PACCAR SuperTruck II

2019 Annual Merit Review

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

Carl Hergart, Ph.D. – Principal Investigator

Mark Brown, P.E., MBA – Kenworth Truck Company

PACCAR Inc

June 13, 2019 Project ID # ACS124

PACCAR SuperTruck II

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 NATIONAL RENEWABLE ENERGY LABORATORY

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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

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Milestones

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

BP 3 Milestone	Type	Description
Engine Components Fabrication Complete	Technical	Final Internal And External Engine Components Are Fabricated
Powertrain Components Fabrication Complete	Technical	Final Electrified Powertrain Components Are Fabricated
SuperTruck II Tractor Component Designs Frozen	Technical	Design Is Frozen For Components Of The SuperTruck II Tractor
SuperTruck II Tractor Design Is Complete	Go/No-go	All Engine And Powertrain Components Have Been Fabricated. SuperTruck II Tractor Design Is Complete

Program Outline

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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

- Engine & Powertrain Testing
- WHR Integration And Initial Testing
- Controls Development
- Vehicle Mule Testing

Year 4 (2021)

Powertrain Testing & Supertruck Build

- Engine And Powertrain Efficiency Demo
- Engine And Powertrain 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

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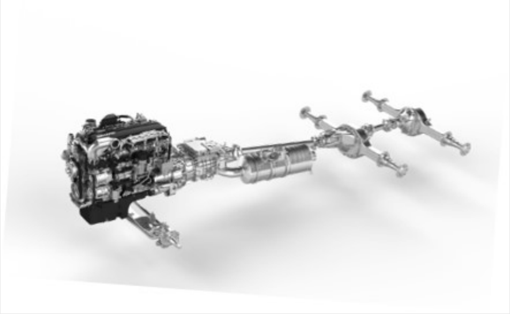
Technical Approach

Engine

Combustion Strategies, Turbomachinery Efficiency, WHR, Accessory Electrification

Powertrain



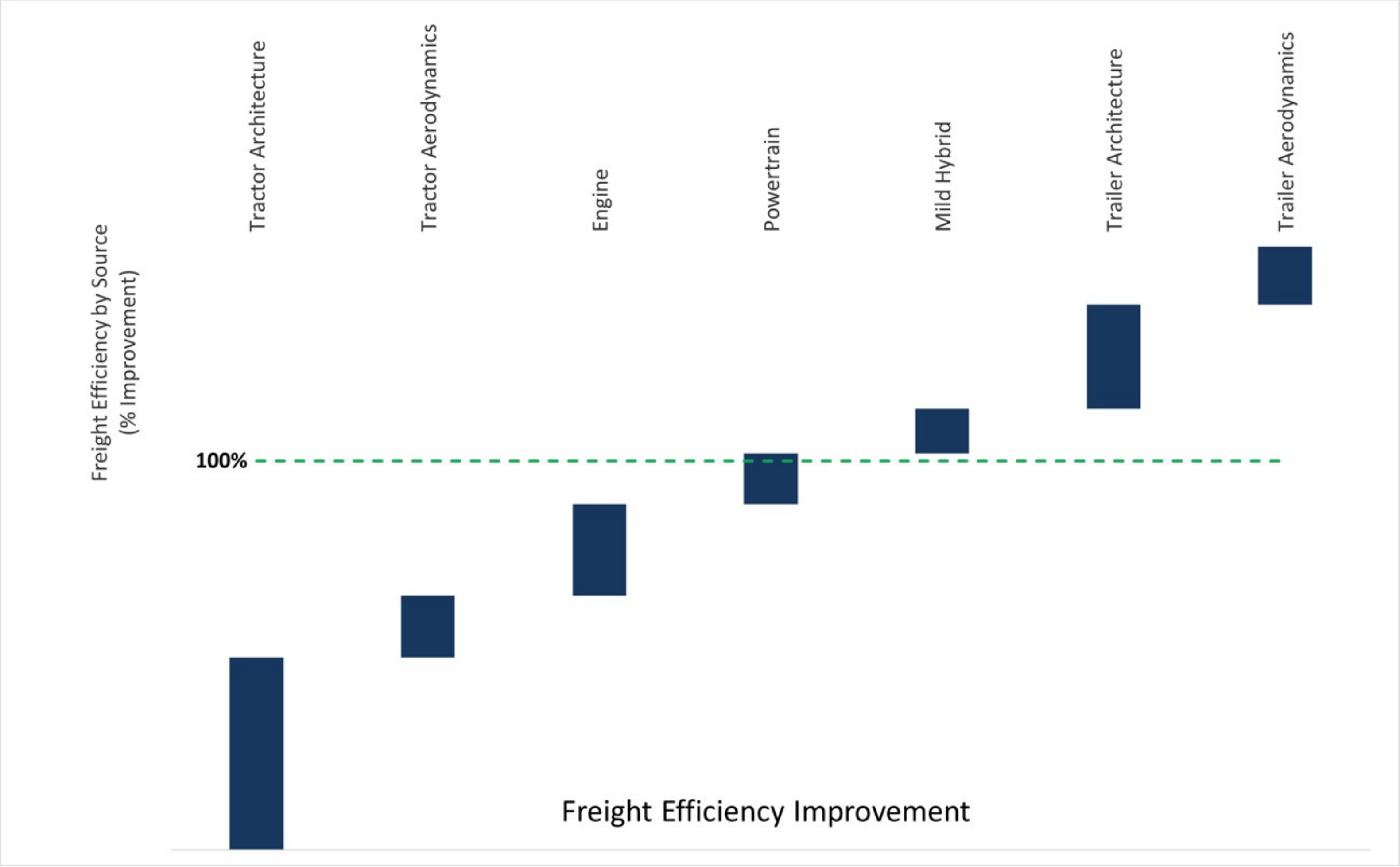
Electrification, Energy Management, Predictive Features, Route Optimization, High Efficiency Transmission And Axles

