LEAN MILLER CYCLE SYSTEM DEVELOPMENT FOR LIGHT-DUTY VEHICLES

2016 U.S. DOE Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting - Arlington, VA
June 9, 2016

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General Motors

Project ID #
ACE093

GENERAL MOTORS

OVERVIEW – LEAN MILLER CYCLE SYSTEM

Timeline

Start Date: January, 2015
End Date: December, 2019
Duration: 5 years

Completion: 23%

Budget

Total funding for 5 years

• $ 8,268,881	DOE Share
• $12,403,320	GM Share
• $20,672,201	Total

FY15 DOE Funding:	$593K
FY16 Planned DOE Funding	$1,882K
Total DOE Funds Rec'd:	$856K*

**thru Jan 2016 Invoice*

Goals

35% Fuel economy over baseline vehicle

Barriers

- Advanced dilute combustion regimes for gasoline engines
- Emission control challenges for advanced combustion concepts
- Effective engine controls for advanced gasoline engines

Project Lead

General Motors

Supplier Support

- AVL – (Single Cyl. Development)
- Bosch
- NGK
- Delphi
- Eaton
- Umicore

RELEVANCE - OBJECTIVES

- Develop and demonstrate a vehicle achieving:
  - 35% fuel economy improvement over 2010 baseline
  - EPA Tier 3 emission limits (30mg/mi NMOG+NOx; 3mg/mi PM)
  - DOE Thermal Efficiency goals:

version: 1.1
date: 11Jul2013

		2010 Baselines				2020 Stretch Goals[3]		
Technology Pathway	Fuel	Peak Efficiency[1]	Efficiency[1] at 2-bar BMEP and 2000 rpm	Efficiency[1] at 2000 rpm and 20% of the peak load	2000 rpm Peak Load[2]	Peak Efficiency	Efficiency at 2-bar BMEP and 2000 rpm	Efficiency at 2000 rpm and 20% of the peak load
Hybrid Application	Gasoline	38	25	24	9.3	46	30	29
Naturally Aspirated	Gasoline	36	24	24	10.9	43	29	29
Downsized Boosted	Gasoline[4]	36	22	29	19	43	26	35
	Diesel	42	26	34	22	50	31	41

Highlighted cell represents most relevant operating point for that technology pathway.

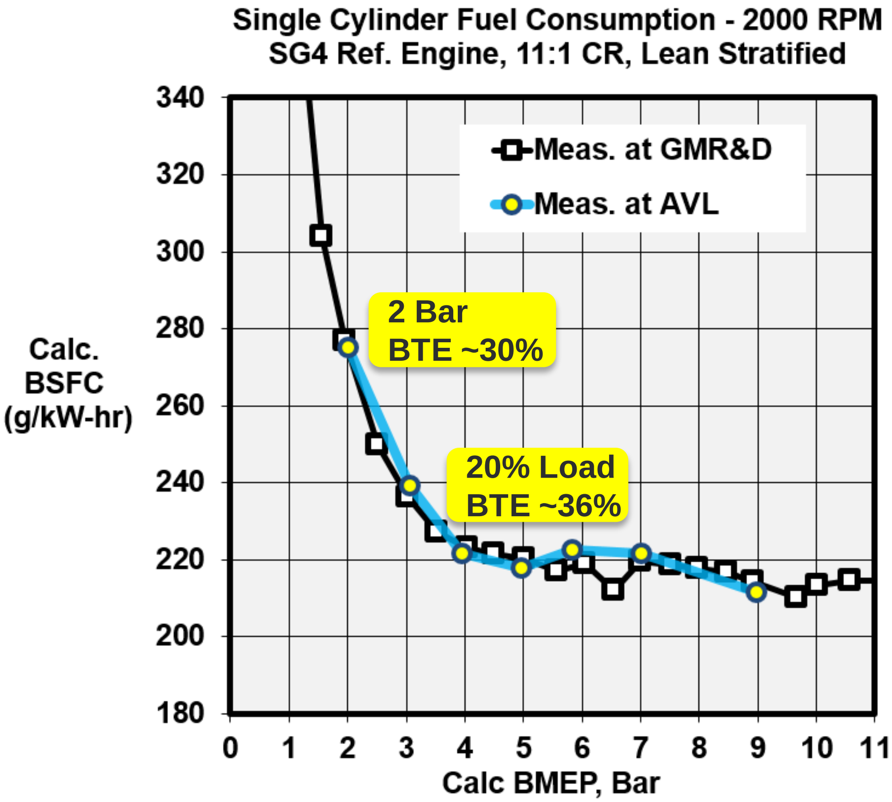
[1] Entries in percent Brake Thermal Efficiency (BTE)

[2] Entries in bar of Brake Mean Effective Pressure (BMEP)

[3] Entries in percent BTE that are equal to 1.2 times the corresponding baseline BTE

[4] Downsized Boosted baseline engine used premium grade fuel and direct injection

