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

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Cummins Inc.

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Project ID: ACE057

This presentation does not contain any proprietary, confidential, or otherwise restricted information
Relevance - Program Objectives  
(DoE Vehicle Technologies Goals)

All Technologies must meet Current US EPA 2010  
Emissions Standards and Transportation/Safety Standards

**Objective 1: Engine Development**

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

**Objective 2: Vehicle Integration & Development**

a: Tractor-trailer vehicle demonstration of 50% or greater freight efficiency  
 improvement (freight-ton-miles per gallon) over a defined drive cycle.

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: Engine Development**

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
**Overview - Program Schedule and Budget**

**Budget:**
- DoE Share $38.8M (49%)
- Contractor Share $40.3 M (51%)
- $20.2 M total DoE share spend to date

**4 Year Program: April 2010 to April 2014**

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<thead>
<tr>
<th>Objective 1: Test cell demonstration of 50% or greater BTE engine</th>
<th>2010</th>
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<th>Objective 2a: Vehicle drive cycle demonstration of 50% or greater freight efficiency improvement</th>
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<th>Objective 2a: Vehicle 24 hour duty cycle demonstration of 68% or greater freight efficiency improvement</th>
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Program closeout
Overview - Program Barriers

- Engine Downspeed (Reduced Engine Speed)
  - Powertrain component response
  - Closed cycle efficiency gains
- High Conversion Efficiency NOx Aftertreatment
  - Fuel Efficient Thermal Management
- Vehicle and Engine System Weight Reduction
- Underhood Cooling with Waste Heat Recovery
- Powertrain Materials
  - Increased Peak Cylinder Pressure with Cost Effective Materials for Block and Head
  - Thermal Barrier Coatings for Reduced Heat Transfer
- Trailer Aerodynamic Devices that are Functional
- Parasitic power reductions

More vehicle specific details are included in Peterbilt’s 2012 AMR presentation ARRA-087
Overview - Program Partners

Cummins Inc.
- Cummins Fuel Systems
- Cummins Electronics
- Cummins Turbo Technologies
- Cummins Emissions Solutions
- Cummins Filtration
- Modine
- VanDyne SuperTurbo Inc.
- Oak Ridge National Lab.
- Purdue University

Peterbilt Motors Company
- Eaton
- Delphi
- Modine
- Utility Trailer Manufacturing
- Bridgestone
- U.S. Xpress
- Dana
- Bergstrom
- Logena
- Bendix
- Garmin
- Goodyear
## Participants – Who’s doing what Roles and Responsibilities

<table>
<thead>
<tr>
<th>Participant</th>
<th>Responsibility</th>
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| Cummins Inc.                       | • Prime contractor  
                                    • Team coordination  
                                    • Engine system  
                                    • Vehicle system analysis |
| Peterbilt Motors Co.               | • Vehicle Build Coordination  
                                    • Vehicle Integration  
                                    • Tractor-Trailer Aero  
                                    • Freight efficiency testing |
| Cummins Turbo Technology           | Turbomachinery & WHR power turbine                                           |
| Cummins Fuel Systems               | Fuel system                                                                   |
| Cummins Emissions Solutions        | Aftertreatment                                                                |
| Eaton                              | Advanced transmission                                                         |
| Delphi                             | Solid Oxide Fuel Cell idle management technology                              |
| Bendix                             | Reduced weight brake system and drive axle control                            |
| Bridgestone & Goodyear             | Low rolling resistance tires                                                  |
| Modine                            | WHR heat exchanger & vehicle cooling module                                   |
| U.S. Xpress                       | • End User Review  
                                    • Driver Feedback  
                                    • Commercial Viability |
| Oak Ridge National Laboratories    | Fast response engine & AT diagnostic sensors                                   |
| Purdue University                 | Low temp combustion control models integrated with VVA                        |
| VanDyne SuperTurbo                | Turbocompounding/Supercharging                                                |
| Utility Trailer                   | Lightweight Trailer Technology                                                |
| Dana                               | Lightweight Drivetrain Technology                                             |
| Bergstrom                         | HVAC                                                                          |
| Garmin                             | Driver interface/display                                                      |
| Logena                             | Network interface                                                             |
Relevance - American Recovery and Reinvestment Act (ARRA) & VT ARRA Goals

• ARRA Goal: Create and/or Retain Jobs
  
<table>
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<tr>
<th>Year</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
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<tr>
<td>Full Time Equivalent</td>
<td>75.5</td>
<td>85</td>
<td>70</td>
<td>45</td>
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• ARRA Goal: Spur Economic Activity
  • Greater than $40M 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
  – Freight transport is essential for economic growth
    • Commercial viability assessment
Approach – Vehicle Energy Analysis

Analysis of 27 Drive Cycles for Class 8 Vehicles with a Variety of Seasons (Summer, Winter, etc.)