Vehicle

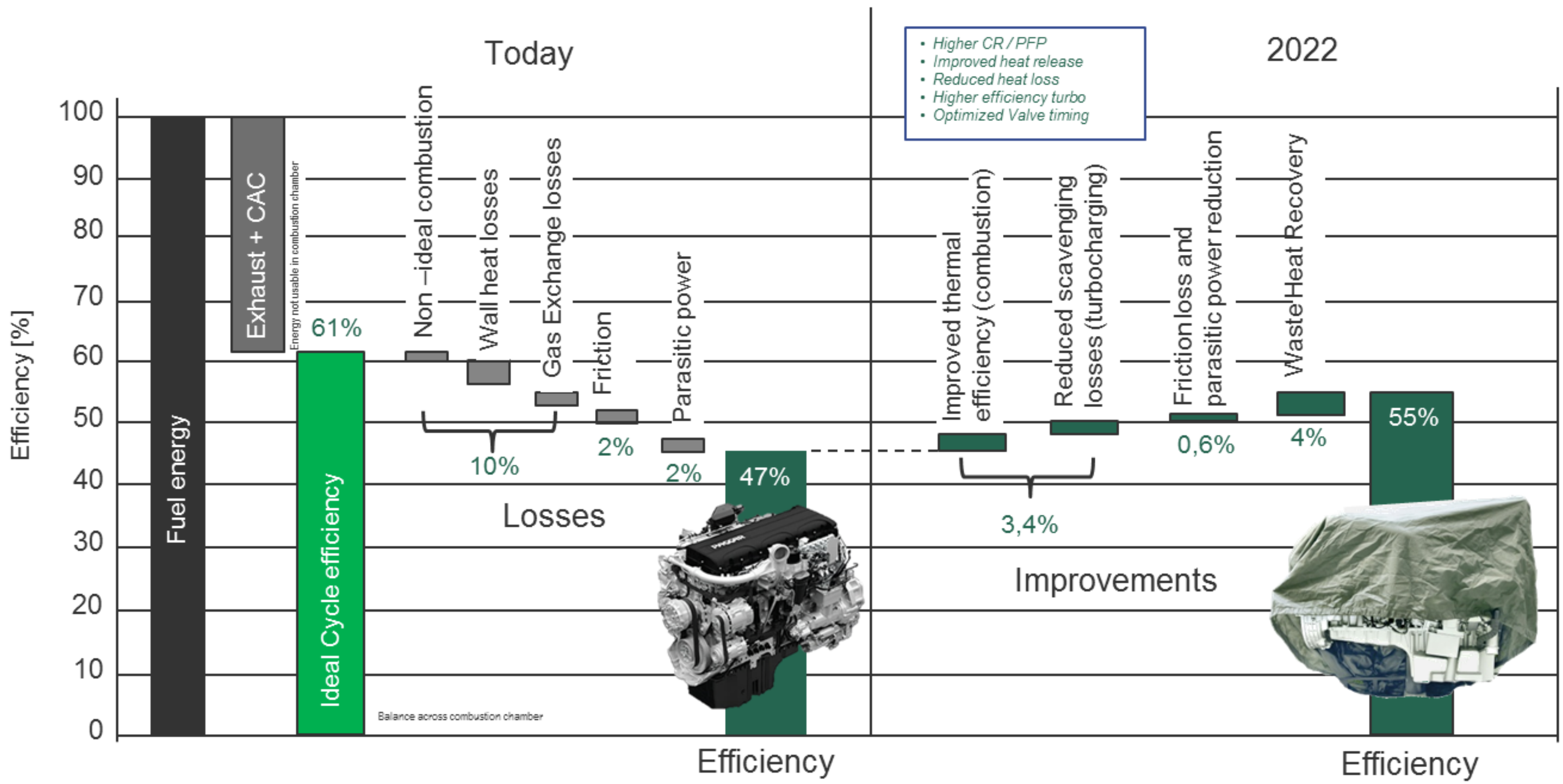
Aerodynamics, Weight Reduction, Anti-idle Climate Control, Modular Chassis Design, Tire Rolling Resistance

Approach: Freight Efficiency

- Freight Efficiency Projection Evolving
- Tracking To Exceed Goal Of 100% Improvement



Approach: Engine Efficiency



ENGINE SECTION

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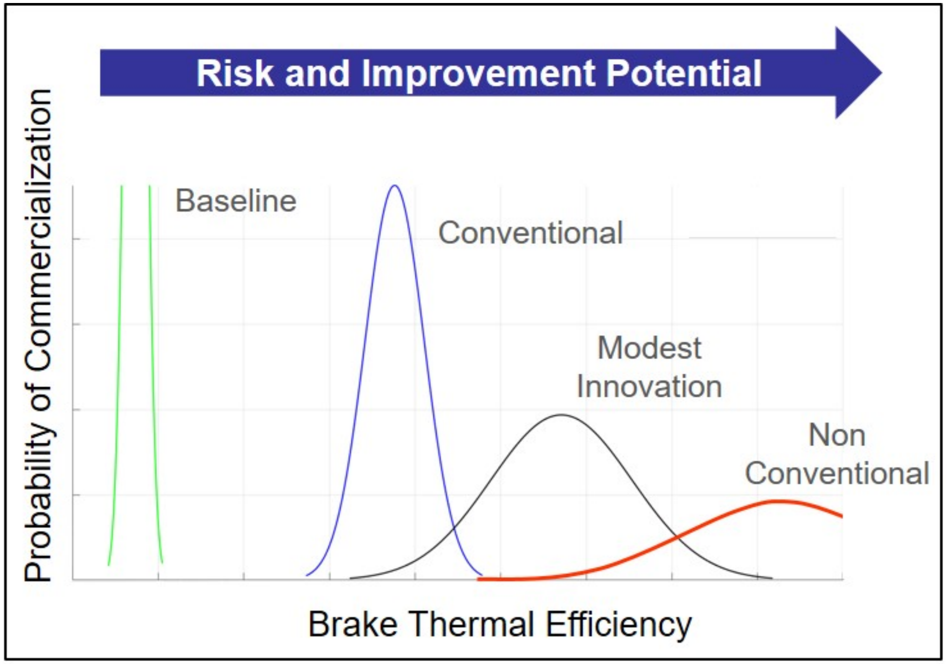
Concept Development

- 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)

