both valves)		• Too limiting for engine breathing reducing volumetric efficiency and torque
<u>Late Intake Valve Closing</u> (one valve)		• Effective compression ratio control • Reduces volumetric efficiency • LIVC with extended duration, same expansion ratio with reduced compression ratio (improved efficiency)
Intake Re-breathing (Intake valve re-opening during exhaust stroke)		• Higher heat losses than exhaust re-breathing • More difficult to open than exhaust valve
<u>Exhaust Re-breathing</u> (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 • Easier to be opened than intake valve • Less heat losses than intake re-breathing





Technical Approach - Hardware

Multi Cylinder Engine – VVA Study

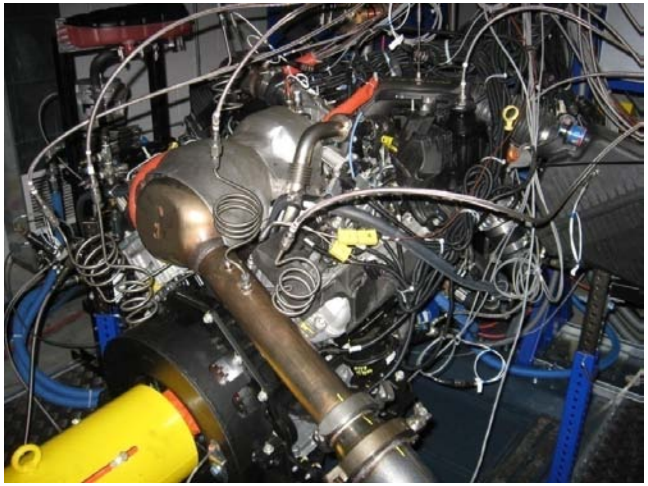
- *Late Intake Valve Closing (phasing of one valve per cylinder)*
- *Exhaust Rebreathing (re-opening of one valve per cylinder) with single and two stage turbocharging*

Concentric
Camshafts and phaser

Two-stage turbocharging

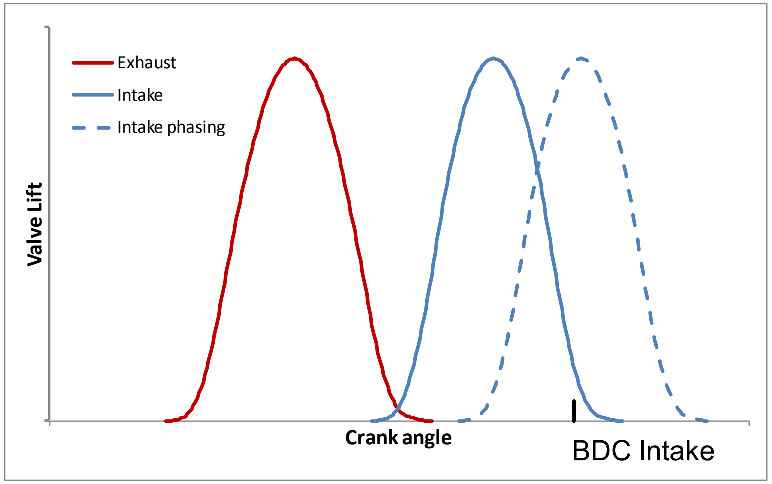
Secondary exhaust
opening profile

Base
Engine Testbed

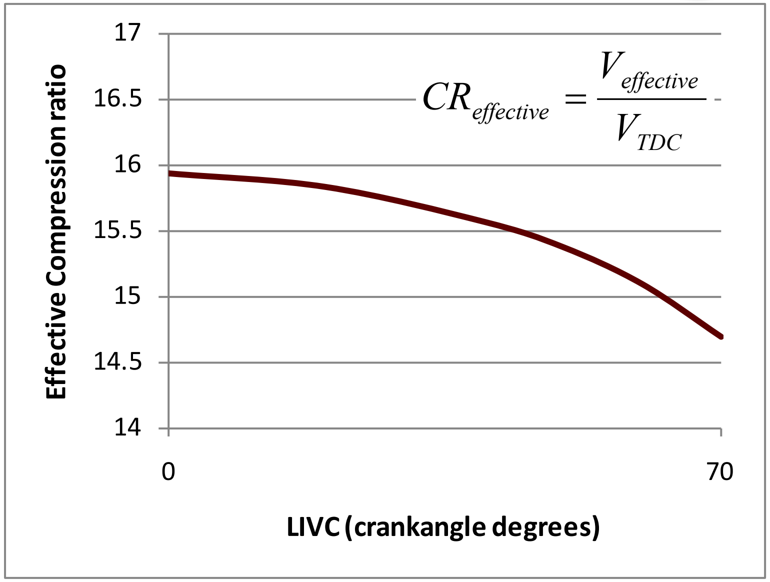


Configuration/Displacement	V8 4.5 liters
Compression Ratio	16.0:1
Bore x stroke	88 mm x 92 mm
Valve Train	DOHC - 4v
Intake Configuration	Outboard intake with integrated cam cover intake manifold
EGR System	Cooled external
Exhaust System	In Vee exhaust with manifold integrated into head
Emissions System	DOC, Urea SCR and DPF

VVA - Late Intake Valve Closing

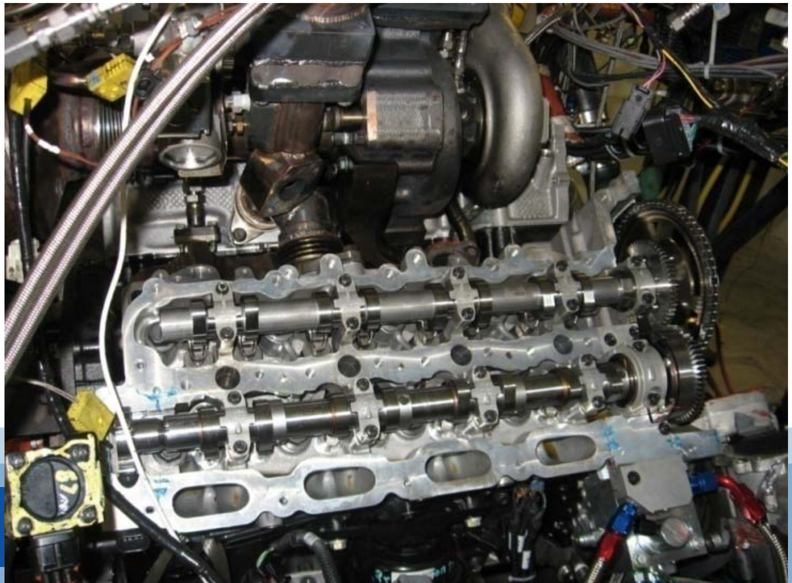


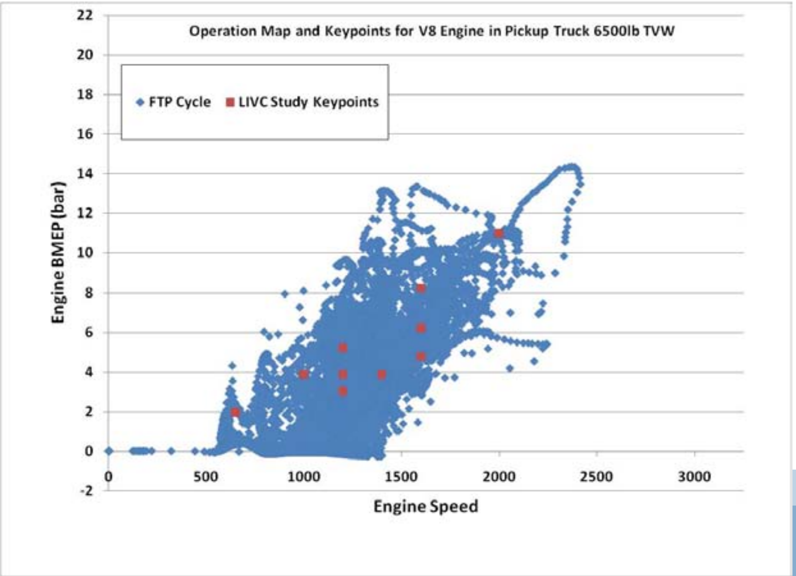
LIVC phasing capability up to 90 ca degrees



Effective compression ratio in LIVC operating range

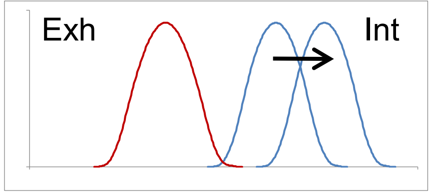
Two stage system, concentric camshaft and phaser in multi-cylinder engine head



