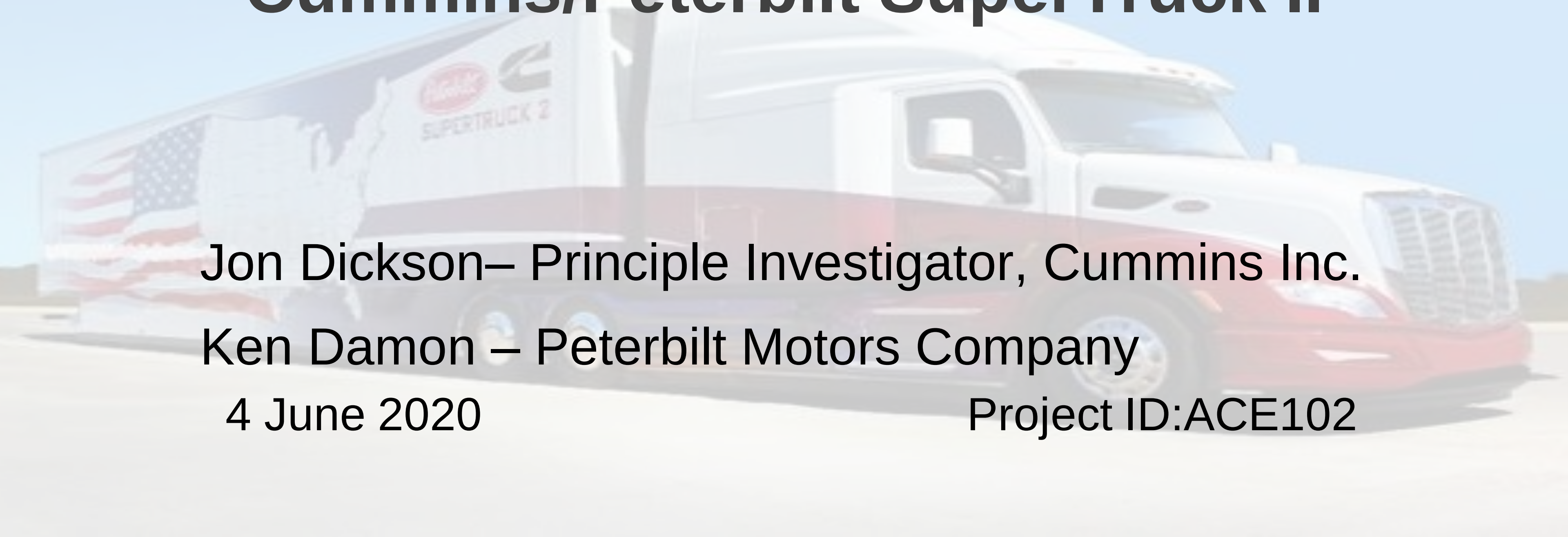
2020 Annual Merit Review

Cummins/Peterbilt SuperTruck II



Jon Dickson– Principle Investigator, Cummins Inc.

Ken Damon – Peterbilt Motors Company

4 June 2020

Project ID:ACE102

Overview

Timeline

- Begin: 10/1/2016
- End: 9/30/2021
- 70% complete (04/20)

Barriers

- Engine Efficiency ≥ 55% BTE
- Freight Efficiency ≥ 100% FTE
- Cost effective solutions

Budget

- Total Project: $40M
- $20M DoE - $20M Partners
- Total Spent: $35.8M
  - $17.9 = Partners
  - $17.9 = DoE

Partners

- Cummins – Powertrain
  - Eaton - Transmission
- Peterbilt - Vehicle
- Bridgestone – Tires
  - Walmart – Customer counsel

Relevance: Objectives

- Demonstrate a ***minimum*** of 55% BTE at a 65 mph cruise, on an engine dynamometer test stand
  - Same engine systems also demonstrated in vehicle, operating on real world drive cycles
- Achieve a ***minimum*** of 125% Freight Ton Efficiency (FTE).
  - FTE = MPG*Tons of Freight
- Track, promote and report on cost effective solutions
  - Prioritize solutions that have ~3 year payback period
  - Utilize customer counsel for understanding payback variables

Relevance: Energy Consumption

- Approximately 20% of U.S. transportation petroleum goes to the production of heavy truck fuel. Proposed improvements would save more than 400 million barrels of oil per year.*
  - Reduce imports and improve energy security
  - Reduce the cost of moving goods
- Heavy Truck GHG emissions account for a CO2 equivalent 420.7 MMT per year (35th edition of the Transportation Energy Data Book).
  - Improved air quality
  - Protect the public health and environment

* https://energy.gov/eere/vehicles/vehicle-technologies-office-moving-america-forward-energy-efficient-vehicles