RELEVANCE – ADDRESSING BARRIERS



***Potential* to achieve DOE stretch goal Brake Thermal Efficiency**

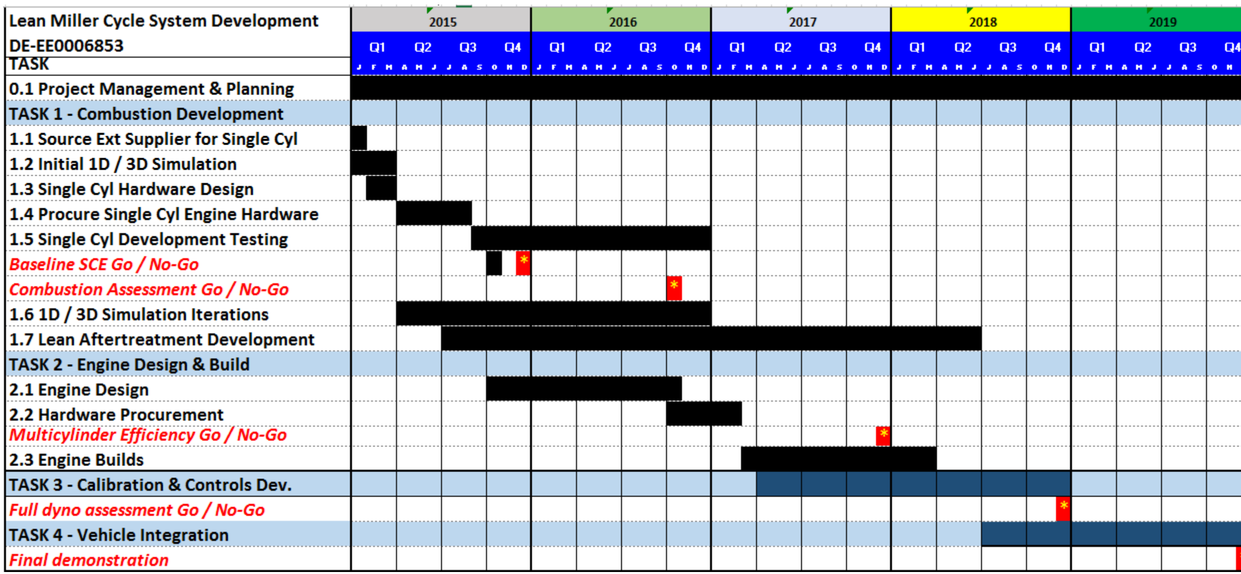
APPROACH – OVERALL MILESTONES

4 Annual Go / No-Go Decision Reviews

1. Dec. 2015 Baseline SCE Design & Testing
2. Oct. 2016 Lean Miller Combustion Assessment
3. Dec. 2017 Multicylinder Efficiency vs. Targets
4. Dec. 2018 Full Dyno Assessment – FE / Performance / Emissions

Project Completion

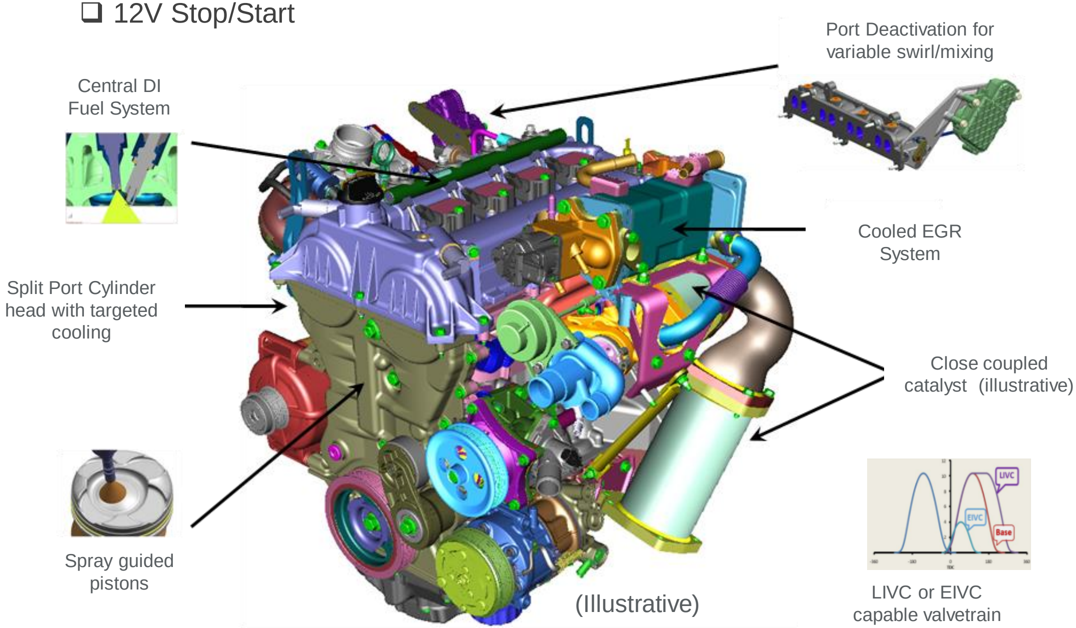
5. Dec. 2019 Final Vehicle Demonstration



APPROACH / INTEGRATED STRATEGY

Lean Miller Cycle Integration

- ❑ Lean Stratified Spray Guided with Miller cycle into one combustion system
- ❑ Optimized engine sizing and minimized friction
- ❑ Optimized high pressure fuel system, piston geometry, valvetrain, and EGR
- ❑ Passive-Active Ammonia SCR lean NOx aftertreatment system
- ❑ Advanced Thermal Management
- ❑ 12V Stop/Start



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APPROACH / STRATEGY
TARGETED EFFICIENCY IMPROVEMENTS

12V Stop/Start

4%

Advanced Thermal Management

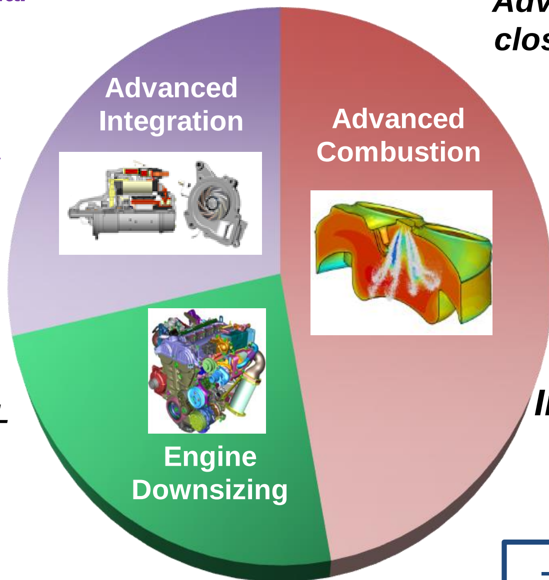
4 %

Friction / Mass Reduction

2%

Downsizing
(3.5L PFI to 2.5L DI Turbo)