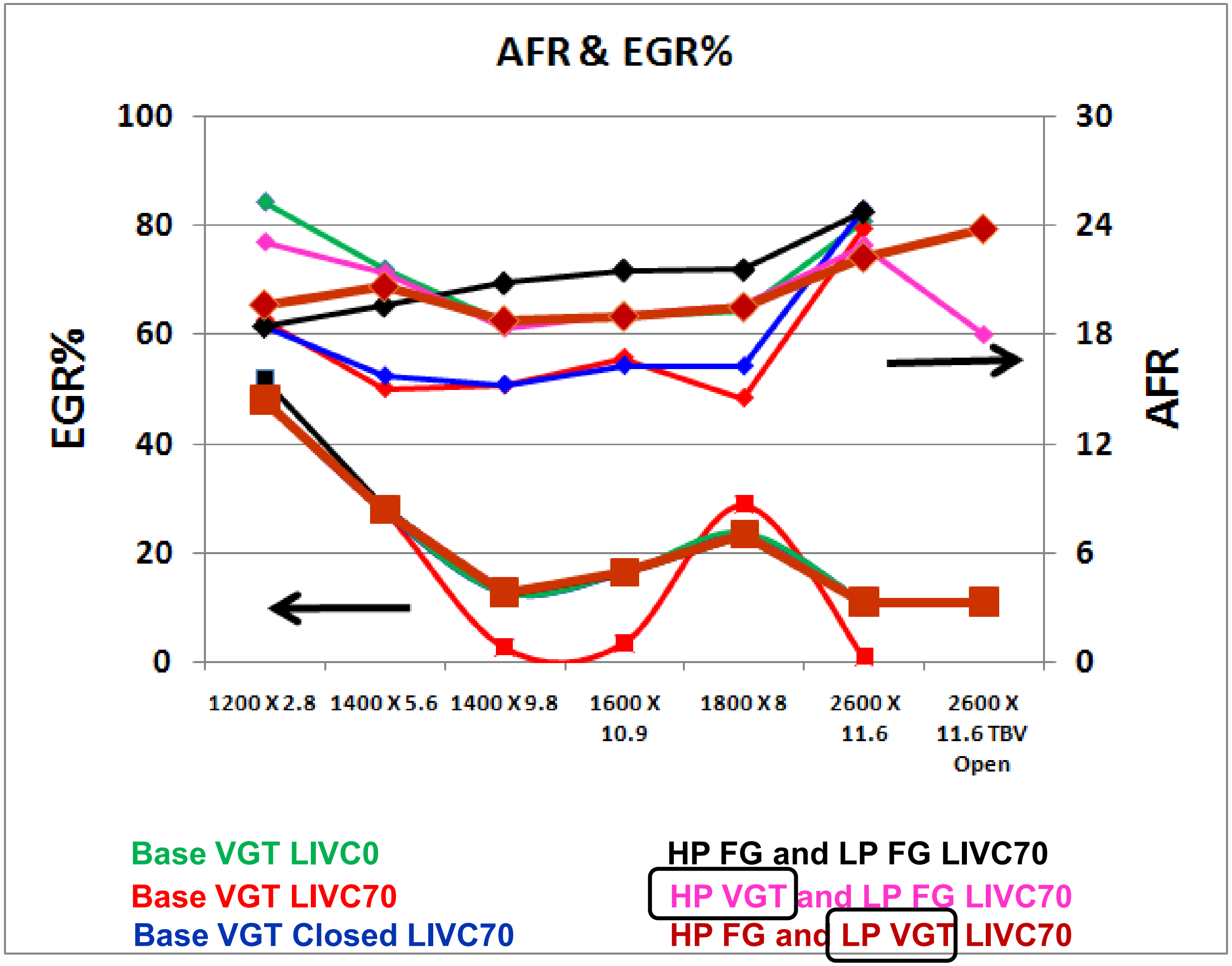


Engine operating map for LIVC study

Turbocharging for LIVC



- 1-D Modeling for LMK 4.5L V8 Diesel Engine

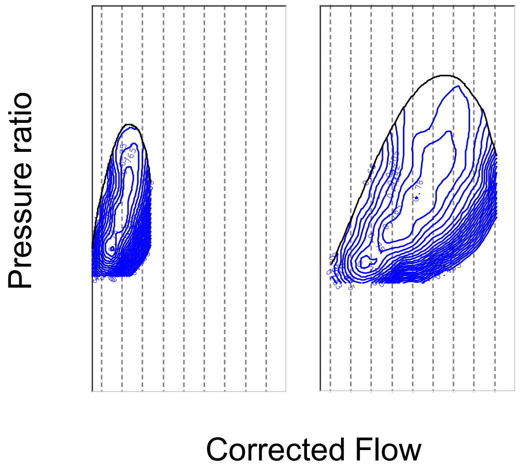


Target: 70 ca deg phasing of one intake valve matching AFR and EGR

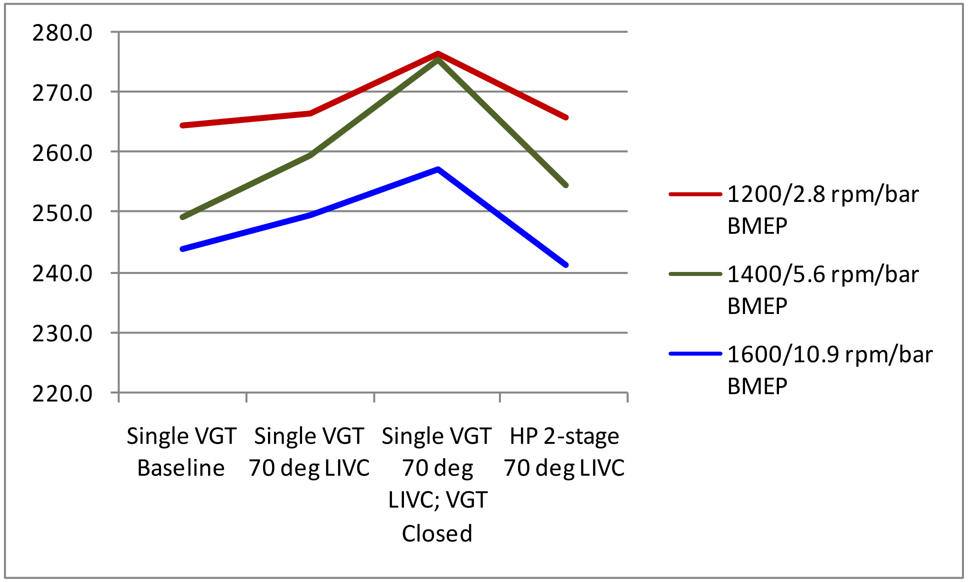
Two stage charging selected

Charging

- **Modeling air handling**
  - **1-D modeling base engine and VVA system**
  - **Charging hardware selection**



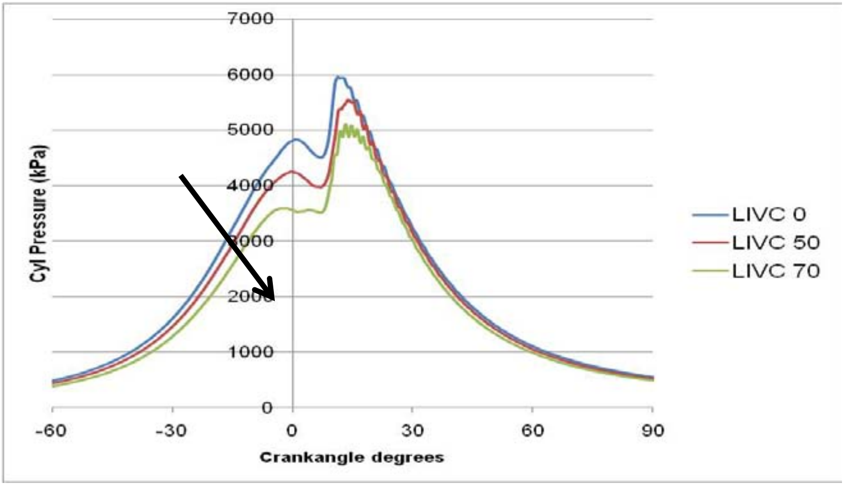
BSFC (g/Kw-h)



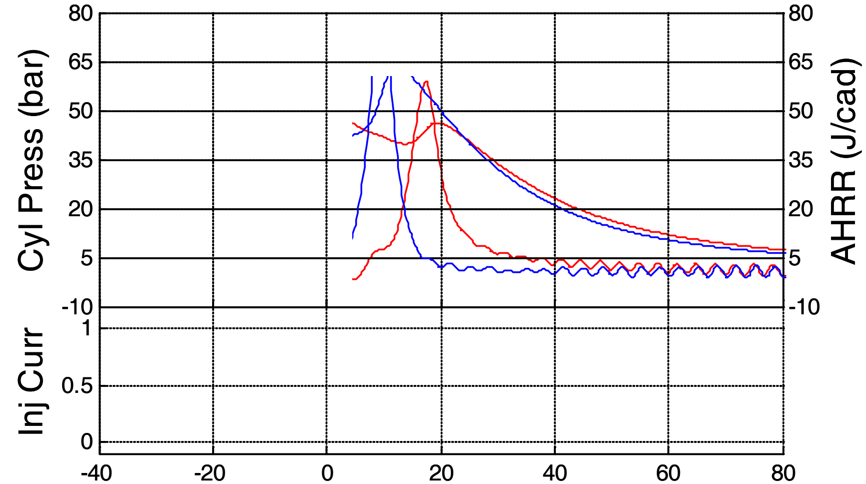
- AFR matching only reached when using a High Pressure VGT not using VNT closing which have detrimental BSFC performance
- Experimental work also have shown emissions benefits with a controlled reduction in AFR

Effective Compression Ratio on Cylinder Pressure

1600 rpm/4.8 bar BMEP
Normal combustion
Coolant @ 88C, Bypass OFF
Constant NOx 1.2 g/kg
Ca50 12 atdc fix