Optimization Performed

- Screening Design Of Experiments: **Assessment Of Technology Impact On BTE**

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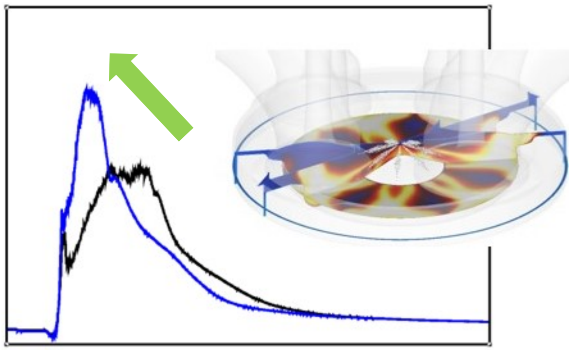
Concept Definition

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



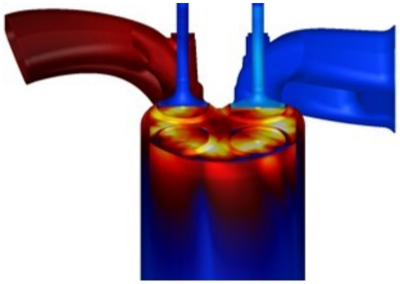
- ✓ Fast Combustion
  - High Flow Injector
  - Bowl Profile And Spray Targeting
- ✓ Compression Ratio
  - Bowl And Stroke
  - Peak Cylinder Pressure And Emissions
- ✓ System Optimization
  - EGR, Swirl, AFR, Charge Temp.
  - Consider Impact on WHR

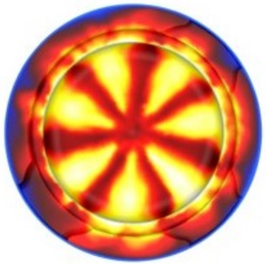
Air Management

- ✓ 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



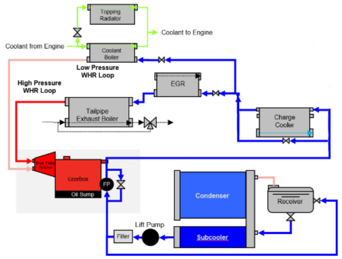


- ✓ Reduced Cooling
  - Coolant And Oil Flow Control
  - Full 3-D CHT Modeling
  - New Design And Material
- ✓ Thermal Barrier Coatings
  - Ports, Manifolds, Turbine Housing
  - Piston, Head, Valves
  - 1-D / 3-D Model Analysis
  - Testing Samples

Friction / Auxiliaries / Restrictions

- ✓ Back Pressure
- ✓ Auxiliary Losses
- ✓ Low Viscosity Oil
- ✓ Aggressive Friction Reduction
  - PCU, Cranktrain, Valvetrain

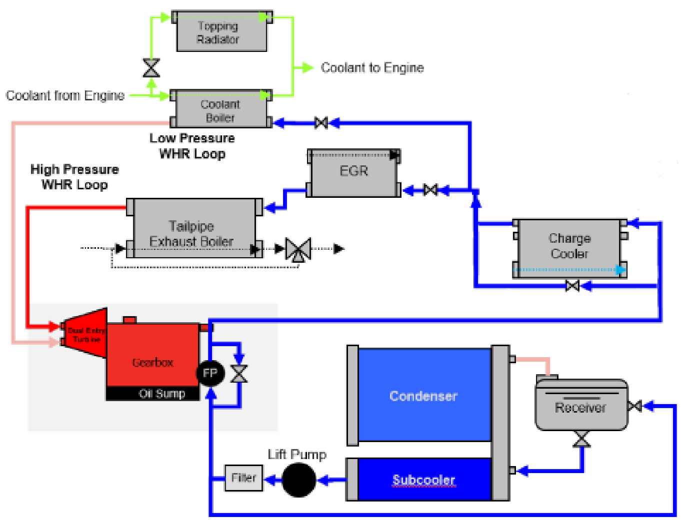
Waste Heat Recovery

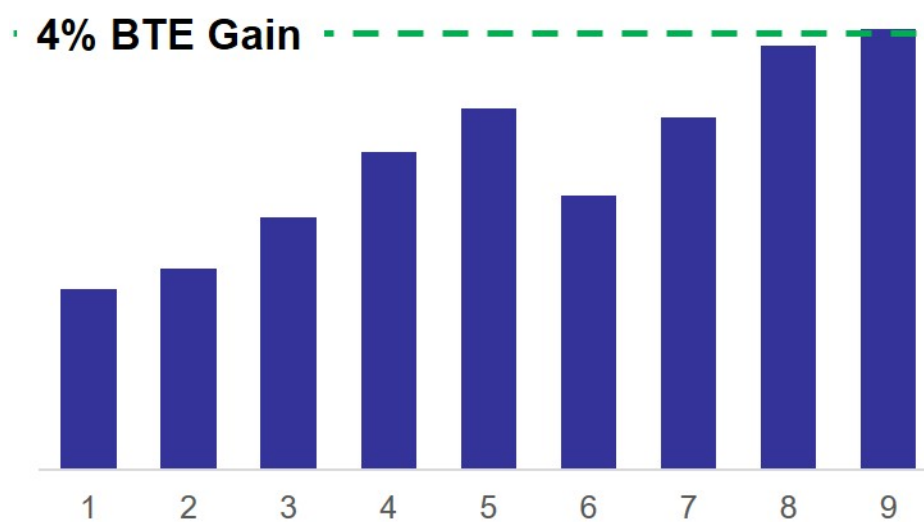


- ✓System Configuration
- ✓Boundary Conditions
- ✓Feasibility Check
- ✓Working with Supplier On Integration

