# 2020 Annual Merit Review

# 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 04, 2020 Project ID # ACS124

PACCAR SuperTruck II

# Overview

## Timeline

- Start Date: October 2017
- End Date: September 2022
- Percent Complete: 53%

## Budget

- Total Project Funding
  - DOE: $20M
  - Partnership: $20M
- FY 2019 Funding: $13.0M
- FY 2020 Funding: $16.7M

## 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, UPS, DAF, PACCAR TECHNICAL CENTER, NREL NATIONAL RENEWABLE ENERGY LABORATORY, THE OHIO STATE UNIVERSITY

# 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**
  - Test Key Engine Technologies
  - Procurement And Build Engine / WHR Components
  - Test Mild Hybrid Powertrain
  - Vehicle Test of Advanced Predictive Features
  - 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

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# Program Outline

### 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
- Proto Vehicles Testing
- New Engine Technologies Testing
- Hybrid Powertrain Testing
- WHR Integration And Initial Testing

### Year 4 (2021)

**Powertrain Testing & SuperTruck Build**

- Engine, And Powertrain Efficiency Demo
- Powertrain And Vehicle Integration
- Initial Testing Of Drivability & Fuel Economy

### Year 5 (2022)

**Engine & Freight Efficiency Demo**

- Engine & WHR 55% BTE Demo
- SuperTruck Freight Efficiency Demo > 100%
- Final Report
- Project Close

- **Year 3 Program on Track, Progress Currently Challenged by Global Epidemic**

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# Milestones

**Budget Period 2: October 2018 - September 2019**

| Milestones | Type | Description | % |
|---|---|---|---|
| Engine Components Selected | Technical | Design Of Internal And External Engine Components With Long Lead Times Is Complete | 100 |
| Powertrain Components Selected | Technical | Design Of Electrified Powertrain Components Is Complete And Components Are Selected For Fabrication | 100 |
| Mule Vehicle Tested | Technical | Mule Vehicle Is Designed, Assembled And Tested | 80 |
| Electrified Powertrain Components Manufacturable | Go/No-go | Designs Of Internal And External Engine And Electrified Powertrain Components Are Verified As Manufacturable | 100 |

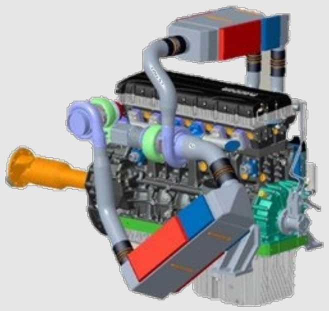
**Budget Period 3: October 2019 – September 2020**

| Milestone | Type | Description | % |
|---|---|---|---|
| Engine Components Fabrication Complete | Technical | Final Internal And External Engine Components Are Fabricated | 30 |
| Powertrain Components Fabrication Complete | Technical | Final Electrified Powertrain Components Are Fabricated | 30 |
| SuperTruck II Tractor Component Designs Frozen | Technical | Design Is Frozen For Components Of The SuperTruck II Tractor | 35 |
| SuperTruck II Tractor Design Is Complete | Go/No-go | All Engine And Powertrain Components Have Been Fabricated. SuperTruck II Tractor Design Is Complete | 30 |

# Approach

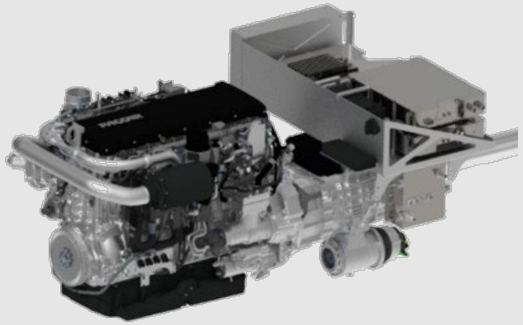
- **Complex System Engineering**
  - Integrated Teams, Combining Areas Of Technical Expertise
  - Leverage Of Existing Development Processes & Tools

### Engine



Combustion Strategies, Thermodynamics, 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

# ENGINE

# From Concept to Design

## Concepts

**Conventional**

- Fast Combustion System
- High Efficiency Air-Management System
- Optimized Friction & Accessories
- Insulate Intake & Exhaust

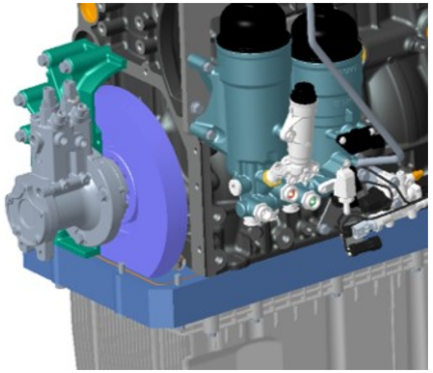
**Modest Innovation**

- Miller Cycle + CR/Stroke
- Pulse Turbocharging
- In-Cylinder Coatings
- Additional Friction Reduction

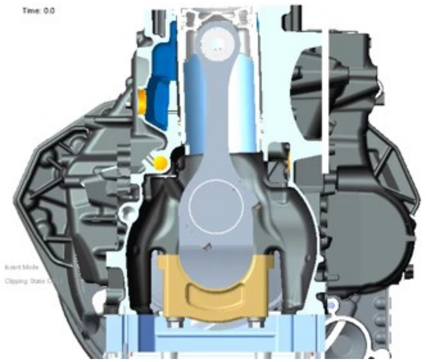
**Non-Conventional**

- Alt. Combustion. Regime
- Aggressive Friction & Mechanical Changes (Casting Impact)

