PACCAR SuperTruck II

2018 Annual Merit Review

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

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PACCAR Inc

June 21st, 2018 Project ID # ACS124

Overview

Timeline

- Start Date: October 2017
- End Date: September 2022
- Percent Complete: 5%

Barriers

- Freight Efficiency is heavily dependent on application and route
- Cost, robustness and packaging needs of engine technologies to achieve 55% BTE
- Ability to demonstrate benefits in more than one application/use case

Budget

- Total project funding
  - DOE: $20M
  - Partnership: $20M
- FY 2017 Funding: $6.19M
- FY 2018 Funding: $11.24M

Partners

KENWORTH, EATON, AVL, MISSISSIPPI STATE UNIVERSITY, DAF, PACCAR TECHNICAL CENTER, NREL NATIONAL RENEWABLE ENERGY LABORATORY, UPS

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
  - Begin Analysis And Simulation Of Alternatives For 55% BTE Engine And Powertrain To Meet > 100% Freight Efficiency Improvement
  - Start Selection Process Of The Engine Technologies To Implement On The 55% BTE Engine
  - Start Selection Process Of The Powertrain Technologies
- 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 1 Milestones	Type	Description
BTE Analysis Completed	Technical	Engineering Analysis of 55% BTE Engine Paths Completed
BTE Design Selected	Technical	55% BTE Engine Design Selected
Powertrain System Selected	Technical	Powertrain System for 100% Freight Efficiency Improvement Selected
Selected Approach Achieves Performance Targets	Go/No-Go	Simulation and Analysis Indicate Selected Paths for 55% BTE Engine and greater than 100% Improvement in Freight Efficiency are Achievable

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

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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

- 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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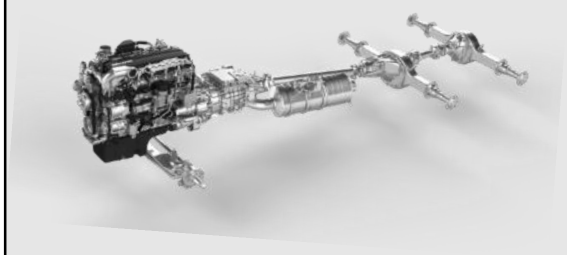
Technical Approach

Engine

Simulation, Design, Development, Testing

Powertrain



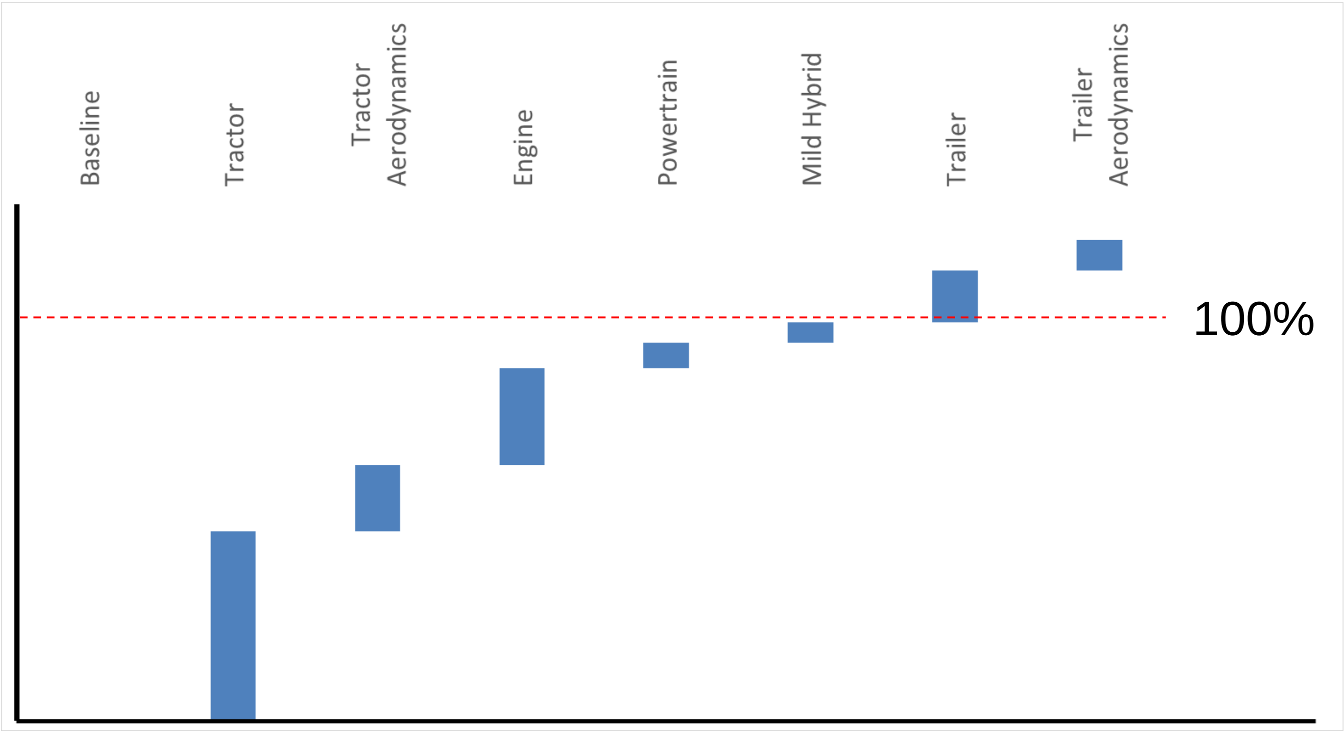
Simulation, Energy Management, Integration, Testing