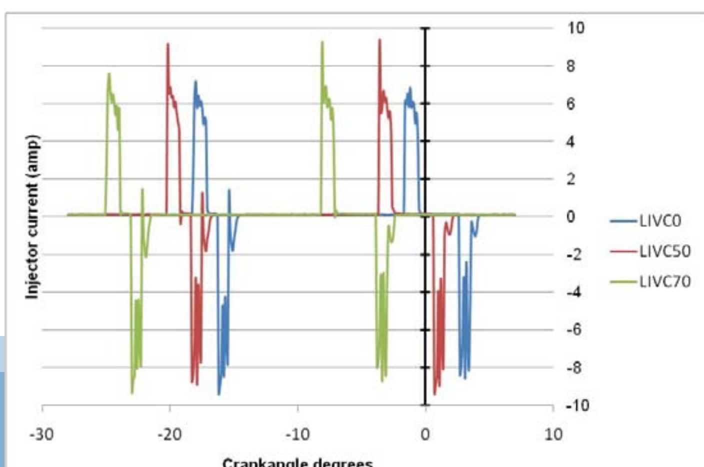


- Peak cylinder pressure reduction resulted by LIVC implementation for lower effective compression ratio

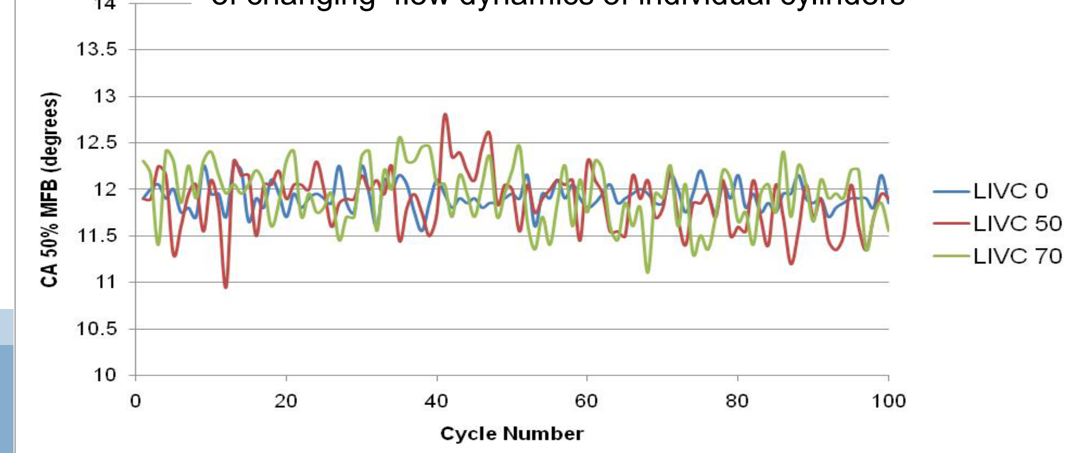


SCE 1600 rpm x 4.2 bar LIVC60 EINOx 0.3 g/kg-f
Early PCCI (blue color, LIVC70) and late PCCI

- Start of injection can be advanced for constant combustion phasing to compensate for longer ignition delay

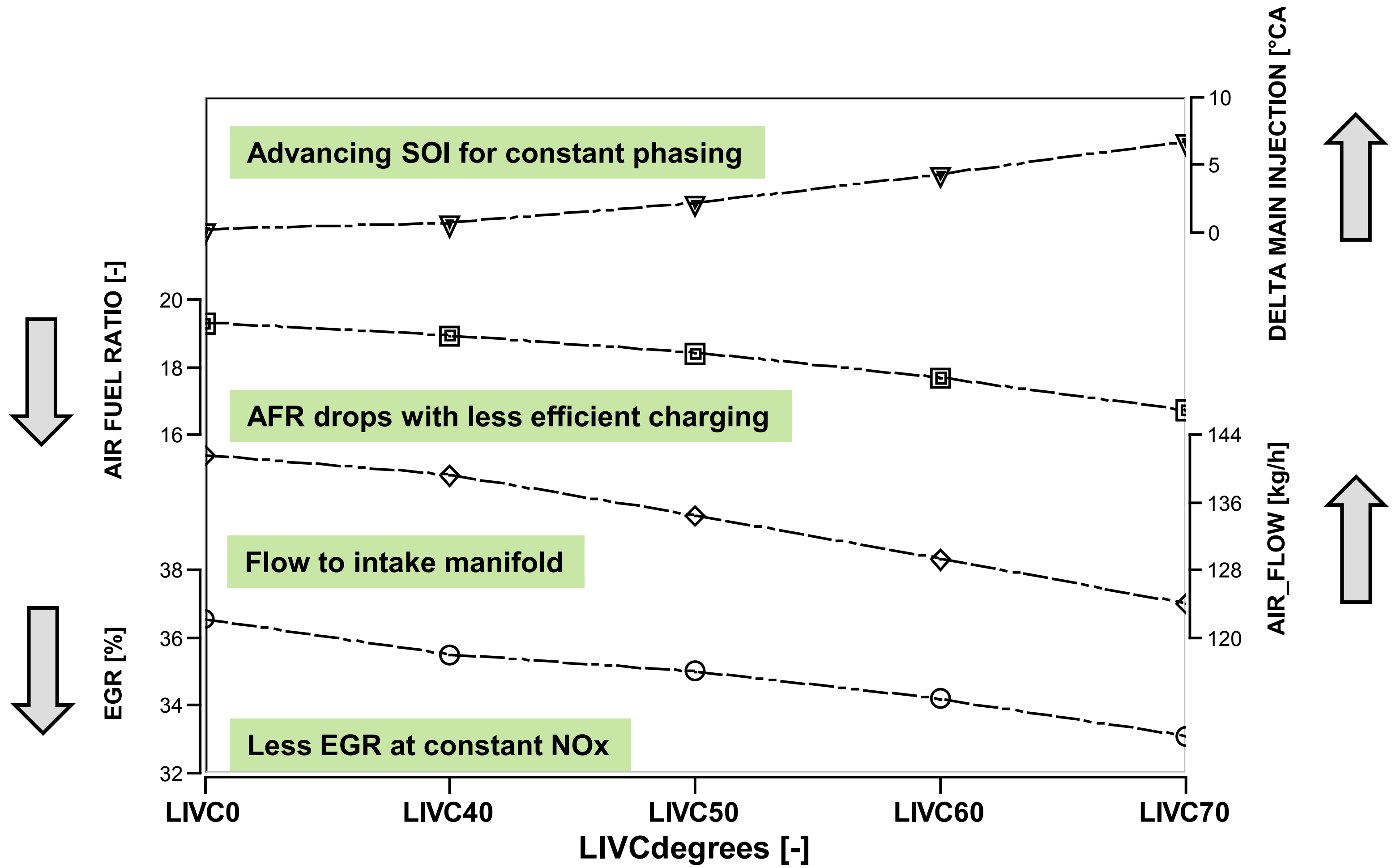


- Coef of Variation of combustion phasing increases with LIVC, cam phasing control stability and impact of changing flow dynamics of individual cylinders



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

1600 rpm/4.8 bar BMEP
Normal combustion
Coolant @ 88C, Bypass OFF
< 1.2 g/kg EINOx
Ca50 12 atdc fix
Fix 70% VNT position



