PACCAR SuperTruck II

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

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PACCAR Inc.

June 23, 2022

Project ID: ACE124

Overview

PACCAR SuperTruck II

Timeline

- **Start Date:** October 2017
- **End Date:** December 2023
- **Percent Complete:** 75%

Budget

Total Project Funding

DOE: $20M

Partnership: $20M

FY 2022 Funding: $34.7M

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

Partners

KENWORTH, EATON, AVL, UNIVERSITY of WASHINGTON, DAF, PACCAR TECHNICAL CENTER, NREL NATIONAL RENEWABLE ENERGY LABORATORY, THE OHIO STATE UNIVERSITY

Program Outline

PACCAR SuperTruck II

Budget Period 1

Analysis & Baseline Testing

- Simulation To Evaluate Engine, Powertrain And Vehicle Efficiency Building Blocks
- Baseline Testing

Budget Period 2

Design & Prototype Build

- Engine Design
- Powertrain And Controls Architecture Selection
- Prototype Builds
- Cab And Chassis Development

Budget Period 3

Component Test And Validation

- Vehicle Controls Development
- Proto Vehicles Testing
- New Engine Technologies Testing
- Hybrid Powertrain Testing
- WHR Integration And Initial Testing

Budget Period 4

Powertrain Testing & SuperTruck Build

- Powertrain And Vehicle Integration **50%**
- Engine Efficiency Demo **75%**
- Initial Testing Of Drivability & Fuel Economy **75%**
- SuperTruck Vehicle Build

Budget Period 5

Engine & Freight Efficiency Demo

- Engine & WHR 55% BTE Demo **50%**
- SuperTruck Freight Efficiency Demo > 120% **50%**
- ROI New Technologies **30%**

Technical Milestones

PACCAR SuperTruck II

Budget Period 3 (Completed)

Milestone	Description	% Complete
Engine Components Fabrication Complete	Final Internal and External Engine Components are Fabricated	**100%**
Powertrain Components Fabrication Complete	Final Electrified Powertrain Components are Fabricated	**100%**
SuperTruck II Tractor Component Designs Frozen	Design is Frozen for Components of the SuperTruck II Tractor	**100%**

Budget Period 4: October 2021 – December 2022

SuperTruck II Vehicle Build is Complete	SuperTruck II Vehicle is Built	**20%**
Powertrain Demonstration Complete	Powertrain for SuperTruck II Demonstrates viability of greater than 100% Improvement in Freight Efficiency in Powertrain Test Cell	**80%**
SuperTruck II Vehicle Field Test Complete	SuperTruck II Vehicle is Field Tested	**0%**
Simple Payback Demonstrated	ROI analyses show that 50% of the new technologies at TRL level 3 and above have a Simple 3-Year Payback	**30%**

Objectives & Relevance

PACCAR SuperTruck II

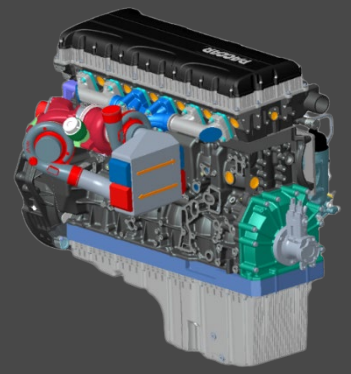
Overall Objectives	> 120% Freight Efficiency Improvement Relative To a 2009 Baseline ≥ 55% Engine Brake Thermal Efficiency 3 Year Payback Period on Developed Technologies
Objectives This Period	• Finalize Engine and WHR Demonstration • Demonstrator Vehicle Build
Impact	• Evaluation of Higher Risk Technologies 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

Key Technologies

PACCAR SuperTruck II

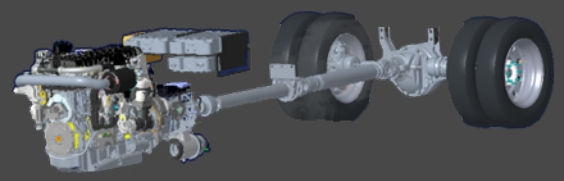
Engine — Fuel Efficient DOHC MX-12

- Long Stroke Concept
- 48V Aux. / FEAD Removal
- Ultra-Low NOx Compliant



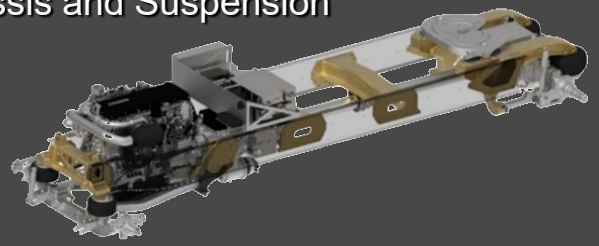
Powertrain — 48V Mild-Hybrid

- 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
- New Suspension Architecture
- 30% Weight Savings Chassis and Suspension
- Ease of Manufacturing



Tractor — Aerodynamic Cab

- Maximized Aero Drag Reduction
- Energy Efficient e-HVAC & e-Hoteling
- Predictive Cruise Control & System Level Energy Management

Engine Design

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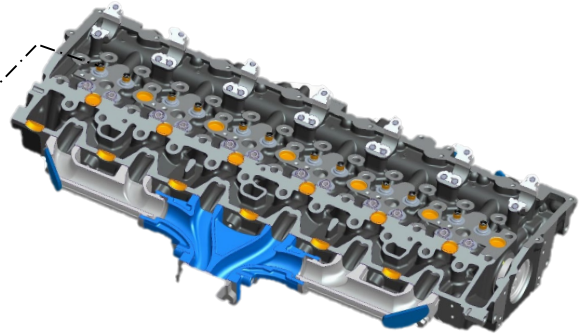
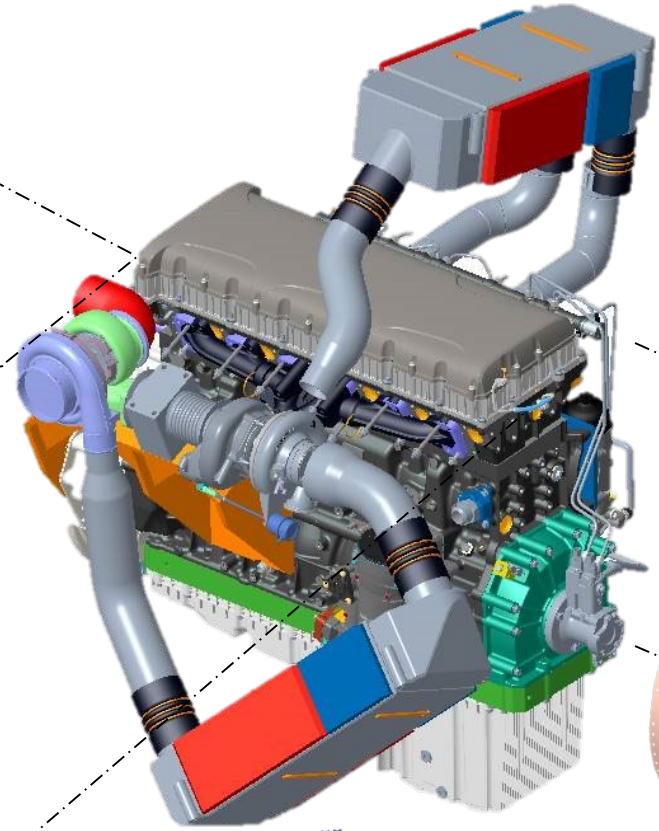
Charge Air Cooler High and Low Pressure

