SuperTruck – Development and Demonstration of a Fuel-Efficient Class 8 Tractor & Trailer Engine Systems

DOE Contract: DE-EE0003303
NETL Project Officer: Ralph Nine
DOE Project Manager: Roland Gravel
Navistar Principal Investigator: Russ Zukouski

DOE MERIT REVIEW

06/09/2016

Project ID: ACE059
# Program Overview

## Timeline

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Project Start:</td>
<td>October 2010</td>
</tr>
<tr>
<td>Project End:</td>
<td>Sept 2016</td>
</tr>
<tr>
<td>% Complete:</td>
<td>91%</td>
</tr>
</tbody>
</table>

## Partners

<table>
<thead>
<tr>
<th>Company</th>
<th>Role</th>
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</thead>
<tbody>
<tr>
<td>Navistar</td>
<td>Principal Investigator, Vehicle Systems Integrator Controls Systems, Engine &amp; Vehicle Testing</td>
</tr>
<tr>
<td>Bosch</td>
<td>Fuel Systems</td>
</tr>
<tr>
<td>Wabash</td>
<td>Trailer Technologies</td>
</tr>
<tr>
<td>ANL</td>
<td>Dual Fuel Engine testing, simulation &amp; evaluation</td>
</tr>
<tr>
<td>LLNL</td>
<td>Aerodynamic CFD</td>
</tr>
</tbody>
</table>

## Barriers

- Achieving 50% freight efficiency while balancing Voice of Customer Needs
- Alignment with business needs
- Reducing tractor weight while adding new systems

## Budget

<table>
<thead>
<tr>
<th></th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Funding:</td>
<td>$76,178,386</td>
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<tr>
<td>DOE:</td>
<td>$35,754,460</td>
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<td>Prime:</td>
<td>$40,423,926</td>
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<td>Funding FY2015:</td>
<td>$8,965,646</td>
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<td>Funding for FY2016:</td>
<td>$4,896,000</td>
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</tbody>
</table>

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Objectives and Relevance

Goals and Objectives
1. Demonstrate 50% improvement in freight efficiency
   20% through Engine technologies
   30% through Vehicle technologies
2. Demonstrate 50% BTE on Engine Dynamometer
3. Demonstrate technical pathway towards 55% BTE

Relevance
✓ Provide a realistic technology demonstrator to reduce petroleum consumption in the truck market:
   → Engine technologies closely worked with business requirements
   → Focus on packaging and customer interface (key in the case of Waste Heat Recovery)
✓ Work with Partners to develop robust products for commercial integration:
   → High efficiency common rail Fuel Injection System (FIS) (BOSCH) for advanced combustion
   → Advanced base engine technologies for friction reduction
   → Worked with Argonne National Labs to provide technical path for alternative fuels and clean combustion systems
✓ Work with Collaborators...
Timing / Milestones

1. Project management
2. DownSpeed and Calibration
3. Cruising Area Optimization
4. Gas Exchange Dev -> Adv
5. Advanced Combustion System
6. After Treatment Dev
7. WHR system
8. Engine Tests and Validations on Dynamometer
9. Vehicle and Evaluations

- Q2-14
- Q3-14
- Q4-14
- Q1-15
- Q2-15
- Q3-15
- Q4-15
- Q1-16
- Q2-16
- Q3-16

- Project management
- Downspeed re-cal
- Vehicle Simulation
- New Air System on Engine
- 1st Round Comb Match w/ New Air System
- Simulation
- Sub-System Contributions
- Project management
- Downspeed re-cal
- Vehicle Simulation
- New Air System on Engine
- 1st Round Comb Match w/ New Air System
- Simulation
- Sub-System Contributions

- Engine Calibration
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- Engine Calibration

- Control Optimization
- Control Optimization
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- Control Optimization

- 2nd Gen. Air System on Engine
- 2nd Gen. Air System on Engine
- 2nd Gen. Air System on Engine
- 2nd Gen. Air System on Engine
- 2nd Gen. Air System on Engine
- 2nd Gen. Air System on Engine
- 2nd Gen. Air System on Engine
- 2nd Gen. Air System on Engine
- 2nd Gen. Air System on Engine

- A/T system and Control
- A/T system and Control
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- A/T system and Control
- A/T system and Control

- 2nd Round Comb Match w/ New Air System
- 2nd Round Comb Match w/ New Air System
- 2nd Round Comb Match w/ New Air System
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- 2nd Round Comb Match w/ New Air System
- 2nd Round Comb Match w/ New Air System
- 2nd Round Comb Match w/ New Air System
- 2nd Round Comb Match w/ New Air System