Milestones by Quarter

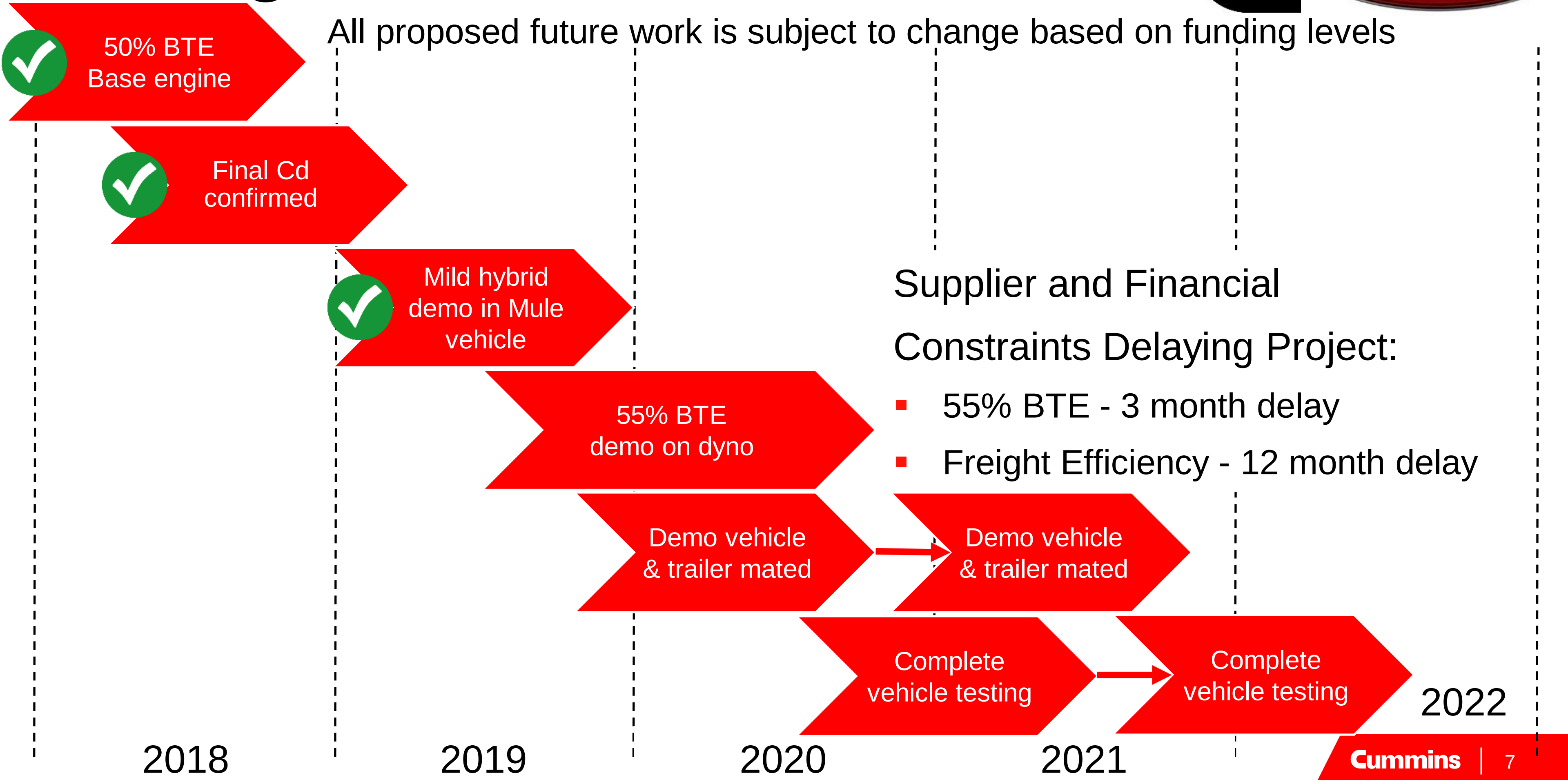
FY 2019	Description
Final Cd via simulation, confirmed ✓	Final adjustment required for produce ability of prototype hardware
Tire RRC confirmed/tested ✓	On-Road/Rig data
ACEM Features selected ✓	Inertia restart, Coasting feature, weather, etc. included in mule testing and validation
HHRR combustion system and Low voltage hybrid ✓	New combustion system for final demonstration and 12/48V system for energy recovery

Milestones by Quarter

FY 2020	Description
Confirmed Vehicle System Path-to-Target ✓	Path to Freight Efficiency objective confirmed with powertrain/hybrid efficiency, aerodynamics/tire, and weight target modelled
Technical Viability Report ✓	Complete commercial viability assessment
55% BTE Demonstration	Dynamometer demonstration of engine system at 55% BTE
Confirmation of ACEM capability	Features selected and integrated into Demo vehicle

Program Level Milestones

All proposed future work is subject to change based on funding levels

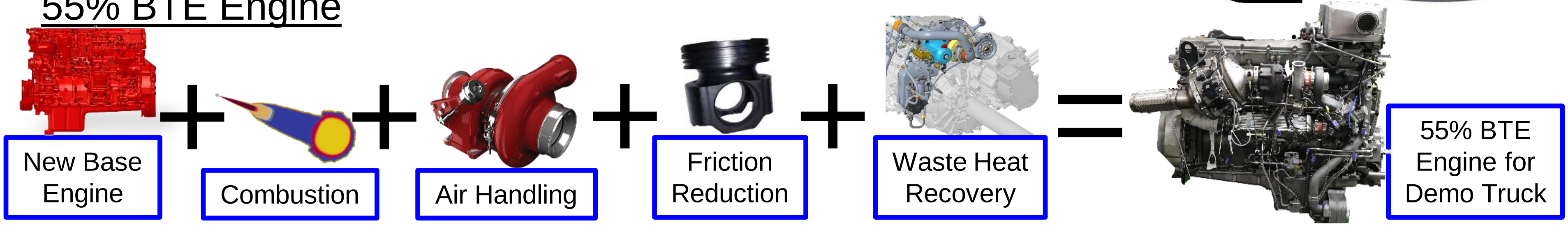


Supplier and Financial Constraints Delaying Project:

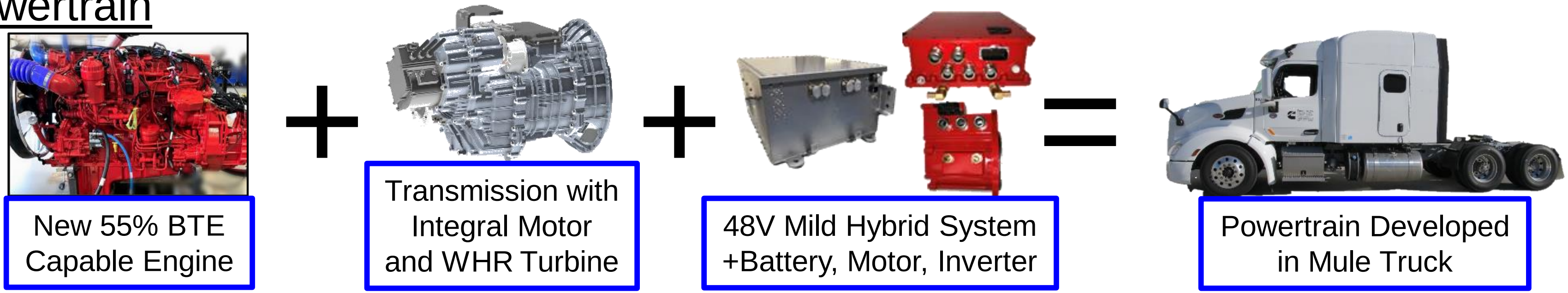
- 55% BTE - 3 month delay
- Freight Efficiency - 12 month delay