48V EGR Pump

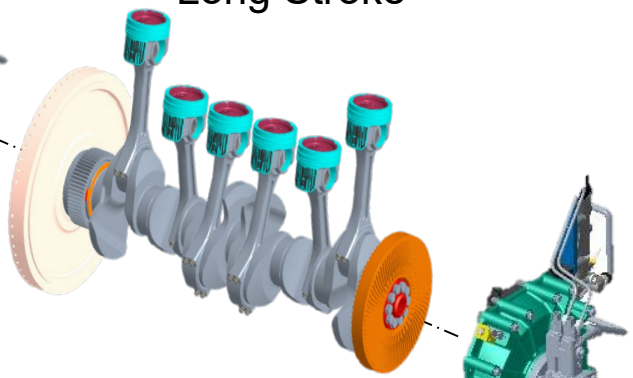
Redesigned Cylinder Head
- Exhaust Pulse Turbo Charging
- Port Insulation



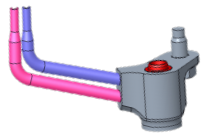
Two Stage Turbo Charging



Long Stroke



Cylinder Pulse Exhaust Manifold
Insulated Exhaust Path



Variable Piston Cooling Jets

Crank Driven Fuel Pump

Ultra Low NO_x

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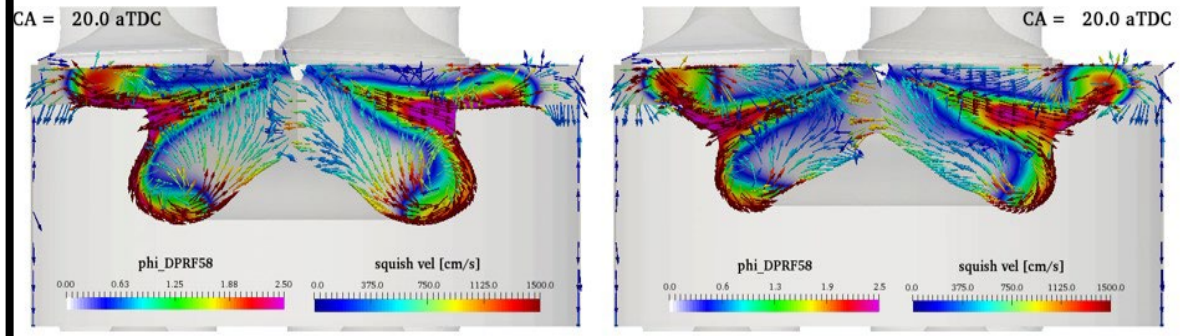
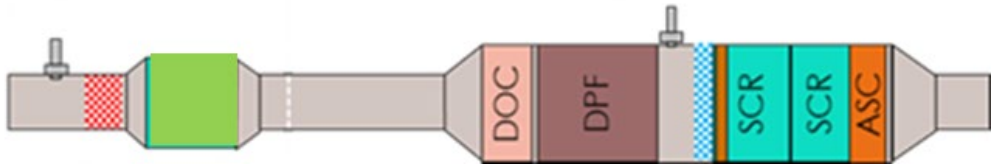
Gasoline Compression Ignition



- Goal: High BTE and low NOx / PM
- Testing Completed
- Diesel Remains Prime Path

Close-Coupled EAS



- Demonstrated 2027 CARB Ultra Low NOx
- 48V Exhaust e-Heater
- Integrated in 48V Architecture for Maximum Fuel Efficiency

Engine Status

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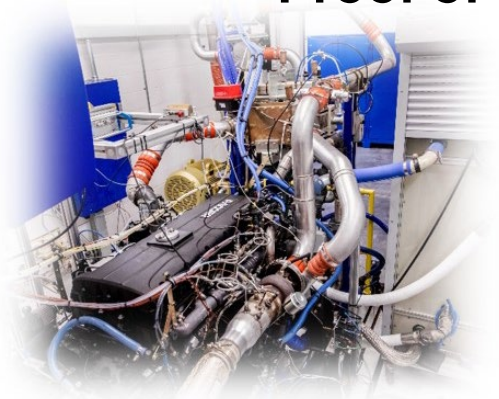
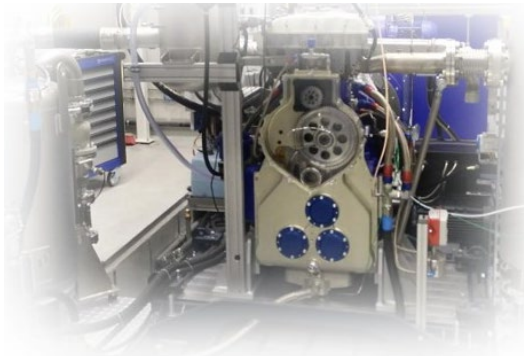
Proof of Concept