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



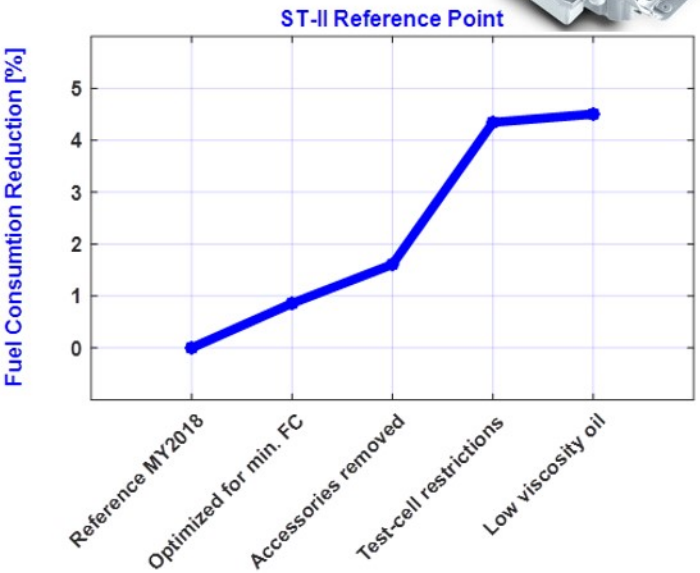


Engine Testing

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



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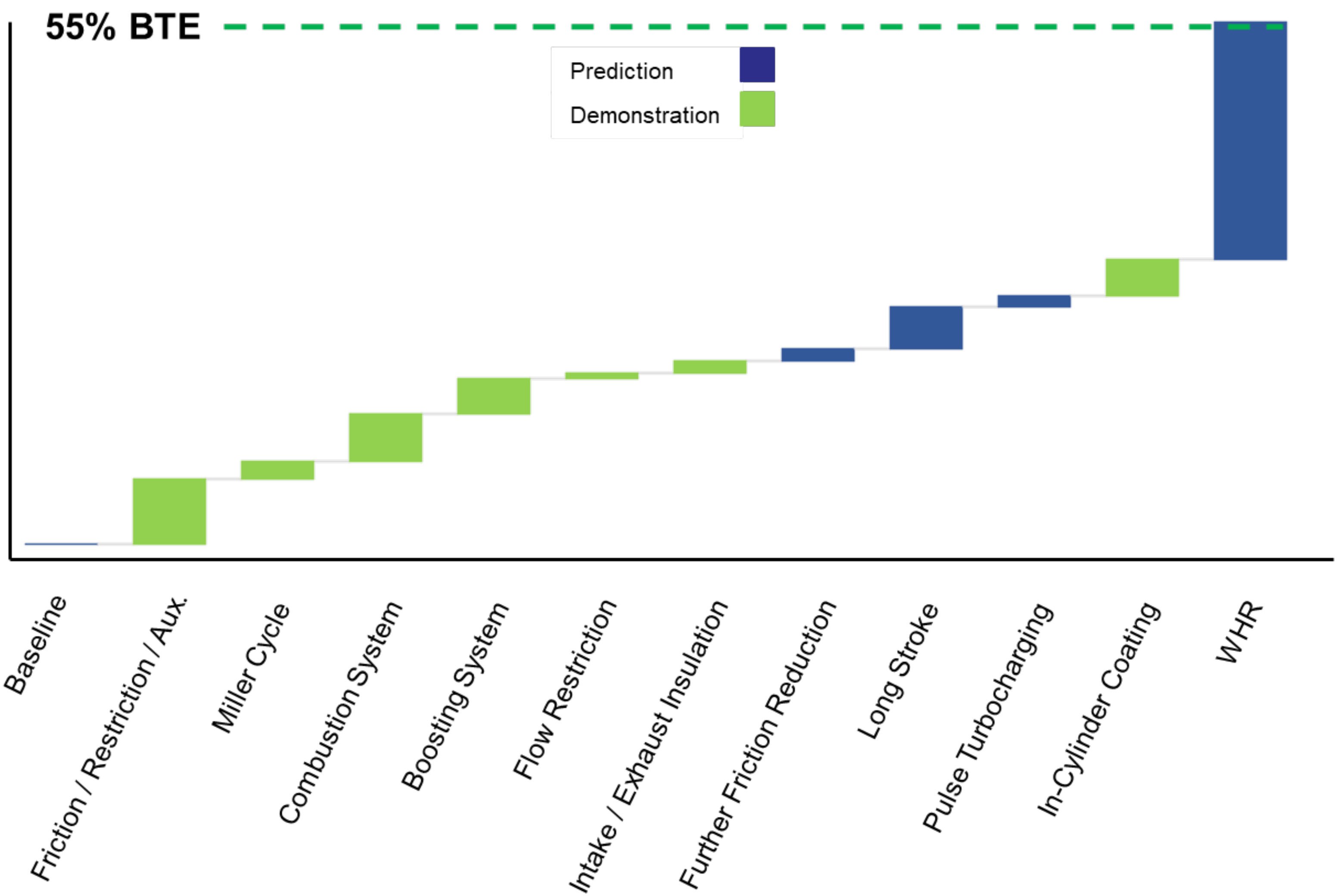
Technology Validation



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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

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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

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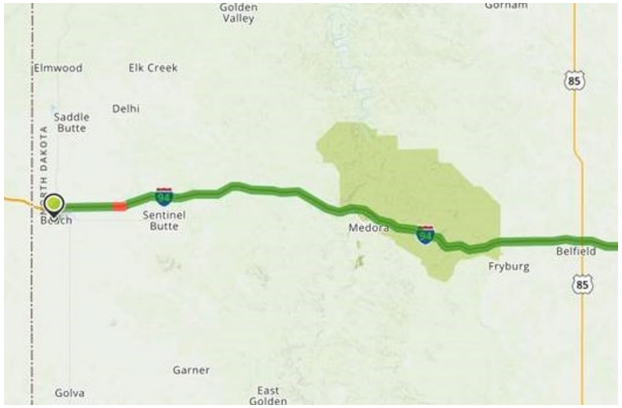
- National Average Drive-Cycle Selected Using Specialized NREL Algorithm

