Innovation You Can Depend On

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

Donald Stanton - Principal Investigator
Cummins Inc.

May 12, 2011

This presentation does not contain any proprietary, confidential, or otherwise restricted information
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
### Overview - Program Schedule and Budget

#### Budget

- **DoE Share**: $38.8M (48%)
- **Contractor Share**: $42.1M (52%)

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
<th>Phase 4</th>
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<tbody>
<tr>
<td>2010</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td>2011</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td>2012</td>
<td>Q1</td>
<td>Q2</td>
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<td>2013</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
</tr>
<tr>
<td>2014</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
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</table>

**Objective 1 - Engine Demo.**
50% or Greater BTE Engine Demonstration

**Objective 2a - Drive Cycle Vehicle Demo.**
Vehicle Demonstration of 50% or Greater Freight Efficiency Improvement

**Objective 2b - 24 hour Duty Cycle Vehicle Demo.**
Vehicle Demonstration of 68.5% or Greater Freight Efficiency Improvement

**Objective 3 - 55% BTE Engine**
55% BTE Engine Demonstration

**Program Close-Out**
Overview - Program Barriers

- Controlling Engine Modes of Combustion
- Engine Downs speed (Reduced Engine Speed)
  - Powertrain components
  - Power Density
- 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
- Engine Sensor Technologies
Relevance - American Recovery and Reinvestment Act (ARRA) Goals

- Create and/or Retain Jobs
- Spur Economic Activity:
  - Greater than $13M Total Spend to Date
- Invest in Long-Term Economic Growth
  - Commercial Viability Assessment
  - Demonstrate Technologies with Acceptable Payback Period
  - Adopt Technologies into Product Plans to Meet GHG and CO₂ Regulations for 2017 and beyond

<table>
<thead>
<tr>
<th>Year</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
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</thead>
<tbody>
<tr>
<td>Full Time Equivalent</td>
<td>75.5</td>
<td>107.5</td>
<td>131.0</td>
</tr>
<tr>
<td>Projections</td>
<td></td>
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</table>

States: Indiana, Texas, Michigan, Wisconsin, Tennessee, Illinois, California
Comprehensive **Approach** to Fuel Consumption and Freight Efficiency Improvements

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

- **Engine Losses**
  - Urban: 58-60%
  - Interstate: 58-59%

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

- **Inertia / Braking**
  - Urban: 15-20%
  - Interstate: 0-2%

- **Auxiliary Loads**
  - Urban: 7-8%
  - Interstate: 1-4%

- **Drivetrain**
  - Urban: 5-6%
  - Interstate: 2-4%

- **Rolling Resistance**
  - Urban: 8-12%
  - Interstate: 13-16%

**Weight Reduction**
Program Participants - Collaborations

- Cummins Inc.
  - Cummins Fuel Systems
  - Cummins Turbo Technologies
  - Cummins Emissions Solutions
  - Cummins Electronics
  - 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

Program Lead
## Participants Roles and Responsibilities

<table>
<thead>
<tr>
<th>Participant</th>
<th>Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cummins Inc.</td>
<td>• Prime Contractor&lt;br&gt;• Team Coordination&lt;br&gt;• Engine System&lt;br&gt;• Vehicle Integration</td>
</tr>
<tr>
<td>Peterbilt Motors Co.</td>
<td>• Vehicle Build Coordination&lt;br&gt;• Vehicle Integration&lt;br&gt;• Tractor-Trailer Aero</td>
</tr>
<tr>
<td>Cummins Turbo Technology</td>
<td>Turbomachinery</td>
</tr>
<tr>
<td>Cummins Fuel Systems</td>
<td>Fuel System</td>
</tr>
<tr>
<td>Cummins Emissions Solutions</td>
<td>Aftertreatment</td>
</tr>
<tr>
<td>Eaton</td>
<td>Transmission</td>
</tr>
<tr>
<td>Delphi</td>
<td>Idle Management Technology (Solid Oxide Fuel Cell APU)</td>
</tr>
<tr>
<td>Bridgestone</td>
<td>Reduced Rolling Resistance</td>
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</table>

