Navistar SuperTruck II

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

Vehicle Systems (Project ID: ACS 103)

DOE Contract: DE-EE0007767
NETL Project Manager: Ken Howden
NETL Project Officer: Ralph Nine

Principal Investigator: Russ Zukouski
Navistar, Inc.

DOE 2020 ANNUAL MERIT REVIEW
June 1 – 4, 2020

Presented for Navistar by:
Engine Chief Engineer: Jim Cigler
Vehicle Chief Engineer: Dean Oppermann

Overview: Navistar & DOE SuperTruck II

Timeline

Start Date	October 2016
End Date	December 2021
Percent Complete:	67%

Technical Barriers and Targets

- #1 – Greater than or equal to 55% engine brake thermal efficiency (BTE) while meeting prevailing emissions
- #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 in terms of a simple payback

Budget

Total Project Funding:

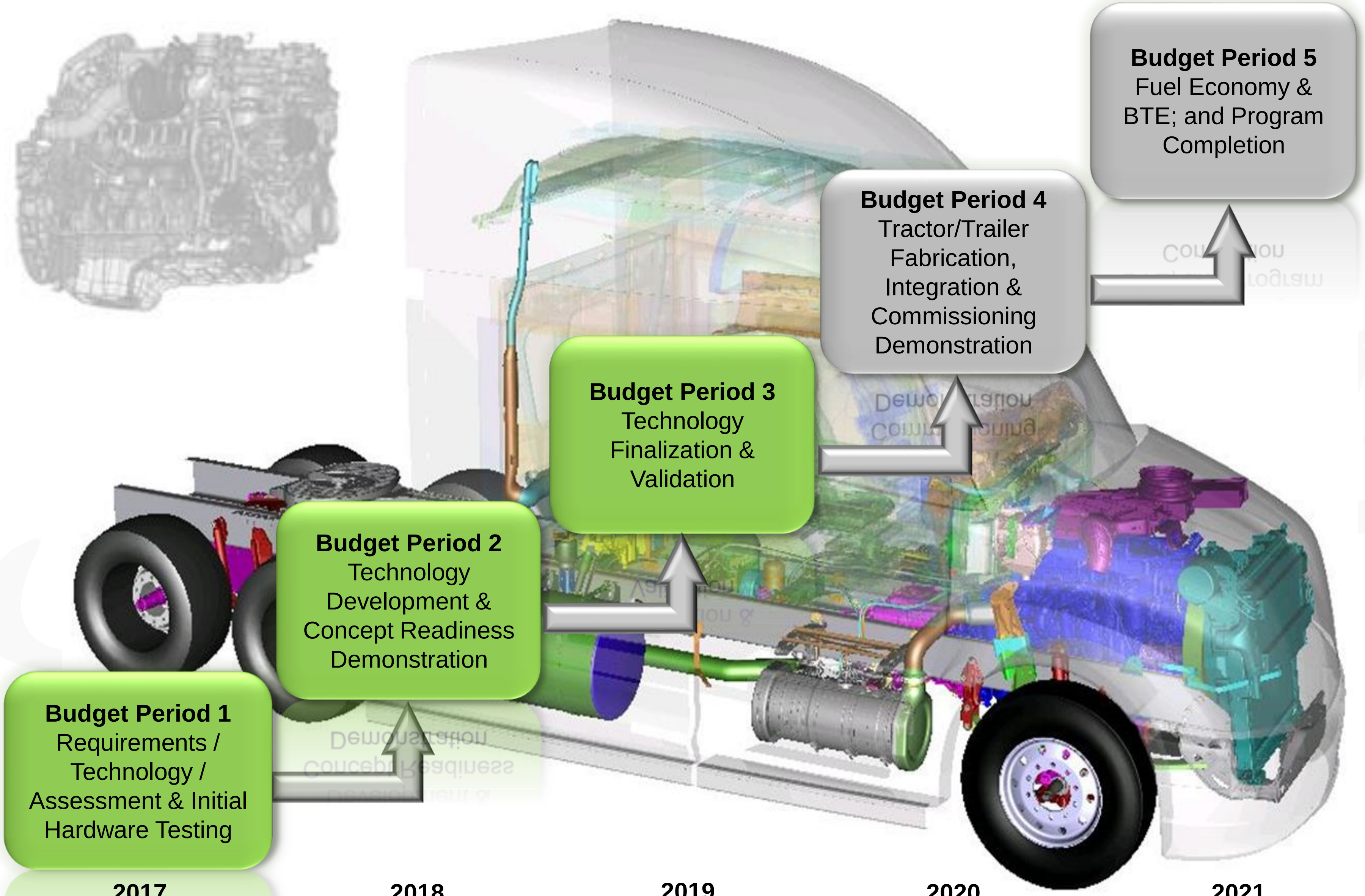
DOE Share	$20M
Navistar Share	$35M

Partners and Laboratories

- Argonne National Laboratory
- Lawrence Livermore National Laboratory
- Bosch
- TPI Composites
- Dana
- J.B. Hunt Fleet Partner

Working together to develop, evaluate, and implement technologies needed to fulfill the promise of fuel efficiency, environment protection, and operational efficiency