8%



Boosted Lean Spray Guided Combustion

Advanced Fuel Injection with closely spaced small pulses, Cooled EGR

18%

Miller Cycle

Increased expansion ratio

-1% PAASS Lean Aftertreatment

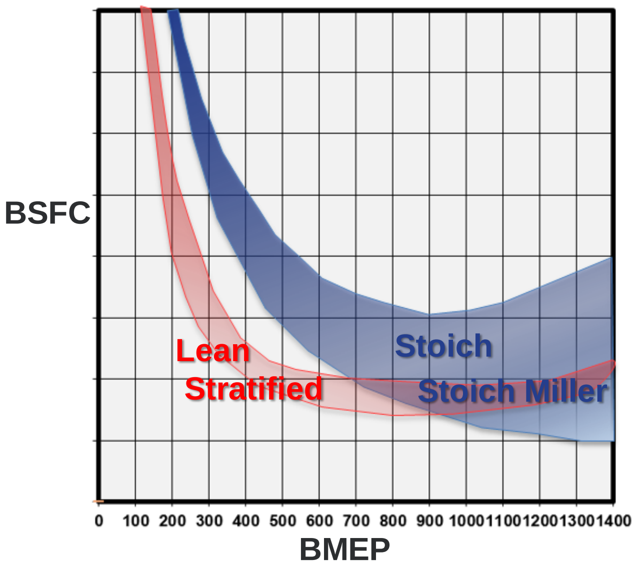
Total = 35%

APPROACH / STRATEGY

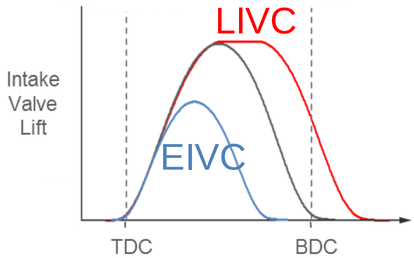
Part Load: Lean stratified
- High thermodynamic efficiency
- Aggressive EGR for reduced NOx

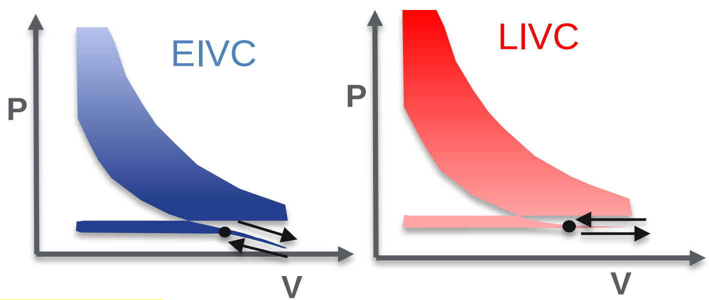
High Load: Miller Cycle
- High expansion ratio for efficiency
- Lower effective CR for knock control and reduced pumping (mainly stoichiometric mode).