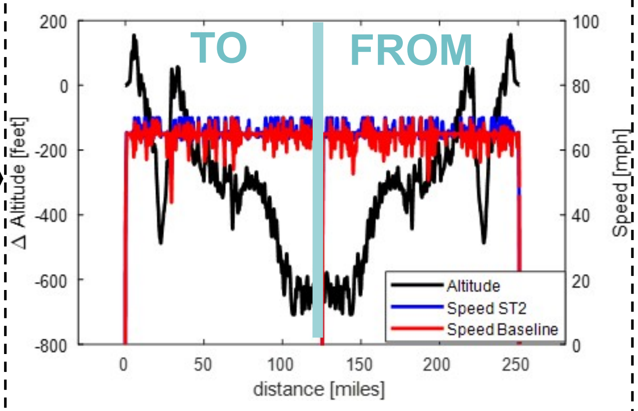
Key metrics

- Gradeability
- Hill length
- Altitude
- Max. Speed
- Hotel Loads

I-94 Beach, ND to New Salem, ND



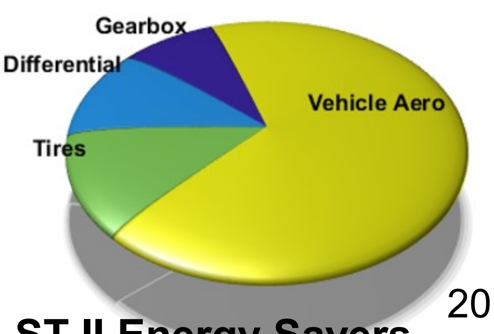
AVL Round Trip Simulations



- Completed Optimizations

Rear-Axle Ratio | Wheels & Tires | Hybrid Configuration | Battery Requirements

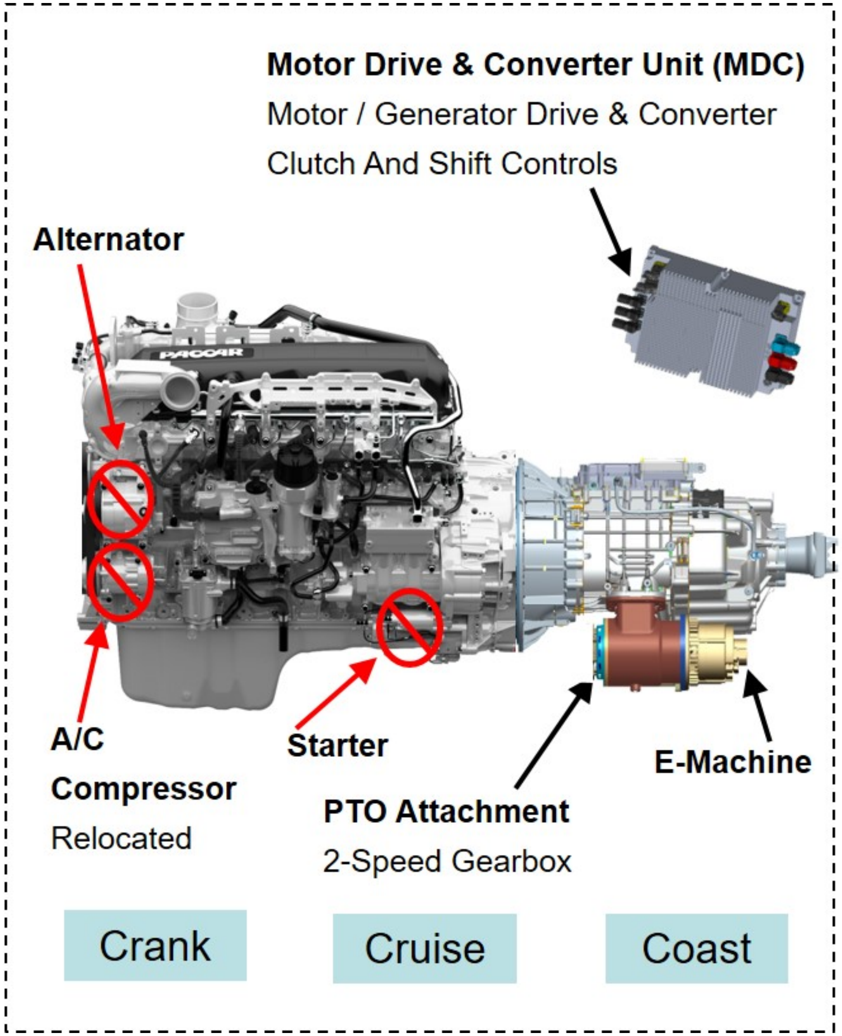
- ST-II Powertrain Performance
  - Validated MY2009 Baseline:
    Kenworth T660 GVW 65k lbs. FE 84.5 Ton-mi/Gal
  - ST-II Powertrain Simulations Indicate:
    <u>System Requires 47.7% Less Energy</u>



ST-II Energy Savers

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



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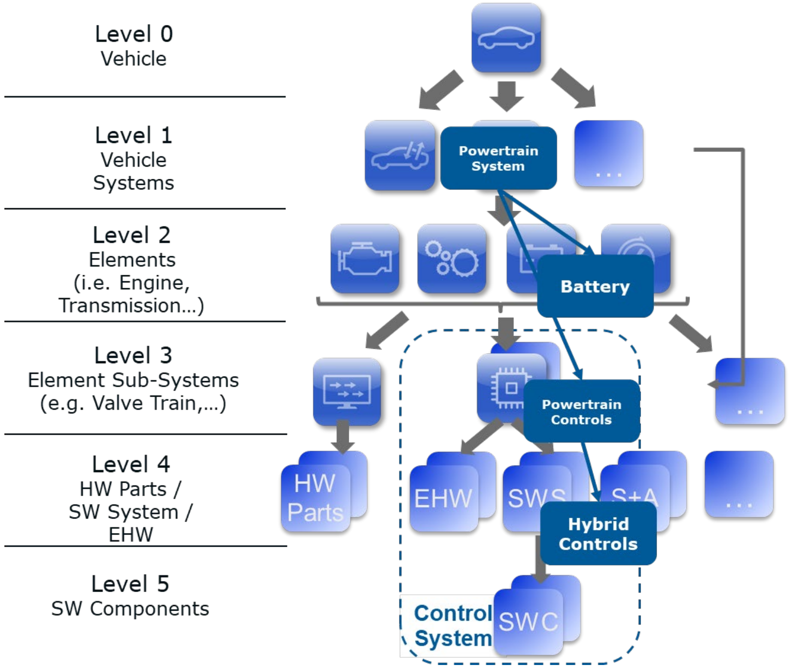
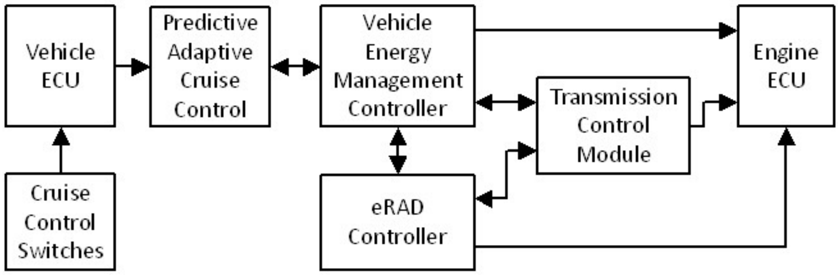
Controls Development