Relevance: Program Milestones and Progress



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

2017 **2018** **2019** **2020** **2021**

Budget Period 3 Milestones

i. *Economic and energy impact analyses of component technologies*

ii. *Down-selection of in-cylinder combustion systems*

iii. *Down-selection of Waste Heat Recovery (WHR) system development.*

iv. *Down-selection of hybrid powertrain systems*

v. *Down-selection of drivetrain and chassis efficiency improvements*

vi. *Down-selection of improved aerodynamics*

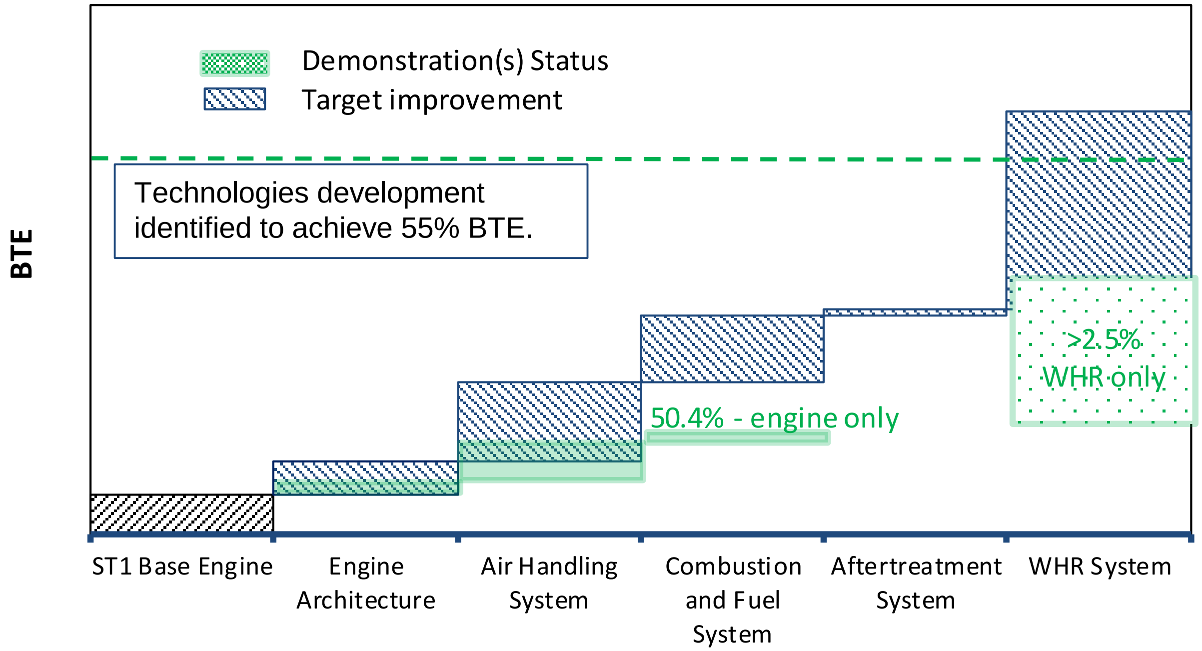
vii. *Down-selection in advanced vehicle electrification system*

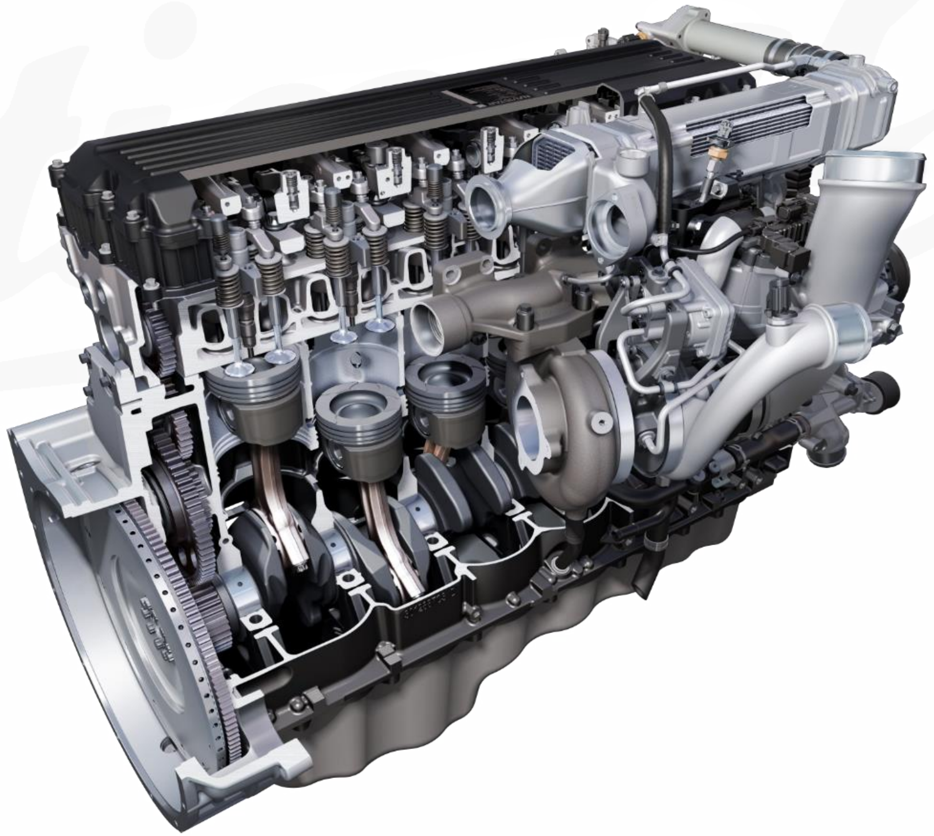
viii. *Down-selection of advanced aftertreatment systems*

Engine: Technical Accomplishments & Progress

Chief Engineer
Jim Cigler

- Attain greater than or equal to 55% BTE demonstrated in an operational engine at a 65-mph cruise point on a dynamometer while meeting prevailing emissions.
- 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

