SuperTruck
Powertrain Technologies for Efficiency Improvement

DOE Contract DE-EE0004232

2016 Annual Merit Review
Washington, DC
June 10, 2016

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Volvo Group Trucks Technology

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Volvo Technology of America
ACE060

Project Overview

Timeline

Project end date
June 2016

Cost

$18,929,194 Funding

> $40,000,000 Total Cost

Powertrain Partners

VOLVO
ExxonMobil
PENNSTATE
DELPHI
RICARDO
UNIVERSITY OF MICHIGAN
LUND UNIVERSITY

Barriers

Cost effective & timely evaluation of complex technologies and systems

Added weight and packaging of technologies

Integration of interdependent technologies

Development of robust solutions with broad application and customer acceptance

Relevance to Program Goals

Bring technologies that enable lower customer operational cost and reduced environmental impact to market ahead of normal product development time cycle

Develop more efficient highway transportation technologies to reduce petroleum consumption

Project Objectives

Objective 1:

Develop powertrain technologies to contribute to **50% freight efficiency** improvement in vehicle testing

Objective 1a:

Develop powertrain technologies capable of **50% engine BTE** in vehicle environment

Objective 2:

Investigate engine technologies capable of **55% BTE** through simulation and scoping studies

Reporting Period Project Objectives

Objective 1:

Test 50% BTE powertrain in concept vehicle

Objective 1a:

Test 50% BTE system

Objective 2:

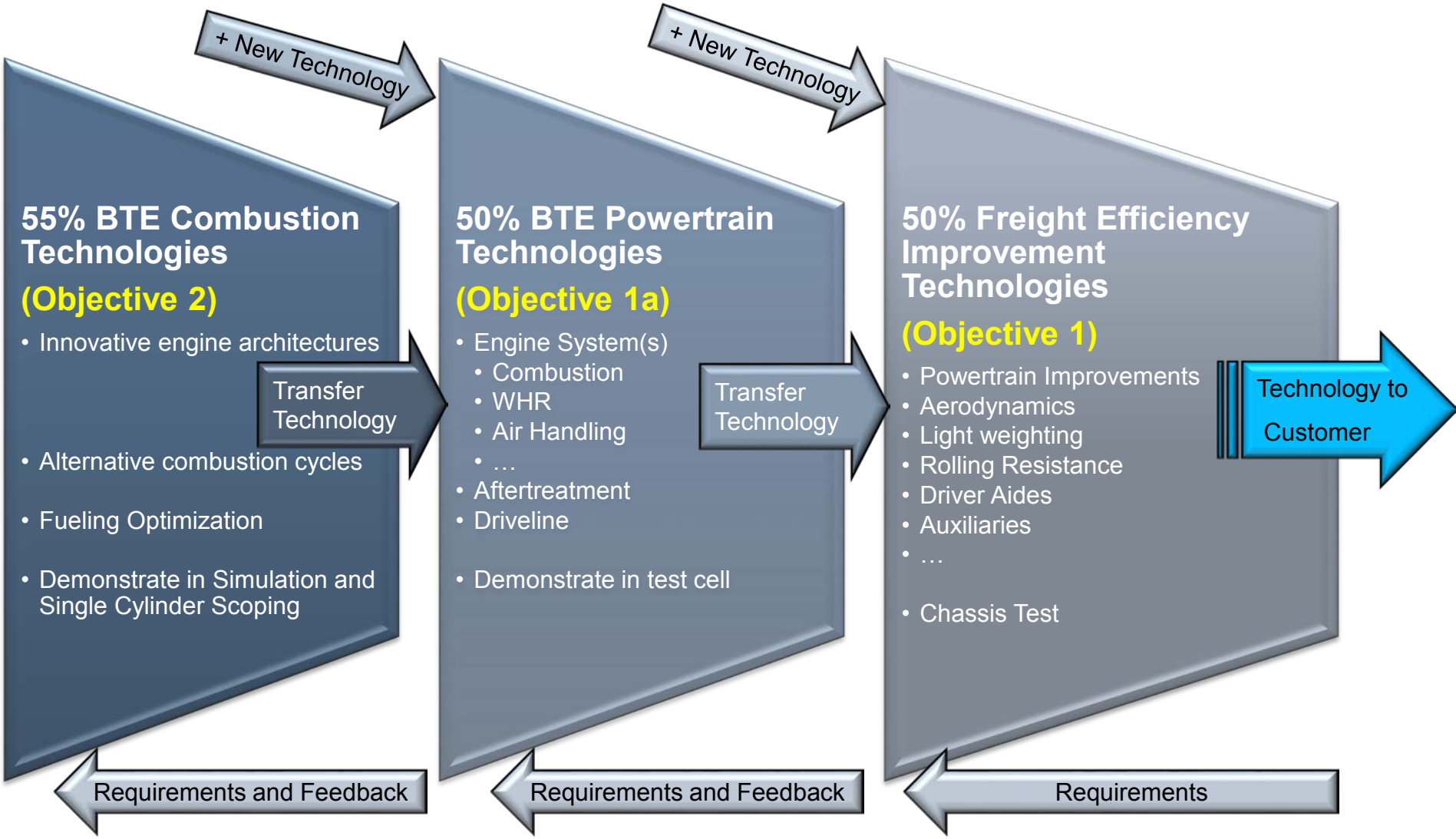
Simulate technologies to achieve 55% BTE

