DETROIT DAIMLER

SuperTruck Program: Engine Project Review

Recovery Act – Class 8 Truck Freight Efficiency Improvement Project

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Detroit Diesel Corporation

June 12, 2015

Project ID: ACE058

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

Timeline

- Project start: April 30th, 2010
- Project end: April 29th, 2015
- Percent complete: 100%

Budget

- Total Budget $79,119,736

- Engine Spending $33,374,821
  - DOE Share* $16,687,411
  - Detroit Share* $16,687,411

* Program spending through March 2015 for engine R&D; vehicle R&D expenses reported separately.

Barriers & Challenges

- Reliability and durability of new prototype systems demonstrated on SuperTruck.
- WHR performance trade-offs and cooling challenges on-board vehicle.
- Complex powertrain and vehicle controls architecture and increased computing demands from on-board ECUs.
- Ability to reliably diagnose additional subsystems requires significant development.
- Cold emissions controls and OBD.
- Practical challenges of a 55% engine BTE roadmap and research.

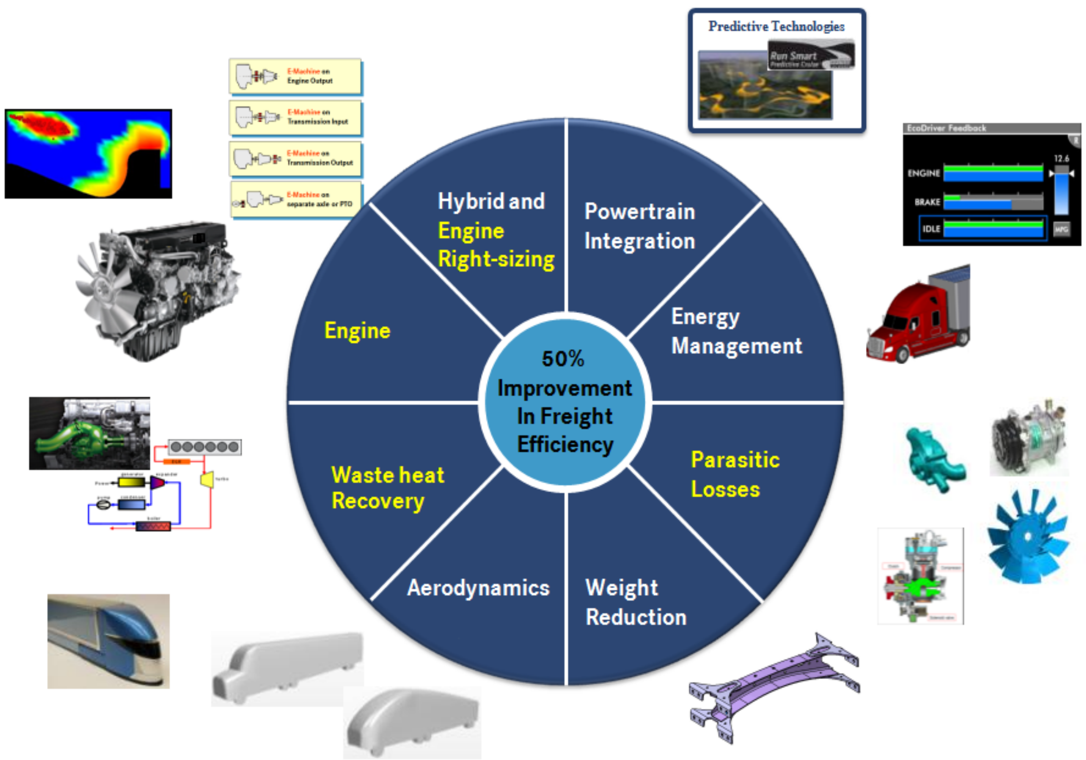
Partners

- Department of Energy
- Oak Ridge National Laboratory
- Massachusetts Institute of Technology
- Atkinson LLC
- Daimler Trucks North America
- Daimler Advanced Engineering

Daimler Truck SuperTruck Program

Develop and demonstrate a 50% increase in vehicle freight efficiency:

- 30% increase via vehicle improvements.
- 20% increase via engine improvements; specifically 50% brake thermal efficiency.
  - Identify pathway to 55% brake thermal efficiency via modeling and analysis.



- ARRAVT080 – DTNA SuperTruck vehicle program; PI – Derek Rotz
- ACE058 – Detroit Diesel SuperTruck engine; PI – Sandeep Singh

Phase 4-5: 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 condensor, 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

A-Sample

Tinker Trucks

Final Demonstrator

Final Demonstrator *(FE Test, Nov 2014 – Jan 2015)*

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

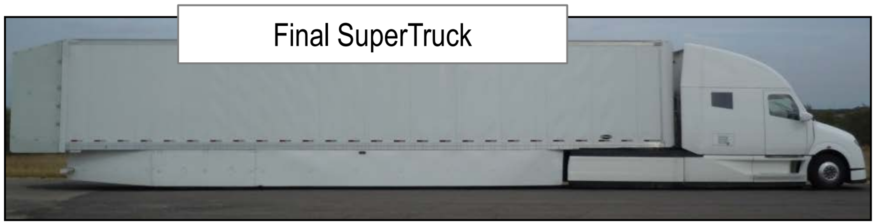
November 2014 – January 2015

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

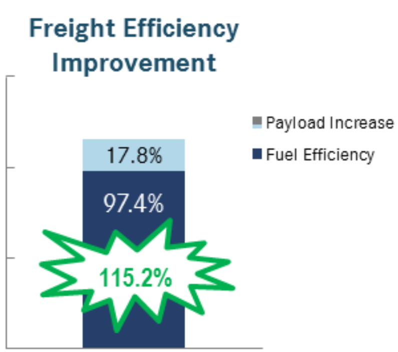
2009 Baseline Cascadia

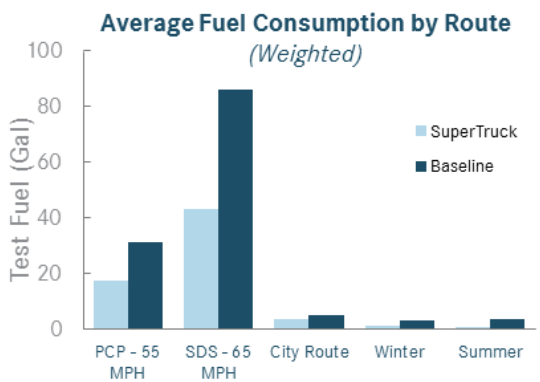
Gross Vehicle Weight (lb)	
Total	**65,000**
Tare	31200
Payload	**33,800**