Vehicle

Aero, Lightweighting, Engine & Powertrain Integration, Testing

Approach: Freight Efficiency

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



Freight Efficiency by Source
(% Improvement over Baseline)

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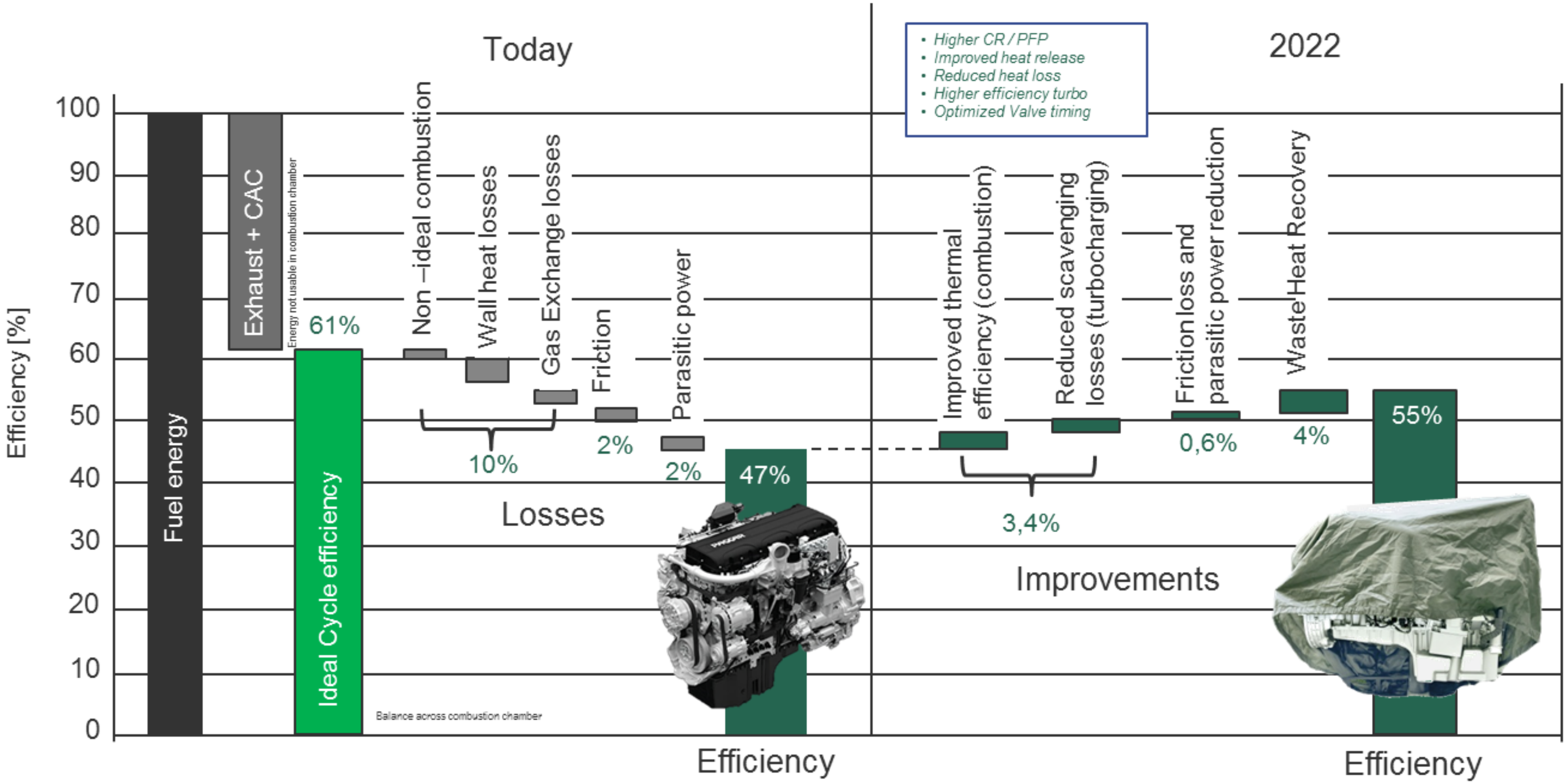
Approach: Engine Efficiency