- **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



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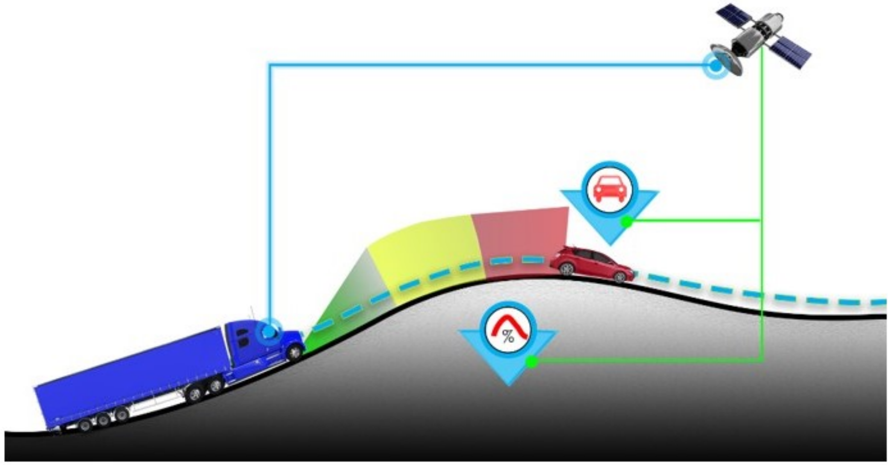
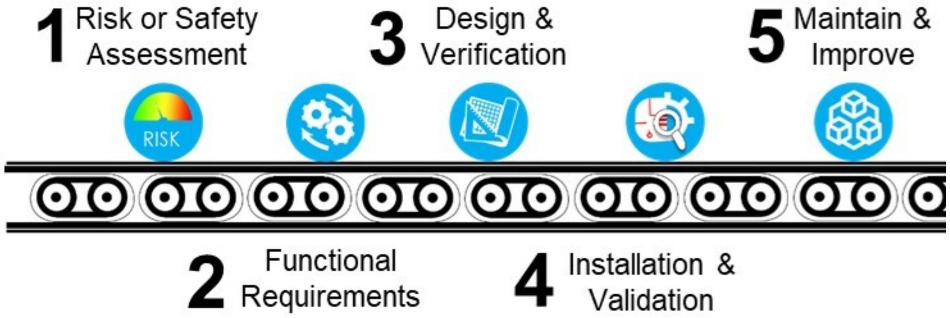
Key Control Concepts

- **Integration Of PCC And ADAS**
  - Provide FE Under <u>All</u> 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

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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

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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.

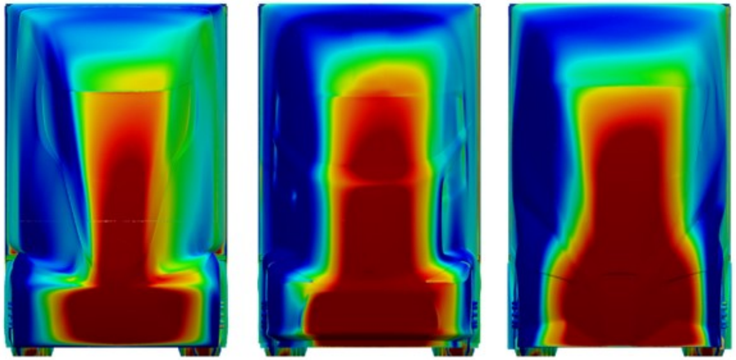
Mark Brown

Kenworth Truck Company

VEHICLE SECTION

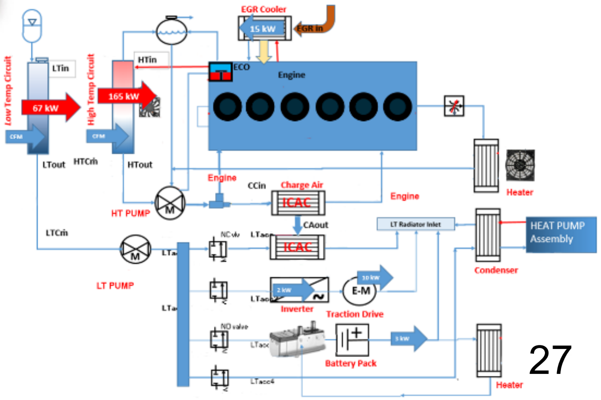
Vehicle Design Strategy

- Aerodynamics
  - Ideal Tractor Shape
  - Trailer Treatment



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

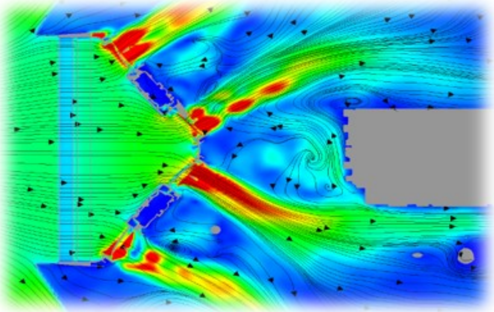
- Customer Needs
  - Voice Of The Customer
  - Driver Package & Interior Amenities
- Energy Management
  - Thermal Treatment
  - Cooling System



