ATP-LD; Cummins Next Generation Tier 2 Bin 2 Diesel Engine

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Cummins Inc
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Next Generation T2B2 Diesel Engine

Overview

Timeline
Start: 10/1/2010
End: 9/31/2014
Complete: <10%

Barriers addressed
High efficiency - 28 MPG CAFE in ½ ton pickup truck
Low emission – Tier2 Bin2
Cost effective solution

Budget
Total Project:
$15M DoE
$15M Cummins
Total Spend to date:
$0.5M DoE
$0.5M Cummins

Partners
Nissan Motors Light Truck
NxtGen Emissions Solution
Johnson-Matthey Inc
Next Generation T2B2 Diesel Engine Objectives

- Engine design and development program to achieve:
  - 40% Fuel Economy improvement over current gasoline V8 powered half-ton pickup truck
  - Tailpipe requirements: US T2B2 new vehicle standards

- FE increase in light trucks and SUVs of 40% would reduce US oil consumption by 1.5M bbl/day
  - Lower oil imports and trade deficits
  - GHG emissions reduction of 0.5 MMT/day
Next Generation T2B2 Diesel Engine Objectives

<table>
<thead>
<tr>
<th></th>
<th>Baseline * vehicle data</th>
<th>DoE Program Target **</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTP – 75 “city”</td>
<td>15.6</td>
<td>21.8</td>
</tr>
<tr>
<td></td>
<td>570</td>
<td>462</td>
</tr>
<tr>
<td>HFET “hi-way”</td>
<td>24.5</td>
<td>34.3</td>
</tr>
<tr>
<td></td>
<td>363</td>
<td>292</td>
</tr>
<tr>
<td>CAFE</td>
<td>18.6</td>
<td>26.0</td>
</tr>
<tr>
<td></td>
<td>476</td>
<td>385</td>
</tr>
</tbody>
</table>

* Baseline data from 2010 EPA database for new vehicle certification for Nissan Titan 2WD at 5500 lb test weight
** DoE program targets base on MPG values
## Milestones

<table>
<thead>
<tr>
<th>% Complete</th>
<th>Milestones</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>Vehicle baseline testing – Fuel Economy, Emissions and Performance</td>
</tr>
<tr>
<td>75%</td>
<td>Engine baseline testing – Fuel Economy and Emissions</td>
</tr>
<tr>
<td>40%</td>
<td>A/T system model available for exercise</td>
</tr>
<tr>
<td>50%</td>
<td>Readied for test, combustion mule engine</td>
</tr>
<tr>
<td>10%</td>
<td>A/T system readied for test</td>
</tr>
<tr>
<td>50%</td>
<td>Mule vehicle complete</td>
</tr>
<tr>
<td>10%</td>
<td>Major reviews complete for new engine design (long lead time items)</td>
</tr>
</tbody>
</table>
## Program Milestones

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar 2012</td>
<td>Demonstration of LA-4 on engine dyno with Engine Out Emissions at target level</td>
</tr>
<tr>
<td>Jul 2012</td>
<td>A/T system architecture is defined, include sensor plan and OBD plan</td>
</tr>
<tr>
<td>Sep 2012</td>
<td>New engine assembly complete</td>
</tr>
<tr>
<td>May 2013</td>
<td>Demonstration of FTP on engine dyno at T2B5 tailpipe</td>
</tr>
<tr>
<td>Nov 2013</td>
<td>New engine operational in vehicle with full A/T system</td>
</tr>
<tr>
<td>Dec 2013</td>
<td>Demonstration of FTP on chassis at T2B5</td>
</tr>
<tr>
<td>May 2014</td>
<td>Demonstration of FTP on engine dyno at T2B2 tailpipe</td>
</tr>
<tr>
<td>Sept 2014</td>
<td>Demonstration of FTP on chassis at T2B2</td>
</tr>
</tbody>
</table>
Technical Approach – High Efficiency

