Improving Transportation Efficiency Through Integrated Vehicle, Engine, and Powertrain Research - SuperTruck 2

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June 24, 2021

Daimler Trucks North America
Project ID: ACE100

This presentation does not contain any proprietary, confidential, or otherwise restricted information
Overview

Timeline

Start
January 1, 2017

End
December 31, 2021

June 2021 Status= 85% Complete

Technical Targets

• Greater than 115% improvement in vehicle freight efficiency (on a ton-mile-per-gallon basis) relative to a 2009 baseline.
• Greater than or equal to 55% engine brake thermal efficiency demonstrated at 65 mph on a dynamometer.
• Develop technologies that are cost effective

Project Total $40Mil

Budget

2020 Summary

DOE Share $20,000,000
Michelin $1,000,000
ORNL $500,000
NREL $203,254
Detroit Share $12,468,918
DTNA Share $5,827,829

Project Partners

• Schneider National
• Strick Trailers
• Michelin
• Oak Ridge National Laboratory
• National Renewable Energy Laboratory
• University of Michigan
• Clemson University
Reduced fuel consumption plan in HD long haul

**Phase 1**
- Simulation
- Goal Setting
- Main Path & Stretch Path Defined

**Phase 2**
- Main Path Design
- A-Sample Design Release
- Bench Testing

**Phase 3**
- A-Sample Build & Test
- 40%/100% Clay
- Content Selection
- Final Demo Design

**Phase 4**
- Finish Final Demo Design & Build
- Optimization

**Phase 5**
- Final Demo Optimization
- FE Validation Test
- Final Report

**Relevance and Objectives**

**Phase Milestone Status Completion Date**

<table>
<thead>
<tr>
<th>Phase 4</th>
<th>Final Demonstrator Design Released</th>
<th>100%</th>
<th>Oct 2020</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Final Demonstrator Assembled</td>
<td>30%</td>
<td>June 2021</td>
</tr>
<tr>
<td>Phase 5</td>
<td>Final Demonstrator FE Validation Test Complete</td>
<td>5%</td>
<td>Q4 2021</td>
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<tr>
<td></td>
<td>Final ST2 Engine Bench Testing Complete</td>
<td>15%</td>
<td>Q3 2021</td>
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<tr>
<td></td>
<td>Final ST2 Report Complete</td>
<td>5%</td>
<td>Q1 2022</td>
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**Approach – SuperTruck 2 Roadmap**

**Baseline Vehicle: 2009 Cascadia/DD15**

ST2 125% Stretch Target @ 65k GVW

ST2 115% Freight Efficient Target @ 65k GVW

Freight Efficiency % (ton-miles/gal)

Baseline to 2017 NGC 61%

On road (Portland-Pendleton-Portland) validation @65k lbs

Focus on high potential workstreams

*Assumes 2,800 lbs mass reduction*
Technical Progress - Exterior Development

**Final Demonstrator**

- Exterior parts received with exceptional fit to vehicle
- Active Tractor Trailer Gap (TTG) feature completed
- Aerodynamic testing confirmed performance in wind tunnel and on the track

**Trailer Build Complete**

- Standard 53’ trailer build completed with 5 enhancements
- Mass savings of ~2,000 lbs over typical trailer
- Controls for ride height and boat tail configured

Images:
- Stowed Position
- Fully deployed
- Completed trailer build & test

Execution on track
Technical Progress – Chassis Developments

Michelin Prototype Tires

- Michelin completed tire build with testing
- Optimized for Adaptive Tandem and TCO

![Adaptive Tandem](image)

Operates like a 6x2 at Hwy Speeds

Performance improvement over 2017 NGC:
1. Steer Tire: 16% Crr reduction
2. Drive Tire: 8% Crr reduction + 30% wear improvement
3. Tag/Trailer Tire: 26% Crr reduction

Dynamic Load Shift (DLS)

- Shifts load to take advantage of extremely low Crr tag tires
  - Traction Mode: More load on drive axle at low speeds
  - Equal Mode: Equal load on drive and tag axles
  - Eco Mode: More load on tag axle at highway speeds
- Axle load determined by suspension pressure.