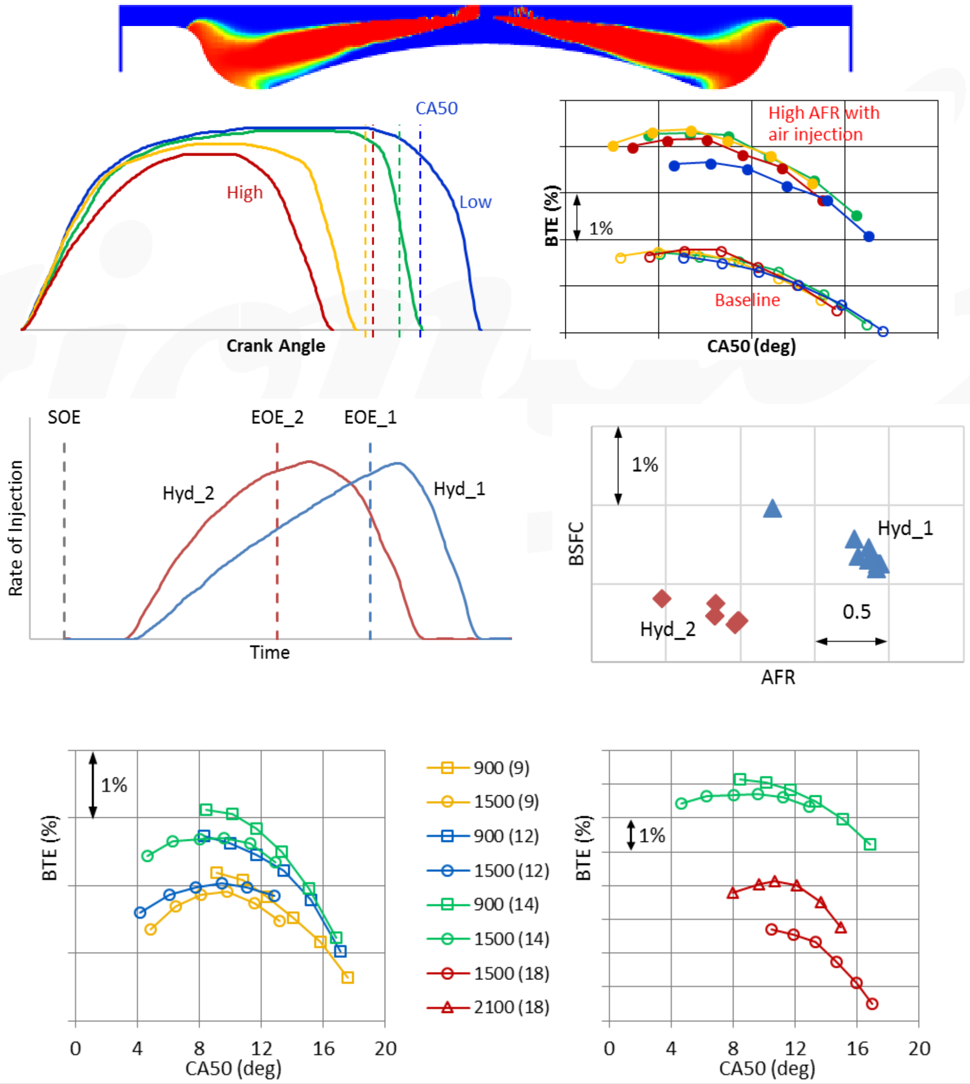
Combustion & Fuel System

Accomplishments

- Continued to incorporate measured results and testing feedback into combustion simulation process
- Built new fuel injectors with variation in number of holes, nozzle flow rates, and rate of injection including internal orifice modification
- Measured improvements in combustion efficiency accompanied by further increases in peak cylinder pressure
- Evaluated the nozzle variations over expected evolution of operating conditions

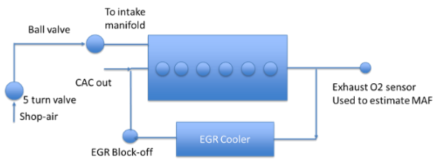
Next Steps

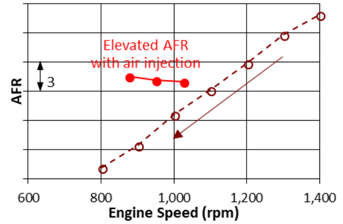
- Investigate spray formation through visualization
- Utilize all feedback to update bowl geometry investigations
- Evaluate new combinations

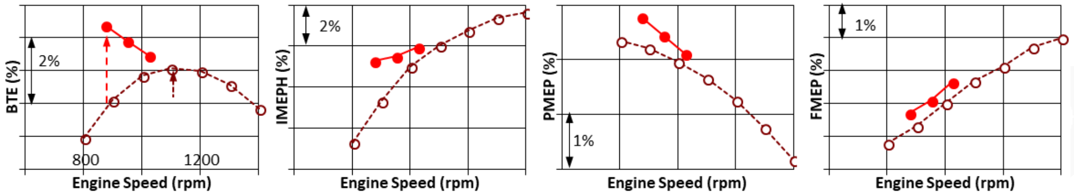


Air Management

BorgWarner





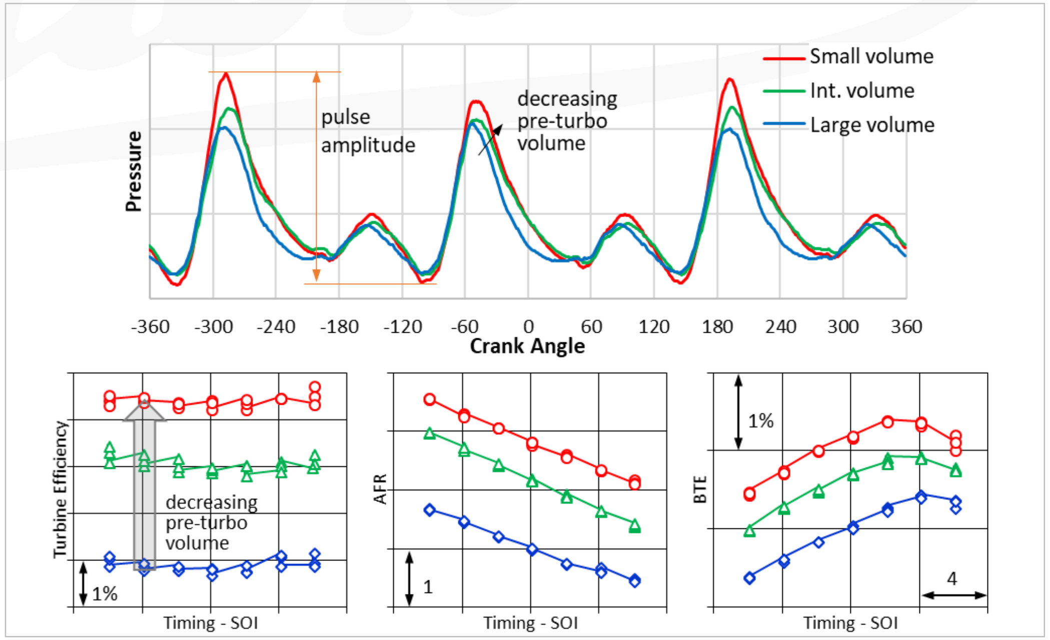


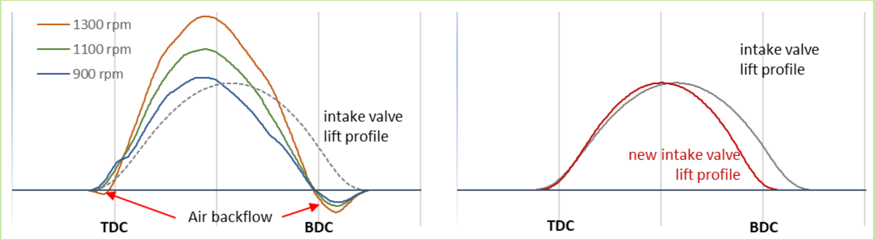
Accomplishments

- Utilized test rig to evaluate and establish requirements for high-efficiency turbochargers
- Investigated variations in the pre-turbo volume for exhaust pulse optimization
- Re-optimized intake valve profile to improve the gas exchange process

Next Steps

- Redesign exhaust manifold and EGR system based on re-turbo volume results
- Evaluate new turbochargers matched to updated specifications
- Evaluate new cam profiles based on updated conditions