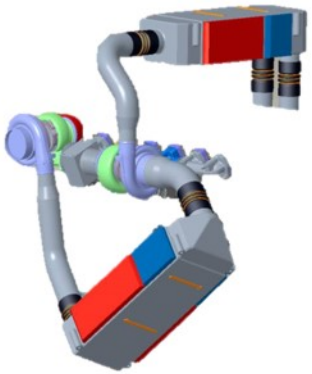
## Design



Integrated Damper



Long-Stroke

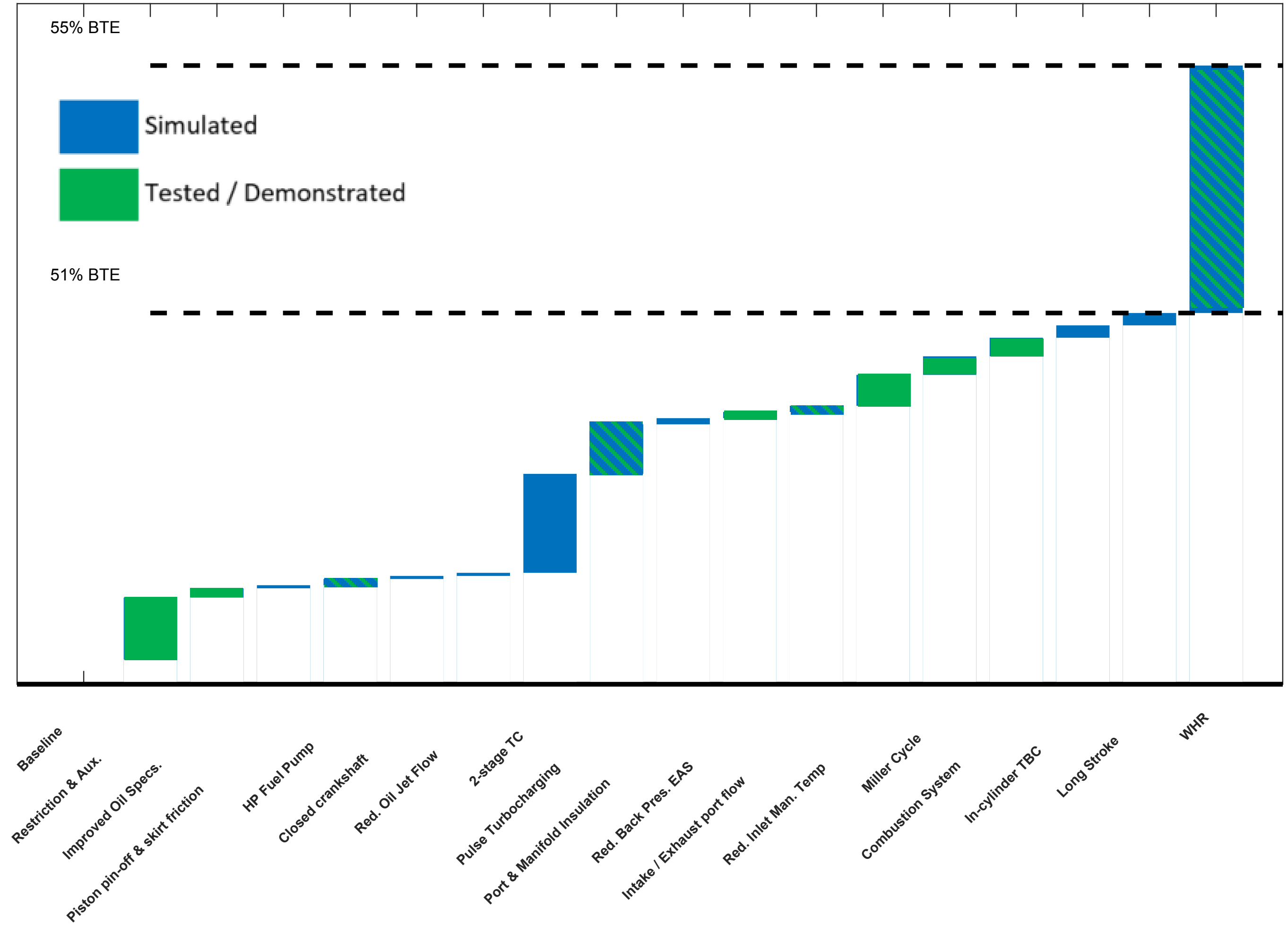


2-Stage Turbo

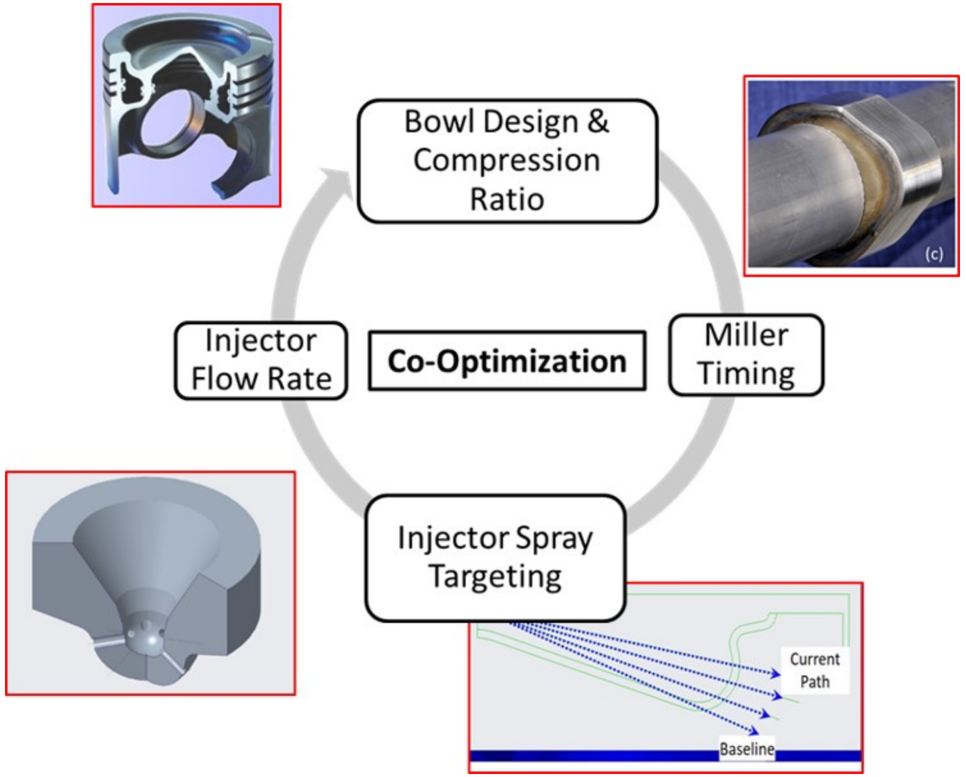
- **Technology Development**
  - Fast Combustion
    - High Flow Injectors, Increased Peak Firing Pressure
  - Increased Expansion Ratio
    - CR / Long Stroke, Late Inlet Valve Closing Miller
  - High Efficiency Turbocharging
    - Pulse Capturing, 2 Stage Fixed Geometry
  - Low Restriction Air And Exhaust System
    - Optimized Manifold, Ports Design
  - Insulation
    - In-cylinder Thermal Swing Coatings, Exhaust