![Dynamic Load Shift Chart](image)

Chassis performance optimized and confirmed
Final Demonstrator solution:
- NREL support to optimize 7kWh LTO battery with off the shelf components
- Developed cell electrothermal model based on tests at Thermal Testing Facility
- Simulation selected package arrangement and reduced order model for cooling control
- Cells remain below manufacturer imposed temperature limit

30 kW BRM in P2.5 position with 3.5:1 transfer case

P2 location enables improved power

Hybrid Strategy with predictive cruise
- Recuperate during negative torque events
- Long haul route minimizes recouped energy
- Finalizing balance to store or use energy

Architecture enabled for energy optimization
A-Sample Integration Results

A-Sample Component Style Testing

- Several weeks of testing reviewing integration performance
- One drive route is Portland-Pendleton-Portland (PPP)
- Route is ~7 hours (~25,000 seconds) round trip
- Significant data being captured
- Results
  - Adaptive tandem ~95% in 6x2 mode
  - Split cooling and trans temp performed well
  - DLS & height control needed further development
  - 48V accessories are stable
  - Hybrid enabled during engine braking

Results driving Final Demonstrator development

Powertrain/Chassis
- 13 Speed Transmission
- Adaptive Tandem Axle
- Clutched Air Compressor
- Dynamic Load Shift & AHC
- Integrated vehicle controls

Split Cooling
- Low Temperature Circuit
- Transmission oil heating and cooling

Energy Management
- 48V Integration
- 48V P0 Mild Hybrid
- 48V eHPS (Steering Pump)
- 48V eAC
- DC-DC converter to 12V
- LFP Batteries
SuperTruck 2 Powertrain

Jeff Girbach, Principle Investigator, Powertrain
Steve Musselman, Detroit Powertrain, Presenter
June 24, 2021

Daimler Trucks North America

Project ID: ACS100
ST2 Engine Overview

**Downspeeding**
- Two stage turbocharging
- Interstage cooling

**Faster combustion enablers**
- High compression ratio
- Higher peak cylinder pressure
- Redesigned bowl shape

**Air System**
- Miller cycle valve timing
- Late exhaust valve opening
- Two stage EGR cooling
- Long loop EGR

**Friction & Parasitics**
- Liner surface conditioning
- Coated piston rings & pin
- Oil flow reduction (crankshaft)
- Closed-loop oil pressure control
- Active piston cooling jets
- Low viscosity oil / higher oil temperature

**Heat Loss Reduction**
- Thermal Barrier Coatings on piston and cylinder head.
- Insulated exhaust manifolds

**Waste Heat Recovery**
- Phase Change Cooling WHR

**Aftertreatment**
- Close-coupled SCR

**Fluid Temperature Management**
- Split Cooling System
Thermal Efficiency Demonstration – 55% BTE Engine System Tested at ORNL

Engine ready for testing at ORNL

PCJ Split Lube System (e.g. 48V pump)

High-Pressure Turbo Stage with two waste-gates

Set of Pistons with Thermal Barrier Coatings

‘Twin-Feed Crankshaft’ for reduced oil flow

Insulated exhaust manifold

Updated Timeline

Q1  Q2  2021  Q3  Q4

Updated Timeline

(significant delays in 2020 due to COVID-19 pandemic)

- All parts available
- Built complete
- Rationality Check at Detroit Lab
- Start of Testing at ORNL
- Final Run/Demonstration
- Reporting & Documentation

Downspeeding enablers
- Two stage turbocharging
- Interstage cooling

Faster combustion enablers
- High compression ratio
- Higher peak cylinder pressure
- Redesigned bowl shape

Air System
- Miller cycle valve timing
- Late exhaust valve opening
- Two stage EGR cooling

Friction & Parasitics
- Liner surface conditioning
- Coated piston rings & pin
- Oil flow reduction (crankshaft)
- Closed-loop oil pressure control
- Active piston cooling jets
- Low viscosity oil / higher oil temperature

Heat Loss Reduction
- Thermal Barrier Coatings on piston, cylinder head in process.
- Insulated exhaust manifolds

Waste Heat Recovery
- Phase Change Cooling System placed on hold, testing to be finished with EGR & Exhaust WHR.

Afttreatment
- Close-coupled SCR

Fluid Temperature Management
- Split Cooling System
Thermal Barrier Coating Development - Simulation Loop and Engine Validation

Coupled CFD and FEA simulation to predict piston surface temperature (baseline vs. coated)

- **1-D Cycle Simulation (GT POWER)** – Combustion chamber heat transfer
  - Total heat transfer reduced by 10% compared to baseline metal
  - Single-cylinder engine showed potential of 0.8% BSFC improvement
  - Multi-cylinder testing in the final 55% BTE demonstration engine at ORNL

- **Single-Cylinder Engine**
  - CFD (ORNL) & FEA (Clemson) models used to evaluate several TBC formulations
  - ‘Gen 3’ coating was downselected for best thermal swing and thermal stability.
  - Up to 1% BSFC improvement based on CFD and 1-D cycle simulation
  - Single-cylinder experimental test showed 0.8% BSFC potential (reference load)
  - 100 hour durability test successfully completed on single-cylinder engine

