Lean Gasoline System Development for Fuel Efficient Small Car DE-EE0003379

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GM Powertrain, Advanced Integration & Emissions

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Project ID: ACE063

OVERVIEW - LEAN GASOLINE SYSTEM DEVELOPMENT

Timeline

- Project start: May 2010
- Project end: May 2013
- Project duration: 3 yrs
- Percent complete: 24%

Budget

- Total project funding: $15,411,724
  - DOE share: $7,705,862
  - GM share: $7,705,862

Partners

- None

Barriers

- Lean gasoline combustion provides substantial fuel economy improvement with detrimental increase in NOx emissions
- Current NOx after-treatment systems have functional implementation limitations (i.e. performance, cost, packaging, etc.)
- Significant fuel economy improvement requires integration of multiple technologies including lean combustion
- Lean after-treatment performance under all lean operating conditions

OBJECTIVES - LEAN GASOLINE SYSTEM DEVELOPMENT

Program Completion (May 2013)

- Demonstrate 25% fuel economy improvement over 2010 Chevrolet Malibu with 2.4L NA PFI while achieving T2B2 emissions capability

FY11 / 1st Milestone (Dec 2010)

- Lean combustion engine and novel after-treatment designed, procured, built and installed along with 12v Stop/Start system ready for integration

Relevance to VT ARRA

- Potential to significantly reduce vehicle fuel use through commercialization of lean gas systems
- Support expanded technical expertise and the saving of existing technical jobs

Develop

- Optimized lean combustion system with reduced engine-out emissions
- Novel cost-competitive lean after-treatment system
- Engine and after-treatment thermal management solutions to support lean combustion
- Torque based engine controls architecture to support lean combustion
- Robust after-treatment controls to support lean combustion
- System level integration knowledge to optimize fuel economy

Transfer

- Commercially viable solutions to GM passenger vehicle production teams

APPROACH - LEAN GASOLINE SYSTEM DEVELOPMENT

Development Process

- Fundamental combustion analysis and experimental investigation
- Lean after-treatment hardware specification and control strategy development
- Engine and after-treatment hardware design, procurement, assembly
- Dynamometer lean combustion strategy system integration
- Engine and after-treatment controls development and implementation
- Dynamometer and vehicle calibration and optimization

Development Resources

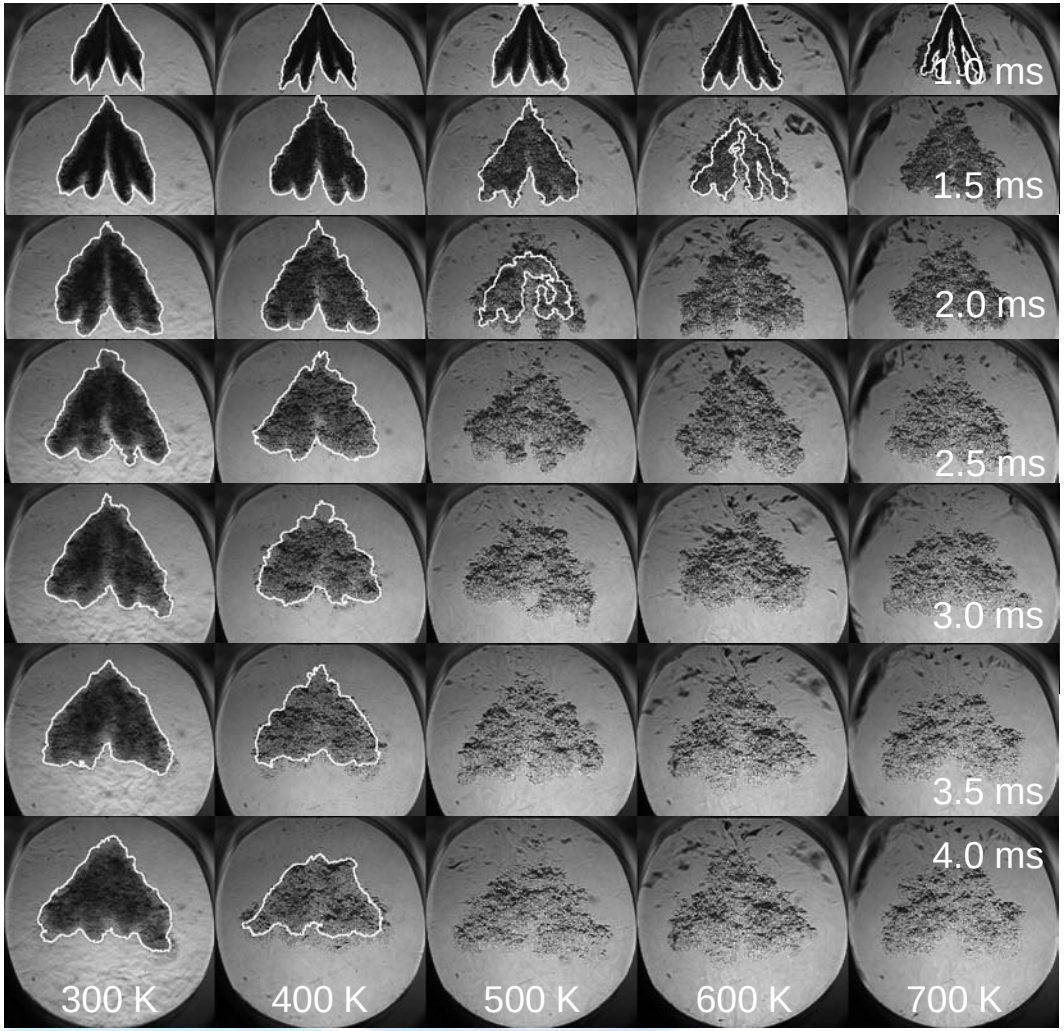
- 30 researchers, engineers, technicians
- 10 spray guided lean engines
- 6 R&D and AdvEng dynamometers
- 4 Chevrolet Malibu Vehicles