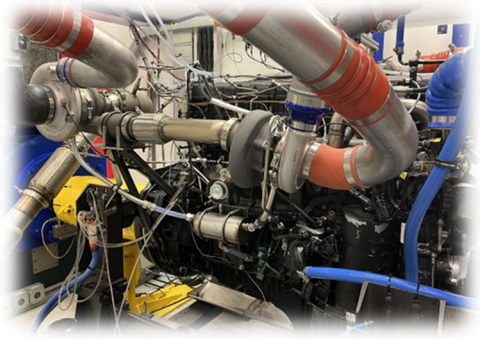


Engine With Artificial Boost

Flow Bench



Long Stroke
Single Cylinder Engine

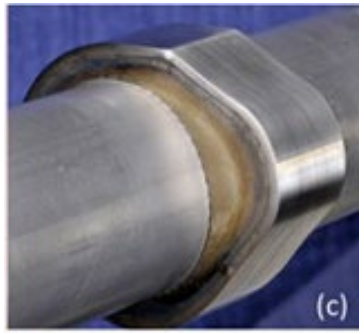


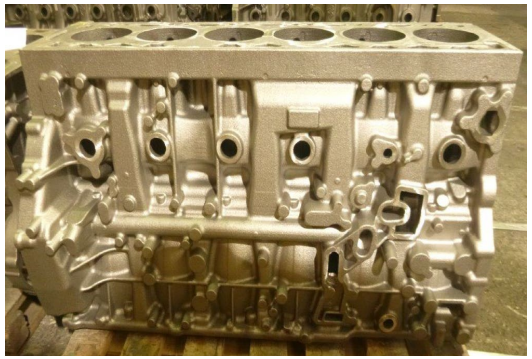
Multi-Cylinder Engine
Turbochargers

✓ Completed

✓ Performance on Track

Final Engine Demo



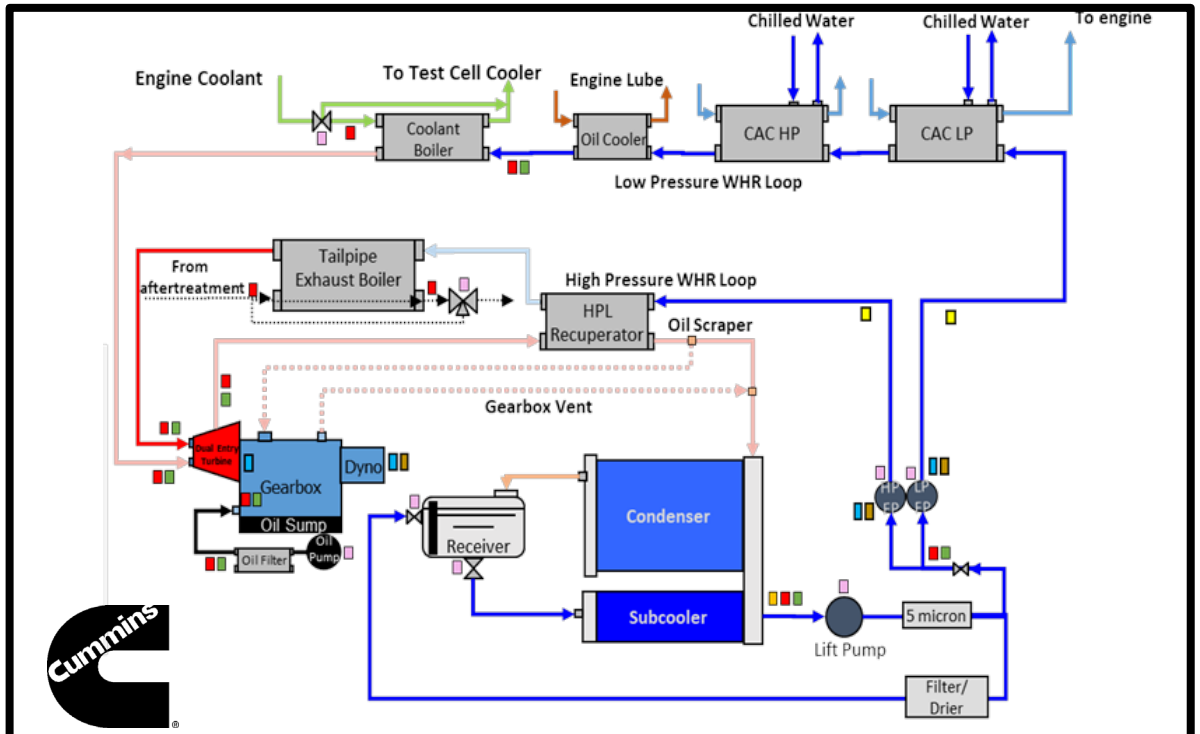


✓ All Components Fabricated

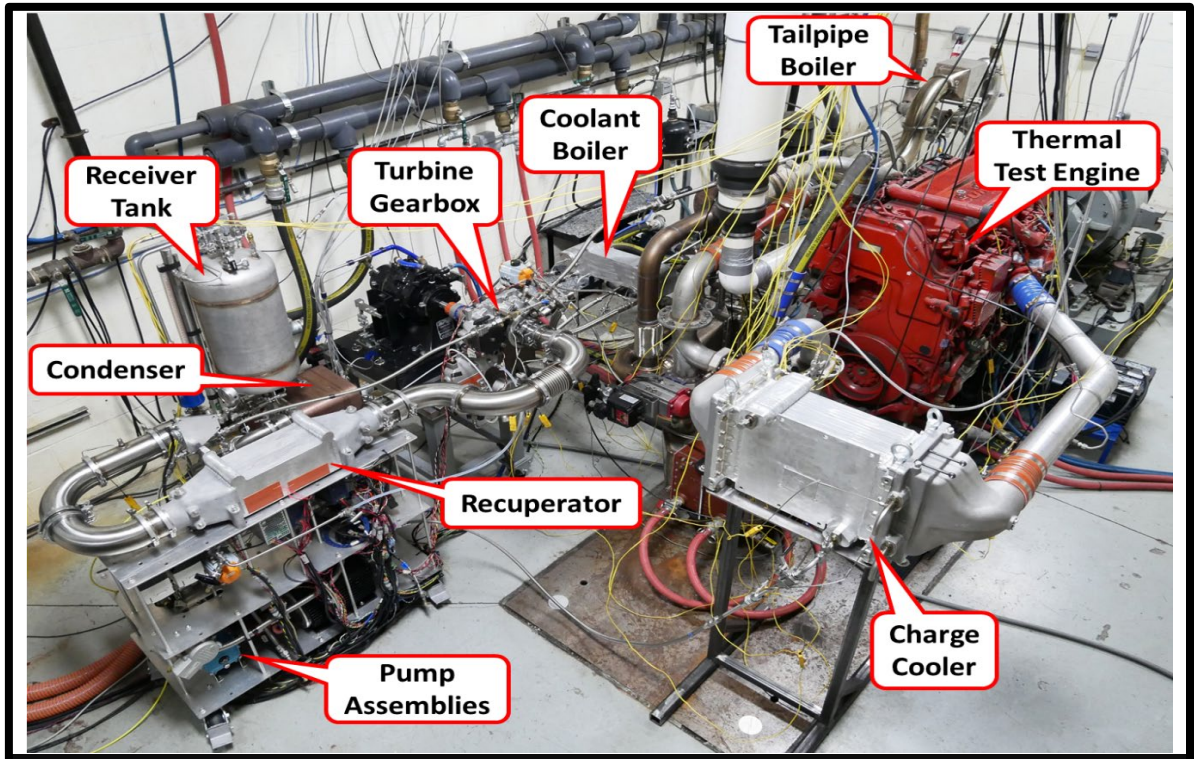
✓ Build Started

Waste Heat Recovery

PACCAR SuperTruck II



- Exhaust-, Coolant-, CAC-, and Oil Heat Recovery
- Dual Entry Turbine Architecture
- Tailored to PACCAR SuperTruck Engine



- All Components Fabricated
- Shakedown Testing Completed Successfully
- WHR Demonstration Testing Completed
- ≥4.0% BTE Achieved