- Initial Evaluation
- Initial Evaluation
- Initial Evaluation
- Initial Evaluation
- Initial Evaluation
- Initial Evaluation
- Initial Evaluation
- Initial Evaluation
- Initial Evaluation

- Refined System Demonstration
- Refined System Demonstration
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- Refined System Demonstration
- Refined System Demonstration

- Q2-14
- Q3-14
- Q4-14
- Q1-15
- Q2-15
- Q3-15
- Q4-15
- Q1-16
- Q2-16
- Q3-16

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Vehicle Partnerships and Completed tasks

<table>
<thead>
<tr>
<th>Phase I</th>
<th>Phase II</th>
<th>Phase III</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Navistar</strong></td>
<td>Concept technologies chosen</td>
<td>T3 Vehicle achieved 70% FE</td>
</tr>
<tr>
<td>Vehicle systems integrator</td>
<td>48.3% BTE achieved</td>
<td>48.9% BTE achieved</td>
</tr>
<tr>
<td>Control Systems</td>
<td>Load biasing evaluated</td>
<td>Load biasing concluded in final build</td>
</tr>
<tr>
<td>Base Engine</td>
<td>Material procured for Mule build</td>
<td>Material procured for Mule build</td>
</tr>
<tr>
<td><strong>Wabash National</strong></td>
<td>Trailer Design</td>
<td>Trailer and system built</td>
</tr>
<tr>
<td>Trailer Technologies</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>BOSCH</strong></td>
<td>Adv comb with FIS</td>
<td>Adv comb with FIS optimization complete</td>
</tr>
<tr>
<td>Fuel Systems</td>
<td>strategies</td>
<td>WHR system developed</td>
</tr>
<tr>
<td><strong>LLNL</strong></td>
<td>Computational Fluid Dynamics</td>
<td>Speed form complete</td>
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<tr>
<td>Computational Fluid Dynamics</td>
<td></td>
<td>wind tunnel testing</td>
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<tr>
<td><strong>ANL</strong></td>
<td>Engine Design</td>
<td>VVA</td>
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<tr>
<td>Engine Design</td>
<td>Controls deployment</td>
<td>1D/3D simulations</td>
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<tr>
<td>Controls deployment</td>
<td></td>
<td>Reduction of Parasitic</td>
</tr>
<tr>
<td>Fuel Reactivity testing</td>
<td></td>
<td>demonstrated</td>
</tr>
<tr>
<td><strong>FE</strong></td>
<td></td>
<td>Fuel Reactivity testing in final stage</td>
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FE = Freight Efficiency (ton-miles/gal)

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<table>
<thead>
<tr>
<th>Engine Collaborators &amp; Completed Tasks</th>
</tr>
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</table>

**Phase II**

- **Mahle**
  - Heat Exchangers

- **Borg Warner**
  - Turbos / Air Systems

- **Jacobs Vehicle Systems**
  - Variable Valve Actuation

- **Philos Technology**
  - Surface Treatment Evaluation

- **Federal Mogul**
  - Accessory prove out
  - Kit procurement

- **C.E.S.**

- **Adiabatics, Inc.**
  - Advanced Thermal Mgmt.
  - Thermal Barrier Coating

**Phase III**

- **Mahle**
  - Pwr cyl optimization
  - WHR system and components re-defined by simulation
  - 55% BTE Demo

- **Borg Warner**
  - Optimized turbocharger system
  - 50% BTE Demo

- **Jacobs Vehicle Systems**
  - Pumping work reduction for specific operating modes
  - 55% BTE Path

- **Philos Technology**
  - 55% BTE Path

- **Federal Mogul**
  - Friction Engine Testing
  - 55% BTE Path

- **C.E.S.**
  - High Efficiency Aftertreatment
  - 50% BTE Demo

<table>
<thead>
<tr>
<th>12-Oct</th>
<th>14-Apr</th>
<th>15-Apr</th>
<th>16-Apr</th>
<th>16-Sep</th>
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<tbody>
<tr>
<td>Phase II</td>
<td>Phase III</td>
<td></td>
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</tbody>
</table>

**Phase III-IV**

- **Mahle**
  - 55% BTE Demo

- **Borg Warner**
  - 50% BTE Demo

- **Jacobs Vehicle Systems**
  - 55% BTE Path

- **Philos Technology**
  - 55% BTE Path

- **Federal Mogul**
  - 55% BTE Path

- **C.E.S.**
  - 50% BTE Demo

- **Adiabatics, Inc.**
  - 55% BTE Path

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Barriers and Technology Roadmap