1. Engine Losses
   - Urban: 58-60%
   - Interstate: 58-59%
   - **Cummins**

2. Aerodynamic Losses
   - Urban: 4-10%
   - Interstate: 15-22%
   - **Peterbilt**

3. Rolling Resistance
   - Urban: 8-12%
   - Interstate: 13-16%
   - **Bridgestone & Goodyear**

4. Drivetrain
   - Urban: 5-6%
   - Interstate: 2-4%
   - **Eaton & Dana**

5. Auxiliary Loads
   - Urban: 7-8%
   - Interstate: 1-4%
   - **Delphi & Bergstrom**

Analyse: Where is the energy going? Identify priority.
Approach - Integration of Cummins Component Technologies

- Air Handling & EGR
- Combustion
- Fuel Systems
- Aftertreatment (AT)
- Electronic Controls
Technical Accomplishment – Engine architecture decision

Question: Does a no-EGR engine architecture provide increased efficiency at lower system cost?

- Cummins data indicates an EGR solution yields best efficiency
- A unique no-EGR AT system design achieved compliance
- System cost analysis not favorable for no-EGR architecture
Technical Accomplishments - Improvements
(Based on Engine, AT & WHR Testing)

Engine System Meets US EPA 2010 Emissions Regulation

Status 2011 Merit Review:
Engine + High Efficiency AT + WHR
(Analysis & Component Testing)

Analysis based improvements

Program Requirement
50% BTE

Status 2012 Merit Review:
Engine + High Efficiency AT + WHR
(Engine, AT & WHR System Testing)

Final Opt.

Engine Brake Thermal Efficiency (%)

\[
\eta_{brake} = \eta_{ig} \eta_{oc} \eta_{m} + \Delta_{WHR}
\]

- Engine demonstration showed improvements in all terms

*WHR - Cummins Organic Rankine Cycle Waste Heat Recovery
Technical Accomplishments – 50% Thermal Efficiency Gains

Gross indicated gains
- Compr ratio increase
- Piston bowl shape
- Injector specification
- Calibration optimization

Gas flow improvements
- Lower dP EGR loop
- Turbocharger match

Parasitic reductions
- Cylinder kit friction
- Cooling pump power

WHR system
- EGR boiler/superheater
- Exhaust boiler
- Recuperator
Technical Accomplishment – Supplemental Emission Test (SET) Weighted Modal Cycle NOx Emissions

- Compliance to prevailing emissions 0.2 g/(hp-hr) demonstrated
- FTP requires additional calibration effort with optimized components

Aftertreatment effectiveness gain by:
- SCR catalyst size optimization
- Improved design of NOx sensing across face of catalyst
- Close loop control
Technical Accomplishment – Freight Efficiency Status

Freight Efficiency Improvement (%)

- Demo #1 Goal
- Demo #2 Goal

2011 Annual Merit Review (AMR) freight efficiency roadmap

Vehicle details are included in Peterbilt’s 2012 AMR presentation ARRA-087
Technical Accomplishment – 55% Engine Technology Scoping

2012 plan

- Combustion system design
- Engine system simulation of roadmap technologies
- Targeted engine tests – correlate to simulation
Collaborations – ORNL & Purdue Participation

• ORNL
  – Sensing methods for:
    • Combustion uniformity studies
      – Spatially and high response temporally resolved EGR variation and its minimization
      – Enables validation of CFD and analysis led design
    • AT performance studies
      – Enhanced SCR understanding to improve models & control methods fundamental to high efficiency AT

• Purdue University
  – Engine control for variable intake valve diesel
    – Effective Compression Ratio estimator model
    – Control-Oriented low temperature combustion timing model
    – Oxygen fraction [O2] estimator
Milestones and Technical Accomplishments

• March 2011 to March 2012 – **Technical Accomplishments**
  – Analysis of Path to Target for Engine and Vehicle Efficiencies
  – Demonstrated the interim milestone toward 50% or greater BTE
  – Aerodynamic aid fabrication and initial vehicle testing
  – Initial vehicle tests of Cummins Waste Heat Recovery System
  – Initial testing of Advanced Transmission
  – Performance assessment of SOFC APU