  - Thermal Management
    - Variable Oil-Jets, Increased Coolant Temperature
  - Friction Reduction And Auxiliaries

# Technology Validation

BTE Improvement:




Co-Optimization Approach:

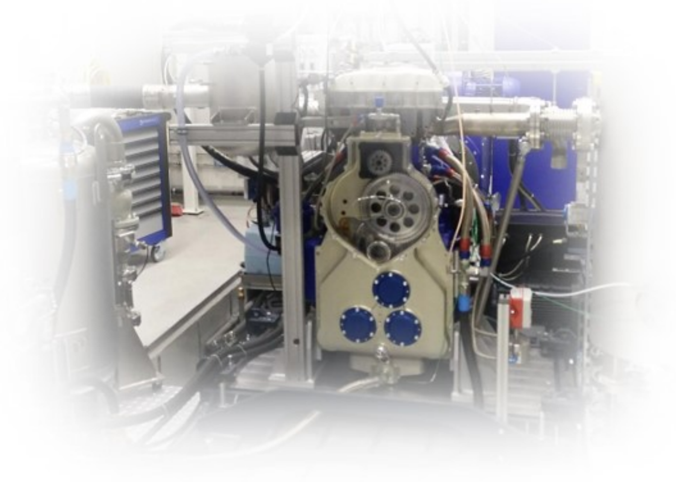



- **Optimization of Highly Coupled Systems, Requires Integrated Simulation and Experimental Methods**

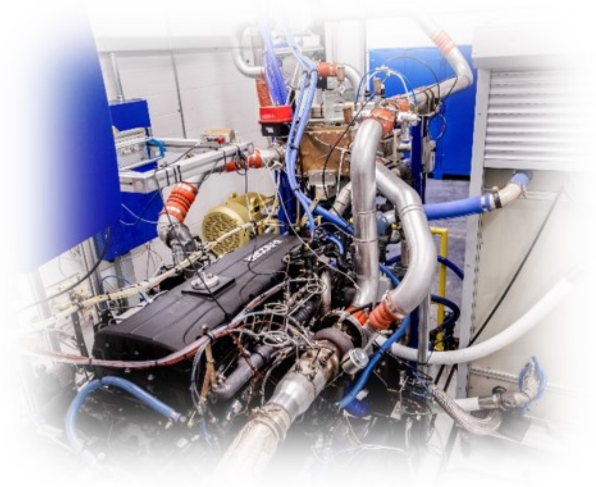
# Iterative Simulations and Testing

- Validation Of Simulation Work, At Component And System Level
- Isolated Proof Of Concept, On Dedicated Test-Rigs
- Detailed Insights Feed Simulations For Final Engine Hardware Design

