Advanced Gasoline Turbocharged Direct Injection (GTDI) Engine Development

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Project ID: ACE065
Overview

- **Timeline**
  - Project Start: 10/01/2010
  - Project End: 12/31/2014
  - Completed: 76%

- **Total Project Funding**
  - DOE Share: $15,000,000.
  - Ford Share: $15,000,000.
  - Funding in FY2013: $4,911,758.
  - Funding in FY2014: $2,428,972.

- **Barriers**
  - Gasoline Engine Thermal Efficiency
  - Gasoline Engine Emissions
  - Gasoline Engine Systems Integration

- **Partners**
  - Lead: Ford Motor Company
  - Support: Michigan Technological University (MTU)
Ford Motor Company has invested significantly in Gasoline Turbocharged Direct Injection (GTDI) engine technology in the near term as a cost effective, high volume, fuel economy solution, marketed globally as EcoBoost technology.

Ford envisions further fuel economy improvements in the mid & long term by further advancing the EcoBoost technology.

- Advanced dilute combustion w/ cooled exhaust gas recycling & advanced ignition
- Advanced lean combustion w/ direct fuel injection & advanced ignition
- Advanced boosting systems w/ active & compounding components
- Advanced cooling & aftertreatment systems
Objectives

Ford Motor Company Objectives:
- Demonstrate 25% fuel economy improvement in a mid-sized sedan using a downsized, advanced gasoline turbocharged direct injection (GTDI) engine with no or limited degradation in vehicle level metrics.
- Demonstrate vehicle is capable of meeting Tier 3 SULEV30 emissions on FTP-75 cycle.

MTU Objectives:
- Support Ford Motor Company in the research and development of advanced ignition concepts and systems to expand the dilute / lean engine operating limits.
Approach

- Engineer a comprehensive suite of gasoline engine systems technologies to achieve the project objectives, including:
  - Aggressive engine downsizing in a mid-sized sedan from a large V6 to a small I4
  - Mid & long term EcoBoost technologies
    - Advanced dilute combustion w/ cooled exhaust gas recycling & advanced ignition
    - Advanced lean combustion w/ direct fuel injection & advanced ignition
    - Advanced boosting systems w/ active & compounding components
    - Advanced cooling & aftertreatment systems
  - Additional technologies
    - Advanced friction reduction technologies
    - Advanced engine control strategies
    - Advanced NVH countermeasures
- Progressively demonstrate the project objectives via concept analysis / modeling, single-cylinder engine, multi-cylinder engine, and vehicle-level demonstration on chassis rolls.
## Milestone Timing

<table>
<thead>
<tr>
<th>Budget Period 1</th>
<th>Budget Period 2</th>
<th>Budget Period 3</th>
<th>Budget Period 4</th>
</tr>
</thead>
</table>

### 1.0 - Project Management

### 2.0 - Concept
- Engine architecture agreed

### 3.0 - Combustion System Development
- SCE meets combustion metrics

### 4.0 - Single Cylinder Build and Test
- SCE meets combustion metrics

### 5.0 - Engine Evaluation on Dynamometer
- MCE MRD, Begin MCE Dyno Development, MCE meets FE and emissions metrics

### 6.0 - Vehicle Build and Evaluation
- Vehicle Parts MRD, Begin Vehicle Development, Vehicle meets 25% FE and T3SULEV30

### 7.0 - Aftertreatment Development
- A/T Concept Selection, A/T System meets emissions metrics

### 8.0 - Combustion Research (MTU)
- A/T Concept Selection
Project Assumptions

- **Attribute Assumptions**

  Peak Power = 80 kW / L @ 6000 rpm
  Peak Torque = 20 bar BMEP @ 2000 - 4500 rpm

  Naturally Asp Torque @ 1500 rpm = 8 bar BMEP
  Peak Boosted Torque @ 1500 rpm = 16 bar BMEP
  Time-To-Torque @ 1500 rpm = 1.5 s
  As Shipped Inertia = 0.0005 kg-m² / kW