Engine Efficiency Breakdown

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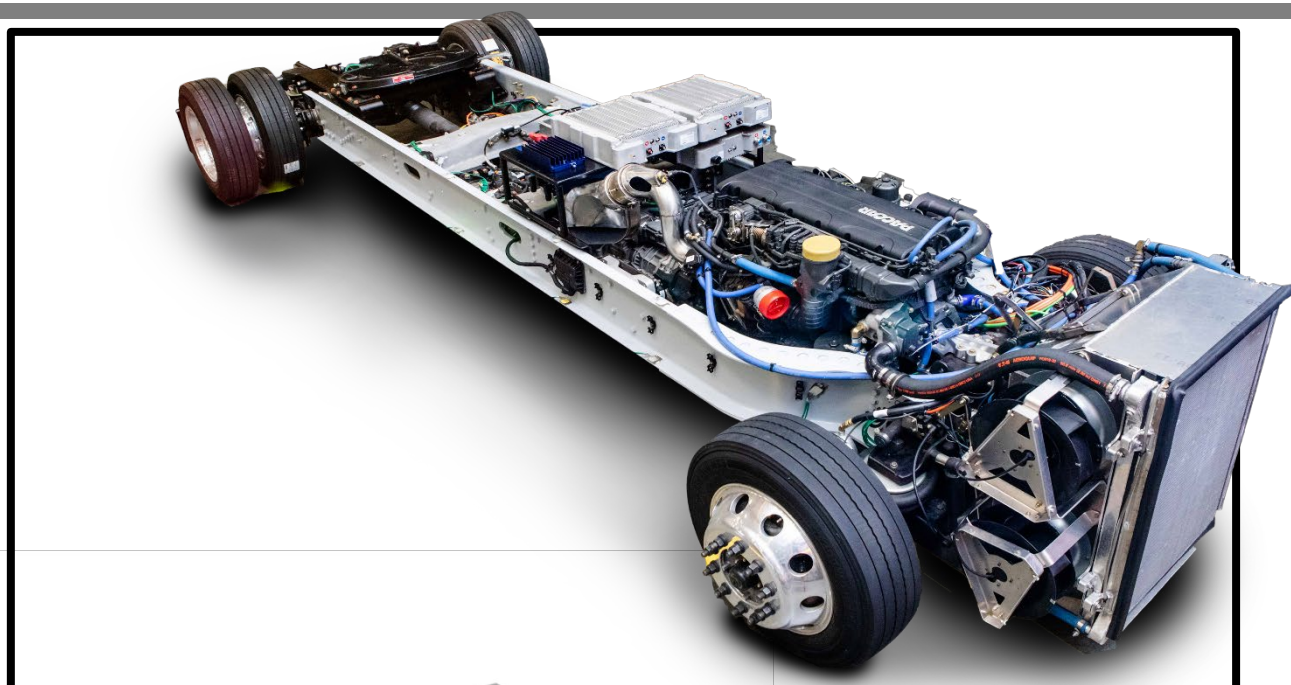
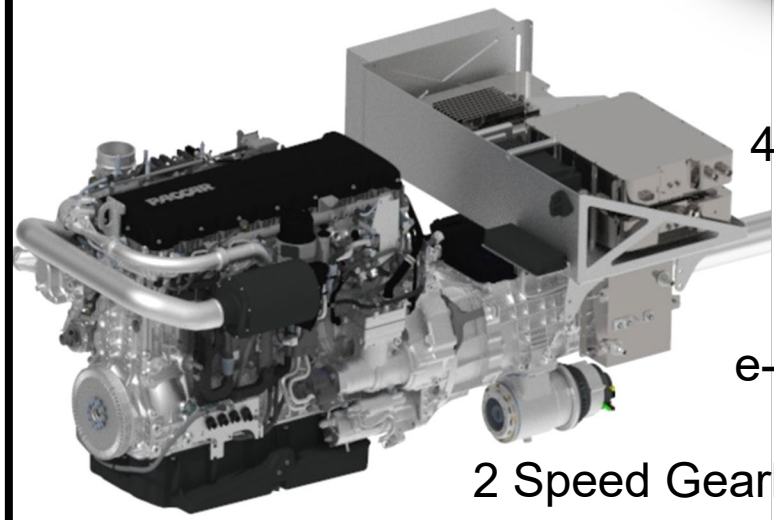
Powertrain

Powertrain Efficiency
40% Improvement

Base Powertrain	21%
Mild Hybrid / Electrification	13%
Low Rolling Resistance Tires	6%

- 48V For Increased Power Capacity
- PTO Mounted 30 kW e-Motor
- Gearbox for Cranking and Optimum Fuel Efficiency
- Tailored 48V Li-Ion Battery-Pack
- Supports e-Hoteling





48V Battery-Pack

e-Motor

2 Speed Gearbox

Powertrain Status

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EATON

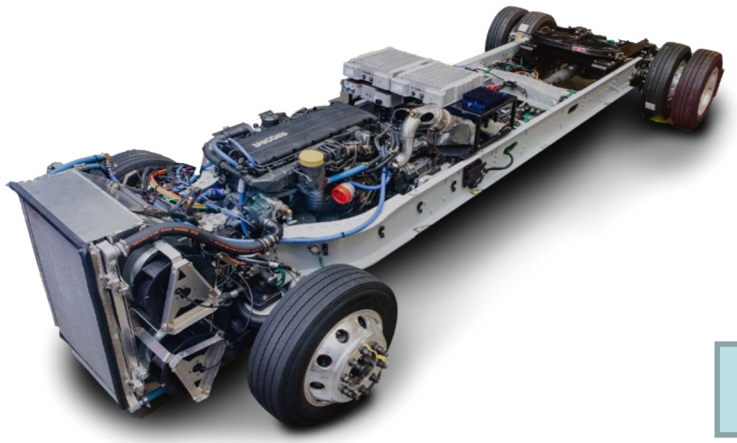
2021

- Battery Integration
- Mild Hybrid Functions
- Testing 48V Components
- On-road Testing

✓

PACCAR TECHNICAL CENTER

Q2 2022



- 48V e-HVAC / e-heater
- Dual Loop Cooling System
- Vehicle Controls

✓

KENWORTH

Q3 2022

- Install on Demonstrator

Vehicle Freight Efficiency

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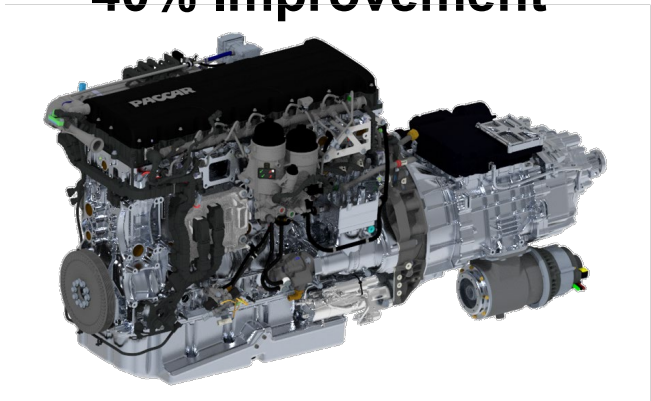
Powertrain Efficiency
40% Improvement



- Engine / Transmission / Axles
- Mild Hybrid / Electrification
- Low Rolling Resistance Tires