ENGINE AND POWERTRAIN SECTION

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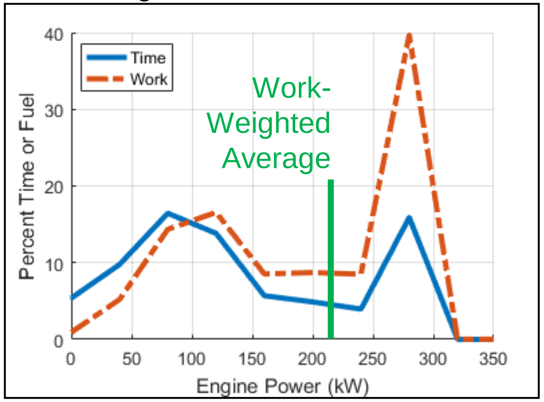
Accomplishments

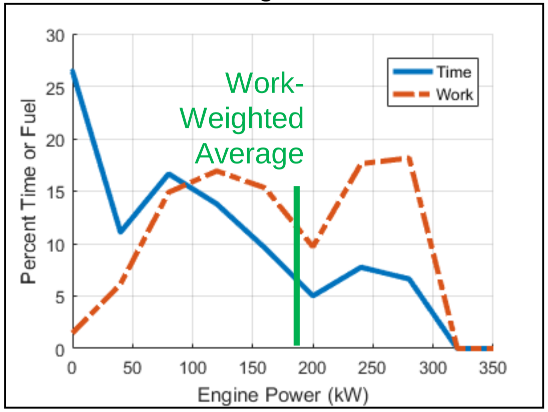
Road Load Selection

- Road Load
  - Work-Weighted Average Power Used To Determine Road-Load - Central Point For Fuel Burn
  - Existing Regulatory And Highway Cycle Simulations Indicate Range Of 180-210 kW Expected

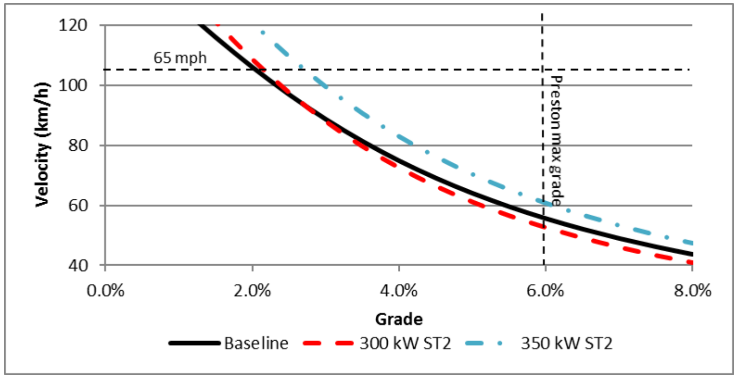
I5 Washington



Mtn. Home, ID to Ogden, UT



- Grade Performance
  - 300 kW to 325 kW Needed To Climb Grades At Same Speed As Baseline Truck



Accomplishments

Engine Requirements

- Preliminary Requirements from Powertrain and Vehicle Analysis:
  - 200 kW Road Load Point
  - 300-325 kW Requirement for Gradeability
  - Baseline Drivability
  - Path to Commercialization
- MX-11 Selected as Platform for Further Development

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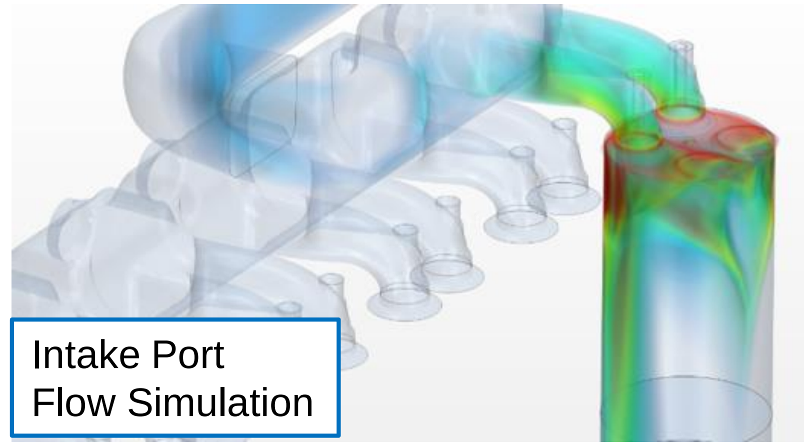
Accomplishments

