Navistar SuperTruck II

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

Vehicle Systems (Project ID: ACE103)

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

Principal Investigator: Russ Zukouski
Navistar, Inc.

DOE 2021 ANNUAL MERIT REVIEW
June 21 – 24, 2021

Presented for Navistar by:
Principal Investigator: Russ Zukouski
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:	80%

Technical Targets

- Greater than or equal to 55% engine brake thermal efficiency (BTE) while meeting prevailing emissions
- Greater than 100% improvement in vehicle freight efficiency (FE) (on a ton-mile-per-gallon basis)
- Development of technologies that are commercially cost effective in terms of a simple payback

Budget

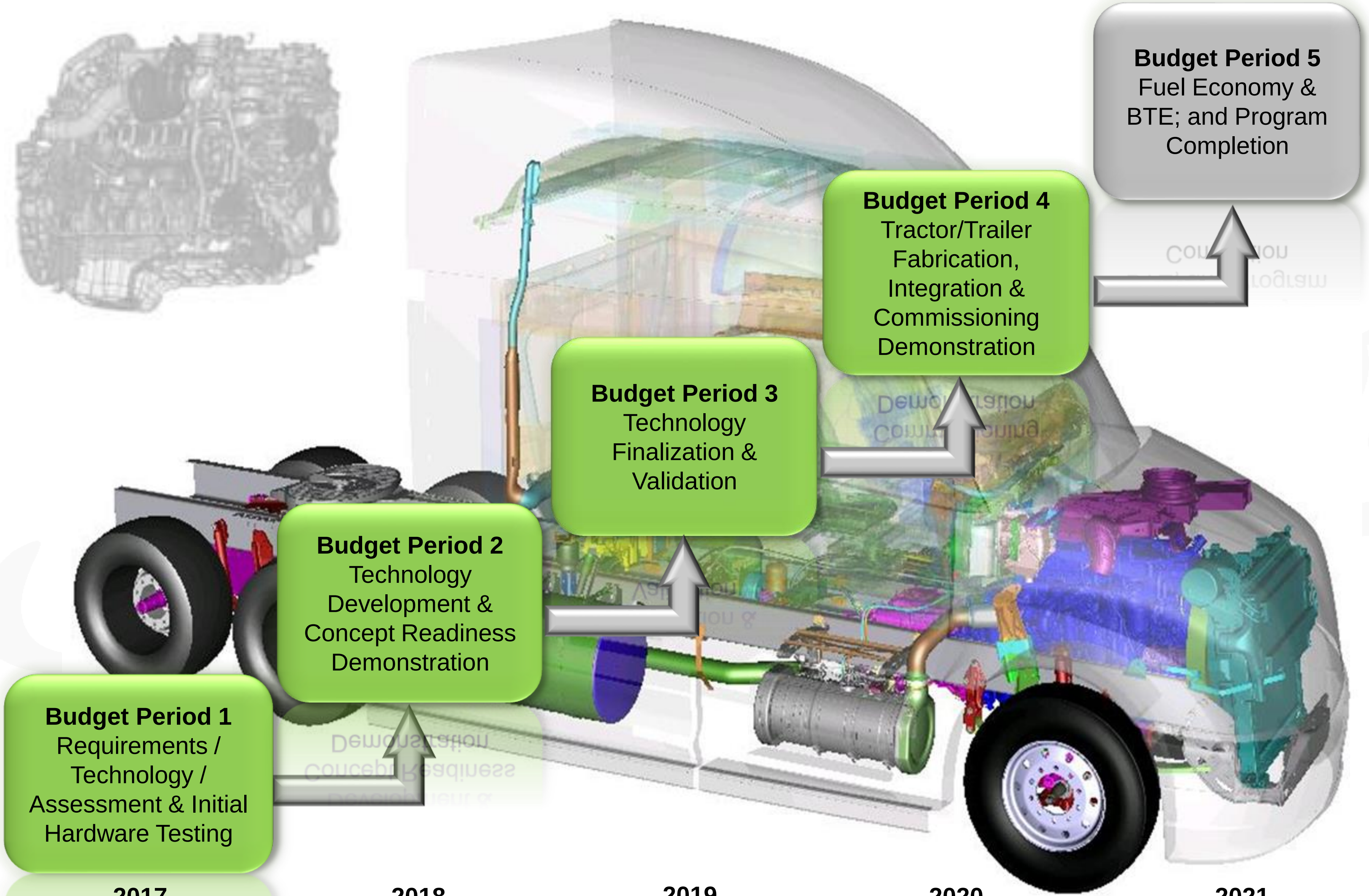
Total Project Funding:

DOE Share	$20M
Navistar / Partners Share	$35M

Project Partners

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

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 4 Milestones

i. *Technology assessment and selections for further prototype development*

ii. *Performance optimization of engine-aftertreatment systems*

iii. *Design-economics analysis*

iv. *Commercial viability study and cost estimates; report*

v. *Procurement of components*

vi. *Assembly and integration of powertrain; performance report*

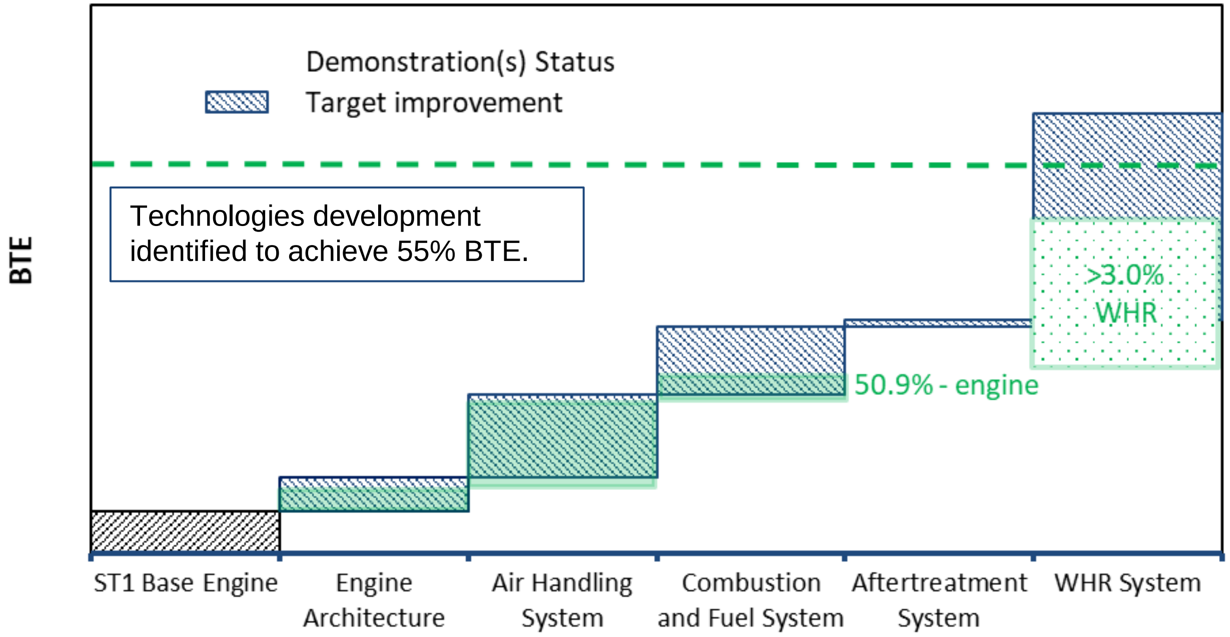
vii. *Assembly and integration of tractor assembly*