- **Architecture Assumptions**

  Displacement / Cylinder = 565 cm³
  Bore & Stroke = 87.5 & 94.0 mm
  Compression Ratio = 11.5:1
  Bore Spacing = 96.0 mm
  Bore Bridge = 8.5 mm
  Deck Height = 222 mm
  Max Cylinder Pressure (mean + 3σ) = 100 bar
  Max Exhaust Gas Temperature = 960°C
  Fuel Octane = 98 RON
Project Assumptions

- **Systems Assumptions**
  - Transverse central DI + ignition w/ intake biased multi-hole injector
  - Twin scroll turbocharger w/ scroll control valve + active wastegate
  - Low pressure, cooled EGR system
  - Composite intake manifold w/ integrated air-water charge air cooler assembly
  - Split, parallel, cross-flow cooling with integrated exhaust manifold
  - Integrated variable displacement oil pump / balance shaft module
  - Compact RFF valvetrain w/ 12 mm HLA
  - Roller bearing cam journals on front, all other locations conventional
  - Electric tiVCT

- Torque converter pendulum damper
- Active powertrain mounts
- Assisted direct start, ADS
- Electric power assisted steering, EPAS

- Three way catalyst, TWC
- Lean NOx aftertreatment, LNT + SCR
Concept Evaluation

- Detailed, cycle-based CAE analysis of fuel economy contribution of critical technologies

<table>
<thead>
<tr>
<th>Architecture / System Assumption</th>
<th>% Fuel Economy</th>
<th>% Fuel Economy</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5L V6 ⇒ 2.3L I4 High Expansion Ratio Architecture</td>
<td>+</td>
<td>15.6% - Engine Architecture / Downsizing</td>
</tr>
<tr>
<td>583 ⇒ 565 cm³ Displacement / Cylinder</td>
<td>~</td>
<td></td>
</tr>
<tr>
<td>1.07 ⇒ 0.93 Bore / Stroke</td>
<td>~</td>
<td></td>
</tr>
<tr>
<td>10.3:1 ⇒ 11.5:1 Compression Ratio</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>PFI ⇒ Transverse Central DI</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>iVCT ⇒ Electric tiVCT</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Split, Parallel, Cross-Flow Cooling &amp; Integrated Exhaust Manifold</td>
<td>+</td>
<td>7.8% - Engine &amp; As-Installed Systems</td>
</tr>
<tr>
<td>Variable Displacement Oil Pump &amp; Roller Bearing Cam Journals</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>DAMB ⇒ Compact RFF Valvetrain</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>3.5L V6 ⇒ 2.3L I4 Idle &amp; Lugging Limits</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Torque Converter Pendulum Damper &amp; Active Powertrain Mounts</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Assisted Direct Start, ADS</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Electric Power Assisted Steering, EPAS</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Active Wastegate</td>
<td>+</td>
<td>4.4% - Air Path / Combustion</td>
</tr>
<tr>
<td>Low Pressure, Cooled EGR System</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Lean NOx Aftertreatment, LNT + SCR</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Torque Converter &amp; Final Drive Ratio</td>
<td>+</td>
<td>0.2% - Engine Match</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>28.0</td>
<td></td>
</tr>
</tbody>
</table>
Accomplishments

#1 – Combustion System / Mechanical Verification
#2 – Cold Start Emissions Development
#3 – Steady State Mapping
#4 – Mechanical Friction Study ⇒ NVH Study

#5 – Performance Development
#6 – Thermal Management Studies
#7 – Mechanical Development Studies
#8 – Spare 😊

Phase 1 Build
3-4Q’12

Phase 2 Build
2-3Q’13

Phase 3 Build
3Q’13

#9  #11  Calibration
#10  #12  Vehicles (4)
Accomplishments

2.3L MiGTDI Pre-X0 Engine #1

- Displacement / Cylinder = 565 cm³
- Bore & Stroke = 87.5 & 94.0 mm
- Compression Ratio = 11.5:1
- Bore Spacing = 96.0 mm
- Bore Bridge = 8.5 mm
- Deck Height = 222 mm

- Transverse central DI + ignition w/ intake biased multi-hole injector
- Advanced boosting system + active wastegate
- Low pressure, cooled EGR system
- Composite intake manifold w/ integrated air-water charge air cooler assembly
- Split, parallel, cross-flow cooling with integrated exhaust manifold
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- Compact RFF valvetrain w/ 12 mm HLA
- Roller bearing cam journals on front, all other locations conventional
- Electric tiVCT
Accomplishments

