Next Generation High Efficiency Boosted Engine Development

Michael Shelby – Principal Investigator
Ford Motor Company

Project ID #: ACE156
DE-EE0008878

June 4th, 2020
1:30 pm
30-Minute
**Project Overview**

**Partners**
- FEV North America Inc.
- Oak Ridge National Lab (ORNL)

**Timeline**
- Project start: 4Q 2019
- Project end: 4Q 2022
- Percent complete: 15%

**Barriers**
- Engine efficiency can be improved by increasing the compression ratio (CR). CR is limited by autoignition (knock), heat losses, and unfavorable combustion chamber shapes.
- Dilute stoichiometric combustion offers benefits in engine efficiency but is limited by combustion stability and exhaust gas recirculation (EGR) flow capacity.
- Engine friction, pumping work, and accessory loads must be minimized to improve net efficiency.
- Reducing vehicle mass improves fuel economy but is limited by structural requirements and manufacturing techniques.

**Budget**
- Total project funding: $10M
- DOE share: $7,566,731
  - EERE: $7,416,731
  - FFRDC: $150,000
- Recipient: $2,433,269
- Budget period 1: $3,419,937
  - Budget period 2: $5,135,831
  - Budget period 3: $1,444,232

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

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Project Relevance

Objective: Design, evaluate, build and test an engine that will achieve 23% fuel economy improvement and 15% weight reduction relative to a 2016MY 3.5L V6 EcoBoost F150 baseline.

Impact: Technologies investigated in this project will reduce CO2 emissions of the highest production volume powertrains found in light duty vehicles by addressing the following barriers:

- Knock mitigation
- Dilute combustion
- Friction reduction
- Thermal management
- Weight reduction

Project supports the VTO Advanced Combustion Engine and Fuels Subprogram goals of improving light-duty engine efficiency, reducing mass and hence improving passenger vehicle fuel economy.

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Delays due to COVID 19 are expected but can not be quantified at this time.

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### Project Milestones

<table>
<thead>
<tr>
<th>#</th>
<th>Date</th>
<th>Event / Milestone</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10/01/19</td>
<td>Conditional award effective</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>11/13/19</td>
<td>DOE on-site kick-off</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>01/27/20</td>
<td>Definitized DOE award executed</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>03/16/20</td>
<td>FEV sub-contract executed, PO issued</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>03/31/20</td>
<td>SCE assumptions, targets &amp; hard points defined</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>06/30/20</td>
<td>SCE hardware frozen, 3-plug and pre-chamber</td>
<td>75</td>
</tr>
<tr>
<td>7</td>
<td>09/30/20</td>
<td>Composite oil pan concept selected</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>12/31/20</td>
<td>Analytical assessment of combustion metrics</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>03/31/21</td>
<td>SCE development complete &amp; MCE ignition selected</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>06/30/21</td>
<td>MCE design frozen</td>
<td>5</td>
</tr>
<tr>
<td>11</td>
<td>09/30/21</td>
<td>MCE hardware procurement</td>
<td>5</td>
</tr>
<tr>
<td>12</td>
<td>12/31/21</td>
<td>Analytical assessment of SCE &amp; MCE design vs. targets</td>
<td>5</td>
</tr>
<tr>
<td>13</td>
<td>03/31/22</td>
<td>MCE built, install and debug complete</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>06/30/22</td>
<td>Initial fuel consumption map complete</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>12/31/22</td>
<td>Final assessment of vehicle fuel economy &amp; engine weight</td>
<td>0</td>
</tr>
</tbody>
</table>
Technical Accomplishments and Progress

1D & 3D modeling used to investigate technologies enabling increased Compression Ratio (CR).

- Baseline CR: 10:1, targeting 13-15:1 enabled by:
  - Miller cycle operation at high load
    » Advanced boost system
    » Continuously variable valvetrain
    » Effective intercooling (exploring additive manufacturing)
  - Thermal management of combustion chamber surfaces
    » Intake port cooling / insulation, thermal barrier coated port side of intake valves, hollow / sodium cooled valves, high thermal conductivity valve guides, valve seats and rings, advanced split cooling, advanced piston cooling
  - Fast burn rate
    » Advanced ignition systems
    » Long stroke -> favorable surface to volume ratio, short flame travel distance, high piston speed for generating charge motion
  - Cooled EGR

1D simulation results show that peak power performance targets are achievable at 14:1 CR. Further improvements for low speed torque are being investigated.