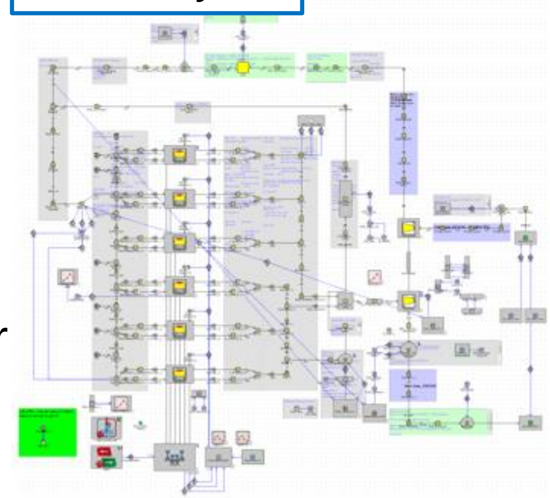
Started 55% BTE Engine Technologies Investigations

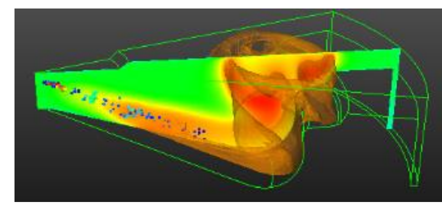
- 1-D Analysis
  - Crank- And Valve-Train Friction
  - EGR Gas Exchange
  - Effects Of Reduced Heat Rejection On BTE
  - Novel Air Management Concepts
  - WHR
- 3-D Analysis
  - Effect Of Longer Stroke
  - Late IVC Timing With Higher Boost
  - Thermal Barrier Coating
  - Intake Port Flow Modeling For Scavenging Eff. Improvement

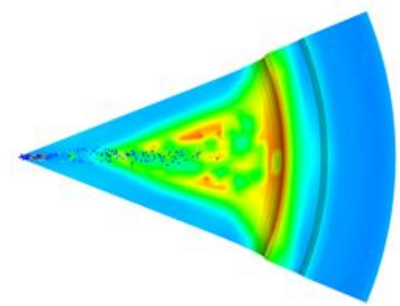


Intake Port Flow Simulation

1-D Analyses





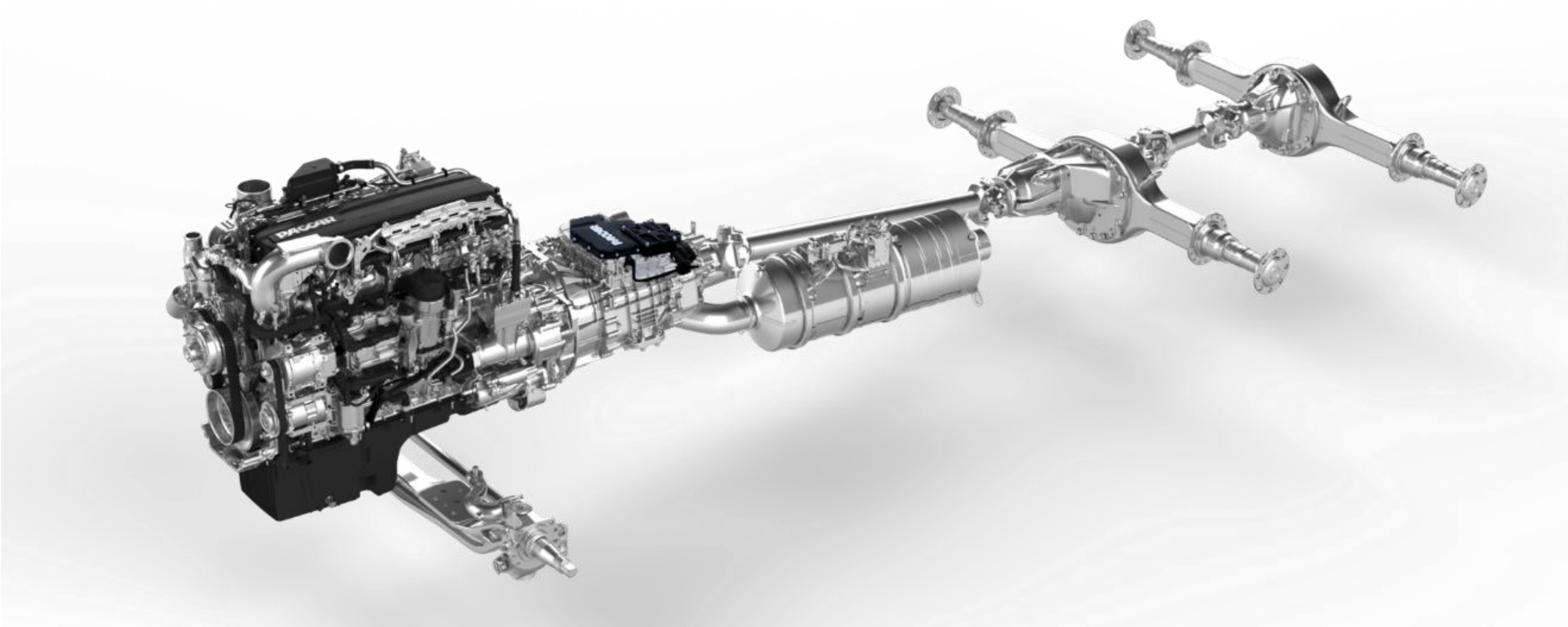


In-Cylinder Modeling

Accomplishments

Powertrain Analysis

- Developed And Validated Vehicle Simulation
- Integrated Hybrid System And Preliminary Energy Management
- Evaluated Effects Of Battery Size And Downhill Speed Overshoot
- Developed Cost And Weight vs. System Configuration
- Analyzed Hybrid Benefit Over Multiple Drive Cycles