• March 2012 to March 2013 – **Future Work**
  – Engine calibration and optimization work
  – Vehicle Testing of Advanced Transmission
  – Testing of Tractor – Trailer Aerodynamics Solution
  – Build and test for Vehicle Demonstration #1 (Objective 2a)
  – Design freeze for Vehicle Demonstration #2 (Objective 2b)
  – Initial vehicle calibration of Second Generation SOFC APU
  – 55% scoping analysis and targeted tests (Objective 3)
Summary

- Program remains on schedule
  - Meeting the ARRA and DoE VT MYPP goals
- Roadmaps updated for freight efficiency and 50% engine efficiency
- Studied alternative engine system architectures
  - Established an EGR engine architecture direction
- Demonstrated an interim milestone toward 50% or greater BTE
- Vehicle packaging and integration proceeding without major issues
- Build and testing of sub-systems are on the planned schedule
  - Cummins Waste Heat Recovery vehicle testing (Objective 2a)
  - Advanced transmission dynamometer and vehicle test (Objective 2a)
  - Solid Oxide Fuel Cell 2nd design iteration lab tests (Objective 2b)
  - Tractor-Trailer aerodynamic aids (Objective 2a)
- Developed working relationship with excellent vehicle and engine system delivery partners
Technical Back-Up Slides
## Approach – Freight Efficiency Path to Target

<table>
<thead>
<tr>
<th>Technology</th>
<th>Drive Cycle Vehicle Demonstration</th>
<th>24 Hour Duty Cycle Vehicle Demonstration</th>
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<tbody>
<tr>
<td></td>
<td>Freight Efficiency Improvement (%)</td>
<td>Freight Efficiency Improvement (%)</td>
</tr>
<tr>
<td>Vehicle Aerodynamics</td>
<td>14%</td>
<td>24%</td>
</tr>
<tr>
<td>Engine</td>
<td>25.5%</td>
<td>27%</td>
</tr>
<tr>
<td>Transmission/Axles</td>
<td>3.5%</td>
<td>3.5%</td>
</tr>
<tr>
<td>Rolling Resistance</td>
<td>3.5%</td>
<td>3.5%</td>
</tr>
<tr>
<td>Route Performance Management</td>
<td>2.5%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Idle Management</td>
<td>N/A</td>
<td>10%</td>
</tr>
<tr>
<td>Vehicle Weight</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>Total</td>
<td>52%</td>
<td>73.5%</td>
</tr>
<tr>
<td>Target</td>
<td>50%</td>
<td>68.5%</td>
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Ref: 2011 AMR - Stanton
Improvements – Technical Accomplishments
(Based on Analysis and Engine Component Testing)

Engine System Meets US EPA 2010 Emissions Regulation

WHR System
• Working Fluid
• Cooling System Controls
• Turbine Expander Efficiency

Program Requirement
50% BTE

Cummins Advanced Engine + High Efficiency AT + WHR*

Increased PCP
Increased CR

Turbo Efficiency Improvements

Power Cylinder Friction Reduction

Powertrain Optimization

Lower $\Delta P$ EGR Volumetric Eff.

Engine Brake Thermal Efficiency (%)

Ref: 2011 AMR - Stanton

*WHR - Cummins Organic Rankine Cycle Waste Heat Recovery
Innovation You Can Depend On

Cummins Waste Heat Recovery

- Organic Rankine Cycle
- Recovery of:
  - EGR
  - Exhaust heat
- Mechanical coupling of WHR power to engine
- Low global warming potential (GWP) working fluid refrigerant
- Fuel Economy improvement goal of ~6%
- 1st vehicle installation Sep2011
Vehicle Aerodynamic Results

- Demo #1: 18% Drag Reduction vs 14% Target
- Demo #2: 21.5% Analytical Potential Drag Reduction vs 24% Target

*Cd’s Shown Are Adjusted to SAE J1252 Baseline Using % Average Deltas From 0 and 6 Degree CFD Runs
Vehicle Weight Reduction – Freight Efficiency Improvement

>3% Freight Efficiency Improvement With Vehicle Weight Reduction

Freight Efficiency Gains/Losses (%)

-6% -4% -2% 0% 2% 4% 6% 8% 10%

-6% -4% -2% 0% 2% 4% 6% 8% 10%

Aero Idle Mgmt Truck Trailer Net Freight

Innovation You Can Depend On