Final SuperTruck



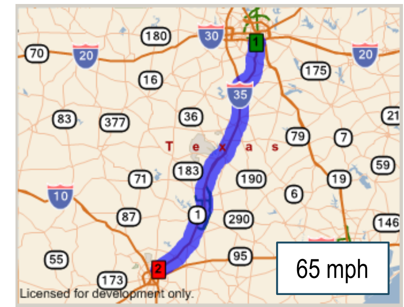
➔ **12.2 mpg average over 5 days of testing on the San Antonio – Dallas Route**





3 Drive Cycle Routes & 2 Parked Tests

San Antonio Dallas

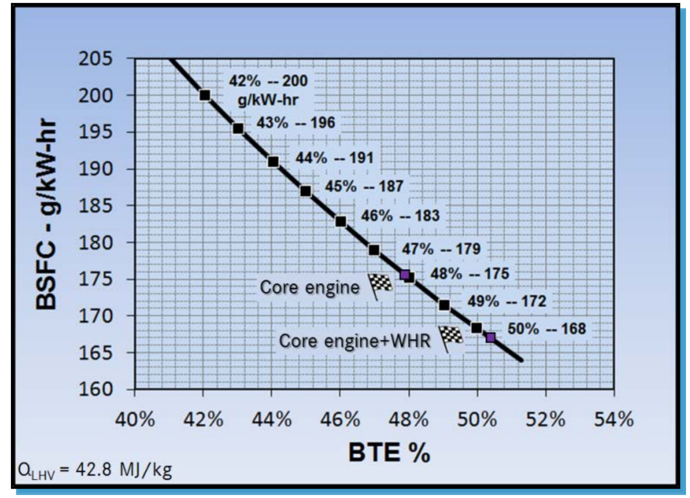


Portland Canyonville

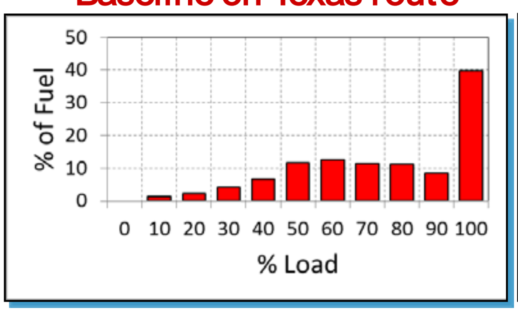
Portland City

SuperTruck Engine – Final Results

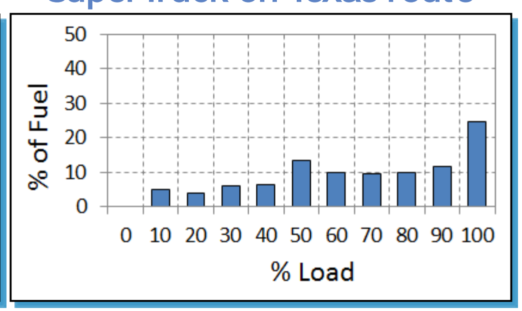
- 50.2% BTE
- Large fuel economy improvement at part load relative to 2009 baseline -- resulting from optimized, downsized, down-sped SuperTruck engine
- Technical focus since last year's AMR
  - Engine & WHR hardware and design freeze
  - Software and calibration freeze
  - Model based engine controller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

