Super Truck Program: Vehicle Project Review

Recovery Act – Class 8 Truck Freight Efficiency Improvement Project

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Daimler Truck North America LLC
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Project ID: ARRAVT080

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Overview

- Project start: April 2010
- Project end: March 2015
- Percent complete: 100%

Resolve thermal & fluid dynamics tradeoffs between aero & cooling
- Rejecting more heat in a smaller, aerodynamic hood & engine compartment
- Development of safe and efficient high voltage power distribution, integrating multiple HV energy sources
- Making tradeoffs between efficiency, cost and weight
- Vehicle controls integration (aux, hybrid, powertrain, waste heat, predictive)

Timeline

Barriers

Budget

- Total project $79,119,736
- Vehicle budget $47,486,735
  - DOE share $ 19,228,552
  - DTNA share $ 19,228,552

Partners

- Detroit Diesel
- Schneider National, Walmart
- National Renewable Energy Lab
- Oregon State University
- Strick Trailer
- Michelin
- ...
## Objectives and Milestones

**Develop and demonstrate a 50% total increase in vehicle freight efficiency:**
- At least 20% improvement through a heavy-duty diesel engine capable of achieving a 50% brake-thermal efficiency
- Identify key pathways towards achieving 55% through modeling and analysis

<table>
<thead>
<tr>
<th>Timeline</th>
<th>Phase Description</th>
<th>Milestones</th>
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</table>
| 4/10–3/11 | **Analysis:**  
(1) Technology Modeling/Analysis and Initial Component Development and Demonstration | Develop analytical roadmap:  
• 50% vehicle freight efficiency improvement  
• 50% engine brake thermal efficiency |
| 4/11–3/12 | **Specification:**  
(2) Experimental Demonstration of Technology Building Blocks for Intermediate Goals | Experimentally demonstrate technology building blocks:  
• 25% vehicle freight efficiency improvement (system level test)  
• 46% engine brake thermal efficiency |
| 4/12–5/13 | **Design:**  
(3) Technology Identifications and Final Component Development and Demonstration | Identify and initially develop technology building blocks:  
• 50% vehicle freight efficiency improvement (system level test & analysis)  
• 50% engine brake thermal efficiency |
| 6/13–6/14 | **Build:**  
(4) Experimental Demonstration of Technology Building Blocks for 50% Engine Thermal Efficiency and 50% Vehicle Efficiency | Experimentally demonstrate technology building blocks:  
• 50% vehicle freight efficiency improvement (system level test)  
• 50% engine brake thermal efficiency |
| 7/14–3/15 | **Test:**  
(5) Final System Integration and Demonstration | Experimental demonstration:  
• 50% vehicle freight efficiency improvement (entire vehicle test)  
• 50% engine brake thermal efficiency (engine test)  
• 55% engine brake thermal efficiency (engine analysis) |
Phase 5: Road to 50%

**A-Sample (Performance Test, April 2014)**
- Aero hood, bumper, active grille
- Stock DD11 Engine, DT12 DD Trans. + eCoast
- Waste Heat Recovery (electrical expander & vehicle cooling)
- 6x2 Axle Config., 2.28:1 RAR + oil baffle
- GHC Hybrid B-sample (120kw eMotor, 360v, 2.4 kw-hr Li-Ion Bat)
- eHVAC (HV compressor, remote condenser, electrical fan)
- eMotor engine start
- Cab insulation package
- Clutched air compressor / electronic air control
- AccuSteer (closed center steering gear + accumulator)
- Low rolling resistance wide based single tires
- Thermal mgt. (variable speed fan, water pump)
- Trailer aero., lightweighting and solar

**Final Demonstrator (FE Test, Oct 2014 – Jan 15)**
A-Sample Technologies, plus…
- Full Tractor Aero
  - cab/sleeper, underbody, drive wheel fairing, mirror cam, steer wheel, full side extender
- 50% BTE DD11 Engine + WHR
- Predictive hybrid controller
- Predictive engine controller
- New final drive active oil management with FE gear oil
- Lightweight Aluminum Frame and cross members
- Ultra Lightweight Air Suspension
- Advanced Loadshift 6x2
- Solar reflective paint
- Enhanced Trailer aerodynamics
SuperTruck Final Demonstration Test
October 2014 – January 2015