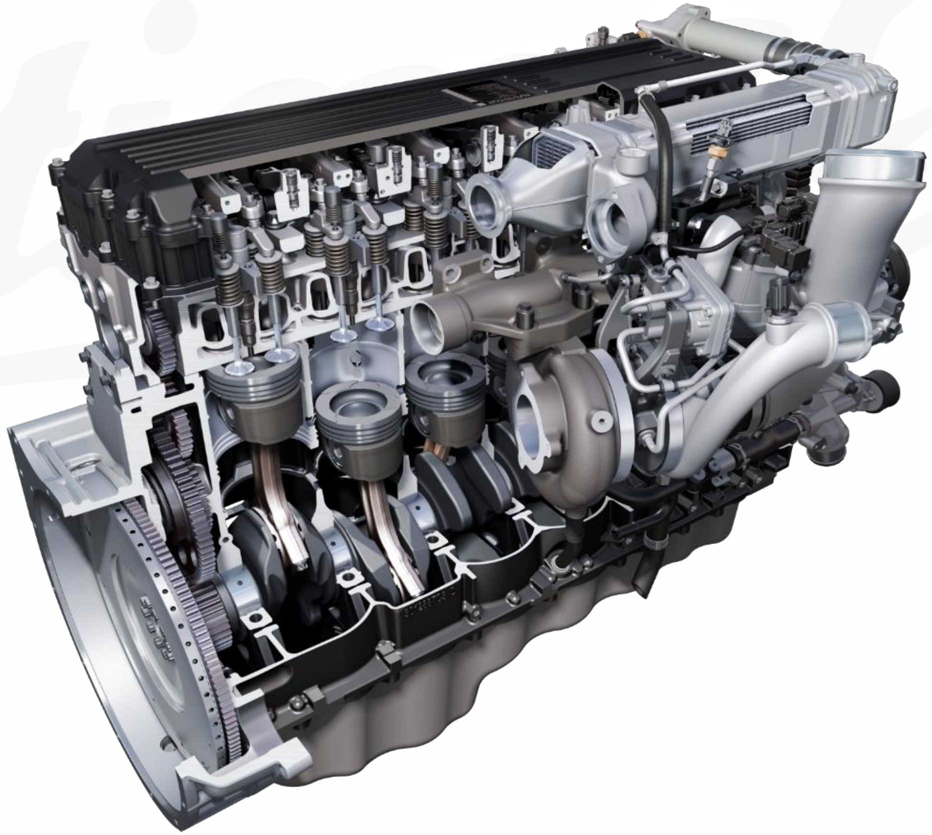
viii. *Vehicle commissioning*

Engine: Objective & Approach

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





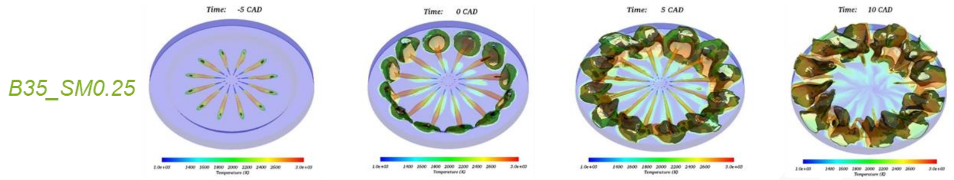
Combustion & Fuel System, Friction

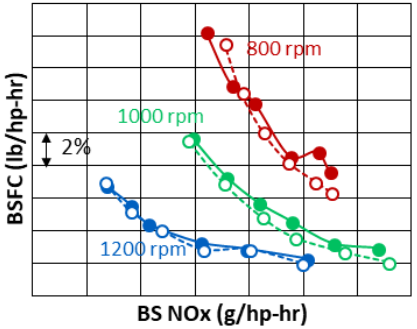
Accomplishments

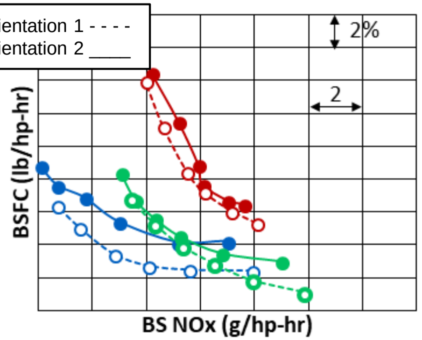
- Continued to incorporate measured results and testing feedback into combustion simulation process
- Utilized genetic algorithms for bowl geometry re-optimization
- Evaluated new fuel injectors with variation in number of holes, nozzle flow rates, and rate of injection including internal orifice modification
- Evaluated 3-injector/cyl. engine based on the work of Okamoto, T. and Uchida, N., SAE 2016-01-0729, with significant refinements required
- Evaluated surface treatments on power cylinder components to enable lower viscosity lubrication

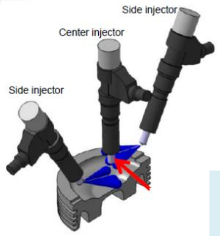
Next Steps

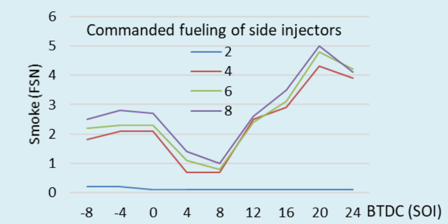
- Final bowl selection and evaluation
- New combustion system with high flow cylinder head

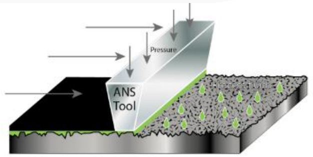




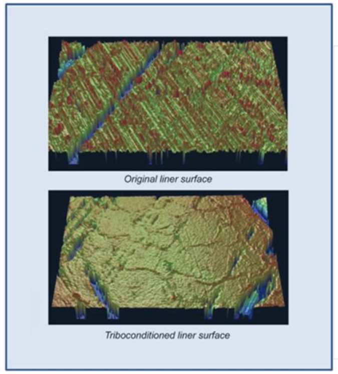


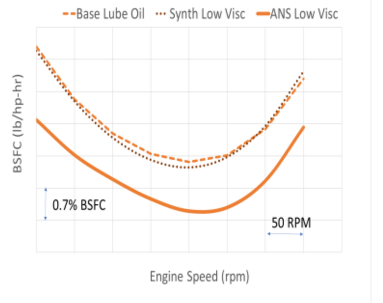






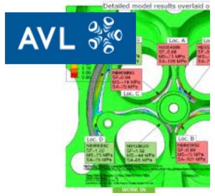
Applied Nano Surfaces





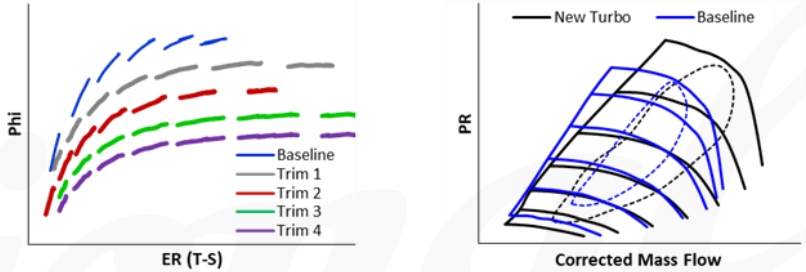
Engine: Technical Accomplishments & Progress