Vehicle Assessment

- Fuel Economy
- Emissions
- Drivability
- Cost Competitiveness

LEAN COMBUSTION FUEL SPRAY FUNDAMENTAL INVESTIGATIONS

Liquid and Vapor Envelopes
(Pfuel = 20 MPa, Pchamber = 5 bar)



- Acquire Schlieren images to obtain liquid and vapor envelopes
- Acquire MIE images (white contours) to obtain liquid only envelope
- Overlay MIE image over Schlieren image to obtain vapor only envelope

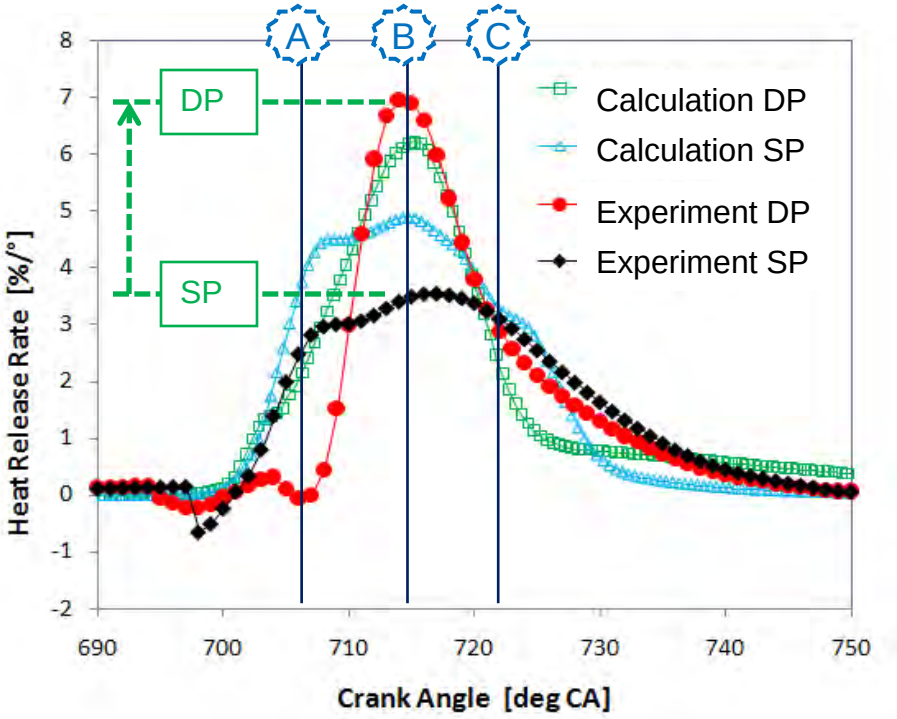
➔ **Obtain a detailed understanding of vaporization process for different spray configurations and engine operating conditions**

➔ **Supply fundamental data for CFD model validation**

LEAN COMBUSTION ANALYTICAL & EXPERIMENTAL OPTIMIZATION

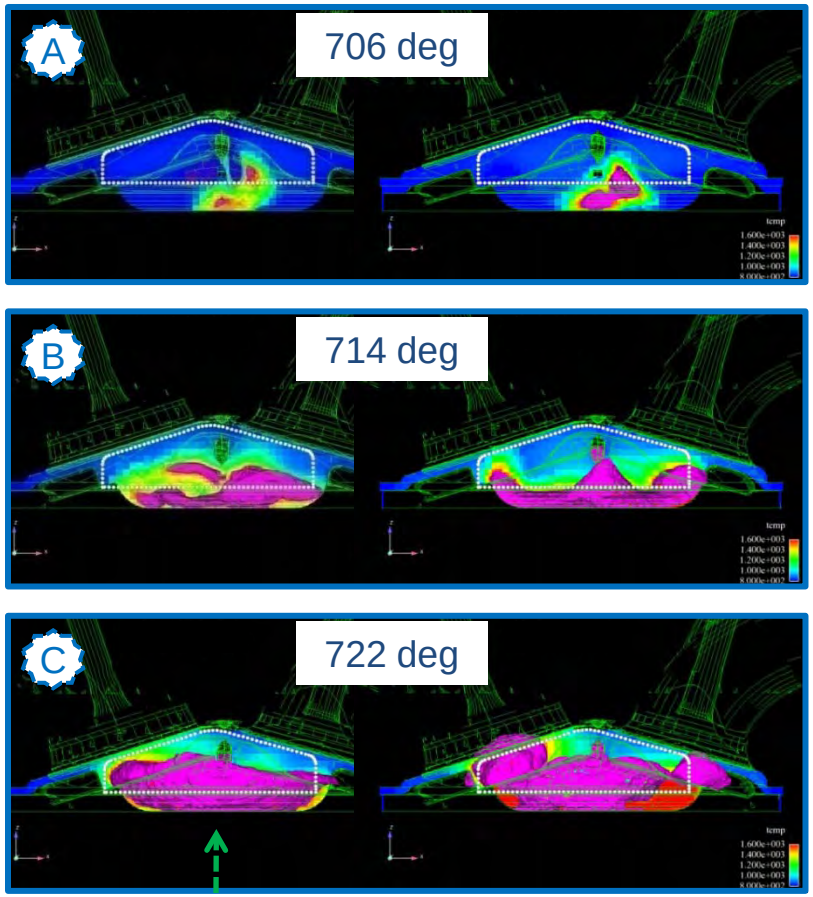
- CFD Analysis extensively utilized to optimize combustion system control parameters
  - Single & Double Pulsing at 800 rpm, 84 kPa NMEP