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

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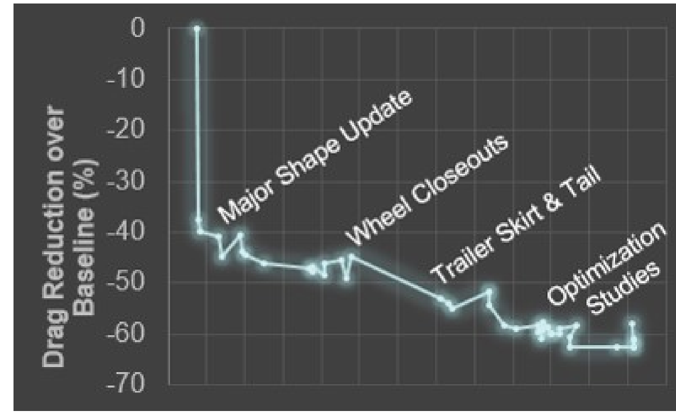
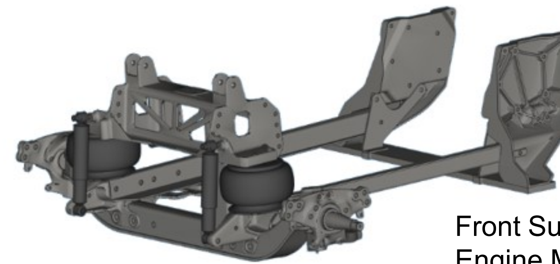
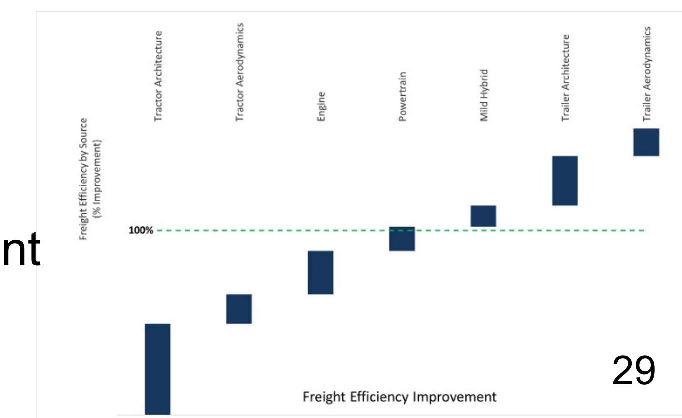
Accomplishments

- 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





Front Suspension
Engine Mounts
Cab Mounts



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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

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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.

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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, Valvetrain and Air Management Systems Development
AVL	Powertrain Analysis, Battery Controls, Engine Development
NREL NATIONAL RENEWABLE ENERGY LABORATORY	Drive Cycle Development Thermal Management
ups	Drive Cycle Development Tech Market Acceptance Advisory
Cummins	Waste Heat Recovery Integration
MERITOR	Axle Integration
Continental	Tire Development

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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

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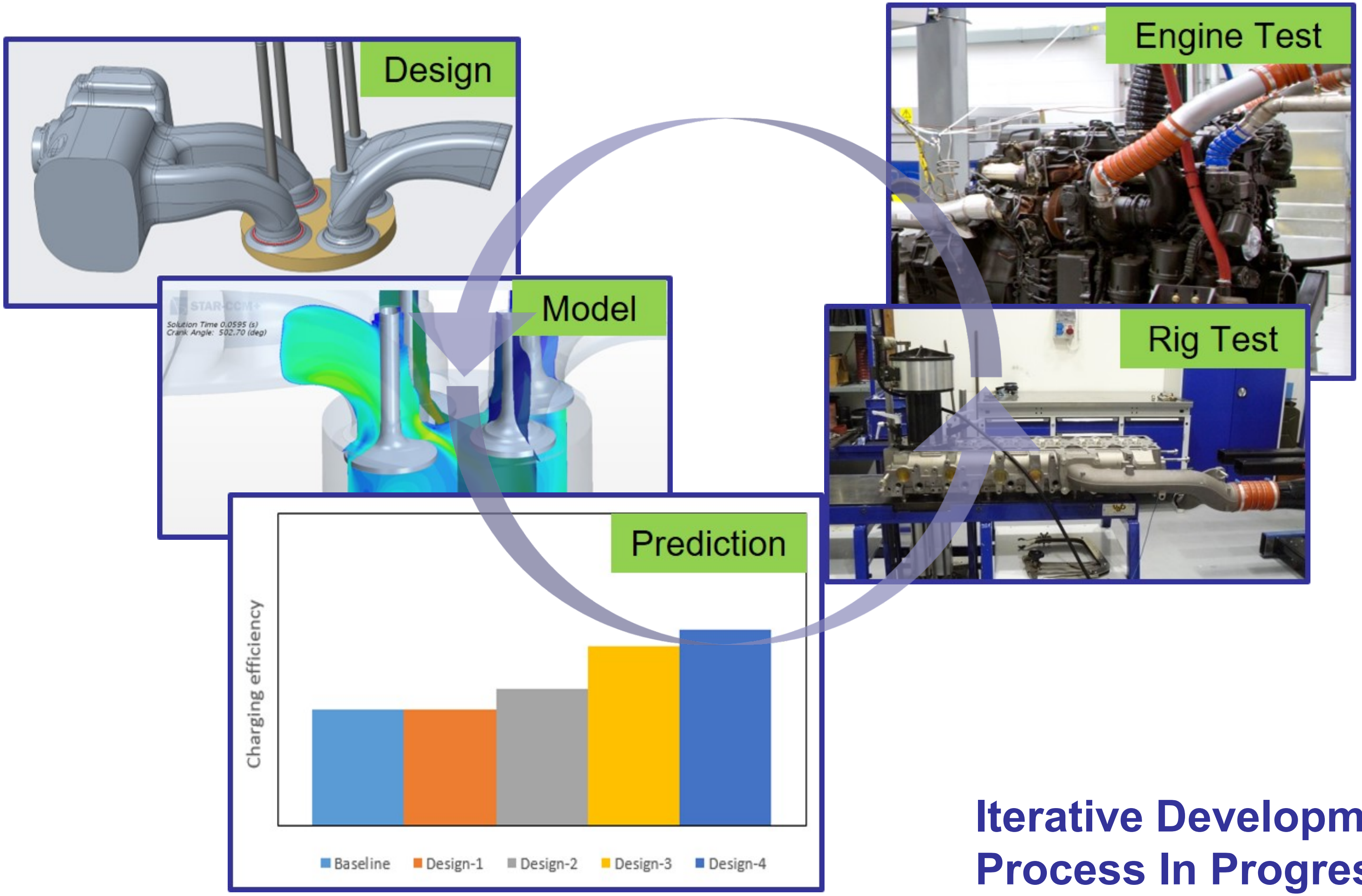
TECHNICAL BACKUP SLIDES

