A MultiAir / MultiFuel Approach to Enhancing Engine System Efficiency

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DOE NETL Project Officer: Ralph Nine

June 19, 2014
Overview

Timeline
• Project Start Date: May 07, 2010
• Project End Date: April 30, 2014
• Percent Complete: 98%
  (Report Pending)

Barriers
• Downsized engines offer higher fuel economy, but the degree of downsizing is limited by transient performance and dynamic range
• For gasoline engines, abnormal combustion (knock) limits the geometric compression ratio, thereby limiting engine efficiency
• EGR improves engine efficiency, but increases in EGR (and efficiency) are limited by combustion instability
• Engine operation in vehicle is not at its most efficient (ideal) state

Budget
• Total: $29,992,676
  - Partner Cost Share: $15,534,104
  - DOE Cost Share: $14,458,572

Partners
• Argonne National Laboratory (ANL)
• Bosch
• Delphi
• The Ohio State University (OSU)
Timeline and Major Milestones

<table>
<thead>
<tr>
<th>#</th>
<th>Date</th>
<th>Milestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nov 2010</td>
<td>Performance Specs / Engine Selection</td>
</tr>
<tr>
<td>2</td>
<td>Jul 2011</td>
<td>Dyno Engine Design</td>
</tr>
<tr>
<td>3</td>
<td>Nov 2011</td>
<td>Procure, Build, Initial Test of Dyno Engine</td>
</tr>
<tr>
<td>4</td>
<td>Jun 2012</td>
<td>Alpha 2 Engine Technology Selection</td>
</tr>
<tr>
<td>5</td>
<td>Sep 2012</td>
<td>Testing Results for Alpha 2 Design Input</td>
</tr>
<tr>
<td>6</td>
<td>Jan 2013</td>
<td>Alpha 2 Engine Design</td>
</tr>
<tr>
<td>7</td>
<td>Mar 2013</td>
<td>Alpha 2 Engine Procurement</td>
</tr>
<tr>
<td>8</td>
<td>Apr 2013</td>
<td>Engine Controls and Vehicle Design</td>
</tr>
<tr>
<td>9</td>
<td>Apr 2013</td>
<td>Alpha 2 Dyno Engine First Fire</td>
</tr>
<tr>
<td>10</td>
<td>Aug 2013</td>
<td>Vehicle Energy Simulator (OSU)</td>
</tr>
<tr>
<td>11</td>
<td>Oct 2013</td>
<td>Vehicle 1 Build</td>
</tr>
<tr>
<td>12</td>
<td>Nov 2013</td>
<td>Engine Dyno Calibration (part load / FTP area)</td>
</tr>
<tr>
<td>13</td>
<td>Jan 2014</td>
<td>Vehicle 2 Build</td>
</tr>
<tr>
<td>14</td>
<td>Apr 2014</td>
<td>Engine Dyno Calibration (full range / EtOH)</td>
</tr>
<tr>
<td>15</td>
<td>Apr 2014</td>
<td>Vehicle Calibration</td>
</tr>
<tr>
<td>16</td>
<td>Apr 2014</td>
<td>Vehicle Demonstration</td>
</tr>
</tbody>
</table>
Project Objectives

• Demonstrate a 25% improvement in combined City FTP and Highway fuel economy for the Chrysler minivan
  – The baseline (reference) powertrain is the 2009 MY state-of-the-art gasoline port fuel-injected 4.0L V6 equipped with the 6-speed 62TE transmission
  – This fuel economy improvement is intended to be demonstrated while maintaining comparable vehicle performance to the reference engine
  – The tailpipe emissions goal for this demonstration is Tier 2, Bin 2

• Accelerate the development of highly efficient engine and powertrain technologies for light-duty vehicles, while meeting future emissions standards

• Create and retain jobs in support of the American Recovery and Reinvestment Act of 2009

• Project content is aimed directly at the listed barriers
Results – Fuel Economy

Goal = 25% improvement in combined FTP City and Highway fuel economy achieved in Powertrain Test Cell, vehicle results are pending

<table>
<thead>
<tr>
<th></th>
<th>FTP City</th>
<th>Highway</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Economy Improvement</td>
<td>30%</td>
<td>17%</td>
<td>26%</td>
</tr>
</tbody>
</table>

Fuel Economy Improvement

This cumulative fuel consumed equates to a 30% improvement in Fuel Economy
Goal = Maintain comparable vehicle performance to the reference engine