Lean Combustion Potential vs. Load



Early vs. Late Intake Valve Closure



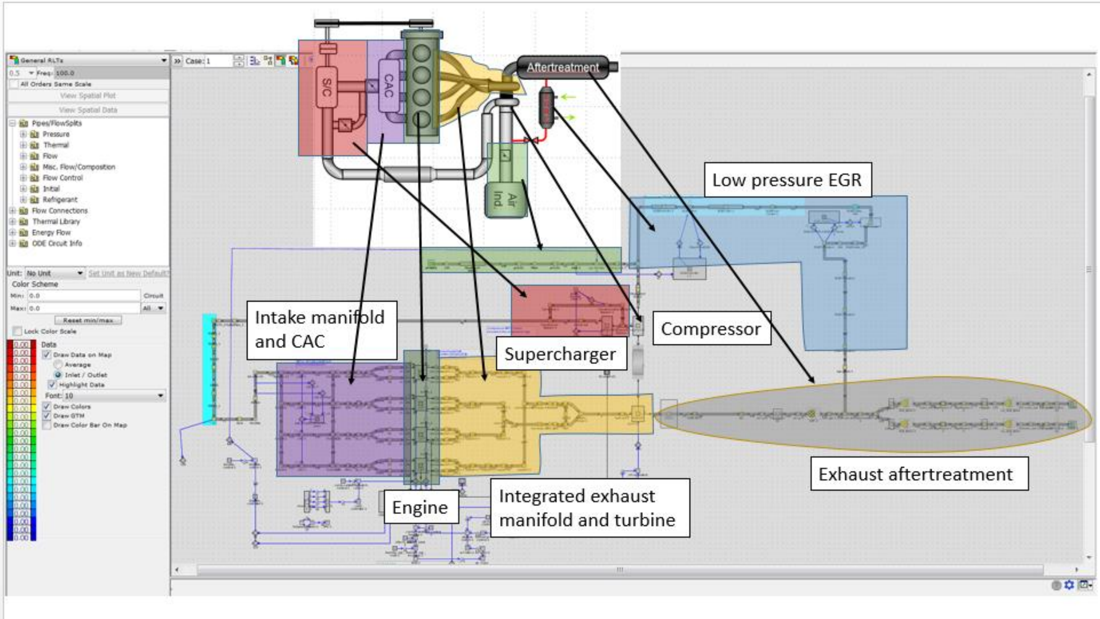


Lean+Miller offers a broad range of efficient operation

APPROACH – 1D ANALYSIS

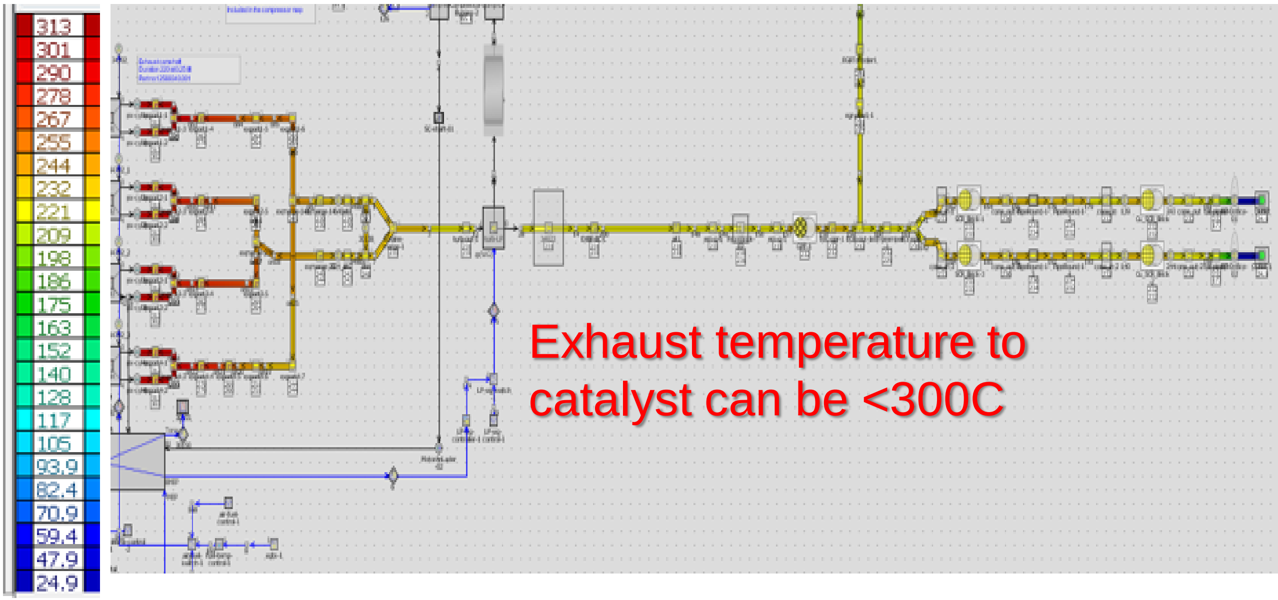
Supports Boost & Aftertreatment Design:

- **Boundary conditions -** for CFD and Single Cyl. test
- **Boost system challenges**:
  - Achieve flows for Lean Air/Fuel & EGR, Power
  - Maintain BSFC with low parasitic losses
- **Exhaust temperature** and catalyst efficiency



APPROACH – 1D ANALYSIS

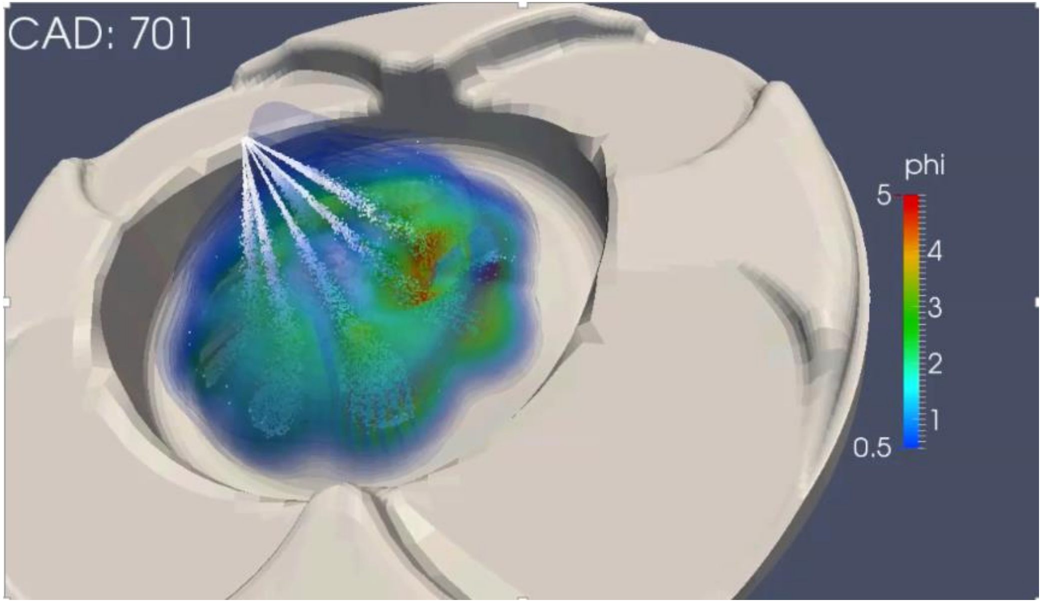
Key aftertreatment challenge:
Low-temperature oxidation efficiency
with lean, efficient part-load combustion



APPROACH – 3D CFD ANALYSIS

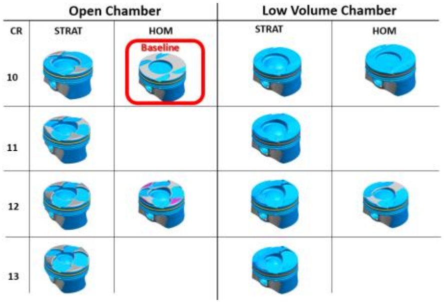
Supports design for:

- Understanding of cold flow / in-cylinder mixing / combustion
  - Identify rich / lean zones, heat transfer effects
- **Interaction of spray with air flow and surface impingement**
- **Intake port, piston bowl, and spray design guidance**
  - **EXAMPLE: PISTON BOWL FEATURE**

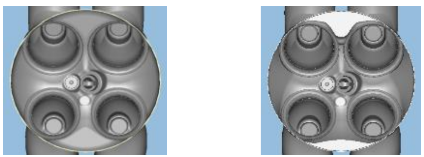


APPROACH – SINGLE CYLINDER

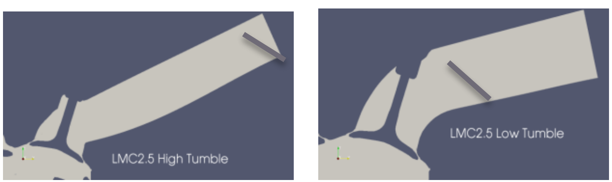
Piston (examples)



