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

David Koeberlein- Principal Investigator
Cummins Inc.

May 16, 2013
Project ID: ACE057
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%)
- $31 M total DoE share spend to date

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

<table>
<thead>
<tr>
<th>Objective 1: Test cell demonstration of 50% or greater BTE engine</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Objective 2a: Vehicle drive cycle demonstration of 50% or greater freight efficiency improvement</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Objective 2a: Vehicle 24 hour duty cycle demonstration of 68% or greater freight efficiency improvement</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Objective 3: Technology scoping and demonstration of a 55% BTE engine system.</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
</tbody>
</table>

**Today**
Innovation You Can Depend On

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 2013 AMR presentation ARRA-081
# Overview - Program Partners

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

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

<table>
<thead>
<tr>
<th>Participant</th>
<th>Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cummins Inc.</td>
<td>• Prime contractor</td>
</tr>
<tr>
<td></td>
<td>• Team coordination</td>
</tr>
<tr>
<td></td>
<td>• Engine system</td>
</tr>
<tr>
<td></td>
<td>• Vehicle system analysis</td>
</tr>
<tr>
<td>Peterbilt Motors Co.</td>
<td>• Vehicle Build Coordination</td>
</tr>
<tr>
<td></td>
<td>• Vehicle Integration</td>
</tr>
<tr>
<td></td>
<td>• Tractor-Trailer Aero</td>
</tr>
<tr>
<td></td>
<td>• Freight efficiency testing</td>
</tr>
<tr>
<td>Cummins Turbo Technology</td>
<td>Turbomachinery &amp; WHR power turbine</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>Advanced transmission</td>
</tr>
<tr>
<td>Delphi</td>
<td>Solid Oxide Fuel Cell idle management technology</td>
</tr>
<tr>
<td>Bendix</td>
<td>Reduced weight brake system and drive axle control</td>
</tr>
<tr>
<td>Bridgestone &amp; Goodyear</td>
<td>Low rolling resistance tires</td>
</tr>
<tr>
<td>Modine</td>
<td>WHR heat exchanger &amp; vehicle cooling module</td>
</tr>
<tr>
<td>U.S. Xpress</td>
<td>• End User Review</td>
</tr>
<tr>
<td></td>
<td>• Driver Feedback</td>
</tr>
<tr>
<td></td>
<td>• Commercial Viability</td>
</tr>
<tr>
<td>Oak Ridge National Laboratories</td>
<td>Fast response engine &amp; AT diagnostic sensors</td>
</tr>
<tr>
<td>Purdue University</td>
<td>• Low temp combustion</td>
</tr>
<tr>
<td></td>
<td>• Control models</td>
</tr>
<tr>
<td></td>
<td>• VVA integration</td>
</tr>
<tr>
<td>VanDyne SuperTurbo</td>
<td>Turbocompounding/ Supercharging</td>
</tr>
<tr>
<td>Utility Trailer</td>
<td>Lightweight Trailer Technology</td>
</tr>
<tr>
<td>Dana</td>
<td>Lightweight Drivetrain Technology</td>
</tr>
<tr>
<td>Bergstrom</td>
<td>HVAC</td>
</tr>
<tr>
<td>Logena</td>
<td>Network interface</td>
</tr>
</tbody>
</table>
Innovation You Can Depend On

Relevance - American Recovery and Reinvestment Act (ARRA) & VT ARRA Goals

• ARRA Goal: Create and/or Retain Jobs
  - Greater than $62M total spend to date

• ARRA Goal: Spur Economic Activity
  - Greater than $62M 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

Projections

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

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%

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

3. Rolling Resistance
   - Urban: 8-12%
   - Interstate: 13-16%

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

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

6. Auxiliary Loads
   - Urban: 7-8%
   - Interstate: 1-4%

7. Weight Reduction

Cummins

Peterbilt

Delphi & Bergstrom

Eaton & Dana

Bridgestone & Goodyear

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

- Combustion
- Fuel Systems
- Air Handling & EGR
- Aftertreatment (AT)
- Electronic Controls
- Waste Heat Recovery
Innovation You Can Depend On

Technical Accomplishments – 50+% Thermal Efficiency Gains

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

Gas flow improvements
- Lower dP EGR loop
- Turbocharger efficiency

Parasitic reductions
- Shaft seal
- VF Lube pump & viscosity
- Geartrain
- Cylinder kit friction
- Cooling & fuel pump power

WHR system
- EGR, Exhaust, Recuperator
- Coolant & Lube

Reference: Objective 1

Net 51.1%

CP2
Engine Friction & Parasitic Reduction

- Mechanical efficiency improved
  - Improvements should be witnessed across speed/load map
    - Greatest efficiency improvements in the lower load portions of map
Technical Accomplishment – Supplemental Emission Test (SET) Weighted Modal Cycle NOx Emissions

- System capability to proceed forward to calibration to prevailing 2010 emissions of 0.2 g/(hp-hr).
- Next process step is calibrating for the RMCSET and FTP cycle with the Demo 2 truck engine during Q1 2013.