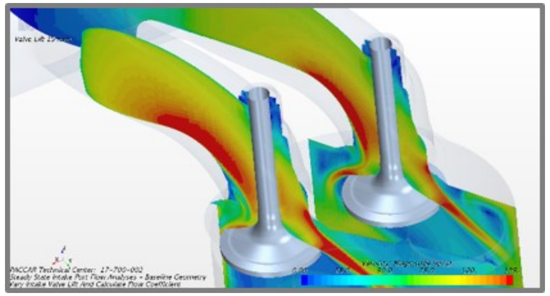
Flow Bench

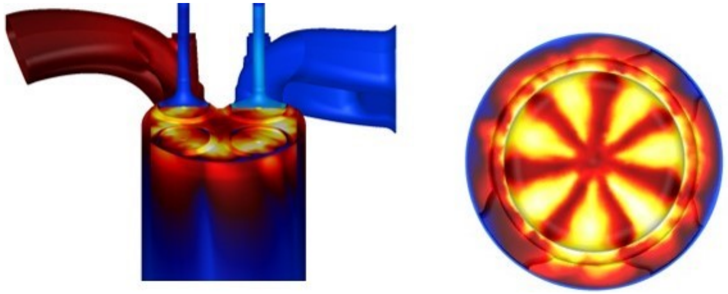


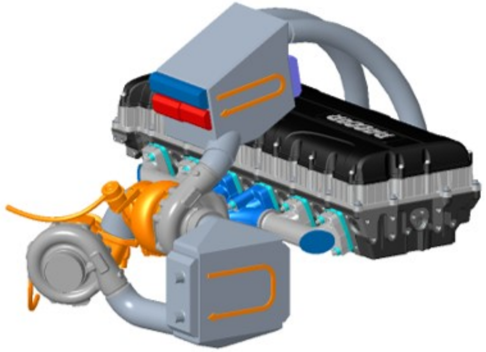
Single Cylinder Engine



Engine With Artificial Boost

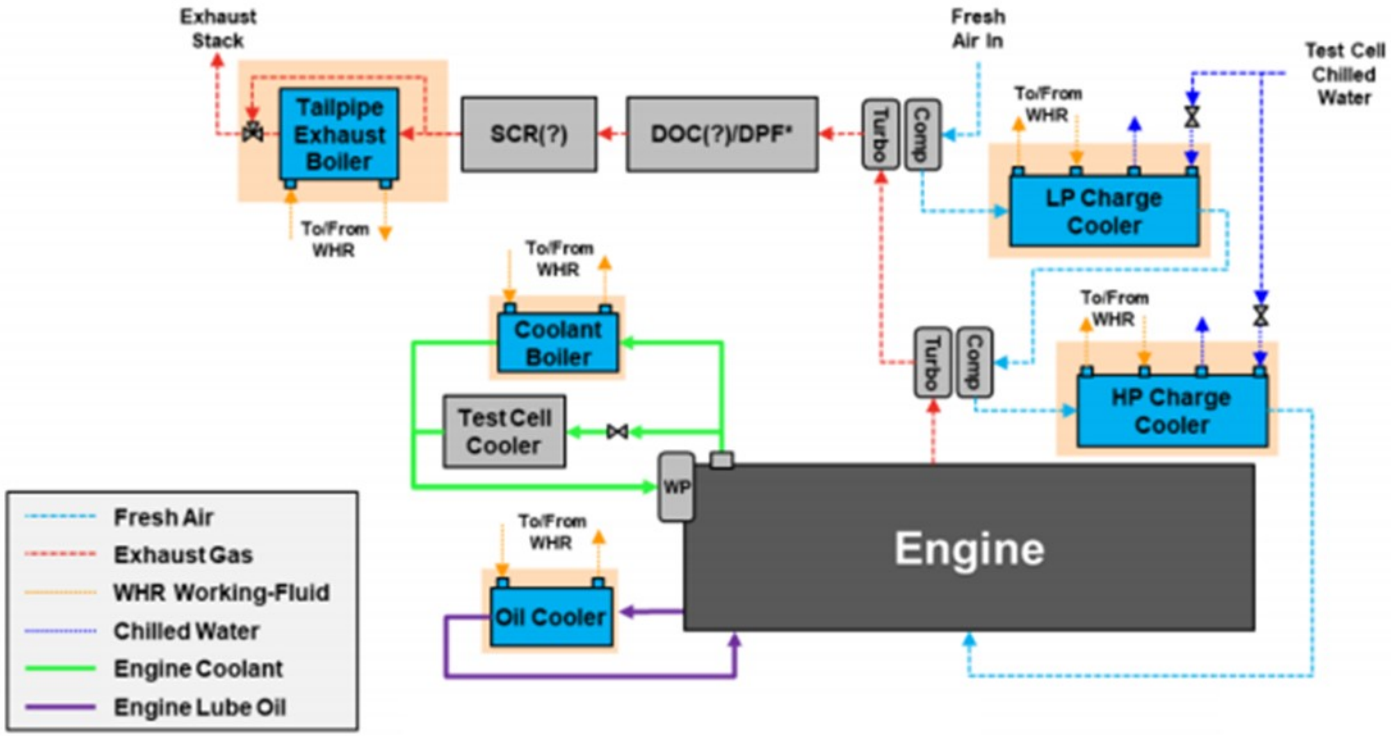






# Waste Heat Recovery

- **Approach**
  - Tailored WHR Architecture, For Maximum BTE Potential
  - Co-Optimized Approach With Engine Simulations
- **Status**
  - Challenged By Low Exhaust Enthalpy
  - Performance On 4%. BTE Target
  - Detailed Component Level Design
  - Procurement Hardware
- **Challenge**
  - WHR Design Freeze While Engine Component Validation is Ongoing



# POWERTRAIN

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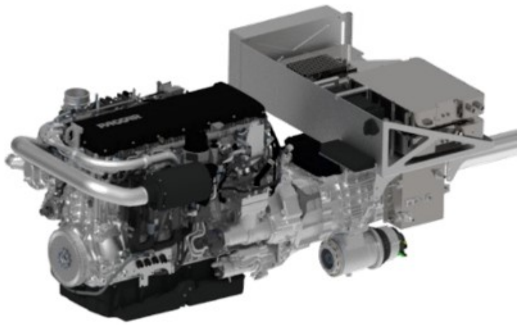
# Powertrain

## Powertrain Efficiency



| | |
|---|---|
| Base Powertrain | 22% |
| Mild Hybrid / Electrification | 13% |
| Low Rolling Resistance Tires | 7% |