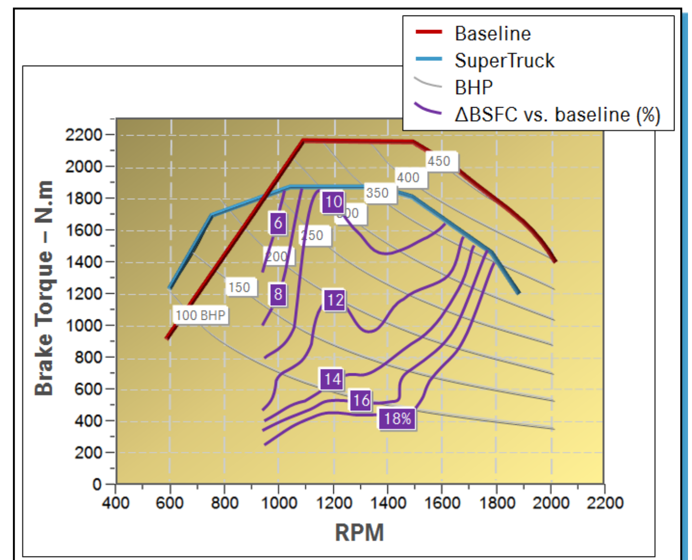


Baseline on Texas route



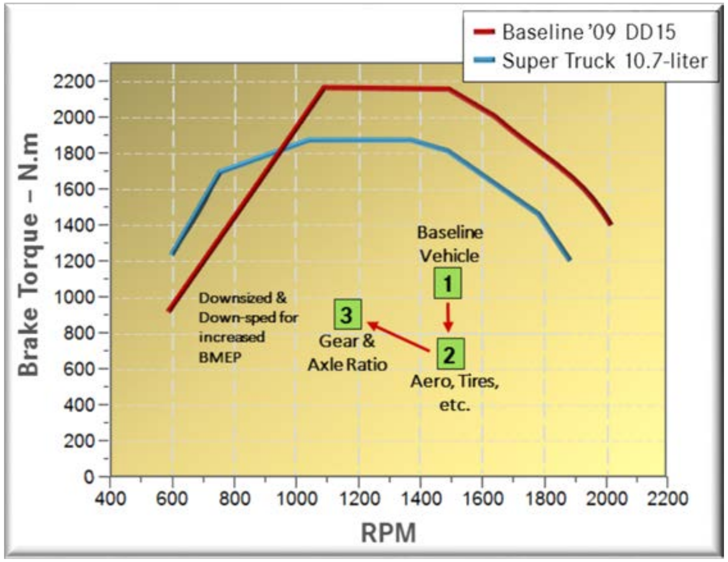
SuperTruck on Texas route

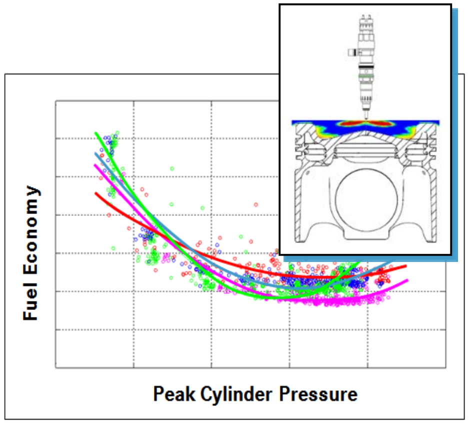


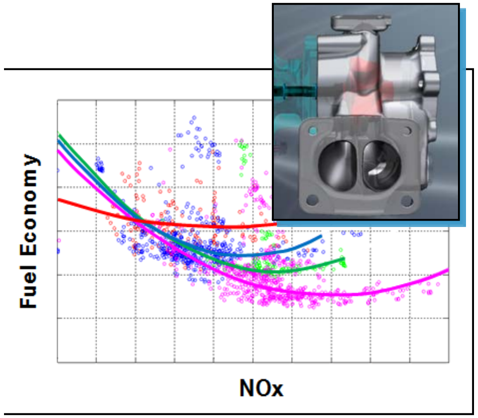


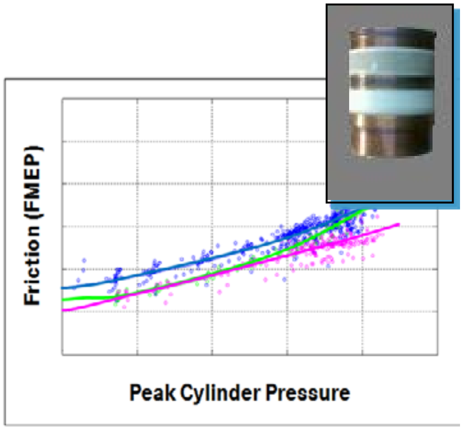
SuperTruck Core Engine 50% BTE Package

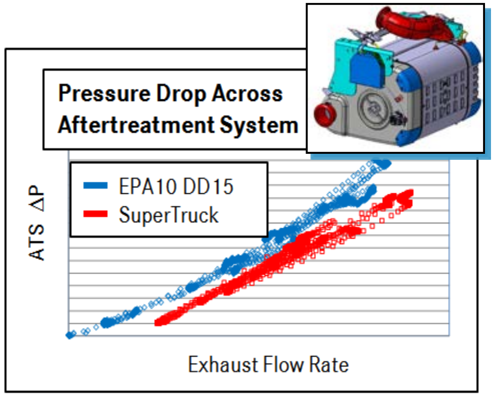
- Downsized to 10.7L from 14.8L baseline
- Higher compression ratio with matching piston bowl & injectors
- Reduced EGR levels
- High efficiency, lower restriction aftertreatment
- Turbo sized for reduced pumping losses
- Peak firing pressure increased by 15%
- Variable speed water pump
- Low viscosity oil and higher oil film temperatures
- Cylinder kit improvements
- Altered cooling to mid-stroke area of the liner