Heat Release Rates



1500 K Temperature Iso-surface

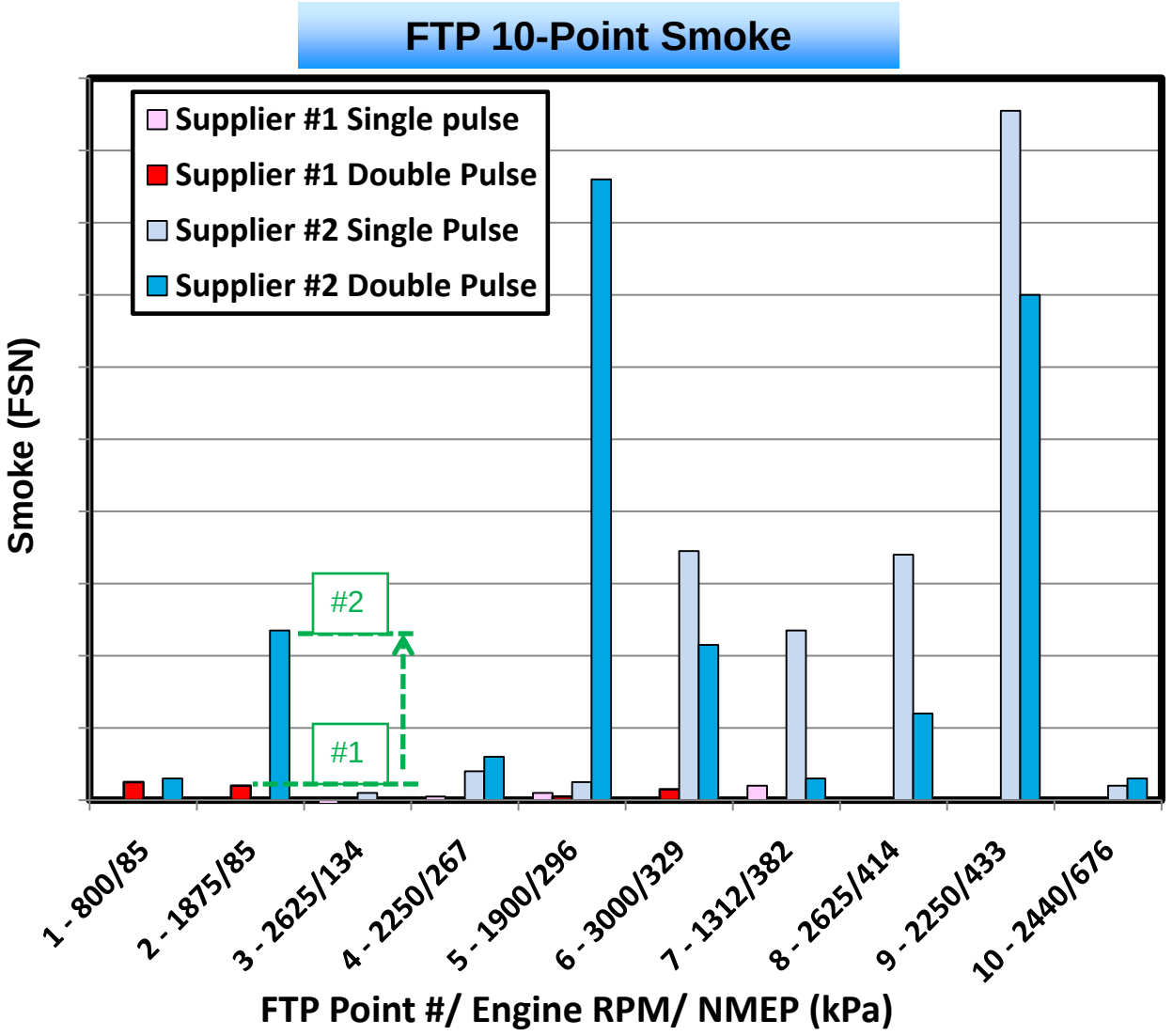
Double Pulsing | Single Pulsing



➔ **Peak Heat release rate is a factor of two higher with double pulsing**

➔ **Fuel-air mixture is contained more within the bowl with double pulsing**

LEAN COMBUSTION FUEL SYSTEM OPTIMIZATION



- Injectors from two suppliers were tested
- For Supplier #1, smoke was very low across the stratified charge load range
- For Supplier #2, smoke was significantly higher
- For Supplier #2,double pulsing reduced smoke at heavy loads, but increased smoke at light loads

➔ **Two equivalently specified injectors do not necessarily perform the same**

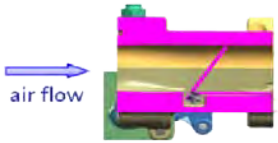
➔ **Fuel spray characteristics need to be matched to the combustion system**

