LEAN MILLER CYCLE SYSTEM DEVELOPMENT FOR LIGHT-DUTY VEHICLES

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Paul Battiston
Principal Investigator
Global Propulsion Systems
General Motors

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Project ID #
ACS093
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:

| Technology Pathway | Fuel         | 2010 Baselines | 2020 Stretch Goals
|--------------------|--------------|----------------|-------------------|
|                    |              | 2010 Baselines | 2020 Stretch Goals
|                    | Peak Efficiency | Efficiency¹ at 2-bar BMEP and 2000 rpm | Efficiency¹ at 2000 rpm and 20% of the peak load | 2000 rpm Peak Load² | 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 | Gasoline⁴    | 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
APPREACH / 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

Central DI Solenoid Multihole Fuel Injection

Split Port Cylinder Head with Targeted Cooling

Spray Guided Bowl-in-Piston

Aftertreatment for Low-Temperature Lean Exhaust with SCR

Variable Speed Supercharger

Port Deactivation Option

Integranted Water Charge Air Cooler

Cooled EGR

LIVC or EIVC Capable Valvetrain

Electric Compressor

Changes since 2017 AMR

eliminated
APPROACH / STRATEGY
TARGETED EFFICIENCY IMPROVEMENTS

Fuel economy gain from electric assist (if used) will be in addition to targeted 35%

Boosted Lean Spray Guided Combustion
Advanced Fuel Injection with closely spaced small pulses, Cooled EGR

Stop/Start
4%

Advanced Thermal Management
4%

Friction / Mass Reduction
2%

Downsizing (3.5L PFI to 2.5L DI Turbo)
8%

Advanced Integration

Advanced Combustion

Engine Downsizing

Miller Cycle
Increased Expansion Ratio

Total = 35% FE gain from engine above baseline

General Motors
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

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**Lean Combustion Potential vs. Load**

**Early vs. Late Intake Valve Closure**

- **LIVC**
- **EIVC**

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Lean+Miller offers a broad range of efficient operation.
## APPROACH – MILESTONES

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

Extending BP3 and BP4: Insourced controls, Procurement timing

<table>
<thead>
<tr>
<th>DE-EE0006853</th>
<th>Lean Miller Cycle System Development</th>
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<tbody>
<tr>
<td><strong>Phase 1</strong> - Singe Cyl Combustion Development</td>
<td>Gate (SCE baseline)</td>
</tr>
<tr>
<td><strong>Phase 2</strong> - Single Cyl Comb System Validation</td>
<td></td>
</tr>
<tr>
<td>Task 1.5 Single Cyl Development Testing</td>
<td></td>
</tr>
<tr>
<td>Task 1.6 1D / 3D Simulation Iterations</td>
<td>Tasks extended to optimize cal strategies</td>
</tr>
<tr>
<td>Task 1.7 Lean Aftertreatment Development</td>
<td></td>
</tr>
</tbody>
</table>

**Phase 2 - Multi Cyl Development**

- **Build1**: Dyno Mule FixedPulley SC
- **Build2**: Dyno & Vehicle, eBooster Concept

**Phase 3 - Dyno Cal. & Controls Dev.**

- Task 3.1 Cal & Control Architecture Dev (GM)
- Task 3.2 Install & Debug Dyno Engine
- Task 3.3 Dyno Development

**Dyno Efficiency Targets Go / No-Go**

**Phase 4 - Transient Dyno Assessment**

- Task 3.4 Final Cal and Controls Verification
- Task 3.5 Cal Verification

**Transient Dyno (FE, Perf, Emissions)Go/No-Go**

**Phase 5 - Vehicle Demonstration**

- Vehicle Build, Integr, & Demo

**Extending BP3 and BP4**

- BP3 extension (no cost)
- Gate (DOE Efficiency)
# Technical Accomplishments & Progress

**Boost System Architecture – Transient Dyno / Vehicle Development**

## Evaluation Criteria

- Exhaust enthalpy for aftertreatment
- Boost / flow capability & efficiency
- Overall engine BSFC
- Transient response / time-to-torque
- Integration complexity

<table>
<thead>
<tr>
<th>Option</th>
<th>CONS</th>
<th>PROS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Turbo</td>
<td>Limited flow and boost, Risks w/ LP EGR, Exhaust enthalpy loss Not Capable</td>
<td></td>
</tr>
<tr>
<td>2 Stage Turbo</td>
<td>Complexity, Highest exhaust enthalpy loss, EGR risk</td>
<td>• No drive parasitics</td>
</tr>
<tr>
<td>Super / Turbo</td>
<td>Complexity, exhaust enthalpy loss, Parasitics</td>
<td>• Potential to meet flow requirements</td>
</tr>
<tr>
<td>2-speed Super-charger</td>
<td>Parasitics</td>
<td>• highest exhaust enthalpy</td>
</tr>
<tr>
<td>Electric Compressor</td>
<td>Cost</td>
<td>• highest exhaust enthalpy, reduced parasitics</td>
</tr>
</tbody>
</table>