<table>
<thead>
<tr>
<th>System</th>
<th>Barriers (challenges)</th>
<th>Technology Roadmap</th>
</tr>
</thead>
</table>
| Engine & Vehicle |  • Cost effective  
                    • Robust (controls, durable)  
                    • Reduced weight             | Rely on analysis to select technology                                             |
| Engine      |  • High combustion efficiency  
                    • High efficiency A/T System  
                    • Air system with minimum losses     | Improve FIS and combustion match  
                                                                                   Advanced combustion regimes  
                                                                                   Improve gas exchange efficiency  
                                                                                   Advanced aftertreatment          |
| Engine      |  • Modest bottoming cycle efficiency  
                    • Parasitic reduction  
                    • WHR system                                | Advanced designs  
                                                                                   Close collaboration with suppliers for new technologies  
                                                                                   Optimum integration to engine |
| Engine      |  • Non optimum fuel formulation  
                    • Optimal dual fuel reactivity             | Introduce reactivity control  
                                                                                   Understanding of chemical kinetics |

Keys: ✓ high confidence to contain  
★ working on improving solution

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Approach – Technology Selection

2. Air System
- VG turbo with improved Efficiency
- High flow cylinder head

3. Friction-Accessories
- VWP
- Power Cylinder Components
- Reduction of pumping loss

4. Aftertreatment
- DOC/DPF + SCR
- Close coupled
- Hi efficiency
- Low DP

5. WHR
- ORC system

Optimize Integration Criteria
- Efficiency gain (BTE)
- Weight (Ton-mile/gallon)

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Accomplishments –
Engine Dyno 49.6% BTE

BTE 49.6%, Feb. 2016

- 2010 Base Engine
- DownSped Calibration
- Gas Flow Optimization
- Advanced Combustion
- Parasitic Reduction

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Accomplishments – Air System / VVA / RSD

- High Efficiency Turbocharger
  - Compressor Map
  - Turbine Map

- VVA installation on the test engine at ANL:
  - Optimal IVC timing for BTE

- RSD (Rocker Stop Device)
  - A/T thermal management
  - Stop/Go operation

Successful implementation of turbo system technology to test engine

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Accomplishments –
Advanced Combustion

Combustion Optimization:

- Compression ratio (CR),
- Combustion chamber and matching fuel injection strategies,
- Combustion phasing

Good air utilization will improve the 2nd half of diesel combustion, MBF50-90%, faster diffusion combustion.
Accomplishments – Reduction of Parasitic Losses

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Accomplishments – Evaluation of WHR Strategy

- eTurbo evaluation

- Prototype system in test cell.

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Accomplishments – 55% BTE Pathway

- Dual-fuel evaluation
  - Rapid heat release
  - Split diesel injections

- In-cylinder heat transfer modeling
  - Conjugate Heat Transfer (CHT)
  - Thermal Barrier Coating (TBC)

- Dual-fuel evaluation
  - Diesel-CNG best points
    - 48.1% at 20 bar
    - 47.4% at 14 bar
  - Diesel only baseline
    - 46.5% at 14 bar

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Future Work – Moving Forward

BTE

- 2010 Base Engine
- DownSped Calibration
- Gas Flow Optimization
- Advanced Combustion
- Parasitic Reduction
- ORC I.
- Dual Fuel + Engine Downsize + Adv Comb + ORC II.

- 50% BTE
- 55% BTE

Mar. 2016

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Wrap-up Work

- ORC system optimization
- Aftertreatment thermal management
- Control Strategy optimization
- System Integration/packaging
- High efficiency air system optimization
- In cylinder thermal management
- Reactivity studies performed with gasoline and alcohol fuel
Project Summary (I)

✅ Technologies/methods utilized to achieve 50% BTE

✔ On engine combustion:
  - Newly designed combustion chambers and system match
  - Investigation and understanding combustion phasing
  - Extended peak cylinder pressure capability

✔ Engine Downspeed
  - Re-cal and optimization

✔ Reduction of Parasitic Losses
  - Base components, lube and cooling, were updated raising BTE
  - Power cylinder components were procured and evaluated

✔ WHR system
  - Simulation to define ORC system components
  - Prototype system was assembled for testing and evaluation.
Advanced 55% BTE technical path

✓ Reactivity studies performed with gasoline and alcohol fuels
  ▪ High engine efficiencies were compatible with very reduced engine emissions
  ▪ Study will continue with enabling features recently added VVA system, such as high compression ratio, new combustion system

✓ Both 1D and 3D simulations are used for technical feasibility study