Weight Reduction
28% Reduction

- Systems Engineering
- Modular Integration
- Materials Application

Aerodynamics
63% Reduction

- Ideal Shape
- Enclosed Wheels
- Trailer Skirt & Pontoon

170% Freight Efficiency Improvement Forecasted

Tractor & Trailer Outerbody

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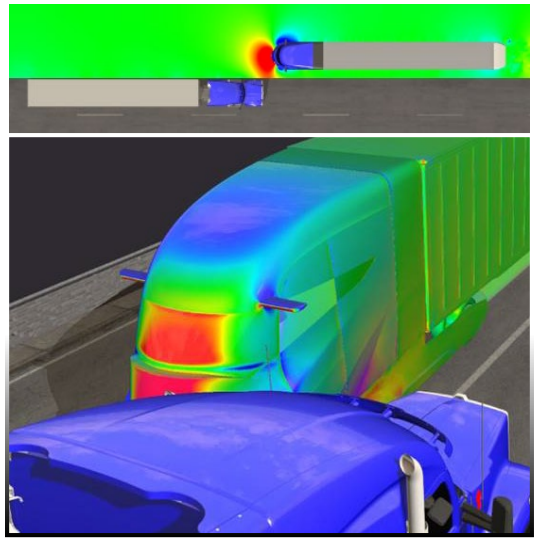
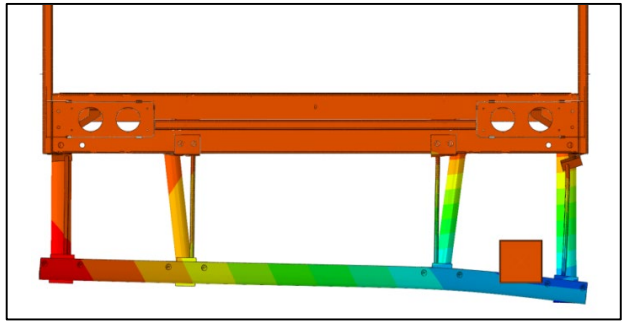
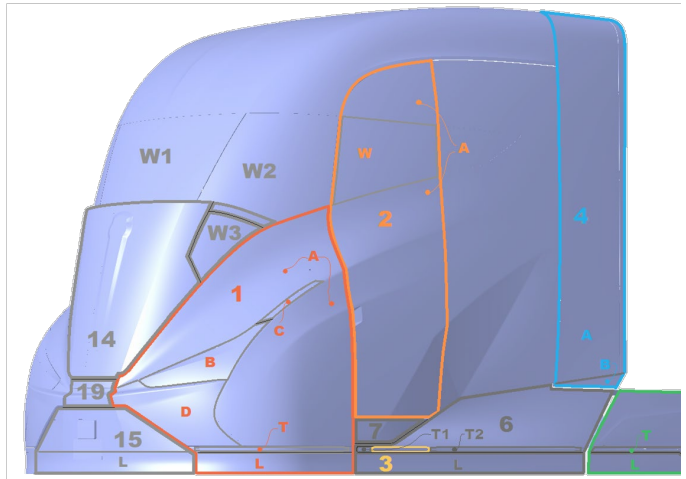
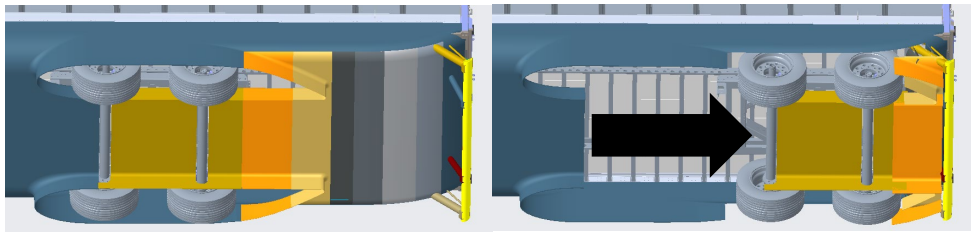








50% Clay Complete, Reviewed and Approved

CFD Complete & Exterior Styling Surfaces Finalized

Panel Breakup / Design Strategy Complete

Passing Vehicle Body Panel Aero Loads Investigated

Quasi-Static Underride Protection Simulation

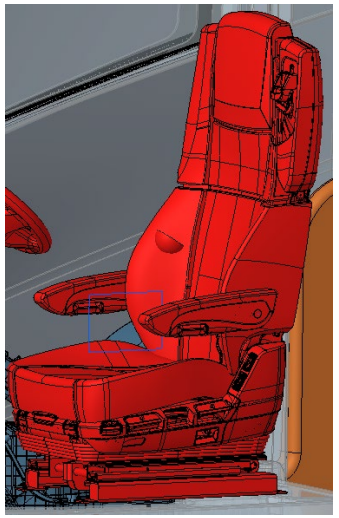
Panel Breakup / Design Strategy Complete

Component Design Nearing Completion

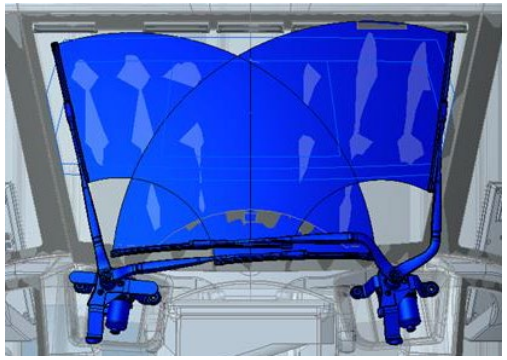
Trailer Bogie – Ramped Slider, Passive Panel System