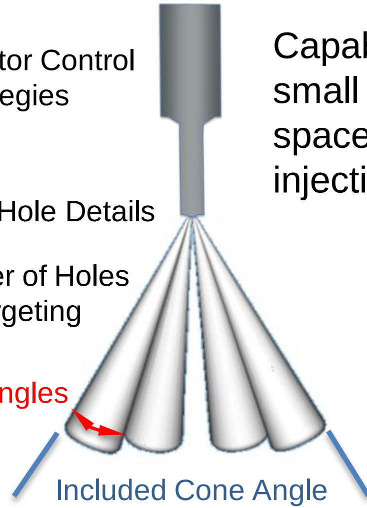
Combustion Chamber (examples)



Intake Port Design (examples)



Injector Parameter (examples)



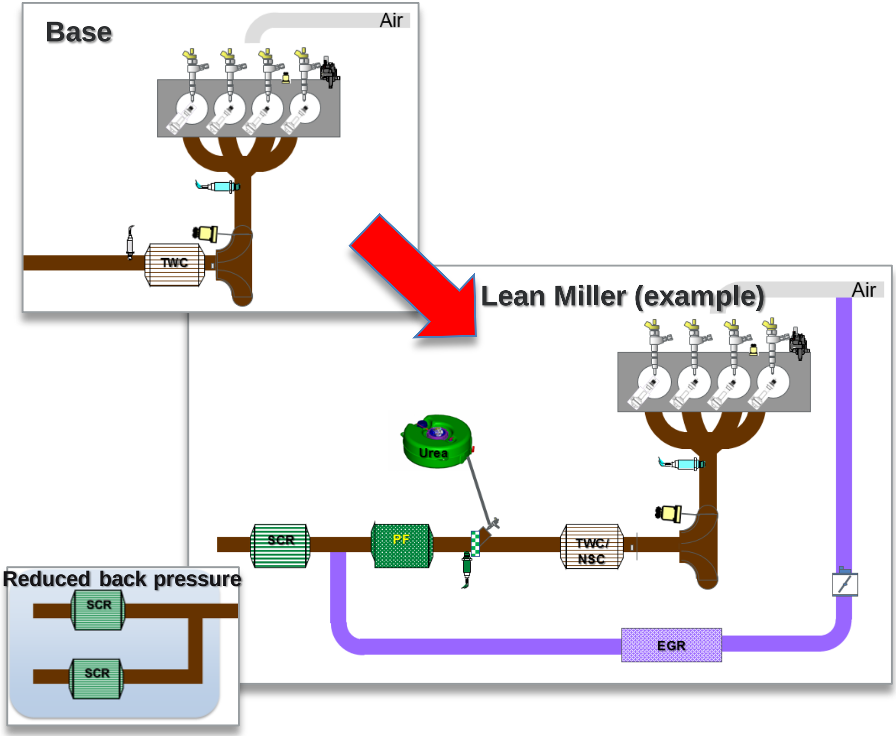
Spray Penetration
Spray Droplet Size
Propensity to Collapse

The single cylinder is used to optimize engine hardware

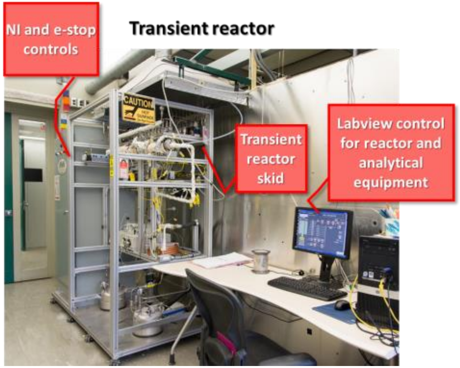
APPROACH – AFTERTREATMENT DEVELOPMENT

Transient reactor capability is used to provide input to engine aftertreatment design (along with analysis)

Aftertreatment Concepts Under Study



Transient reactor



Analytical equipment for transient reactor

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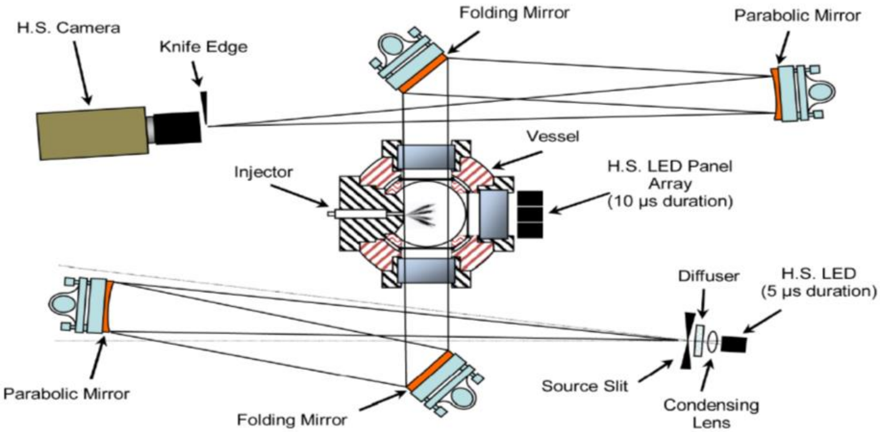
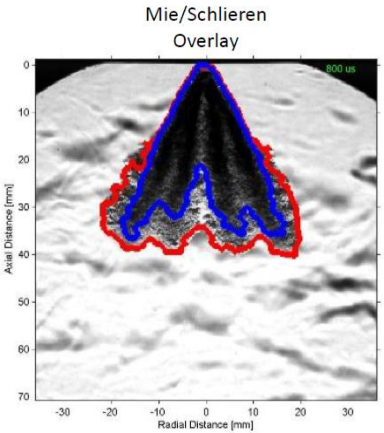
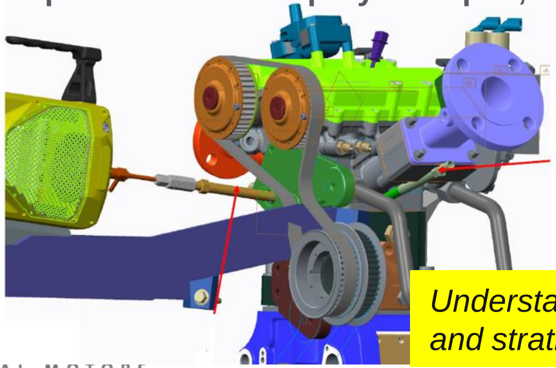
APPROACH –SPRAY IMAGING TOOLS

