DoE SuperTruck Program
Technology and System Level Demonstration of Highly Efficient and Clean, Diesel Powered Class 8 Trucks

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Presenter: Kenneth Damon, P.E.
Peterbilt Motors Company

Project ID: ARRAVT081
19 June 2014

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Relevance - Program Objectives
(DoE Vehicle Technologies Goals)

**Objective 1:** Engine system demonstration of 50% or greater BTE in a test cell at an operating condition indicative of a vehicle traveling on a level road at 65 mph.

**Objective 2**

a: Tractor-trailer vehicle demonstration of **50% or greater freight efficiency improvement** (freight-ton-miles per gallon) over a defined drive cycle utilizing the engine developed in Objective 1.

b: Tractor-trailer vehicle demonstration of **68% freight efficiency improvement** (freight-ton-miles per gallon) over a defined 24 hour duty cycle (above drive cycle + extended idle) representative of real world, line haul applications.

**Objective 3:** Technology scoping and demonstration of a 55% BTE engine system. Engine tests, component technologies, and model/analysis will be developed to a sufficient level to validate 55% BTE.

Baseline Vehicle and Engine: 2009 Peterbilt 386 Tractor and Cummins 15L ISX Engine
Relevance - American Recovery and Reinvestment Act (ARRA) Goals

• Create and/or Retain Jobs
• Spur Economic Activity
  – Greater Than $72.6M Total Spend To Date
• Goals Align With VT Multi-year Program Plan 2011-2015
  – Advanced Combustion Engine R&D (ACE R&D):
    • 50% HD Engine Thermal Efficiency By 2015 (Ref: VT MYPP 2.3.1)
  – Vehicle And Systems Simulation And Testing (VSST):
    • Freight Efficiency Improvement of 50% by 2015 (Ref: VT MYPP 1.1)
• Invest In Long Term Economic Growth
  – Commercial Viability Assessment
  – Adopt Technologies into Product Plans to Meet GHG and CO2 Regs

<table>
<thead>
<tr>
<th>Year</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
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<tbody>
<tr>
<td>Full Time Equivalent</td>
<td>75.5</td>
<td>85</td>
<td>60</td>
<td>46</td>
<td>17</td>
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</table>

States: Indiana, Texas, Michigan, Wisconsin, Tennessee, Illinois, New York, Ohio, Mass, California
Response to 2013 AMR Reviewer Comments

- Long list of suppliers was misleading
  - List partners supported as subcontractors to the program
  
  **Addressed in Slides 5 & 12**

- Be sure to include detailed plans on battery sizing and durability
  
  **Addressed in Slide 10**
Collaborations - Peterbilt Participants

- **Sub-contractors**
  - Eaton – Transmissions
  - Delphi – Solid Oxide Fuel Cell

- **New Supplier in 2013 (Not Sub-contracted)**
  - Corvus Energy – Lithium Ion APU

- **OEM (Not Sub-contracted)**
  - Utility Trailer Manufacturing

- **End User**
  - US Xpress
### Overview - Schedule and Budget

**Budget**
- DoE Share: $38.8M (49%)
- DOE Spend To-Date: $36M
- Contractor Share: $40.3M (51%)

4-1/2 Year Program: April 2010 to Sept 2014

<table>
<thead>
<tr>
<th>Objective 1 – Engine Demo.</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
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<tbody>
<tr>
<td>50% or Greater BTE Engine Demonstration</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
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<table>
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<tr>
<th>Objective 2a – Drive Cycle Vehicle Demo.</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
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<td>Vehicle Demonstration of 50% or Greater Freight Efficiency Improvement</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
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<tbody>
<tr>
<td>Vehicle Demonstration of 68.5% or Greater Freight Efficiency Improvement</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
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<table>
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<th>Objective 3 – 55% BTE Engine</th>
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<th>2014</th>
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<td>55% BTE Engine Demonstration</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
</tr>
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Program Close-Out
## Overview - DoE SuperTruck Program

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
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<th>2012</th>
<th>2013</th>
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<tr>
<td>4Q</td>
<td></td>
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</tbody>
</table>

- **2010**: Funding Approval
- **2011**: Cummins Hardware Devo and Lab Testing, 50% BTE Engine Demonstration
- **2012**: Set Duty Cycle and Baseline Testing, Model 587 Mule Build, WHR System Calibration
- **2013**: Model 579 Demo 2 Build, USX Driver Feedback, 68% Freight Efficiency Demo