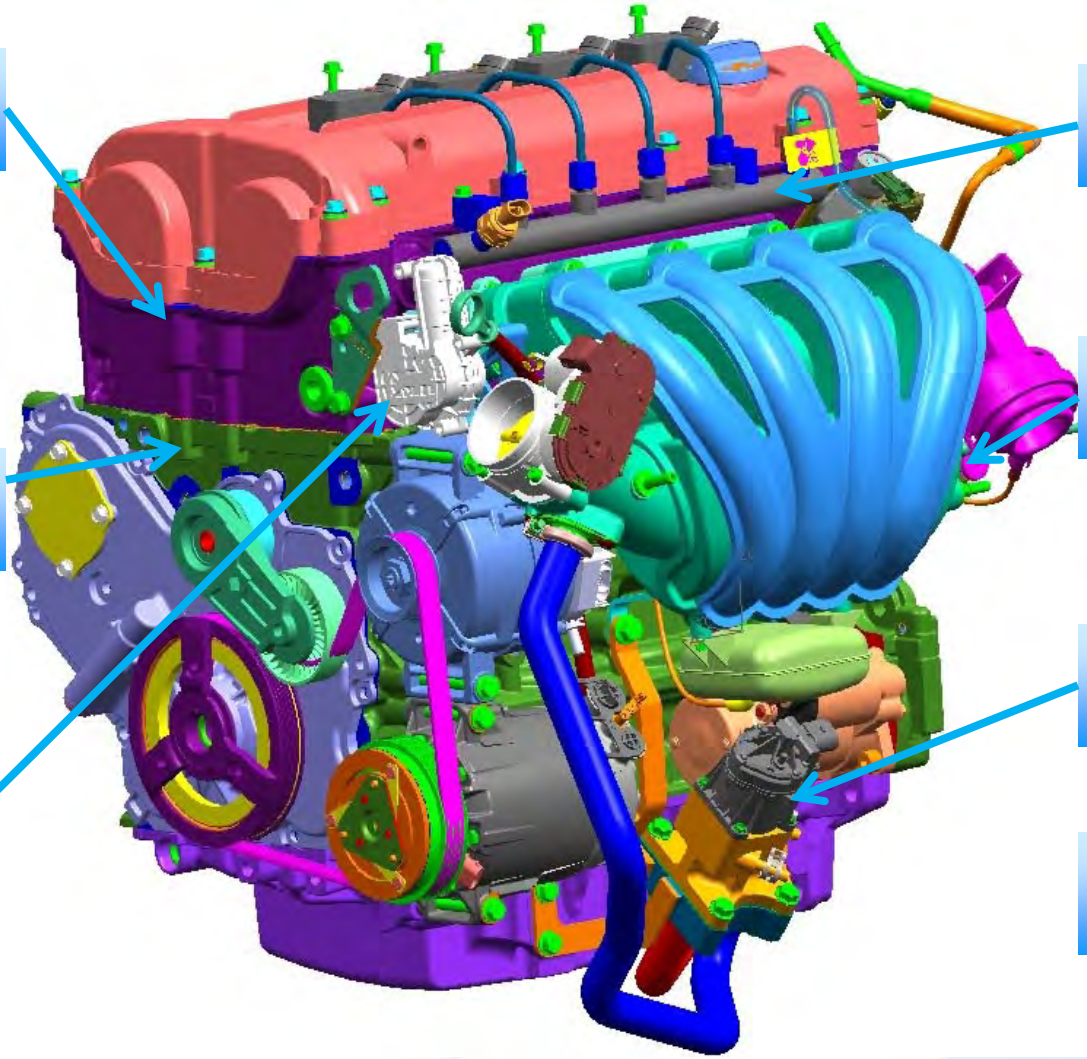
LEAN GASOLINE COMBUSTION ENGINE SYSTEM

Central Injection Cylinder Head

Lean Combustion Piston

Intake Port Deactivation





HP Fuel System

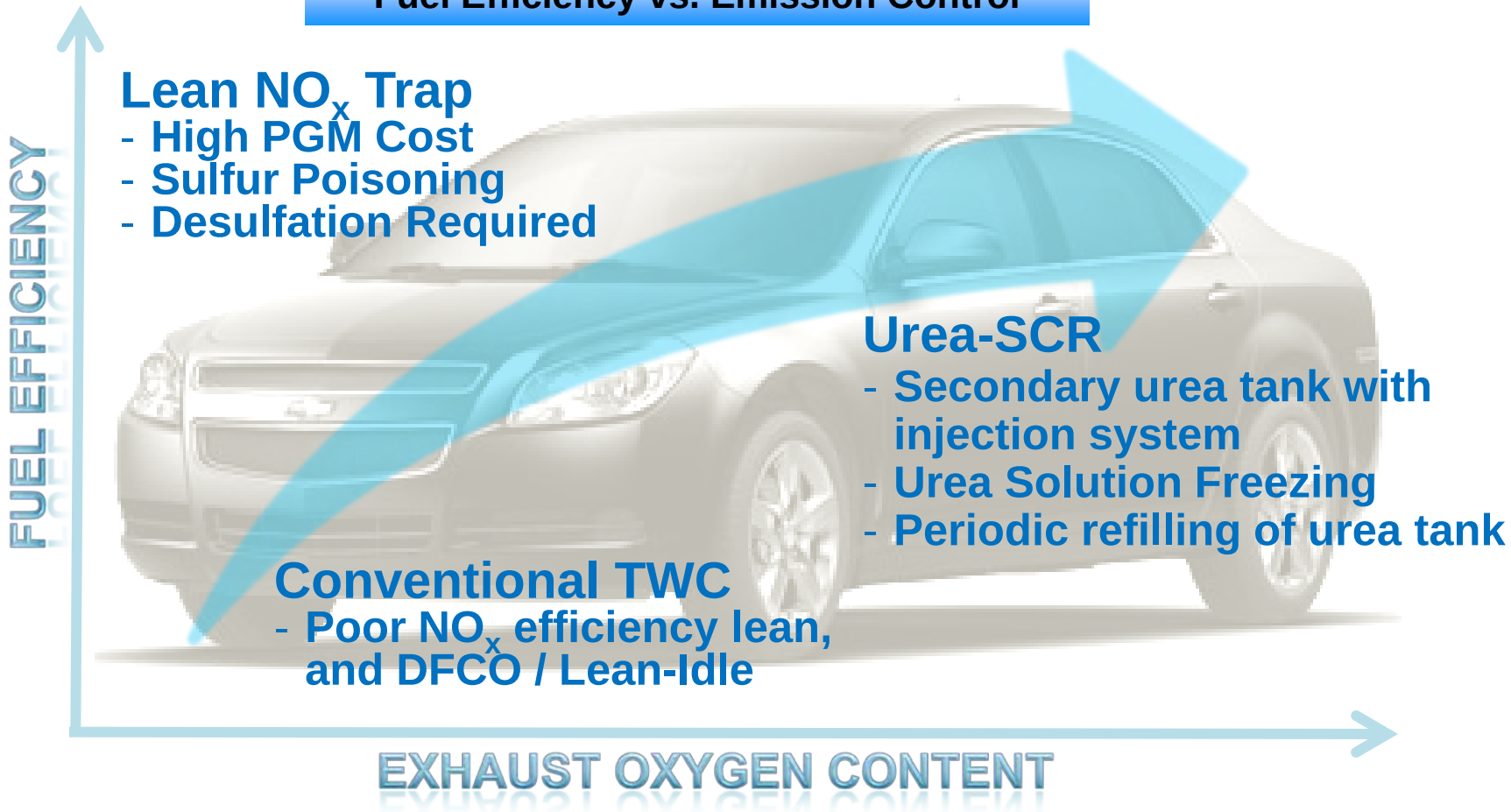
Variable Intake Manifold

High flow EGR

12v Stop/Start Starter

NOVEL LEAN AFTER-TREATMENT MOTIVATION