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

1600 rpm/4.8 bar BMEP
Normal combustion
Coolant @ 88C, Bypass OFF
< 1.2 g/kg EINOx
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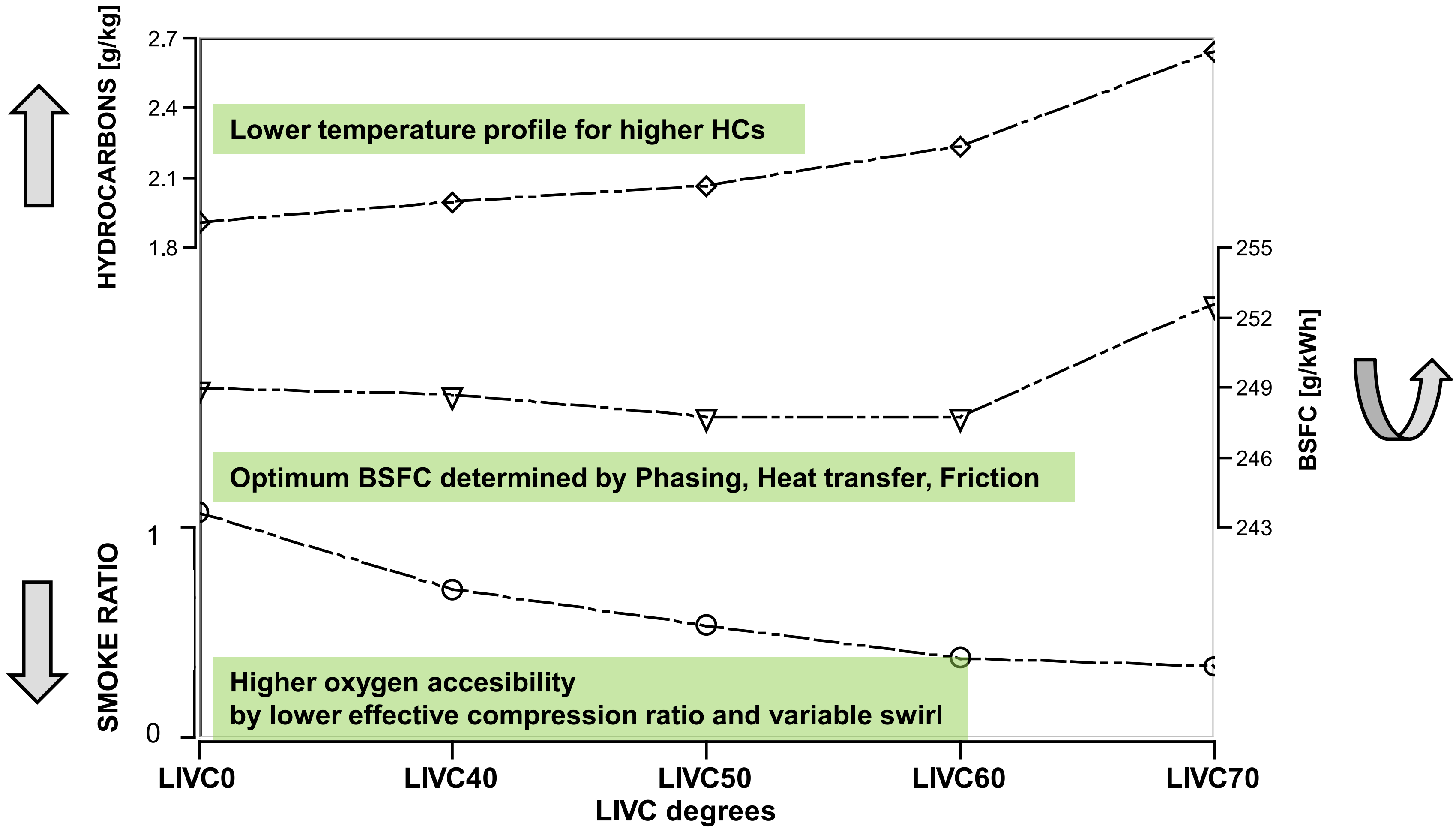
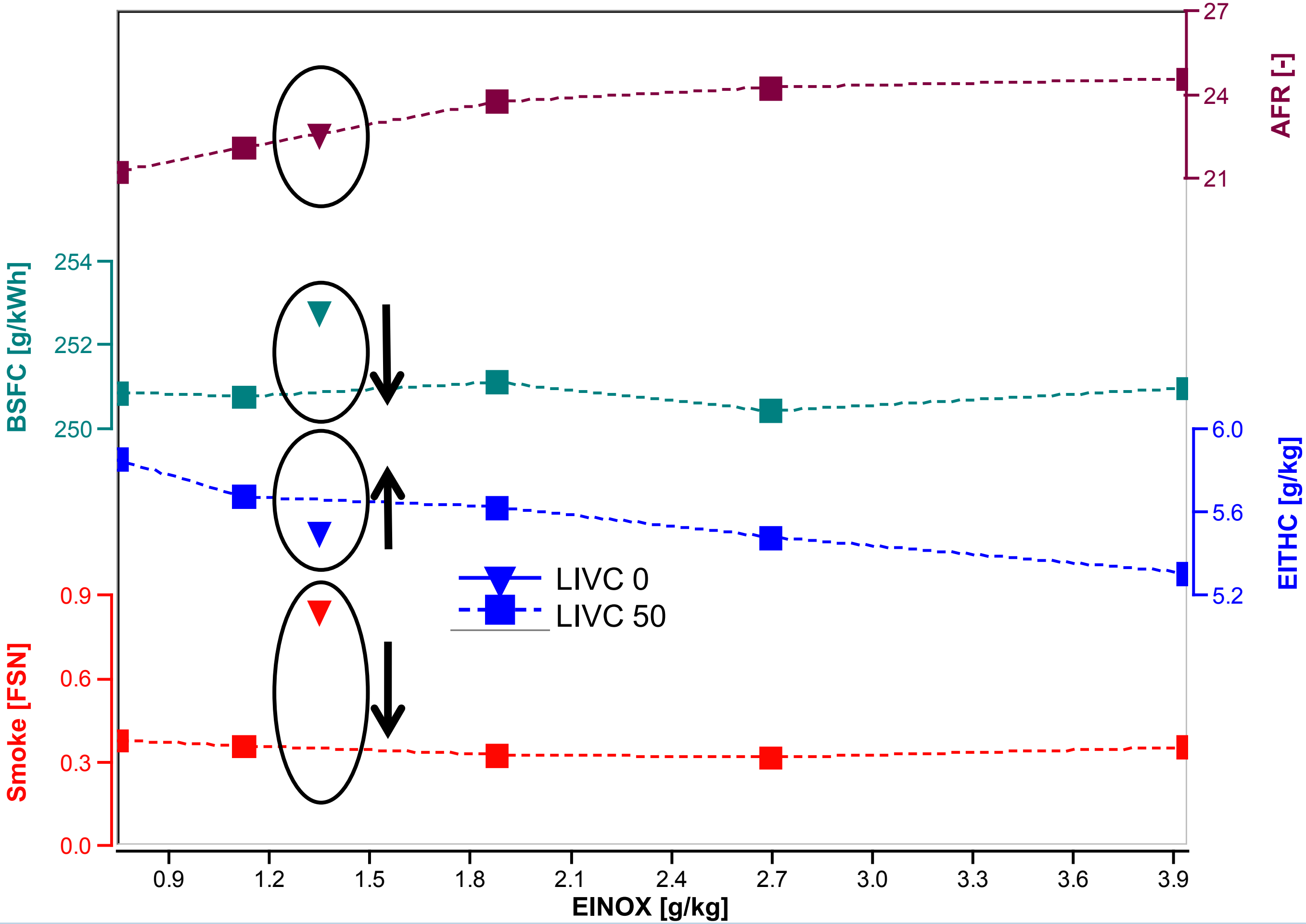
Fix 70% VNT position



AFR, BSFC, HC, Smoke with LIVC Phasing

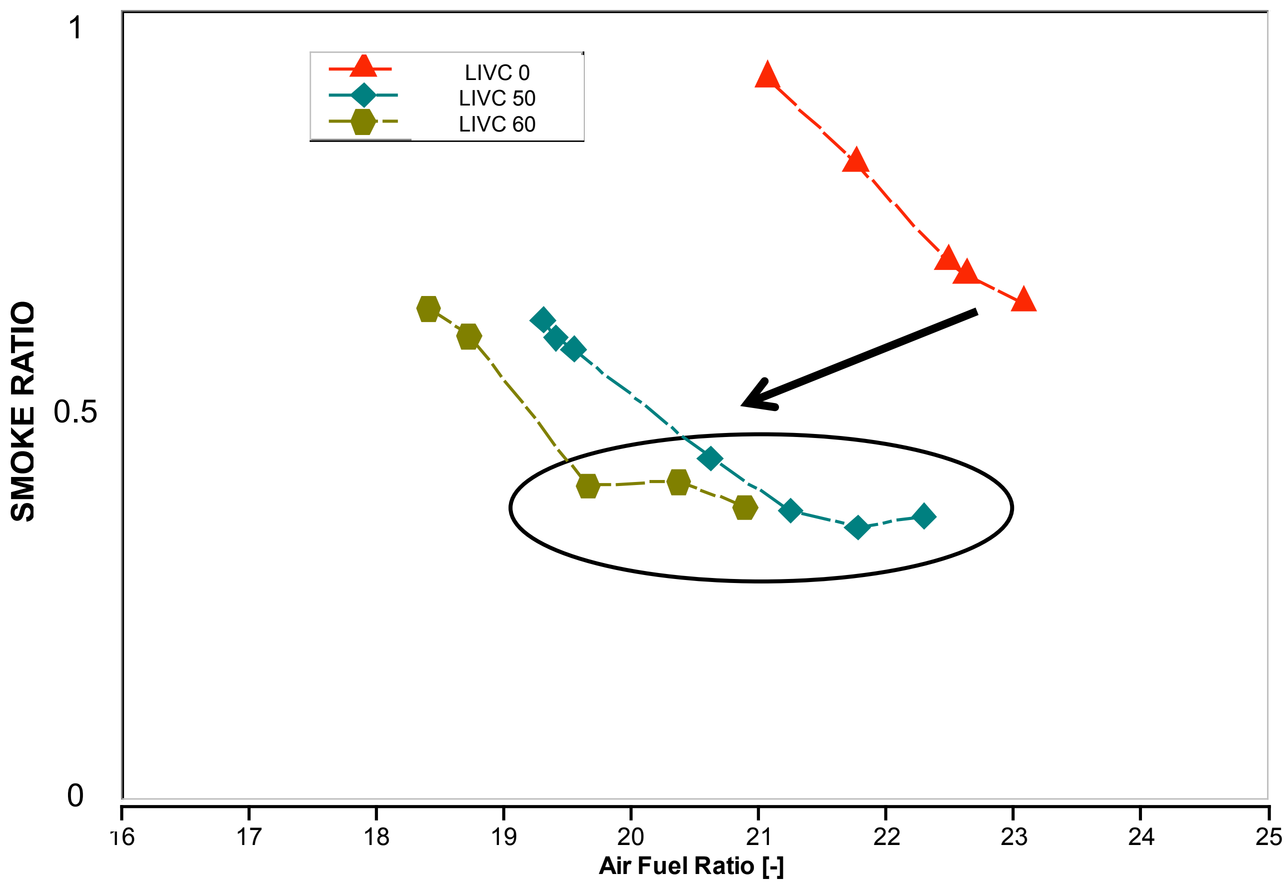
Base and LIVC 50 ca degreees
1200 rpm/3.9 bar BMEP
Normal combustion
Coolant @ 88C, Bypass OFF
Ca50 9 atdc fix
Fix 72% VNT position
30-42% EGR sweep



Consistent trends are observed at different keypoints

Smoke vs AFR at Low NOx with LIVC Phasing for PCCI Combustion Modes

1600 rpm/4.8 bar BMEP
Coolant @ 88C, Bypass OFF
Two stage HP TC. Ca50 12 atdc fix
Fix 50% VNT position
High % EGR sweep
NOx << 1 g/kg fuel



Early PCCI encounters either high smoke or high noise if using a conventional valve lift profile.