Cab and Interior

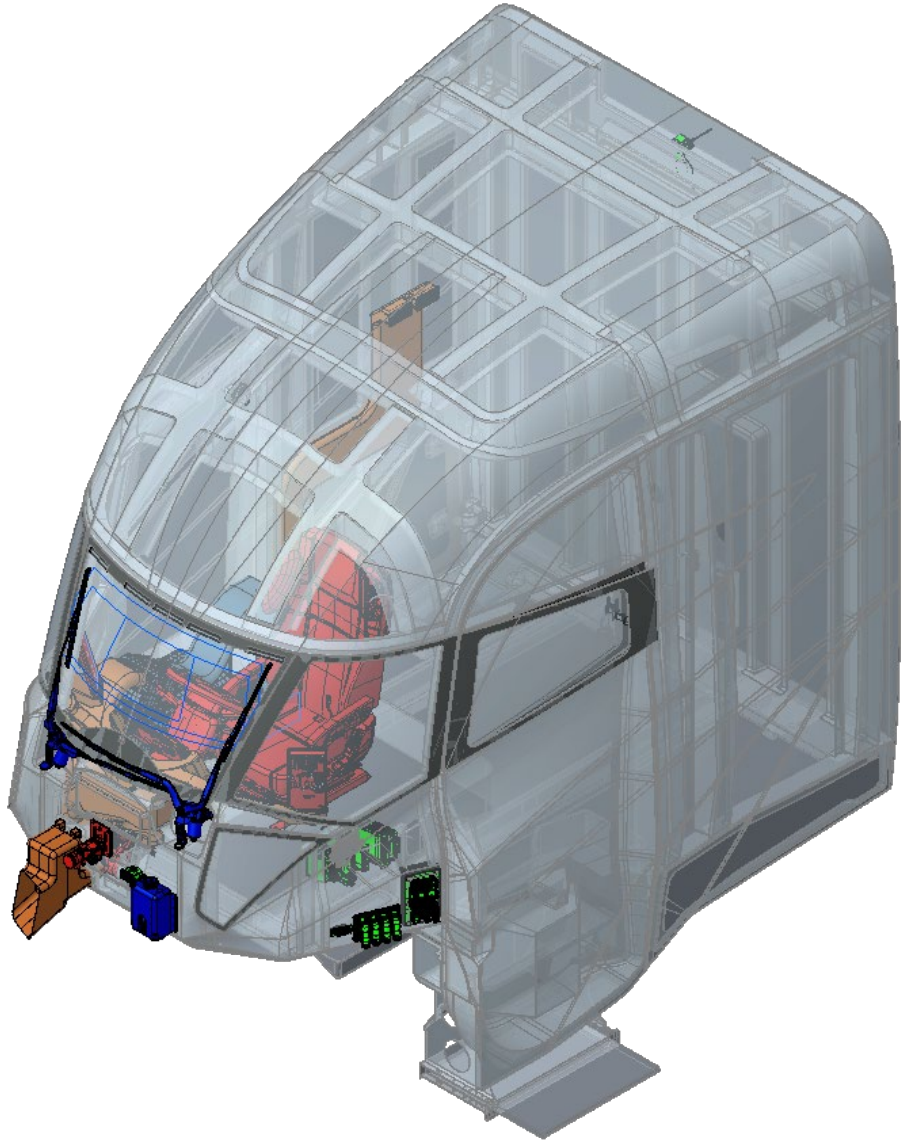
PACCAR SuperTruck II



Removed Air Suspension
Integrated Power Adjustments
Incorporated Seat Belt Structure

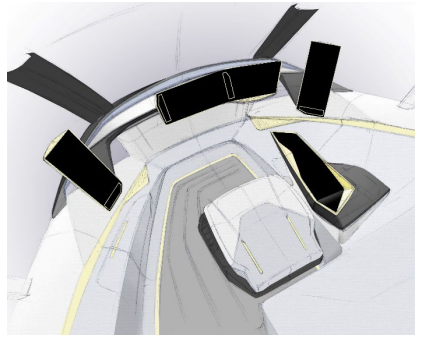


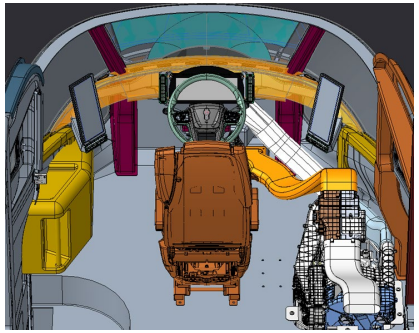
All Glass Designs Frozen
Wiper System Complete
Heated Glass Removed
Windshield Coating



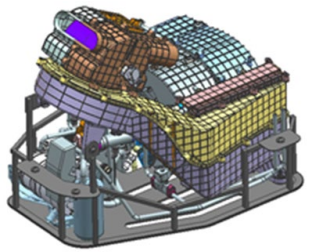
Demonstration Vehicle Cabin

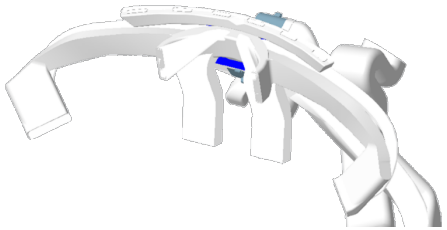
Interior Sketches to Concept Models

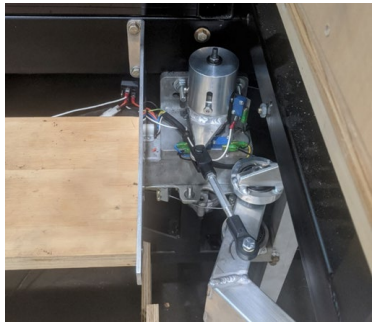


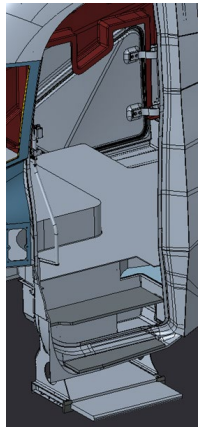


48V Heat Pump, HVAC Distribution, HMI Structure









Steps, Grab Handles, Door Opening Mechanism, Aperture & Seals defined

Chassis & Powertrain

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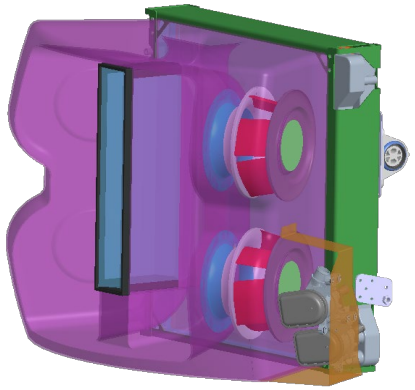
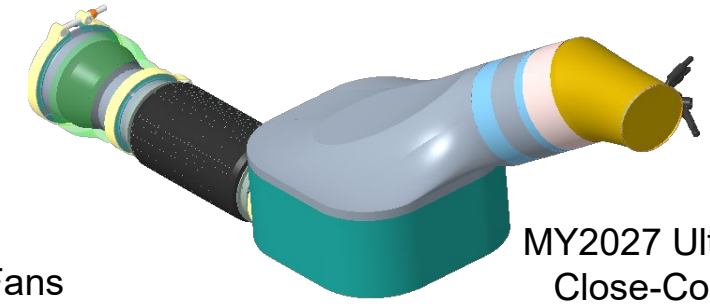
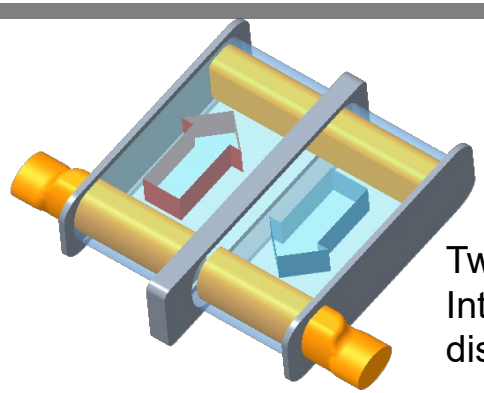


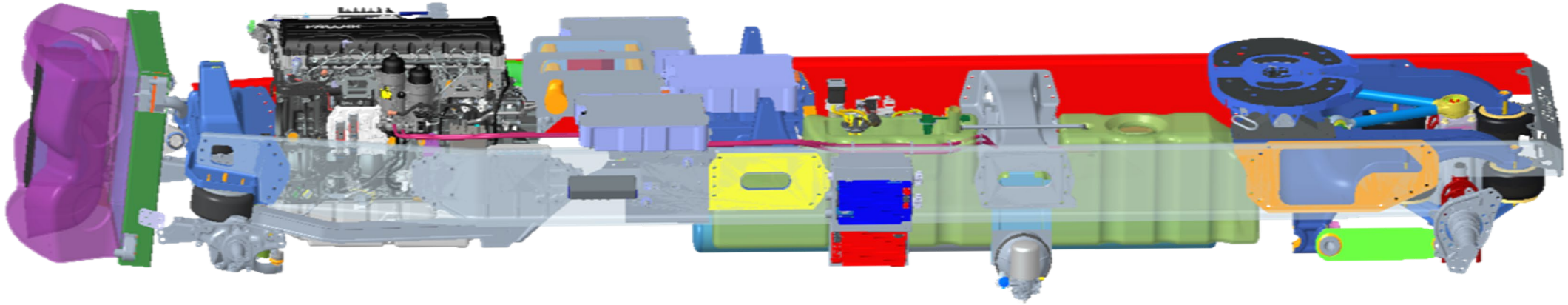
Two Circuit Cooling
Two-Stage iCAC
40% Frontal Open Area
Integrated Air Cleaner
Centrifugal 48V Pusher Fans