Goal Achieved

### Accomplishment/Progress

#### Results – Performance

<table>
<thead>
<tr>
<th>Engine Type</th>
<th>0 to 30 MPH Time (sec)</th>
<th>0 to 60 MPH Time (sec)</th>
<th>1/4 Mile Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAMF 2.4L</td>
<td>3.20</td>
<td>8.73</td>
<td>16.80</td>
</tr>
<tr>
<td>4.0L</td>
<td>3.31</td>
<td>8.66</td>
<td>16.77</td>
</tr>
</tbody>
</table>
Accomplishment/Progress

Results – Tailpipe Emissions

<table>
<thead>
<tr>
<th></th>
<th>FTP City Cycle</th>
<th>Highway Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bag Weighted g/mi</td>
<td>NMOG</td>
<td>NOx</td>
</tr>
<tr>
<td>Vehicle Status</td>
<td>0.014</td>
<td>0.009</td>
</tr>
<tr>
<td>Emission Standard</td>
<td>0.010</td>
<td>0.020</td>
</tr>
</tbody>
</table>

Goal = Tailpipe emissions demonstrated at Tier 2, Bin 2
Goal was not yet achieved, but the equivalent Tier 3 standard was
Technology Approach & Contribution

**Engine Efficiency**
- High compression ratio
- Engine downsizing, and 2-stage boosting
- Cooled EGR, DI, and spray bore liners, EtOH for improved knock resistance
- Advanced ignition for improved stability with high dilution

**Fuel Economy Improvement = 26%**
- Base Engine Design, Controls, & Calibration: 12%
- Ideal Engine Operation: 6%
- Low Lock-up Speed: 6%
- Reduced Losses: 6%

**Thermal Management**

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The Alpha 2 engine fuel consumption is at or below goal throughout the load range.

The Alpha 2 engine fuel consumption is well below the 4.0L at a given torque.

Engine efficiency alone yields a 12% Fuel Economy improvement (combined cycle)
Accomplishment/Progress

**Ideal Engine Operation - Low Lock-up Speed**

**Engine Downspeeding Enabler**
- Fixed Crank @ Ring Gear
- Fixed Crank @ Trans. Input
- Pend. Crank @ Ring Gear
- Pend. Crank @ Trans. Input

<table>
<thead>
<tr>
<th>Engine Speed (RPM)</th>
<th>Second Order Amplitude (deg p-p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1000</td>
<td>4.5</td>
</tr>
<tr>
<td>2000</td>
<td>3.5</td>
</tr>
<tr>
<td>3000</td>
<td>2.5</td>
</tr>
<tr>
<td>4000</td>
<td>1.5</td>
</tr>
<tr>
<td>5000</td>
<td>0.5</td>
</tr>
</tbody>
</table>

40-45% reduction

Surrogate vehicle trans-input vibration below 1/3 deg. p-p to 1100 rpm: low speed lock-up enabler

Assessed Fuel Economy Gain Over Baseline = 6.3% (combined)

**Vehicle Downspeeding Response (FTP Combined)**

- 6.3%

**Engine Downspeeding Response @ 5.7kW**

- 13.5%

This presentation does not contain any proprietary, confidential, or otherwise restricted information
Rapid Warm-Up Time Optimization
OSU developed an optimized thermal system control strategy to transfer energy from engine coolant to oil and transmission fluid (ATF), achieving rapid warm-up. Increased temperatures reduce viscosity and friction losses, improving vehicle fuel economy.

Energy-Efficient Coolant Temp Conditioning
Control algorithm coordinates hybrid coolant pump, electric thermostat and radiator fan to optimize energy consumption during fluid conditioning. An energy balance conducted in simulation illustrates the effects of the control strategy in reducing various energy losses on the engine crankshaft.