Thermal Barrier Coating – ≤ 500 K difference spatially (same increment of time)
Split Lubrication System

- Downsized main oil pump/system and supplemental oil circuit for piston cooling jet supply
- Fixture testing validated flow targeting at piston cooling gallery.
- Flow Rate Testing confirmed maximum flow rate capability and nozzle-to-nozzle flow variation within acceptable level
- Simulated potential for 0.5% BSFC Improvement, will be confirmed on 55% BTE Engine
Final Demonstrator Vehicle Engine and Transmission

- DD13 engine
- Two stage turbocharging
- Late Miller timing camshaft
- Late exhaust valve opening camshaft
- High BMEP potential for down-sped PT configuration
- Low temperature (LT) cooling circuit
  - Efficient Interstage cooling
  - Split EGR cooler (HT/LT)
- Significant BSFC improvement over best available engine, especially at lower engine speeds
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<tr>
<th>Comment</th>
<th>Response</th>
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<tr>
<td>Little or no discussion of trailer and trailer partner efforts in the project yet significant savings identified in the FE plan. No discussion of trailer tire Crr improvement.</td>
<td>With limited time and presentation slides available, not all work is highlighted during the AMR. Strick Trailers has been an integral part of SuperTruck 2 development. Strick has produced a 53’ trailer that is about 2,000 lbs. lighter than typical with innovative aero components that could be adapted to the approximately 2 million trailers found on the road today.</td>
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<td>Friction hardware shows significant improvements in BSFC over stock hardware implies it will be a big part of the final demonstrator package, but the data shown is a combined effect of these coatings, along with lower viscosity oil, so a lower pumping loss. With no numbers on the graph, I have doubts that the benefit will be worth the cost and risk involved with these coating (long term durability and effect on oil consumption).</td>
<td>Referring to friction &amp; parasitics slides from the 2020 AMR, we demonstrated approximately 0.5% fuel consumption reduction for the friction reduction package in the stand-alone test of the friction package. A 0.5% fuel consumption reduction is significant for a friction package and would be worth consideration on a business case basis.</td>
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<td>Optimizing tire Crr differently between tag and pusher tires did not consider TCO ramifications to fleet operations and replacement rates, retreading, etc.</td>
<td>TCO was considered throughout tire development. The tag tire can also be used on the trailer axle since it is not a tag specific tire. As a consequence, the fleets will not have additional inventory for replacement (Tractor + Trailer still has to deal with three tire types: steer, drive, tag/trailer). The tag tire can be retreaded with the appropriate tread on either the drive/tag/trailer axles.</td>
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Collaboration and Coordination

- Schneider National
  - Project scoping
- Strick Trailers
  - Low mass trailer with production available aerodynamic features
- Michelin
  - Low rolling resistant tires balanced with fleet TCO
- Solution Spray Technologies
  - TBC coating development
- Oak Ridge National Laboratory
  - Engine friction and parasitics, testing
- National Renewable Energy Laboratory
  - Thermal development, management and testing
- University of Michigan
  - Model based controls and testing
- Clemson University
  - Engine TBC analysis and development
Remaining Challenges

**Technical**

- Integration of new engine into Final Demonstrator
- Evaluation and optimization of hybrid during multiple drive cycles.
- Integration of new smaller 48v battery system.

**Resources**

- Starting late in March 2020, supply chain disruptions and work arrangements changed delaying critical part delivery such as the engine about 8 months. Recovery plans are in place, but have risk to finish all testing before end of 2021.

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

*Plans in place to address challenges*
Summary and Future Work

Phase 5 Activities
- Hybrid optimization
- ST2 engine integration into Final Demonstrator
- Fuel Economy testing
- 55% BTE Engine Testing
- Final Report Writing

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

Accomplishments

A-Sample Integration Vehicle
- Completed several weeks of testing in Fall 2020
- Continued through 2021 to integrate most new features

Engine Development
- 55% engine completed build and shipped to ORNL for final testing
- Final demonstrator engine completed dynamometer calibration

Final Demonstrator donor vehicle received April 2020
- Chassis torn down and rebuilt awaiting engine expected in May 2021
  - Michelin built and tested tires exceeding original Crr reduction goals
- Completed exterior build including trailer with testing
- Testing and simulation show good path towards >115% freight efficiency
- Coronavirus caused supply chain disruptions
  - Have aggressive plan to complete testing in 2021 with increasing risk
Questions?