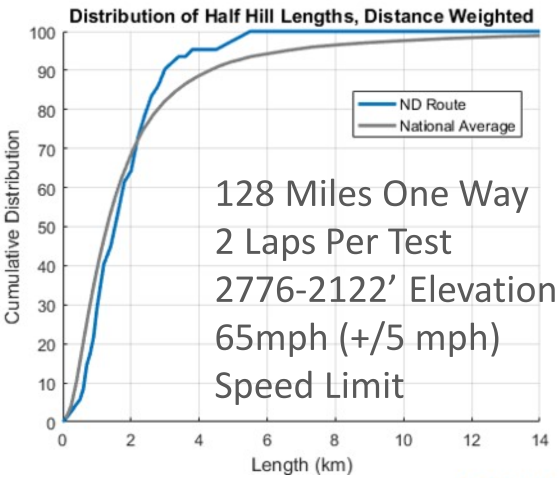
Technology Development

Reduction Of Flow Restriction



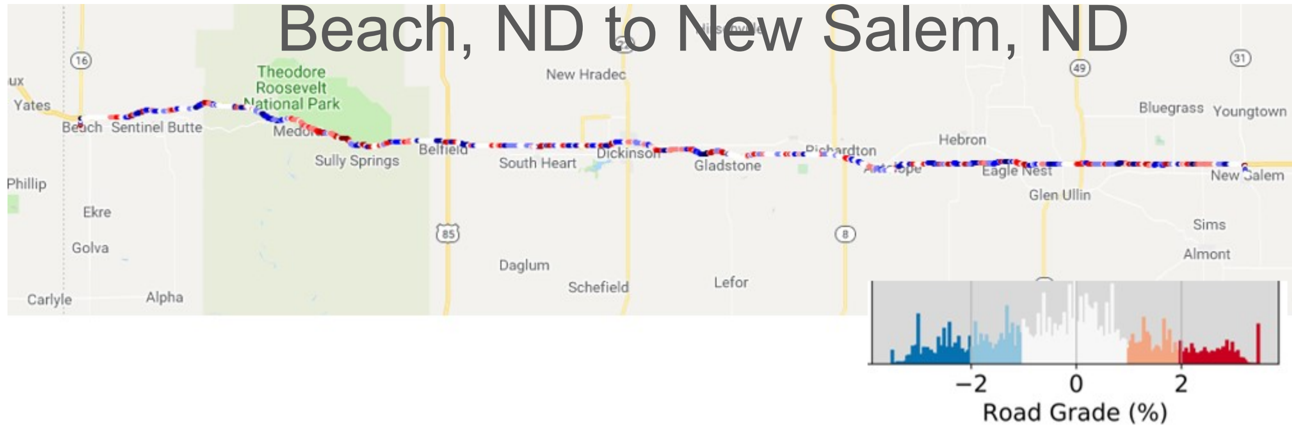
Iterative Development Process In Progress

Drive-Cycle & Cruise Model



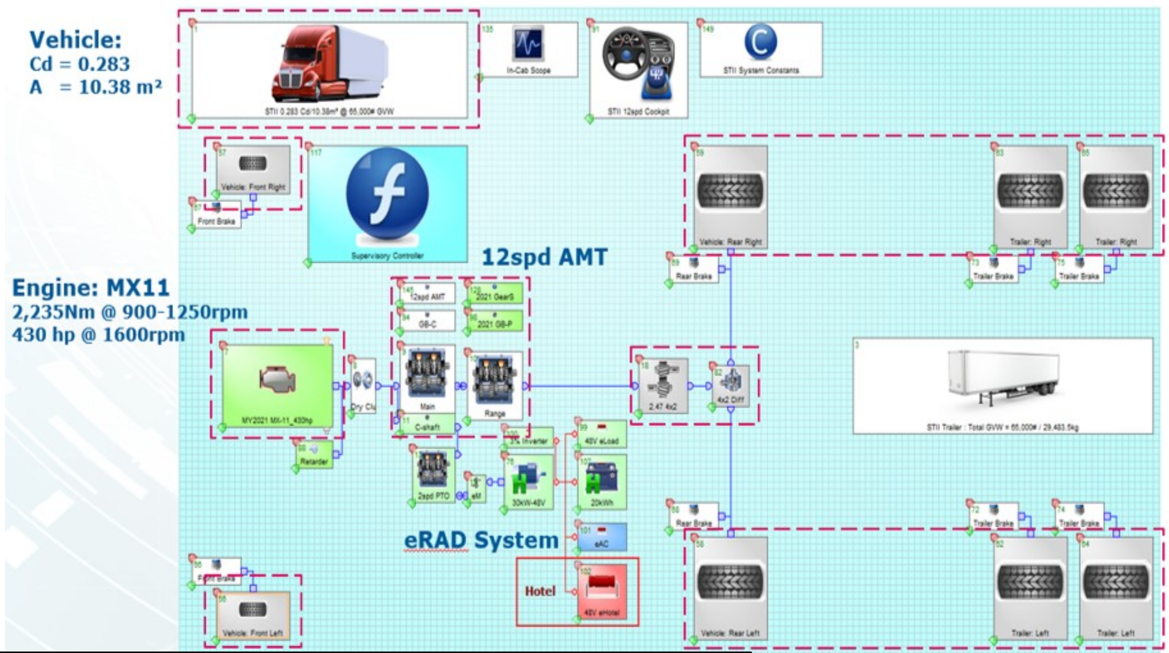
128 Miles One Way
2 Laps Per Test
2776-2122' Elevation
65mph (+/5 mph)
Speed Limit

Beach, ND to New Salem, ND



Vehicle:
Cd = 0.283
A = 10.38 m²

Engine: MX11
2,235Nm @ 900-1250rpm
430 hp @ 1600rpm



Tires:
Crr = 4.7 All

Final Drive:
4x2 Losses
½ of 6x4 Losses

	Vehicle Drag [m2]	Engine	Gearbox	Tires			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)			4x2 Losses