<table>
<thead>
<tr>
<th>Energy Loss</th>
<th>Baseline</th>
<th>Optimized</th>
<th>Difference</th>
<th>% Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission</td>
<td>2.838 MJ</td>
<td>2.755 MJ</td>
<td>0.083 MJ</td>
<td>3.0%</td>
</tr>
<tr>
<td>Engine</td>
<td>0.716 MJ</td>
<td>0.679 MJ</td>
<td>0.037 MJ</td>
<td>5.2%</td>
</tr>
<tr>
<td>Coolant Pump</td>
<td>0.147 MJ</td>
<td>0.125 MJ</td>
<td>0.022 MJ</td>
<td>15.4%</td>
</tr>
<tr>
<td>Radiator Fan</td>
<td>0.032 MJ</td>
<td>0.007 MJ</td>
<td>0.025 MJ</td>
<td>78.9%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3.733 MJ</strong></td>
<td><strong>3.566 MJ</strong></td>
<td><strong>0.168 MJ</strong></td>
<td><strong>4.5%</strong></td>
</tr>
</tbody>
</table>

% Fuel Economy Improvement

<table>
<thead>
<tr>
<th></th>
<th>City</th>
<th>Highway</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC Reduction [%]</td>
<td>1.1%</td>
<td>0.5%</td>
<td>0.85%</td>
</tr>
</tbody>
</table>
Ancillary Loads Reduction

Vehicle Electrical System Control
OSU developed a supervisory energy management strategy to utilize the battery as an energy buffer to reduce alternator loads, improving fuel economy.

The OSU control (Adaptive Pontryagin Minimum Principle, A-PMP) manages the current split between battery and alternator for fuel economy, in presence of constraints (on voltage, current and battery charge).

Experimental tests conducted in vehicle show that the control strategy improves fuel economy and maintains battery charge without degrading its life.

Fuel Consumption Comparison with Baseline Control Strategy

<table>
<thead>
<tr>
<th>% Fuel Economy Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>City</td>
</tr>
<tr>
<td>1.3%</td>
</tr>
</tbody>
</table>

This presentation does not contain any proprietary, confidential, or otherwise restricted information.
Two vehicles were built for development and demonstration of performance, emissions and fuel economy

Accomplishments:

• Packaging: Emissions and fuel economy hardware was packaged in the vehicle including thermal protection

• Communication: Network utilizing a Gateway was developed to manage the communication between the vehicle and powertrain systems

• Software: Prototype control software was developed to manage the operation of emissions and fuel control devices

• Instrumentation: Full powertrain instrumentation was complete and packaged in vehicle Stow-n-Go compartment

• Thermal Management: High and Low Temperature Radiators were developed and packaged to efficiently manage thermal energy
Cold Start Emissions Control

- Low catalyst temperatures were observed during the FTP cycle (especially at cold start)
- Exhaust system mass was decreased with Dual Wall Air Gap (DWAG) exhaust manifold and optimized exhaust flow path

Catalyst Light-Off Temperatures (FTP City)

Hardware changes resulted in 250ºC catalyst brick temperature increase
Emissions Results (Hardware Evaluation)

Powertrain Test Cell FTP City Emissions Results

- NMOG
- NOx
- CO/10

<table>
<thead>
<tr>
<th>Secondary Air</th>
<th>Secondary Air</th>
<th>Secondary Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast Stainless Steel Manifold</td>
<td>DWAG Manifold</td>
<td>DWAG Manifold</td>
</tr>
<tr>
<td></td>
<td>Bypass Tube</td>
<td>Bypass Tube</td>
</tr>
<tr>
<td></td>
<td>Flow Diverter Valves</td>
<td>Flow Diverter Valves</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Optimized Catalyst</td>
</tr>
</tbody>
</table>

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ANL Dual Fuel: Gasoline + Diesel

CFD Modeling
- Extensive validation of diesel & GDI single and multi-hole sprays against X-ray data from the Advanced Photon Source
- Both RANS and LES turbulence models tested - both captured trends well
- Genetic Algorithm used to optimize key engine parameters under Diesel Micro Pilot (DMP) operation

Engine Testing: Conventional Diesel and Gasoline Fuels
- Achieved 210 g/kW-hr BSFC during Diesel Assisted Spark Ignition (DASI) operation
- Decreased the diesel percentage needed for DASI operation by 3%

Engine Testing: Alternative Fuels (Fischer Tropsch Diesel and Ethanol Blends)
- Increased DASI operation Break Thermal Efficiency from 40% to 45% using E85 and FT diesel
- Knock does not limit efficiency like with conventional fuels
- Increased DMP operational range from 160 kPa boost down to 130
- Increased off-peak engine Break Thermal Efficiency by 2 – 3%
- Decreased the diesel percentage needed for DASI and DMP operation by 5%
Partnerships / Collaborations

Providing computational fluid dynamics (CFD) modeling, spray measurements, and in-cylinder combustion high-speed imaging to support combustion development and control

Supplied fuel injectors, lines, pumps, harnesses and controllers for the DI gasoline and DI diesel fuel systems, and collaborated with Chrysler to integrate the injector drivers

Supplied Ion Sense coils and developing combustion feedback system to allow closed loop combustion control

Developed Vehicle Energy Simulator (VES) and supervisory controller (Vehicle Energy Manager – VEM) that oversees and integrates energy management of vehicle subsystems
Project Summary

- A downsized, highly-diluted, spark-ignited concept engine has been demonstrated and comes very close to meeting all the project goals.