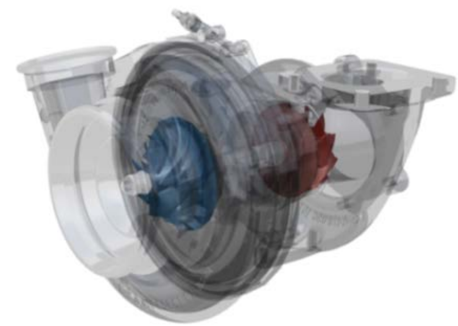




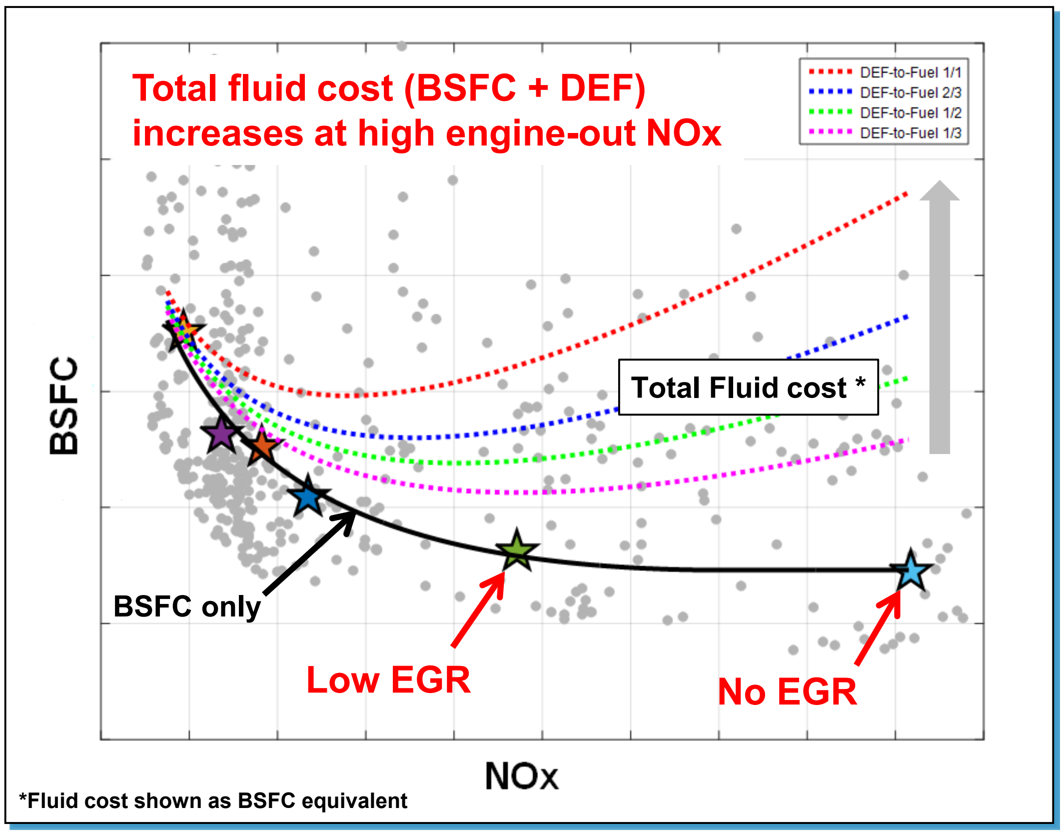


- **Engine downsized, downrated, and downsped**
- **Matched to SuperTruck vehicle load – 65K truck with superior aero, rolling resistance and hybrid & EHR assist**

Turbocharger – 55% Scoping Work



- Investigate the peak efficiency potential without requiring EGR
- Reduce backpressure and optimize the entire air system for best fuel economy
- Explored different geometries on both the compressor and turbine housing
- Mapped performance at 9 key operating points



Results

- Best BSFC demonstrated with no EGR at very high NOx
- BSFC improvements diminish as NOx increases
- Total fluid cost becomes prohibitive at high engine-out NOx
- Low EGR turbos show a more favorable trade-off of fluid consumption and emissions

Predictive Engine Controls

Objectives

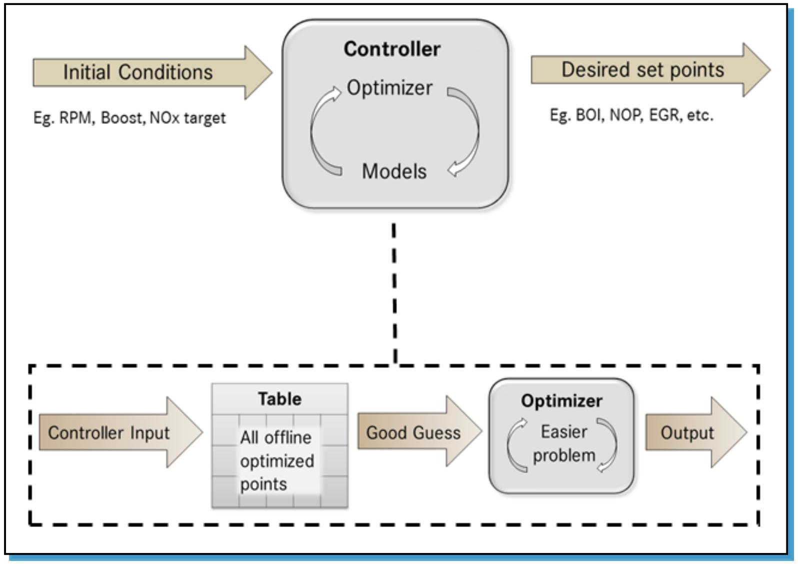
- Develop a predictive controller
- Take advantage of increasing ECU computing power
- Estimates NOx, CO, CO2, CA50, TCRPM, PMAX
- Use non-traditional set-points
    - Engine-out emissions and combustion timing
- On-board optimization
    - Minimizes controller error
    - Minimizes CO and CO2

Technical Approach

- Control logic optimizes fuel economy and constrains emissions in real time
- On-board models are based on extensive transient & steady state mapping
- Both offline & real time optimization of engine set-points for improved transient performance & fuel economy
- Main limitation – Environmental and aging adaptation

Implementation

- 100-msec Update rate
- Models are evaluated 800 times, 10-times per second
- dSPACE Micro-Autobox



One unique feature is the controller's ability to target specific engine-out NOx levels and satisfy that demand in real-time.