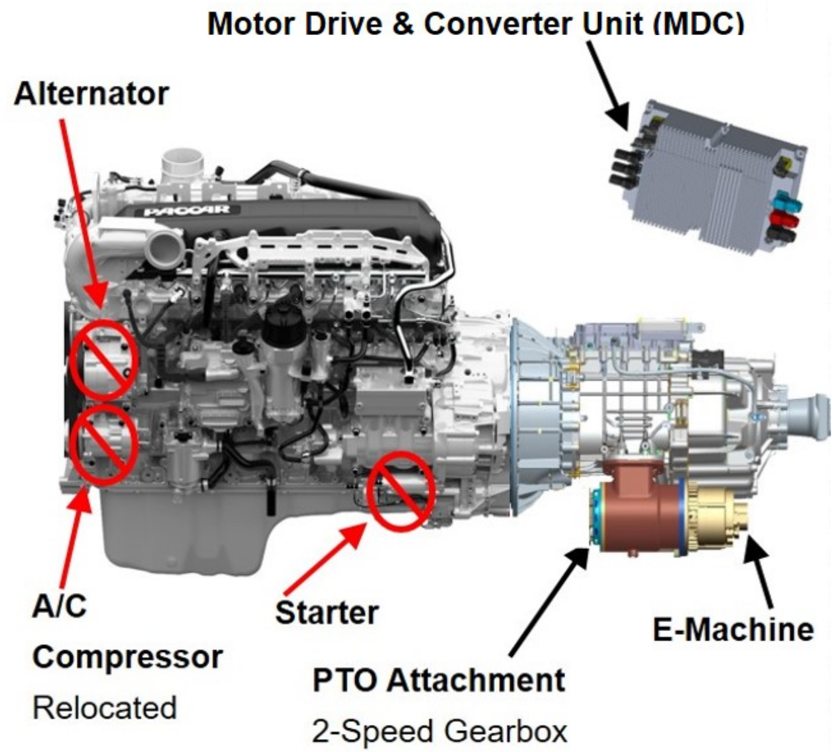
- **Approach**
  - High Efficient Engine, Transmission, And Drive Axles
  - Development Of 48V Mild-Hybrid Powertrain
  - Integration of Optimized 48V Li-Ion Battery System
  - Vehicle Level Energy Management Controller
- **Status**
  - New Controls Developed
  - Validation of Components and Sub-Systems
  - System Integration on Proto Vehicles

# Hybridization

- **High Commercialization Potential**

- **Hybrid Powertrain**
  - Based On FE Sim. And Customer Feedback
  - 48V For Increased Power Capacity
  - PTO Mounted 30 kW E-machine
  - Gearbox For Cranking And Optimum FE
  - Component / System Testing Ongoing

- **Battery System**
  - Tailored 48V Li-Ion Akasol System
  - Considering Driver Needs (e.g. Hoteling)
  - Energy 10 kWh / Peak Power 30 kW,
    For Energy Storage & Power Requirements
  - Ready for First Performance Tests



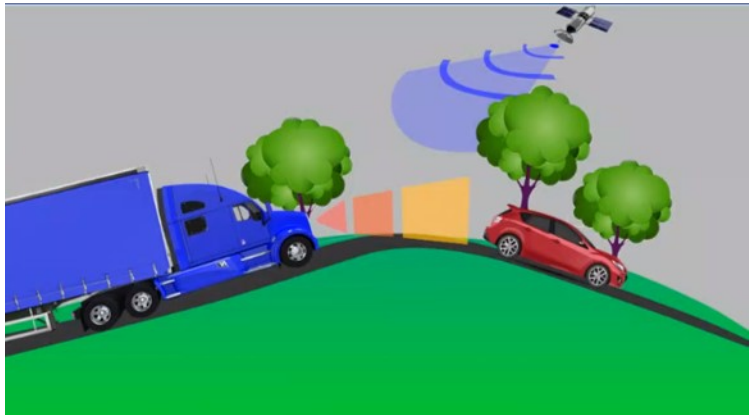

Mild-Hybrid

48V Li-Ion Battery

# Key Control Concepts

- **Control Software**
  - Mild Hybrid System, Electric Accessories, Cooling
- **Controls Truck**
  - Predictive Adaptive Cruise Control Up-fit
  - Additional Sensors in Route
- **Integration Of Predictive Cruise Control (PCC), And Adaptive Cruise Control (ACC)**
  - Improves Fuel Economy
  - Optimizes Battery Charging For Hoteling
  - Improves Customer Experience
- **Functional Safety**
  - Increased Powertrain Automation
  - Requires Appropriate Safety Approach

