Development and Demonstration of Advanced Engine and Vehicle Technologies for Class 8 Heavy-Duty Vehicle (SuperTruck II)

Maarten Meijer, Ph.D. – Principal Investigator
Ben Grover – Kenworth Truck Company
PACCAR Inc.
June 24, 2021

Project ID # ACE124

This presentation does not contain any proprietary, confidential, or otherwise restricted information
Timeline
- Start Date: October 2017
- End Date: September 2022
- Percent Complete: 75%

Barriers
- Identifying Cost Effective, Production Representative Process For Cab Structure
- Cost, Robustness And Packaging Needs Of Engine Technologies To Achieve 55% BTE
- Ability To Demonstrate Benefits In More Than One Application/Use Case

Budget
- Total Project Funding
  - DOE: $20M
  - Partnership: $20M
- FY 2021 Funding: $32.4M (Project Total)
Objectives and Relevance

• **Overall Objectives**
  – Greater Than 100% Freight Efficiency Improvement Relative To a 2009 Baseline
  – Greater Than or Equal to 55% Engine Brake Thermal Efficiency
  – Target is a 3 Year Payback Period on Developed Technologies

• **Objectives This Period**
  – WHR Demonstration
  – Engine Build
  – Mild Hybrid Powertrain Validation & Integration
  – Freeze Vehicle Design

• **Impact**
  – Evaluation of Higher Risk Technologies With Potential For Energy Efficiency
  – Potential Modernization of Key Technologies in Freight Transport Industry
  – Evaluation of Impact of Technologies in More Than One Real-World Drive Cycle
# Program Outline

<table>
<thead>
<tr>
<th>Year</th>
<th>Activities</th>
</tr>
</thead>
</table>
| **Year 1 (2018)** | **Analysis & Baseline Testing**  
- Simulation To Evaluate Engine, Powertrain And Vehicle Efficiency Building Blocks  
- Baseline Testing |
| **Year 2 (2019)** | **Design & Prototype Build**  
- Engine Design  
- Powertrain And Controls Architecture Selection  
- Prototype Builds  
- Cab And Chassis Development |
| **Year 3 (2020)** | **Component Test And Validation**  
- Vehicle Controls Development 50%  
- Proto Vehicles Testing 50%  
- New Engine Technologies Testing 75%  
- Hybrid Powertrain Testing  
- WHR Integration And Initial Testing |
| **Year 4 (2021)** | **Powertrain Testing & SuperTruck Build**  
- Powertrain And Vehicle Integration 30%  
- Engine Efficiency Demo  
- Initial Testing Of Drivability & Fuel Economy  
- Final Report  
- Project Close |
| **Year 5 (2022)** | **Engine & Freight Efficiency Demo**  
- Engine & WHR 55% BTE Demo  
- SuperTruck Freight Efficiency Demo > 100%  
- Final Report  
- Project Close |
Milestones

Budget Period 3: October 2019 – December 2020 – September 2021

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Type</th>
<th>Description</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Components Fabrication Complete</td>
<td>Technical</td>
<td>Final Internal And External Engine Components Are Fabricated</td>
<td>75%</td>
</tr>
<tr>
<td>Powertrain Components Fabrication Complete</td>
<td>Technical</td>
<td>Final Electrified Powertrain Components Are Fabricated</td>
<td>100%</td>
</tr>
<tr>
<td>SuperTruck II Tractor Component Designs Frozen</td>
<td>Technical</td>
<td>Design Is Frozen For Components Of The SuperTruck II Tractor</td>
<td>45%</td>
</tr>
<tr>
<td>SuperTruck II Tractor Design Is Complete</td>
<td>Go/No-go</td>
<td>All Engine And Powertrain Components Have Been Fabricated. SuperTruck II Tractor Design Is Complete</td>
<td>75%</td>
</tr>
</tbody>
</table>

- Budget Period 3 Extended by 9 Months
- No Extension of the Program Deadline at This Point
Key Concepts

**Engine**
- Fuel Efficient DOHC MX-12
- No Basic Architecture Changes
- Engine Efficiency Over WHR
- 48V Aux. / FEAD Removal
- Ultra Low NOx Compliant

**Powertrain**
- 48V Mild-Hybrid
- 30kW P2.5 e-Motor / Generator
- Supports Vehicle Aux. Electrification
- Dev. of 48V Components
- Next Gen. Li-Ion Batteries