Technical Approach

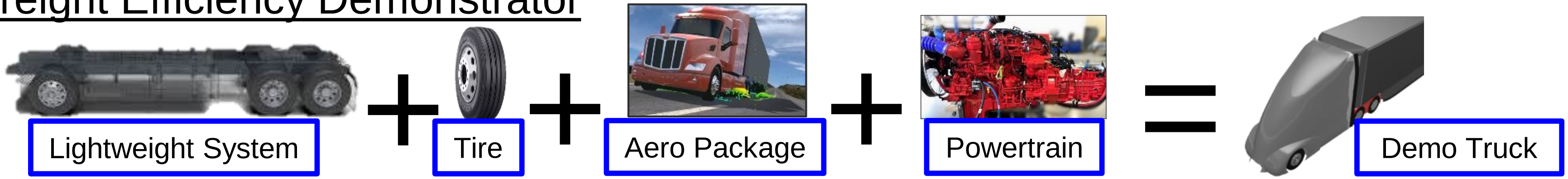
55% BTE Engine



Powertrain



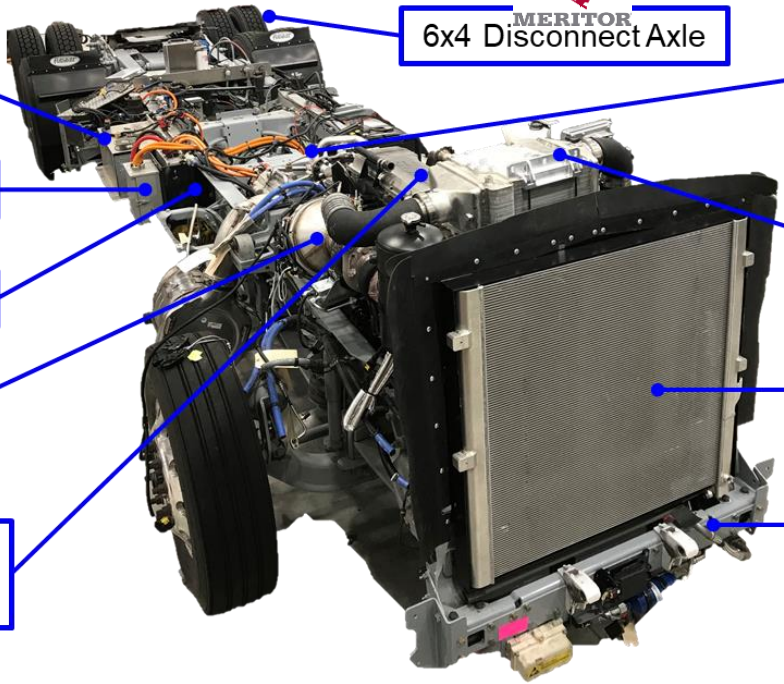
Freight Efficiency Demonstrator



New Hardware: Engine & 55% BTE technology, transmission & 48V hybrid, axle, truck chassis, cab, aero, and tires.

Accomplishment
Powertrain Vehicle System Integrated

Integration of 55% BTE engine into Powertrain Mule Truck

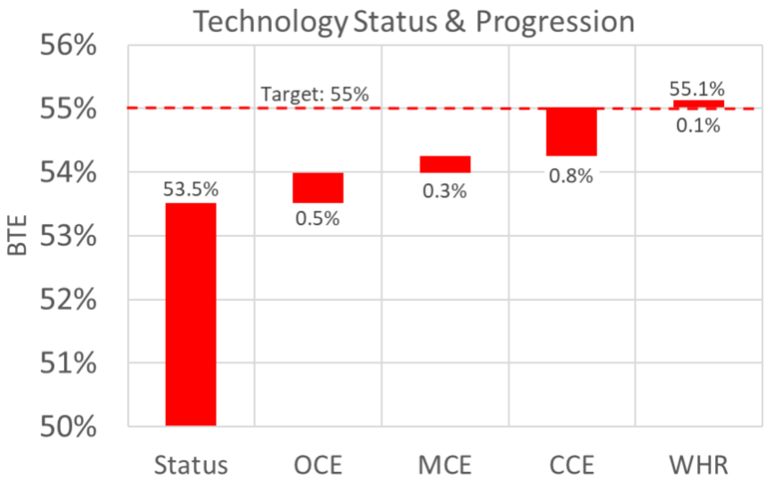


- 48V Battery & Chiller
- 48V Power Distribution
- 48V Power Electronics
- On-engine DOC/DPF
- Dual Loop EGR
  55% BTE Capable Engine
- 6x4 Disconnect Axle
- CERD Transmission w/ Integral M/G and WHR Turbine
- WHR Mixed Charge Cooler
- WHR Condenser with 48V (4) eFans
- 48V WHR Lift Pump

- Hardware integration
- Controls systems integration
- Advanced Cycle Efficiency Manager Development
- Correlation of simulation results

Progress and Remaining Challenges- 55% BTE

- Approach:
  - Build on 50% BTE Success
  - Assess Theoretical Opportunity
- Current Status: 53.5% BTE
- Remaining Key Technologies on Order
  - OCE: Improved efficiency turbocharger
    - Increased turbine efficiency- pulse optimized aero
    - Improved match for LHT system
  - MCE: Reduced engine friction
    - Lube system changes- lower pressure & viscosity
    - Match fit bearings with superfinish crank
  - CCE: Combustion system
    - Piston / cylinder head LHT technology
    - Higher cup flow and improved targeting of Injector
  - WHR: System performance validated
    - Final turbine build
    - Final optimization in process
- 55% BTE Engine System will be applied in Freight Efficiency Demo Vehicle