Accomplishments

Hybrid Selection Methodology

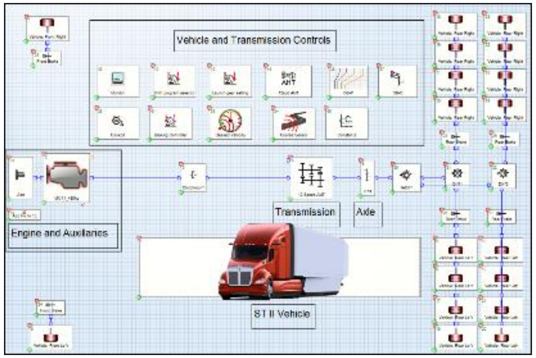
1. Select Evaluation Criteria

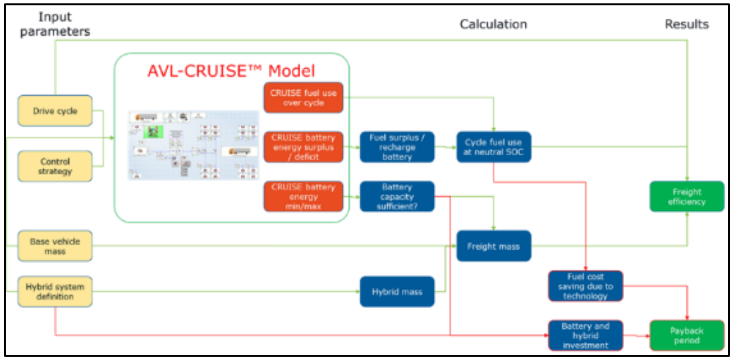
Freight Efficiency	Customer Payback	Serviceability	Volume Potential	Customer Cost	Commercialization Cost

2. Select Configuration Scenarios

eMotor Power	15kW	30kW	45kW	60kW	90kW	120kW
System Voltage	48V	48V	650V	650V	650V	650V
Mounting	PTO	PTO	PTO	Integrated	Integrated	Integrated