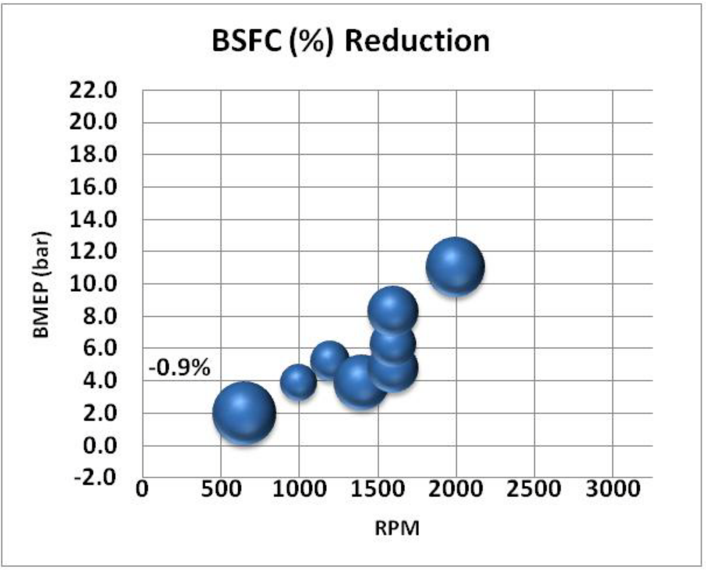
For LIVC, a single injection strategy could achieve good overall engine performance.

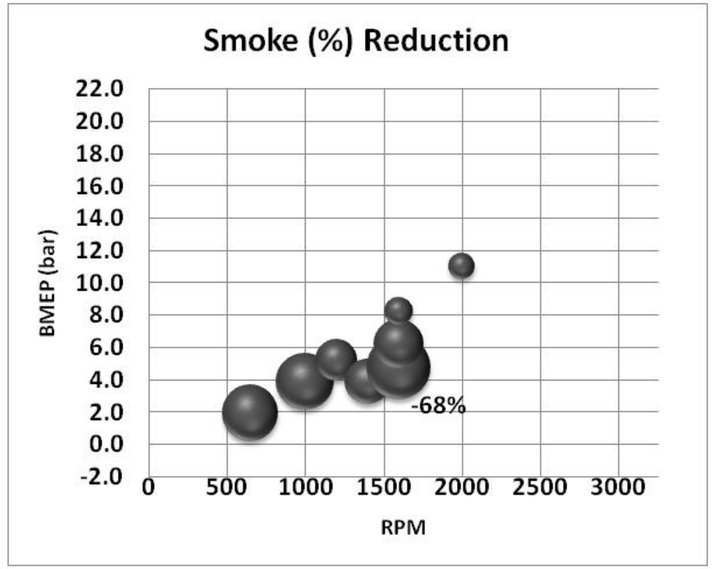
By using LIVC, the combustion phasing can be advanced for better fuel economy.

The AFR can be reduced because smoke emissions are lower due to longer ignition delay.

The combustion noise is controlled within the noise limits by adjusting the injection timing.

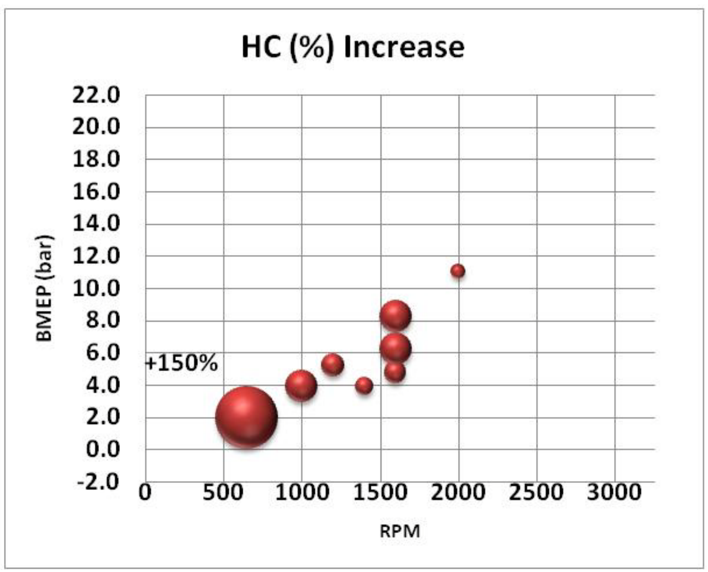
LIVC 50 ca delay - Overall Effects

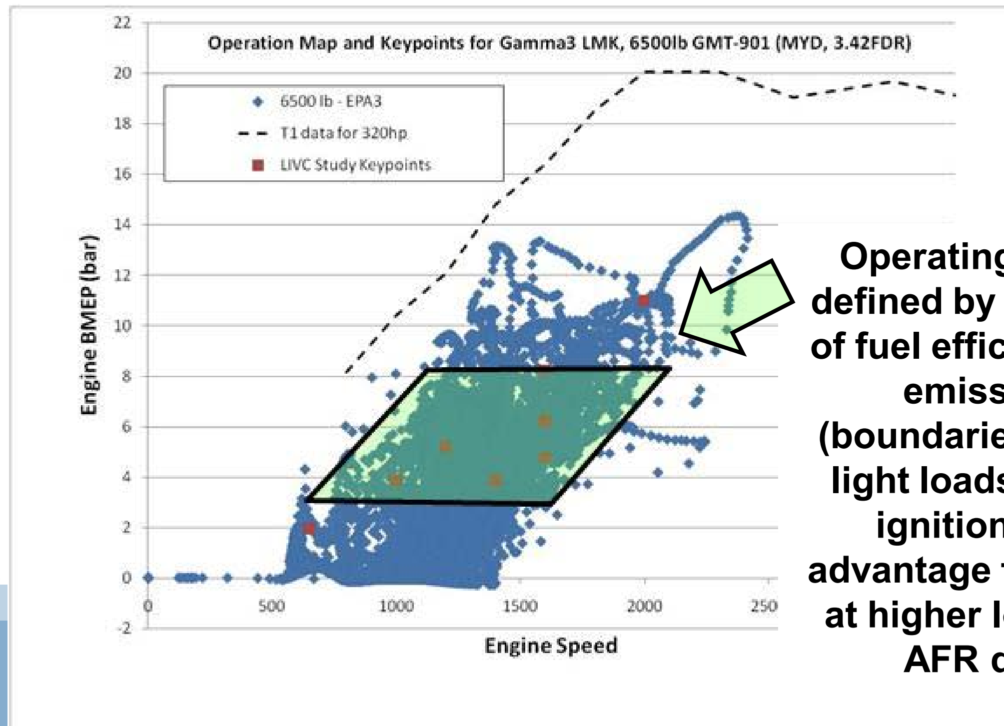




Impact FTP Cycle

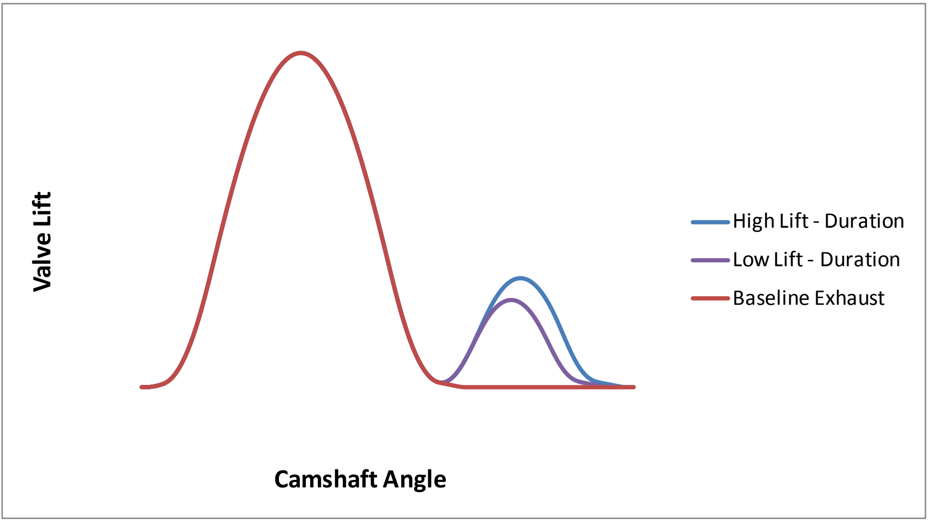
- BSFC ~ -0.5%
- PM ~ -25%, > 50% at keypoints
- HC > +17%