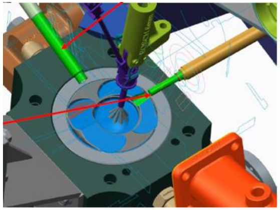
Spray Vessel - Mie / Shlieren –Spray Liquid / Vapor Imaging





Endoscope available for Spray Collapse, Impingement , Combustion





Understanding sprays for CFD calibration and stratified combustion optimization

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

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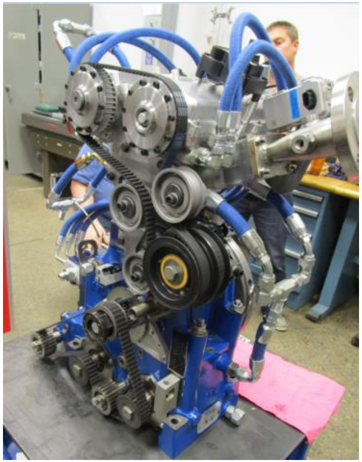
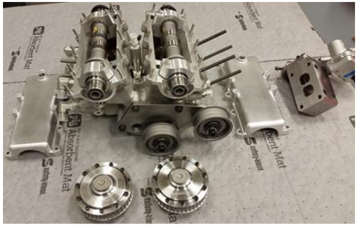
STATUS RELATIVE TO KEY MILESTONES

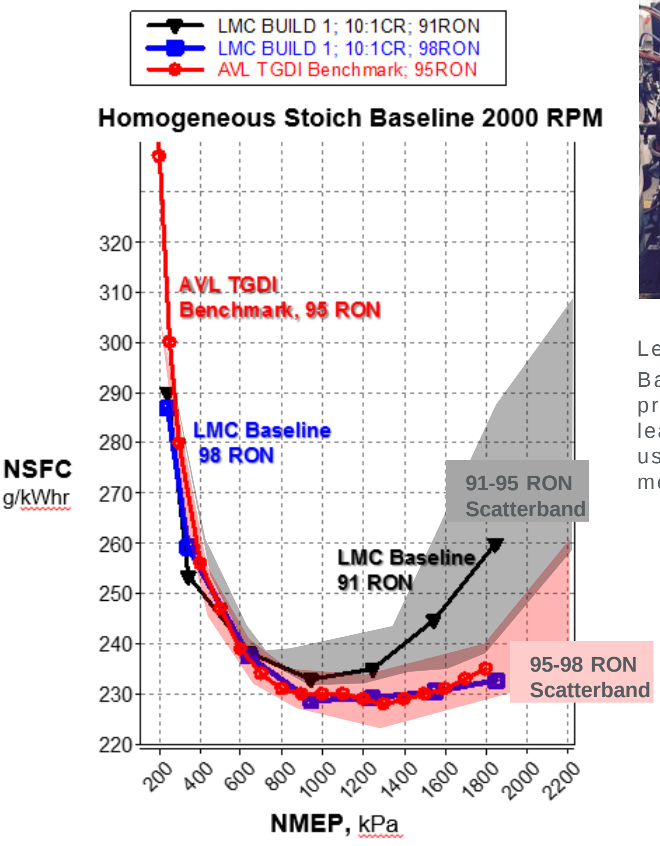
Development Task	Completion Date	Progress ✓
1.2 Initial 1D / 3D Simulation	3/31/2015	Complete ✓
1.3 Single Cyl Hardware Design	3/31/2015	Complete ✓
1.4 Procure Single Cyl Engine Hardware	8/31/2015	Complete ✓
1.5 SCE Baseline Test	12/4/2015	Complete ✓
1.5.1 GO / NO-GO GATE		PASSED
1.5 SCE Injector & Piston Optimization	9/30/2016	Underway
1.6 1D / 3D Simulation Iterations	12/20/2016	Underway
1.7 Lean Aftertreatment Development	12/20/2016	Underway
2.1 Multicylinder Engine Design	9/30/2016	Underway
2.0 GO / NO-GO GATE REVIEW	10/2016	Decision Gate
2.2 Multicylinder Hardware Procured	2/28/2017	
2.3 First multicylinder engine built	4/30/2017	
3.2 Multicylinder ready for test	6/30/2017	

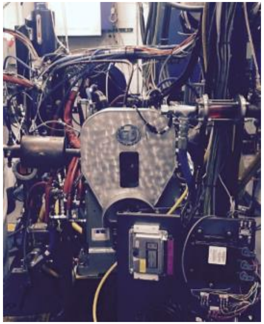
TECHNICAL ACCOMPLISHMENTS AND PROGRESS

BASELINE TESTING COMPLETED ON NEW SINGLE CYL ENGINE
STRATIFIED TESTING NOW UNDERWAY







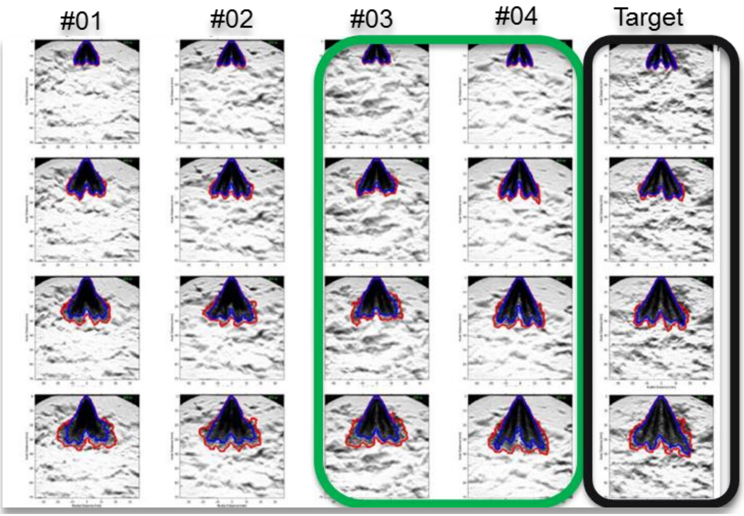


Lean Stratified "SG4"