Relevant Research

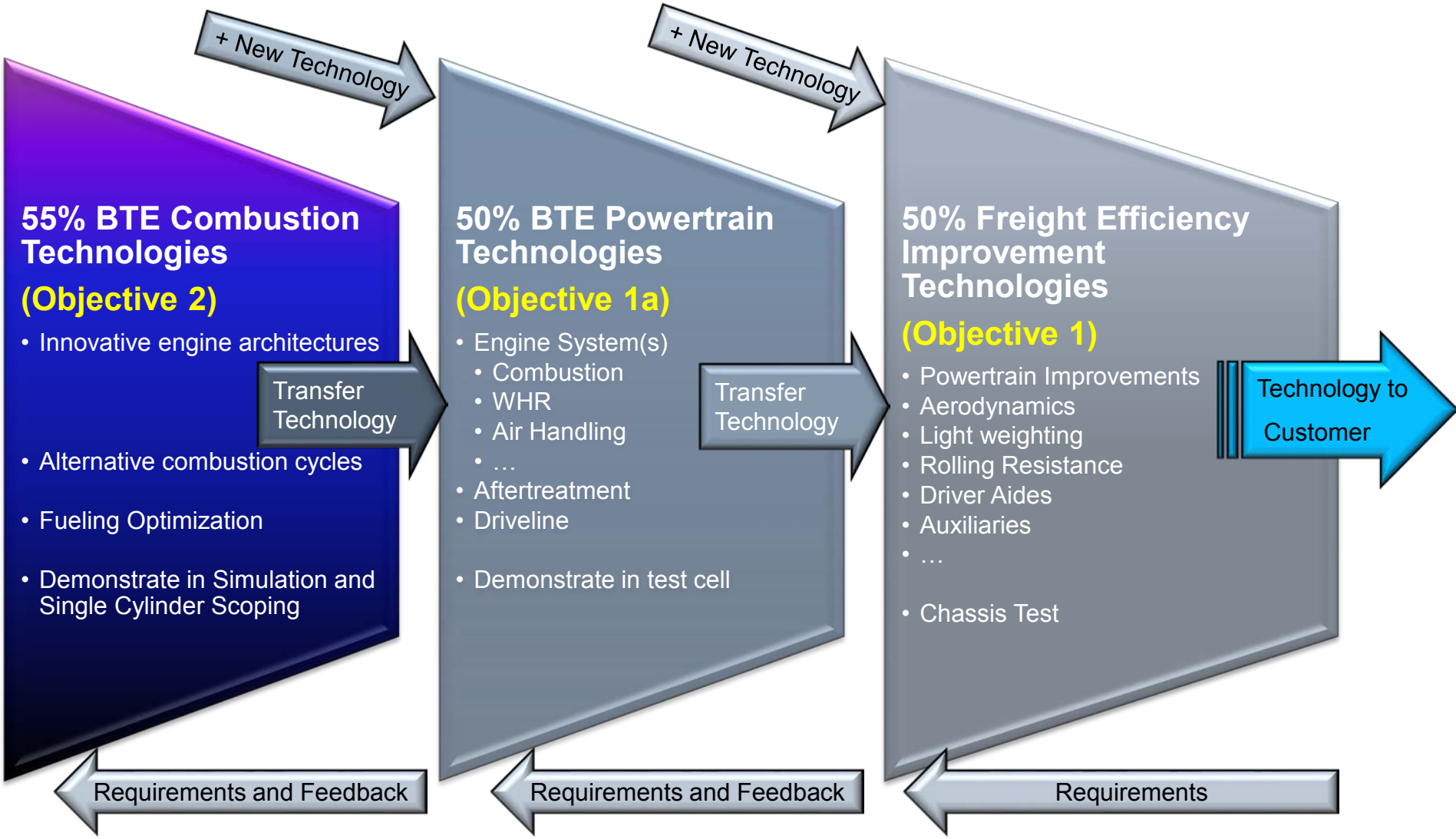
Projects supporting the objective to develop more efficient highway transportation technologies to reduce petroleum consumption, operating cost, fuel consumption, environmental impact, and time to market for high risk high complexity items are as follows:

- DOE & NETL under Award Number DE-EE0004232
- DOE & NETL under Award Number DE-FC26-07NT43222
- FFI 2012-006053 at Energimyndigheten, project 36699-1

Powertrain Workflow Approach / Strategy



Powertrain Workflow Approach / Strategy



Approach for 55% BTE Engine (Objective 2)

2011	2012	2013	2014	2015	2016

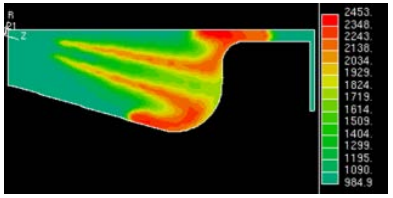
Phase I - Tools & Method Development

Penn State - CFD Development

PDF Diesel Development

PDF PPC Validation

GT Power modelling & Eff. Calculations



"Concept 55" Chosen

Phase II - Concept Development

Concept 55 CFD Simulations

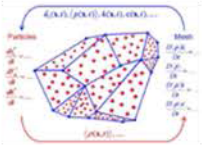
Concept 55 model validation

Concept 55 GT Power

Fuel Mechanism Research

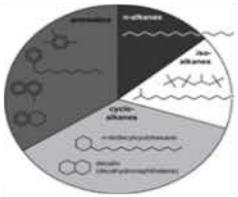
Goal: Define a powertrain system capable of 55% engine BTE using an integrated computational method. Verify assumptions for robustness.

Approach for 55% BTE Engine (Objective 2)

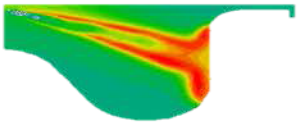


PDF method

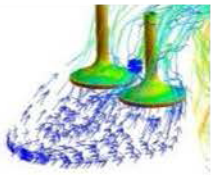
Fuel Spray Model



Chemical Mechanisms

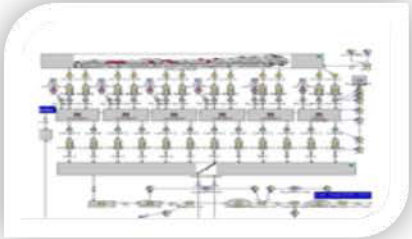


3D Combustion Simulations



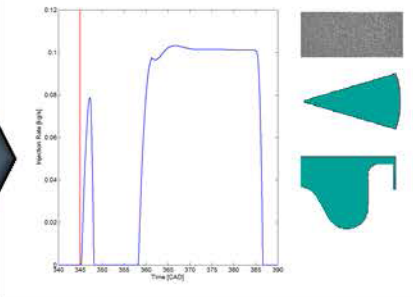
Gas Exchange Simulations

Integrate Components into System Model



Engine Model

Test for Validation



Fuel mixing analysis

Many major advancements (simulation methods or engine technologies) were selected for validation via test, with results used to tune models.