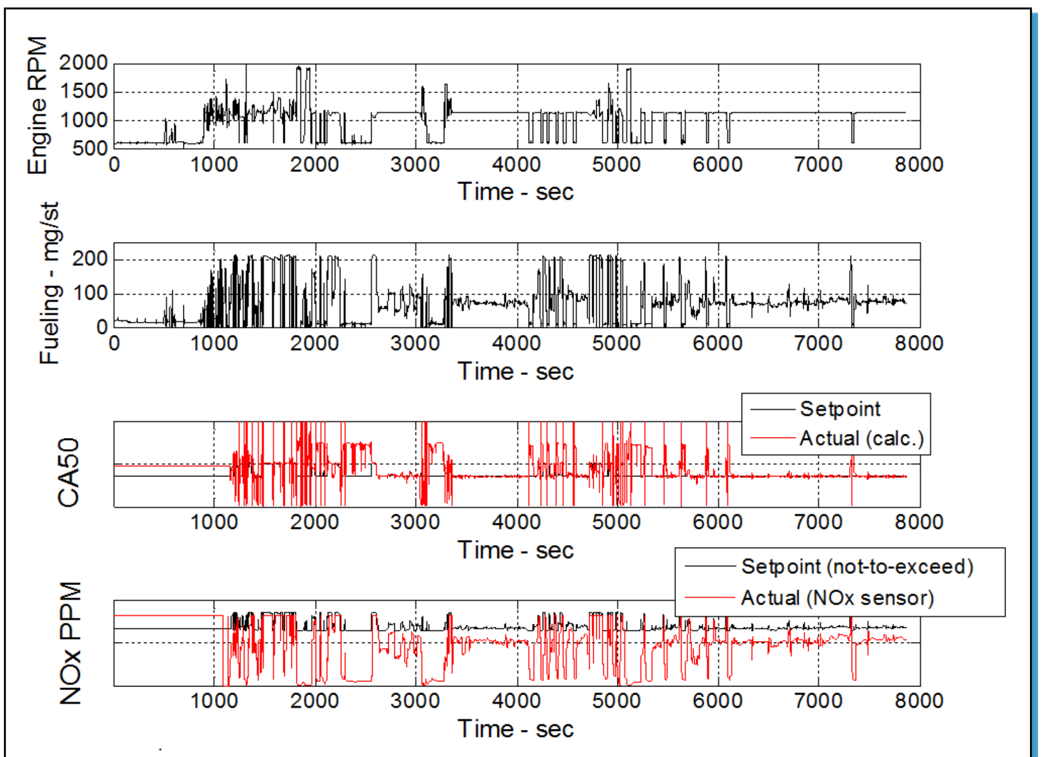
Predictive Engine Controls – Systems Integration

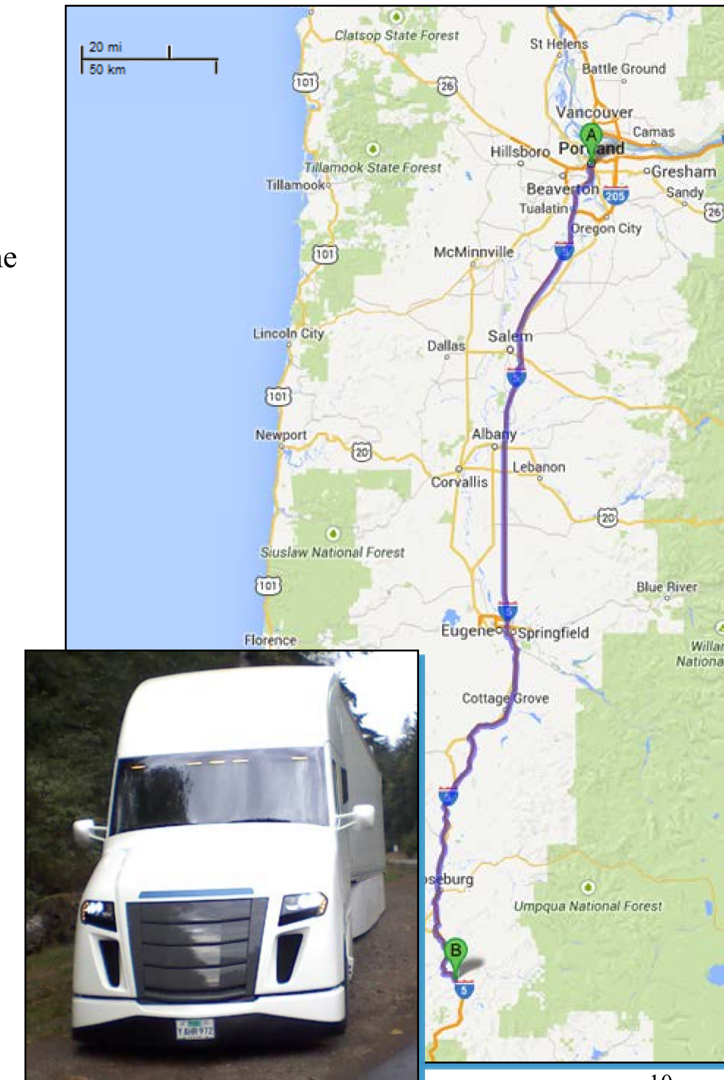
Status

- Predictive controller successfully deployed over the road in the SuperTruck demonstrator vehicle.
- Active control of NOx against an acceptable target and chosen CA50 parameter.

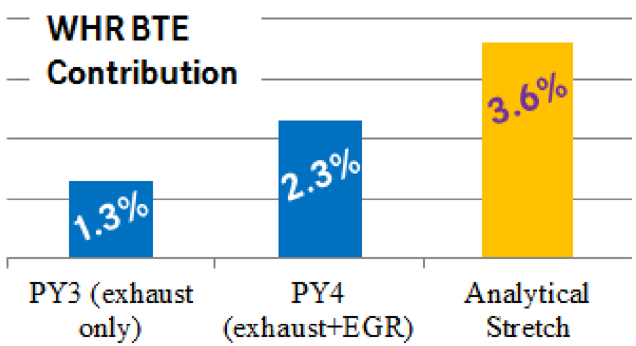
Next Steps

- Include on-board model adaptation functionality.
- Deploy on-board models in near-term products to enable improvements in engine diagnostics, calibration optimization and/or transient performance.



