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

*Engine Systems*

**DOE Contract:** DE-EE0003303

NETL Project Manager: Samuel Taylor

Program Investigator: Dennis W. Jadin, Navistar

**DOE MERIT REVIEW**

WASHINGTON, D.C.

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National Energy Technology Laboratory
Department of Energy

Project ID: ACE059

This presentation does not contain any proprietary or confidential information
Outline

- Program Overview
- Barriers and Technology Roadmap
- Approach
- Technical Accomplishments
- Future Work
- Summary
Program Overview

Goals and Objectives
Demonstrate 50% improvement in overall freight efficiency of a combination Tractor-Trailer:

30/50% improvement achieved through tractor/trailer technologies
20/50% improvement achieved through Engine technologies

Attain 50% BTE Engine
Demonstrate path towards 55% BTE Engine

Barriers
Assemble a cost effective, robust, reduced weight technologies for 50% freight efficiency
Increase BTE while maintaining low engine emissions (simplify NOx aftertreatment)
Non optimum fuel formulation for best efficiency - emission tradeoff

Budget
Total Project Funding: DOE $37,328,933
Prime Contractor $51,801,146

DOE Funding Received in FY2011: $ 5,440,636

Navistar and our respective program partnerships thank the DOE Vehicle Technologies Program for their support and funding of this innovative project.
### Program Overview

**Partners, Collaboration and Coordination with Other Institutions**

<table>
<thead>
<tr>
<th>Name</th>
<th>Role/Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Navistar</td>
<td>Principal Investigator, Vehicle Systems Integrator Controls Systems, Engine &amp; Vehicle Testing</td>
</tr>
<tr>
<td>Behr America</td>
<td>Cooling Systems</td>
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<tr>
<td>Bosch</td>
<td>Diesel Fuel Injection Systems</td>
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<tr>
<td>Federal Mogul</td>
<td>Friction Reduction</td>
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<tr>
<td>Argonne National Lab</td>
<td>Testing of Dual Fuel Engine</td>
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</tbody>
</table>
### Barriers And Technology Roadmap

<table>
<thead>
<tr>
<th>System</th>
<th>Barriers</th>
<th>Technology Roadmap</th>
</tr>
</thead>
</table>
| Engine & Vehicle     | Assemble a **cost effective, robust, reduced** (vehicle) **weight** technologies for 50% BTE. | - Rely on analysis (tradeoff) to select technology  
                        |                                                                          | - Couple technology to road cycle selection                                     |
| Engine               | Increase BTE while **maintaining low engine emissions** (simplify NOx aftertreatment) | - Improved Technologies (Fuel Injection, Combustion Regimes, WHR, AT, Controls, Lo-Friction, Air Handling, Thermal Management, Advanced Materials) |
| Engine               | Limited experience and understanding of **new high-efficiency combustion regimes** (e.g. PCCI) | - Improve fundamental understanding chemical kinetics  
                        |                                                                          | - Introduce combustion feedback                                                 |
| Engine               | Non optimum **fuel formulation** for best efficiency-emission tradeoff   | - Introduce reactivity control (dual fuel)                                         |
# Approach: Technology Roadmap - Engine

## Technologies Assembled in 50-55% Demonstrator Engine
(highlight 2010-2011 activities)

<table>
<thead>
<tr>
<th>Technology Category</th>
<th>Area of Concentration</th>
<th>Status</th>
</tr>
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<tbody>
<tr>
<td>Engine</td>
<td>MAXXFORCE 13L</td>
<td></td>
</tr>
<tr>
<td>Advanced Fuel Injection</td>
<td>High Pressure Common Rail increase to 2900 bar</td>
<td>Deployed Oct 2010</td>
</tr>
<tr>
<td>New Combustion Regimes</td>
<td>Diesel + PCCI (main path)</td>
<td>Currently used</td>
</tr>
<tr>
<td></td>
<td>Reactivity Control with Dual Fuel (parallel path)</td>
<td>Deploy Sep 2011</td>
</tr>
<tr>
<td>Heat Recovery</td>
<td>Electrical Turbocompounding</td>
<td>Deployed April 2010</td>
</tr>
<tr>
<td></td>
<td>Rankine Cycle Applied to EGR flow (optional)</td>
<td></td>
</tr>
<tr>
<td>Aftertreatment</td>
<td>DPF</td>
<td>Deployed April 2010</td>
</tr>
<tr>
<td></td>
<td>Solid Amonia NOx reduction (optional)</td>
<td>Deployed April 2010</td>
</tr>
<tr>
<td>Contols</td>
<td>Combustion Feedback</td>
<td>Currently used</td>
</tr>
<tr>
<td></td>
<td>Variable Valve Actuation</td>
<td></td>
</tr>
<tr>
<td>Low Friction Features</td>
<td>Power Transfer</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power Cylinder</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Accessories</td>
<td></td>
</tr>
<tr>
<td>Air Handling</td>
<td>High Efficiency Series Turbocharging (improved by 4%)</td>
<td>Deploy Apr 2011</td>
</tr>
<tr>
<td></td>
<td>Reduced flow restriction</td>
<td>Deploy Apr 2011</td>
</tr>
<tr>
<td>Thermal Management</td>
<td>Variable Coolant and Fan Clutches</td>
<td></td>
</tr>
<tr>
<td>Advanced Materials</td>
<td>Increased Cylinder Pressure Capability to 220bar</td>
<td>Currently used</td>
</tr>
</tbody>
</table>
Approach: Technology Roadmap - Technologies