**Aftertreatment Progress**
- Phase 2 50% Aftertreatment changes:
  - SCR catalyst formulation
- Phase 1 50% improvements:
  - Improved design of NOx sensing across face of catalyst
  - Close loop control
  - WHR heat exchanger integration
Freight Efficiency Enabling Technologies

- WHR Engine System
- Transmission/Axle Technology
- Idle Management (APU)
- Advanced Aerodynamics
- Weight Reduction
- Route Management System
- Driver Display with Fuel Economy Tools
- Next Generation LRR Tires
Technical Accomplishment – Freight Efficiency Test Results

50 + % Achieved!

Reference: Objective 2

- Vehicle details are included in Peterbilt’s 2013 AMR presentation ARRA-081
Technical Accomplishment – Freight Efficiency Status

Reference: Objective 2
- Vehicle details are included in Peterbilt’s 2013 AMR presentation ARRA-081
Approach – 55% Thermal Efficiency

\[ \eta_{thermal} = \eta_{closed} \times \eta_{open} \times \eta_{mechanical} + WHR \]

1. Exhaust
2. Coolant/Lube
3. Air

Using 50% testing formulation
Innovation You Can Depend On

Technical Accomplishments - Improvements
(Based on Engine, AT & WHR Testing)

- Objective 1: 50% BTE
- Objective 3: 55% BTE

Program Baseline – 42%

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

Status 2013 Merit Review:
Engine + High Efficiency AT + WHR
(Engine, AT & WHR System Testing)

Final Opt.

Achievement to date

42% 43% 44% 45% 46% 47% 48% 49% 50% 51% 52% 53% 54% 55%

Engine Brake Thermal Efficiency (%)

*WHR - Cummins Organic Rankine Cycle Waste Heat Recovery
Approach –
55% Engine Technology Scoping - Fuels

1. Analytical >> Experimental
2. Design Space is Broad
3. Fuel Study
   - Lower Heat Transfer
   - Control Burn Duration
   - Increase Effective Expansion

Diagram:
- Conventional Diesel
- Diesel PreMix
- Diesel LTC
- Dual Fuel AFCI
- Dual Fuel HCCI
- Single Alternate Fuel Compression Ignition

Axes:
- Premix Fuel Quantity**
- Quantity of Alternative Fuel*

* Fuel types: Conventional Diesel, Dual Fuel AFCI, Dual Fuel HCCI, Single Alternate Fuel

** Fuel quantities: 0% - 100%
Technical Accomplishment – 55% Engine Analytical Data

2013 advancement plan

- Combustion design
- Air handling system matching
- Cycle simulation
- WHR integration
- Targeted engine tests
  - Correlate to simulation

Single cylinder validated

55% Goal

Increased efficiency
Collaborations—ORNL & Purdue Participation

• ORNL
  – Sensing methods for:
    • Combustion uniformity studies
      – High response spatial & temporal EGR variation study
      – Enables validation of CFD and analysis led design
      – Experimental testing complete
        » Dec 2012

• Purdue University
  – Completed diesel PCCI study
    – Explore range expansion
  – Diesel engine VVA
    – Commissioned intake & exhaust VVA test bed
    – VVA functional analysis

Modeling & Simulation
Presented:
ACE077 - Partridge
Milestones and Technical Accomplishments

• March 2012 to March 2013 – **Technical Accomplishments**
  - √ Demonstrated 50+% BTE (Objective 1)
  - √ Demonstrated 61% freight efficiency improvement (Objective 2a)
  - √ Completed wind tunnel and vehicle testing of Waste Heat Recovery
  - √ Tested advanced transmission
  - √ Performance tested SOFC APU
  - √ Path-to-Target analysis for a 55% thermal efficient engine

• March 2013 to March 2014 – **Future Work**
  - Engine “vehicle” calibration and optimization work
  - APU technology study – investigate alternatives to SOFC
  - Build and test for Vehicle Demonstration #2 (Objective 2b)
    - Vehicle freight efficiency on 24hr cycle
      - Hotel load APU testing
  - End user testing of Tractor – Trailer Aerodynamics Solution
  - 55% analysis and demonstration tests (Objective 3)
Summary

• Program remains on schedule
  – Meeting the ARRA and DoE VT MYPP goals
• Demonstrated a 50+% BTE engine system
• Demonstrated a 60+% vehicle freight efficiency improvement
• Analytical roadmaps updated with experimental component data
• Vehicle packaging and integration proceeding without major issues
• 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 lab and vehicle tests (Objective 2b)
  – Tractor-Trailer aerodynamic aids (Objective 2a)
• Developed framework and analysis for 55% thermal efficiency
• 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>
</tr>
</thead>
<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>
</tr>
</tbody>
</table>

Ref: 2011 AMR - Stanton
Engine System Meets US EPA 2010 Emissions Regulation

- Cummins Advanced Engine + High Efficiency AT + WHR*
- WHR System
  - Working Fluid
  - Cooling System Controls
  - Turbine Expander Efficiency
- 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
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.

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

Engine Brake Thermal Efficiency (%)

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

- Engine demonstration showed improvements in all terms

Ref: 2012 AMR - Koeberlein

*WHR - Cummins Organic Rankine Cycle Waste Heat Recovery
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 Freight Efficiency of Aerodynamic Drag Reduction

* 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