**Chassis**
- Light-Weight & Modular
- Supports All New Powertrains
- 30% Weight Savings Chassis and Suspension
- Ease of Manufacturing
- e-Steering

**Tractor**
- Aerodynamic Cabin
- Energy Efficient
- e-HVAC & e-Hoteling
- Predictive Adaptive Cruise Control
- System Level Energy Management
55% BTE Engine

Efficiency Improvement Contributions

- Friction = 10%
- WHR = 40%
- Scavenging = 35%
- Combustion = 15%

- Engine Design Completed
- Long-Stroke Concept Validated
- SuperTruck II Engine Build: Q4 2021
**Engine Design**

- New Casting: Taller Deck
- Two Stage Turbo Charging
- Optimized / Coated Pistons
- Long Stroke
- Variable Piston Cooling Jets
- Fluid Dampener
- WHR Optimized Inter-Coolers
Engine Design

- Charge Air Cooler High and Low Pressure (Liquid Cooled)
- 48V EGR Pump
- Cylinder Pulse Exhaust Manifold
- Insulated Exhaust Path
- Redesigned Cylinder Head
  - Exhaust Pulse Turbo Charging
  - Port Insulation
- Crank Driven Fuel Pump
Waste Heat Recovery

Approach
- Tailored WHR Architecture, For Maximum Overall BTE Potential
- Co-Optimized Approach With Engine Simulations

Status
- All Components Fabricated
- Performance of Key Components, Including the Turbine Expander, Experimentally Validated
- 4%. BTE on Track
Ultra Low NOx

Gasoline Compression Ignition
- High BTE and ULN
- Simulations Show Potential
- Testing Q4 2021
- Diesel Remains Prime Path for Engine Demo

Close-Coupled EAS
- 48V e-Heater
- Carb ULN 2027 (FTP 0.02 g/bhp-hr)
- Included in Vehicle Demo
### Powertrain Efficiency

40% Improvement

<table>
<thead>
<tr>
<th>Component</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Powertrain</td>
<td>22%</td>
</tr>
<tr>
<td>Mild Hybrid / Electrification</td>
<td>13%</td>
</tr>
<tr>
<td>Low Rolling Resistance Tires</td>
<td>7%</td>
</tr>
</tbody>
</table>

**Status**

- Validated on Dyno-stand
- Integrated on Proto Vehicle
Hybrid Powertrain
- 48V For Increased Power Capacity
- Development of 48V Components
- PTO Mounted 30 kW e-Machine
- Gearbox for Cranking and Optimum FE

Battery System
- Tailored 48V Li-Ion BMS
- Supports e-Hoteling
Path to Freight Efficiency

**Powertrain Efficiency**
- 40% Improvement
  - Base Engine
  - Mild Hybrid / Electrification
  - Low Rolling Resistance Tires

**Weight Reduction**
- 25% Reduction
  - Systems Engineering
  - Modular Integration
  - Materials Application

**Aerodynamics**
- 60% Reduction
  - Ideal Shape
  - Flow Management
  - Trailer Skirt & Tail

175% Freight Efficiency Improvement Forecasted
Demonstration Vehicle

Styling and Aerodynamics
- ½ Scale Model Complete
- Outerbody Design → Final Styling Tuning

Customer Feedback, Market Feasibility
- Refined Demonstrator Designs
- ROI Assessment

Vehicle Design
- Cab Structure Refinement Phase
- Body in White In Progress → Next Step Building
- Chassis and Powertrain Hardware Procurement
• Key Element to Improving Freight Efficiency

• Ideal Tractor Shape:
  – Enclosed Front Wheels
  – Shorter Nose

• Skirt and Tail Aero Treatments
  – 30% Drag Reduction

• Total Drag Reduction 60%
Chassis and Suspension

Final Design
Improve Suspension Performance
Updates Result in 250lbs Reduction

Revised Design Based on Mule Testing
Cab Anti-Dive System Proved Extremely Effective.