Goal: Leverage Technologies and Optimum Integration to attain:

- 50% max BTE
- 20% improvement over the engine map

Evaluation at Highway Road-Load Conditions (65mph and 65,000lb vehicle weight)
Approach:
Technology Roadmap - Timeline

Break Thermal Efficiency (target ~A75)

Advanced Fuel Injection System
Increased Peak Cylinder Pressure
Electrical Turbo Compounding

Currently Demonstrated
Projection
Original Proposal

DOE target

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DE-EE0003303
**Approach:**

**Engine Baseline**

**Base Engine**

**MY 2010 MAXXFORCE 13**

- Rated Power: 475hp
- Best BTE: 42%
- Engine out NOx: 0.35g/bhp-hr

**Technical highlights:**
- 2200 bar Common Rail
- 2-Stage turbocharger with intercooler
- 2-stage HP loop EGR cooling
Program leverages skilful teams and modern testing facilities

Navistar – MLP:
- Combustion Development
- Heat Recovery Technology
- Emissions
- Performance Benchmark

BOSCH – FH:
- Fuel Injection System Strategy

ANL:
- Fuel Reactivity
Accomplishments:

1. Combustion Efficiency

Comprehensive CFD and DOE techniques

- Coupled simulation and experimental work
- Enhanced CFD code
- Detailed Fuel Injection System Mapping (2200 to 2900bar)
- **Guide hardware selection** for improved injector – bowl match
- **Guide multiple Injection** strategy

Optimum NOx-PM-BTE

- Leverage Navistar EGNR technology
  - Minimum NOx for ‘breakpoint’ with engine technology package
- Target DPF regeneration fueling 0-1%
Accomplishments:

1. Combustion Efficiency (cont.)

- Phase I tests yielded 3 - 6% BTE improvements across engine map
- Targets were met in B-C speeds
- Further work necessary at the A speed

Phase I test data

![Graph showing BTE improvements across different phases and phases]

Charge System Rematch

- A75: 3.6
- B50: 5.8
- C100: 5.7

Injectors - iteration 1

Increase Fuel Pressure

Target
Accomplishments:

1. Combustion Efficiency (cont.)

A speed: Combustion system match optimization was limited
Fuel Injection system played a minor role

B-C speeds: Combustion system match and FUP played major roles

Phase I test data

Charge System Rematch
Injector - iteration 1
Injector - iteration 2
Injector - iteration 3
Increase Fuel Pressure
Target

Delta BTE% improvement

A75
B50
C100
Accomplishments:

2. Air System

**A speed:** Charge air improvement was significant **but more is needed**
- Next Gen turbocharger hardware target 4% turbomachinery eff increase
- May have to relax current engine-out NOx target benchmark

**B-C speed:** targets are being met

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**Accomplishments:**

**2. Air System**

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Three major engine categories are being considered (13 subsystems)
Three performance categories are addressed
Target BTE improvement of 1 or more percent

<table>
<thead>
<tr>
<th>Categories</th>
<th># of sub systems</th>
<th>Friction</th>
<th>Increased Cylinder Pressure</th>
<th>Thermal Management</th>
<th>Procurement Benchmarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Cylinder</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>on target</td>
</tr>
<tr>
<td>Power Transfer</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>on target</td>
</tr>
<tr>
<td>Crankcase</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>on target</td>
</tr>
</tbody>
</table>

Projected 1% BTE
Projected 220 bar
High target 240 bar
Projected 0.5% BTE (vehicle)

Comprehensive Friction Test
at Federal Mogul
Target Start November 7 2011
Several Base Engine components are ahead of schedule, including the advanced Variable Oil Pump

- The VOP is effective in the drive cycle
- Provides 0.75% BTE improvement at B50 (lab tests)
Accomplishments:
3. Base Engine (VWP)

Engine and Vehicle teams are collaborating in the implementation of an advanced Variable Speed Water Pump

- Pump works in conjunction with vehicle variable speed fan
- Effective in the drive cycle (0.5% BTE improvement at B50)
- Savings based on simulation using engine and vehicle data.

