Development and Demonstration of a Fuel-Efficient Class 8 Tractor & Trailer SuperTruck

Vehicle Systems (Project ID: ace_103)

DOE Contract: DE-EE0007767
NETL Project Officer: Ralph Nine DOE Technology Manager: Ken Howden
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Navistar, Inc.

DOE MERIT REVIEW
June 11-13, 2019
October 1, 2017 – October 1, 2018

Overview: Navistar & DOE SuperTruck II

Timeline

Start Date 12-2016

End Date 12-2021

Technical Barriers and Targets

- **#1 –** Greater than or equal to 55% engine brake thermal efficiency (BTE)
- **#2 –** Greater than 100% improvement in vehicle freight efficiency (FE) (on a ton-mile-per-gallon basis)
- **#3 –** Development of technologies that are commercially cost effective

Budget

Total Project Funding:

- DOE Share $20M
- Navistar Share $35M

Partners and Laboratories

- Department of Energy
- Argonne
- Lawrence Livermore
- Bosch
- TPI - Composites
- Dana

Resources Navistar Utilizes in DOE ST II Program

Partnerships and Laboratories

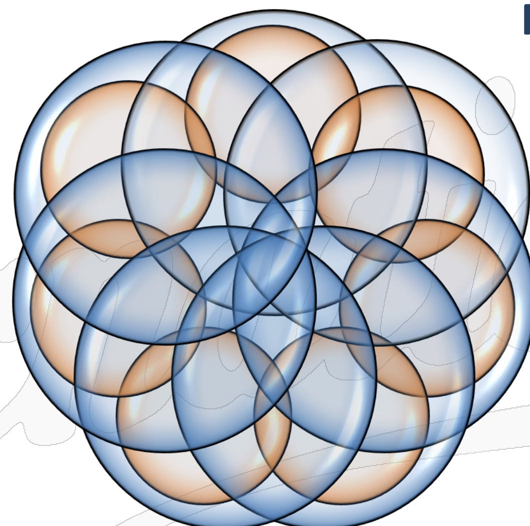
Navistar

DOE

Product Development Process

SuperTruck I Processes, Practices

Bosch



Program management

Product Development Process

TPI Composites

Argonne

Advanced Technology & Global Innovation

Integrated Product Development (IPD)