3. Perform Analysis

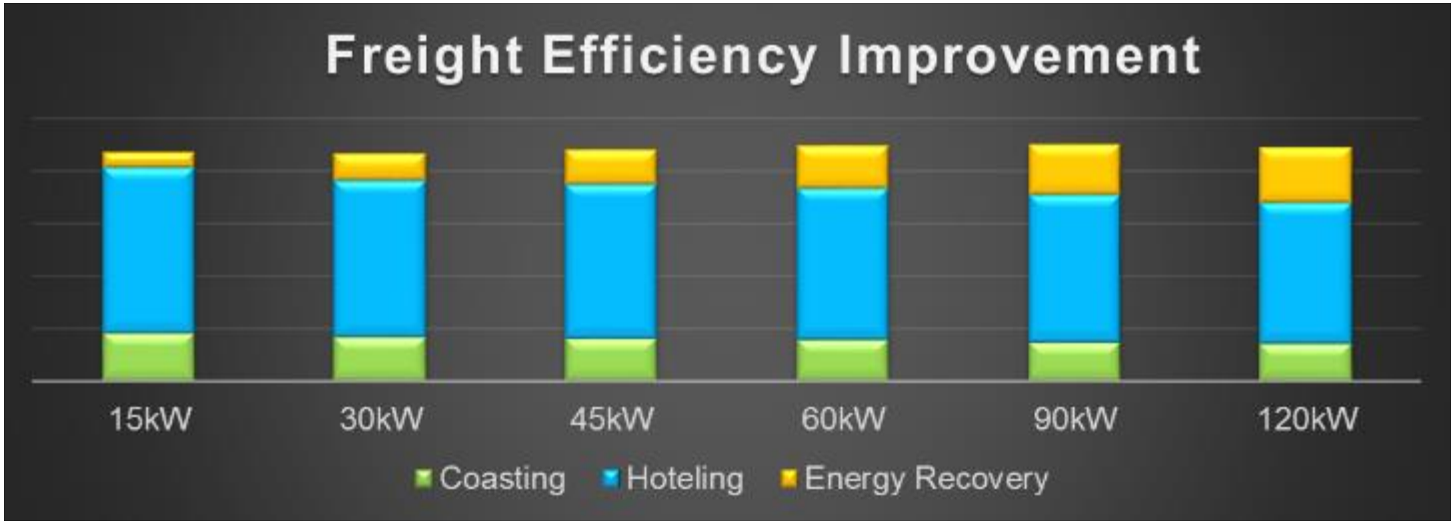




4. Evaluate And Rank

Accomplishments

Powertrain Analysis Results



Accomplishments

Hybrid Configuration Selection

eMotor Power Battery (e = energy, p = power) System Voltage Integration	15 kW e 10 kWh 48 V PTO	30 kW e 10 kWh 48 V PTO	45 kW p 10 kWh 650 V PTO	60 kW p 10 kWh 650 V Integrated	90 kW p 10 kWh 650 V Integrated	120 kW p 10 kWh 650 V Integrated
Contribution to ST2 Freight Efficiency	G	G	G	G	G	G
Customer Payback	G	Y	R	R	R	R
Serviceability	G	G	Y	Y	Y	Y
Volume Potential	G	G	Y	R	R	R
Customer Cost	G	Y	Y	Y	R	R
Commercialization Cost	Y	Y	Y	R	R	R

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Remaining Challenges

- 55% BTE Engine
  - Finalize WHR System Selection
  - Correlation of Simulation Results to Prototype Testing
  - Path to Commercialization Assessment
    - Integrity of Thermal Barrier Coatings
    - Engine Peak Cylinder Pressure Capability
- Powertrain
  - Optimization Of Mild Hybrid Architecture
  - Development Of Battery Capability And Cost
  - Integration Of Hybrid Controls With Advanced Predictive Features

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Proposed Future Research

FY2018

- Engine
  - Investigate Integration of WHR with Supplier
- Powertrain
  - Analysis of Mild Hybrid Architecture
  - Define Hybrid System Requirements
  - Develop HiL/SiL Tools for Definition of Control Strategies

FY2019

- Engine
  - Select and Fabricate Long Lead Time Components
  - Produce Test Data for Simulation Correlation
  - Adjust/Recalibrate Models
- Powertrain
  - Select and Fabricate Long Lead Time Components
  - Design Battery Pack
  - Define Control Architecture, Functional Decomposition, and Low-Level Requirements

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

Mark Brown
Kenworth Truck Company

VEHICLE SECTION

Vehicle Design Approach

- Baseline Vehicle: Kenworth T660-72”
- Primary Opportunities
  - Powertrain Efficiency
  - Aerodynamic Enhancements
  - Weight Reduction
- ST-II Tractor
  - Cab Size Optimized For Future Market
  - Shape Optimized For Aerodynamics
  - Optimized Design And Material Selection
- ST-II Trailer
  - Limit Barriers For Adoption
  - Significant Lightweighting Opportunities

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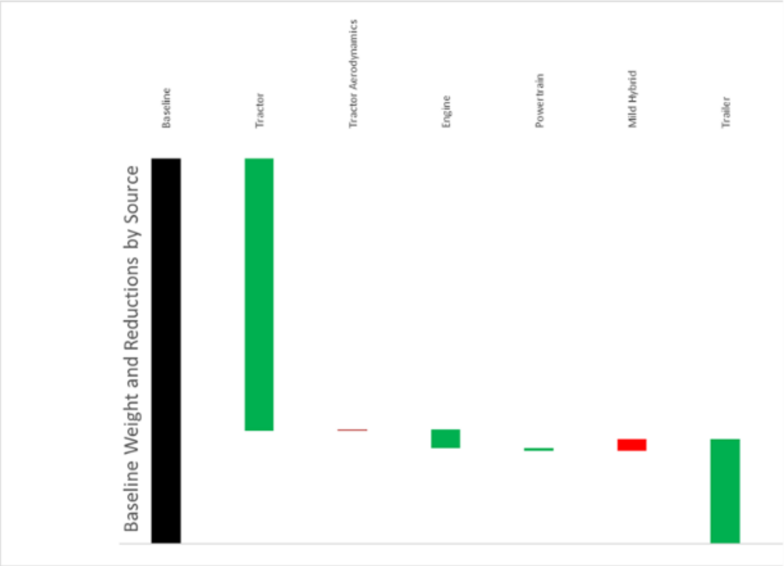
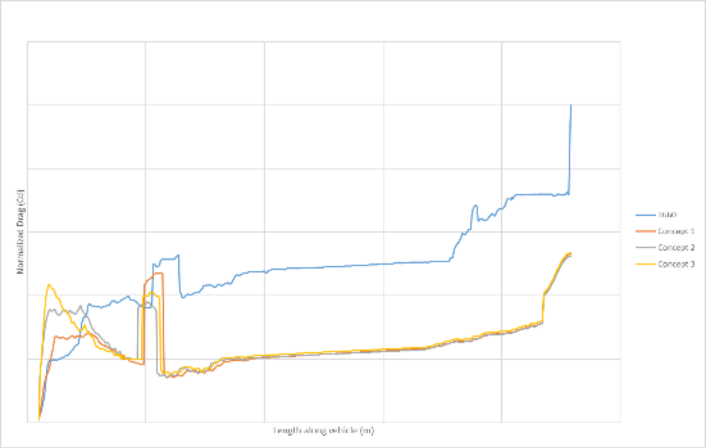
Accomplishments