Assumes fan speed adjustment to keep same coolant temperature
Estimates retain boiling criteria
Design uses increased drive ratio to account for slip

DELTA BTE with variable speed water pump

![Graph showing DELTA BTE with variable speed water pump estimates based on Dyno-Vehicle test data]

0.5% BTE

Estimates based on Dyno-Vehicle test data
Accomplishments:

4. **Heat Recovery**

Sources of Waste Heat Recovery considered:

**a) Turbo-compounding**

a) Recovers energy from the exhaust
b) Adds a turbine wheel *placed behind aftertreatment*
c) Requires redesign of turbo system (*high efficiency units to counteract increased backpressure*)

**b) Rankine Cycle**

- Recovers energy from EGR circuit and coolant
- Builds upon Navistar GEN 1 hardware
- Synergistic with high EGR

Installed in Test Cell April-2011
Deploy on Truck Sep-2011
Feasibility (cost effective) study in place
Accomplishments:

4a. Heat Recovery (Turbo-compound)

- Electric turbocompounding (ETC) design complete and installed in test cell
- Hardware tests begin April 2011
- Estimations completed (5% BSFC improvement at B50)

![ETC Hardware, coolant and power electronics cart](image-url)
Accomplishments:

4b. Heat Recovery (ORC)

✓ Organic Rankine Cycles have been evaluated:
  • ORC extract heat from the EGR stream and can tap into other heat sources
  • Evaluating most effective condenser cooling (high and low temperature coolant circuit loops, air-cooled)
  • Evaluating working fluid
  • Evaluating recuperator circuit

✓ Challenges of ORC:
  • System complexity, weight and size
  • Achieve emissions (must maintain EGR and intake manifold temperatures)
  • Operate under transient conditions
  • System cost

✓ Target Decision Point will be in May 2011
  • Summarize efficiency gains, controls, costs
  • Outline next steps
Technology selection stacks up differently with capability to manage engine emissions.
ETC with improved combustion and base engine improvements are close to the proposed targets.
Accomplishments
55% BTE target with Dual Fuel Engine

Engine Modifications (completed April 2011)
- New intake plenum with PFI installation
- Modified head with improved flow

Close collaboration with WERC:
- Extensive CFD simulation
- Support engine design hardware selection
- Establish operating boundary conditions

Benefits:
- High efficiencies
- Clean combustion (e.g. de-content NOx aftertreatment)

Enablers:
- Hi-EGR capable engine
- Hi-efficiency charge air system, previously developed combustion feedback technology (DE-FC26-05NT42413)

Ref Hanson, 2009
Remaining Activities for 2011

Electrical Turbo-compounding (ETC) Engine:
- Complete dyno demonstration of ETC hardware by July 2011.
- Deploy ETC unit on hybrid vehicle with controls and power electronics, and demonstrate functionality by Sept 2011.

Efficiency and Emissions Demo Engine:
- Integrate second ETC hardware onto hi-efficiency development engine.
- Demonstrate interim Break Thermal Efficiency target of 3%-5% BTE gain.

Other Activities:
- Deploy Dual-Fuel engine to Argonne as facility becomes available (approx. July 2011)
- Complete Organic Rankine Cycle feasibility study – if results are positive deliver design architecture and project plan for Phase II.
**Approach**: Project is focused on assessing and developing engine and vehicle technologies to improve freight efficiency while providing a cost effective, robust and reduced weight combination class 8 truck and trailer integrated design.

**Technical Accomplishments**: The MAXXFORCE 13L engine is well posed to:

- Deliver 20% BTE gain across the engine map and the 50% MAX BTE target as seen from present tests and projections from heat recovery.

- To date the following technologies have been incorporated:
  - Extended peak cylinder pressure capability (190→220 bar)
  - Higher injection pressure (2200→2900 bar)
  - Electrical turbo-compounding with advance air system (results due July 2011)

- The following systems will be procured and put on test stand in 2011:
  - Dual Fuel Engine (May)
  - Friction reduction Package (Sept)