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

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PACCAR Inc
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Project ID # ACS124

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Overview

Timeline
- Start Date: October 2017
- End Date: September 2022
- Percent Complete: 20%

Budget
- Total project funding
  - DOE: $20M
  - Partnership: $20M
- FY 2018 Funding: $5.7M
- FY 2019 Funding: $13M

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 and Use Case

Partners

- KENWORTH
- EATON
- AVL
- UPS
- DAF
- PACCAR TECHNICAL CENTER
- NREL
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
  – Design And Prototyping Of Critical Engine Components For Current Path To 55% BTE Engine
  – Order Key Components Of WHR System
  – HiL And Vehicle Test Of Advanced Predictive Features
  – Begin Fabrication Of Main Subsystems For The Electrified Powertrain
  – Build And Test Mule Vehicle With Selected Powertrain Features

• 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
# Milestones

## BP 2 Milestones

<table>
<thead>
<tr>
<th>BP 2 Milestones</th>
<th>Type</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Engine Components Selected</td>
<td>Technical</td>
<td>Design Of Internal And External Engine Components With Long Lead Times Is Complete</td>
</tr>
<tr>
<td>Powertrain Components Selected</td>
<td>Technical</td>
<td>Design Of Electrified Powertrain Components Is Complete And Components Are Selected For Fabrication</td>
</tr>
<tr>
<td>Mule Vehicle Tested</td>
<td>Technical</td>
<td>Mule Vehicle Is Designed, Assembled And Tested</td>
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<tr>
<td>Electrified Powertrain Components Manufacturable</td>
<td>Go/No-go</td>
<td>Designs Of Internal And External Engine And Electrified Powertrain Components Are Verified As Manufacturable</td>
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## BP 3 Milestones

<table>
<thead>
<tr>
<th>BP 3 Milestone</th>
<th>Type</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Engine Components Fabrication Complete</td>
<td>Technical</td>
<td>Final Internal And External Engine Components Are Fabricated</td>
</tr>
<tr>
<td>Powertrain Components Fabrication Complete</td>
<td>Technical</td>
<td>Final Electrified Powertrain Components Are Fabricated</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>
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<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>
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## Program Outline

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<tbody>
<tr>
<td><strong>Analysis &amp; Baseline Testing</strong></td>
<td><strong>Design &amp; Prototype Build</strong></td>
<td><strong>Component Test And Validation</strong></td>
<td><strong>Powertrain Testing &amp; Supertruck Build</strong></td>
<td><strong>Engine &amp; Freight Efficiency Demo</strong></td>
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<tr>
<td>Simulation To Evaluate Engine, Powertrain And Vehicle Efficiency Building Blocks</td>
<td>Engine Design</td>
<td>Engine &amp; Powertrain Testing</td>
<td>Engine And Powertrain Efficiency Demo</td>
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<td>Baseline Testing</td>
<td>Powertrain And Controls Architecture Selection</td>
<td>WHR Integration And Initial Testing</td>
<td>Engine And Powertrain Vehicle Integration</td>
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<td>Prototype Builds</td>
<td>Controls Development</td>
<td>Initial Testing Of Drivability &amp; Fuel Economy</td>
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<td>Cab And Chassis Development</td>
<td>Vehicle Mule Testing</td>
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<td>Final Report</td>
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<td>Project Close</td>
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- Engine & WHR 55% BTE Demo
- Supertruck Freight Efficiency Demo > 100%

- Final Report
- Project Close
Technical Approach

**Engine**
- Combustion Strategies, Turbomachinery Efficiency, WHR, Accessory Electrification

**Powertrain**
- Electrification, Energy Management, Predictive Features, Route Optimization, High Efficiency Transmission And Axles

**Vehicle**
- Aerodynamics, Weight Reduction, Anti-idle Climate Control, Modular Chassis Design, Tire Rolling Resistance
Approach: Freight Efficiency

- Freight Efficiency Projection Evolving
- Tracking To Exceed Goal Of 100% Improvement
Approach: Engine Efficiency
ENGINE SECTION
Concept Development

• Compiled List Of Potential Engine Technologies
  - 177 Ideas Sorted By BTE Improvement Potential And Risk