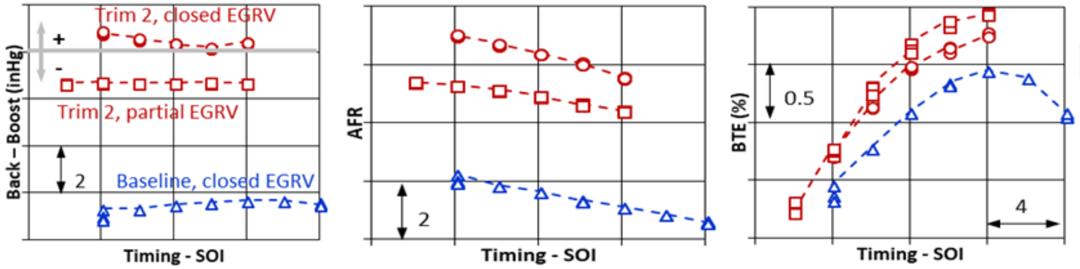
Air Management



Accomplishments

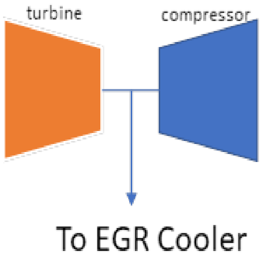
- Demonstration of improved flow cylinder head ports
- Updated cylinder head design and procurement
- Simulation of new intake valve timings to match new cylinder head flow and turbo performance
- Simulation of valve timing including Miller cycle
- Demonstration of re-matched turbochargers
- Simulation and demonstration of alternate EGR technology

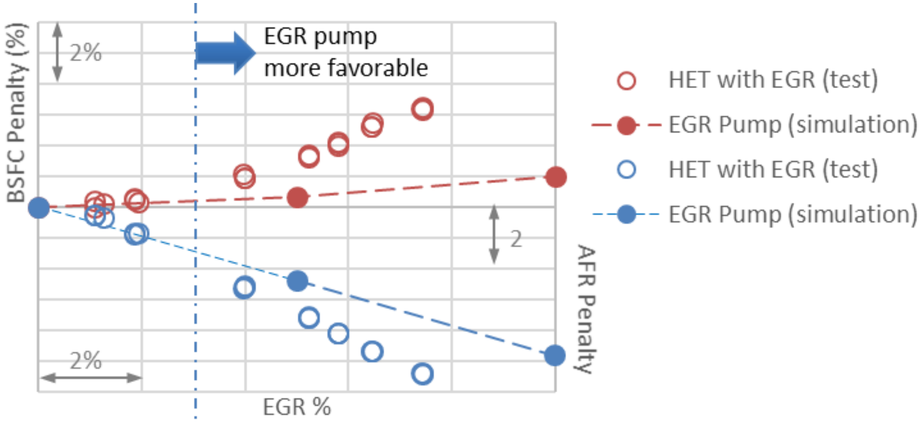




Next Steps

- Demonstration of updated cylinder heads
- Incorporate final turbocharger matches
- Assemble and calibrate new engines for 55% demonstration





Engine: Technical Accomplishments & Progress

Cylinder Deactivation

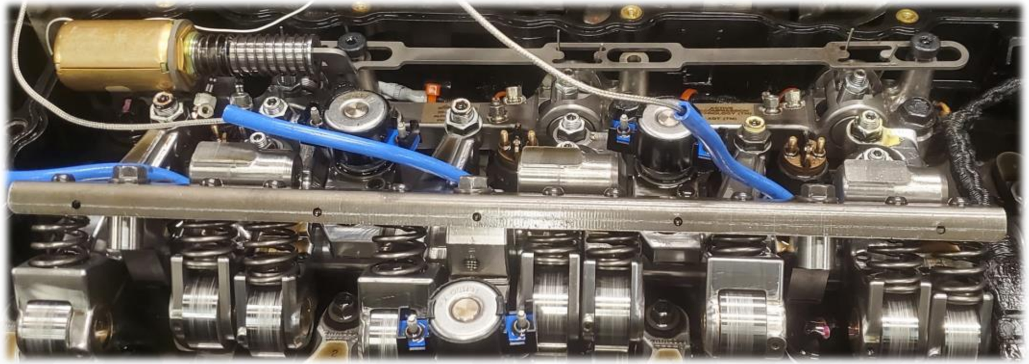
Jacobs Vehicle Systems®

Accomplishments

- Assembled a High-Power Density (HPD)+Cylinder Deactivation Actuation (CDA) system with Active Decompression Technology (ADT) system on an ST2 engine
- System tuning and demonstration at Jacobs
- Evaluated controls updates for more precise transitions

Next Steps

- Calibrate the system in a dyno test cell for truck demo operations
- Support ST2 final demonstrations



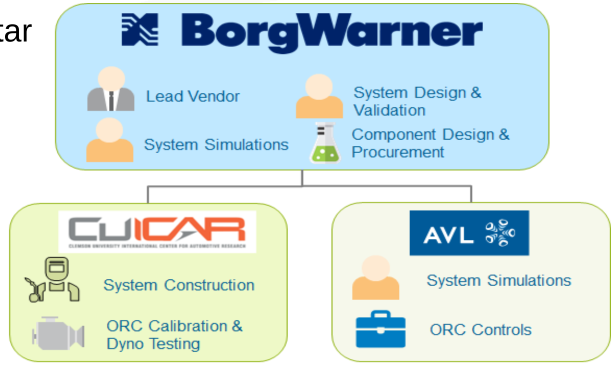
WHR & System

Accomplishments

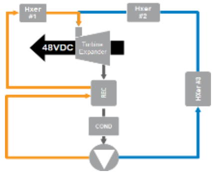
- Completed system control model calibrations
- Insulated critical components
- Demonstration at Clemson University was successfully repeated at Navistar (achieved >3.0% BTE contribution with the 55% BTE operational target boundaries achieved using a mule A26 engine)
- Updated hardware and software with final design specifications