- MCE Evaluation on Dynamometer – Electric tiVCT Cam Timing 2000 RPM / 5 bar BMEP
Accomplishments

- MCE Evaluation on Dynamometer – Part Load Fuel Consumption

- Overall, meeting fuel consumption targets toward project objective
- Substantially better vs. comparator 2.0L GTDI engine
- All points with 15% EGR
Accomplishments

- MCE Evaluation on Dynamometer – Part Load CO Emissions

- Meeting CO emissions target at all points
- Indicates good air / fuel mixing
Accomplishments

- MCE Evaluation on Dynamometer – Part Load PM Emissions

- Meeting PM emissions target at all points
- Indicates good air / fuel mixing
Accomplishments

- MCE Evaluation on Dynamometer – Full Load Performance

- Meeting full load performance targets at all speeds

- 20 bar BMEP @ 2000 rpm
- 20 bar BMEP @ 4500 rpm
- 80 kW / L @ 6000 rpm
Accomplishments

- MCE Evaluation on Dynamometer – Full Load Performance

- Stoichiometric air / fuel to 3500 rpm forecasts good on-road fuel consumption
- Typical GTDI combustion phasing indicates good attribute balance
MCE Evaluation on Dynamometer – “Micro” Stratified Charge

Air Flow & Air / Fuel Spatial & Temporal Evolution

“Micro” Stratified Charge

- Overall Lean Homogeneous
- Early Primary Injection
- Air / Fuel ~ 20-30:1

+ 

- Locally Rich Stratified
- Late Secondary Injection
- “Micro” Second Pulsewidth

Advantages of “micro” stratified charge capability

- Good fuel economy
- Low NOx emissions
- Low PM emissions
- Practical controls
- Acceptable NVH
- Good stability
- Extends lean combustion capability to region of good aftertreatment efficiency, potentially enabling an LNT / SCR or passive SCR system
Accomplishments

- MCE Evaluation on Dynamometer – “Micro” Stratified Charge 1500 RPM / 5.0 bar BMEP

- “Micro” Strat ~ 6% BSFC benefit
- “Micro” Strat low NOx
- “Micro” Strat good stability
Accomplishments

- MCE Evaluation on Dynamometer – Cold Start Emissions
  
  ✓ Substantially completed transient emissions verification testing, including steady state cold fluids development and transient cold start development
  
  ✓ Received concurrence on transitioning Tier 2 Bin 2 to Tier 3 SULEV30 emissions

<table>
<thead>
<tr>
<th>Tailpipe Standards</th>
<th>Tier 2 Bin 2</th>
<th>Tier 3 SULEV30</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMOG</td>
<td>10 mg / mi</td>
<td>--</td>
</tr>
<tr>
<td>NOx</td>
<td>20 mg / mi</td>
<td>--</td>
</tr>
<tr>
<td>NMOG + NOx</td>
<td>--</td>
<td>30 mg / mi</td>
</tr>
<tr>
<td>PM</td>
<td>10 mg / mi</td>
<td>3 mg / mi</td>
</tr>
</tbody>
</table>

- Meeting 20°C Cold Start Feedgas Targets – Derived From Tailpipe Standards

<table>
<thead>
<tr>
<th>Cold Start Attribute</th>
<th>Units</th>
<th>Target&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20s Cumulative FGHC + FGNOx</td>
<td>mg</td>
<td>&lt; 227</td>
<td>224</td>
</tr>
<tr>
<td>0-20s Cumulative Particulate Mass (PM)</td>
<td>mg</td>
<td>&lt; 3.0</td>
<td>1.3</td>
</tr>
<tr>
<td>5-15s CSER stability (RMS_SDIMEP)</td>
<td>bar</td>
<td>&lt; 0.350</td>
<td>0.375</td>
</tr>
</tbody>
</table>

<sup>1</sup> Evaluated at a CSER heat flux that achieves ~350°C catalyst mid-bed @ 20 seconds after engine start
MCE Evaluation on Dynamometer – Mapping