• Three Conceptual Paths:
  - Conventional
    • Fast Combustion System
    • High Efficiency Air-Management System
    • Optimized Friction & Accessories
    • Insulate Intake & Exhaust
  - Modest Innovation
    • Miller Cycle + CR/Stroke
    • Pulse Turbocharging
    • In-Cylinder Coatings
    • Additional Friction Reduction
  - Non-Conventional
    • Alt. Combustion Regime
    • Aggressive Friction & Mechanical Changes (Casting Impact)

• Screening Design Of Experiments: **Assessment Of Technology Impact On BTE**
Concept Definition

Current Path Chosen:

- Fast Combustion With Higher Effective Expansion Ratio
- High Efficiency Boosting System
- Low Restriction Air And Exhaust System
- Optimized Friction And Accessories
- Insulation (Thermal Barrier Coatings)
- Miller Cycle
- Pulse Turbocharging With Optimum Exhaust Manifold Design
- In-Cylinder Thermal Swing Coatings
- Advanced Low Friction Technologies
Technology Verification

Combustion

- Fast Combustion
  - High Flow Injector
  - Bowl Profile And Spray Targeting
- Compression Ratio
  - Bowl And Stroke
  - Peak Cylinder Pressure And Emissions
- System Optimization
  - EGR, Swirl, AFR, Charge Temp.
  - Consider Impact on WHR

Air Management

- Flow Restriction Reduction
  - Port And Valve Geometry Design
  - CFD Modeling And Analysis
  - Rapid Prototyping and Rig Tests
- Miller Cycle
  - Early IVC Vs. Late IVC Analysis
  - Engine Performance Testing
- High Efficiency Boosting System
  - Exhaust Manifold Design
  - Low-pressure Loop EGR
Technology Verification

Thermal Management

- Reduced Cooling
  - Coolant And Oil Flow Control
  - Full 3-D CHT Modeling
  - New Design And Material

- Thermal Barrier Coatings
  - Ports, Manifolds, Turbine Housing
  - Piston, Head, Valves
  - 1-D / 3-D Model Analysis
  - Testing Samples

Friction / Auxiliaries / Restrictions

- Back Pressure
- Auxiliary Losses
- Low Viscosity Oil

- Aggressive Friction Reduction
  - PCU, Cranktrain, Valvetrain

Waste Heat Recovery

- System Configuration
- Boundary Conditions
- Feasibility Check
- Working with Supplier On Integration
Waste Heat Recovery

• Feasibility Study Showing 4% BTE Gain
  - Boundary Conditions From Engine Concept Model
  - Thermodynamic Analyses For 3 Configurations And 9 Variants
  - Variants: Coolant Temperature, Condenser Size, Turbine, Heat Exchanger And Pump Efficiency
Baseline Engine Testing

Baseline Engine – PACCAR MX-11
Model Year 2018

- Re-Calibration For Minimum FC
  - W/O PCP And Turbocharger Max. Speed Restriction
  - Electrical Coolant Pump Driven By Mild Hybrid
  - Electrical Fuel Lift Pump
- Test Cell Restriction Sensitivity Study
  - High Sensitivity To Exhaust BP And IMT
- Low Viscosity Oil Study
  - 3 Low Viscosity Oils Tested

Fuel Consumption Reduction [%]

Reference MT/2018
Optimized for min. FC
Accessories removed
Test-cell restrictions
Low viscosity oil
Technology Validation

55% BTE

Prediction
Demonstration

Baseline
Friction / Restriction / Aux
Miller Cycle
Combustion System
Boosting System
Flow Restriction
Intake / Exhaust Insulation
Further Friction Reduction
Long Stroke
Pulse Turbocharging
In-Cylinder Coating
WHR
Remaining Challenges

- Integration and optimization of the WHR System

- Key Technology Assessment
  - In-Cylinder Thermal Barrier Coatings
  - Pulse Turbocharging
  - Aftertreatment System With Low Flow Restriction

- System-Level Performance Validation
  - Investigate Technology Interactions
  - System-Level Optimization
Proposed Future Research

FY2019

- Further Evaluate WHR System Integration
- Boosting System Optimization With Exhaust Manifold Design Update
- Continue Technology Verification on SCE and MCE
  - Thermal Barrier Coatings
  - Combustion System
  - Flow Restrictions
- Investigate Alternative Combustion Concept
- Improve Model Correlation For Further Proof-Of-Concept

FY2020

- System-Level Performance Validation
- Continue PoC & Design Refinement
  - Combustion
  - Air Management
  - Mechanical
- Design Release
- Engine Build
- Engine Calibration For Emissions Compliance