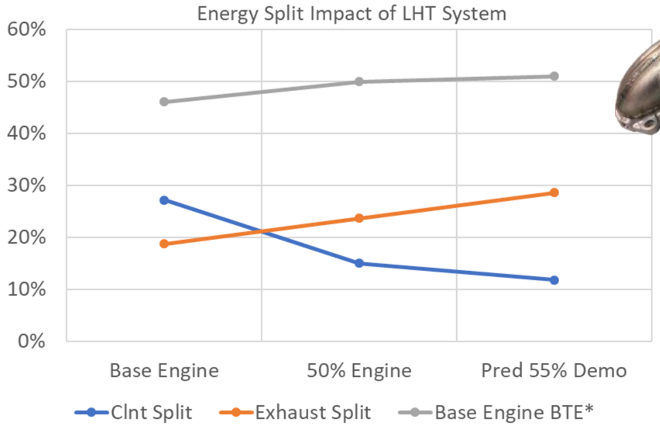


Current Status Technology:

- OCE: Improved turbo efficiency via matching, turbine housing material, low pressure EGR
- MCE: Reduced friction low friction rings, improved liner profile, improved lube system design
- CCE: High heat release rate combustion, high compression ratio, increased combustion temperature
- WHR: Charge air, EGR, Coolant, Exhaust

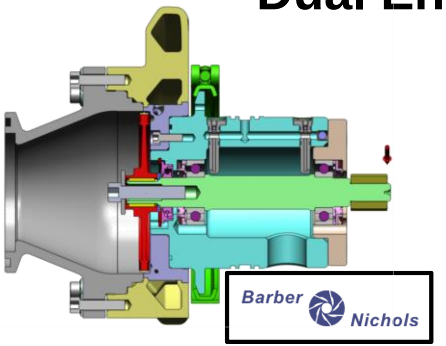
Accomplishments
Low Heat Transfer

- System Objectives:
  - Retain heat where it can best be utilized
    1. Closed cycle efficiency (CCE)
    2. Deliver energy to turbocharger at high Open Cycle Efficiency (OCE)
    3. Provide higher quality exhaust heat to WHR
- Key Technology Elements:
  - Retain heat in piston via material selection and component design
  - Reduce energy loss to coolant in cylinder head
    - Head material and limit interactions with coolant
    - Insulate bottom of head fire deck
  - Reduce loss of exhaust energy
    - Dual wall exhaust manifold
    - Turbine case material selection and insulation
  - Oil energy management piston cooling nozzle control
    - Reduce heat loss from combustion chamber
- Accomplishment:
  - Generated BTE gains & exhaust energy for WHR



*Base engine BTE, without WHR

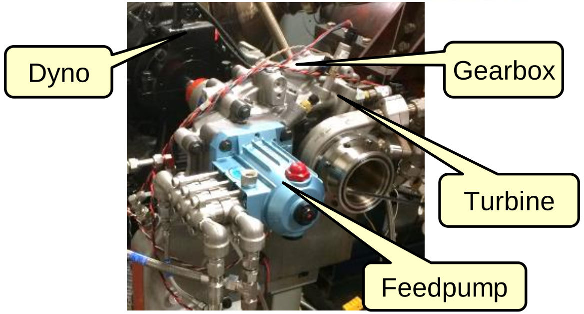
Accomplishments
Dual Entry Turbine Design and Performance