Lawrence Livermore

Dana

U-Michigan

Functional Areas

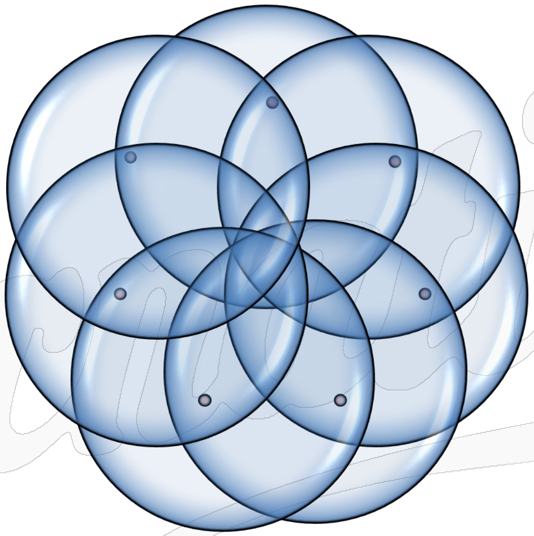
Vehicle Architecture

Automation

Aero

Aftertreatment

Combustion



Power Train

Electronics

WHR

Fuel system

Material science

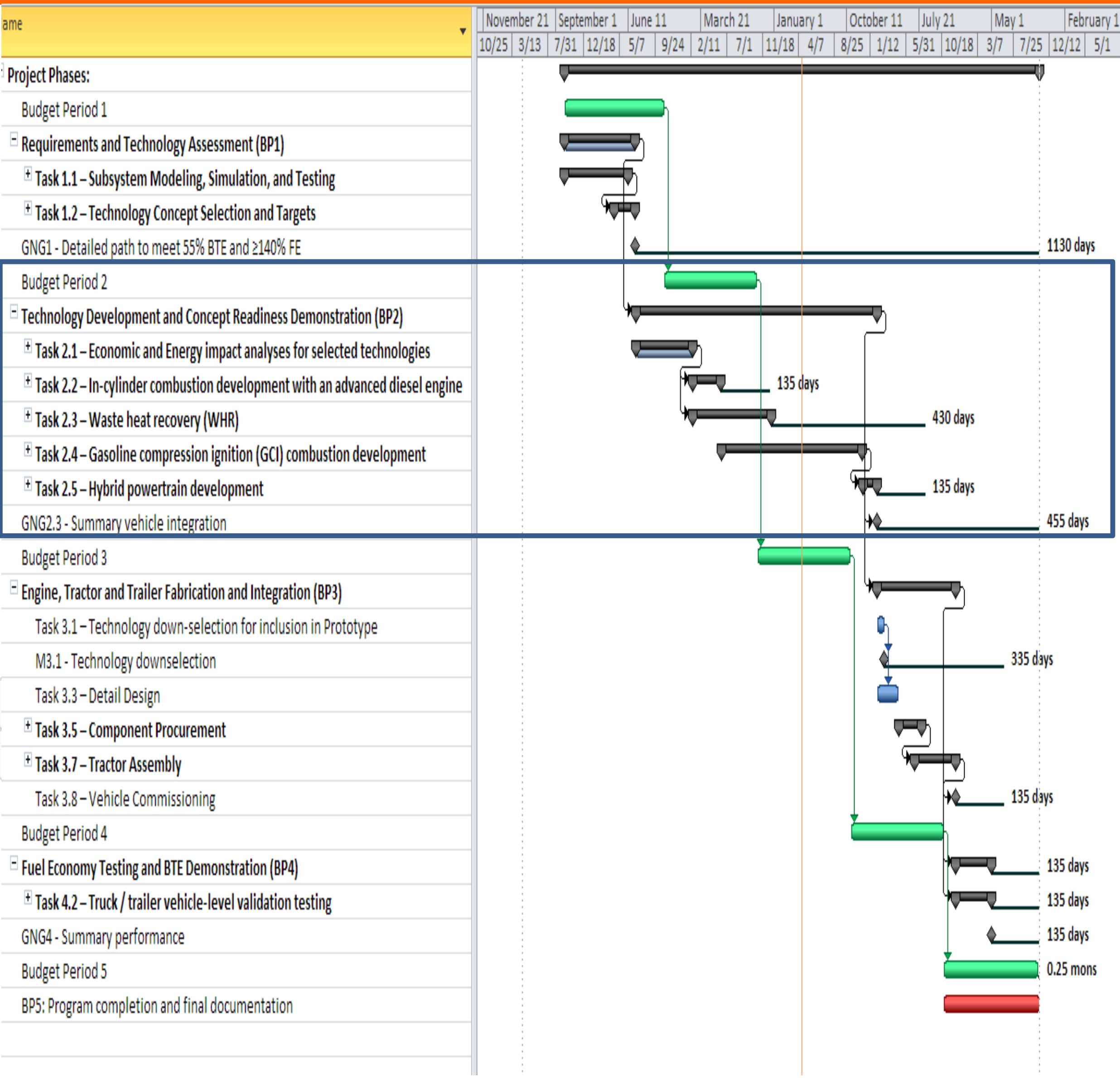
Hybrid

Thermal Management

Engine Architecture

Air Handling

Program Plan



MILESTONES

Budget Period 1 Requirements / Technology Assessment & Initial Hardware Testing

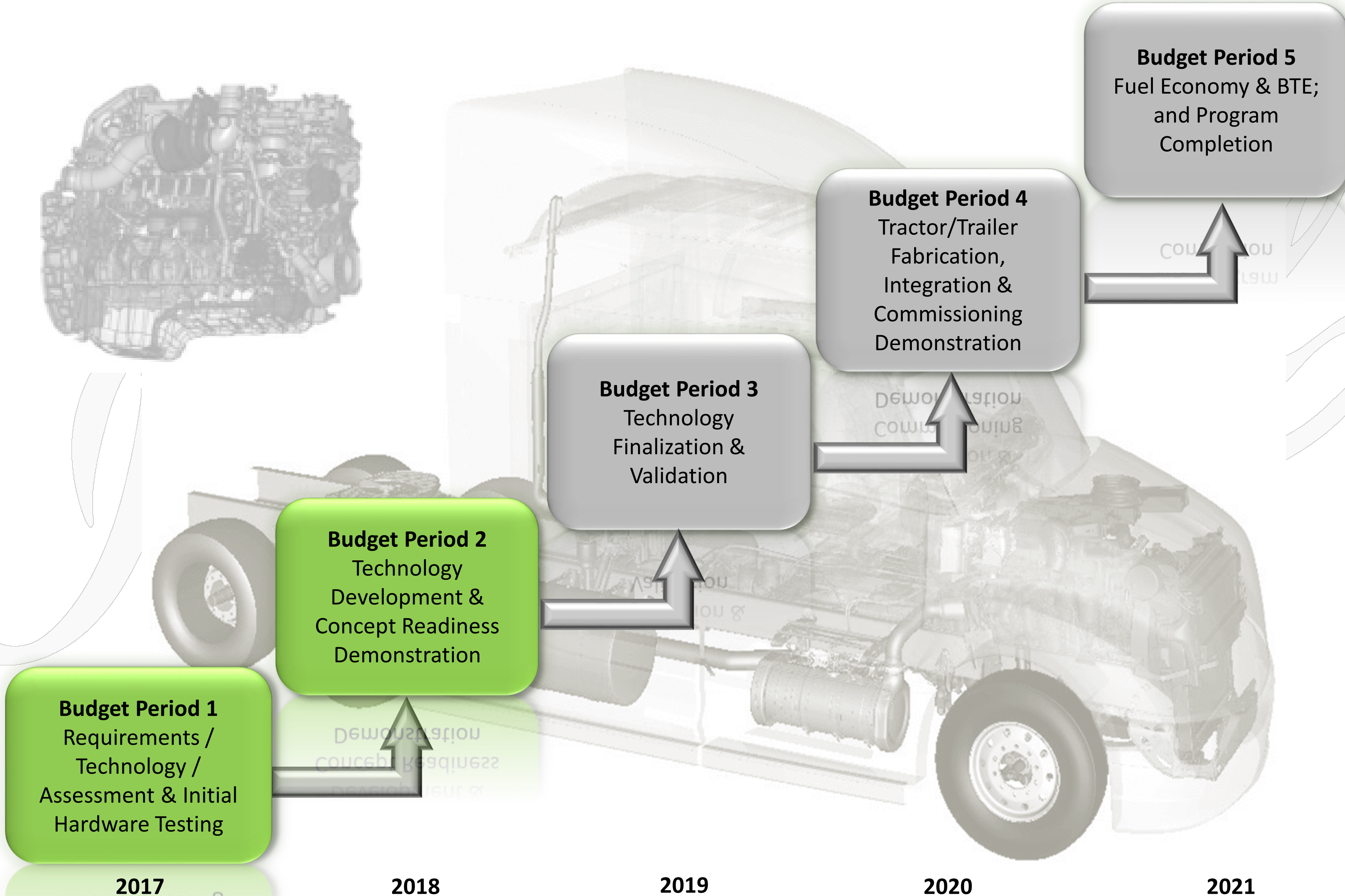
Budget Period 2 - Technology Development & Concept Readiness Demonstration

Budget Period 3 - Technology Finalization & Validation

Budget Period 4 - Tractor/Trailer Fabrication, Integration & Commissioning Demonstration

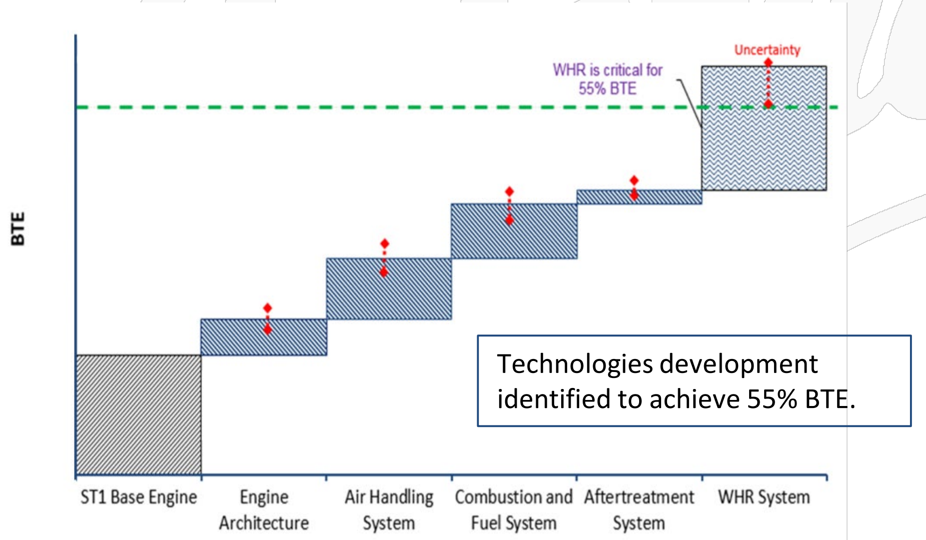
Budget Period 5 - Fuel Economy & BTE; and Program Completion