- Substantially progressed engine mapping in support of vehicle calibration, including effectively utilizing “auto test” control for autonomous engine mapping
  - Electric tiVCT Cam Timing Optimization
  - DI Fuel Injection Timing Optimization
  - DI Fuel Rail Pressure Optimization
  - Naturally-Aspirated Air Charge – Throttle Sweeps
  - Boosted Air Charge – Scroll / Wastegate Control Sweeps
  - Full Load Performance – BLD / MBT Spark Sweeps
  - Preliminary “Auto” Calibration

- Initiated mapping validation testing and additional detailed mapping factorials as required to ensure accuracy
Accomplishments

- MCE Evaluation on Dynamometer – Friction Testing

![Graph of Engine Motoring Friction for 5W30 GF5 Oil at 200°F](image)
Accomplishments

- MCE Evaluation on Dynamometer – Friction Testing

Engine Motoring Friction - Blnc Shft / Oil Pump Off

- Below or near benchmark low limit across speed range
- Indicates good synergy of low friction component actions (e.g. low tension rings, polymer coated bearings, low tension seals)
Accomplishments

- Vehicle Build and Development – Engine As Installed In 2013 Fusion
Accomplishments

- Vehicle Build and Development – Engine As Installed In 2013 Fusion
Accomplishments

- Vehicle Build and Development – Engine As Installed In 2013 Fusion

Vehicle #1 Completed, Starting Calibration Development

Vehicles #2 – 4 Build In Progress … Online Soon
Collaboration

- **Combustion Research (MTU)**
  - ✔ Completed all six research tasks focused on expansion of dilute engine operating limits
  - ✔ Continued three research tasks with Ford funding, using the pressure vessel and two EcoBoost engines

1. Advanced Ignition & Flame Kernel Development – Published & presented SAE 2013-01-1627
2. Advanced Ignition – Impact on Dilute Combustion – Published & presented SAE 2013-01-1630
3. Air / Fuel Mixing via PLIF for GDI – Completed test plan in pressure vessel; report in progress
4. Combustion Sensing & Control – Demonstrated closed loop control of combustion phasing & stability; report in progress
5. Advanced Knock Detection & Control – Completed development of stochastic knock algorithms; SAE paper in progress
Optimization of VOIS discharge pattern for successful flame initiation and propagation yields similar results in engine and pressure vessel.
Optimization of VOIS discharge pattern for successful flame initiation and propagation

Conditions
- Combustion vessel
- Double fine wire plug
- 1.2 mm gap
- 10% EGR, $\lambda = 1.6$
- 150 deg C, ~ 4 bar
- 2 – 3 m/s cross flow

Multiple flame kernels merge for success!
“On time to revised timeline (revised architecture)”

- Original architecture was 1.8L I4 / 25 bar BMEP; during concept evaluation, revised architecture to 2.3L I4 / 20 bar BMEP

“Vehicle integration will be challenging in 12 months”

- Project end 12/31/14; likely to request no cost extension to 09/30/15

“Stopped work on lean aftertreatment”

- Given the DeSOx challenges of a TWC + LNT / SCR system, and the uncertainty of a TWC + passive SCR system, received concurrence on lean aftertreatment transitioning to stoichiometric at the vehicle level.

- Continued lean combustion “Micro” Stratified Charge development at the dyno level (results presented herein); lean aftertreatment challenges persist.
Future Work

- **Budget Period 4 – Vehicle Development** 01/01/2014 – 09/30/2015

  - Vehicle demonstrates greater than 25% weighted city / highway fuel economy improvement and Tier 3 SULEV30 emissions on FTP-75 test cycle
The project will demonstrate a 25% fuel economy improvement in a mid-sized sedan using a downsized, advanced gasoline turbocharged direct injection (GTDI) engine with no or limited degradation in vehicle level metrics, while meeting Tier 3 SULEV30 emissions on FTP-75 cycle.

Ford Motor Company has engineered a comprehensive suite of gasoline engine systems technologies to achieve the project objectives, assembled a cross-functional team of subject matter experts, and progressed the project through the concept analysis, design, development, and evaluation tasks with material accomplishments to date.

The outlook for 2014 is stable, with accomplishments anticipated to track the original scope of work and planned tasks, with the exception of milestone "Vehicle build, instrumented, and development work started" deferred from 12/31/2013 to 02/14/2014.