LEAN MILLER CYCLE SYSTEM DEVELOPMENT FOR LIGHT-DUTY VEHICLES

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ACS093

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GENERAL MOTORS

OVERVIEW – LEAN MILLER CYCLE SYSTEM

Timeline

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

Completion: 70%

Goals

35% Fuel economy over baseline vehicle

Barriers

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

Budget

Total funding for 5 years

•	$ 8.27M	DOE Share
•	$12.40M	GM Share
•	$20.67M	Total

FY17 DOE Funds Rec'd:	$1.09M
FY18 Planned DOE Funding	$1.73M

Project Lead

General Motors

Supplier Support

- AVL – (Single Cyl. Dev.)
- BASF
- Bosch
- Delphi
- Eaton
- NGK
- Umicore
- BorgWarner

National Lab Support

- ORNL - Lean aftertreatment studies

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)

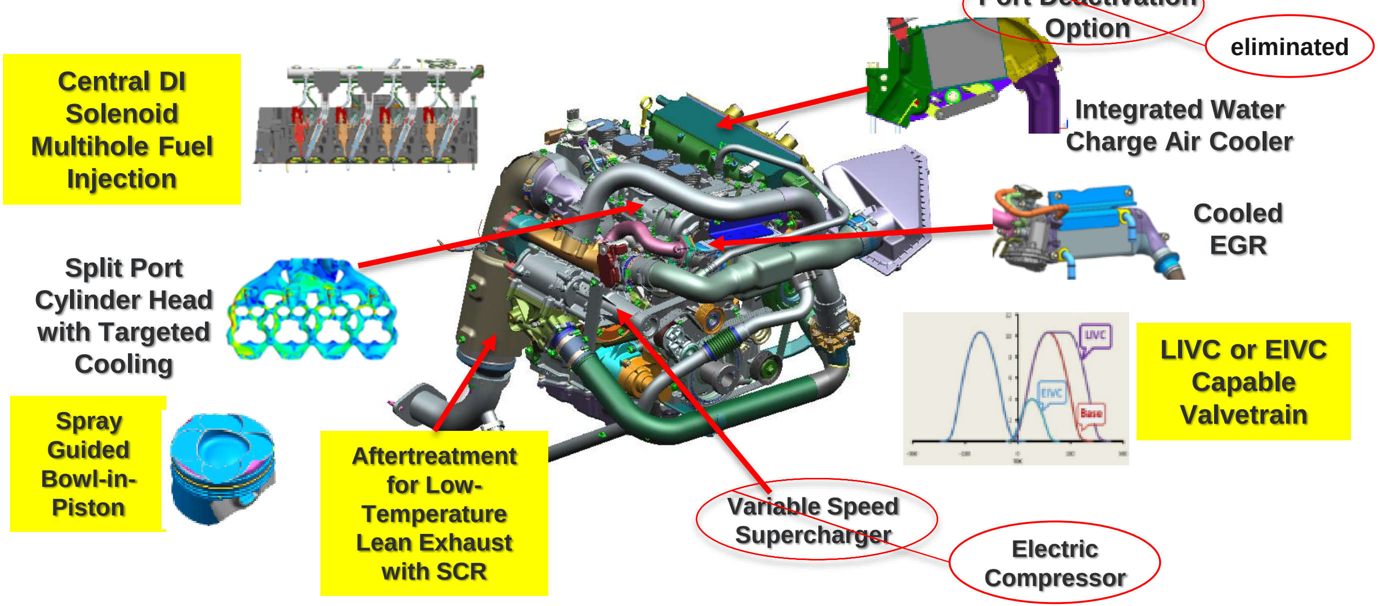
[3] Entries in percent BTE that are equal to 1.2 times the corresponding baseline BTE

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

APPROACH / INTEGRATED STRATEGY

Lean Miller Cycle Integration

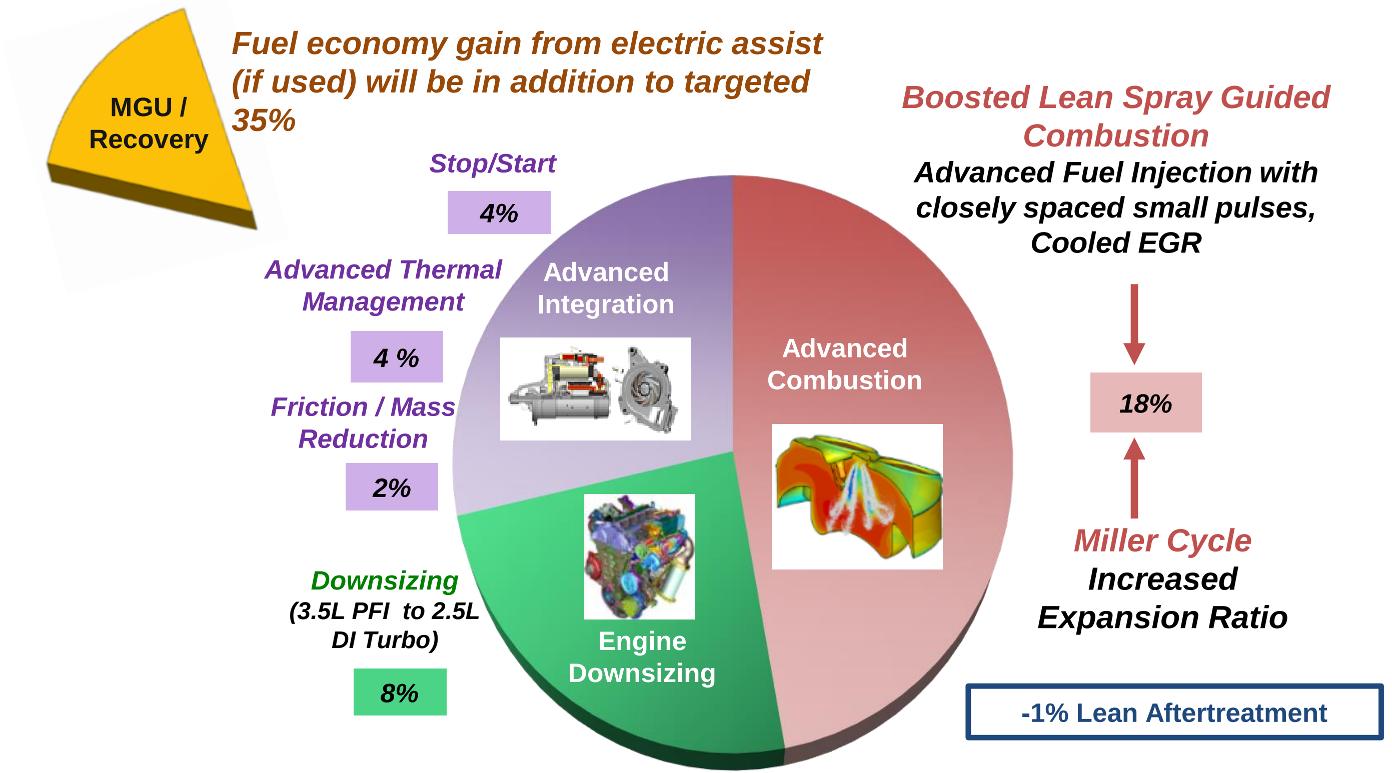
- Lean-stratified spray-guided with Miller cycle in one combustion system
- Optimized boost, high pressure fuel system, piston geometry, valvetrain, and EGR
- Optimized engine sizing, thermal management, minimized friction
- Passive ammonia / Active urea SCR lean NOx aftertreatment system
- Stop / Start



