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

Vehicle Systems

DOE Contract: DE-EE0003303

NETL Project Manager: Samuel Taylor

Program Investigator: Dennis W. Jadin, Navistar

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National Energy Technology Laboratory
Department of Energy

Project ID: VSS064

This presentation does not contain any proprietary or confidential information
• 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
Packaging of hybrid drive unit and supporting systems
Novel approach to cooling flow integration challenges traditional CFD Development methods

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)

Navistar, Principal Investigator, Vehicle Systems Integrator Controls Systems, Engine & Vehicle Testing
Alcoa, Lightweight Frame & Wheel Materials
ATDynamics, Trailer Aerodynamic Devices
ArvinMeritor, Hybrid Powertrain, Axles
Behr America, Cooling Systems
Michelin, Low Rolling Resistance Tires
TPI, Composite Material Structures
Wabash National, Trailer Technologies
Argonne National Lab, Hybrid Drive Simulation and Controls & Battery Testing
Lawrence Livermore National Lab, Aerodynamic Testing
## Barriers and Technology Roadmap

<table>
<thead>
<tr>
<th>System Area</th>
<th>Barriers</th>
<th>Technology Roadmap</th>
</tr>
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<tbody>
<tr>
<td>Engine &amp; Vehicle</td>
<td>Assemble a <strong>cost effective, robust, reduced</strong> (vehicle) <strong>weight</strong> technologies for 50% BTE.</td>
<td>- Rely on analysis (tradeoff) to select technology</td>
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<td>- Couple technology to road cycle selection</td>
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<tr>
<td>Vehicle</td>
<td><strong>Packaging</strong> of hybrid drive unit and supporting systems</td>
<td>- Hybrid Drive Unit, Battery &amp; Accessory design progression shrinkage</td>
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<tr>
<td></td>
<td></td>
<td>- Component integration</td>
</tr>
<tr>
<td>Vehicle</td>
<td><strong>Aerodynamic correlation</strong> between modeling and full scale vehicle powertrain cooling/underhood air flow effects on exterior Cd measurements</td>
<td>- Aerodynamic mapping of powertrain cooling system and underhood design features and flow characteristics during exterior aerodynamic tests</td>
</tr>
</tbody>
</table>
Approach:
Technology Roadmap - Chassis Efficiency

% Fuel Economy Improvement

Hybrid
- Dual Mode Hybrid Drive
- Electrified Accessories
  - Power Steering
  - Air Compressor
  - AC Compressor

Driveline
- SMARTandem 6x2 Gears
- Next Gen Wide Based Singles Tires
- Tire Inflation Maintenance System
- Opti Lube Level Axle Fill
- Electronic Leveling Air Consumption

Lightweight
- SMARTandem 6x2 axles
- Composite Cab
- Composite Trailer Structure
- Next Gen Wide Based Singles and Wheels

Aero Enhancements
- Gap Reduction
- Aero Drop at Highway Speed
- Surrogate Camera Mirrors
- Tractor Shapes
- Trailer Shapes & Features

Target
30%
**Approach:**

**Technology Roadmap - Vehicle**

- **Accumulative**
- **Aero Enhancements**
- **Hybrid Drive**
- **Driveline Parasitics**
- **Lightweighting**

<table>
<thead>
<tr>
<th>Year</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
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<tbody>
<tr>
<td>2010</td>
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<td>2014</td>
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<td>2015</td>
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</tbody>
</table>

- **1/8 Scale Wind Tunnel**
- **Hybrid Drive Mules**
- **SMARTandem 6x2**
- **1/3 Scale Wind Tunnel**
- **Gen III Hybrid Drive Mules**
- **Full Scale Wind Tunnel**
- **SuperTruck Demonstrators**

**DE-EE0003303**

*SuperTruck – Development and Demonstration of a Fuel Efficient Class 8 Tractor & Trailer*
**Approach:**