Engine: Technical Accomplishments & Progress

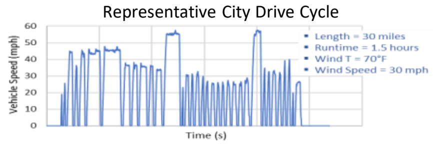
Cylinder Deactivation

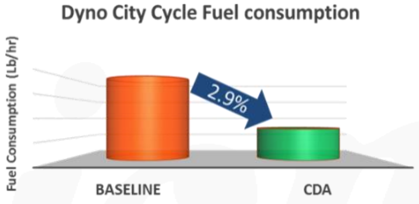
Accomplishments

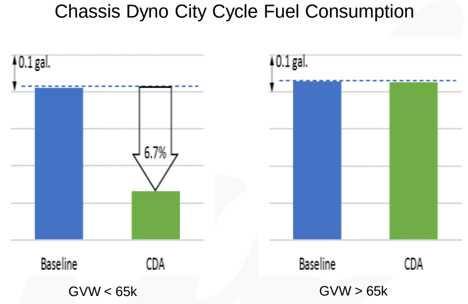
- Implemented dynamic control system for transient operation
- Calibrated deactivation and reactivation details
- Demonstrated drive cycle FE impact on engine and vehicle dynamometers

Next Steps

- Update actuation system with updated design and calibrate for ST2 vehicle operation







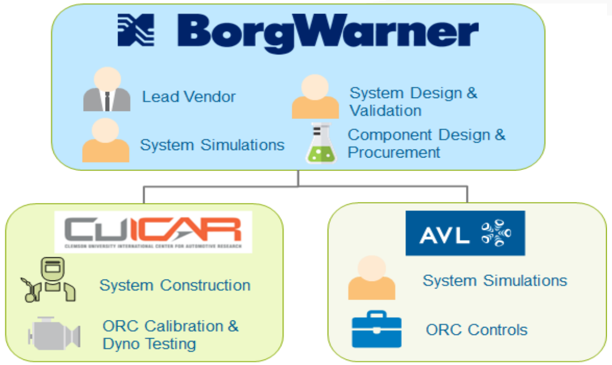
WHR & System

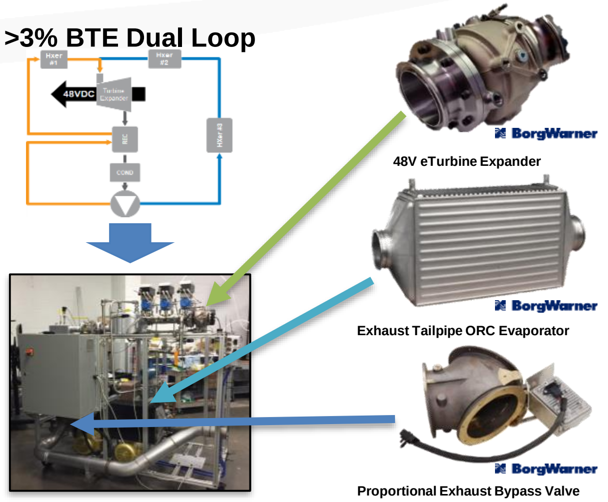
Accomplishments

- Functional demonstration system assembled
- Measured over 2.5% BTE contribution
  - Expander efficiency >73%
  - Evaporator efficiencies >80%
- Implemented CAN-based ORC Control System
- Initial control system model calibrations populated
- Identified updates to achieve >3.0% BTE contribution

Next Steps

- Update hardware with final design specifications and software updates
- Update system control model calibrations
- Insulate critical components





Engine: Technical Accomplishments & Progress

Gasoline Compression Ignition

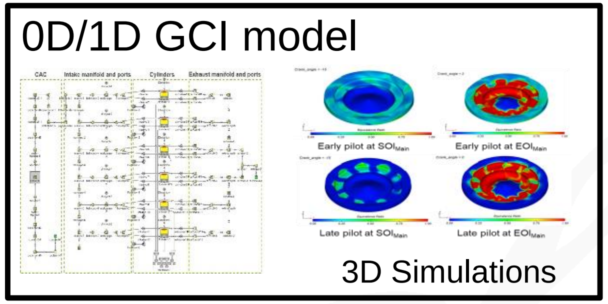
Accomplishments

- Developed a 0D GCI model to gain insight into fundamental processes in and around fuel injection and GCI combustion.
- Validated 1D GT-Power model and 3D CFD simulations for multiple injection strategies (PFI/DI, early pilot and late pilot).
- Improved engine operation at low load and smooth cold-start with 20.5 CR and reduced injection pressure resulting in higher cylinder pressure-temp
- BTE improvement from 2019 efforts: 1.3% for early pilot and 0.7% for late pilot injection strategy (shown here).

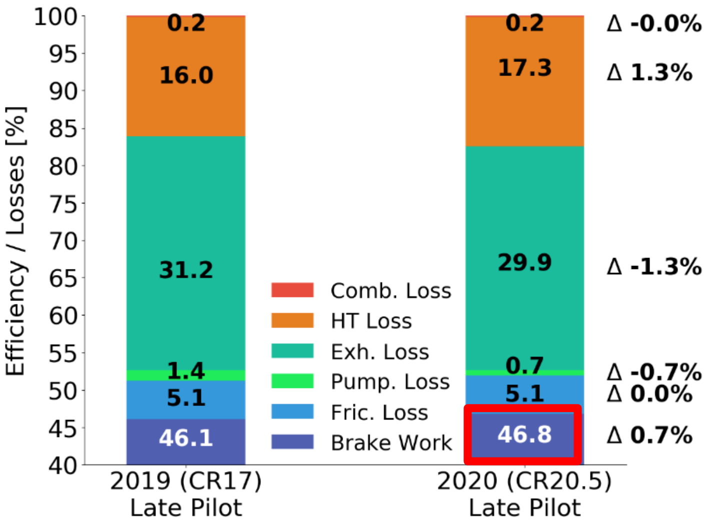
Next Steps

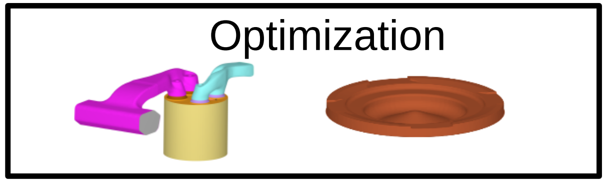
- Combine optimization of injection strategy and piston geometry through 3D CFD to improve GCI combustion.
- Improve thermal management with updated engine hardware.
- Optimize operating conditions to maximize efficiency gain over CR17 with use of modified boosting system.