Fuel Efficiency vs. Emission Control

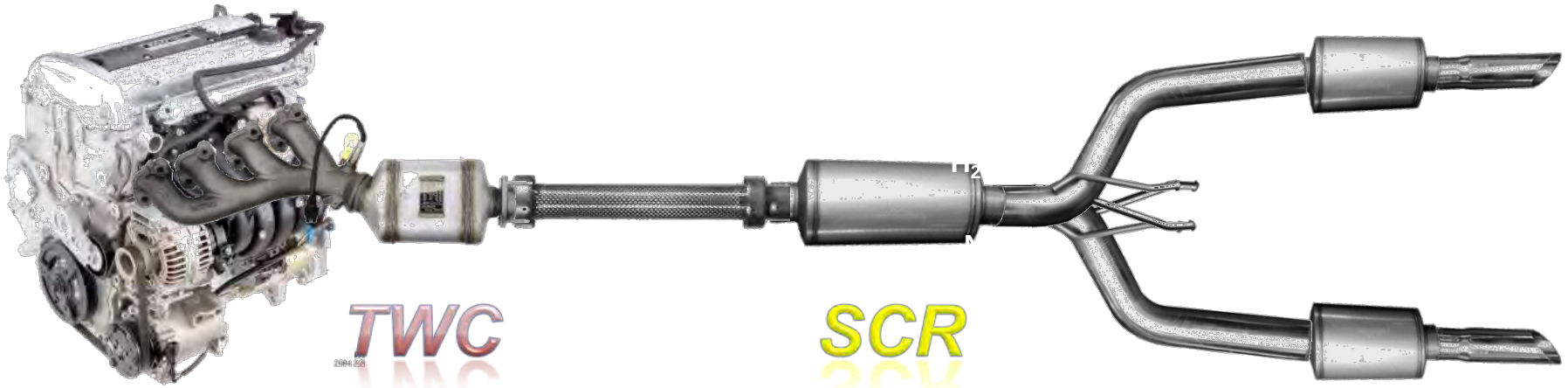


➔ **Current systems have functional implementation limitations (i.e. performance, cost, packaging, etc.)**

NOVEL LEAN AFTER-TREATMENT SYSTEM

Passive Ammonia SCR System (PASS)

*A Urea-Free SCR System



DURING RICH:

$$NO_X + H_2/CO \Leftrightarrow NH_3 + CO_2$$

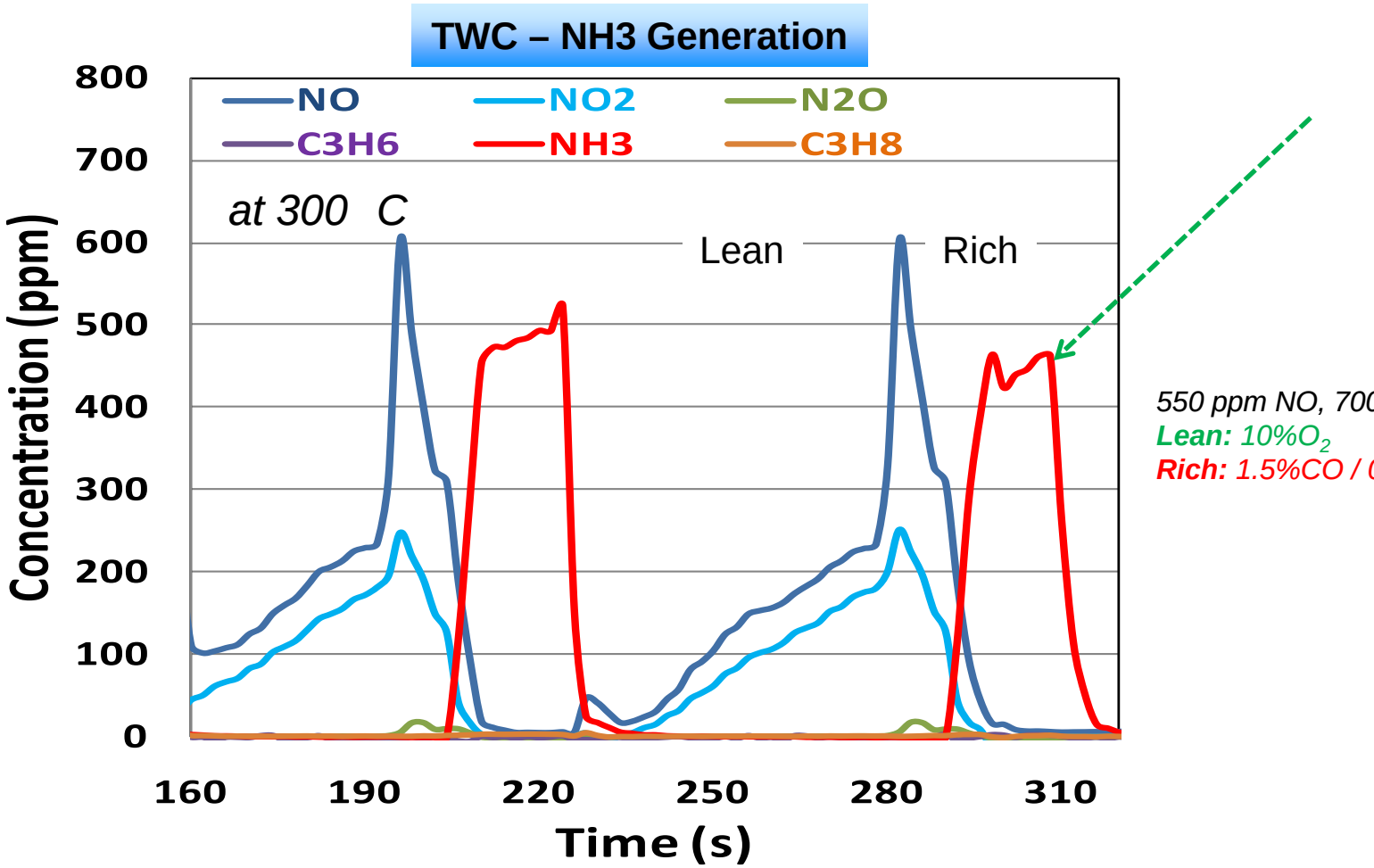
➔ Uses H2 and CO to generate NH3 over TWC and store NH3 in multiple SCRs

DURING LEAN:

$$NO_X + NH_3 \Leftrightarrow N_2 + H_2O$$

➔ Uses the stored NH3 for lean NOx conversion

LEAN AFTER-TREATMENT TWC REACTOR INVESTIGATIONS

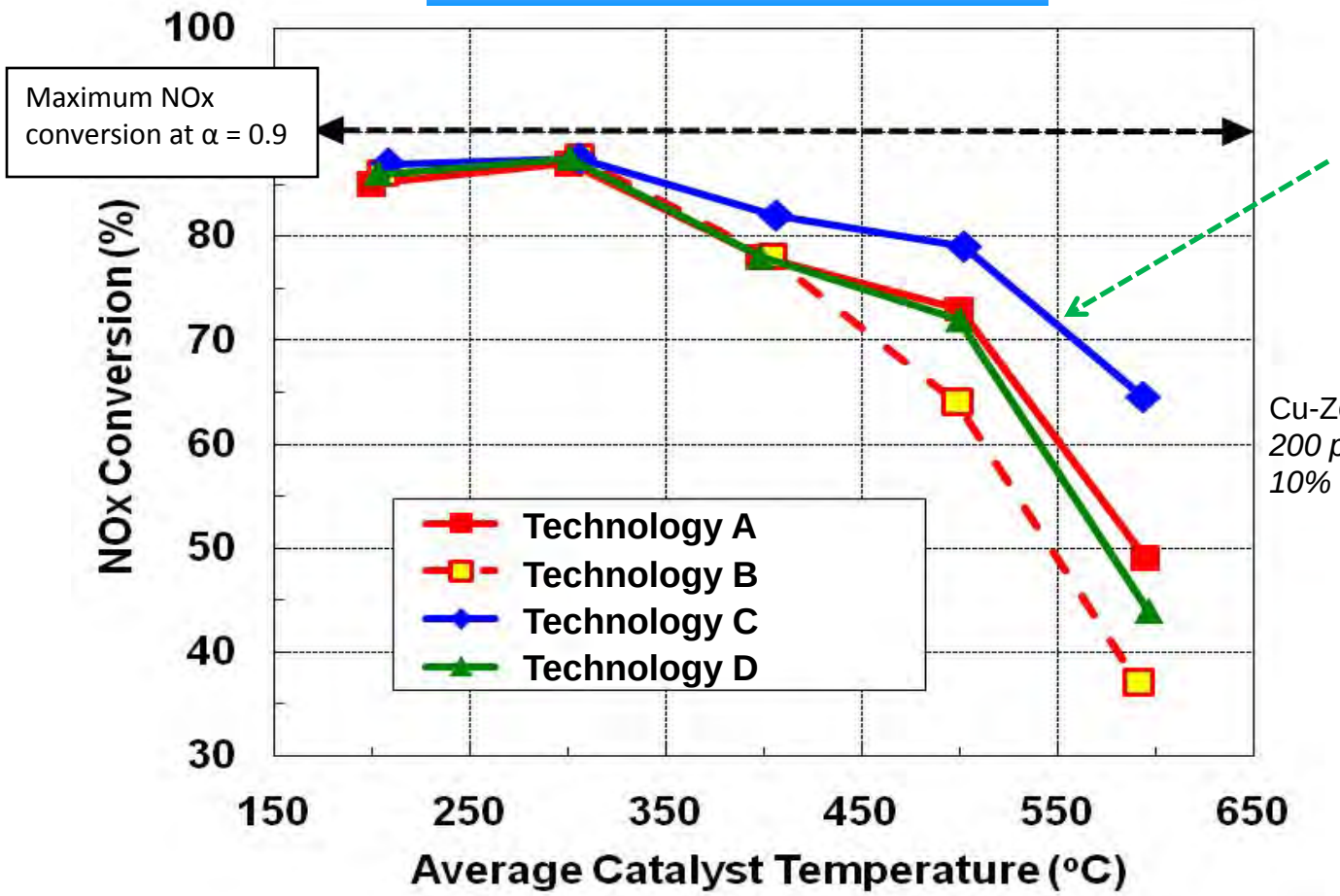


550 ppm NO, 700 ppm HC
Lean: *10%O_2*
Rich: *1.5%CO / 0.5%H_2 / 0.5%O_2*

➔ **Experimental TWC investigations by lab reactors provided efficient screening of PGM formulations prior to dynamometer evaluation**

LEAN AFTER-TREATMENT SCR REACTOR INVESTIGATIONS

SCR Technology Comparison

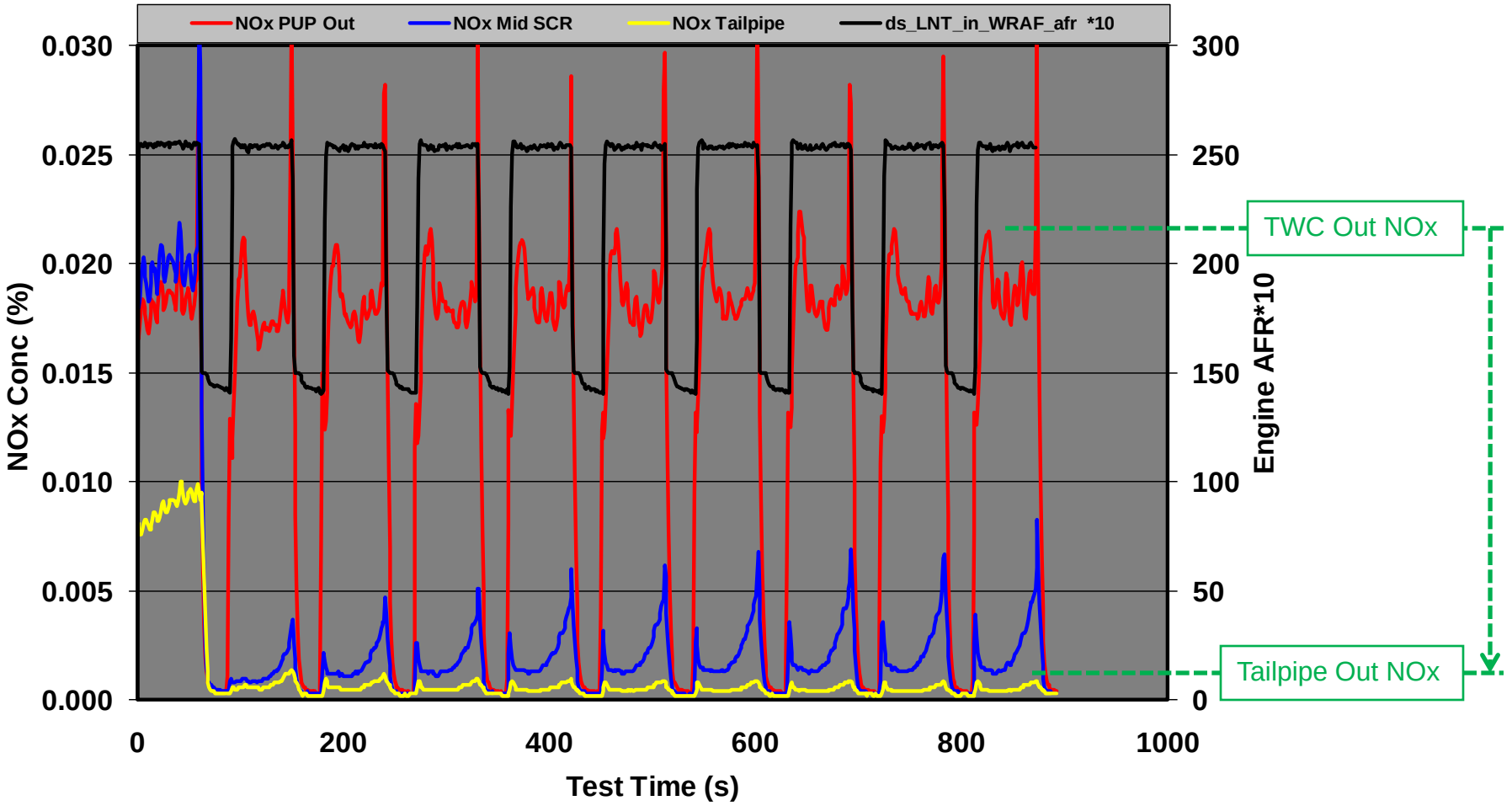


Cu-Zeolite (HTA, 72h) / 30,000 h^{-1}
200 ppm NO / 180 ppm NH_3
10% O_2 / 5% H_2O / 8% CO_2