Turbine Design Phase

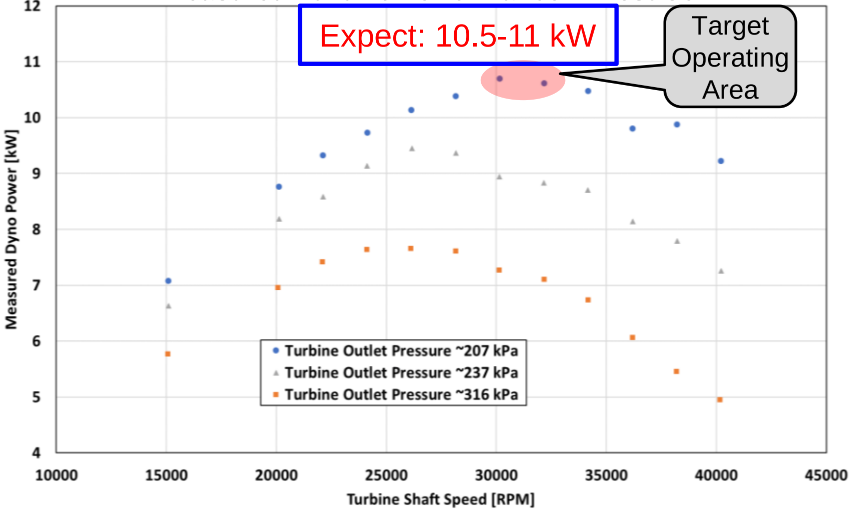

Additive Manufacturing


Fully Assembled



Testing the Gearbox and Turbine

Measured Turbine Performance in Test Cell

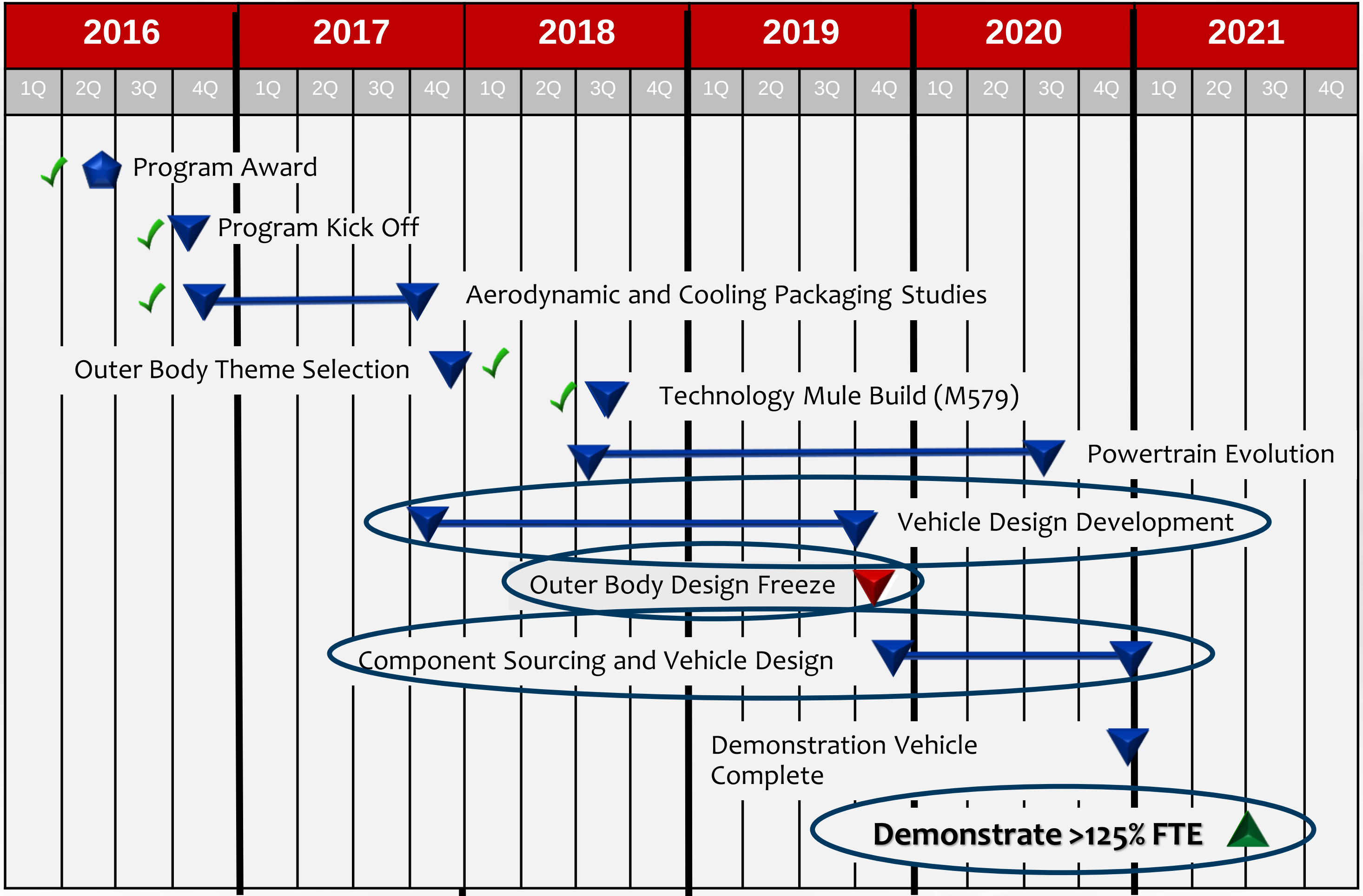


- Dual-entry turbine testing performed
  - Provides maximum benefit from both high and low grade heat sources
- Turbine performed as expected to meet 55% BTE objective
  - Performance tested over range of inlet / outlet pressures and speeds
  - Completed functional checks on the turbine, gearbox and feed pump

Ken Damon

Principle Engineer

Schedule


2016
2017
2018
2019
2020
2021
1Q 2Q 3Q 4Q
Program Award
Program Kick Off
Aerodynamic and Cooling Packaging Studies
Outer Body Theme Selection
Technology Mule Build (M579)
Powertrain Evolution
Vehicle Design Development
Outer Body Design Freeze
Component Sourcing and Vehicle Design
Demonstration Vehicle Complete
Demonstrate >125% FTE

Technical Approach: Path to Target

Engine

Aerodynamics

Transmission/Axle

Downspeeding

Lightweighting

Route Management

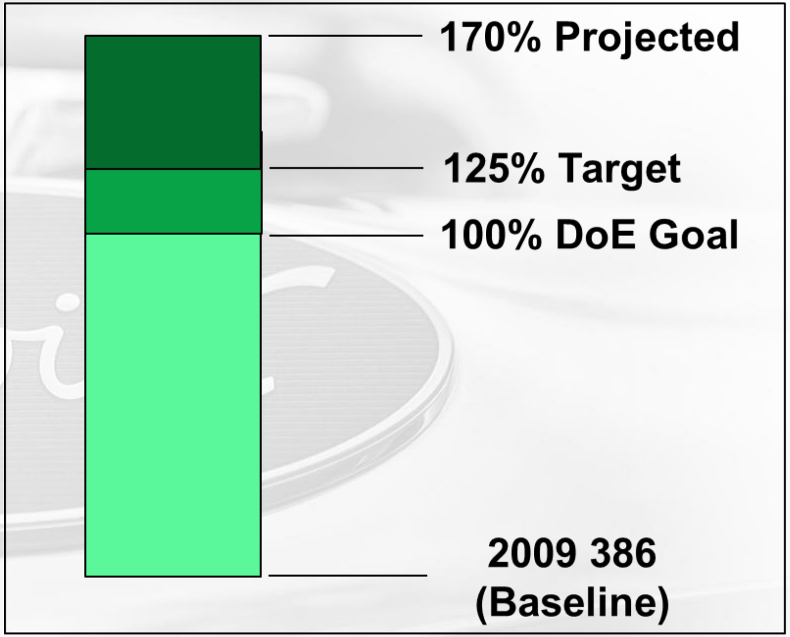
Rolling Resistance

Mild Hybrid/Solar

Peterbilt

Technical Approach: Path to Target

- 55% Engine Efficiency
  - On Target ✓
- Goals vs. 2009 Baseline
  - Goal: 56% Aerodynamic Drag Reduction
  - 63% Achieved ✓ +
  - Goal: 3800lb Weight Reduction
  - 4700lb Achieved ✓ +
  - Goal: 30% Reduced Rolling Resistance
  - 33% Achieved ✓ +