Changes since 2017 AMR

APPROACH / STRATEGY

TARGETED EFFICIENCY IMPROVEMENTS



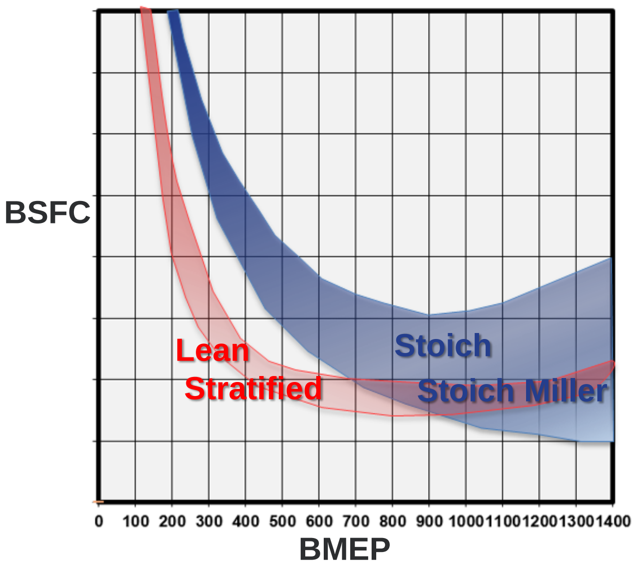
Total = 35% FE gain from engine above baseline

APPROACH / STRATEGY
LEAN+MILLER CONCEPT

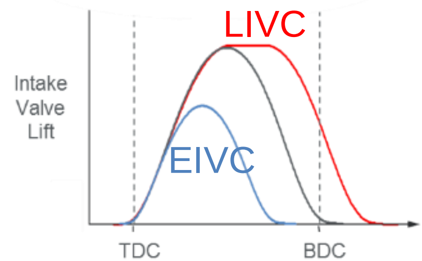
Part Load: Lean stratified
- High thermodynamic efficiency
- Aggressive EGR for reduced NOx

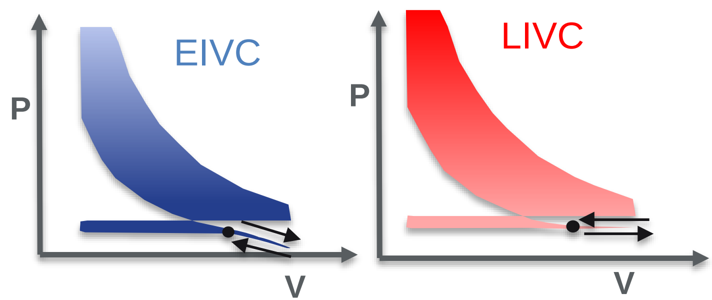
High Load: Stoich Miller Cycle
- High expansion ratio for efficiency
- Lower effective CR for knock & reduced pumping