Control Testing Vehicle



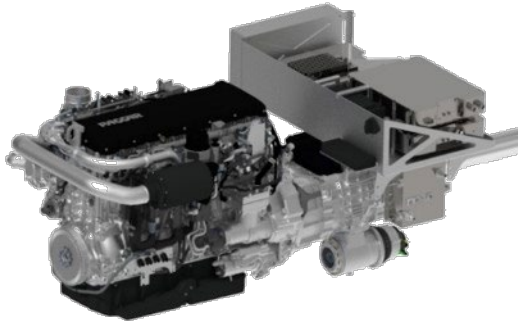
Predictive Adaptive Cruise Control

Ben Grover

# VEHICLE

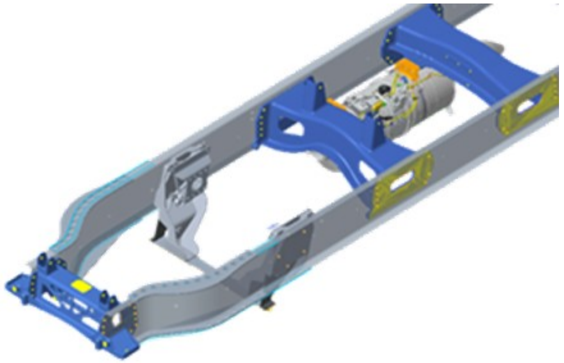
# Path to Freight Efficiency

## Powertrain Efficiency
**40% Improvement**



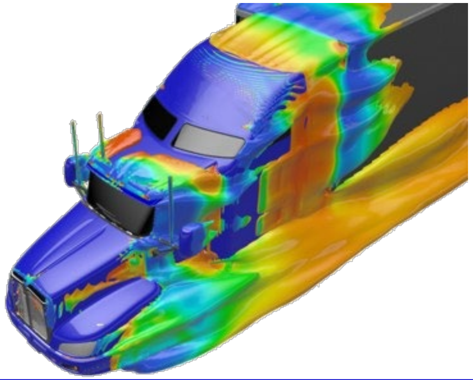
- Base Engine
- Mild Hybrid / Electrification
- Low Rolling Resistance Tires

## Weight Reduction
**25% Reduction**



- Systems Engineering
- Modular Integration
- Materials Application

## Aerodynamics
**60% Reduction**



- Ideal Shape
- Flow Management
- Trailer Skirt & Tail

**> 125% Freight Efficiency Improvement Forecasted**

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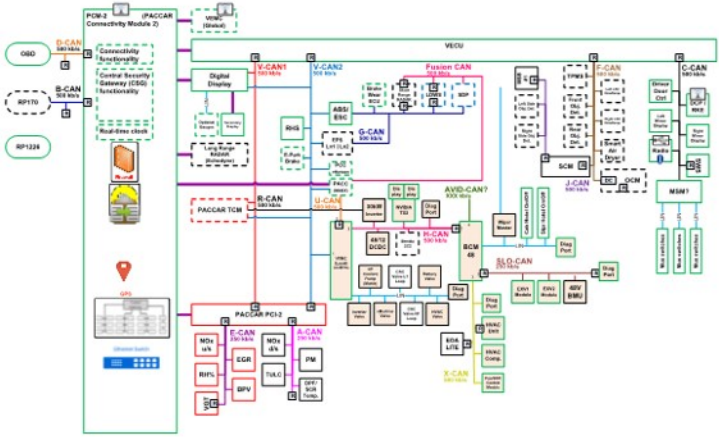
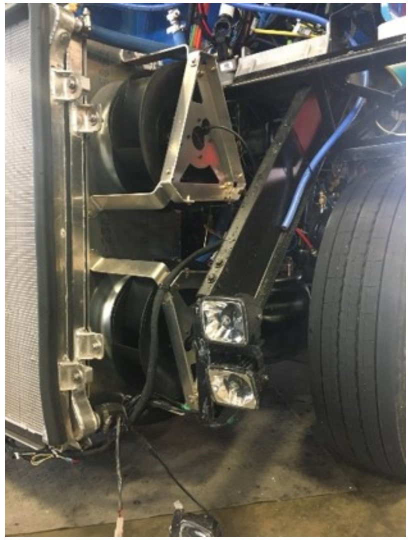
# Mule Vehicle Design and Build

- **Modular Chassis**
  - Consolidated Load Paths
  - Centralized Mass
  - Improved Manufacturing
- **Electronics and Controls**
  - New Architecture
  - 48V Bus, Power Electronics
- **Powertrain**
  - Electrified Accessories, FEAD Delete
  - Two Loop Cooling System
- **Advanced HVAC**
  - 48V Heat Pump
  - 100% Improvement to R-Value

Modular Chassis Assembly



Electrical Architecture



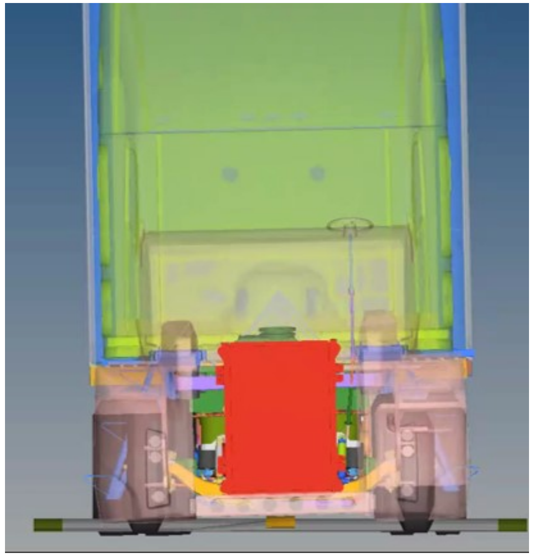
Two Loop Cooling


Insulation and Heat Pump

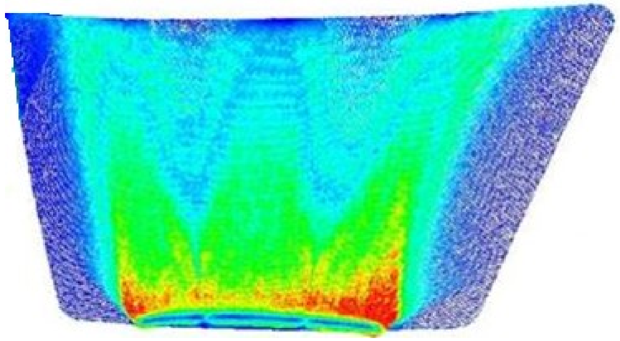
# Mule Testing, Analysis

- **Chassis Loading**
  - Strain Gage Data
  - Wheel End Force
  - Chassis Twist
- **Powertrain & Controls**
  - 48V Acc. on Mule 1.0
  - Mild Hybrid on Mule 2.0
- **HVAC**
  - System Capacity
  - Defrost Performance
- **Ride & Handling**
  - Dynamic Behavior
  - Vehicle Simulation Model