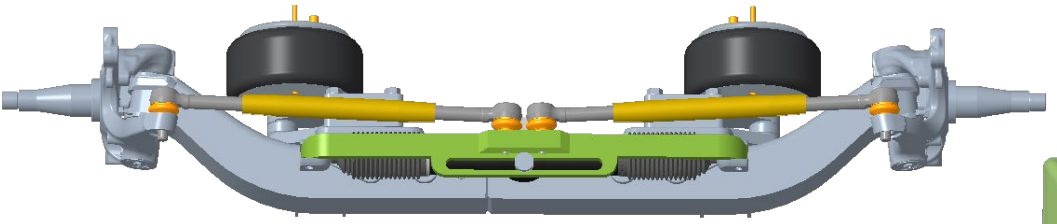


MY2027 Ultra-Low NOx
Close-Coupled EAS

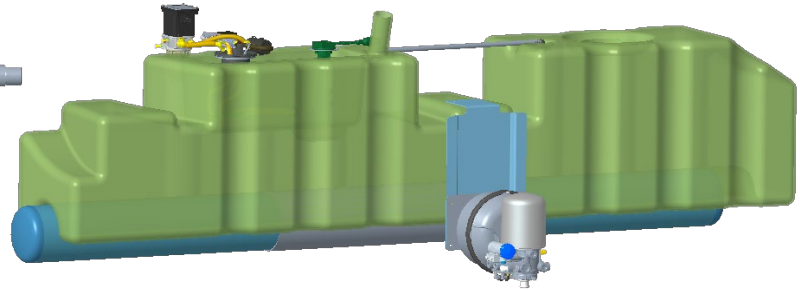


Two-Stage iCAC
Integrated coolant distribution

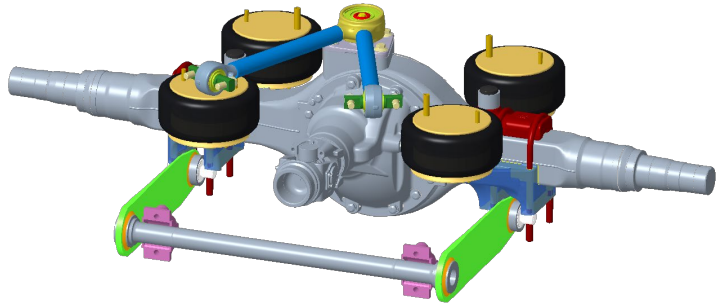




Narrow Track Axle - Aerodynamics
Reduced Scrub – Steering Power
Rack & Pinion – Weight / Ackerman



Combined Fuel / Air / Drier/ DEF Module



Lightweight Triangulated 3-Link Suspension

Electrical & Controls

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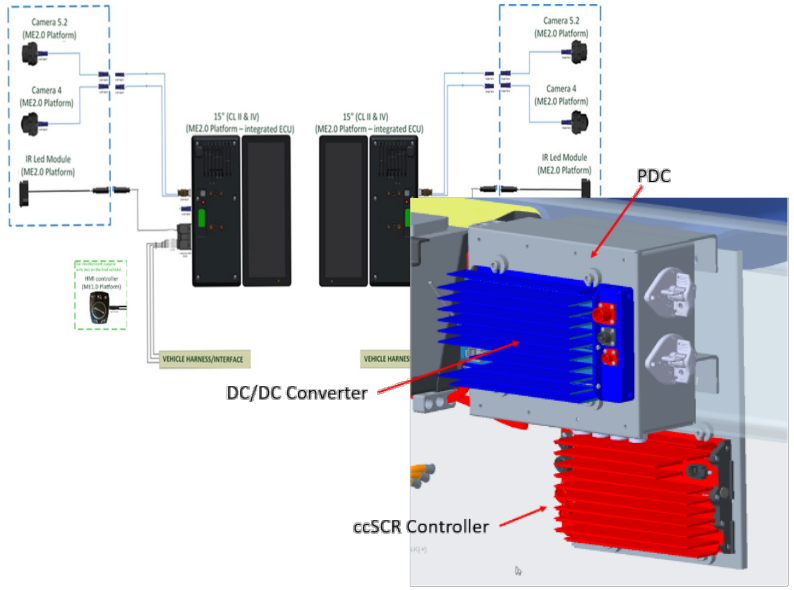
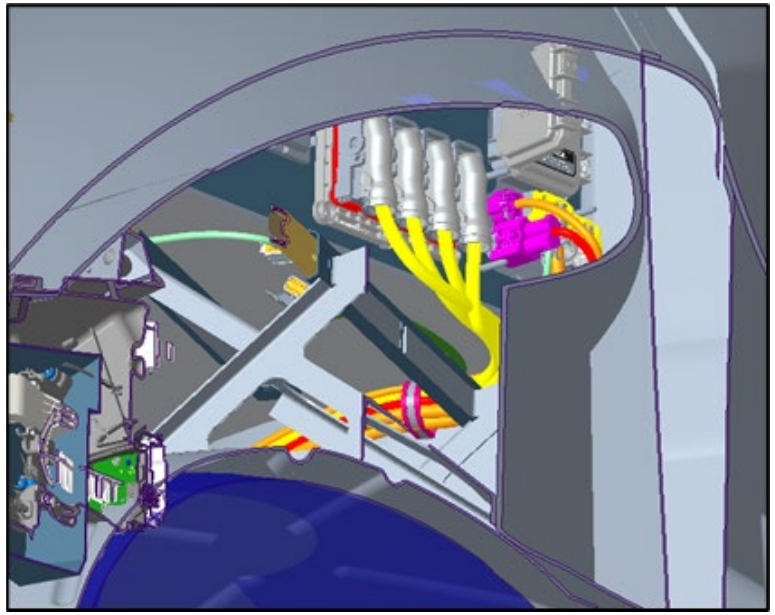
12V/ 48V Electrical



Packaging



Controls & Architecture

GCM 196

RCM 112

MicroAutoBoxII

- High Current Power Distribution Complete
- Electrical Component Definition in Process
- Harness Circuit Mapping in Process

- ECU Hotel & Packaging Complete
- Vehicle Routing Strategy 60% Complete
- HMI Component Definition Frozen

- CAN Architecture for Demonstrator is 70% Complete
- Controls Development In Progress