Lean Combustion Potential vs. Load



Early vs. Late Intake Valve Closure





Lean+Miller offers a broad range of efficient operation

APPROACH – MILESTONES

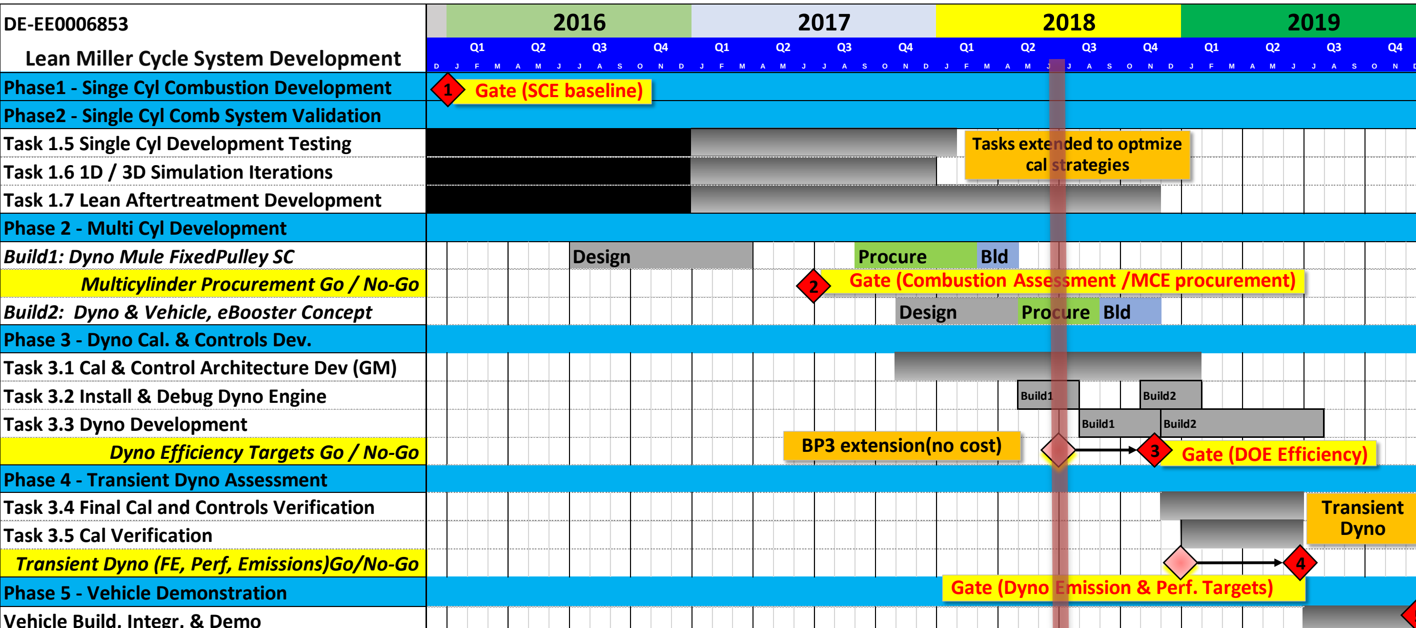
Development Task		Completion Date	Revised Date	Status
1.2 Initial 1D / 3D Simulation		3/31/2015		Complete ✓
1.3 Single Cyl Hardware Design		3/31/2015		Complete ✓
1.4 Procure Single Cyl Engine Hardware		8/31/2015		Complete ✓
1.5 SCE Baseline Test		12/4/2015		Complete ✓
1.5.1 Go / No-Go Gate		12/9/2015		PASSED ✓
1.5 SCE Injector & Piston Optimization		2/15/2018		Complete ✓
1.6 1D / 3D Simulation Iterations		1/31/2017		Complete ✓ GM funded Combustion CFD
1.7 Lean Aftertreatment Development		6/30/2018	11/30/2018	On track, through MCE development
2.1 Multicylinder Engine Design	Build 1: steady-state	1/31/2017		Complete ✓ fixed-pulley supercharger
	Build 2: Transient	5/15/2018		Complete ✓ eBooster
2.0 Go / No-Go Gate Review		6/19/2017		PASSED ✓
2.3 MCE Hdwr Released for Procurement		9/30/2017		Complete ✓
2.4 Phase 1 Engine Build #1		5/1/2018		Complete ✓
3.1 Phase 1 Cal & Controls		12/30/2017	6/30/2018	GM insourced controls
3.2 Install & Debug Phase 1 Engine		5/30/2018	9/30/2018	cadenced to hardware and controls
3.3 Dyno Development		6/30/2018	11/30/2018	controls & cal development, steady-state
3.0 Go / No-Go Gate		6/30/2018	11/30/2018	Dyno efficiency: status to targets

APPROACH - TIMING

Four Annual Go / No-Go Decision Reviews

1. Dec. 2015 Baseline SCE Design & Testing
2. June 2017 Lean Miller Combustion Assessment
3. June → Nov 2018 Multicylinder Efficiency vs. Targets
4. Dec. 2018→ June 2019 Full Dyno Assessment – FE / Performance / Emissions
5. Dec. 2019 Final Vehicle Demonstration

Extending BP3 and BP4: Insourced controls, Procurement timing



TECHNICAL ACCOMPLISHMENTS & PROGRESS

BOOST SYSTEM ARCHITECTURE– TRANSIENT DYNO / VEHICLE DEVELOPMENT

Evaluation Criteria	Option		CONS	PROS
• ***Exhaust enthalpy for aftertreatment*** • ***Boost / flow capability & efficiency*** • ***Overall engine BSFC*** • ***Transient response / time-to-torque*** • ***Integration complexity***	~~Single Turbo~~	✖	• Limited flow and boost, Risks w/ LP EGR, Exhaust enthalpy loss **Not Capable**	
	2 Stage Turbo	✖	• Complexity, Highest exhaust enthalpy loss, EGR risk	• No drive parasitics
	Super /Turbo	✖	• Complexity, exhaust enthalpy loss, Parasitics	• Potential to meet flow requirements
	2-speed Super-charger	✓	• Parasitics	• highest exhaust enthalpy
	Electric Compressor	✓	• Cost	• highest exhaust enthalpy, reduced parasitics

Intent for transient dyno & vehicle development

BorgWarner 48v eBOOSTER®
- **variable speed, fast response**
- **lower overall parasitics**
- **Integration flexibility**
- **synergistic with 48v**

Estimated reduction in FMEP: eBooster v. 2spd-supercharger			
RPM	1200 to 3500	2500	5000
BMEP(bar)	8 - 15	WOT	WOT
% FMEP reduction	38% (avg)	36%	20%

Boost System Revisited

2-Speed Supercharger *proposed at Gate 2*

ACCOMPLISHMENTS AND PROGRESS

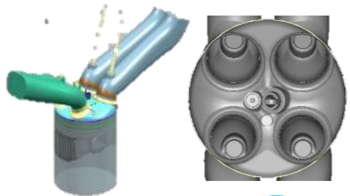
COMBUSTION SYSTEM DEFINED FOR MCE

Summary of SCE testing completed in 1Qtr2018

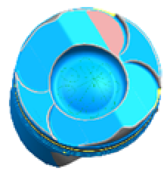
- **Combustion system hardware for MCE**
- **Calibration strategy development**
  - Part-load, 21pt mini-map optimization
  - Full load
  - Exhaust heating
  - Rich combustion for NH_3 reactant formation

ACCOMPLISHMENTS AND PROGRESS

COMBUSTION SYSTEM DEFINED FOR MCE



<u>Open chamber with high tumble</u>
works well with closely-spaced multiple pulse strategies without need of port throttle