Focus on Weight Reduction
Accommodating Ride Height Changes
Structural Streamlining for Weight Reduction
Vehicle Energy Management

**e-HVAC**

- No idle Requirement
- Improved Insulation
- Built-in Heat Pump
- Hybrid, BEV, and Fuel-Cell

**Single In-Cab Design**

**Cooling System**

**2-Loop Design**

**Windshield**

- UW Project
- Spontaneous Solar Energy Control
- Maintaining Sufficient Luminous Transmission

**Multilayer IRR Coating**

**Hoteling**

- Probabilistic Models for Hotel Loads
- As a Function of:
  - Weather
  - Route

**Predictive**
Vehicle 48V Electrification

DC-DC converter

Cooling Pump

Fans
Responses to Reviewers’ Comments

• It would be helpful if PACCAR can point out specific differences between PACCAR & its competitor WHR structures.
  – The PACCAR ORC-based dual-loop WHR system features a completely unique system architecture tailored to the PACCAR engine heat sources and operating conditions, including first of its kind dual-core two-stage charge coolers, and dual-core tailpipe boiler. Additionally, is the first and, to date, only system to use the latest dual-entry turbine technology from Cummins, demonstrating the highest efficiency of any turbine of this type.

• The path to target 55% BTE clearly identified WHR as required, but discussion in Q&A indicated this team did not think WHR was commercially viable and was pursuing hybrid electric solutions.
  – For the 55% BTE (engine demo) WHR is key. For optimum Freight Efficiency (vehicle demo) the fuel savings under transient conditions don’t outweigh the additional weight, and impact on aerodynamics. In addition, the cost and complexity of a highest BTE WHR system remains a challenge for near future commercialization.
    GHG regulations May Alter This Assessment.

• The aero was not as clear. PACCAR shows aero drag reduction of 20% and 5% on the trailer. Does this mean there will be 35% reduction in the tractor aero to equate to 60% reduction overall?
  – Our latest simulations show a 60% reduction overall, with a 30% trailer / 30% tractor distribution.

• It would be helpful if the company logo can be inserted to the slides, where those partners have made the contribution to the program
  – Acknowledged
## Partnerships/Collaborations

<table>
<thead>
<tr>
<th>Company</th>
<th>Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kenworth</td>
<td>Vehicle Development, Vehicle Level Supervisory Controls</td>
</tr>
<tr>
<td>DAF</td>
<td>Engine Development, Engine Management Systems</td>
</tr>
<tr>
<td>PACCAR Technical Center</td>
<td>Powertrain Development, Advanced Predictive Features, Program Administration</td>
</tr>
<tr>
<td>Eaton</td>
<td>Electrified Powertrain, Transmission, and Air Management Systems Development</td>
</tr>
<tr>
<td>AVL</td>
<td>Engine Development</td>
</tr>
<tr>
<td>NREL</td>
<td>Drive Cycle Development, and Thermal Management</td>
</tr>
<tr>
<td>CONTINUUM</td>
<td>Waste Heat Recovery Integration</td>
</tr>
<tr>
<td>Meritor</td>
<td>Axle Integration</td>
</tr>
<tr>
<td>Continental</td>
<td>Tire Development</td>
</tr>
<tr>
<td>The Ohio State University</td>
<td>Model Development for Cabin Hoteling Optimization</td>
</tr>
<tr>
<td>University of Washington</td>
<td>Windscreen coating and engine thermal barrier coatings</td>
</tr>
</tbody>
</table>
Remaining Challenges

- For all Technology Concepts: Detailed Feasibility for Commercialization

**Engine**
- Turbo-Charger Efficiency
- Thermal Barrier Swing Coatings

**Powertrain & Vehicle**
- Final System Integration On Mule for Controls Tuning
- Demonstration Vehicle Build & Performance Testing
Proposed Future Research

**Engine**

- Testing
  - 2-Stage Pulsed Turbo-Charger
  - GCI Combustion Concept
  - Thermal Barrier Coatings

- Engine Build

- Engine 55% BTE Demo

**Powertrain & Vehicle**

- Vehicle Controls Validation With all Components Integrated

- Finalize Vehicle Design

- Demonstration Vehicle Commissioning

- 175% Freight Efficiency Demo
Summary

• Engine
  – 55% BTE Concept Validation on Dedicated Test-rigs
  – Engine Design Completed
  – Tailored WHR System Validated

• Powertrain
  – Mild Hybrid Powertrain & 48V Battery System Integrated

• Vehicle
  – Updated Freight Efficiency Roadmap To 175% Improvement
  – Final Vehicle Demonstrator Design in the Final Stage