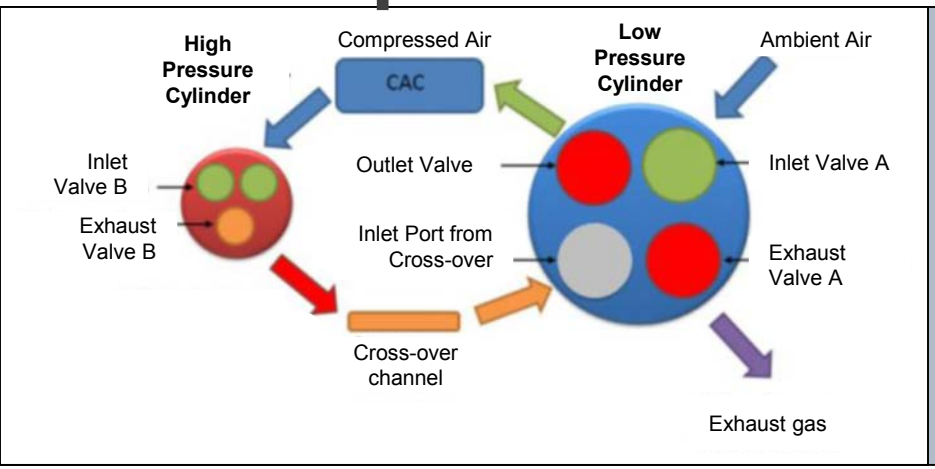
Optical engine

Feedback for model improvement

Combustion studies

The approach relied on a high level of contribution from academic partners: Penn State University, University of Michigan, Lund University

Accomplishments towards 55% BTE Engine

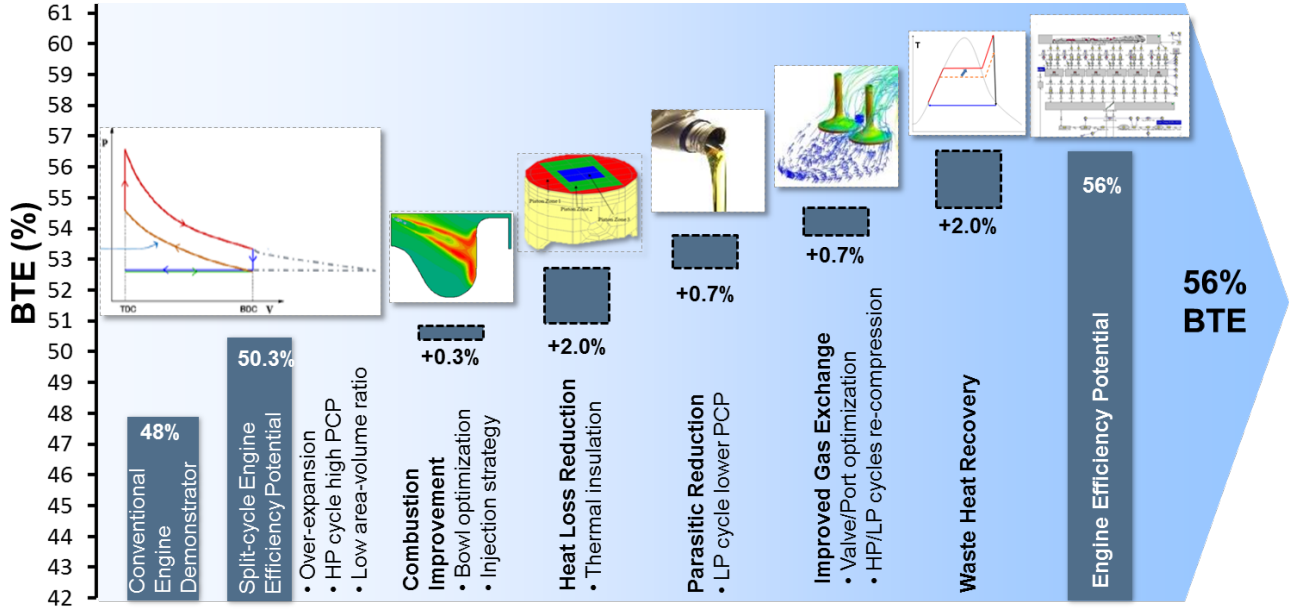


The main track to achieve 55% BTE relies on the implementation of a novel engine architecture, with two compression stages and two expansion stages, an effective compression ratio of 55:1 and 300bar PCP.