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Technical Accomplishments and Progress

Two Versions of Single Cylinder Combustion System Hardware Designed and Analyzed

Three traditional spark plug concept
- Conservative approach using known technology
- Allows largest valve sizes to maximize flow
- Single cylinder hardware manufacture almost complete

Active Pre-chamber concept
- Promises faster burn rate than 3-plug
- Cartridge system allows separate or premixed fuel + air
- Includes a main-chamber spark plug for cold start

- Improved package efficiency and synergistic integration with valvetrain, fuel and cooling subsystems
- Port fuel injection (PFI) and side direct injection (DI) on both concepts, plus third fuel injector for prechamber concept

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Technical Accomplishments and Progress

- 0.75 Bore/Stroke ratio selected for favorable combustion chamber shape at high compression ratio.

- Long stroke provides high piston speed and strong charge motion for improved burn rate and mixing.

- Combustion system port design parameterized and optimized for flow, mixing and burn rate improvement using 3D computational fluid dynamics (CFD)

3D modeling has been extensively used to design the intake ports and combustion chamber surface geometry for dilute stoichiometric combustion

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Technical Accomplishments and Progress

Heat Loss Reduction Strategy and Evaluation

Reduced Surface-to-Volume Ratio
- Reducing bore-to-stoke ratio results in less fuel energy lost as heat to chamber walls and the cooling system
- Fuel consumption and design sensitivity studies were conducted to evaluate benefits and trade-offs of long stroke designs
- A target bore-to-stoke ratio of 0.75 was established for the project

Low Heat Capacity Coatings
- Coating combines low conductivity and low heat capacity so surface ‘follows’ gas temperature
- Multiple coatings evaluated analytically for brake thermal efficiency (BTE), knock tendency, engine durability and application production feasibility
- Compared to traditional engine deposits at an equivalent thickness, coatings provided up to 2% BTE improvement and better knock performance
- A coating was selected and applied to prototype parts for evaluation

Reducing heat losses to the combustion chamber / cooling system is critical to fuel economy and guided component design requirements for the project.

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Technical Accomplishments and Progress

There are many areas being optimized for reduced friction, including:

Cylinder Bore-

- Cylinder bore shaping via articulated honing tools (mechanically honing an inverse shape) and improved cooling (reducing non-uniform thermal expansion) via split cooling are being developed to improve the hot, running cylinder bore shape to reduce piston skirt friction and enable a reduction in ring tensions without negatively impacting oil consumption.

- Several iterations of block geometry and cooling strategies have been analyzed on the I6 block, as well as surrogate work (I3 cooling jackets shown) to improve the bore geometry.

- High porosity (good oil retention for lubrication) thermally sprayed cylinder liners combined with a mirror finish is in development to improve ring and skirt sliding friction.

- Surrogate testing has been ongoing using different coatings to assess friction opportunities as well as ring surface finish (nitriding, physical vapor deposition (PVD), diamond-like coating (DLC)).

Reducing skirt friction and lowering ring tensions are major focus of friction reduction

Any proposed future work is subject to change based on funding levels
Technical Accomplishments and Progress

Additional developments in reduced friction include:

• 10 mm crank offset to reduce piston side forces on the cylinder liner

• Implementing a roller bearing on the #1 crank main to replace a traditional journal bearing (see larger bore required in block) for lower friction

• Using non-contacting (low friction) crank seals, front and rear.

• Lubrication team is testing lower viscosity oils to better understand
  – Wear rates and durability concerns (rings, oil pump, etc.)
  – Measuring friction reduction under various operating conditions
  – Effects on subsystem function (i.e. oil pump sizing and main oil gallery pressure)

• A fully variable mechanical oil pump as well as an optional supplemental electric oil pump are being investigated to reduce pump size requirements and parasitic losses

Multiple actions across subsystems being investigated & implemented to reduce total engine friction

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Technical Accomplishments and Progress

**Planned Weight Actions**
Architecture change, advanced materials, integrated exhaust manifold, additive cores, continuously variable valve lift (CVVL), plasma transfer wire arc (PTWA) bores instead of cast iron liners

**Weight Risks**
Additional hardware such as sensors, advanced boost system, longer stroke, and pre-chamber hardware

Weight reduction will be a challenge for the project. Considerable attention needs to be given to weight during the component design and development process to understand the trade-offs.