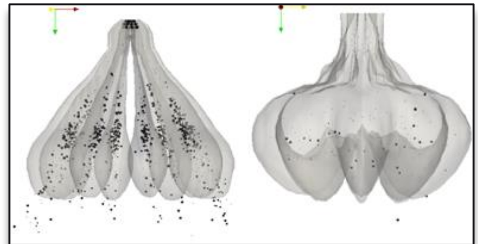
Baseline testing of previously developed lean spray guided used to verify measurements

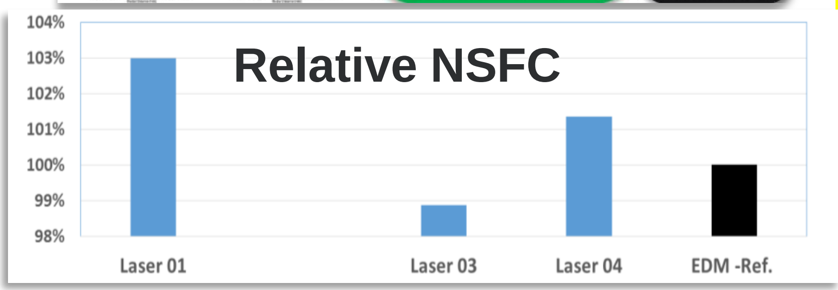
TECHNICAL ACCOMPLISHMENTS AND PROGRESS

SINGLE CYLINDER AND CFD SPRAY ASSESSMENT



CFD Spray Modeling



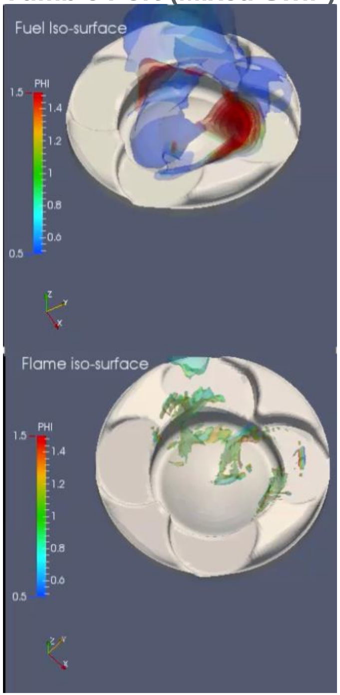


- **Avoiding spray collapse is essential**
- **Narrower spray beams required**
- **Using CFD to understand impact on mixture preparation**

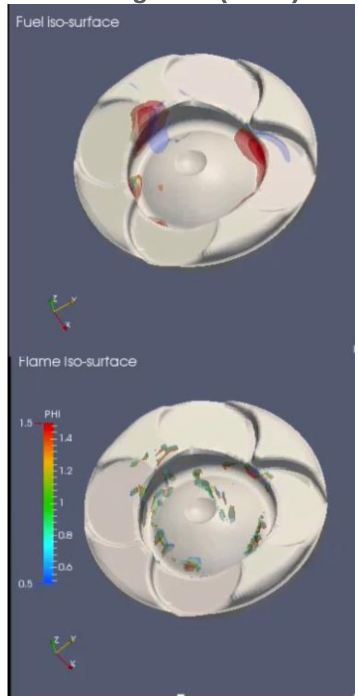
TECHNICAL PROGRESS
– *UNDERSTANDING MIXING & COMBUSTION*

STRATIFIED LEAN 2000 /2.6 BAR (32^{0} BTDC → 102^{0} ATDC)

Tumble Port (Mixed Swirl)



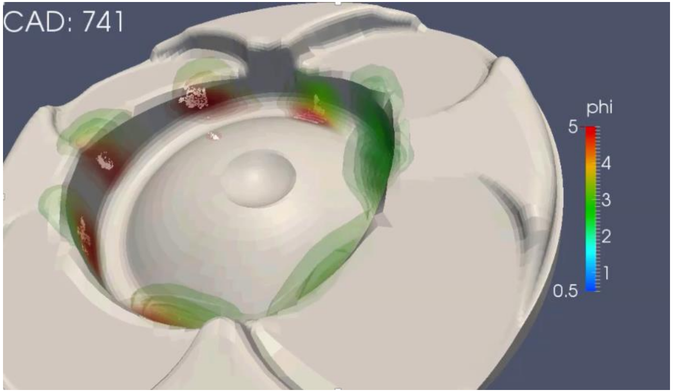
Filling Port (Swirl)



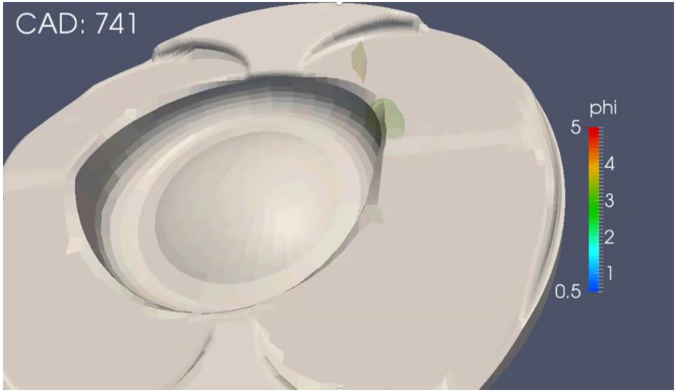
- CFD identifies key features of the physics of fuel injection, stratification and mixing process
- Applied to design of ports, piston bowls and sprays to optimize across the speed-load range