Freight-Ton Improvement

Technical Approach: Applied Technologies

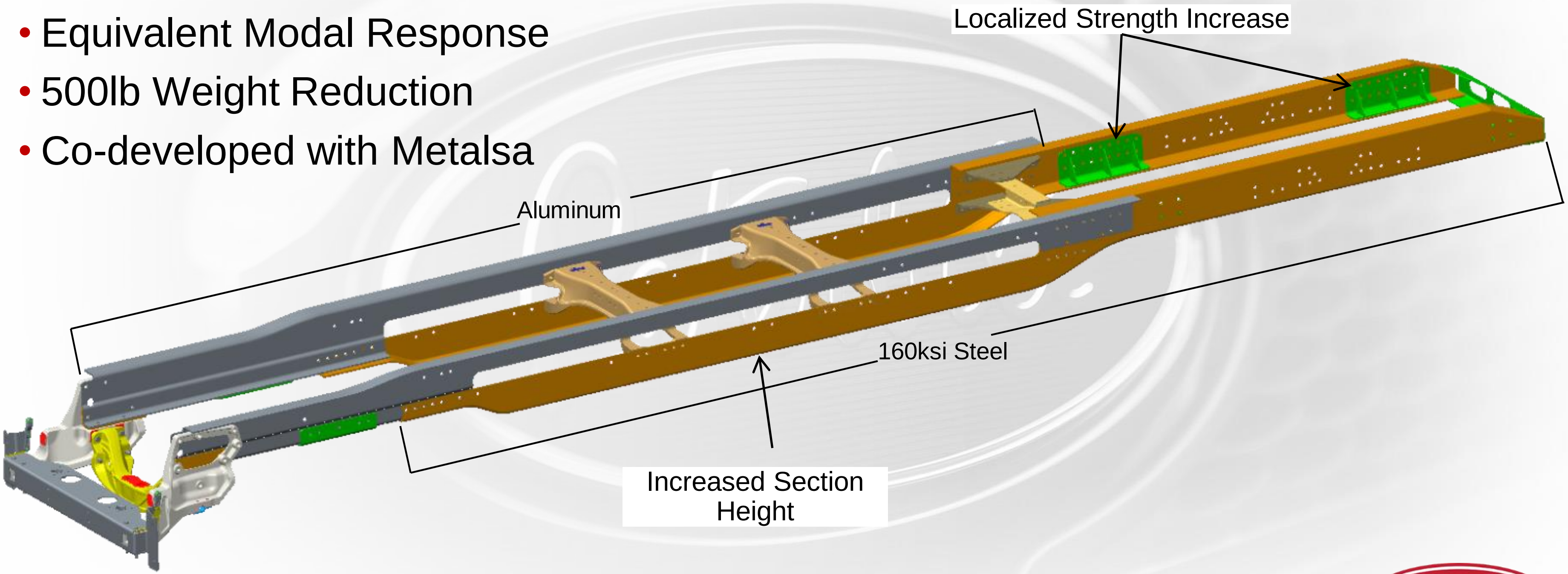
- Active Extenders
- Aerodynamic Body
- Forward-Looking Yaw Sensor
- 6x4/6x2 Disconnect Tandems
- Cameras/Displays
- MMC Brake Drums
- 48v ePower Steer
- Chassis Height Control

- Lighweight Chassis
- Low Crr Tires
- High Efficiency Engine/Transmission
- 24.5” Aluminum Wheels
- 48v eHVAC
- Advanced Cycle Efficiency Manager
- Mild Hybrid Driveline

Technical Progress: Advanced Chassis

Lightweight Chassis

- Hybrid Steel/Aluminum
- Equivalent Modal Response
- 500lb Weight Reduction
- Co-developed with Metalsa



Technical Progress: Chassis Systems

Forward Chassis Section

- Front Deep Drop Axle/Air Suspension

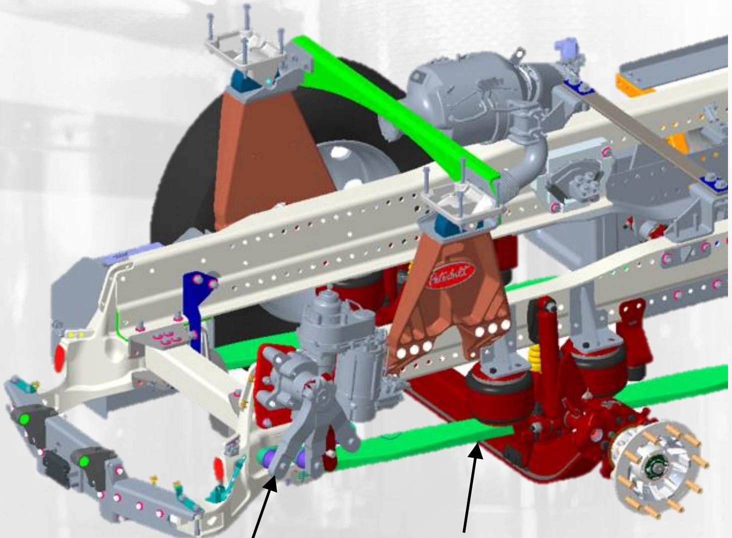
  HENDRICKSON

- Enables Chassis Height Control
  - Low Speed (<30mph); High Ground Clearance
  - High Speed (>35mph); Low Ground Clearance
  - 4” High to Low Delta

- Controls for Chassis Height System

  IMI NORGREN

- 48v ePower Steer ZF
  - Reduced Engine Parasitics
  - Control During Engine-off Coast