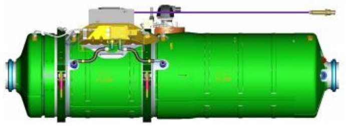
Argonne NATIONAL LABORATORY



A50: 1038rpm, 14bar BMEP - Tier II EEE

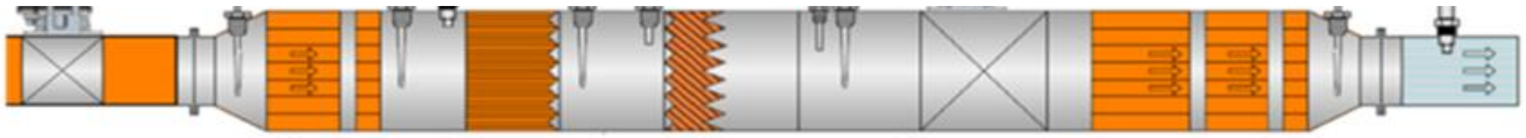






Emission Control
Performance Demonstration

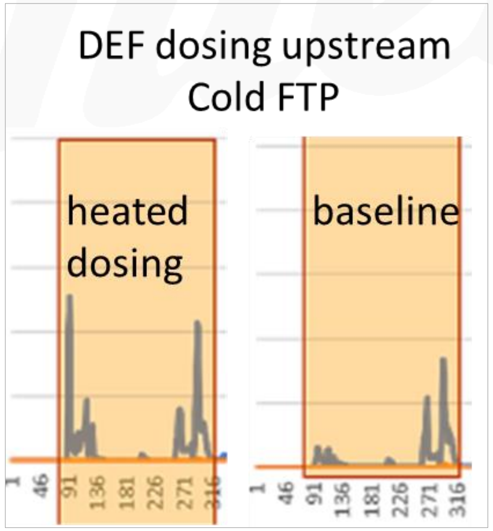
- Upstream SCR/AMOX combination required to minimize NH_3 slip to the DOC
- High selectivity of N_2O observed when NH_3 exposed to the DOC/DPF
- Copper formulation shows high NOx conversion at lower temperatures
- Copper formulation did not show high N2O formation that has been reported when
- catalyst is located downstream of DOC/DPF
- “Main” SCR components have long thermal lag and do not achieve light-off until 600 seconds in the cold FTP. The used of the upstream SCR adds to this thermal lag
- Potential for component size reduction: DOC delete and smaller ‘main’ SCR



Aftertreatment: Technical Accomplishments and Progress

Earlier Introduction of DEF

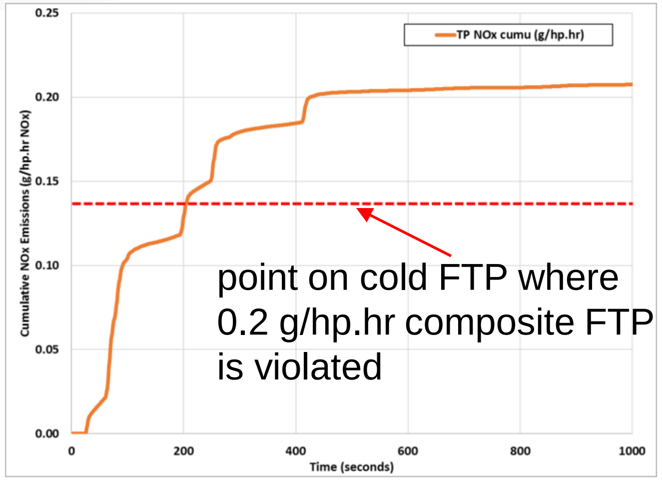
- Heated diesel exhaust fluid (DEF) injector was used in the upstream location
- New injector allowed earlier introduction of reductant (150° versus 190°C)
- Better vaporization observed which allowed higher DEF dosing at similar UI target
- Benefit over very small portion of cold FTP



Challenges to Ultra-Low NOx

- Ability to meet ultra-low NOx is primarily a function of start of high NOx conversion
- Minimizing EO NOx during the period where NOx conversion is < 90% or thermal management actions results in fuel penalty
- High EO NOx can meet 0.2 g/hp.hr but Navistar needed to lower EO NOx for 0.05 g