Next Steps

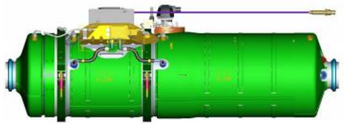
- Build lower restriction configurations and alternate match expanders
- Test a ST2 engine with the final design specifications of WHR system for the demo (target: total BTE of 55%)



Dual Loop ORC

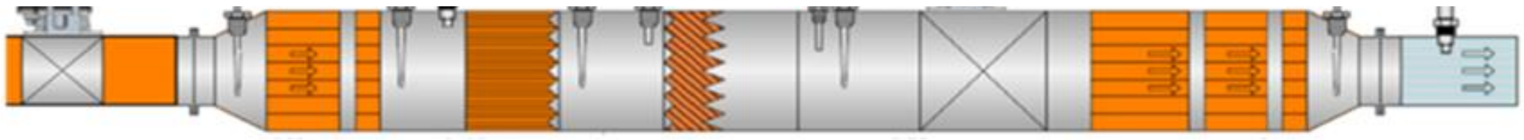


Aftertreatment: Objective & Approach



Emission Control
Performance Demonstration

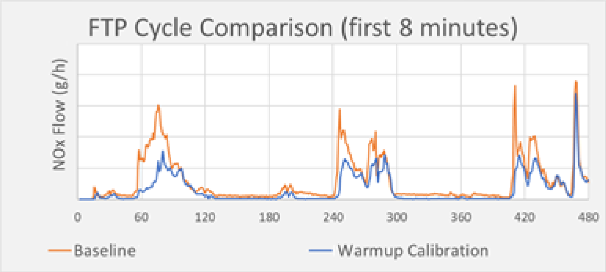
- Upstream SCR/AMOX combination required to minimize NH_3 slip
- High selectivity of N_2O observed when NH_3 exposed to the DOC/DPF
- Improved cold start calibration to minimize TP NOx
- Electric heater provides earlier light-off for downstream SCR
- Heated DEF dosing allows earlier introduction of reductant
- Ultra-Low TP NOx can be achieved, but durability and fuel penalty not determined

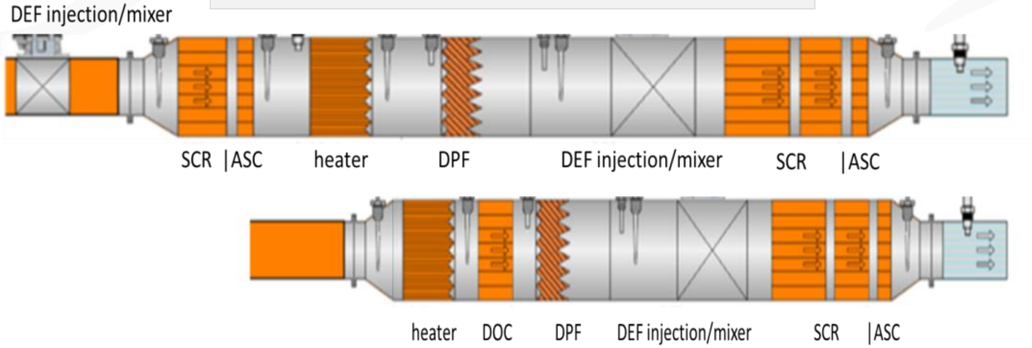


Aftertreatment: Technical Accomplishments & Progress

Improved Cold Start Performance

- Lower EO NOx during cold start
- Electric heater located after upstream SCR/ASC for dual DEF dosing layout
- Electric heater located upstream for single DEF dosing layout
- Benefit only for cold start / low load cycles

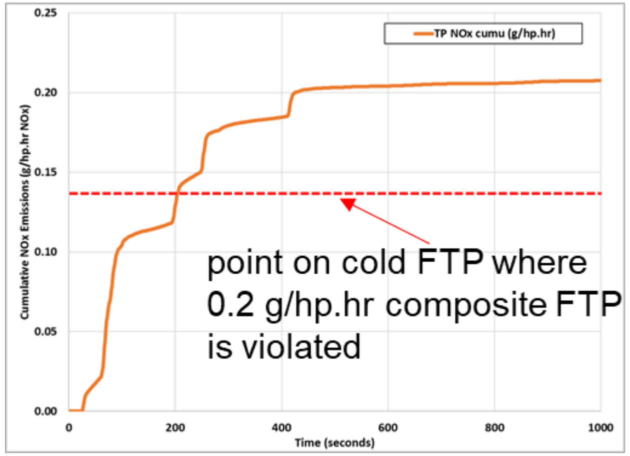




Challenges for TP NOx

- Exhaust gas temperatures need to maintain SCR > 200°C for high 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
- Durability needs to be validated