Drop Axle and Air Suspension

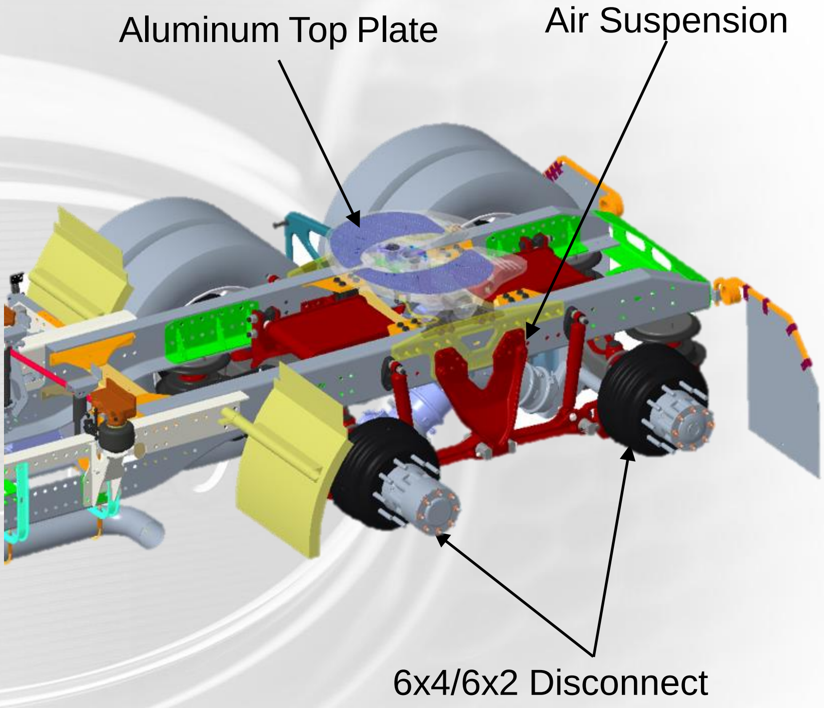
48v ePower Steer

Peterbilt

Technical Progress: Chassis Systems

Aft Chassis Section

- Air Suspension HENDRICKSON
  - Parallel Link
  - Enables Chassis Leveling
    - 4” High to Low Clearance
- 6x4/6x2 Disconnect Axles MERITOR
  - 6x4 for Low Speed Traction
  - 6x2 for Cruise (Disengage Forward Axle)
- MMC Brake Drums ACCURIDE
- Aluminum Top Plate Fifth Wheel SAF Holland



Technical Progress: Active Aerodynamics

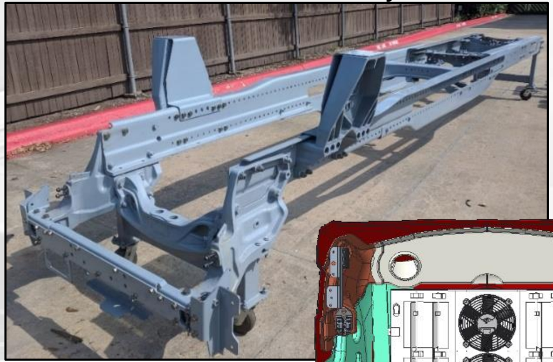
- Dynamic Sleeper Extender
  - Pneumatically Controlled Surface
  - Input from Forward-looking Yaw Sensor
  - Yaw Mitigation (Trailer Gap)

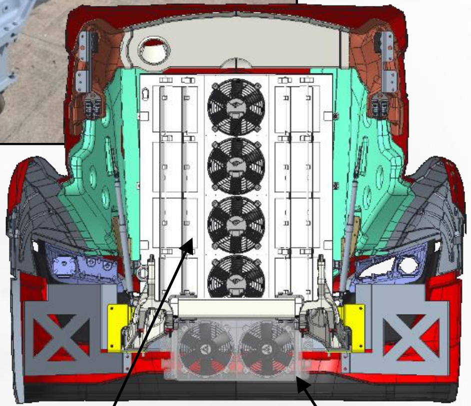
- Accomplishments
  - Extender Complete
  - Control System Demonstrated
    - Refinements On-going
  - Yaw Sensor
    - Concept in Work
    - Prime Path: LiDAR

Demonstrator Technical Accomplishments/Collaboration

- Parts and Tasks Complete
  - Outer Body Design Freeze
  - Lightweight Wheels ARCONIC Innovation, engineered.
  - Tire Development, Samples BRIDGESTONE
  - Wiper System Valeo
  - Interior 3D CAD POINT INNOVATION Product Development
- Builds Initiated:
  - Roof and Cab Body in White RMC A NanoXplore COMPANY MAGNA
  - Cooling Module w/ Cooling Fans MAHLE
  - Windshield and Glass
  - Frame Rails, Axles, Suspension HENDRICKSON Metalsa
  - 48v eHVAC Bergstrom Climate Control Systems

Chassis Assembly





WHR Condenser & Fans

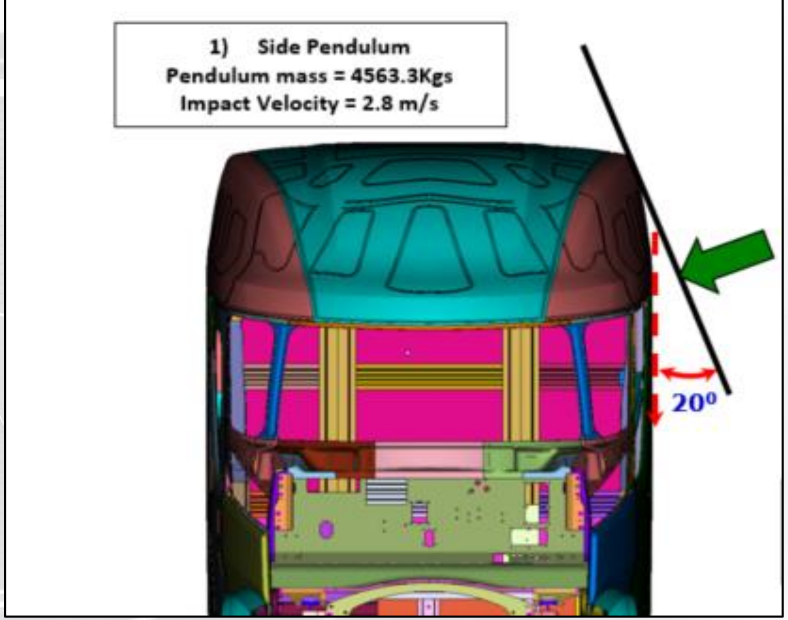
Radiator & Fans

Peterbilt

Validation: Safety Analysis

- A-Pillar Impact
- Door Check Overload
- Door Sag
- Durability – Extreme Loads
- Floor Stiffness
- Global Static Stiffness
- Jackknife Impact
- Roof Crush/Rollover