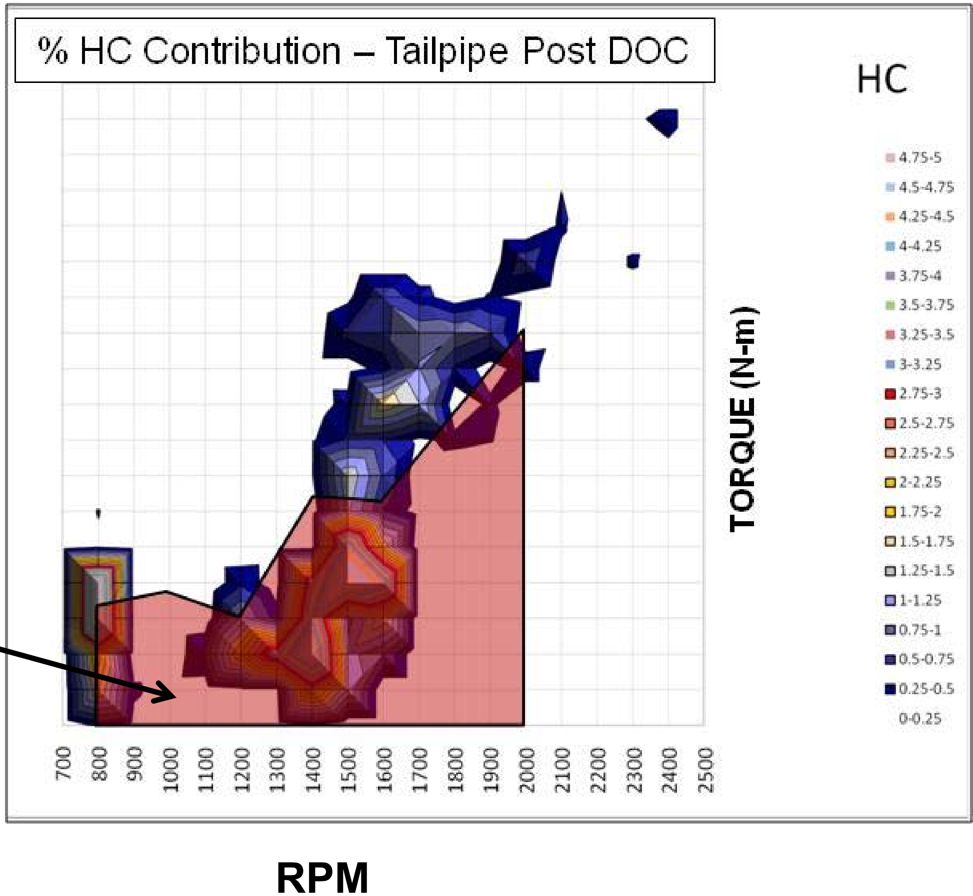




Operating region defined by trade-offs of fuel efficiency and emissions (boundaries: HCs at light loads; loss of ignition delay advantage for mixing at higher loads and AFR drop)

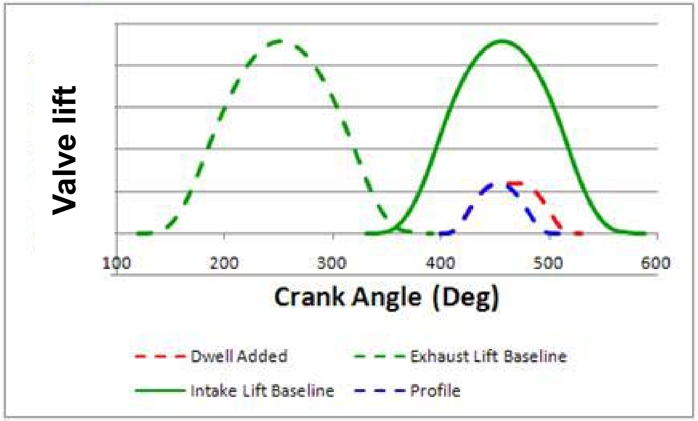
Internal EGR
Exhaust rebreathing events





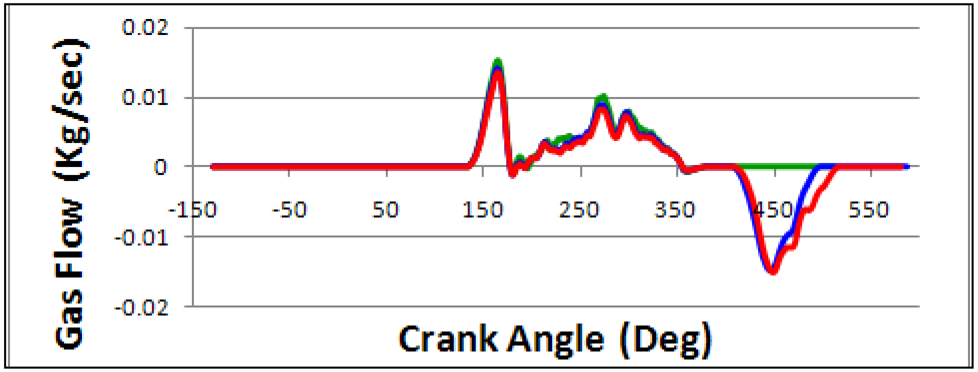
- **Keypoints operating area selected by HC contribution to cold start FTP cycle**
- **High/Low Lift and duration profiles**
- **Valvetrain exhaust implementations opposite to intake helical and tangential ports**

Internal EGR approach

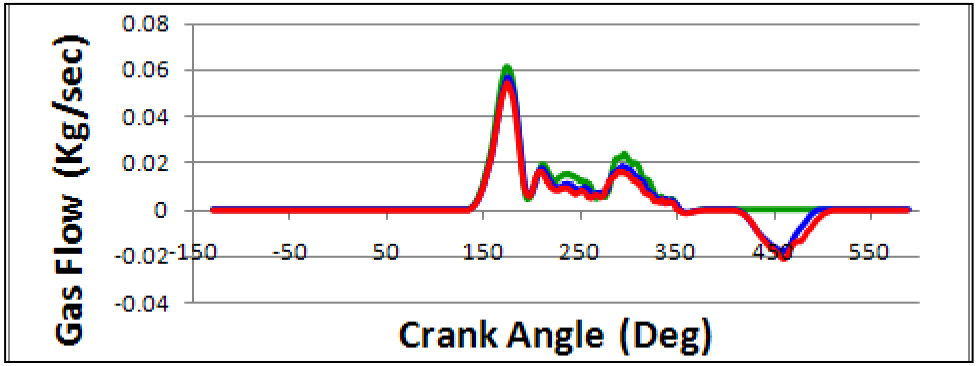


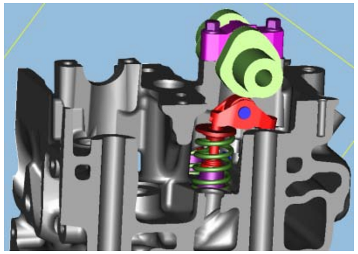
- Representative IEGR profiles
- Modeling of HC and NOx contributing keypoints