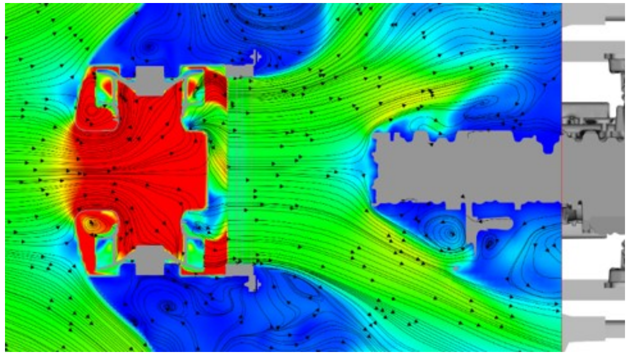
Mule Vehicle 1.0 Testing



Dynamic Simulation Model



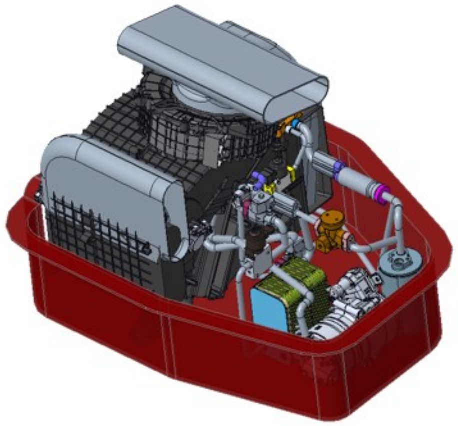
Windshield Defrost Simulation
- 5 Minutes to Clear



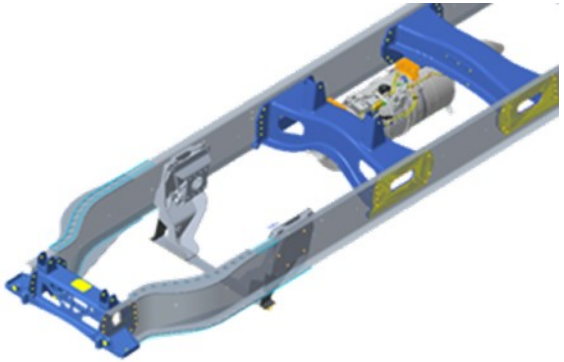
Fan and Cooling Optimization
10% Efficiency Improvement

# Demonstration Vehicle Progress

- **Styling and Aerodynamics**
  - 1/8th Scale Model Complete, ½ Scale in Progress
  - Outerbody Design Under Development
- **Vehicle Design**
  - Chassis & Suspension Designed
  - Electronics & Controls Architecture Complete
  - Interior Content Defined, Mockup complete
  - Modular Heat Pump Defined
  - Powertrain Defined, Design in Progress
  - Cab Structure Under Development
- **Customer Feedback, Market Feasibility**
  - Multiple Customer Councils
  - ROI Assessment