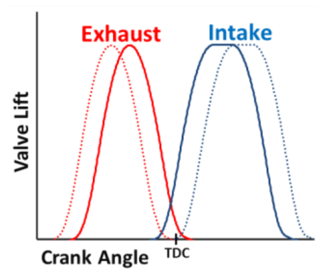


<u>12:1 CR, spray-guided bowl-in-piston</u>
optimized with chamber for light-load lean-stratified combustion

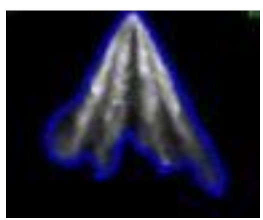
Combustion CFD supported Single-Cylinder Testing

<u>16 hardware sets tested</u>

- Injector variants
- Chamber and Bowl Variants
- Low & High Tumble
- 11, 12, 13:1 CR
- EIVC, LIVC



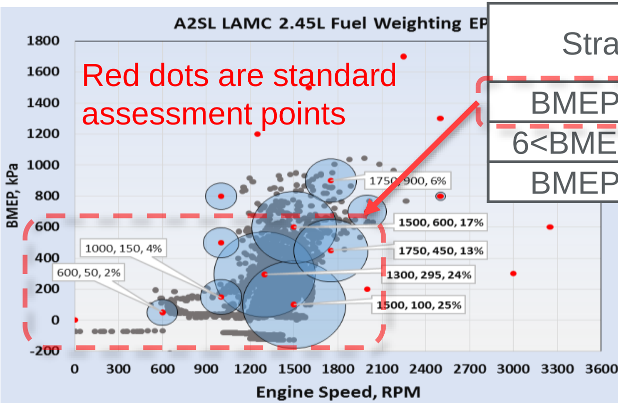
<u>LIVC</u> best compromise between light-load stratified and WOT torque and power



<u>Injector design meets spray/control requirements</u>
Closely-spaced small pulses
35MPa injection pressure

ACCOMPLISHMENTS AND PROGRESS

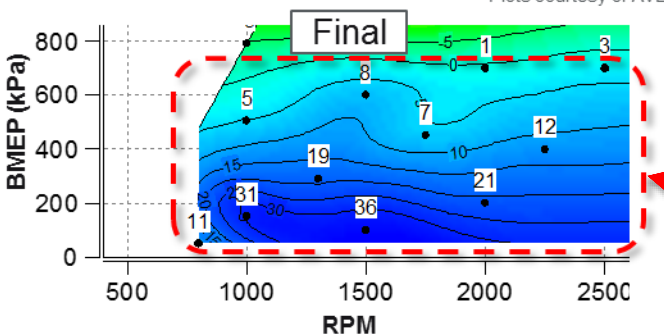
SCE 21PT MINI-MAP: CAL STRATEGY FOR MCE

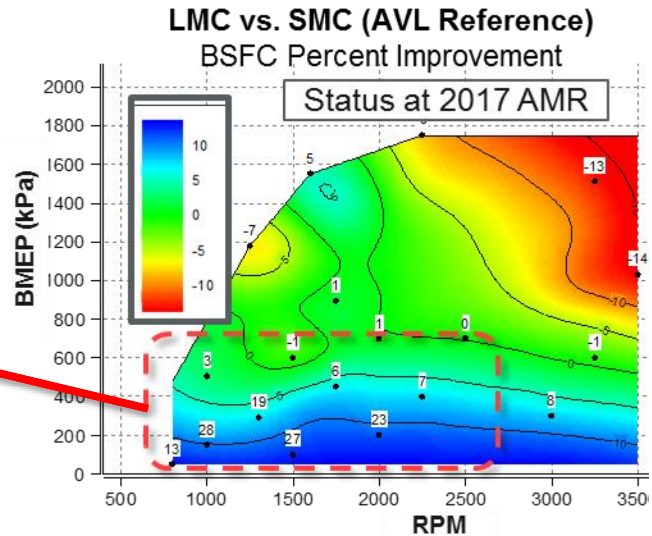


Strategy	Mode	Mixture	Boost	External EGR
BMEP<6bar	Stratified	Lean**	0.95-1bar	yes
6<BMEP<9bar	Homogeneous	Stoich	0.95-1bar	no
BMEP>9bar	Homogeneous	Stoich	>1bar	no

**up to 38:1 A/F

Plots courtesy of AVL



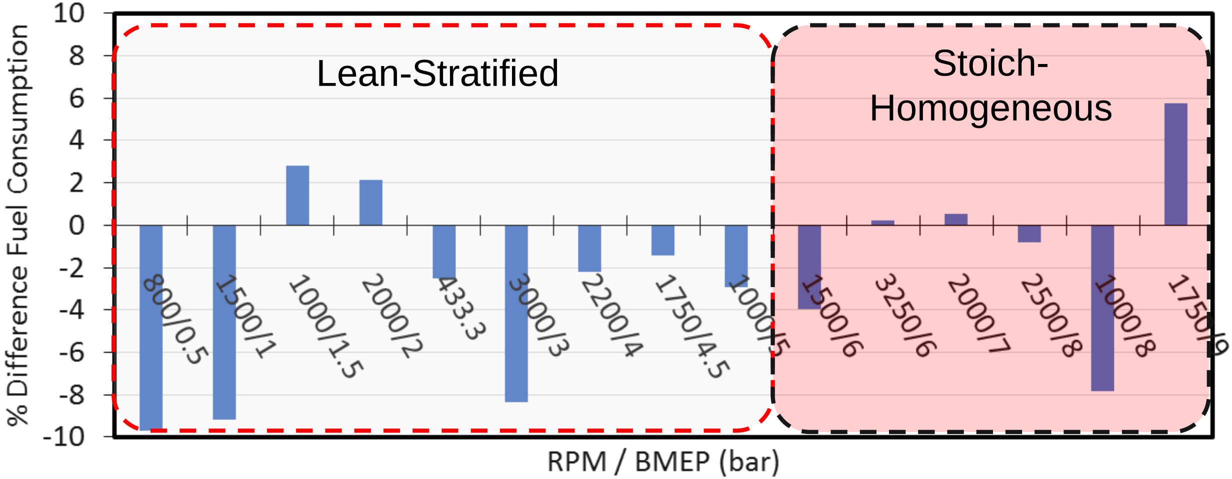


Fuel economy potential improved at part-load region (70% of FTP)