- Fueling with two fuels, though very efficient, does present challenges:
  - Durability / fouling of the fuel injector for the lesser-used fuel
  - A single, high performance fuel would be preferred
  - For the demonstration vehicle SI case, it means a higher Octane fuel

- High engine efficiency, presents challenges as well:
  - Namely low exhaust temperatures and poor catalyst performance
  - Further exploration in developing catalyst materials that operate at lower temperatures is of high value

- Two-stage turbocharging presents challenges regarding cold start emissions:
  - A systems approach that addresses thermal mass and engine efficiency must be taken
Thank You
Technical Back-Up Slides
Results

- Systems tested: 1-plug and 3-plug baseline systems, Federal Mogul Advanced Corona Ignition System (ACIS)
- For each ignition system, EGR rate at each operating point is selected to minimize BSFC while maintaining combustion stability
- All systems tested thus far show 1-5% benefit over single-plug conventional system
Ion Sense / Combustion Feedback

- **Delphi Ion-Sense Combustion Sensing**
  - Ignition Coil technology coupled to an Ion Sense Development Controller (ISDC). ISDC electronics have been updated to accept a wider range of ion current input that is generated by the Alpha 2 engine at high speeds and loads.

- **Algorithm and Software Development**
  - All algorithm and software development activities have been completed for all combustion feedback parameters including combustion phasing, knock, and combustion stability.

- **Real-Time Ion-Sense Combustion Feedback on Dyno and Vehicle**
  - Real-time combustion feedback has been implemented and demonstrated on three engine dyno installations and installed on two vehicles.

- **Combustion Phasing**
  - Combustion phase detection range of operation expanded by 38% from last year’s performance.

- **Knock Detection calibration work continues**
  - Refinement for combustion feedback spark control.

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*Ion-sense Combustion Feedback hardware integrated into demonstration vehicle for real-time control*

*Combustion phasing range extended while maintaining accuracy*

*Ion-sense knock feedback mimics pressure-based reference*
Vehicle Status - BSG

Belt-Starter Generator (BSG) was intended to be used for Stop / Start operation, but it is not likely needed to achieve the 25% fuel economy savings. If needed, the BSG reduces fuel consumption by shutting off the engine during idle conditions saving an estimated 4% fuel during an FTP city cycle (3.2% savings combined).

Accomplishments:
- BSG is operational and able to maintain vehicle battery charge and hot start the vehicle
- Calibration complete on the E-Tensioner torque request vs. tensioner force
- Prototype software was developed to control transmission, E-Tensioner, and BSG during a shut down and start up event

Stop Start FTP FE benefit estimate

FTP City estimated benefit: +4%
### Approach & Accomplishment/Progress

#### ANL Spray Modeling & Engine Optimization Through CFD

- Extensive validation of diesel/GDI single and multi-hole sprays against x-ray data from APS

![GDI x-ray](image1) ![GDI CFD](image2)

- Both **RANS** and **LES turbulence models** tested. Both models **could capture global trends quite well**. The need for improved turbulent dispersion model with LES was identified

- **Genetic Algorithm** was used to **optimize the key engine parameters** under DMP stable conditions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Baseline</th>
<th>Optimized</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGR ratio (%)</td>
<td>35.3</td>
<td>35</td>
</tr>
<tr>
<td>ICL (° CA ATDC)</td>
<td>461.8</td>
<td>452</td>
</tr>
<tr>
<td>DMP ratio (%)</td>
<td>13.4</td>
<td>6.6</td>
</tr>
<tr>
<td>DMP SOI (° CA BTDC)</td>
<td>19.5</td>
<td>27.8</td>
</tr>
<tr>
<td>Soot (g/Kw-h)</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>NOx (g/Kw-h)</td>
<td>0.08</td>
<td>0.06</td>
</tr>
</tbody>
</table>

- DASI or other highly unstable operating conditions need advanced LES turbulence modeling to define a criteria for stability