TECHNICAL PROGRESS
– *UNDERSTANDING PISTON INTERACTION*
STRATIFIED LEAN 1300 RPM / 3 BAR BMEP

Initial Design



Improved Design



- CFD identifies key features of the physics of fuel injection, stratification and mixing process
- Applied to design of piston bowls and sprays to optimize across the speed-load range

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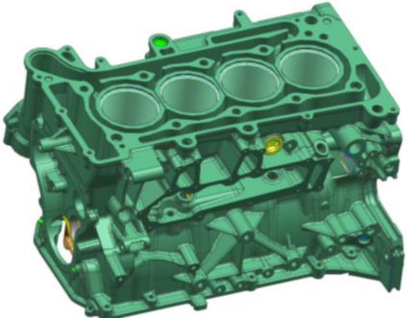
BOOST SYSTEM CHALLENGE:
HIGH FLOW (LEAN + EGR), LOW EXHAUST ENTHALPY

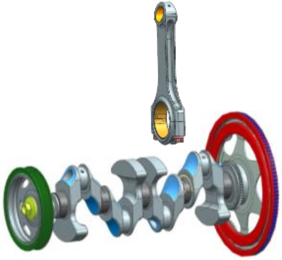
Designs analyzed using 1D modeling

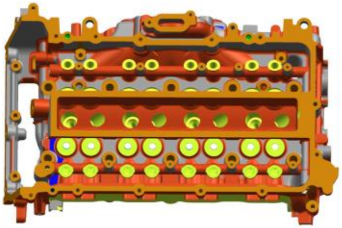
Option	Pros	Cons
Single Supercharger	• Highest exhaust enthalpy for cat • Boost is independent of exhaust enthalpy • Compatibility with EGR	• Parasitics (need to mitigate) • May require variable speed
Super-Turbo or Turbo-Super	• Potential to meet flow requirements	• Complexity • Low exhaust enthalpy available • Enthalpy loss for aftertreatment • Parasitic
Turbo-Turbo	• Potential to meet flow requirements • Eliminates drive parasitic	• Highest enthalpy loss for cat • Complexity • Risks w/ low pressure EGR
~~Single Turbo~~	• Efficient / Simple	• Limited flow and boost • Risks w/ LP EGR • Low exhaust enthalpy • **Not capable**

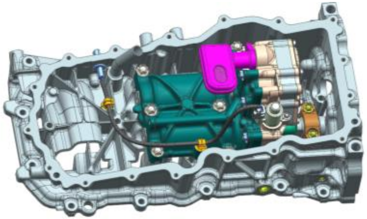
MULTICYLINDER HARDWARE DESIGN

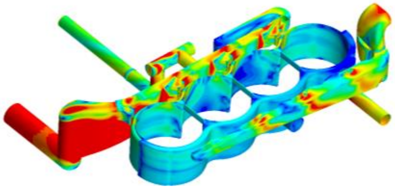
- Initial design work for major components is underway per plan
- Completion in 4th Quarter
- Attention paid to thermal management

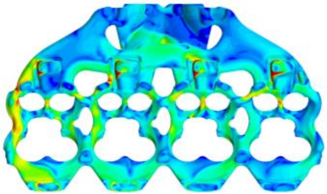












COLLABORATION AND COORDINATION

- Single cylinder subcontractor: **AVL**
- Strategic suppliers for – fuel injection, ignition, boost, aftertreatment systems:
  - **Bosch**
  - **NGK**
  - **Delphi**
  - **Umicore**
  - **Eaton**

RESPONSES TO 2015 REVIEWER'S COMMENTS
(LAST AMR WAS AT 5% COMPLETION)

"…approach will likely need some form of NOx sorption…for cold-start NOx"

We plan on having a TWC with limited NOx storage capability and high thermal durability.
The LAMC engine is expected to be capable of fast lightoff with retarded spark and combustion.

"…1D and 3D modeling, optimizing piston bowl: details not provided..." "…CFD tool was not clarified…how will the codes be calibrated and assessed for accuracy…what will be achieved...what is to be modeled?

We included several slides to explain use of 1D and 3D modeling. GM is self-funding the CFD work outside of DOE. The code is "GMTEC" and has been calibrated generically, as well as against our specific spray and engine test data.

"only one other institution identified: AVL. It was also unclear whether there was a contributing partner, or a supplier..."
We have six strategic suppliers at this time. For multicylinder that may increase

".. this will directly reduce petroleum via engine efficiency gains for gasoline engines if successful. The gasoline-dominant U.S. fleet means the relevance is high."
Thanks, we agree that this project addresses DOE objectives

CHALLENGES

- Optimizing BSFC for stratified part-load, with minimum compromise to high-load
- Designing aftertreatment system for low temperature oxidation

    .....and lean NOx reduction

- Boost system that meets flow requirements given exhaust enthalpy
- **Integration of all key systems to meet efficiency and emissions targets at a competitive cost-benefit ratio!**

TECHNOLOGY TRANSFER

- **Three patent applications filed**

PROPOSED FUTURE WORK

FY 2016

- Optimize SCE – piston, sprays, ports, injection & dilution strategies
- Optimize Miller Cycle strategies (LIVC, EIVC)
- Design multicylinder engine with new boost and aftertreatment

FY 2017

- Procure hardware and build multicylinder engines
- Optimize multicylinder engine on dynamometer
- Demonstrate fuel efficiency targets

SUMMARY

LEAN MILLER CYCLE SYSTEM DEVELOPMENT

- Project is relevant to DOE objectives
- Achieved all milestone targets
- Focusing on:
  - Single cylinder optimization
  - Aftertreatment challenge
  - Multicylinder design
- All are supported by 1D and 3D modeling
- Cost and complexity needs to be contained
- Go / No-Go Gate in October, 2016

THANK YOU!