Validated beyond requirements of the SuperTruck contract.

Details available in SAE paper 2015-01-1260

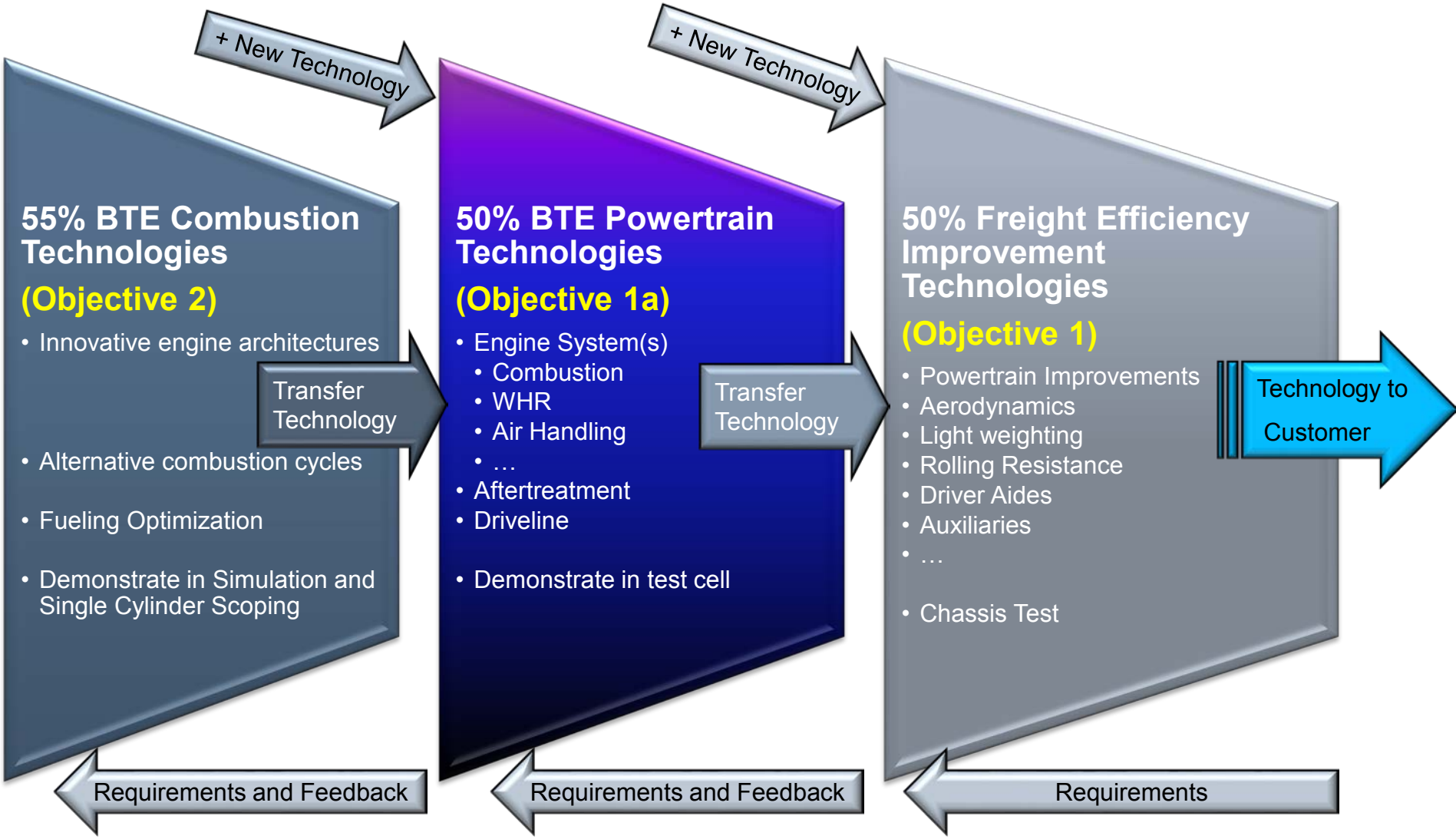
Developed in collaboration with FFI project



A system capable of 56% BTE has been well defined, exceeding the project goal of 55% with a more robust simulation and test procedure than proposed during project definition.