2009 Baseline Cascadia

Gross Vehicle Weight (lb)
- Total 65,000
- Tare 34,000
- Payload 31,000

SuperTruck Final Demonstrator

Gross Vehicle Weight (lb)
- Total 65,000
- Tare 31,200
- Payload 33,800

→ 12.2 mpg average over 5 days of testing on the San Antonio – Dallas Route

Freight Efficiency Improvement
- 17.8%
- 97.4%
- 115.2%

Average Fuel Consumption by Route (Weighted)

3 Drive Cycle Routes + 2 Parked Tests
- San Antonio Dallas: 65 mph
- Portland Canyonville: 55 mph
- Portland City

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Torque Reduction: A-Sample vs Final Demonstrator

Comparison of A-Sample and Final Demonstrator on the same section of road
- Similar weather conditions between each run.
- Large reduction in torque on flat ground.

➤ Significant reduction of road load observed in lower engine torque levels.
SuperTruck Final Demonstrator

Lower rating, size & speed results in more fuel at peak torque

Improved vehicle efficiencies decrease engine load

Fuel burned during eCoast

Reduction in engine speed during cruise

Baseline 2009 Cascadia

→ Performance enhancements based on smaller engine spec, improve vehicle efficiency and eCoast

Note: Data extracted from representative test day 10/21 PCP
eCoast Benefits Enhanced on SuperTruck

Closed Test Track
- 5 Coast Sections: 40%–43% Coast time
- Improved vehicle extends eCoast intervals
- Hybrid enabled, but seldom used

eCoast performance enhanced
- Lower vehicle drag provides more eCoast opportunity
- Predictive Technologies enhance eCoast with 3D map data
Brake Energy Evaluation
A-Sample vs. Final Demonstrator Vehicles on San Antonio – Dallas Route

An increase in brake energy on the final demonstrator translates into more engine braking, rather than hybrid recuperation.

Battery Performance Results
(+): Adequate Battery Sizing (sufficient SoC)
(−−): Required braking power exceeded battery charging limits
(−): Long braking duration caused battery derate
Exhaust Heat Recovery Performance Dependent on Vehicle Design and Operations

- Tradeoff observed: expander ‘loses steam’ during coasting

- Exhaust insulation needed to minimize temperature loss to the EHR boiler
SuperTruck Technology Evaluation

Commercially viable technologies

- Engine (e.g. variable water pump, rating, downspeeding)
- Predictive Tech. (e.g. cruise control, shifting)
- Powertrain (e.g. direct drive AMT, eCoast)
- Aerodynamics (e.g. cab/chassis side extenders, bumper, windshield seals)
- Tires (e.g. energy efficient, wide based singles)
- Trailer (e.g. EPA Smartway aerodynamics)

Commercialization hurdles remain
(e.g. regulatory, economic and/or technical)

- Engine (e.g. higher compression ratio, peak firing pressure)
- Aerodynamics (e.g. drive wheel fairing, under body cover, active grille)
- MirrorCam
- Auxiliaries (e.g. clutched compressor, power steering pump)

Not commercially viable any time soon

- Hybrid Electric Powertrain (predictive technologies - alternative low cost solution)
- Exhaust Heat Recovery
- Lightweight Materials (e.g. carbon fiber)
Breakdown of Fuel Economy Improvements

SuperTruck vs. Baseline 2009
55mph / 65,000 lbs GVW

Non-OEM Systems

OEM Systems

Engine/Vehicle Red
Engine/Vehicle Yellow
Engine/Vehicle Green

2009 Baseline (Cascade tractor with DD15 engine)

Tires (tractor/trailer)

Trailer Aero

Legend
- Commercially viable technologies
- Commercialization hurdles remain
- Not commercially viable any time soon

DAIMLER
Technical Accomplishments

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SuperTruck Partnerships and Collaborations

Department of Energy: ➔ Roland Gravel ➔ Gurpreet Singh ➔ Ken Howden ➔ Carl Maronde