Program Milestones



Engine Objective

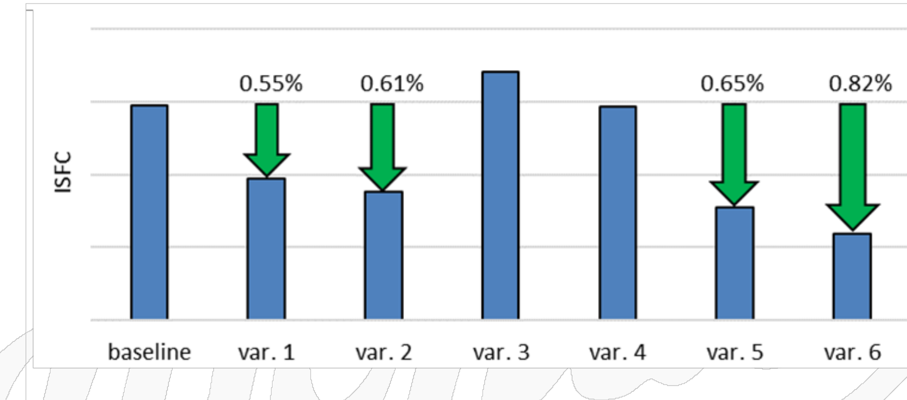
- Attain greater than or equal to 55% BTE demonstrated in an operational engine at a 65-mph cruise point on a dynamometer.
- Develop engine technologies that are commercially cost effective.
- Contribute to greater than 100% improvement in vehicle freight efficiency (FE) relative to a 2009 baseline.

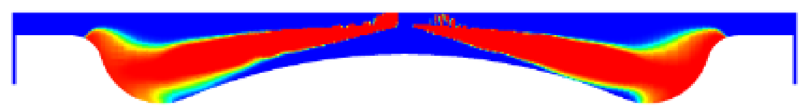


Engine Technical Accomplishments & Progress

Combustion & Fuel System

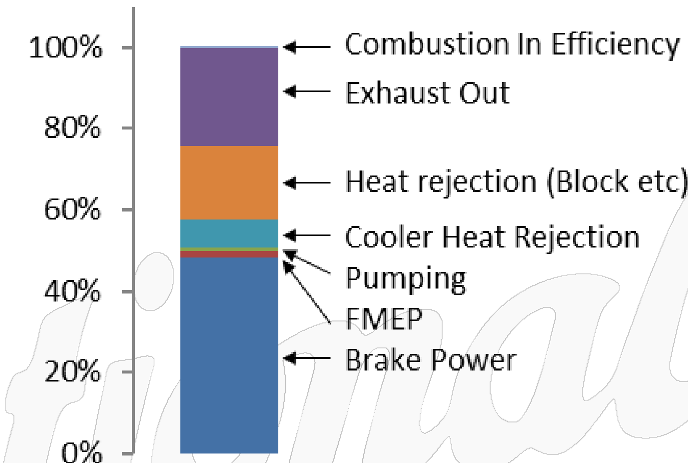
- Combustion system focus remains on optimizing the combustion process
- Key parameters of fuel-injection configurations include number of holes and nozzle flow rates
- Rapid break-up of spray core results in faster combustion
- Peak efficiencies achieved through optimizing air utilization and mixing process control
- Increasing PCP improves combustion efficiency

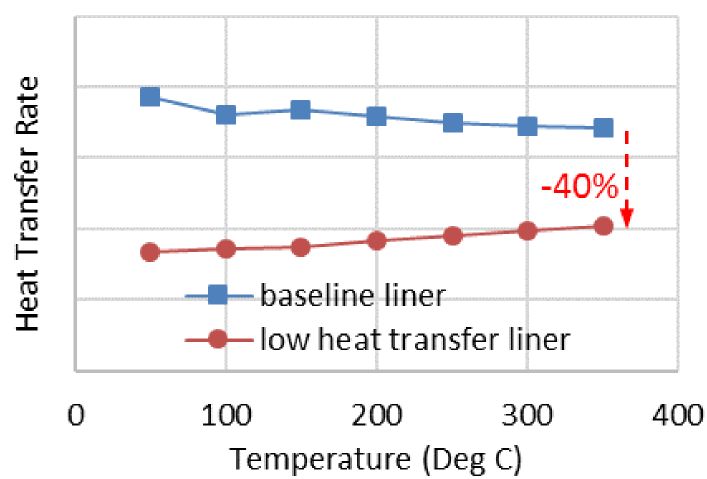




Energy Balance

- Analysis had shown a significant amount of heat rejection to engine coolant
- A low-heat transfer liner was procured and investigated to minimize the heat loss to coolant
- The results showed that block heat rejection was reduced as expected – however, an increase of oil heat rejection was observed
- As a result, the BSFC remains similar between the baseline and the low-heat transfer liner