- **Learning from LDECC program**
  - High charge flow improves NOx/PM potential via extended PCCI operating range
  - High charge flow reduces energy available for A/T

- **Appropriate sized engine**
  - Displacement for power, thermal management, fuel economy

- **Reduce FE penalty due to emission controls**
  - Low pressure EGR to reduce EGR pumping work
  - Fast exhaust warm up via design features

- **Diesel application weight control**
  - Engine weight control via design features
Innovation You Can Depend On™

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Technical Approach – High Efficiency

Appropriate sized engine

- Down sized engine => Increased power density => Maintain vehicle drivability & Improved FE

Addressable market based on power and torque band in base offerings.

Ideal positioning given current capabilities is shown with a ‘star’.

Value proposition is ‘high FE’ with acceptable power/torque.
Technical Approach – High Efficiency

Appropriate sized engine

- Down sized engine => increased loads => higher exhaust gas temperature => Improved A/T performance
Technical Approach – High Efficiency
Reduce FE penalty due to emission controls

- Low pressure EGR to reduce pumping work

Steady speed and load, Fixed A/F ratio, EGR sweep

- Increasing Pumping Work to Drive EGR
- Reducing Intake Manifold O2 Concentration
- Increased Gas Cooling

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Technical Approach – High Efficiency
Reduce FE penalty due to emission controls

- PNA to control NOx under cold start w/o FE penalty

- A passive NOx Adsorber (PNA) stores NOx at low temperature and desorbs as the catalyst temperature increases

- With an optimal formulation release of NOx when the SCR reaches operating temperature

- PNA stores approximately 75% of the NOx released by the engine up to 180s into the cold FTP cycle

- This stored NOx is released around 180s when the exhaust temperature reaches 200°C

- Nearly all NOx captured by PNA during cold start
Technical Approach – High Efficiency
Reduce FE penalty due to emission controls
Design features for fast warm up

- Fabricated exhaust manifold instead of cast iron
- Close coupled aftertreatment
  - DOC/DPF assembled onto engine
  - Dual wall exhaust pipe work underbody
- Minimized exhaust port “wetted” area

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Technical Approach – Engine weight control via design features

Goal: equivalent application weight as baseline engine

- Light weight steel piston for reduced friction & compression height with increased power density
  - Reduce deck height, reduced cylinder block weight
- Aluminum cylinder head for weight and size optimization
  - Reduced development time and cost to program
  - Make common with LDD V8 (previous DoE program engine)
- Fabricated manifold for rapid exhaust warm up
  - Reduced weight vs standard cast iron
- Forged crankshaft with smaller (than cast) journals and increased strength for power density
  - Smaller and lighter vs standard cast iron
APT LD CAFE Fuel Economy Plan

Fuel Economy (mpg)

- Conversion to diesel fuel
- Closed cycle efficiency
- High Eff NOx Aftertreatment
- High Eff HC Aftertreatment
- Close coupled DPF
- Low Pressure EGR Circuit
- Variable Swirl / Adv port design
- Exh thermal management design
- Acc drive control optimization
- VVA operation
- Cycle tuning
- Internal engine parasitics

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APT Light Duty Tailpipe NOx Strategy

Closed cycle efficiency
High Eff NOx Aftertreatment
High Eff HC Aftertreatment
Close coupled DPF
Low Pressure EGR Circuit
Variable Swirl / Adv port design
Exh thermal management design
Acc drive control optimization
VVA operation
Cycle tuning
Internal engine parasitics

Conversion to Diesel
Tailpipe NOx (g/mi)
Technical Accomplishments and Progress

- Baseline engine performance testing complete and correlated to GT-Power model
  - Included FE response to oil viscosity testing
- Baseline vehicle performance testing complete
  - Basis for front end of vehicle model
- Combustion Mule Engine
  - Design and procurement of variable swirl system
  - Design and procurement of Generation 3 Piezo FIE adapted to engine
  - Design and procurement of HP/LP EGR system
- Mule Vehicle for drive train optimization
  - Build complete, first fire in April 2011
  - Development of shift strategy, acc load management, etc.
Technical Accomplishments and Progress