- Baseline Vehicle Performance
  - Preparation For Drive Cycle Data Collection
- Freight Efficiency Roadmap
  - Improvement Forecast, >100%
  - Allocation Complete Across Technology Areas
- Weight Reduction Roadmap
  - Allocation Complete Across Product Areas
- Aerodynamic Progress
  - 3 Vehicle Profiles Evaluated
  - Trailer Enhancements Required
  - Confidence In 35% Reduction

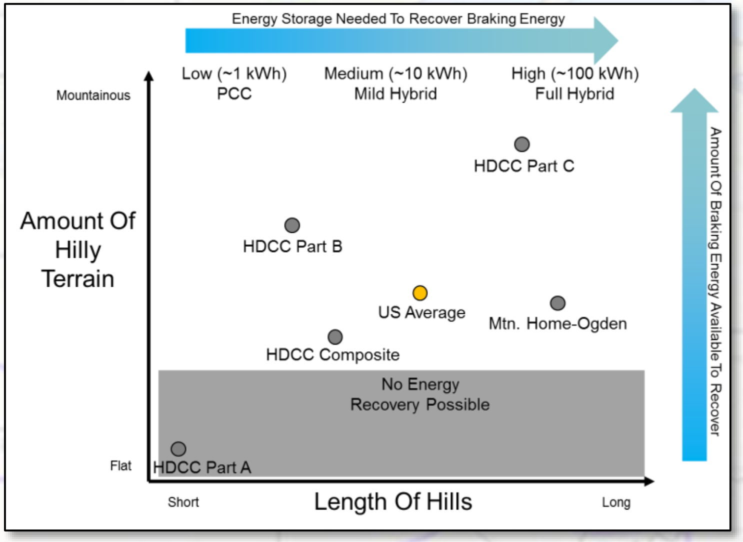




Aero Drag Analysis
(Baseline vs. Alternatives)

Drive Cycle Selection

- Partnership w/ UPS
- Real World Route Data Collection
  - Vehicle Instrumentation - NREL
  - (7) UPS Routes Evaluated
- Next: Non-mountainous And Hoteling Loads



Route Evaluation

	Key Metrics				
	Grade Dist.	Hill Length	Avg Speed	Idle Time	Hotel Loads
PACCAR HDCC	✓	✓	✗	✗	✗
Mtn. Home → Ogden	✓	✗	✓	✓	✓

Remaining Challenges

- Complete Definition Of Representative Drive Cycle
- Engine And Powertrain Integration And Packaging
  - Effects Of Electrified Powertrain On Cooling, Packaging And Vehicle Dynamics
- Vehicle Development
  - Aerodynamics Of Tractor Trailer Combination
  - Habitability And Ergonomics Of Highly Aerodynamic Tractor

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Proposed Future Research

<u>FY18</u>

- Final Drive Cycle Selection
  - Baseline Vehicle Data Collection
- Build Cab Buck
  - Evaluate Occupant Environment
  - Floorplan Validation

<u>FY19</u>

- Build Vehicle Mule
  - Systems Integrations
  - Tractor / Trailer Aero Integration
  - Advanced Chassis Proof of Concept
  - Evaluate Dynamic Vehicle Height
  - Evaluate Mild Hybrid Solution
- Reduced Rolling Resistance Tire Development

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

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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
NREL NATIONAL RENEWABLE ENERGY LABORATORY	Drive Cycle Development Thermal Management
ups	Drive Cycle Development Tech Market Acceptance Advisory

Summary

- Preliminary Road Load Point and Drive Cycles Defined for Initial Analysis
- Selected MX-11 Engine as Base for 55% BTE Engine Design
- High-Level Engine Technology Roadmap to 55% BTE
- Discussions with Supplier of WHR Initiated
- Selected Mild Hybrid (15-30kW) to Meet Freight Efficiency Targets
- Three Tractor Cab Shapes Analyzed and Meeting Targets
- Freight Efficiency Roadmap to > 100% Improvement
- Baseline Vehicle Defined, Analyzed and Truck Available