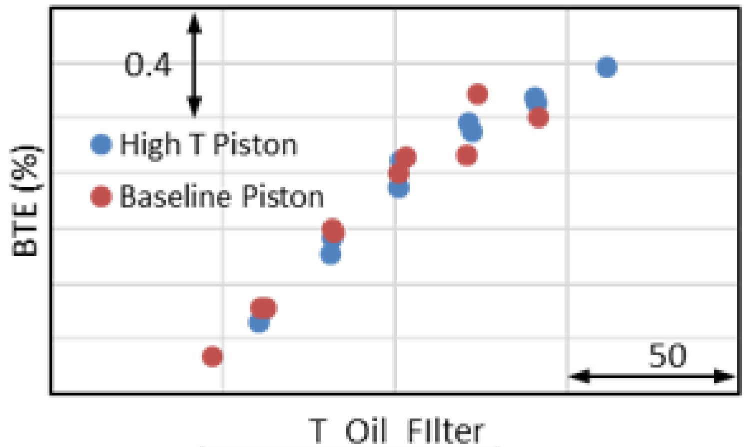


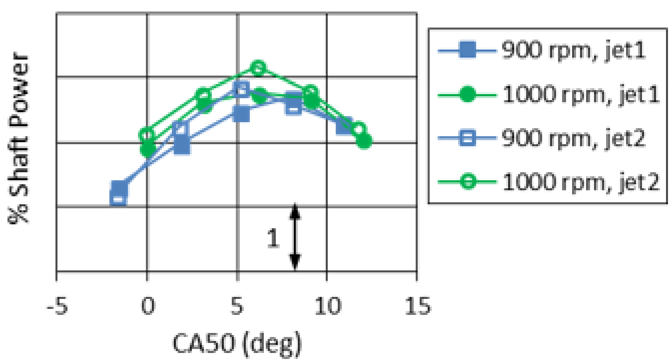


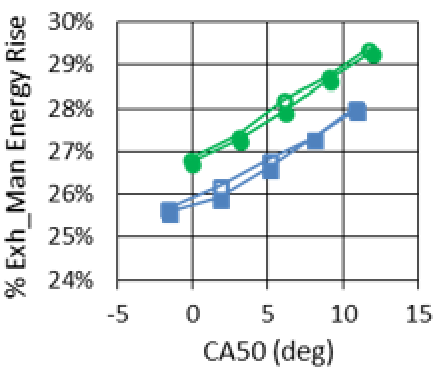
Engine Technical Accomplishments & Progress

Thermal Management

- High-temperature pistons investigated
- New piston design resulted in higher exhaust temperature – helpful to ORC, but worse for BSFC
- As a result of this work, we found that increasing oil temperature by ~100°F resulted in 1% BTE gain

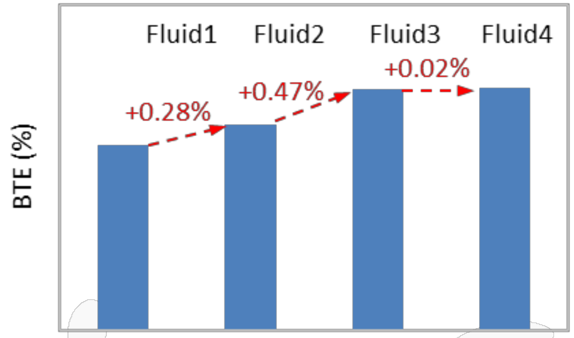


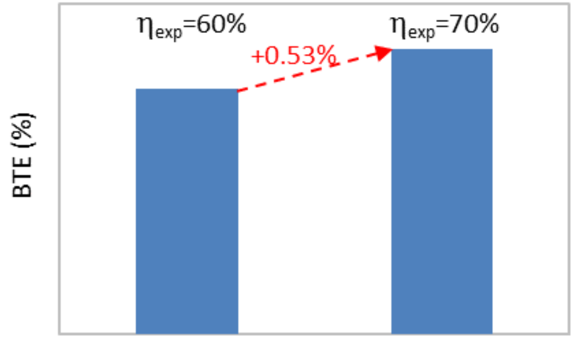


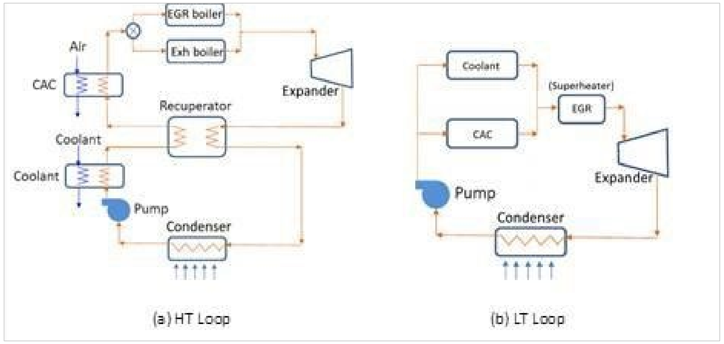


WHR & System

- Based on the temperature characteristics of the heat sources, the ORC system was optimized
- Different working fluids were evaluated, including refrigerant
- The expander's efficiency has a direct impact to ORC BTE gain
  - A 10% increase in expander efficiency results in a gain of 0.5% in ORC BTE for the same working fluid



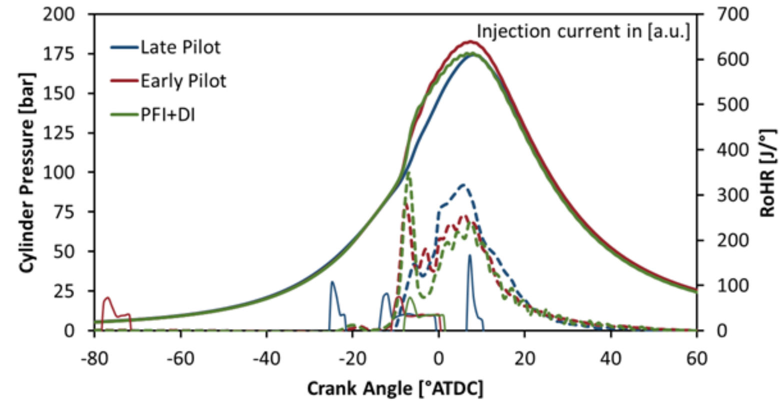


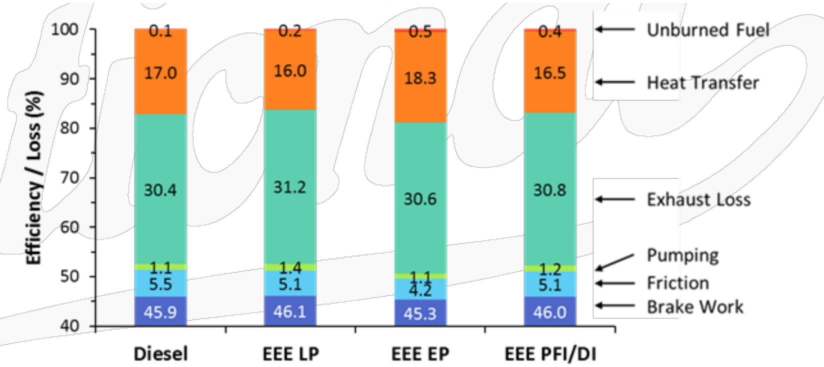


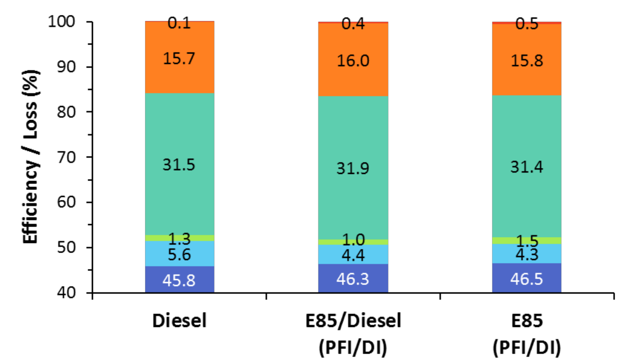
Engine Technical Accomplishments & Progress