*Technology Roadmap - Vehicle*

<table>
<thead>
<tr>
<th>Technology Category</th>
<th>Area of Concentration</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aerodynamics</strong></td>
<td>Advanced Tractor Shape - Speed Form Study</td>
<td>Deploy April 2011</td>
</tr>
<tr>
<td></td>
<td>Surrogate Rear View Mirrors</td>
<td></td>
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<tr>
<td></td>
<td>Advanced Trailer Shapes - PIV - Particle Image Velocimetry</td>
<td>July 2011</td>
</tr>
<tr>
<td></td>
<td>Tire Skirting; Steer, Drive &amp; Trailer</td>
<td></td>
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<tr>
<td></td>
<td>Tractor-Trailer Gap Reductions; Dyn. 5th wheel, Cab Extenders</td>
<td></td>
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<tr>
<td></td>
<td>Aero Drop, Electronic Suspension Leveling, Tractor &amp; Trailer</td>
<td>2Q 2012</td>
</tr>
<tr>
<td><strong>Parasitic Losses</strong></td>
<td>Next Gen Wide-Based Single, Low Rolling Resistance Tires</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tire Pressure Monitoring and Inflation</td>
<td>2Q 2012</td>
</tr>
<tr>
<td></td>
<td>Efficient Drive Axle, 6x2 Configuration</td>
<td>1Q 2012</td>
</tr>
<tr>
<td><strong>Hybrid Drivetrain</strong></td>
<td>Mule Vehicles (2)</td>
<td>May &amp; June 2011</td>
</tr>
<tr>
<td></td>
<td>Electrified Accessories; Power Steering, AC &amp; Air Compressors</td>
<td>May &amp; June 2011</td>
</tr>
<tr>
<td><strong>Air Flow Management</strong></td>
<td>Cooling System Modularization</td>
<td></td>
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<tr>
<td></td>
<td>Cooling System Exhaust location Impacts on Aerodynamics</td>
<td></td>
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<tr>
<td><strong>Vehicle Lightweighting</strong></td>
<td>Advanced Modular Chassis Construction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Efficient Drive Axle, 6x2 Configuration</td>
<td>1Q 2012</td>
</tr>
<tr>
<td></td>
<td>Composite Cab and Trailer Construction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Optimized Wide-Based Single Tires &amp; Wheel End Equipment</td>
<td></td>
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</tbody>
</table>
Approach: Technology Roadmap - Hybrid Powertrain

Simulation and Modeling

- Driveability development
- Durability development
- Fuel economy testing
- Provide better data to the simulation effort

Full Vehicle Development

- Establish control of components on bench
- Establish CAN communication
- Calibrate and refine control algorithms
- Control design validation

Hardware in the Loop

- Explore alternative layouts
- Optimize component sizes
- Evaluate control algorithms
- Explore various drive cycles
- Obtain fuel economy estimates

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Hybrid Powertrain – Performance Modeling

Detailed Vehicle Models Developed

Hybrid Truck Specification

**Battery:**
- EIG Li-ion
- 20 Ah (cell), 40 Ah (pack)
- 28 kWh
- 500 kW (dis.) / 222 kW (chg.)
- 432 Cells

**Motor 1 (Traction):**
- 360 kW (Peak), 200 kW (Cont.)
- Base Speed: 2,100 RPM / Top Speed: 10,000 RPM
- Peak Torque: 1,637 Nm
- Inertia = 1.54 kg.m²
- Switch Reluctance, Includes Spin Losses

**Motor 2 (Generator):**
- 400 kW (Peak), 220 kW (Cont.)
- Base Speed: 2,100 RPM
- Top Speed: 3,200 RPM
- Peak Torque: 1,819 Nm
- Inertia = 1.61 kg.m²
- Switch Reluctance, Includes Spin Losses

**Gearbox:**
- ArvinMeritor Dual Mode
- Low Gear: 1:1, 100% eff.
- High gear: 0.59:1, 98% eff.

**Torque Coupling:**
- 6.5:1, 98% eff.

**Mechanical Accessories:**
- 1 kW

**Electrical Accessories:**
- 3 kW

RED = DATA FROM NAVISTAR

Powertrain models will be used to predict performance and evaluate hardware alternatives.

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Freight-Specific Fuel Economy (ton-mile/g) Improvements from Simulation*

**Weight Assumptions**

<table>
<thead>
<tr>
<th>Load</th>
<th>Conv.</th>
<th>HEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% (empty truck)</td>
<td>32,925</td>
<td>34,925</td>
</tr>
<tr>
<td>50% (10,000 kg)</td>
<td>54,951</td>
<td>56,951</td>
</tr>
<tr>
<td>100% (GVW)</td>
<td>80,000</td>
<td>80,000</td>
</tr>
</tbody>
</table>

*Freight-specific fuel economy improvements are significant, but dependent on drive cycle*

*A 2000-lb hybrid weight penalty is assumed for the development vehicles ONLY. SuperTruck will weigh much less.*
Controls Hardware-in-Loop System is Operational

Simulated
- Route
- Driver
- Vehicle
- Powertrain

Real (articles under test)
- Engine Control Module
- Hybrid Supervisor Control Module
- Transmission Control Module
- Shift Mechanism and Actuator Module

Inputs: Various routes and drive cycles

Outputs: All control signals and communications
Physical movement of shift mechanism

The HiL bench is an effective environment for control system development
Hybrid Powertrain Development Vehicles

360 kW Generator

Inverter /Controller

Two-Speed Overdrive Transmission

360 kW Traction Motor

The first development vehicle is nearing completion
Technical Accomplishments

Hybrid Powertrain – Electrified Accessories

- Air Compressor
- Power Steering
  - Closed-center steering gear (more energy-efficient)
- HVAC Compressor
- All driven by efficient 350V motors

Benefits of Electrified Accessories
- Enables EV operation
- Extended engine-off hoteling
- More efficient
  - Constant rpm
  - Turn on/off as needed
Technical Accomplishments

Hybrid Powertrain – Component Packaging

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

- Generator
- Traction Motor
- Power Steering Pump
- HVAC Compressor
- High-Voltage Distribution Box
- Battery
- DC/DC Converters
- Air Compressor
- Generator
- Traction Motor
- Power Steering Pump
- HVAC Compressor
- High-Voltage Distribution Box
- Battery
- DC/DC Converters
- Air Compressor
Technical Accomplishments