Cumulative TP NOx on cold FTP

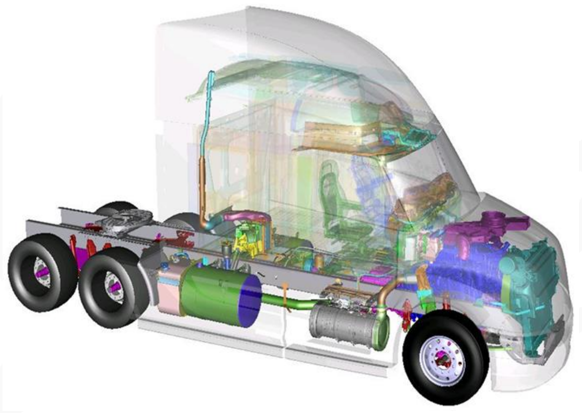


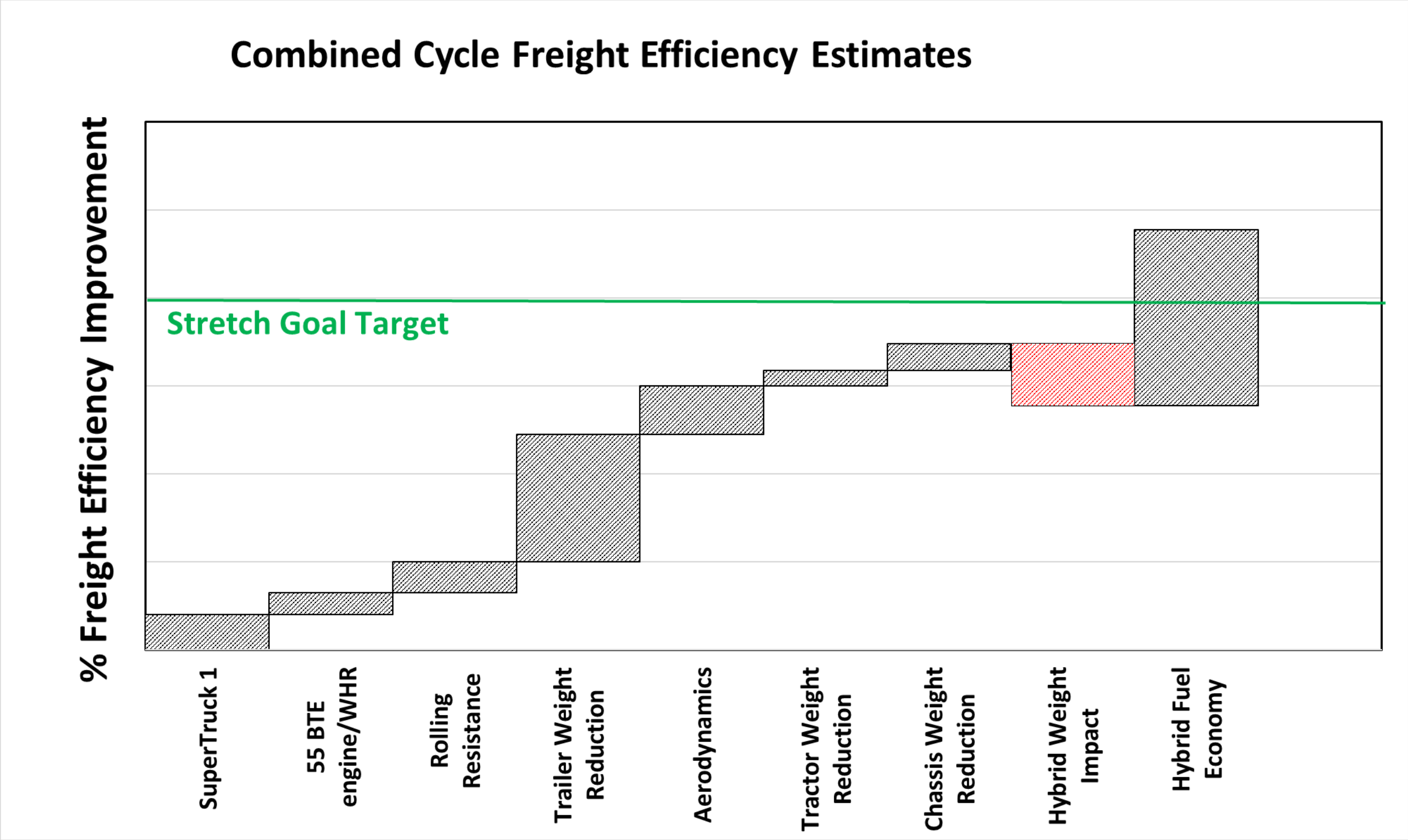
Vehicle: Objective and Approach

Chief Engineer
Dean Oppermann

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
- Stretch goal of >140% improvement
- Development of technologies that are commercially cost effective in terms of a simple payback

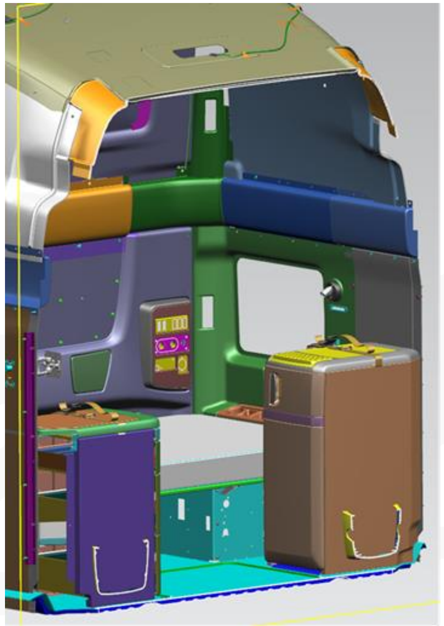




Vehicle: Technical Accomplishments and Progress

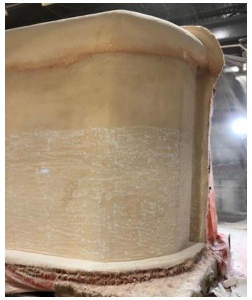
Aerodynamics

- Frozen aero surface design, including tradeoff evaluations
- Mounting design of aero components 50% complete
- Interior trim package determined
- Frozen trailer box aero surface design
- Trailer fabrication started:
  - Trailer tooling fabricated
  - Trailer material on order
- Trailer "underbelly" aerodesign complete
  - Mounting strategy and fabrication feasibility study complete

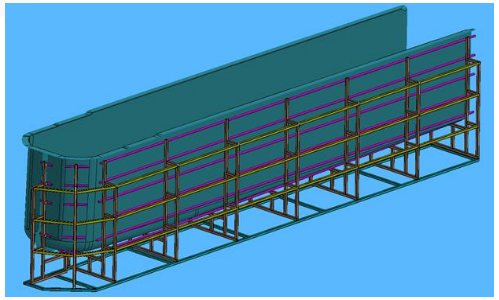


Sleeper Portion of the Tractor

Completed Trailer Plug, Transported On Trailer



Mold Material Added To Trailer Front



CAD Model of Truss Structure

Steel Structure Being Built

tpi COMPOSITES.

Vehicle: Technical Accomplishments and Progress

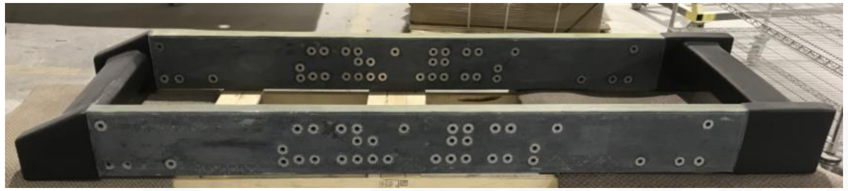
Chassis Weight Reduction

- Frame rail design direction made; move forward with HSS option and continue evaluation of composite option analytically and through bench testing:
  Reasons for decision:
  - Thermal loading concerns
  - Localized areas of stress
  - Manufacturing feasibility and weight
  - Time and resource allocation

- Composite framerail:
  - Accessory mounting investigations
  - Modal FEA
  - Test samples manufactured for shaker demonstration

- HSS framerail development:
  - Modal FEA testing of 5 different shapes
  - Material testing of HSS options
  - Frozen shape and thickness
  - Redesign of single and multi-piece cross members