Energy Management

Hybrid

Aero/Cooling

Lightweighting

Powertrain/Parasitics

Fleet

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Summary and Future Work

Successful completion of phases 1-5; Phase 5 targets exceeded

✓ 50% Vehicle Freight Efficiency target exceeded on Final Demonstrator vehicle through testing on Portland-Canyonville, San Antonio-Dallas, Portland City and Idle cycles
✓ 50% Engine Brake Thermal Efficiency target exceeded in engine test cell

Mission Accomplished
Backup
Phase I Milestone Completed

Analytical roadmap development to 50% vehicle FEI & 50% engine BTE

Baseline Tractor

- 2009 Cascadia 125"BBC, 72"RR
- DD15 Engine 455hp/1550 lb-ft

Vehicle Test

- Baseline Performance Measurements
- Highway Cycle (55 & 65 mph)
- Idle Cycle (summer, winter)
- City Cycle

SuperTruck

Modeling & Analysis

- Establish System Level Technical Targets

Roadmap: Vehicle

Roadmap: Engine

(Engine topics covered in separate session)
Phase 2 & 3 Milestone Status

Experimental testing to 25% & 50% vehicle freight efficiency*

Freight Efficiency Improvement % - (system level measurements)

- Engine: 14.5%
- Parasitic Losses: 1.0%
- Energy Management: 3.5%
- Lightweight: 5.0%
- Powertrain Drivetrain (incl. hybrid): 16.5%
- Aerodynamics (Scale WT): 16.0%

* Technical Accomplishments covered in the 2012-2013 Annual Merit Reviews
Vehicle Level Performance Test ✅

March-April, 2014: On Highway Fuel Economy Test

<table>
<thead>
<tr>
<th>Gross Vehicle Weight (lb)</th>
<th>2009 Baseline Cascadia</th>
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<tbody>
<tr>
<td>Total</td>
<td>65,000</td>
</tr>
<tr>
<td>Tare</td>
<td>34,000</td>
</tr>
<tr>
<td>Payload</td>
<td>31,000</td>
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<table>
<thead>
<tr>
<th>Gross Vehicle Weight (lb)</th>
<th>A-Sample Test Vehicle</th>
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<tbody>
<tr>
<td>Total</td>
<td>65,000</td>
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<tr>
<td>Tare</td>
<td>32,450</td>
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<tr>
<td>Payload</td>
<td>32,550</td>
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1550 lbs. additional freight on A-Sample ➔ 5% Freight Efficiency Improvement

<table>
<thead>
<tr>
<th>Freight Efficiency Improvement (measured)</th>
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<tbody>
<tr>
<td>PCP</td>
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<tr>
<td>57%</td>
</tr>
<tr>
<td>52.0%</td>
</tr>
<tr>
<td>SDS</td>
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<tr>
<td>66%</td>
</tr>
<tr>
<td>61.6%</td>
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<table>
<thead>
<tr>
<th>A-Sample % improvement (ton-mpg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCP</td>
</tr>
<tr>
<td>5.0%</td>
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<tr>
<td>SDS</td>
</tr>
<tr>
<td>5.0%</td>
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<table>
<thead>
<tr>
<th>Daily Fuel Economy</th>
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<tbody>
<tr>
<td>PCP</td>
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<tr>
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<tr>
<td>3/27</td>
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<tr>
<td>4/9</td>
</tr>
<tr>
<td>4/10</td>
</tr>
<tr>
<td>SDS</td>
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San Antonio Dallas (SDS) 65 mph Grade Profile

Portland Canyonville (PCP) 55 mph Grade Profile

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SuperTruck Engine – Final Results

- 50.2% BTE
- Large fuel economy improvement at part load relative to 2009 baseline -- resulting from optimized, downsized, down-sped SuperTruck engine
- Technical focus since last year’s AMR
  - Engine & WHR hardware and design freeze
  - Software and calibration freeze
  - Model based engine controller commissioned on the SuperTruck demonstrator vehicle
- SuperTruck vehicle integration
- 55% BTE scoping activities

- SET: 6.9 g/bhp-hr E.O. NOx -- 0.15 g/bhp-hr T.O. NOx
- FTP: 3.0 g/bhp-hr E.O. NOx -- 0.50 g/bhp-hr T.O. NOx