ANL – Gasoline Compression Ignition (GCI)

- GCI Goal: Increase portion of premixed combustion, using three strategies (focused at ST I A50 condition):
  - Early pilot injection (EP)
  - Late pilot injection (LP)
  - Early/late pilot injection and port fueled injected/direct injection (PFI/DI)
- Two gasoline fuels selected for evaluation:
  1. EEE, EPA Tier II Certification Gasoline
  2. E85, blended in-house with 85 vol% dry ethanol and 15 vol% EEE
- Results:
  - EEE gasoline performed best with late pilot injection strategy
  - E85 gasoline performed better with PFI/DI strategy
  - Both EEE & E85 could achieve better brake efficiency than the diesel baseline



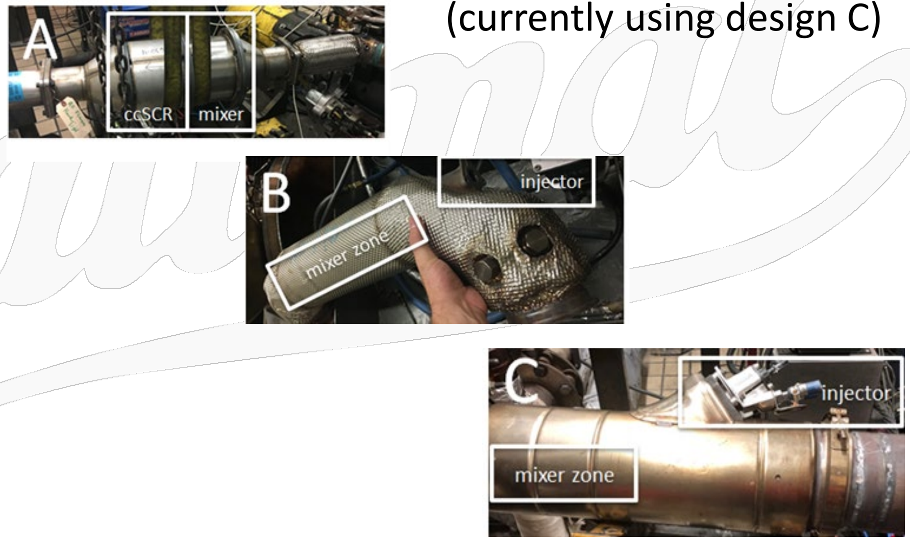


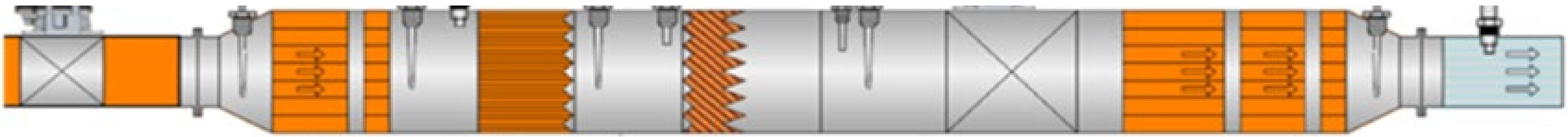


Emission Control
Mixer Development and AT Architecture

- Evaluation of close-coupled SCR (CCSCR) showed the best performance when using a large diameter
- CCSCR brick was installed upstream of the DOC and packaged within a common converter
- Smaller diameter CCSCR system displayed high restriction; bypass valve did not package well
- Next Steps: System assessment in progress for optimal AT design and installation

Components installed near turbo outlet (currently using design C)





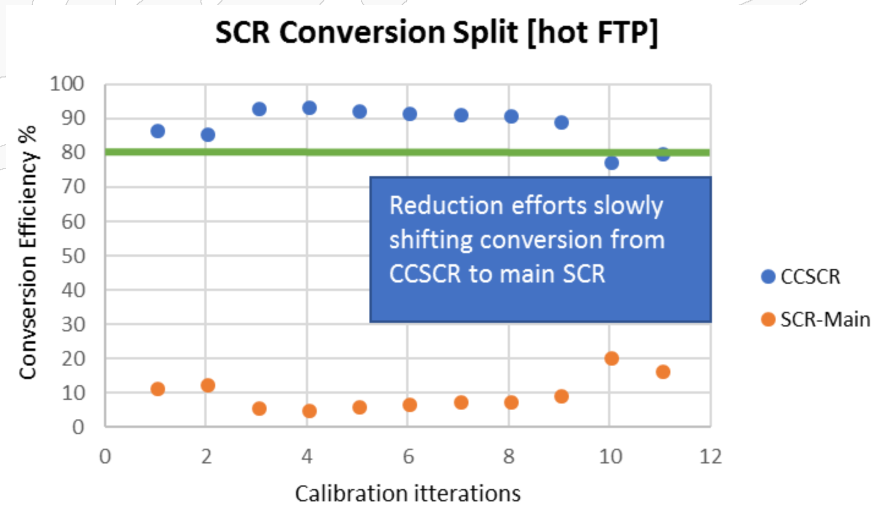
Aftertreatment Technical Accomplishments & Progress

Balancing NOx conversion Over Upstream and Downstream SCR

- TP NOx over composite FTP and RMC is below 0.2 g/hp.hr
- AT system provided over 98% NOx conversion over composite FTP
- Adjusting calibration table allowed for dynamic dosing
- Upstream SCR efficiency 70%-95% composite FTP and 80%-95% hot FTP
- Goal is tunable from 50% to 95% (composite)
- No evidence of DEF deposits at upstream DEF dosing