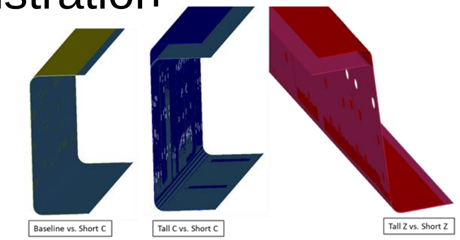
Composite Cross Member



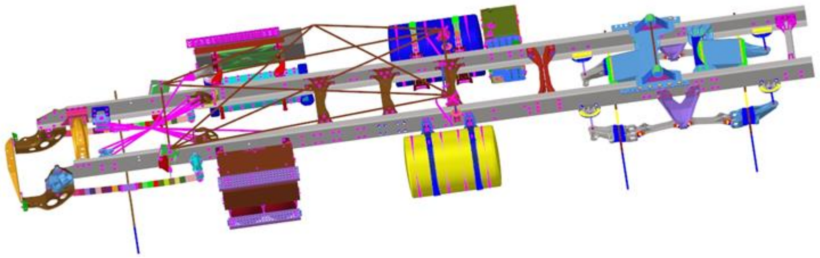
Assembled Frame Rail Section

Box Section Frame Rails With Suspension Mounting Holes

Composite End Cap Structure



Frame Rail Cross-Member Dimensions

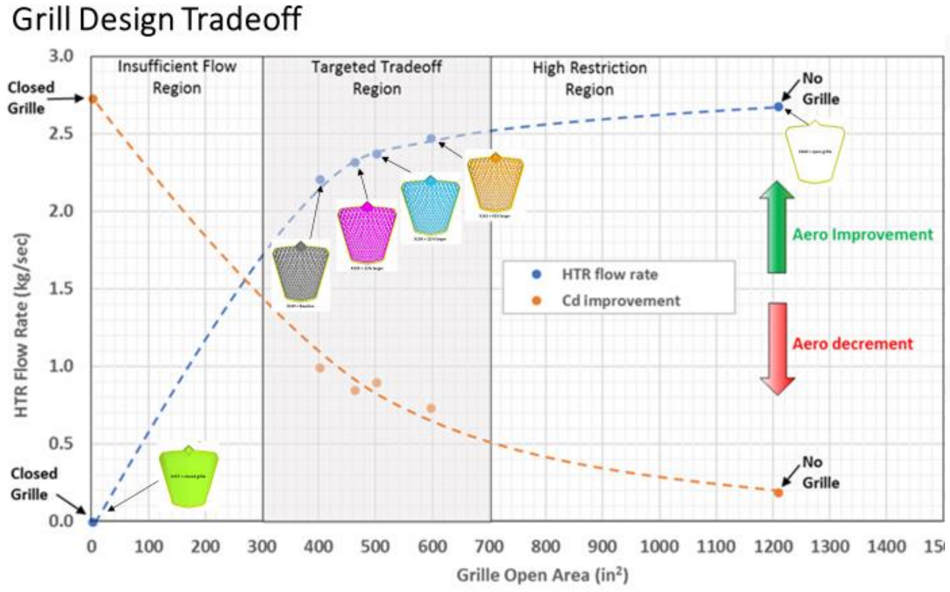


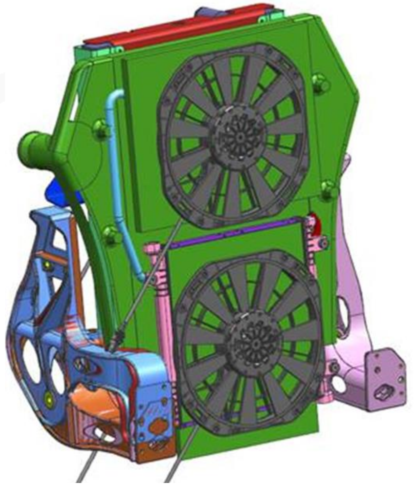
Chassis Frame Used for FEA Modeling

Advanced Cooling

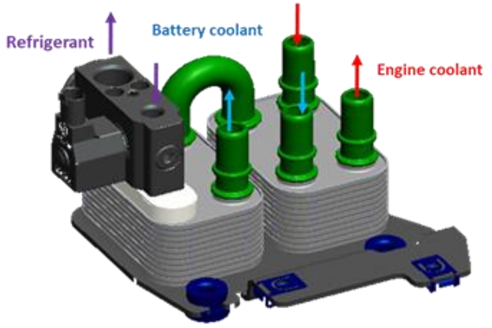
Optimizing cooling-system configuration for vehicle tradeoffs:

- Vehicle aerodynamics vs grill-flow study complete
- Cooling module packaging studies
- Individual fan control strategy development
- AC condenser location study completed
- CAC end-tank design simulation
- Active battery conditioning:
    - Module selection
    - Packaging
    - Controls development





Exchanger Package

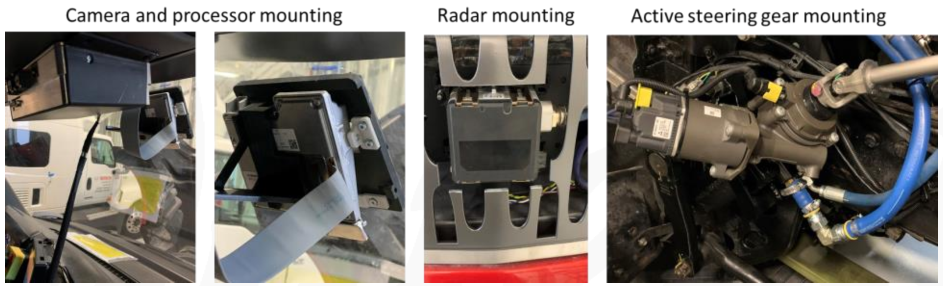


Multiple Ports On The Secondary Heat Exchanger

Vehicle: Technical Accomplishments and Progress

Powertrain

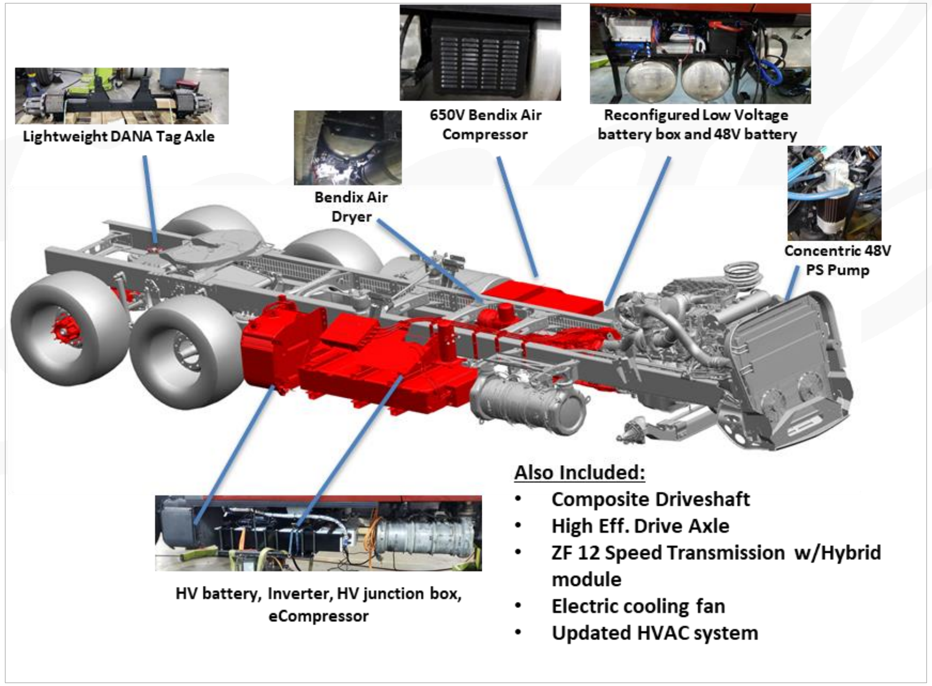
- Completed mule vehicle update with Hybrid, zero-Emission technologies
- Completed mule vehicle update with Sensor Fusion Technologies (Camera/Radar)