TECHNICAL BACKUP SLIDES

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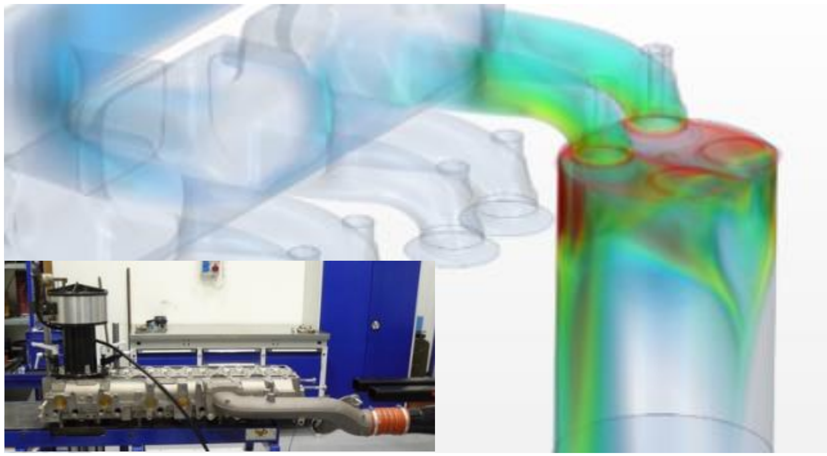
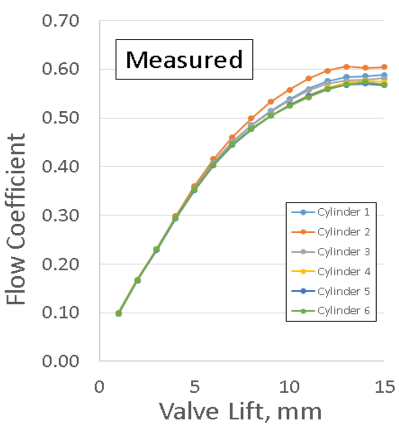
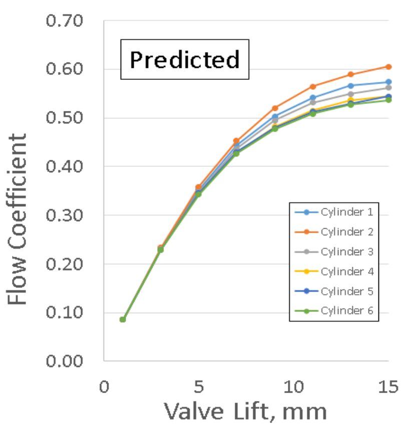
Engine 3-D CFD

Intake Port Flow Simulation

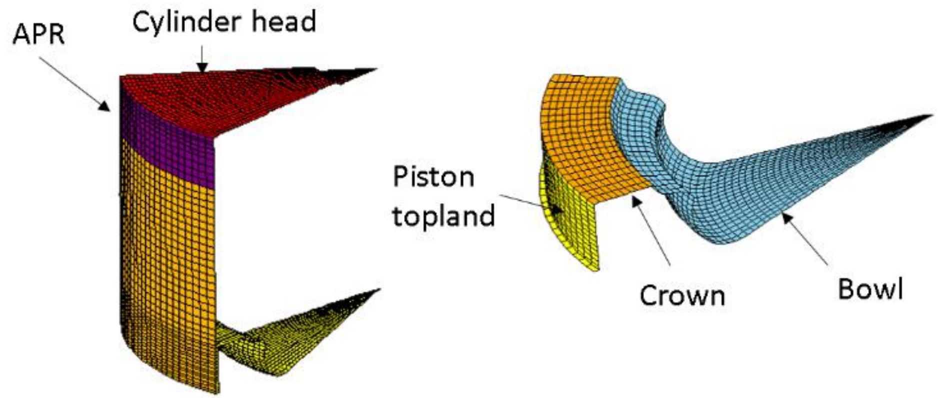


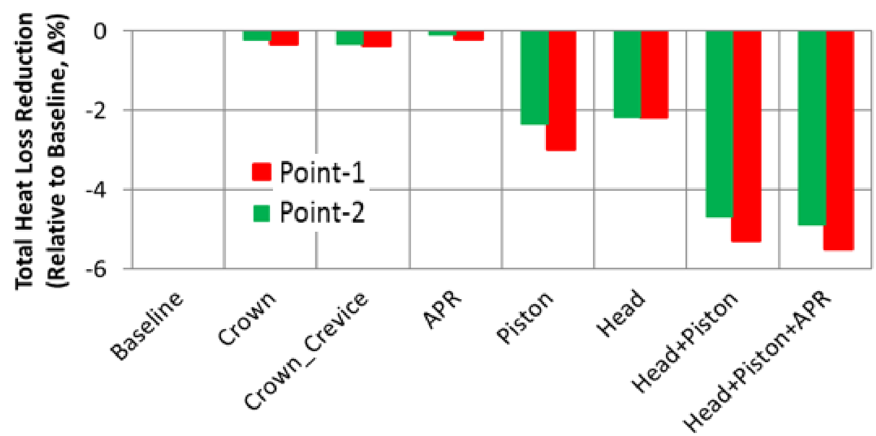




- Flow coefficient correlation done
- Model captures cyl-to-cyl variations

Heat Rejection Reduction / TBC





- Component-by-component merit evaluated
- Coating application and testing planned

Hybrid Decision Backup