ACCOMPLISHMENTS AND PROGRESS

SCE 21PT MINI-MAP: CAL STRATEGY FOR MCE NATURALLY ASPIRATED KEYPOINTS

Cal refinement progress for MCE hardware set



Estimated ~2% additional FE improvement on FTP based on keypoint weightings

Cal strategy ready for MCE deployment

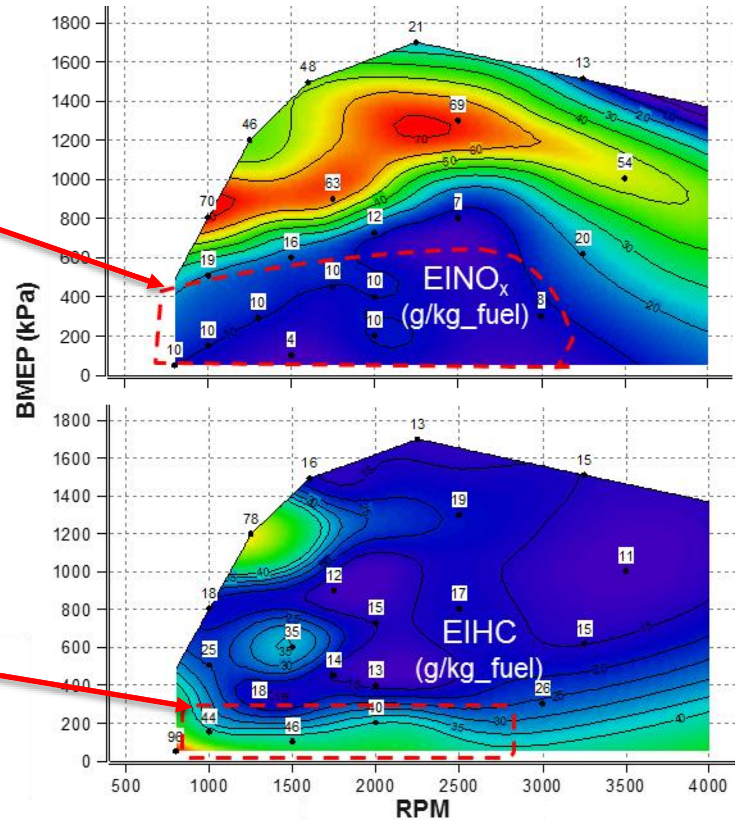
ACCOMPLISHMENTS AND PROGRESS

SCE 21PT MINI-MAP: CAL STRATEGY FOR MCE NATURALLY ASPIRATED KEYPOINTS

Lean-Stratified Region

NO_x

- ✓ **Target Achieved (≤10g/kg-fuel)**
- ✓ **minimize lean aftertreatment burden**



