SuperTruck Program: Engine Project Review

Recovery Act – Class 8 Truck Freight Efficiency Improvement Project

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Project ID: ACE058

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**Overview**

**Timeline**
- Project start: April 2010
- Project end: March 2015
- Percent complete: 60%

**Budget**
- Engine Budget: $31,633,001
  - DOE Share*: $8,802,373
  - Detroit Share*: $8,802,373

* Program spending through February 2013 for engine R&D; vehicle R&D expenses reported separately.

**Challenges**
- Getting systems to work together in vehicle; new vehicle, new cooling system, hybrid, new controllers for engine and vehicle, downsized engine, new combustion system, new turbocharger, high efficiency aftertreatment, waste heat recovery, etc.

**Partners**
- Department of Energy
- Oak Ridge National Laboratory
- Massachusetts Institute of Technology
- Atkinson LLC
- Daimler Trucks North America
- Daimler Advanced Engineering
Daimler Truck SuperTruck Program

- **ARRAVT080** – DTNA SuperTruck vehicle program; PI – Derek Rotz, reported @ Crystal Gateway
- **ACE058** – Detroit Diesel SuperTruck engine; PI – Kevin Sisken, reported @ Crystal City
SuperTruck Objective

Develop and demonstrate a 50% increase in vehicle freight efficiency:

- 30% increase via vehicle improvements.
- 20% increase via engine improvements; specifically 50% brake thermal efficiency.
  - Identify pathway to 55% brake thermal efficiency via modeling and analysis.

Status

Vehicle:
- 42% measured on system level; currently implementing into demonstration vehicle.

Engine:
- 15% gain via engine improvements.
  - 48.1% BTE demonstrated (46.8% engine + 1.3% WHR).
  - Hardware in hand to demonstrate 50% BTE.
- Pathway to 55% BTE has been initiated (results end of year 4).
Engine Down-speed and Down-size

1 → 2
- Impact of vehicle getting more efficient.

2 → 3
- Change gear and axle ratio to drop cruise rpm toward higher BSFC points.

3 → 4
- Downsize from 15L to 11L to increase BMEP at road load, giving better mpg at road load.
Technical Accomplishments and Progress

Piston and Compression Ratio

- New piston bowl shapes based on extensive single cylinder testing; engine hardware now available.
- Compression ratio being increased.
- Firing pressure will be increased up to 20% over baseline engine.

Fuel Injection System

- Best combinations of injector tip, bowl, and compression ratio determined via single cylinder testing; best combinations being engine tested.
- Design of experiments being utilized to optimize injection and engine parameters.
Increased Engine Out NOx

- Combustion system being optimized with engine out NOx lightly controlled (3-5 times higher than baseline engine).
- Good for thermal efficiency; increased demand on SCR system.

Aftertreatment

- Require very high NOx conversion efficiency.
- System resized for high NOx flux (substrates and DEF doser).
- Backpressure must be reduced for high engine efficiency.
Two Generations of Aftertreatment Hardware

- Generation 1 has new DOC, DPF, and SCR.
  - DOC and DPF met expectations; SCR had room for improvement.
  - ΔP and NOx conversion efficiency below target.
- Generation 2 has new SCR. DOC and DPF largely unchanged.
  - Gen 2 has lower pressure drop and better SCR conversion. Performs well at high NOx flux.
- Generation 2 will be on the SuperTruck demonstration vehicle.
Air System Rematch

- Best BTE ➔ higher engine out NOx ➔ lower EGR rates ➔ turbocharger rematch
  - Down-speed engine offers rematch opportunities.
  - Baseline turbocharger provides back pressure for high EGR rates.
- Turbocharger V2 has well matched compressor map.
  - EGR valve still partially closed to reduce EGR rates.
- Turbocharger V3 being delivered with reduced turbine backpressure.
Parasitic Reductions – Implemented

- Water pump, lower viscosity oil, and ring modification included in 48.1% BTE demonstration.

Parasitic Reduction – Planned

- Modifications to be tested include:
  - Altered cooling to mid-stroke area of the liner (MIT).
  - Oil circuit and pump optimizations (MIT).
  - New lubricant formulation (MIT + oil supplier).
  - Bundled cylinder kit improvements.
SuperTruck Engine Controls – Objective

- Developed a **predictive** engine controller.
- Includes a fuel efficiency optimizer.
- Integrates predictive vehicle information.
- Reduced calibration complexity.

Extensive engine mapping is used in neural network model training.