Cumulative TP NOx on cold FTP

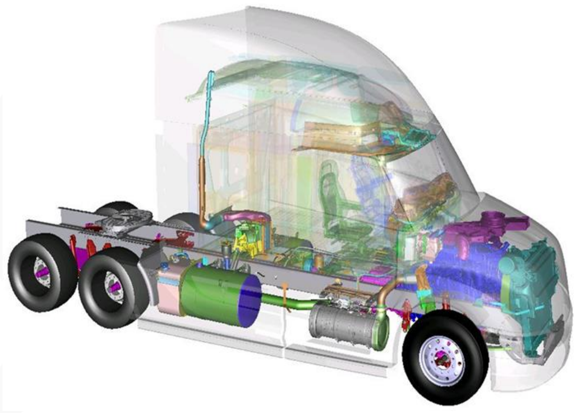


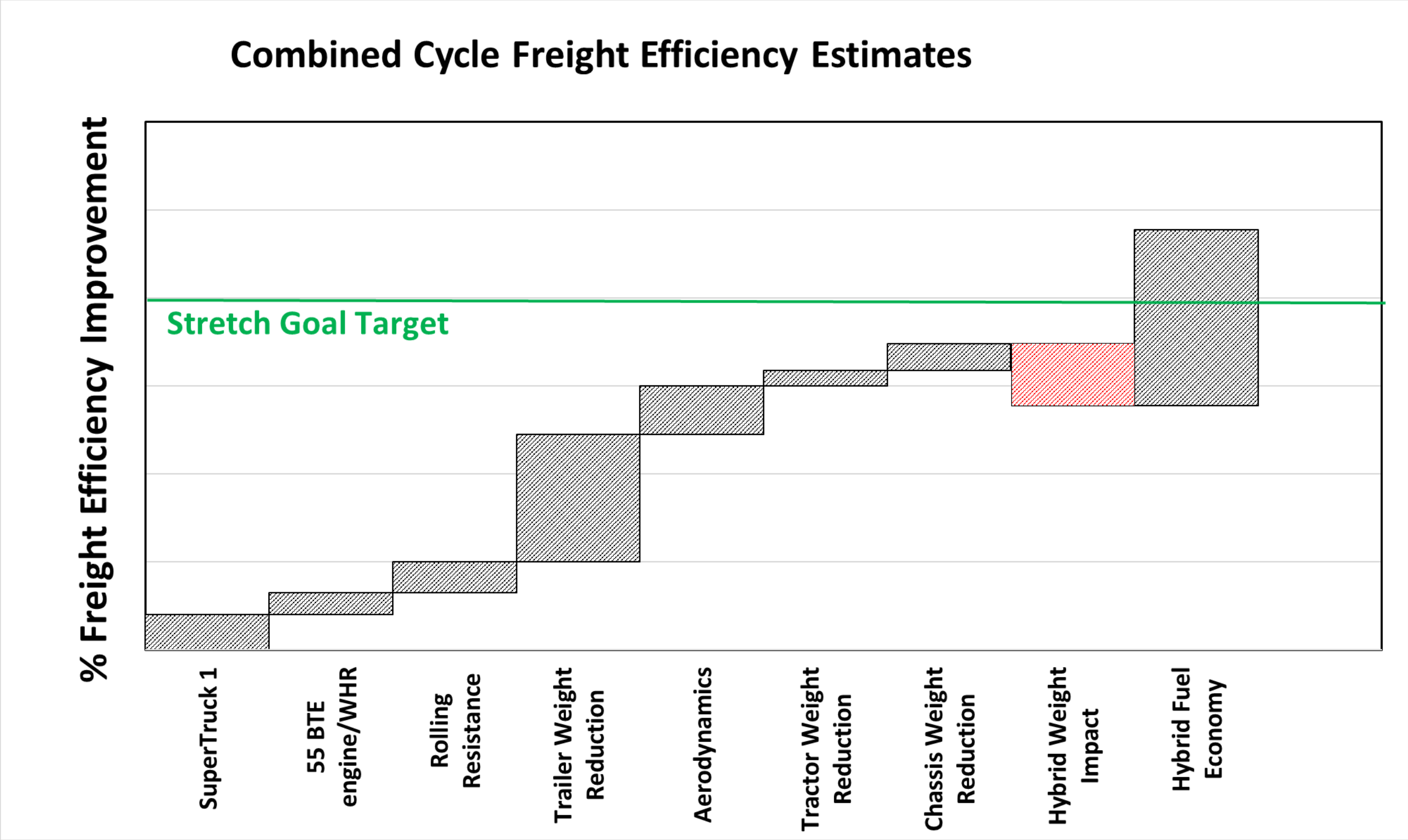
Vehicle: Objective & Approach

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

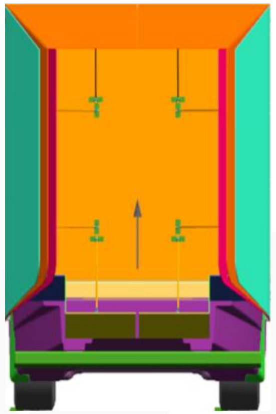
Chief Engineer
Dean Oppermann

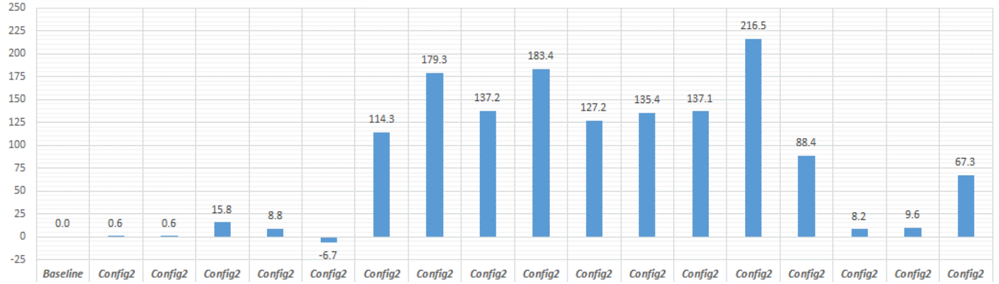




Aerodynamics

- Completed CFD analysis of adjustable aerodynamic components for nominal targeting
    - Boat Tail
    - Cab side extenders
    - Drive wheel deflectors
- Completed component-level CFD evaluations for business case analysis of add-on aerodynamic devices
    - Trailer
    - Trailer underfloor aero devices
    - Boat tail comparison
    - Tractor aerodynamic components
- Completed attachment designs for tractor and trailer aero Surfaces



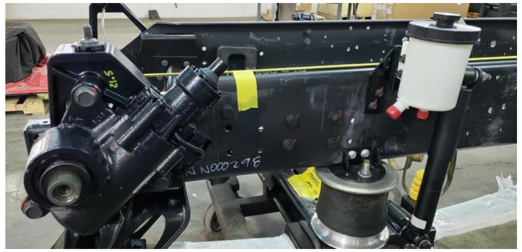


Chassis Build Status

- Frame Ladder Assembly Completed
  - High strength steel frame rails with tuned form factor
  - Aluminum Multi piece cross members
  - 2-piece radiator brackets

- Suspension Installation Completed
  - Light weight Hendrickson HTB Rear Suspension
    - Prototype DANA down sped RAR
    - Light weight
  - Modified Hendrickson AirTech NXT front suspension

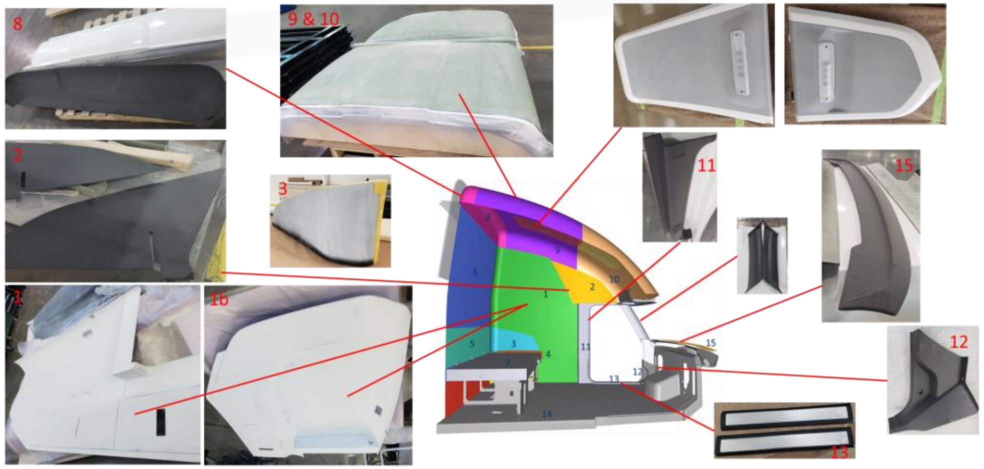
- Steering Installation In Process