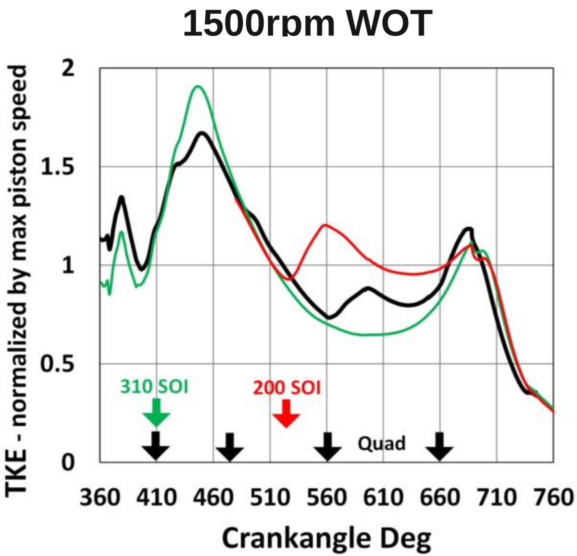
HC vs. stoich-homogeneous

- ✓ **Lower for BMEP > 3bar**
- ✗ **2x for BMEP < 3bar**

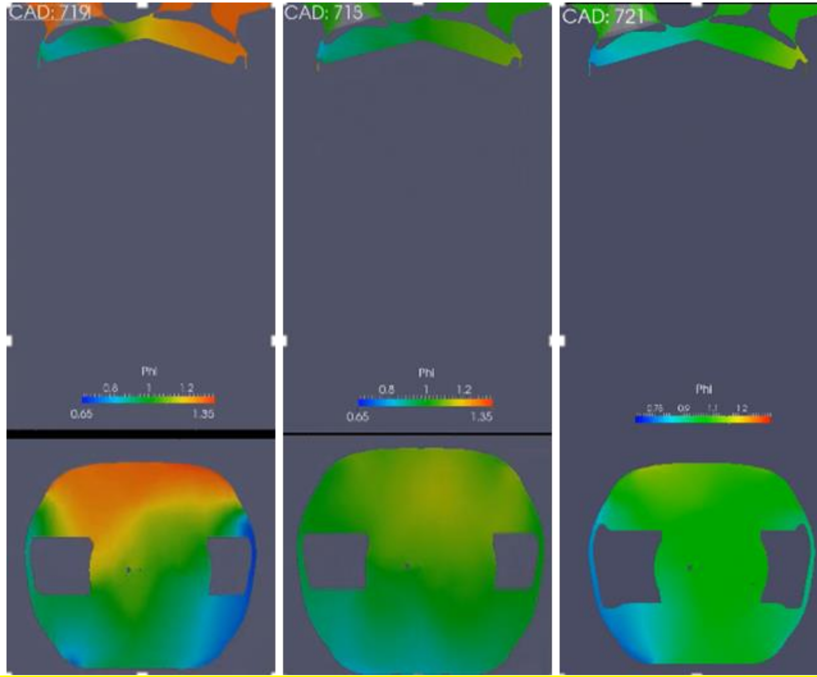
ACCOMPLISHMENTS AND PROGRESS

COMBUSTION CFD RESULTS

INJECTION STRATEGY INVESTIGATIONS



200 SOI | 310 SOI | Quad Injection

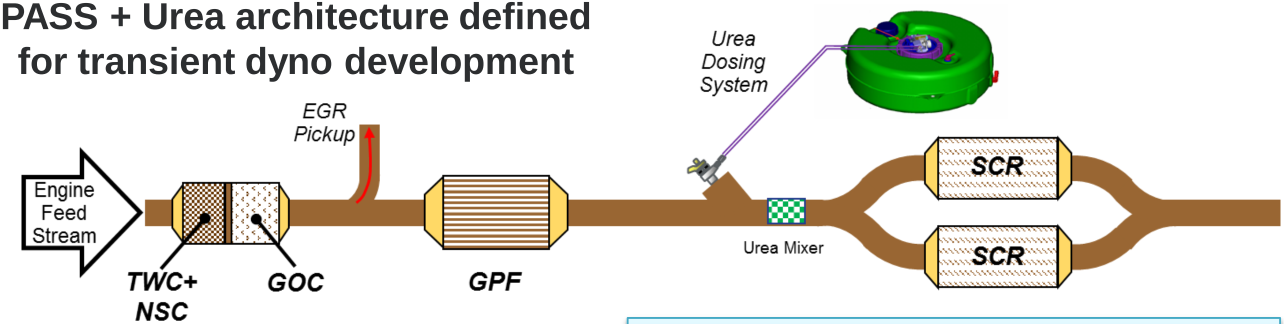


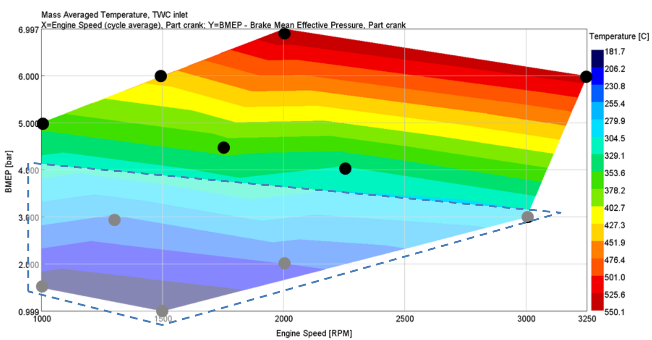
- **CFD predictions of tumble modification, spray generated TKE, mixing, flame TKE, symmetric flame propagation, and burning rate are the major parameters**
- **CFD supported development of multiple injection strategies**

ACCOMPLISHMENTS AND PROGRESS

CHALLENGE: LEAN / LOW TEMPERATURE AFTERTREATMENT

PASS + Urea architecture defined for transient dyno development





Exhaust temperature <300C

Hardware Solutions:

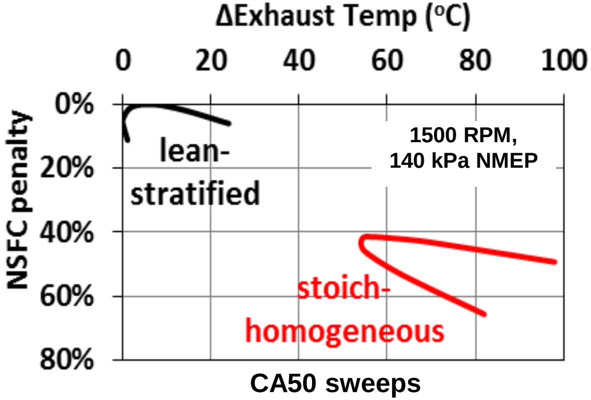
- Close-coupled catalysts
- High PGM
- SCRF, EHC & HC Trap eliminated

Combustion Solutions (FE penalty):

- Reduce AF ratio (less lean)
- Combustion phasing (retard)
- Post-injection
- Cam phasing strategy
- Lower Effective CR

CHALLENGE: LEAN / LOW TEMPERATURE AFTERTREATMENT

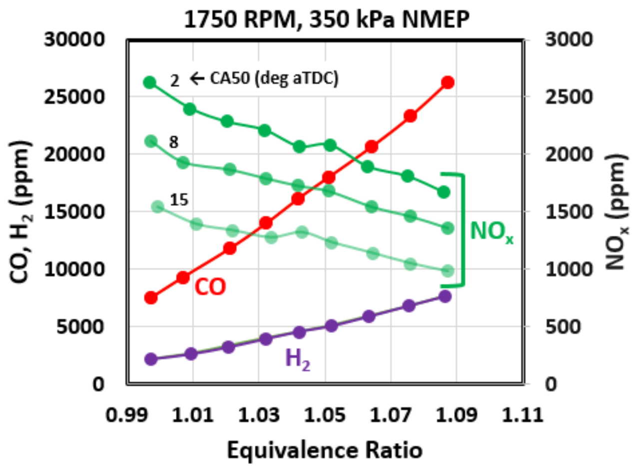
Exhaust heating
(simulation results)



effectiveness

Parameter
A/F
Combustion phasing
Effective CR

Rich combustion for NH_3 reactant formation (single-cyl results)



- NH_3 formation over TWC at EQR>1
- H_2 is primary reductant for NO→NH_3 reaction
- CO and HCs also contribute to H_2 formation
- CO breakthrough remains primary concern

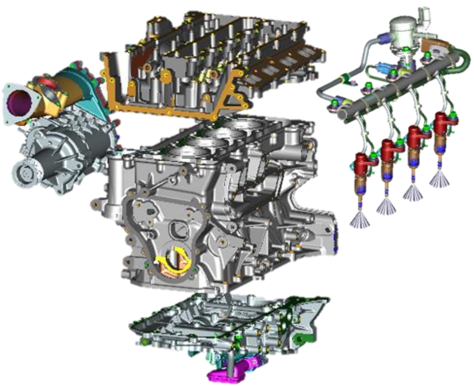
Calibration explored to guide aftertreatment management strategies on MCE