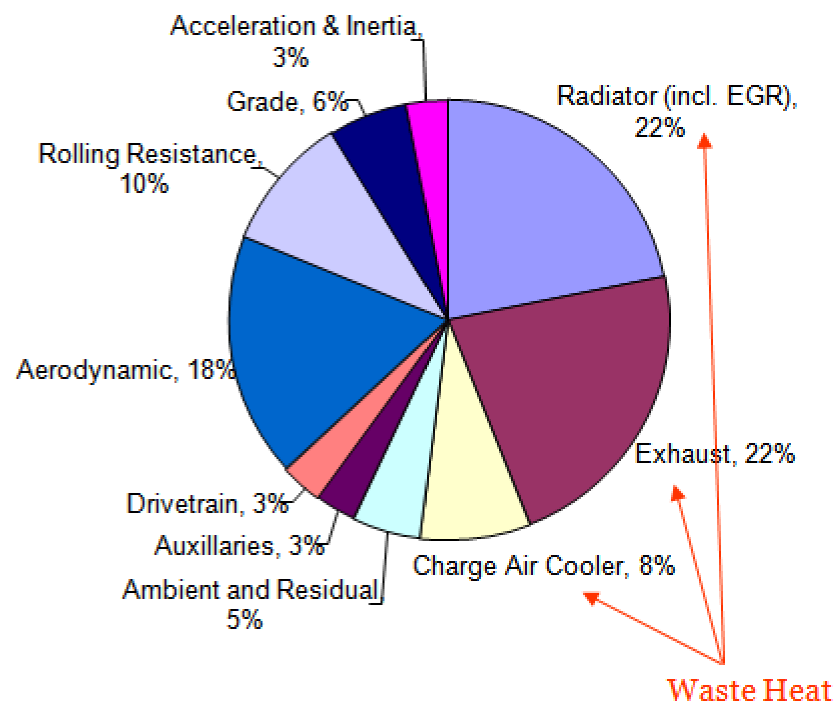


WHR Progress & Accomplishments



Waste Heat Sources	Temperature Potential	Quantity
Exhaust	High	High
EGR	High	Low
CAC	Low	Low
Coolant	Low	High

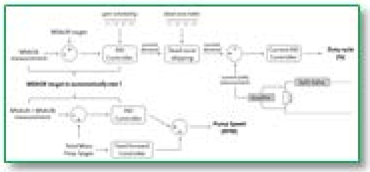
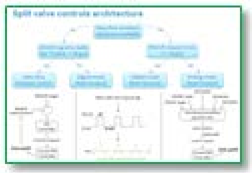
- Primary contributor to PY4 efficiency improvement is EGR heat recovery and component optimizations.
- Current approach has numerous vehicle integration challenges.
- Analytical stretch projections assume improved component efficiencies, CAC heat recovery, and a low temperature condenser approach.
- Analytical stretch may prove to be impractical with state of the art vehicle technology.



Highlights of the 2014 WHR Activities

JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

Controls development for electrical WHR for ST demo

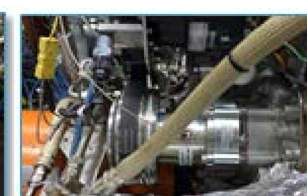
Prototype electrical WHR design finalized, built and commissioned for ST demo




Successful SuperTruck demonstration test with electrical WHR system

Integrated 50.2% BTE demonstrated with SuperTruck engine and WHR electrical system



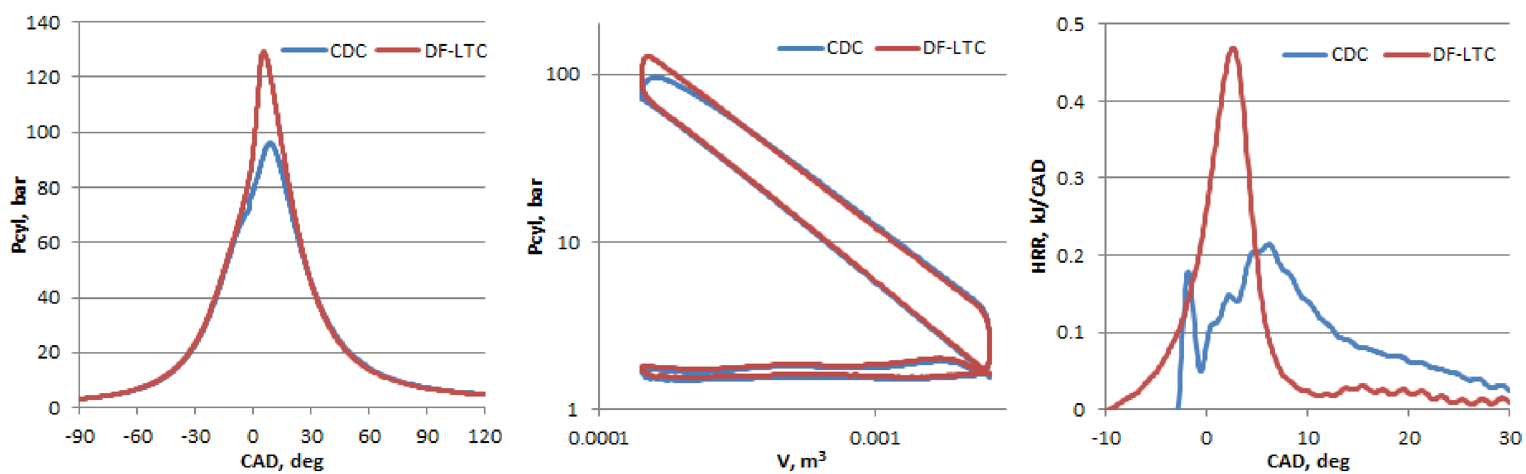
Mechanical WHR system designed, implemented & commissioned in pursuit of improved efficiency

- Detroit electrical WHR test bench
- SuperTruck demonstration electrical WHR system
- Detroit mechanical WHR test bench