Any proposed future work is subject to change based on funding levels.
POWERTRAIN SECTION
Powertrain Optimization

- National Average Drive-Cycle Selected Using Specialized NREL Algorithm

- Completed Optimizations
  - Rear-Axle Ratio
  - Wheels & Tires
  - Hybrid Configuration
  - Battery Requirements

- ST-II Powertrain Performance
  - Validated MY2009 Baseline:
    - Kenworth T660 GVW 65k lbs. FE 84.5 Ton-mi/Gal
  - ST-II Powertrain Simulations Indicate:
    - System Requires 47.7% Less Energy
Hybridization

- **Hybrid Powertrain Defined**
  - Eaton + PACCAR Development
  - Based On FE Sim. And Customer Feedback
  - High Commercialization Potential
  - 48V For Increased Power Capacity
  - PTO Mounted 30 kW E-machine
  - Gearbox For Cranking And Optimum FE

- **Li-ion Battery Selection**
  - Detailed Specifications & Strategy In Place
  - Considering Driver Needs (e.g. Hoteling)
  - Energy 10 kWh / Peak Power 30 kW, For Energy Storage & Power Requirements
Controls Development

- Development Process
  - Following Established V-cycle SW Process
  - Requirements Cascade Management System
  - Enables Linking Of Requirements To Facilitate Efficient Vehicle Development Across Functional Team

- Control System
  - Requirements & Interface In Place
  - Revised CAN Architecture & Functions
  - Streamlined Approach To Powertrain Energy Arbitration
  - Commercialization In Mind
Key Control Concepts

• **Integration Of PCC And ADAS**
  – Provide FE Under All Driving Conditions
  – Optimized Regeneration / Hybrid System

• **Functional Safety**
  – Increased Powertrain Automation Requires Appropriate Safety Approach
  – E.g. Redundant System For E-Steering

PCC: Predictive Cruise Control
ADAS: Advanced Driver Assistance Systems
Remaining Challenges

• Hybrid Powertrain
  – Upscaling Motor Drive & Converter (MDC) Unit To 30 kW

• Control
  – Development Functional Safety Concept / Architecture
  – Mil Verification & Preliminary Vehicle Calibration
  – Implement Mission Control

• Battery
  – Supplier Selection Based On Requirements
  – Pack Design & Procurement
### Proposed Future Research

**FY2019**

- Hardware In The Loop (HiL) Controls Testing
- Integrated Testing 10 kW Hybrid Vehicle And Controls
- Characterize 30 kW eMotor
- Commission 30 kW 48V Mild Hybrid Test Rig

**FY2020**

- Rig Test 48V Mild Hybrid
- Battery Assembly & Testing
- Test Energy Management System
- Functional Safety Bench Validation
- Start Hybrid Powertrain Testing

*Any proposed future work is subject to change based on funding levels.*
Mark Brown
Kenworth Truck Company

VEHICLE SECTION
Vehicle Design Strategy

- Aerodynamics
  - Ideal Tractor Shape
  - Trailer Treatment

- Weight Reduction
  - Systems Engineering
  - Function Consolidation
  - Chassis Load Analysis

- Customer Needs
  - Voice Of The Customer
  - Driver Package & Interior Amenities

- Energy Management
  - Thermal Treatment
  - Cooling System
Vehicle Design Progress

- **Outerbody Development**
  - Detailed Analysis Completed
    - Cooling Air Flow
    - Windshield / Wiper Solution
    - Multi-Variable Design Studies
    - External Shape Defined

- **Cab And Sleeper Packaging**
  - Interior Content Defined
  - Layout / Packaging Complete
  - Mockup Built And Reviewed By Customers

- **Chassis & Powertrain**
  - Chassis Concept Complete
  - Two-Loop Cooling System
  - Electrified Accessories
Accomplishments

• Baseline Vehicle Test Complete

• Aerodynamics: 60% Reduction
  – Trailer Gap Treatment
  – Innovative Skirt & Tail ~ 10% Reduction
  – Tire Size & CRR Vs. Cd Optimization

• Weight Reduction: 30% Reduction
  – Trailer Partner Selected, Path Defined
  – Tractor Assessment Complete

• Freight Efficiency: > 100% Improvement
  – Mild Hybrid & Momentum Recovery
  – No Idle HVAC, Thermal Loss Improvement
  – 25% Tire CRR Improvement
Remaining Challenges