TECHNICAL ACCOMPLISHMENTS AND PROGRESS
MULTI-CYLINDER DYNO-MULE DEVELOPMENT

Build 1 (fixed-pulley supercharger) for steady-state dyno

Procurement Complete

(40 suppliers)



1st Build Complete

(status as of 4/18)

Control Hardware Development

HIL Bench & Engine Start-Cart

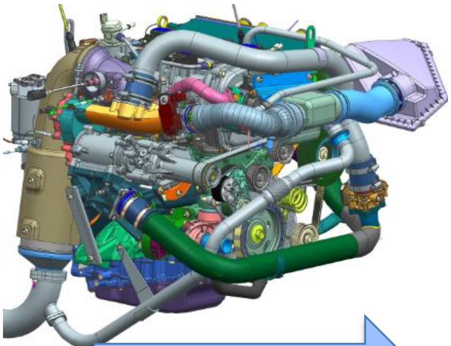
(on-track to deploy on dyno)

Engine start-cart

Dyno installation

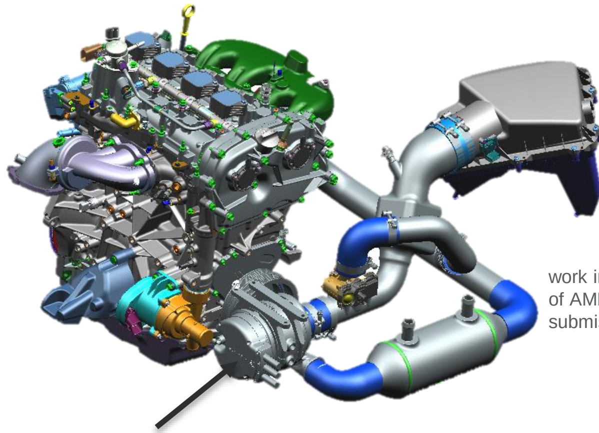
(underway)

Build 1
(fixed-pulley SC)
steady-state dyno



Build 1 Carryover
- Head/Block/Thermal
- Covers/Ventilation/Lube
- Combustion/FIS/Ignition
- Cranktrain/Valvetrain

Build 2
Transient Dyno mule (eBooster)
Target design complete 5/15/18



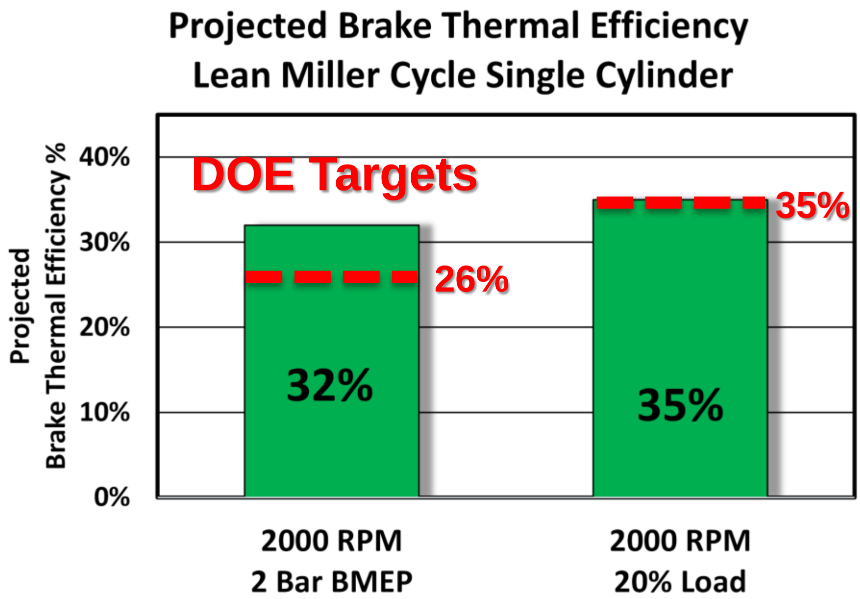
work in process at time of AMR material submission

- **Integration of eBooster for Transient Dyno testing**
  - 48v buss from dyno bench
- **New Designs:**
  - Intake air path, Intake manifold, EGR system (cooled)
  - Viable vehicle package design underway (w/ 48v architecture)

STATUS RELATIVE TO TARGETS

TECHNICAL ACCOMPLISHMENTS & PROGRESS

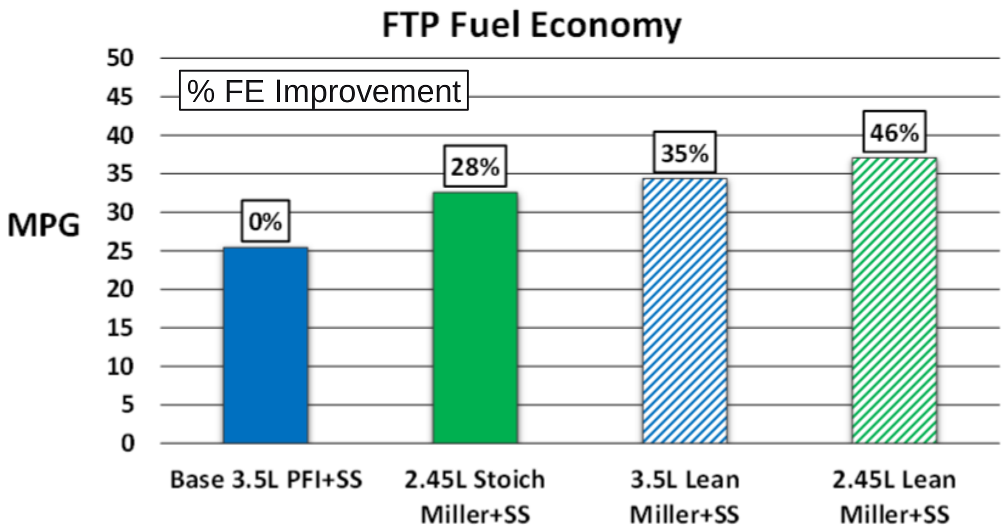
SINGLE CYLINDER THERMAL EFFICIENCY AT TARGET