Benefits of Upstream SCR

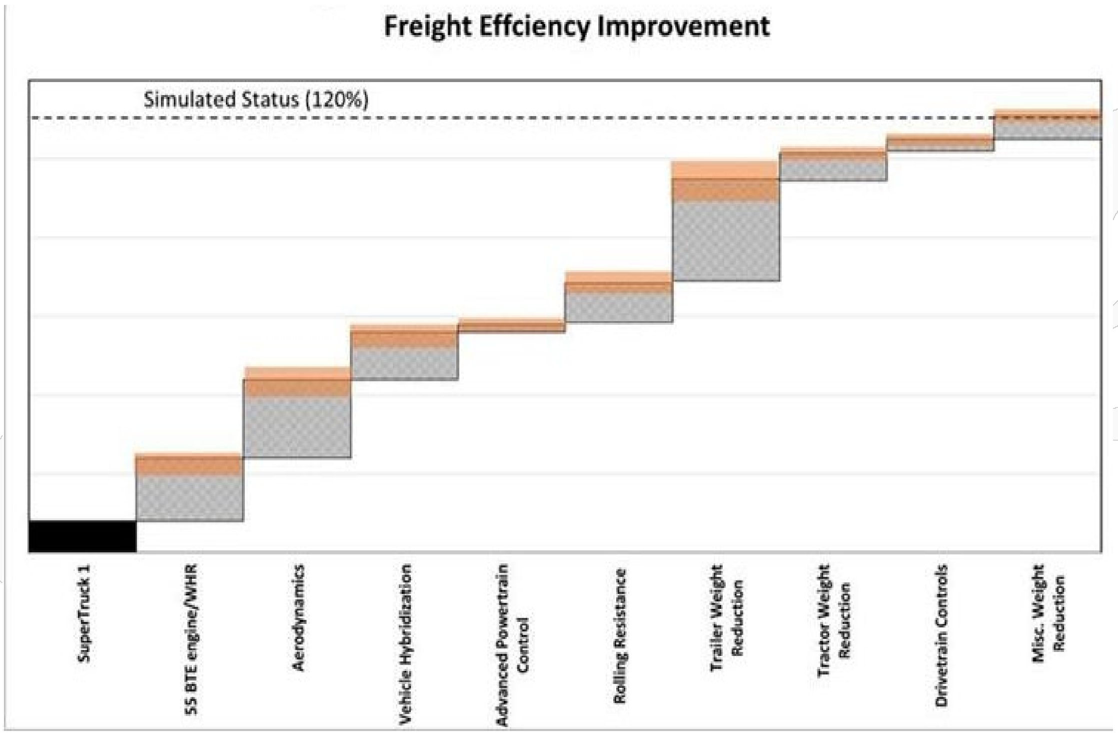
- Rapid light-off observed ➔ within first minute of cold FTP
- High NOx conversion
- Addition of AMOX zone minimized N_2O formation ➔ no NH_3 slip to DOC/DPF

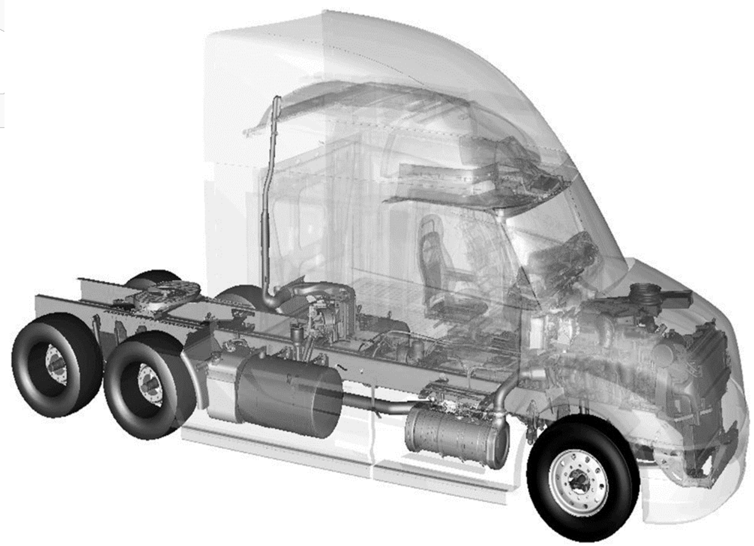


Vehicle Objective

Research, develop, and demonstrate a vehicle that achieves the following goals:

- Greater than 100% improvement in vehicle freight efficiency (FE) (on a ton-mile-per-gallon basis) relative to a 2009 baseline with a stretch goal >140% improvement.

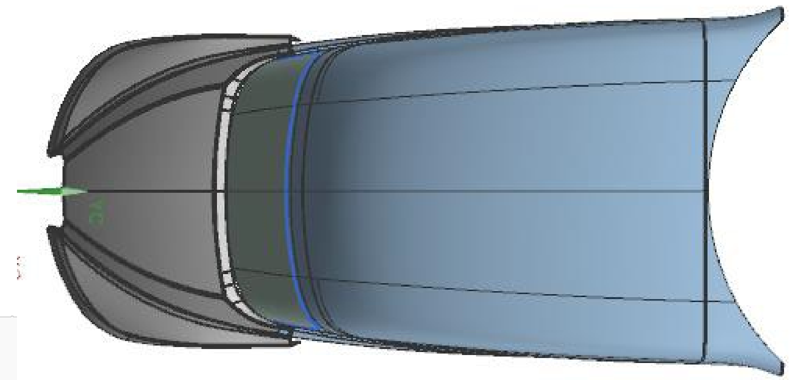


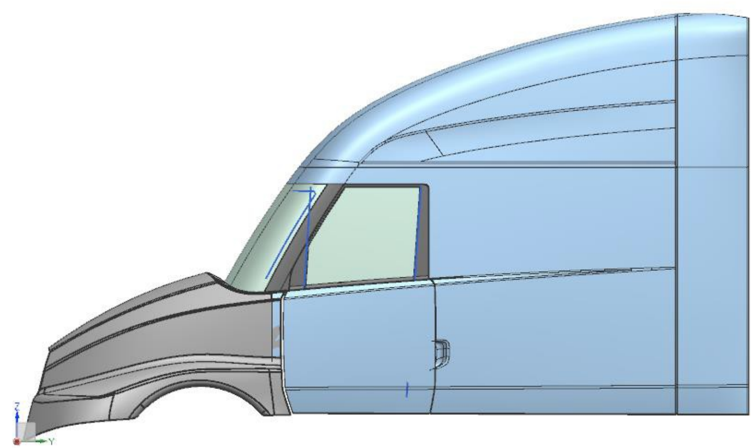


Vehicle Technical Accomplishments & Progress

Aerodynamics

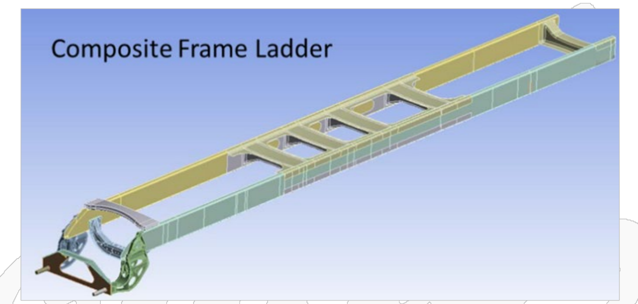
- Body, Aero, Trailer and Composite Frame Rail execution continued through detailed design phase.
- Employed aerodynamic ducting approaches to reduce pressure in stagnant leading surfaces for overall reductions.
- Initial composite material selection was done with a completive production cost. Carbon-fiber utilization minimized.
- Estimated mass reduction for body structure, hoods, and exterior aero devices is >500 lb.
- Trailer will utilize high-level of composite material.