- **Baseline Truck Model 386**
- **Integrated Tractor-Trailer CFD Analysis**
- **Mule Definition and Design**
- **Model 587 Demo 1 Build**
- **System and Fuel Economy Testing**
- **Demo 1**
- **Demo 2**

**USX Driver Feedback**
Overview - Program Barriers

- Underhood Cooling with Waste Heat Recovery
- Vehicle and Engine System Weight Reduction
- Engine Downsspeed (Reduced Engine Speed)
  - Powertrain Components
  - Vibration/Customer Acceptance
- Vehicle and Powertrain Communication Speed
- Trailer Aero Devices That Meet Operational Requirements
- Alternate Power Unit – Technology Change
Technical Progress - Program Barriers

Alternate Power Unit

• Solid Oxide Fuel Cell (SOFC)
  – Integrated into Demo 1 (Aug 2012)
  – Functionality Verified (Dec 2012)
  – Development Challenges
    • Warm Up Time
    • Peak Power
    • Efficiency
    • Weight
  – Delphi Put Development on Hold (Jan 2013)
  – Demo 2 Options:
    • Use Demo 1 Level SOFC
    • Choose Another Technology
  – Request to Pursue Alternate Technology
    Approved By DOE Feb 2013
Technical Progress - Program Barriers
Alternate Power Unit

- Lithium Ion APU
  - (4) Li Ion Pack + Start Battery
  - 240a Alternator
  - 13.2 kW-h Capacity
  - 12.2 kW-h Load Profile
  - 400lb Battery, Structure, and Cables
  - 6hr Highway Re-charge
  - Capable Development Level System
Technical Progress
Model 579 Demo 2

- Advanced Formula Aftertreatment
- Cummins 15L High Efficiency ISX Engine
- High Speed Routers
- Waste Heat Recovery System
- GPS Cruise Control
- Advanced Super Single Tires
- Cab and Trailer Aero Components
- Pneumatically Retractable Trailer Skirts
- 180° Trailer Tandem Service Door
- High Efficiency Cooling Package
Collaboration

- Cooling Package and Heat Exchangers
- Ceramic Brake Drums
- Power Distribution
- Route Display
- Li Ion Start Batt & APU
- Alum Hybrid Driveshaft
- Downspeed-enabling Transmission
- Magnesium Crossmembers
- Variable Gage Steel Frame Rails
- 6x2 Rear Tandem w/ eTrac
- Light Steer Axle and Trailer Tandem
- Alum 5th Wheel
- Advanced Light Wheels
- Integrated Air Suspension Bags
Objective 2b: 24 hr Duty Cycle Testing
Technical Progress

Start of Testing: Dec 2013
Objective 2b: 24 hr Duty Cycle Testing
Technical Progress

- Identical 12.2 kW-hr Load over 10 Hours
- Baseline Supported with Engine Idling
- Demo 2 Supported with Lithium Ion Batteries

Hotel Cycle/Battery Conditioning
### Objective 2b: 24 hr Duty Cycle Results

#### Technical Accomplishment (Dec 2013)

<table>
<thead>
<tr>
<th></th>
<th>GVW (lb)</th>
<th>Freight (lb)</th>
<th>MPG (Range)</th>
<th>(Avg) FTMPG Improvement</th>
<th>(Avg) MPG Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>579 Demo 2</td>
<td>65k</td>
<td>32,576</td>
<td>9.4-9.5</td>
<td><strong>86%</strong></td>
<td><strong>75%</strong></td>
</tr>
<tr>
<td></td>
<td>+1305</td>
<td></td>
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</table>

Temp Min/Avg/Max: 30/46/70°F  
Wind Avg/Max Gust: 14/28 mph  

Goal: 68%
# Testing Beyond Scope

**Demo 2 vs. Baseline - Drive Cycle Route**

## Technical Accomplishment

<table>
<thead>
<tr>
<th></th>
<th>GVW (lb)</th>
<th>Freight (lb)</th>
<th>(Avg) FTMPG Improvement</th>
<th>(Avg) MPG Improvement</th>
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</thead>
<tbody>
<tr>
<td>579 Demo 2</td>
<td>65k</td>
<td>32,576</td>
<td><strong>76%</strong></td>
<td><strong>66%</strong></td>
</tr>
<tr>
<td></td>
<td><strong>+1305</strong></td>
<td></td>
<td>(Demo 1: 61%)</td>
<td>(Demo 1: 54%)</td>
</tr>
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</table>

**Temp Min/Avg/Max:** 22/36/52°F  
**Wind Avg/Max Gust:** 13/33 mph
Technical Accomplishment
Freight Efficiency Status

- 24 hour Cycle - Objective 2b
- Drive Cycle (2a)