Capable of meeting DOE part load stretch goal Brake Thermal Efficiency
BSFC estimated using MCE boundary conditions and friction

TECHNICAL ACCOMPLISHMENTS & PROGRESS

FUEL ECONOMY PROMISING BASED ON VEHICLE FE SIMULATIONS

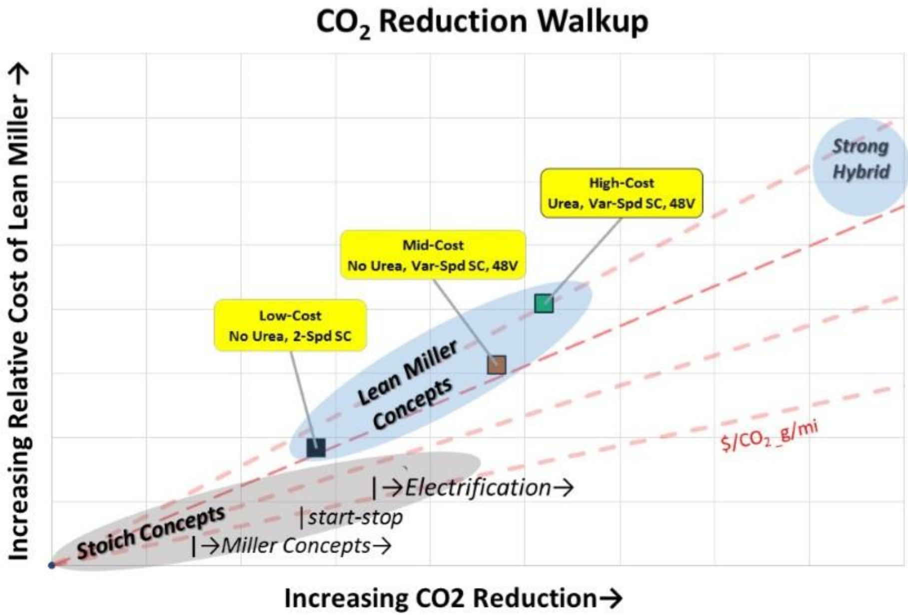


- **Potential to meet 35% FE goal**
- **Translates to 36% on a CO_2 – fuel consumption basis**
- **Does not include advantage of thermal management**

Simulations do not account for passive ammonia make, catalyst-light off, transient controls and calibration tradeoffs

TECHNICAL ACCOMPLISHMENTS & PROGRESS

COST / CO2 ASSESSMENT



- **LMC continues to be assessed versus other technology options**
- **Potential synergy after electrification, eBooster under study**
- **Aftertreatment remains primary cost driver**

RESPONSES TO 2017 REVIEWER'S COMMENTS

"…Chances are BSFC targets will be hit" relative to aftertreatment… "but for brake mean effective pressure less then 3 bar there will be challenges."
We agree and acknowledge the design and control of the aftertreatment package will present tradeoffs to achieve best BSFC at light-load conditions due to lower exhaust enthalpy. However, over 25% BSFC improvement has been measured below 3bar BMEP region over comparative stoichiometric systems. MCE engine needed to confirm boundary conditions for aftertreatment and efficiency tradeoffs.

"…aftertreatment work,"... "might be more difficulty than envisioned at low load"… "one can borrow much from LDD:LNT/TWC + SCRF+SCR."
We are leveraging light-duty diesel technology. A urea dosing system will be integrated to study efficiency tradeoffs with passive ammonia. Lean-stratified region held NO_x to 10g/kg-fuel to minimize passive NH_3 formation and burden on lean-aftertreatment package. Modeling indicates Tier 3 is possible. We recognize that the aftertreatment system presents a cost and complexity challenge.

"……the project is combining various production technologies into a new package with optimization."…."project stands a good chance of meeting the goals, and being that it is "incremental"," it might be implemented sooner than more risky approaches"
The combination of selected technologies is unique and posses technical risk to deploy. Aftertreatment cost, controls complexity, system robustness remain key challenges for commercialization. Passive-ammonia system is crucial for business case.

COLLABORATION AND COORDINATION

- Single-cylinder engine subcontractor: **AVL**
- Strategic suppliers & support for fuel injection, ignition, boost, aftertreatment systems:
  - **Bosch**
  - **BASF**
  - **Delphi**
  - **Eaton**
  - **NGK**
  - **Oak Ridge Nat. Lab**
  - **Umicore**
  - **BorgWarner**

REMAINING CHALLENGES

- Integrating systems to achieve fuel efficiency and TIER3 emissions targets
  - Cost-effective aftertreatment system for low temperature oxidation and lean NO_x reduction
  - Transient controls and calibration development to manage combustion mode transitions and maximize aftertreatment efficiency
- Confirming ability to achieve optimum BSFC for stratified part-load with minimum compromise to high-load
- Confirming boost system to meet high-load and WOT flow requirements with minimal parasitics

PROPOSED FUTURE WORK

FY 2018

- Steady-state cal development on multi-cylinder engine to demonstrate fuel efficiency to targets
- Go / No-go decision based on MCE efficiency in November 2018

FY 2019

- Optimize transient performance of multi-cylinder engine on dynamometer
- Demonstrate controls feasibility and FE projections to target
- Go / No-go decision to continue execute vehicle development for final demonstration to targets

Any proposed future work is subject to change based on funding levels

SUMMARY

LEAN MILLER ENGINE

- Relevant to DOE objectives
- Significant fuel economy potential, with risk:
  - Hinges on technical and commercial advances in:
    - Low temp. oxidation, cost-effective lean NOx aftertreatment
    - Efficient boost systems
    - Fuel injection capability for advanced multi-pulse strategies
    - Electrification synergy
- Combustion system downselected and calibration refined for multi-cylinder deployment
- Lean technology is potential next step, possibly after advanced stoichiometric engines and mild electrification

THANK YOU!