➔ **Lab reactor system utilized to efficiently evaluate SCR washcoat for NOx efficiency, durability and NH3 storage**

LEAN AFTER-TREATMENT PASS SYSTEM EVALUATION

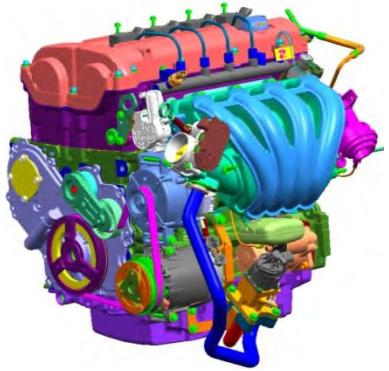
Dynamometer Steady-State Result (2000 RPM, 2.0bar, lean → rich)



➔ **TWC generates sufficient NH3 to reduce engine out NOx during lean operation**

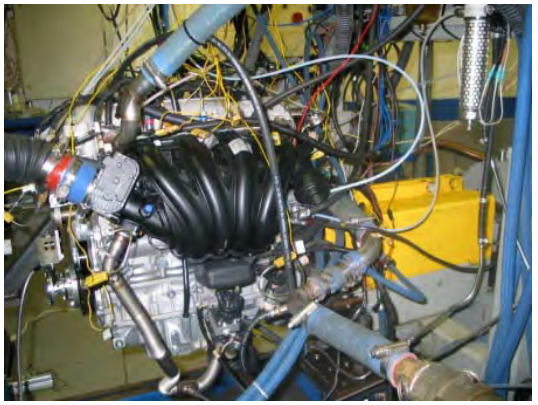
LEAN ENGINE & AFTER-TREATMENT HARDWARE

Lean Combustion Engine
Designed, Procured, Assembled & Verified



Novel After-treatment System
Specified, Procured & Fabricated

Dynamometer Development
and Vehicle Installation



- ➔ **Lean engine & novel after-treatment system designed, procured, assembled**
- ➔ **Engine & after-treatment systems installed on 4 dynamometers and in 3 vehicles**

PROGRESS TO FY11 1ST MILESTONE TECHNICAL TARGETS

Timeline	Evaluation Milestone	Status
May 2010	**Program Kick-off**	Complete
Lean combustion fundamental analysis and experimental investigation		√
Novel after-treatment experimental investigation & strategy development		√
Lean engine hardware design, procurement, assembly, build verification		√
Novel after-treatment Gen 1 hardware specification, procurement, fabrication		√
12v Stop/Start system ready for integration		√
Design and analysis for active thermal management systems		√
Vehicle installations of lean engine and novel after-treatment		√
Dec 2010	**SG Engine Installed and 12v Stop/Start Ready**	Complete

REMAINING FY11 AND FUTURE WORK TO MILESTONES

Timeline	Evaluation Milestone	Status
Lean engine torque based controls with high flow EGR		ongoing
Novel after-treatment automatic NH3 generation controls		ongoing
Lean engine & A/T thermal management solutions - support lean combustion		ongoing
Lean engine calibration – combustion stability, fuel economy, emissions		ongoing
June 2011	**Hwy FE > 13% and NOx Eff. > 60% on H18**	**On-target**
Lean combustion system strategies – NH3 gen. FE penalty minimization		ongoing
Novel After-treatment Gen 2 A/T hardware performance optimization		planning
Lean combustion and after-treatment particulate mitigation solutions		planning
Vehicle calibration – fuel economy, emissions, drivability		planning
Dec 2011	**Cold ftp & Hwy FE > 13% and Gen 2 A/T dyno results**	**Planning**
Vehicle calibration – fuel economy, emissions, drivability refinement		planned

- Risk Mitigation development pathways
  - Boosted lean stratified single cylinder development to explore FE improvement potential

SUMMARY - LEAN GASOLINE SYSTEM DEVELOPMENT

- Lean combustion engines have been designed and are being developed
  - Optimized bsfc over the widest operating range
  - Confirmed combustion system on single cylinder and multi-cylinder engines
  - Meets production combustion stability targets, and lean engine out NOx targets
  - Engine designed with production feasible and cost-effective hardware

- Novel after-treatment system has been designed and is being developed
  - Incorporates cost-effective SCR technology without active dosing system complexity
  - Modular TWC experiments guided EO emission interactions with Pd, Rh, and OSC in TWC
  - Simulation, reactor and engine development to support NH3 production optimization
  - Minimizes PGM while improving fuel economy potential

- Synergistic technologies being developed to support vehicle integration
  - 12v Stop/Start is for fuel economy and after-treatment thermal management
  - Engine thermal management critical to improving warm-up as lean combustion efficiency will cause longer warm-up