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<thead>
<tr>
<th>Participant</th>
<th>Responsibility</th>
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</thead>
<tbody>
<tr>
<td>Modine</td>
<td>Cooling System Development</td>
</tr>
<tr>
<td>U.S. Xpress</td>
<td>• End User Review&lt;br&gt;• Driver Feedback&lt;br&gt;• Commercial Viability</td>
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<tr>
<td>Oak Ridge National Laboratories</td>
<td>Sensor and Diagnostics</td>
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<tr>
<td>Purdue University</td>
<td>VVA and Low Temperature Combustion Controls</td>
</tr>
<tr>
<td>VanDyne SuperTurbo</td>
<td>Turbocompounding/Supercharging</td>
</tr>
<tr>
<td>Utility Trailer</td>
<td>Lightweight Trailer Technology</td>
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<tr>
<td>Dana</td>
<td>Axle Technology</td>
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<tr>
<td>Bergstrom</td>
<td>HVAC</td>
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### 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>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Freight Efficiency Improvement (%)</strong></td>
<td></td>
<td></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>
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<tr>
<td>Vehicle Weight</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>52%</td>
<td>73.5%</td>
</tr>
<tr>
<td><strong>Target</strong></td>
<td>50%</td>
<td>68.5%</td>
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## Vehicle Technologies

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<td>Freight Efficiency Improvement (%)</td>
<td>Freight Efficiency Improvement (%)</td>
</tr>
<tr>
<td>Vehicle Aerodynamics</td>
<td>Harmonized Tractor-Trailer</td>
<td>Harmonized Tractor-Trailer</td>
</tr>
<tr>
<td>Engine</td>
<td>WHR, Low Temperature Combustion, Base Engine, AT, etc.</td>
<td>WHR, Low Temperature Combustion, Base Engine, AT, etc.</td>
</tr>
<tr>
<td>Transmission/Axles</td>
<td>Advanced Transmission, Smart Axle, Shift Optimization Reduced Parasitics</td>
<td>Advanced Transmission, Smart Axle, Shift Optimization Reduced Parasitics</td>
</tr>
<tr>
<td>Rolling Resistance</td>
<td>Robustness to wear, low resistance</td>
<td>Robustness to wear, low resistance</td>
</tr>
<tr>
<td>Route Performance Management</td>
<td>GPS, Adaptive Cruise, Driver Feedback</td>
<td>GPS, Adaptive Cruise, Driver Feedback</td>
</tr>
<tr>
<td>Idle Management</td>
<td>N/A</td>
<td>Solid Oxide Fuel Cell APU</td>
</tr>
<tr>
<td>Vehicle Weight</td>
<td>Lightweight tractor and trailer construction, engine weight, etc.</td>
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</tr>
<tr>
<td>Total</td>
<td>52%</td>
<td>73.5%</td>
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<td>Target</td>
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Approach – Engine Technology Roadmap

- Base Engine
  - PCP
  - Friction/Parasitics
- Fuel System
- Advanced Combustion
- Controls
- Materials
- Waste Heat Recovery
- Variable Valve Actuation
- EGR Loop
- Turbo Technology
- Aftertreatment

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Approach - Engine System Architecture

Engine Combustion Strategy

- **Conventional Diffusion Controlled**
  - Moderate EGR Rates Diffusion Controlled
  - Early PCCI
  - Poor Efficiency Moderate PM and NOx
- **Lifted Flame Diffusion Controlled**
  - Early PCCI
  - High Efficiency Low PM and NOx

+ **SCR Aftertreatment**

**TORQUE (ft-lbs)**

**SPEED (rpm)**
Approach - Integration of Cummins Component Technologies

- Air Handling & EGR
- Combustion
- Fuel Systems
- Aftertreatment
- Electronic Controls
Engine System Meets US EPA 2010 Emissions Regulation