Dual-fuel LTC as potential pathway toward 55% BTE

- Initial scoping study to assess potential of dual-fuel, low temperature combustion strategies as enabling pathway toward 55% BTE while meeting emissions standards
- Stock DD15 engine modified for PFI natural gas to supplement/displace DI diesel fuel
  - ✓ NG provides additional petroleum-displacement benefits
  - ✓ Low carbon-number helps offset CO increases
  - ✓ Low soot production
  - ✗ Low-temperature methane aftertreatment performance not yet well understood
- Investigating dual-fuel LTC strategies to stratify fuel reactivity, temperature, and equivalence ratio
- Early DI diesel fuel with port injection of natural gas

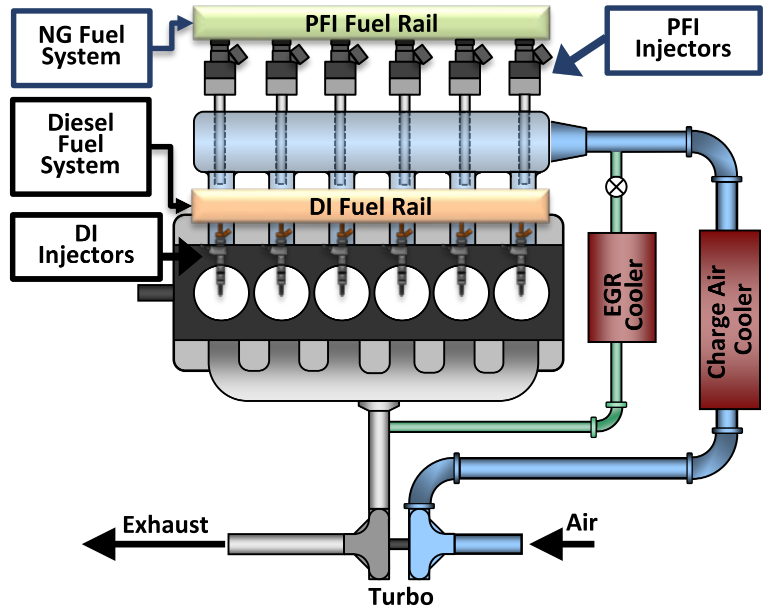
Comparison of dual-fuel LTC operation with conventional diesel (CDC) baseline at 1200 RPM and 40% load

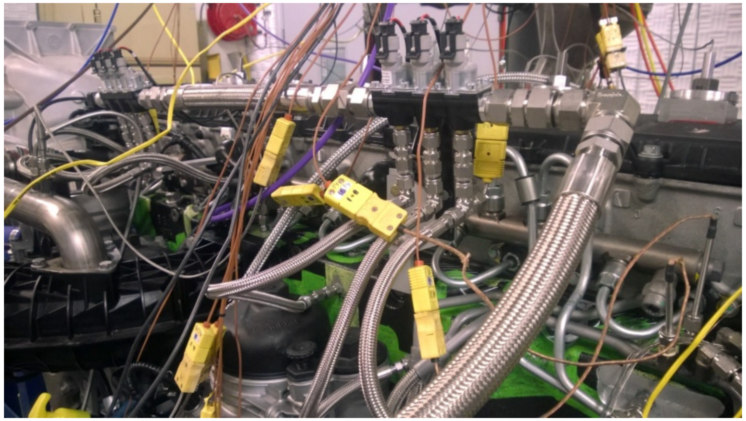


Dual-fuel enabled DD15 engine installed and operational at ORNL

- Baseline engine: DD15
- Natural gas sequential port injection system
  - Utility gas compressed to approximately 6.5 bar (95 psig)
  - Full independent injection control for each cylinder
  - Injection timed to occur while intake valve open
  - Injection tubes introduce the natural gas from each injector into the port runner upstream of the split
- Diesel injection parameters and all other engine functions controlled using stock engine controller

Schematic of dual-fuel DD15 engine setup at ORNL



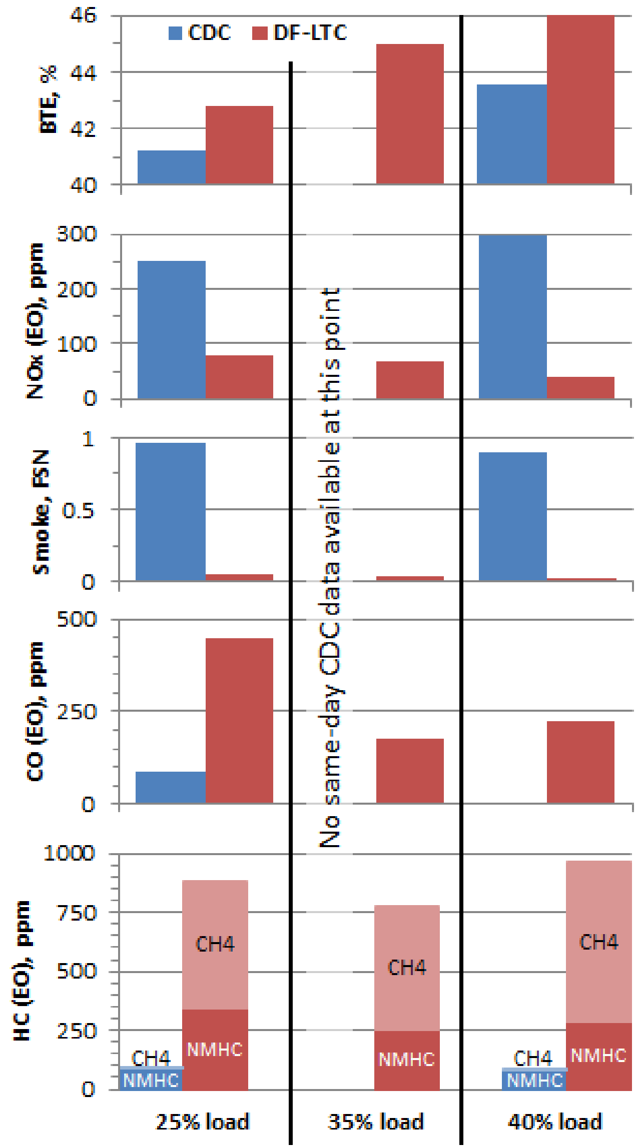


DD15 engine with natural gas sequential port injection system fully installed and instrumented at ORNL