## Intent for transient dyno & vehicle development

- 2-Speed Supercharger proposed at Gate 2

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

## Estimated reduction in FMEP: eBooster v. 2spd-supercharger

<table>
<thead>
<tr>
<th>RPM</th>
<th>1200 to 3500</th>
<th>2500</th>
<th>5000</th>
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<tbody>
<tr>
<td>BMEP(bar)</td>
<td>8 - 15</td>
<td>WOT</td>
<td>WOT</td>
</tr>
<tr>
<td>% FMEP reduction</td>
<td>38% (avg)</td>
<td>36%</td>
<td>20%</td>
</tr>
</tbody>
</table>
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

Combustion CFD supported Single-Cylinder Testing

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

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

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

LIVC best compromise between light-load stratified and WOT torque and power

Injector design meets spray/control requirements
Closely-spaced small pulses
35MPa injection pressure
**ACCOMPLISHMENTS AND PROGRESS**

**SCE 21PT MINI-MAP: CAL STRATEGY FOR MCE**

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Mode</th>
<th>Mixture</th>
<th>Boost</th>
<th>External EGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMEP&lt;6bar</td>
<td>Stratified</td>
<td>Lean**</td>
<td>0.95-1bar</td>
<td>yes</td>
</tr>
<tr>
<td>6&lt;BMEP&lt;9bar</td>
<td>Homogeneous</td>
<td>Stoich</td>
<td>&gt;1bar</td>
<td>no</td>
</tr>
</tbody>
</table>

Red dots are standard assessment points

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

**LMC vs. SMC (AVL Reference)**

BSFC Percent Improvement

Status at 2017 AMR

Plots courtesy of AVL

**up to 38:1 A/F**
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\textsubscript{x}

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

HC vs. stoich-homogeneous

✓ Lower for BMEP > 3bar
× 2x for BMEP < 3bar
• 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
PASS + Urea architecture defined for transient dyno development

**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
**ACCOMPLISHMENTS AND PROGRESS**

**CHALLENGE: LEAN / LOW TEMPERATURE AFTERTREATMENT**

**Exhaust heating (simulation results)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/F</td>
<td></td>
</tr>
<tr>
<td>Combustion phasing</td>
<td></td>
</tr>
<tr>
<td>Effective CR</td>
<td></td>
</tr>
</tbody>
</table>

- **ΔExhaust Temp (°C)**
  - 0 20 40 60 80 100

- **NFSFC penalty**
  - 0% 20% 40% 60% 80%

- **CA50 sweeps**
  - lean-stratified
  - stoich-homogeneous

- **1500 RPM, 140 kPa NMEP**

**Rich combustion for NH₃ reactant formation (single-cyl results)**

- **1750 RPM, 350 kPa NMEP**

- **CO, H₂ (ppm)**

- **NOₓ (ppm)**

- **Equivalence Ratio**
  - 0.99 1.01 1.03 1.05 1.07 1.09 1.11

- **NH₃** formation over TWC at EQR>1
- **H₂** is primary reductant for NO→NH₃ reaction
- **CO** and **HCs** also contribute to **H₂** formation
- **CO breakthrough** remains primary concern

**Calibration explored to guide aftertreatment management strategies on MCE**

**GENERAL MOTORS**

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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)
TECHNICAL ACCOMPLISHMENTS AND PROGRESS
MULTI-CYLINDER ENGINE HARDWARE

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

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

PROJECTED BRAKE THERMAL EFFICIENCY
Lean Miller Cycle Single Cylinder

DOE Targets

2000 RPM 2 Bar BMEP
32%

2000 RPM 20% Load
35%

TECHNICAL ACCOMPLISHMENTS & PROGRESS
SINGLE CYLINDER THERMAL EFFICIENCY AT TARGET
TECHNICAL ACCOMPLISHMENTS & PROGRESS
FUEL ECONOMY PROMISING BASED ON VEHICLE FE SIMULATIONS

- Potential to meet 35% FE goal
- Translates to 36% on a CO₂ – 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
• 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 NOₓ to 10g/kg-fuel to minimize passive NH₃ 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\textsubscript{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!