Roof Crush/Rollover (SAE J2522)

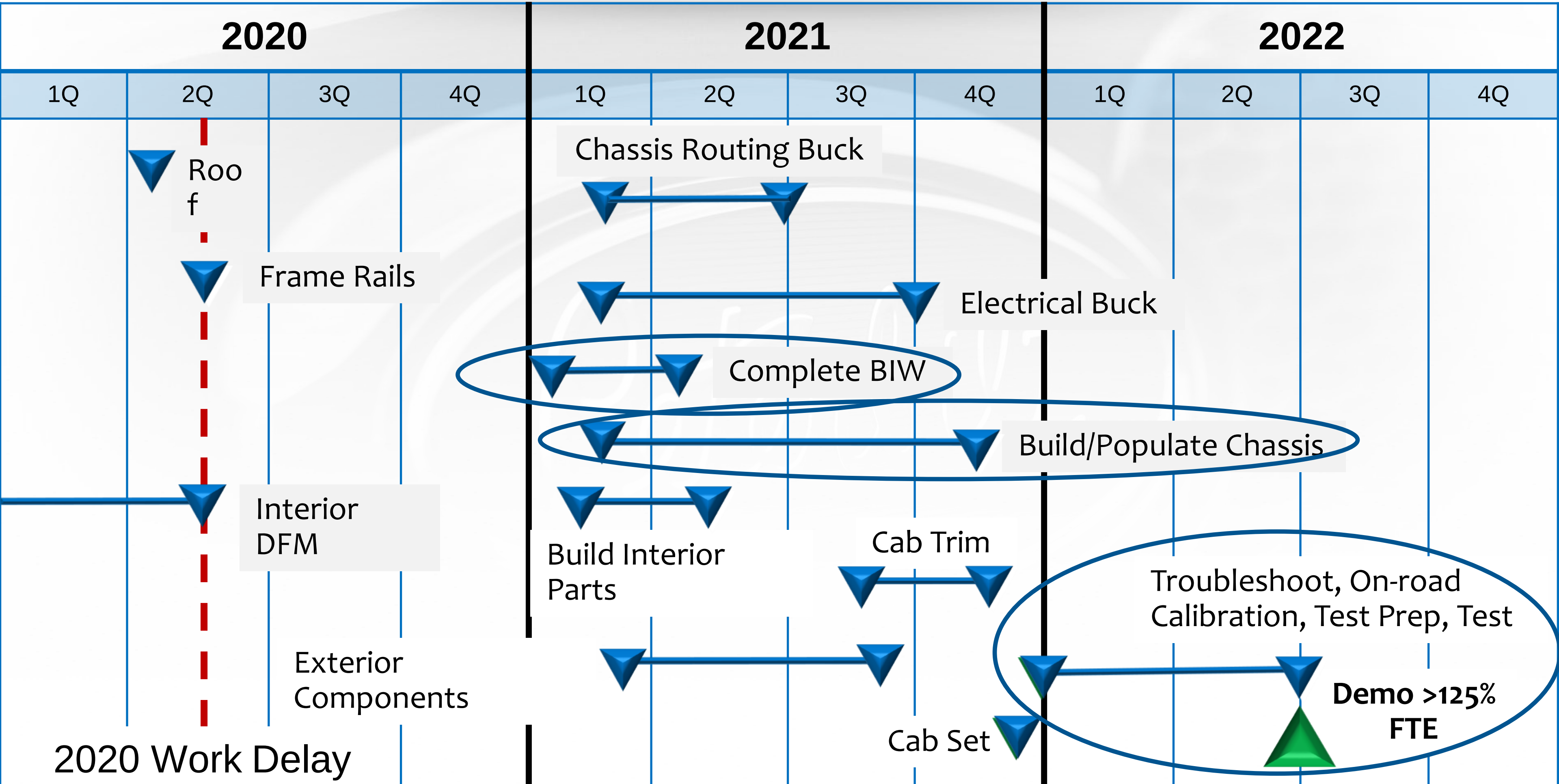


Validation: Cab Electrical

- Simulate In-Use Truck Environment
  – 1Q through 2Q20
- Test Input/Output and Functionality
  – Architecture
  – Displays
  – Control Modules
- Harvest Parts for Demo Build

Cab Electrical Buck

Revised Program Schedule



Proposed Future Research

- 55% BTE Demo Work
  - Procure and test final pistons and WHR turbine
  - Complete final system integration and 55% BTE demonstration
- Deliver Cost Effective Solutions
  - Refine cost/payback model optimization
  - Assess manufacturing alternatives for low heat transfer components
- Demonstrate >125% FTE improvement
  - Powertrain Mule truck evolution
    - Final calibration of 48V system and Advanced Cycle Efficiency Manager
  - Refine and build Demonstrator truck and trailer
    - Final procurement of cab system
    - Build demonstrator truck and trailer
    - Complete on-road testing and confirm Freight Efficiency Objective

All proposed future work is subject to change based on funding levels

Program Summary

- Powertrain
  - Powertrain development in mule vehicle is on plan
  - Engine development on target to meet 55% BTE
- Vehicle
  - Chassis and cab design complete
  - Aerodynamic system is ahead of target
  - Weight reduction is exceeding target and chassis has been prototyped
  - Bridgestone has completed build and verified exceeding Crr reduction target
  - Sourcing selection complete with critical parts underway
- Cummins and Peterbilt will deliver a minimum 125% FTE and 55% BTE!

THANK YOU!

QUESTIONS