48V Modular Heat Pump

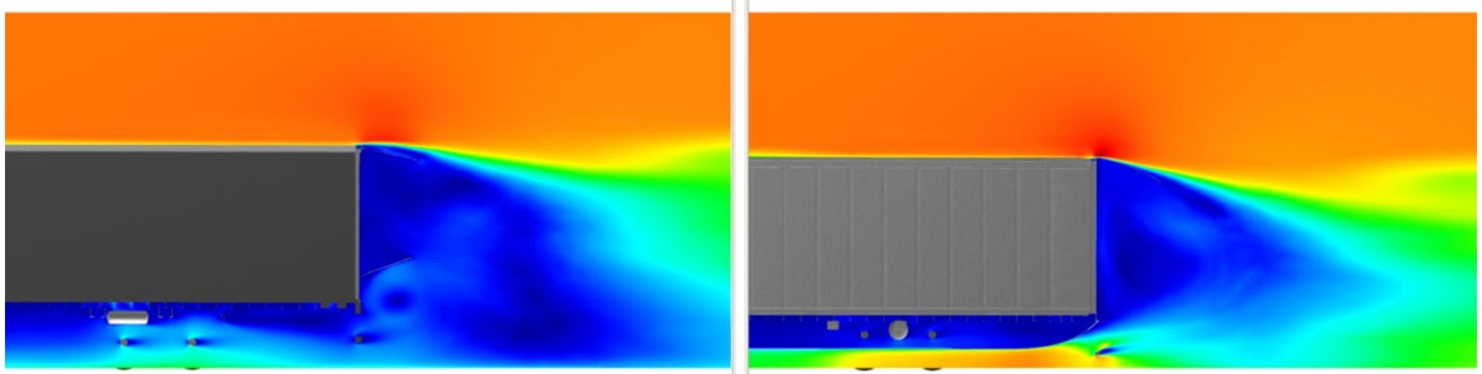


Frame and Crossmembers


Contributions To Exceed 100% Freight Efficiency Improvement

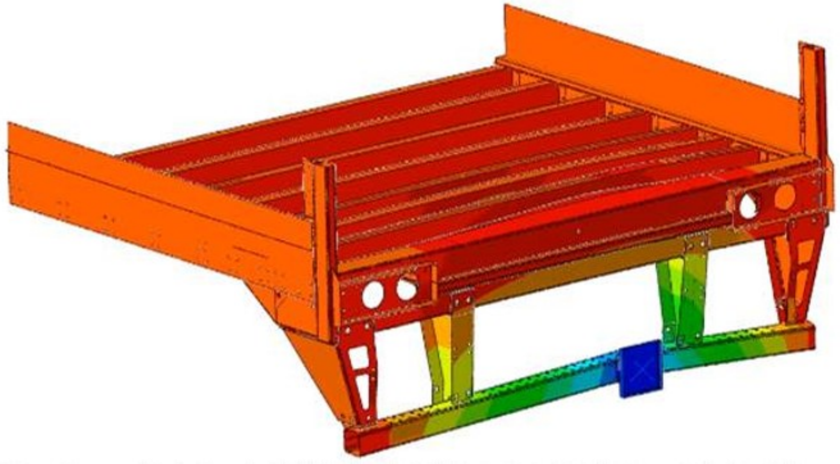
# Trailer Development Progress

- **Aerodynamics**
  - Rails, Corners, Header/Bolster
  - Skirt & Bogie Cover
  - Under Run Protection
  - Tail Shape and Mechanism
  - Ride Height / Docking Solution



Skirt and Tail Aero Treatments – 20% Drag Reduction

- **Structure**
  - Floor & Cross Members
  - Aluminum Composite Walls
  - Wide Based Tires, Aluminum Wheels



Trailer Under Run Redesign Utilizing FEA – Enables 5% Drag Reduction

# Responses to Reviewers' Comments

- **It was not clear which have been experimentally validated and which are via simulation. Nor was it clear if the technologies have all been tested in combination or if each one has been tested independently.**
  - Each technology is developed using simulations and experimental testing in an iterative approach. Moreover, experimental validation is first done on a dedicated test-rig and second in a combined system approach.
- **The reviewer commented that no research and further development are needed on WHR in the engine proposed future plan in FY 2020, because its competitor WHR system is used. This could create an uneven playing field for other competitors.**
  - The WHR system is tailored to the PACCAR ST-II Engine, using co-optimized simulations. It isn't an of the shelf solution. Architecture and component sizing is therefore unique.
- **Over 50% of the freight-efficiency improvement is due to lightweighting. Although an acceptable action to meet the goals, the reviewer thought that commercialization of fuel-efficiency technologies should be a higher percentage.**
  - Lightweighting is definitely part of the strategy, guided by industry input. Aerodynamics and fuel-efficiency technologies are included as well, such as new tractor and trailer designs, a high efficiency 48V mild hybrid, control concepts, and tires.  WHR is not included in our prime vehicle path because of the weight penalty / ROI vs. Freight Efficiency potential trade-off.

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# Partnerships/Collaborations

| | |
|---|---|
| KENWORTH | Vehicle Development, Vehicle Level Supervisory Controls |
| DAF | Engine Development, Engine Management Systems |
| PACCAR TECHNICAL CENTER | Powertrain Development, Advanced Predictive Features, Program Administration |
| EATON | Electrified Powertrain, Transmission, and Air Management Systems Development |
| AVL | Powertrain Analysis, Battery Controls, Engine Development |
| NREL NATIONAL RENEWABLE ENERGY LABORATORY | Drive Cycle Development, and Thermal Management |
| ups | Drive Cycle Development, and Tech Market Acceptance Advisory |
| Cummins | Waste Heat Recovery Integration |
| MERITOR | Axle Integration |
| Continental | Tire Development |
| The Ohio State University | Model Development for Cabin Hoteling Optimization |

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# Remaining Challenges

- **Progress Currently Challenged by Global Epidemic**
- **For all Technology Concepts: Detailed Feasibility for Commercialization**

## Engine

- Turbo-Charger Efficiency
- Thermal Barrier Swing Coatings
- Integration Engine / EAS / WHR

## Powertrain & Vehicle

- Demonstration Vehicle Design and Build
- Controls Tuning
- Integration Battery System in Vehicle
- Trailer Build and Structural Testing
- Demonstration Vehicle Performance Testing

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# Proposed Future Research

## Engine

- **FY20**
- Investigate Alternative Combustion Concept
- Testing
  - 2-Stage Pulsed Turbo-Charger
  - In-cylinder and Manifold Insulation
  - Single Cylinder Long Stroke
- Engine Build
- **FY21**
- Low Back-pressure Aftertreatment System
- Engine & WHR Testing

## Powertrain & Vehicle

- **FY20**
- 2.0 Software Release
- Battery & Mild-Hybrid System Validation
- Mule Vehicle Testing
- Mule 2.0 – Mild Hybrid & Battery Retrofit
- Demonstration Vehicle Design
- Electronics, Controls & Wiring
- **FY21**
- Demonstration Vehicle Assembly
- Demonstration Vehicle Commissioning

*Any proposed future work is subject to change based on funding levels.*

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# Summary

- **Engine**
  - 55% BTE Concept Validation on Dedicated Test-rigs
  - Final Design and Iteration Hardware Simulations
  - Tailored WHR Architecture Defined, Design And Procurement of Components
- **Powertrain**
  - Controls Developed and Testing On-Going
  - Mild Hybrid Powertrain Concept Under Validation
  - 48V Battery System Developed and Ready for Integration
- **Vehicle**
  - Updated Freight Efficiency Roadmap To >120% Improvement
  - Testing on Mule Vehicle for Chassis Concept / Cooling System and eHVAC ongoing
  - Final Vehicle Demonstrator Design on Track

# TECHNICAL BACKUP SLIDES