VOLVO

Powertrain Workflow Approach / Strategy



Volvo SuperTruck Fueling System Explained

A distributed pump common rail system was developed. This system has improved injection pressure and control compared to the unit injectors it replaced, yet with reduced cost compared to typical common rail systems.

As many as 10 injection events per combustion cycle have been tested, with up to 3000bar injection pressure capability.

This system enabled improved combustion efficiency yet with reduced noise and emissions.

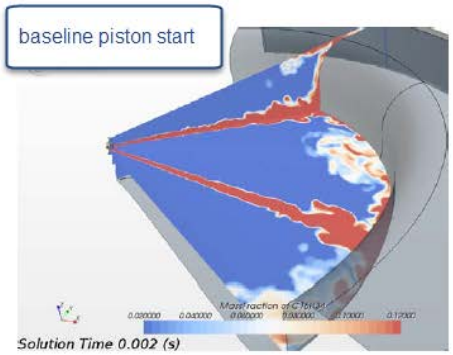
Image courtesy of Delphi

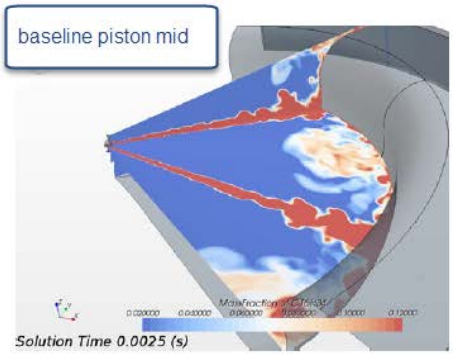
The distributed pump common rail fuel injection system will be in production for all Mack and Volvo 11 and 13liter engines starting in model year 2017.

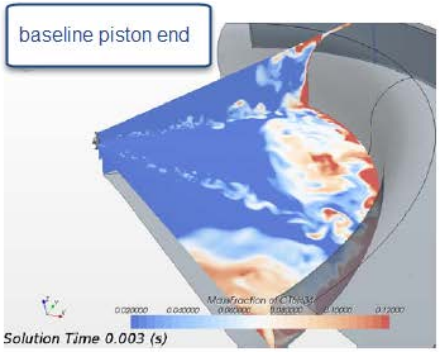
Technology to Customer

Volvo SuperTruck Combustion System Explained

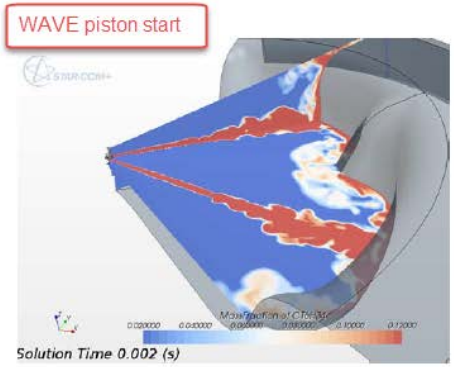
Fuel spray and flame impingement in a conventional piston leads to significant loss of gas jet velocity as the jets contact each other. When the flame fronts meet rich zones occur as available oxygen is depleted, quenching the flame and resulting in soot.