Freight Efficiency Improvement (%)

- Aerodynamics
- Engine
- Transmission/axle
- Tire Rolling Resistance
- Route Management
- Idle Management
- Vehicle Weight
- Demo2: Drive Cycle - Final
- Demo2: 24 hr Cycle - Final

Status

- 76
- 86

Legend:
- 24hr duty cycle
- Drive Cycle
## Testing Beyond Scope

### Demo 2 vs. Demo 1 - Drive Cycle Route

#### Technical Accomplishment

<table>
<thead>
<tr>
<th>GVW</th>
<th>Run 1</th>
<th>Run 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>579 Demo 2</td>
<td>65k</td>
<td>9.9</td>
</tr>
<tr>
<td>587 Demo 1</td>
<td>65K</td>
<td>8.9</td>
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Temp Min/Avg/Max: 38/47/53°F
Wind Avg/Max Gust: 6 mph/steady
Testing Beyond Scope
Technical Accomplishment

Peak MPG

Demo 2 Tractor w/ Trailer Skirts
65K GVW

9.4
Temp Min/Avg/Max: 55/68/77°F
Wind Avg/Gust: 9/18 mph

Demo 2 Tractor w/ Demo 2 Trailer
80K GVW

10.4
Temp Min/Avg/Max: 49/56/64°F
Wind Avg/Gust: 6.5 mph/steady

Demo 2 Tractor w/ Demo 2 Trailer
32.5K GVW (Empty Trailer)

12.7
Temp Min/Avg/Max: 54/63/68°F
Wind Avg/Gust: 23/40 mph
Aerodynamic Improvements – Technical Progress

- Demo 1 - 14% Target
- Demo 2 - 24% Target

Demos Progress
Since Last Review
Target Exceeded
Demo 2 Truck/Trailer Weight
Technical Progress

1305 lb Bonus Freight
Driver Acceptance Collaboration

- US Xpress Drive Event, Demo 1
  - Mar 21, 2013
  - Irving, TX to Laredo, TX
    (950 mile round trip)
  - Commercial Freight
  - US Xpress Drivers

- Feature/Functional Evaluation
  - Loading/Unloading Aero Trailer
  - Drivability

- Very Positive Event

- Critical and Valuable Feedback
Driver Acceptance
Collaboration/Technical Progress

Added Trailer Features for Demo 2

Service Access
Retractable Skirt
Promoting the DOE Program
Technical Progress
White House Press Event
February 18, 2014
Technical Accomplishment

Safeway Distribution Center
Upper Marlboro, MD
Technical Accomplishment/Collaboration

Mid-America Truck Show
March 27-29, 2014
Milestones and Technical Accomplishments

• March 2013 to March 2014 – Technical Accomplishments
  √ Demonstrated 86% freight efficiency improvement (Objective 2b – 24hr)
    √ 75% fuel economy increase
  √ Demonstrated 76% freight efficiency improvement (Objective 2a – Drive)
    √ 66% fuel economy increase
  √ Demonstrated Li-Ion Battery & SOFC capability
  √ Completed wind tunnel and vehicle testing of Waste Heat Recovery
  √ Validated an advanced transmission efficiency model
  √ Path-to-Target analysis for a 55% thermal efficient engine
    √ Demonstrated 49.4% BTE in engine only (Objective 3)

• March 2014 to September 2014 – Future Work
  • 55% BTE path to target roll-up analysis (Objective 3)
  • Final Report and Commercial Development
Summary

- Program remains on schedule
  - Meeting the ARRA and DoE VT MYPP goals
- Demonstrated a 50+% BTE engine system (Objective 1)
- Demonstrated a 70+% vehicle freight efficiency gains (Objective 2a & 2b)
  - Analytical roadmaps updated with experimental component data
- Built and tested sub-systems
  - Cummins Waste Heat Recovery vehicle testing (Objective 2a)
  - Advanced transmission dynamometer and vehicle test (Objective 2a)
  - Solid Oxide Fuel Cell APU in lab and vehicle tests (Objective 2b)
  - Li-Ion battery APU (Objective 2b)
  - Tractor-Trailer aerodynamic aids (Objective 2a)
- Developed framework and analysis for 55% thermal efficiency
  - Completed analytical roadmaps for both diesel and dual fuel approaches
  - Completing targeted engine tests to validate roadmaps
- Developed working relationship with excellent vehicle and engine system delivery partners
FTE Deliverables On Track
Technical Accomplishment

Demo 1:
- 50%
- 61%

COMPLETE!

Demo 2:
- 68%
- 86%