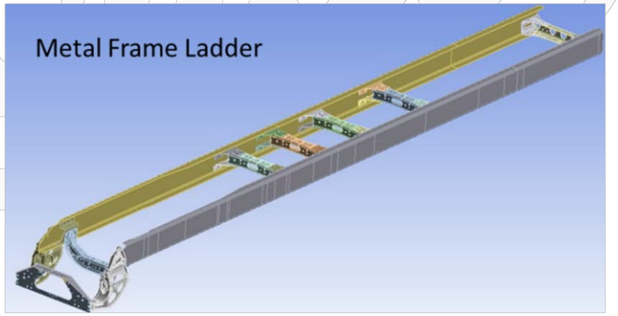




Composite Frame

- Simulation indicates up to a 25% mass savings vs. a steel-frame ladder, assuming integrated crossmembers and channel design.
  - Mass reduction – On target (mass reduction over steel frame ladder)
- Design Status: Recovery loads
  - Horizontal Towing – Pass
  - 45-deg conical Recovery – Pass
  - Frame Deflection – Pass (comparable to metal frame)
  - Racking Loads (Turning) – Conditional Pass (comparable)
  - Chassis twist – Conditional Pass (comparable)
  - Cross twist – Conditional Pass (comparable)
- Remaining Analysis/Testing/Development
  - Develop epoxy matrix material properties – Targeting a matrix material Need to develop fatigue curve with chosen matrix material
  - Consolidate connection points – Design to limit or reduce the number of through-bolts.





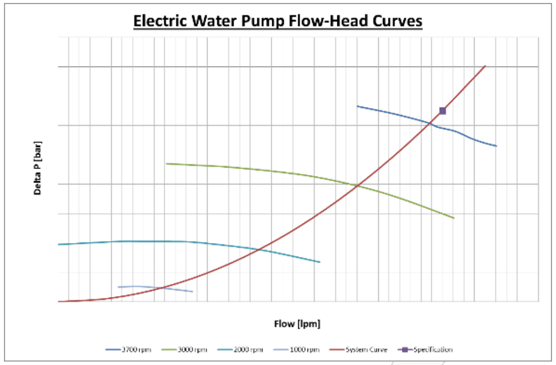
Vehicle Technical Accomplishments & Progress

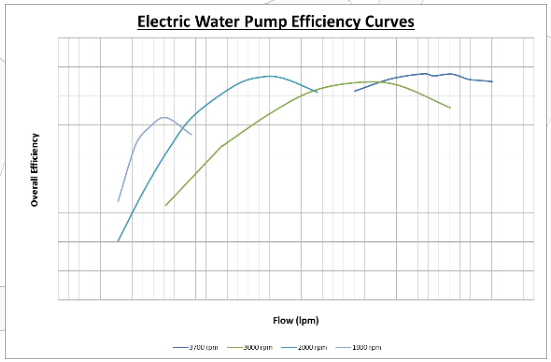
Advanced Cooling

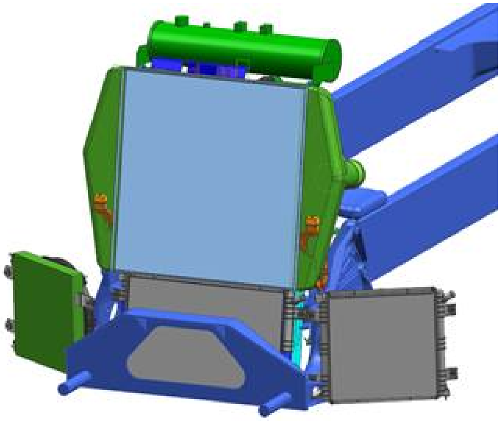
Continued optimizing the cooling-system configuration for the truck

- Radiator to handle engine cooling with smart flow control
- Low-temperature loop will be used to supply coolant for battery, electric motor/generator, and other accessories
- Electric fans will be used for cooling
- Eclectic driven water pump.
- AC condenser and fan will be a stand-alone unit
- Continued the cooling-system-packaging study, with preliminary results illustrated.

Aerodynamic team and Analytic Group are evaluating cooling-module placement, together with the truck frontal design themes







Vehicle Technical Accomplishments & Progress

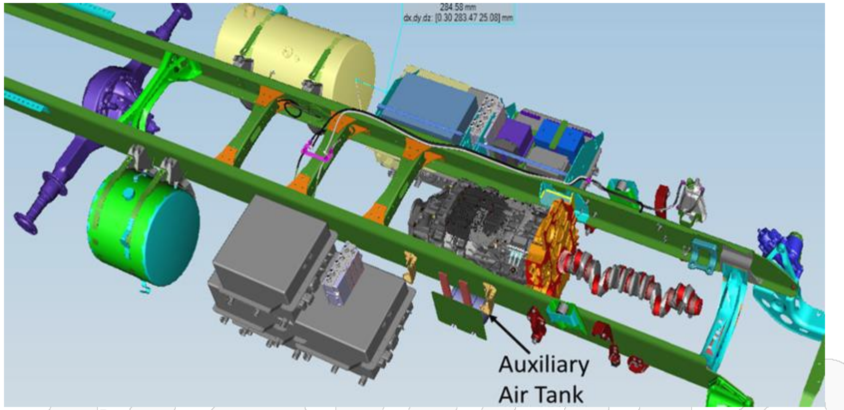
Powertrain

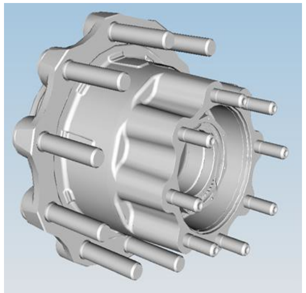
Completed 3D-CAD packaging study to fit extra components on the truck

- Sized-up 48V Lithium batteries pack

Completed (Build Books)

- Procured all major components and required installation parts:
  - AMT transmission
  - DANA Ultra fast drive axle
  - DANA Carbon Fiber composite drive shaft
  - lightweight prototype hub design from Timken for ST II tag axle
- 3+ lb/hub weight reduction vs. ST I
- Aluminum casting with integrated Gen.2 PDEF bearing.