Freight Efficiency Contributions

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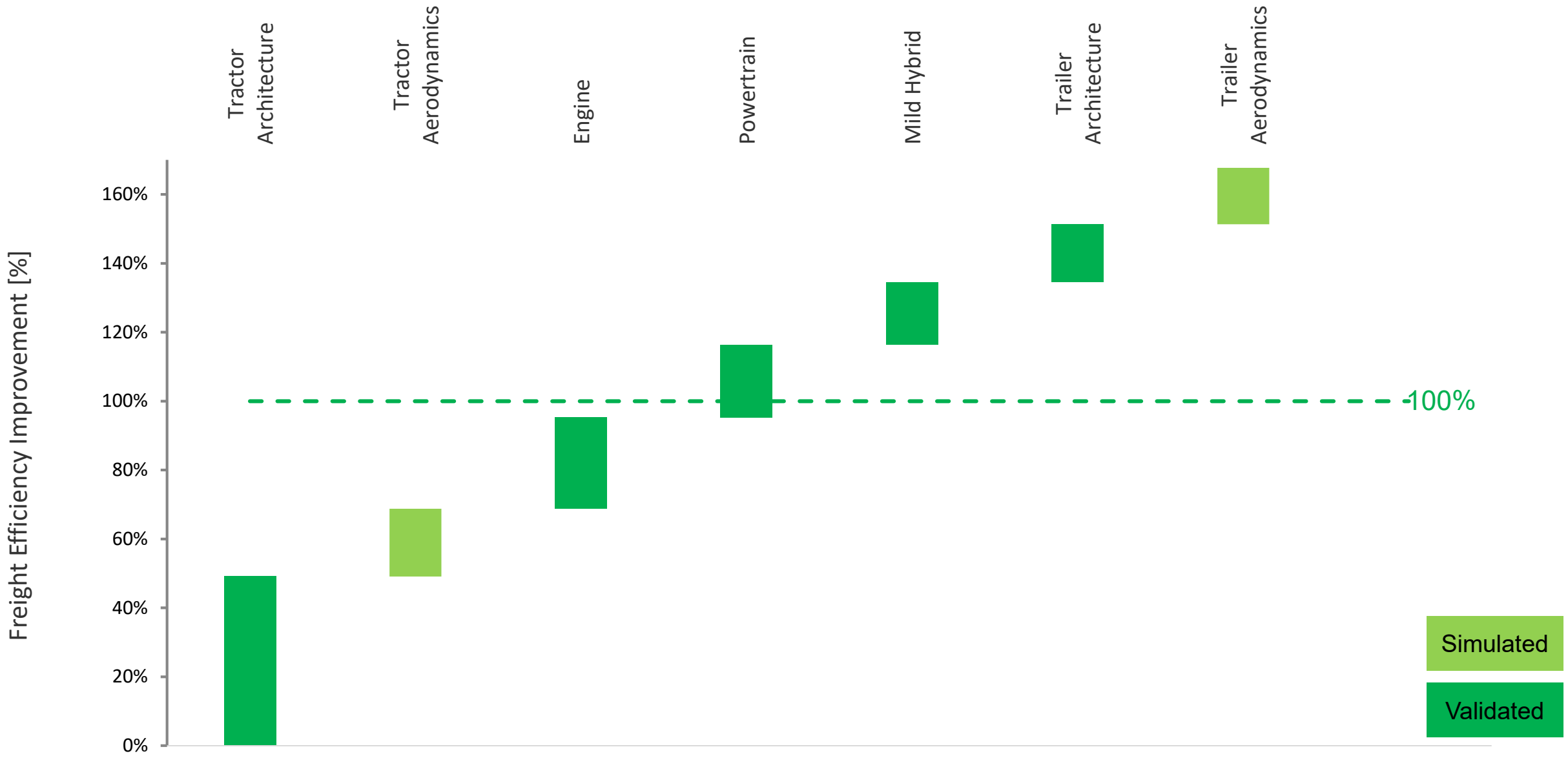

Response to Reviewers' Comments

PACCAR SuperTruck II

- **It Will be Interesting to see if the Exploration of GCI for Both High Efficiency and Low NOx Works out, and it's Good to see a SuperTruck II Team Explore Some Unique Solutions**
  - After our PoC testing, GCI has not been selected as the prime-path. However, explorations of unique solutions is indeed in the spirit of this DOE program: "Evaluation of Higher Risk Technologies With Potential For Energy Efficiency". Many unique solutions have been developed under this program (cab, cab Interior, e-HVAC, predictive e-hoteling, vehicle suspension, long stroke, EAS, etc). The implementation of these unique solutions has been successful.
- **Tackling the ultra low NOx is quite aggressive. The pathway to reach that was not detailed in the presentation**
  - Ultra-Low NOx has been tackled by the close-coupled EAS solution included in this presentation. Architecture and controls details are confidential. However, insights have been shared with the relevant agencies.
- **I expect to see more details in a waterfall chart on the efficiency improvements**
  - Last years AMR focused on addressing the technology concepts and design status. This year, we included more details on (validated) engine BTE and vehicle freight efficiency.
- **The next review should include details on fleet engagement**
  - The program has incorporated review, feedback, and design improvements based on detailed council with our fleet partner UPS. In addition, two broader customer council reviews have been held representing 10 major US fleets in vocational and OTR operations . The PACCAR vehicle designs illustrated today represent the incorporation of collective feedback while recognizing that achieving this level of vehicle efficiency will drive changes to product architecture and driver utilization.

Partnerships/Collaborations

PACCAR SuperTruck II

KENWORTH	Vehicle Development, Vehicle Level Supervisory Controls
DAF	Engine Development
PACCAR TECHNICAL CENTER	Powertrain Development, Advanced Predictive Features, Program Administration
EATON	Electrified Powertrain, Transmission, and Air Management Systems Development
AVL	Engine Development
NREL NATIONAL RENEWABLE ENERGY LABORATORY	Drive Cycle Development, and Thermal Management
Cummins	Waste Heat Recovery Integration
MERITOR	Axle Integration
Continental	Tire Development
THE OHIO STATE UNIVERSITY	Model Development for Cabin Hoteling Optimization
UNIVERSITY of WASHINGTON	Windscreen coating and engine thermal barrier coatings

Remaining Challenges

PACCAR SuperTruck II

Engine

- Complete 55% BTE Demo

Powertrain & Vehicle

- Demonstrator Vehicle Build

- **For all Technology Concepts: Continue Detailed Feasibility for Commercialization**

Proposed Future Research

PACCAR SuperTruck II

Engine

- Engine 55% BTE Demo

Powertrain & Vehicle

- 175% Freight Efficiency Demo

Summary

PACCAR SuperTruck II

PROGRAM ON TRACK TO MEET TARGETS:

Engine	• All Hardware Fabricated • Key Engine Technologies Demonstrated • WHR System Performance Demonstrated
Powertrain	• All Hardware Fabricated • All Systems Integrated on Proof of Concept Vehicle • Vehicle Controls Implemented
Vehicle	• Updated Freight Efficiency Roadmap to 175% Improvement • Final Vehicle Demonstrator Design in the Final Stage • Hardware Fabrication Started