- Mule Vehicle Assembly
- Mule Vehicle Commissioning
- Design, Analysis, And Validation
  - Cab And Sleeper Material Utilization
  - Cab Prototype, Representative Process
  - Tire Performance Optimization
  - Controls Development
Proposed Future Research

FY19
• Mule Vehicle Build Completion
• Mule Vehicle Validation
• Tire Development

FY20
• Electronics & Controls Calibration
• Demonstration Vehicle Design

Any proposed future work is subject to change based on funding levels.
Responses to Reviewers’ Comments

• The reviewer stated that the proposed approach includes many key elements of technologies. However, nothing is mentioned on tires and axles, both of which are critical to the success of this program.
  – The team now includes Continental and Meritor to develop tire and axle solutions, respectively.
• The reviewer observed that no devices were developed or tested.
  – The first year of the project was mostly dedicated to analysis and simulation. At the time of last year’s AMR, the project had only been active for a few months.
• Although the program started 1 year late compared to its competitors, the reviewer remarked that lack of WHR experience could be a show-stopper moving forward because there would be no other alternative to achieving 55% BTE without the help of WHR. The reviewer opined that the issue becomes even more severe due to a lack of overall program experience on such a large scale for the program because PACCAR was not part of the SuperTruck I program.
  – We agree that WHR is a high risk item. The team now includes Cummins who will be supplying a state-of-the-art WHR solution for the PACCAR program. Even though the PACCAR team was not part of the SuperTruck I program, the team comprises experienced contributors to the PACCAR global engine and vehicle development programs.
## Partnerships/Collaborations

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<tr>
<th>Company</th>
<th>Services</th>
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<tbody>
<tr>
<td><strong>KENWORTH</strong></td>
<td>Vehicle Development, Vehicle Level Supervisory Controls</td>
</tr>
<tr>
<td><strong>DAF</strong></td>
<td>Engine Development, Engine Management Systems</td>
</tr>
<tr>
<td><strong>PACCAR TECHNICAL CENTER</strong></td>
<td>Powertrain Development, Advanced Predictive Features, Program Administration</td>
</tr>
<tr>
<td><strong>EATON</strong></td>
<td>Electrified Powertrain, Transmission, Valvetrain and Air Management Systems Development</td>
</tr>
<tr>
<td><strong>AVL</strong></td>
<td>Powertrain Analysis, Battery Controls, Engine Development</td>
</tr>
<tr>
<td><strong>NREL</strong></td>
<td>Drive Cycle Development, Thermal Management</td>
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<tr>
<td><strong>UPS</strong></td>
<td>Drive Cycle Development, Tech Market Acceptance Advisory</td>
</tr>
<tr>
<td><strong>Cummins</strong></td>
<td>Waste Heat Recovery Integration</td>
</tr>
<tr>
<td><strong>MERITOR</strong></td>
<td>Axle Integration</td>
</tr>
<tr>
<td><strong>Continental</strong></td>
<td>Tire Development</td>
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Summary

- Path For 55% BTE Engine Developed
  - Road Load Point Selected
  - Encouraging Initial Test Results
  - Plan In Place To Fabricate First Piston Prototypes
  - Supplier Of WHR Selected

- Demonstration Drive Cycle Defined
  - Baseline Vehicle Tested
  - Hoteling To Be Demonstrated On Climatic Chamber

- Energy Management Strategies Selected
  - Completed Requirements For Powertrain
  - Controls Strategies For Predictive Features In HiL Testing

- Tractor-Trailer Combination Aerodynamic Design Near Completion
- Modular Chassis Design Completed
- Extensive Vehicle Electrification
- Updated Freight Efficiency Roadmap To > 100% Improvement
Technology Development

Reduction Of Flow Restriction

Iterative Development Process In Progress
Drive-Cycle & Cruise Model

Beach, ND to New Salem, ND

128 Miles One Way
2 Laps Per Test
2776-2122’ Elevation
65mph (+/-5 mph)
Speed Limit

Vehicle Drag [m2] Engine Gearbox Final Drive
Baseline 7.48 Cummins ISX15 450hp 18 Spd MTX 5.7 (Steer) 6.6 (Drive) 6.0 (Trailer) 6x4 Losses
ST-II 2.94 PACCAR MX-11 430hp 12 Spd AMT 4.7 (All) 6x2 Losses