Detailed view inside intake manifold showing injection tube which introduces injected natural gas into the port runner upstream of the split

Preliminary results from DF-LTC initial scoping study

- **Focus of initial scoping study on demonstration of DF-LTC at 1200 RPM and up to 50% load (~8-bar BMEP)**
- **Limited sweeps of key operating parameters to roughly optimize efficiency**
  - Diesel SOI, diesel/NG ratio, boost, EGR, etc.
  - Self-imposed limit of 10-bar/deg on pressure rise rate
  - 74 - 86% replacement of diesel on energy basis
  - Repeatability confirmed over multiple days
- **Observed significant improvements in efficiency and NOx and soot emissions compared to convention diesel (CDC) operation**
  - 3.8 - 5.7% improvement in BTE over CDC baseline
  - 70 - 85% reduction in engine-out (EO) NOx
  - Soot levels near lower detectability limit of AVL Smokemeter
  - Turbine-out temperatures maintained at 280°C for all loads
- **Some increase in engine-out CO and HC**
  - Relative increase in CO less than that seen in ORNL's experience with LD diesel/gasoline RCCI
    - Lower carbon-number fuel
  - Methane responsible for majority of HC emissions
    - Performance of low-temperature aftertreatment devices with methane not yet well understood
- **Future efforts will pursue more detailed exploration of optimization space and higher-load operation**

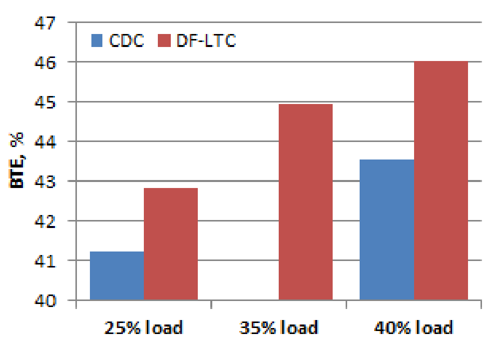


Ongoing and future efforts toward the pathway to 55% BTE

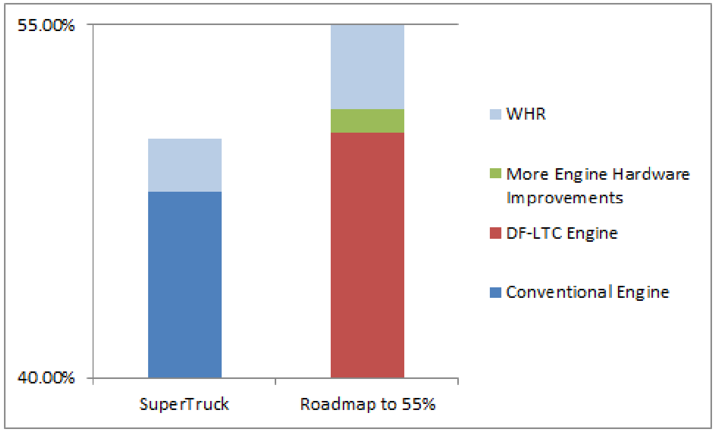
- **DF-LTC combined with further hardware improvements similar to those explored during SuperTruck can be a possible R&D approach towards 55% BTE investigations, but numerous challenges remain…**
  - **Load expansion to near peak-BTE loads on base engine is challenging, as well as drive-cycle transient operation**
  - **Design and implementation of low heat transfer pistons with optimum compression ratio, profile and matching of DI fuel injectors**
  - **Additional air handling improvements for…**
    - Limiting pumping losses to better realize gains in indicated efficiency
    - Tailoring EGR and boost controls for dual-fuel operation
      - *e.g.*, EGR less important for emissions control allowing turbo to provide more boost
  - **Improvements to the experimental setup and controls…**
    - Full control over diesel SOI while maintaining OEM ECU controls
    - High-flow PFI NG injectors for higher load operation and greater flexibility on NG/diesel ratio
  - **Low-temperature CH4 aftertreatment**

Daimler and ORNL look to continue DF-LTC efforts beyond SuperTruck to address these issues

Achieving 55% BTE is expected to require advanced combustion strategies such as DF-LTC plus additional improvements in parasitic reductions, component efficiencies, WHR, etc. beyond those achieved during SuperTruck



Possible R&D roadmap to 55%



SuperTruck Partnerships and Collaborations

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

Engine

Massachusetts Institute of Technology
Atkinson LLC
BOWMAN ENERGY RECOVERY SYSTEMS
Air Squared 40 Years of Scroll Technology
DAIMLER
OAK RIDGE NATIONAL LABORATORY MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Aftertreatment

CORNING
JM Johnson Matthey
Eberspächer

Hybrid

FUSO
MBtech Mercedes-Benz technology
Mercedes-Benz
itk ENGINEERING

Aero/Cooling

CD-adapco
BEHR
MODINE

Powertrain/Parasitics

DETROIT Transmission
DAIMLER Daimler Trucks North America
Bendix

Fleet

SCHNEIDER NATIONAL
Walmart Save money. Live better.

SuperTruck Program Summary

- SuperTruck project goals met
  - 50.2% engine BTE demonstrated including WHR.
  - 115% freight efficiency improvement demonstrated relative to MY2009 baseline
  - Plausible 55% BTE R&D roadmap created, with numerous demonstrable challenges to be overcome
  - Successful integration of complex technologies – WHR, hybrid & HV systems, controllers and network architecture, new cooling layout, new hydraulic systems, 10.7L engine & powertrain, model based engine control system