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Response to Previous Year Reviewers’ Comments

• Not applicable. This is the 1st AMR presentation for this project.
Collaboration and Coordination with Other Institutions

Industry Subrecipient Project Partner
- Co-design / co-development of pre-chamber
- Intake air system design / development
- EGR system design / development
- Piston design / development
- Lubrication system design / development
- CAD support for various components

DOE VTO National Laboratory Partner
- Co-design / development of composite structural oil pan
- Material selection, tool development, part production

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Remaining Challenges and Barriers

- The technologies added to achieve the engine efficiency goals have increased the challenge of meeting the weight reduction target.
- Limited active pre-chamber experimental data is available for correlating 3D combustion models.
- Peak power results look promising at the target compression ratio, but 1D modeling predicts a shortfall in full load torque at low engine speed.
- Meeting the crank stiffness requirements to avoid torsional vibration challenges have resulted in larger main bearings increasing friction and mass.
Proposed Future Research

• **Budget Period 1 – Concept Design and Analysis**  
  
  – Single Cylinder Engine (SCE) Development
    » Build two SCEs with different combustion chamber configurations; a multi-plug design and a pre-chamber design
    » Use dynamometer testing to demonstrate the capabilities of each concept to meet intermediate combustion metrics (dilution tolerance, burn rate etc.) to support fuel economy and emission objectives.
  
  – Multi-Cylinder Engine (MCE) Design
    » Select leading SCE concept to move forward into the MCE design effort
    » Initiate cylinder head, cylinder block and other long lead/interfacing components

• **Budget Period 2 – Component Development & SCE Testing**  
  
  – Continue SCE dynamometer testing to support MCE-specific design concerns
  – Deliver MCE cylinder head hardware by mid-Q3 2021
  – Deliver remaining MCE hardware by late Q4 2021

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Summary

• This project has recently started but significant design and analysis work has been completed.
• The first single cylinder engine is under construction and the second single cylinder engine design work is nearly complete.
• Designs are not yet mature enough to assess against the 23% fuel economy and 15% weight targets. Status updates will be available in subsequent AMR presentations.
• Delays due to COVID 19 are expected but can not be quantified at this time.
Technical Backup Slides
Objectives

Design, evaluate, build and test an engine achieving 23% fuel economy improvement and 15% weight reduction relative to a 2016MY 3.5L V6 EcoBoost F150.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>2016MY F150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Displacement</td>
<td>3.5L 6 Cylinder GTDI 4V</td>
</tr>
<tr>
<td>Transmission</td>
<td>6R80 Auto</td>
</tr>
<tr>
<td>Weight</td>
<td>5250 lbs ETW</td>
</tr>
<tr>
<td>Fuel Economy</td>
<td>4WD: 17MPG (15 City / 20 Hwy)</td>
</tr>
<tr>
<td>Emissions Level</td>
<td>Tier 2 Bin 4</td>
</tr>
<tr>
<td>Fuel Type</td>
<td>Regular Gasoline</td>
</tr>
<tr>
<td>Engine As Shipped Weight</td>
<td>184 kg</td>
</tr>
<tr>
<td>Peak Thermal Efficiency</td>
<td>36.7%</td>
</tr>
<tr>
<td>Peak Power</td>
<td>365HP @ 5000rpm</td>
</tr>
<tr>
<td>Peak Torque</td>
<td>420lb-ft @ 2500rpm</td>
</tr>
<tr>
<td>Passenger and Cargo</td>
<td>7599 GVWR</td>
</tr>
<tr>
<td>Towing Capabilities</td>
<td>12,200 lbs</td>
</tr>
</tbody>
</table>

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## Estimated Fuel Economy Benefits