Exhaust Valve Flows
650 rpm/2.2 bar



Exhaust Valve Flows
1600 rpm/6.8 bar

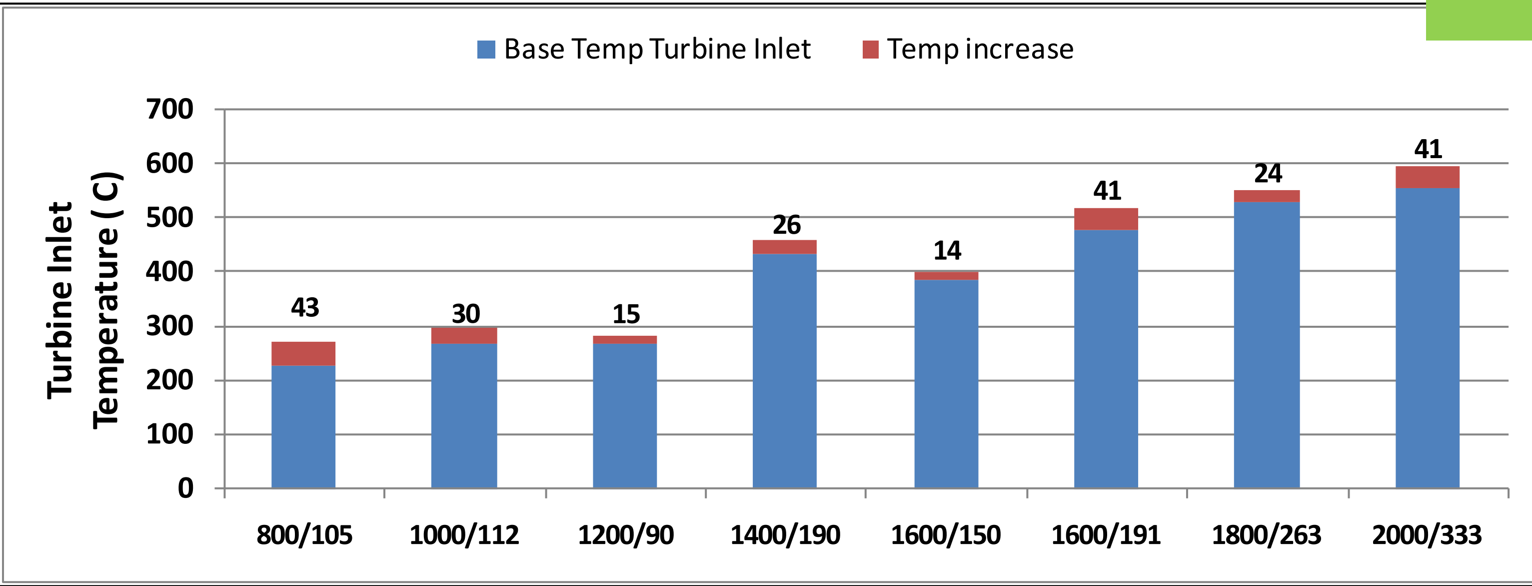


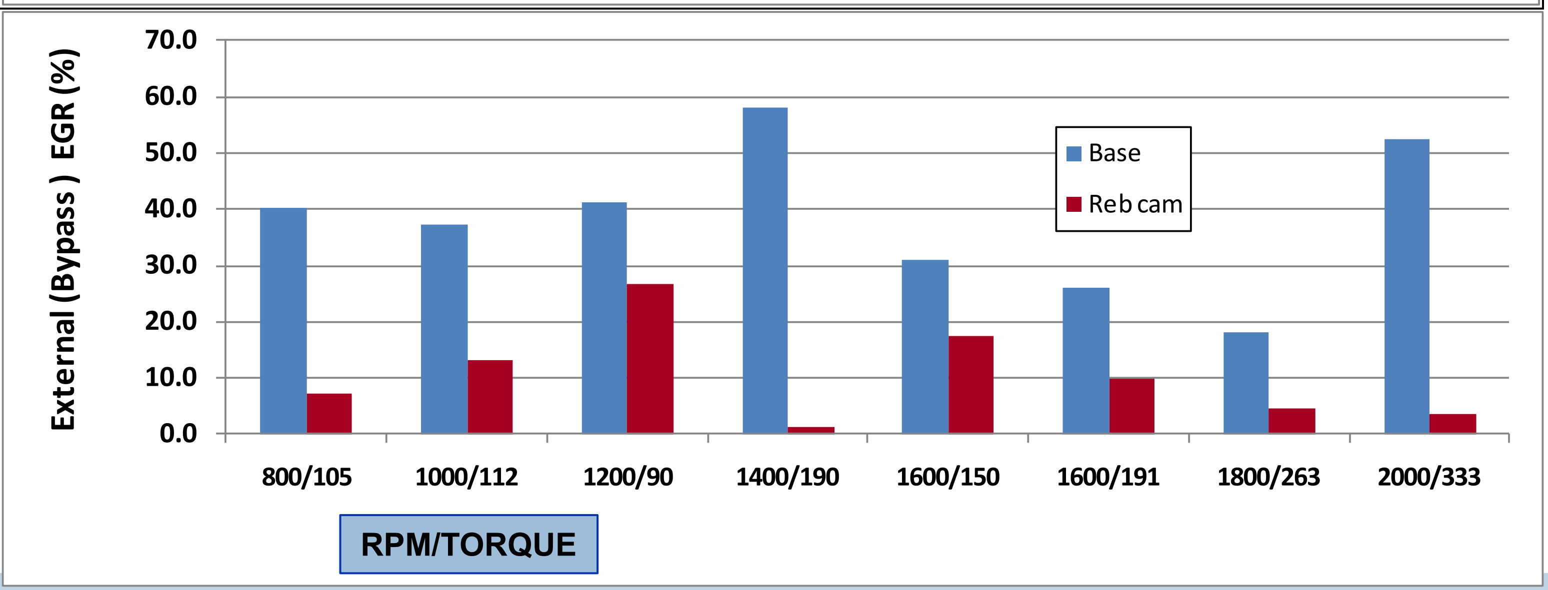


Fixed cams for switching profiles options

Internal EGR relative to Baseline

Fix RPM/BMEP keypoints
In 200 sec warm-up phase
Coolant @ 40C, Bypass ON
NOx ≤ target

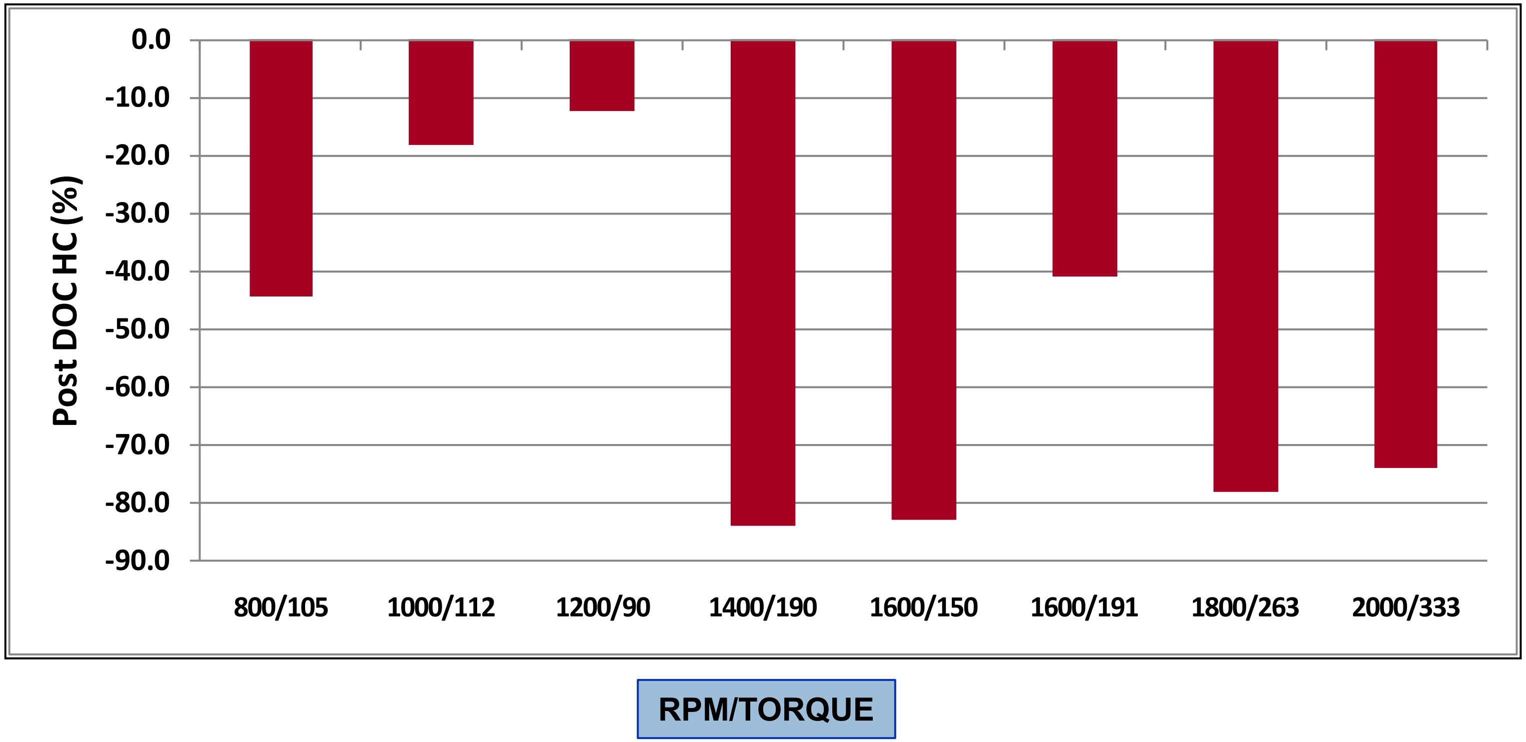




- **Turbine In temperature can be increased along all the operating range**
- **Can induce light-off for the DOC catalyst**
- **Varies with heat transfer, AFR by substitution of External (Bypass) EGR (%)**
- **Internal EGR amount by model based approach**

Internal EGR relative to Baseline

Fix RPM/BMEP keypoints
In 200 sec warm-up phase
Coolant @ 40C, Bypass ON
NOx ≤ target



- DOC inlet and Post DOC temperature can be further increased by HC/CO additional conversion (also changes in turbine operating point efficiency)
- Post DOC performance, (as HC % of reduction) is favored by less engine out emissions plus faster light-off and higher conversion by higher operating temperature

Impact of IEGR

Fix RPM/BMEP keypoints
In 200 sec warm-up phase
Coolant @ 40C, Bypass ON
NOx ≤ target