Sensor Fusion Hardware Installed Into Navistar Mule Vehicle

- Completed mule vehicle update with electronic braking system (EBS)
- Started System Integration and Calibration

Navistar Mule Vehicle On Navistar's Test Track (Melrose, Park, IL)



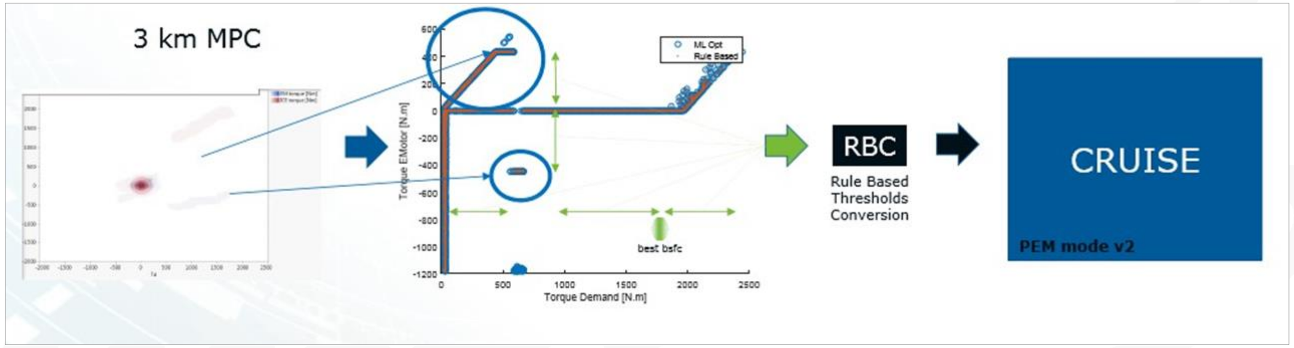
Vehicle Chassis Upgrade: New Hardware Illustrated

Connected Cruise Control

- Completed co-simulation of MPC Simulink model with CRUISE plant model for Hybrid fuel-economy improvements

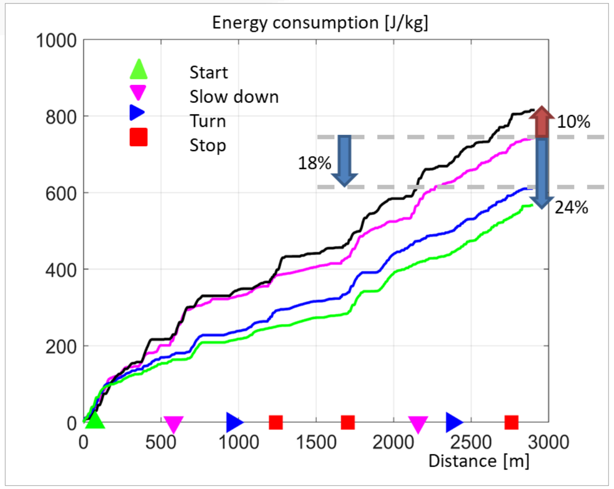
- Continued development of Predictive Cruise Control (PCC) strategy
  - Feature additions
  - Migration of plant model to SimuLink

- Continued co-development of PCC / Adaptive Cruise Control (ACC) with University of Michigan:
  - Hardware update of Mule vehicle
  - Testing on defined route multiple drivers
  - Energy consumption analysis



Progression of Model Development: Heat Map, eMotor Optimum Usages, and Analysis

Navistar Proving Grounds
(New Carlisle, IN)



Plot of Distance vs Energy Consumption

Remaining Challenges and Barriers

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

Continue efforts:

- **Engine**
  - ✓ Waste Heat Recovery (WHR) system development
  - ✓ Engine-aftertreatment system performance calibration/optimization.
  - ✓ Powertrain Assembly and Integration: Commission powertrain assembly on a dynamometer
  - ✓ Demonstrate 55% BTE capability while meeting prevailing emissions

- **Vehicle**
  - ✓ Interface requirements of composite Cab/Sleeper to a class 8 tractor
  - ✓ Hybrid energy balance control and optimization
  - ✓ PCC/ACC speed control & optimization for fuel economy
  - ✓ Demonstration vehicle build and test

Responses to 2019 Comments

Categories	Reviewer Comments	Navistar Response
Approach to performing the work - the degree to which technical barriers are addressed, the project is well-designed and well-planned	In general, comments are positive, noting that Navistar has clearly defined objectives; a realistic approach. One reviewer commented that Slide 15 covers all key technology areas, thus providing a reasonably good opportunity to achieve the program goal. **However, it was <u>not clear to the reviewer why a gasoline engine is being used in this program</u>.**	The light load at cruise speed and level of power that a gasoline engine provides could potentially be a low-cost option – especially with a heavy electrification powertrain to provide the required torque for hill climbs.
Technical Accomplishments and Progress toward overall project goals—degree to which progress has been made and plan is on schedule.	Reviewers indicated that technical progress appeared good to the reviewer and advanced well beyond ST I. **It was noted that <u>Slide 13 seemed to use one long box in a sequence manner, which is not efficient packaging</u>.**	This is a model-based diagram. A packaging study has been completed for the system.
Proposed Future Research - degree to which the project has effectively planned future work in a logical manner by incorporating appropriate decision points, considering barriers to realization of proposed technology, and, when sensible, mitigating risk by providing alternate development pathways.	Reviewers agree that future projected work appeared to be thought-out with risk and unforeseen events properly considered.	Navistar development pathways were not expressly discussed due to the complex evolution of potential changes. The presentation provided direction that results-based flexibility would guide future work.

Thank you