<table>
<thead>
<tr>
<th>Proposed Actions</th>
<th>Baseline</th>
<th>% FE Improvement</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>13:1–15:1 CR</td>
<td>10:1</td>
<td>6-8</td>
<td>Requires significant knock mitigation. Airpath thermal mgt., split and optimized cooling system, miller valve events, lube system optimization for piston cooling, high conductivity valve seats and guides</td>
</tr>
<tr>
<td>35-50% Cooled EGR</td>
<td>0%</td>
<td>2-5</td>
<td>Requires advanced ignition (active pre-chamber, multi-plug or other unconventional ignition technologies) and boost system improvements</td>
</tr>
<tr>
<td>B/S opt: 0.72-0.82</td>
<td>1.06</td>
<td>1.0-2.0</td>
<td>Efficiency / CR enabler, likely requires architecture changes</td>
</tr>
<tr>
<td>CVVL</td>
<td>Ti-VCT</td>
<td>2.5-3.5</td>
<td>Enables Miller and transient fuel economy</td>
</tr>
<tr>
<td>Stop-Start</td>
<td>-</td>
<td>3.0-4.0</td>
<td></td>
</tr>
<tr>
<td>Down speeding</td>
<td>6 speed</td>
<td>2.0-4.0</td>
<td>10 speed transmission in place of 8 speed</td>
</tr>
<tr>
<td>Temperature swing coatings</td>
<td>-</td>
<td>1-2</td>
<td>Reduced heat losses with less intake charge heating</td>
</tr>
<tr>
<td>Friction reduction</td>
<td>base</td>
<td>1-2</td>
<td>Form hone, high porosity PTWA with mirror finish, roller bearings, variable displacement oil pump, offset crank, advanced cooling strategy, split and optimized flow paths.</td>
</tr>
<tr>
<td>Fast warm-up</td>
<td>base</td>
<td>0.2</td>
<td>Advanced cooling system</td>
</tr>
<tr>
<td>Weight reduction</td>
<td>1</td>
<td></td>
<td>Weight reduction achieved through architecture change, composite materials, and additive manufacturing largely offset by adding EGR system and upgrading the boost system.</td>
</tr>
<tr>
<td>Engine upsizing</td>
<td>base</td>
<td>-1.7</td>
<td>Increased displacement to offset lower power density</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>~23</td>
<td></td>
</tr>
</tbody>
</table>

*Any proposed future work is subject to change based on funding levels*
## Estimated Engine Weight Walk

<table>
<thead>
<tr>
<th>Proposed Actions</th>
<th>% Weight Reduction</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine architecture</td>
<td>5.2</td>
<td>Shift from a “V” to an “I” architecture</td>
</tr>
<tr>
<td>Advanced materials</td>
<td>2.7</td>
<td>Carbon fiber compression-molded oil pan, composite carbon fiber compression-molded front cover (not included), additive hollow titanium connecting rods (not included), composite engine mounts (not included), composite rear seal carrier (not included)</td>
</tr>
<tr>
<td>Exhaust manifolds</td>
<td>3.6</td>
<td>Eliminate two cast steel manifolds and integrate into the cylinder head</td>
</tr>
<tr>
<td>Single bank aftertreatment</td>
<td>3.5</td>
<td>Reduced number of catalysts bricks, cans and sensors.</td>
</tr>
<tr>
<td>Optimized cylinder head</td>
<td>1.2</td>
<td>Use indirect additive manufacturing to optimize head for weight</td>
</tr>
<tr>
<td>CVVL</td>
<td>1.3</td>
<td>Delete (2) intake cams and valvetrain hardware</td>
</tr>
<tr>
<td>Optimized cylinder block</td>
<td>0.8</td>
<td>Use indirect additive manufacturing to optimize block for weight. (not included in prototype)</td>
</tr>
<tr>
<td>PTWA</td>
<td>1.2</td>
<td>Replace (6) cast iron bore liners with plasma transfer wire arc (PTWA) coating</td>
</tr>
<tr>
<td>Battery optimization</td>
<td>3.4</td>
<td>Replace 12V flooded / wet cell lead acid with Li-ion 12V starter battery</td>
</tr>
<tr>
<td>EGR system</td>
<td>-3.3</td>
<td>Baseline does not have an EGR system so there is a weight increase for hardware (valve, cooler, tubes, sensors, and wiring)</td>
</tr>
<tr>
<td>Engine thermal actions</td>
<td>-1.8</td>
<td>Additional piston cooling jets, valves and sensors to manage the advanced cooling system, liquid cooled CAC – dry weight</td>
</tr>
<tr>
<td>Long stroke</td>
<td>-2.7</td>
<td>Deck height increase up to 20mm</td>
</tr>
<tr>
<td>Net Weight Savings</td>
<td>15.1</td>
<td></td>
</tr>
</tbody>
</table>

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