Hybrid Powertrain – Development Progress

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Oct</td>
<td>Nov</td>
</tr>
<tr>
<td><strong>Truck 1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Convert to Hybrid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibration, Development</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Development, FE testing</td>
<td></td>
<td></td>
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<tr>
<td>FE Data to DoE</td>
<td></td>
<td></td>
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<tr>
<td><strong>Truck 2</strong></td>
<td></td>
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<tr>
<td>Baseline FE Testing</td>
<td></td>
<td></td>
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<tr>
<td>Convert to Hybrid</td>
<td></td>
<td></td>
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<tr>
<td>Calibration</td>
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Closed Center Steering Gear required in order to provide efficient assist during EV mode operation.

- **Open Center Design**
  = Constant Flow / Variable Pressure
- **Closed Center Design**
  = Constant Pressure / Variable Flow
- Projected FE improvement in line haul application is ~0.4%
- On road evaluation in Sept, 2011
Advantages of Reduced Tractor/Trailer Gap

• Projected 1.75% Highway Fuel Economy Improvement
• Systems can be independent of trailer
• Potentially better aerodynamic/fuel economy payback than trailer mounted devices for fleets with large trailer to tractor ratios
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Technical Accomplishments

Industrial Design/Aero Shape Development

Year 1-2: Basic exterior aerodynamic shape & form development
Baseline 1/8th scale wind tunnel testing & CFD

Year 1-2: Integration of heat exchangers & cooling system w/CFD & tunnel testing correlation

Year 1:
Industrial Design

SuperTruck Aerodynamic Development Process Steps

Year 2-3: Detailed exterior aerodynamic component development
Scale Models Wind Tunnel 1/3rd Scales

Year 3-4: Full Scale Wind Tunnel Testing at NFAC 80’ x 120’ wind tunnel
Validation of integrated managed airflow package (exterior aerodynamics and cooling flow)

Year 5: On Road Verification

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Technical Accomplishments

Vehicle Aerodynamics - Baseline

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# Technical Accomplishments

## Aerodynamics – Development Progress

<table>
<thead>
<tr>
<th>Activity</th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Tunnel Tests (1/8th Scale)</td>
<td>Oct</td>
<td>May</td>
</tr>
<tr>
<td>Wind Tunnel Evaluation (1/3rd Scale)</td>
<td>Dec</td>
<td>Jun</td>
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<tr>
<td>CFD</td>
<td>Jan</td>
<td>Jul</td>
</tr>
<tr>
<td>Cooling Flow</td>
<td>Feb</td>
<td>Aug</td>
</tr>
</tbody>
</table>

*Note: The table indicates progress made in each month from October 2010 to September 2011.*
**Remaining Activities for 2011**

- **Demonstrate on road 5-10% freight efficiency improvement demonstration of ArvinMeritor GenII DMHP utilizing functional regenerative braking.**
- Complete **Voice-of-the-Customer interviews** with fleet partnerships.
- **Define and map real road test cycle route** that is representative of a typical long-haul Class 8 truck consisting of minimum of 75 percent of the distance traveled under highway conditions.
- **Complete installation** of ArvinMeritor Dual Mode **Hybrid Powertrain** (DMHP), accessory electrification and electrical/cooling system modifications in two (2) ProStar development vehicles.
- Develop, optimize and evaluate **hybrid related control system algorithms** for DMHP regenerative braking system, battery SOC and transmission overdrive operation to rebalance energy conservation vs. on-road vehicle performance.
- Develop, optimize and evaluate **electrified accessories** control algorithms to rebalance energy conversation vs. real world on-road system performance.
- **Complete CFD** and 1/8th scale model **wind tunnel testing** of tractor speed shapes to allow down-selection and incorporation of powertrain cooling system aerodynamic mapping and underhood airflow assessments.
**Project Summary**

**Relevance:**
- The potential of a class 8 truck and trailer combination configured to save 9 billion gallons of diesel fuel per year, reduce our dependence on foreign oil and improve our environment by reducing green house gases has significant national and global interests.

**Approach:**
- Project focus is on assessing and developing a balance of both 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:**
- On target to meet Phase 1 milestones and deliverables.
- Project achievements after six months since 10/1/10 contract start date has shown accelerated progress towards long term and interim targets.
- Hybrid Powertrain simulation shows promising improvement over standard industry drive cycles between 5-12%.
- In vehicle Hybrid powertrain development hardware has proceeded to allow availability of two development vehicles for start of on-road testing of non-aero subsystems in Summer 2011.
- Industrial design, CFD and baseline 1/8th scale modeling of both base line and speed form shapes have substantiated 20% improvement in Cd is achievable.

**Partnerships & Collaborations:**
- Cross-functional and industry partnership teams are working well together. Good mix of skills and resources to address the technical tasks in this project.

**Future Directions:**
- Continue to progress towards a vehicle and engine demonstration of various efficiency improvement technologies.