Program
Baseline – 42%

Cummins Advanced Engine + High Efficiency AT + WHR*

Engine Brake Thermal Efficiency (%)

42% 43% 44% 45% 46% 47% 48% 49% 50% 51%

Program Requirement
50% BTE

*WHR - Cummins Organic Rankine Cycle Waste Heat Recovery
Improvements – Technical Accomplishments
(Based on Analysis and Engine Component Testing)

Engine System Meets US EPA 2010 Emissions Regulation

Program
Baseline – 42%

Cummins Advanced Engine + High Efficiency AT + WHR*

- Increased PCP
- Increased CR

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

Power Cylinder Friction Reduction

Powertrain Optimization

Lower $\Delta P$ EGR Volumetric Eff.

Turbo Efficiency Improvements

Engine Brake Thermal Efficiency (%)

42% 43% 44% 45% 46% 47% 48% 49% 50% 51%

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Program Requirement
50% BTE

*WHR - Cummins Organic Rankine Cycle Waste Heat Recovery
• Establish requirements for future vehicle communication architecture

• New level of vehicle and powertrain optimization for fuel efficiency
  (Algorithms completed and Simulation Completed: Hardware-in-the-loop testing on-going)
Milestones and Technical Accomplishments

• March 2010 to March 2011 – **Technical Accomplishments**
  – Analysis of Path to Target for Engine and Vehicle Efficiencies
  – Baseline Vehicle Testing
  – Engine Demonstration of 47% BTE & US EPA Emissions
  – CFD Analysis of Vehicle Demo. #1 Aero
  – Integration of Cummins Waste Heat Recovery System
  – Design of Advanced Transmission
  – Performance Assessment of SOFC APU

• March 2011 to March 2012 – **Future Work**
  – Engine Demonstration of 50% BTE (Objective 1)
  – Vehicle Testing of Advanced Transmission
  – Testing of Tractor – Trailer Aerodynamics Solution
  – Design Freeze for Vehicle Demonstration #1 (Objective 2a)
  – Design Complete of Second Generation of SOFC APU
Summary

• Program remains on schedule with 100% milestone completion
• Meeting the goals for American Recovery and Reinvestment Act (ARRA)
• Completed baseline vehicle testing
• Engine efficiency and vehicle freight efficiency roadmaps updated with evidence to meet or exceed targets
• Current engine BTE is 47.5%. Identified and implementing technology to exceed 50% BTE target (Objective 1)
• Significant progress on the Cummins Waste Heat Recovery system
• Cummins Component Business technology development on schedule
• Completed design of advanced transmission – part procurement on-going
• Vehicle packaging and integration proceeding without any major issues
• Completed CFD analysis of tractor-trailer aerodynamic design for vehicle #1 (Objective 2a)
Technical Back-Up Slides
Cummins Waste Heat Recovery

- Organic Rankine Cycle
- Recovery of:
  - EGR
  - Charge Air
  - Exhaust heat
- Mechanical coupling of WHR power to engine
- Fuel Economy improvement of ~6%
- Reduced system size for vehicle packaging
Progress Beyond Current Material and Engine Design Limits – Cylinder Pressure

Cummins SuperTruck Program

7% Engine Weight Reduction

Overcoming Materials Barriers
Achieving Significant Weight Reductions

Peak Cylinder Pressure (PCP) BAR

Sub-component Limitations

Vehicle and Engine Cooling System Design
Underhood Air Flow and Temperature Analysis

Successful Packaging of the Engine + Waste Heat Recovery
In the Aerodynamic Vehicle Design

Velocity Profile

Pressure Differential
Vehicle Aerodynamics Technical Accomplishments

- Truck #1 Accomplished a 36% Reduction in Drag – Exceed 28% target
- Truck #2 Analysis Indicates a 43% Potential Reduction in Drag – More Worked Required to Reach 48% 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 (Technical Accomplishment)

>3% Freight Efficiency Improvement With Vehicle Weight Reduction