  - Kinematic review completed
  - Design finalized
  - Electric assist steering gear and accessories installed



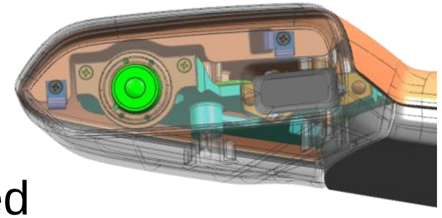
Tractor Build

- Composite Cab/Sleeper
  - Cab/Sleeper assembly fabricated and delivered
  - Doors assemblies fabricated and delivered
  - Interior trim component design completed
  - Prototype trim components fabricated
  - Trim components dry fit (in process)

- Aero Devices
  - Chassis skirts fabricated and delivered
  - Hood components (molds in process)
  - Accessory devices (molds in process)



- Powerfold Camera design
  - Camera pod position frozen
  - Mounting provisions frozen
  - Bracket and cover design completed
  - Hardware fabrication (in process)



Vehicle: Technical Accomplishments & Progress

Trailer Build Status

- Box fabrication completed
  - Integrated/bonded cross members
  - Fiberglass composite with localized carbon reinforced
  - Aluminum rear door assembly
  - Steel king pin plate assembly
- Slider assembly installation
  - ULTRAA-K lightweight tandem slider
  - TABS controller module
  - Low RR super singles
- Solar panel assembly installation
  - Reconfigured panels for "Back Bone" harness
  - Wireless communication
- LED lights with Rowe iPDM power distribution