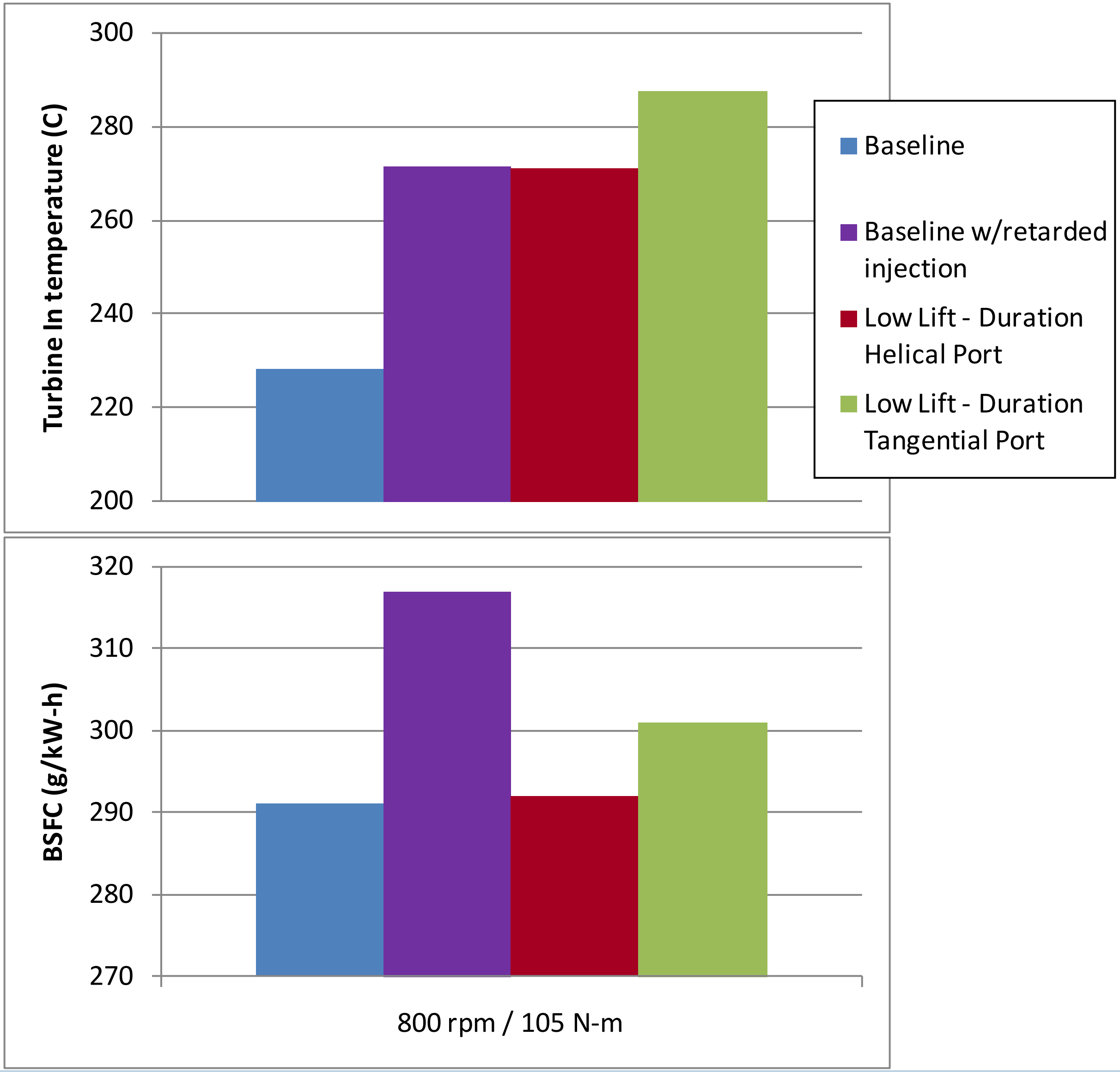
Whole FTP Cycle

- **Fuel consumption ~ +0.3%**
- **Tailpipe Hydrocarbons ~ -20% (-50% first 200 sec of FTP cycle)**

- **First 200 sec in the warmup phase FTP Cycle – Estimate by weighting factors**
  - Test vehicle weight 7000 lbs. Exhaust Gas temperature Management at low coolant temperature >20 % of the fuel consumed in FTP cycle
  - Smoke impact constrains for maximum applied engine bmeps

Comparing exhaust heating strategies

Fix RPM/BMEP keypoints
In 200 sec warm-up phase
Coolant @ 40C, Bypass ON
NOx ≤ target

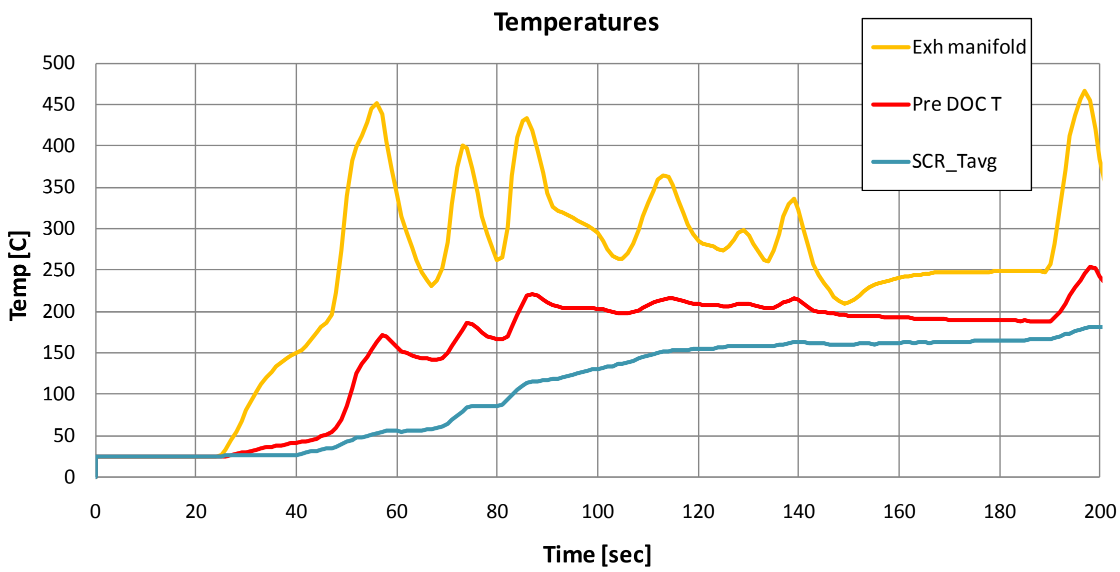


- **For matching exhaust temperature, IEGR by exhaust rebreathing shows promising results for a competitive strategy to retarded timing at idle**

- **Sources of sensitivity to port location to be subject of detailed investigation**

IEGR Strategy / Aftertreatment modeling

Vehicle TVW 7000 lbs



- **Phase 1 with highest contribution to HC and NOx overall tail-pipe emission for FTP**
- **Increasing exhaust temperature by 40 degrees**
  - Overall emission for FTP can be reduced by 25% (HC) and 17%(NOx)
    - Total HC reduction Engine-out plus higher conversion 35%

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

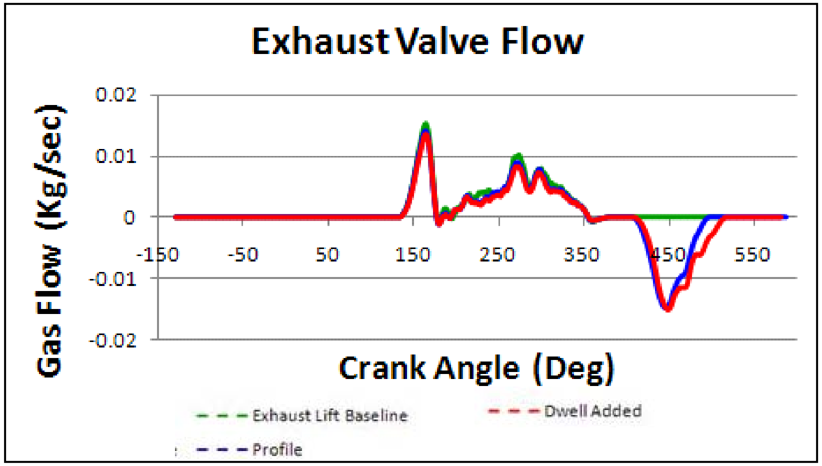
The application of switching roller finger followers on the exhaust valvetrain of multi-cylinder diesel engines for selectively producing the re-opening of exhaust valves for internal EGR control

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

Ways to apply the system:

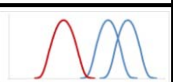
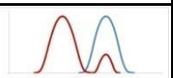
- Single Exhaust valve per cylinder - allows one discrete rebreathing profile to be used, switchable
- Both exhaust valves per cylinder - single actuator, allows a higher amount of EGR to be introduced based on a single actuator
- Both exhaust valves per cylinder - dual actuator circuit, allow combinations 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)

1-D Simulation
Idle
Internal EGR replacing external EGR



Summary

- **Late Intake Valve Closing for Changing Effective Compression Ratio and Exhaust Rebreathing for Internal EGR have been investigated with promising results**
- **Operating envelope**
  - LIVC operation at part loads for emissions and FE of hot FTP cycle, constrained by charging system capability
  - IEGR operation from idle to part loads for warm-up and emissions of cold FTP cycle. Max BMEP determined by smoke limitations

VVA		Major impacts		Benefits / Limitations					
Strategies Intake Exhaust	Profiles	FTP75 cycle fuel cons.	FTP75 cycle emissions.	NOx	PM	HC	CO	Comb noise	Exhaust temp
LIVC		1% * reduction	50% PM reduction	+	++	-	-	+	O
Internal EGR		0.3-0.5% increase **	~20% HC reduction	O	-	+	+	O	+

Higher FE potentialimprovement for LIVC including the benefit for increased DPF regen interval

*: Depending on charging capability
**: Compensation by warm-up strategy and aftertreatment impact

Key:
+ improved
o neutral
- worse

Summary

- Variabe valvetrain techniques have significant impacts on fuel efficiency and emissions with packaging and control challenges for implementation with different alternative valvetrain mechanisms in new engine designs
- Late intake valve closing and exhaust rebreathing provide further optimization opportunities for fuel efficiency and emissions
- Experimental impacts and estimations for the assessment of application are highly dependent on engine architecture and engine performance and emissions targets