Emissions & fuel economy models enable on-board BSFC optimization.

Calibration Constraints
- Drivability
- Durability
- Fuel economy
- Life-cycle cost
- NOx / PM / NMHC / CO₂
- OBD
- Exhaust temperature
- GPS / Route / Traffic info.

Predictive route information enables enhanced use of engine optimization.
SuperTruck Engine Controller Results

- Controller continues to performed well on DD13.
- System prepared for vehicle implementation.
- Recalibrated for SuperTruck engine in late 2012.
  - Controller showed no NOx vs. BSFC trade-off.
  - Table based calibrations did improve BSFC at high NOx.
  - Lesson learned: model was not trained over a wide enough range of actuator positions.
- Will re-train controller with finalized set of engine hardware (pistons, turbo, etc.).
Waste Heat Recovery (WHR)

- Waste heat recovery has significant potential for meeting efficiency goals.
  - Rankine cycle has the most potential among available options.
- Will recover energy from exhaust and EGR.
- SuperTruck objective: demonstrate 2% BTE improvement via WHR.
- Current Status: demonstrated 1.3% BTE with exhaust heat only. EGR boiler on engine and will be evaluated for BTE shortly.

<table>
<thead>
<tr>
<th>Waste Heat Sources</th>
<th>Quality</th>
<th>Quantity</th>
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<tbody>
<tr>
<td>Exhaust</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>EGR</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>CAC</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Coolant</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>
WHR -- Test Bed

- Test stand functional with ethanol as the working fluid.
- Initial system characterization complete.
- EGR energy recovery now added to engine.
  - Targeting > 2% BTE with this configuration.

WHR -- Control System

- Test bed control system fully functional.
- Model refinements, diagnostics, and integration with other control systems ongoing.
Generator Development

- ORNL developing new design generator for WHR.
  - Low cost wound field generator.
  - No inverter required, simple controls for voltage regulation, brushless, air cooled.
- Iteration 1 could only generate 20% of desired power.
- Iteration 2 generates desired power; mapping in process.

Generator Controls

- Controls development and performance testing of the integrated expander and generator ongoing at ORNL.
- Demonstrated expander speed control and load dumping.
Waste Heat in Vehicle

- Vehicle packaging of Rankine components complete; system assembly in process.
- Build and test in 2013.
Plan to 50% BTE → Need 1.9%

- Engine → need +1.2%
  - Combustion system: new bowl shape, higher CR, higher PFP, fuel system optimized via DOE.
  - Turbo with reduced back pressure.
  - Parasitic reductions: liner cooling, cylinder kit improvements, oil system improvements, new oil.
- WHR → need +0.7%
  - Addition of EGR boiler.
  - Minor component optimizations (plumbing, etc.).
Plan to 55% BTE → Need 5.0%

- Engine → need +4.5%
  - Baseline model calibrated, will be refined for latest and greatest hardware when data is available (summer 2013).
- Turbocompound will be engine tested.
- Over 15 engine improvement items will be evaluated.
- WHR → need > +0.5%
  - System refinements.
  - Potential for coolant and/or charge cooler WHR.
  - WHR >> 2.5% BTE
- Results at end of year 4
## SuperTruck Partnerships and Collaborations

### Department of Energy:
- Roland Gravel
- Gurpreet Singh
- Ken Howden
- Carl Maronde

### Engine
- MIT
- BOSCH
- DAIMLER
- Oak Ridge National Laboratory
- Atkinson LLC

### Aftertreatment
- CORNING
- Johnson Matthey
- Eberspächer

### Hybrid
- FUSO
- MBtech
- Mercedes-Benz
- itk ENGINEERING

### Aero/Cooling
- CD-adapco
- BEHR
- MODINE

### Powertrain/Parasitics
- DETROIT
- Bendix
- Daimler Trucks North America

### Fleet
- Schneider National
- Walmart
SuperTruck Program Summary

- Achieved significant increase in performance; baseline 42% BTE, currently 48.1% BTE.
- Remaining 2 years of SuperTruck.
  - In the next 6 months, demonstrate 50% BTE.
    - Combustion system (pistons, CR ratio, fuel injection, etc.), new turbocharger, further reduced parasitics (liner cooling, cylinder kit modification, etc.) and WHR including from the EGR system.
  - Move to final engine validations and implementation into SuperTruck vehicle.
  - Define building blocks for 55% BTE.
  - Continued system refinements (controls, WHR including generator, etc.).