- **Base engine**
  - crank analysis completed for new mat’l, main and pin sizes – design included low viscosity oil properties
  - power cylinder kit designed for short comp height and low friction ring pack
  - detailed GT model (capable of coupling with vehicle and A/T)

- **Control system**
  - Completed first order HP/LP operational model
  - Designed and implemented mule vehicle control network

- **Aftertreatment modeling**
  - New A/T technology first order model (PNA)
  - Full model for A/T options (SCR vs NAC)
  - Detailed model for target development of 0-180 sec

- **Vehicle model**
  - Baseline for mule development underway
Collaborations

- **Partners**
  - **Johnson-Matthey** – (industry, subcontractor) Advanced aftertreatment formulations and architecture
    - Passive NOx adsorbers for cold start NOx emission mitigation
    - Close coupled SCR on filter for improved cost and effectiveness
  - **Nissan** (industry, partner) – Vehicle integration and guidance on engine technical profile.
  - **NxtGen** – (industry, subcontractor) exhaust thermal enhancer via syngas generation

- **Other involvement**
  - **Rose-Hulman** – (institution, contract) Control system development to reduce sensor needs and improve robustness of controls
  - **ORNL** – (Nat’l Lab, association) working with light weight CRADA team to integrate advanced material process into base engine components
Future Work

- 2011: Complete combustion mule development in order to specify technical design requirements for:
  - HP/LP EGR and air handling system (control, cooling, restrictions, etc)
  - Fuel injection system (Nozzle specs, operational specs, etc..)
  - Variable swirl system and base cylinder head specifications
  - Aftertreatment system architecture and materials

- 2011: Complete single cylinder engine work to investigate variable valve motion (VVA and VVT)

- 2011: Complete mule vehicle development in order to specify technical design requirements for:
  - Drive train (Shift conditions, warm up methods, rear axle, acc drive…)

- 2012: Procure and build new engine based on mule development and technical specifications
  - Testing of new engine planned for September 2012
Summary

- Sound technical strategy to achieve 40% FE improvement and T2B2 tailpipe emissions.
- Program built on previous program (LDECC) learnings:
  - High charge flow, low O2 combustion scheme
  - Push premixed combustion zone to higher loads
- Collaboration with OEM to ensure the application is designed with minimum impact on vehicle systems and interface.
  - Package majority of emission control system on engine (charge air cooler, Urea doser, DOC/DPF and LP EGR)
- Evaluation of technology based on:
  - Value (performance vs cost)
  - Weight – effect on FE and vehicle impact (component change)
- Cummins will work within current manufacturing strategy to improve commercial opportunities.
  - Minimize impact of new engine on capital investment and supply base
Technical Backup slides
Technical Approach – High Efficiency

Appropriate sized engine

- Down sized engine => Small engine => increased loads => higher efficiency

![Engine Speed vs. Load Diagram](attachment:engine_speed_vs_load_diagram.png)
Mule Vehicle Build
Marketing Research Data on ½ Ton P/U Truck Buyers (Morpace Research Group – 2010)

Relative Feature Importance

- Reliability: 33.2
- Initial Price: 27.3
- Durability: 12.2
- Fuel Economy: 9.3
- Horsepower: 5.7
- Torque: 4.3
- Length of Base Warranty: 3.2
- Cost of Routine Maintenance: 1.3
- Cost of Unscheduled Service: 1.3
- Ease of Maintenance: 1.1
- Fuel Type: 0.6
- Cost of Extended Warranty: 0.6

Reliability is a ticket into the game
Big hitter: Initial Price
#3 is Fuel Economy
HP/LP EGR on Combustion Mule