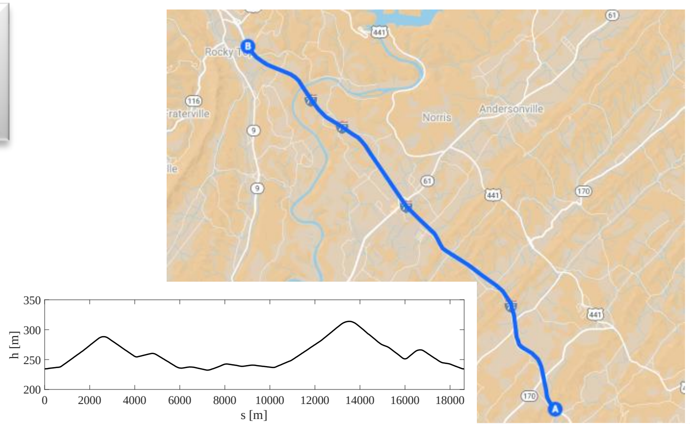
HENDRICKSON

Continental
The Future in Motion

Bendix

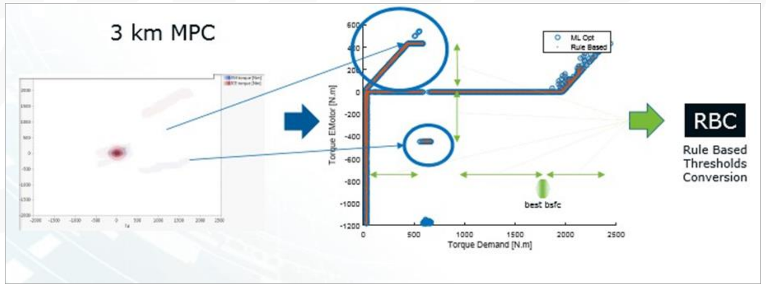
Control Development and Integration

- Continued co-development of integrated PCC+ACC:
  - Road test with real traffic data using the mule vehicle
  - Performance analysis concluding



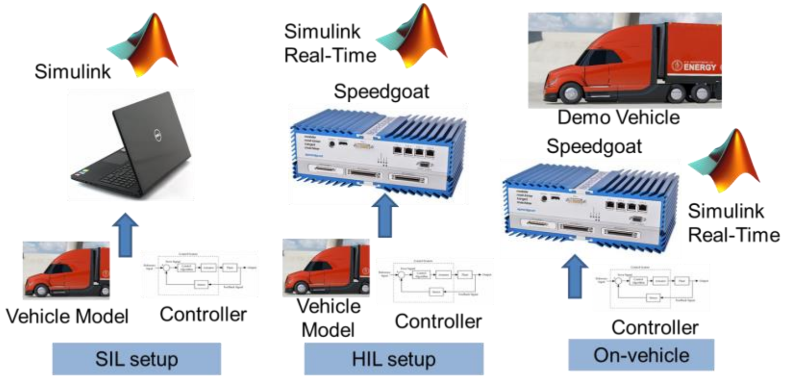
Test route and elevation

- Continued development and tuning of the hybrid powertrain control strategy
  - New Features developed:
    - MPC-based hybrid control strategy
    - Rule-based hybrid control (RBC) strategy
    - Integrated Predictive Cruise Control (PCC) + Adaptive Cruise Control (ACC)



MPC vs RBC hybrid strategy

- Established different levels of tuning and calibration and final integration
  - Software in the loop (SIL) for offline tuning
  - Hardware in the loop (HIL) for bench real-time tuning
  - On-vehicle tuning and calibration



Remaining Challenges and Barriers

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

Continue efforts:

- **Engine**
  - ✓ Incorporating the late efficiency improvement hardware in the demonstration engine builds
  - ✓ Waste Heat Recovery (WHR) system performance with final engine configuration
  - ✓ Engine-aftertreatment system performance calibration/optimization
  - ✓ 55% BTE demonstration while meeting prevailing emissions

- **Vehicle**
  - ✓ Hybrid economy vs. weight tradeoff.
  - ✓ Demonstration vehicle build and test:
    - ✓ Supply base challenges resulting from Covid-19
    - ✓ Resource availability due to Covid-19
    - ✓ Hardware availability due to technology shifts away from ICE
  - ✓ Hybrid w/Predictive Cruise Control (PCC) strategy development and calibration

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

Responses to 2020 Comments

Categories	Reviewer Comments	Navistar Response
Approach to Performing the Work	The project demonstrated approaches to attaining or exceeding FOA program goals. However, there are a significant number of system design selections or optimizations still in process at the engine level late in the project. The extensive use of carbon fiber for cab structure and trailer was described by the presenter as far from commercial viability due to the raw cost of carbon fiber for the foreseeable future.	The program is in Year 3 of a five-year program. As a result, we are still reviewing a number of options to optimize the system in order to achieve the best efficiency numbers. We are using a combination of different composite materials to minimize weight and cost.
Technical Accomplishments and Progress toward Overall Project Goals	Cylinder activation work results applied to representative city drive are an impressive 2.9% fuel consumption gain. But this vehicle application is likely to be longer haul. Overall, it would be advisable that Navistar applies the FE criteria for all their technology portfolio on the same cycle. This is important for assessing the overall FE impact.	We have assessed these performances through all three cycles: city, flatland, and hilly, as real-world driving conditions. We use these cycles to develop our commercial products.
Collaboration and Coordination Across Project Team	The project team includes a cross section of expertise as desired in the FOA with the exception of a tire manufacturer. Input from the trailer or fleet team members was not significantly discussed in the presentation... The trailer team member was not identified in the slides, only the composites manufacturer.	Continental is our tire supplier. The trailer is a collaborative development with TPI Composites and Transport Equipment, Inc.

Thank you