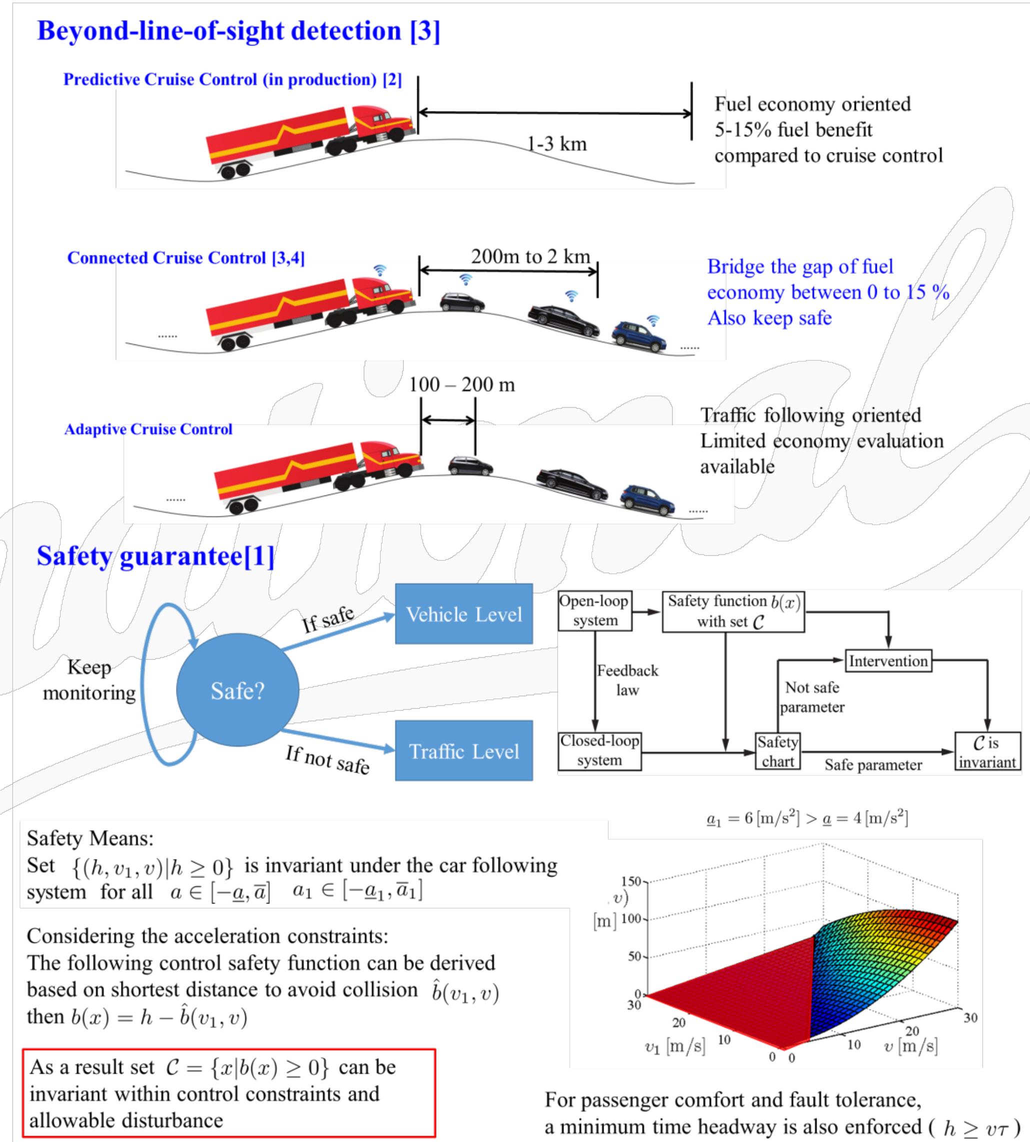


Vehicle Technical Accomplishments & Progress

Connected Cruse Control

Improving Fuel Economy of Heavy Duty Vehicle in Traffic using Connectivity and Automation

- Continued development on ACC/CCC
- Moved development to vehicle
  - Collected data necessary for developing feed-forward-control portion of algorithm
  - Creating response maps for a given control input.
- Down-selection of components is complete.
- Evaluating code and port to the new API



Summary: Budget Period 2

Technology Development & Concept Readiness Demonstration

Approach: Develop & implement detailed R&D path for required components / subsystems, ensuring successful completion of overall program goals

Overall

- Continued economic & energy impact analyses of component technologies to prepare for BP3

Engine: ≤ 55% BTE Architecture

- Continued investigation of further reductions related to friction model
- Completed exhaust and EGR system design modifications; continued air system turbocharger efficiencies
- Used optimized WHR model configurations
- ANL, used new GCI strategy to continue evaluation of system and fuel performance opportunities
- Aftertreatment demonstrated dual DEF dosing concept that is capable of reducing high engine-out NOx to less than 0.2 g/hp.hr over the FTP and RMC

Vehicle: >100% improvement in FE

- Finished Mule build, including addition of hybrid transmission, wiring harnesses, and lightweight tag axle; evaluating integrated disc brakes
- Upgraded control strategy, GPS-based gear shift optimizer; and improved drive-off and overall shift quality
- Worked to increase battery life and performance (e.g., hybrid batteries)
- Optimized cooling system configuration (e.g., radiators, fans, water pumps, cooling-module, HVAC system)
- Continued controls architecture development, evaluating braking strategies, integration of ZF systems, and ACC/CCC

Budget Period 3 - Technology Finalization and Validation

Complete economic & energy impact analyses of component technologies, as well as GCI combustion and nanofluid development

Approach:

- Finalize down-selection of:
  - In-cylinder combustion systems
  - Hybrid powertrain systems
  - Advanced vehicle electrification system
  - Advanced aftertreatment systems

- Continue evaluation and selection for:
  - Waste Heat Recovery (WHR) system development
  - Drivetrain & chassis efficiency improvements
  - Aerodynamics improvements

Questions - Comments