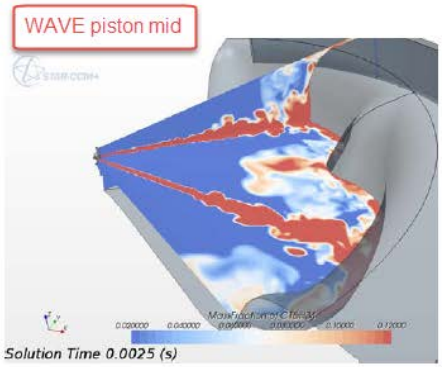


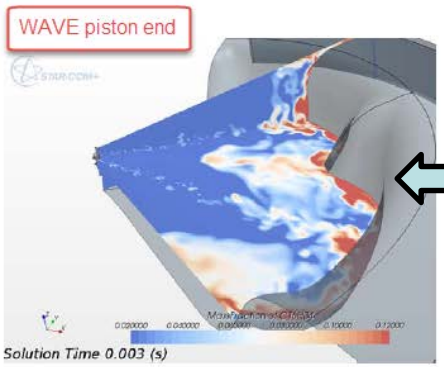




Baseline piston







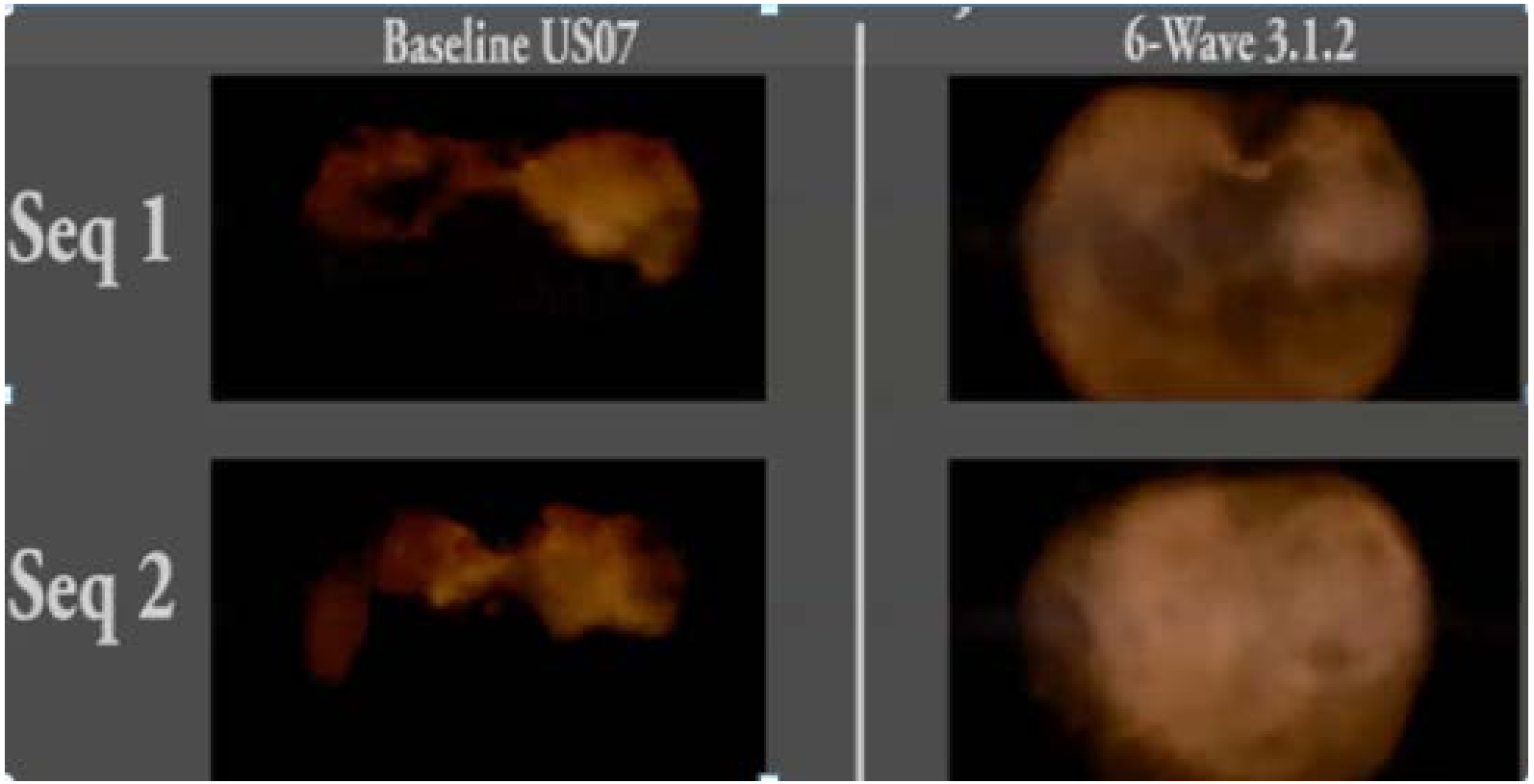
"WAVE" protrusion added

By adding piston bowl protrusions (named WAVE bumps), the fuel / flame jets re-enter the bowl center, maintaining jet velocity in an oxygen rich environment for more complete combustion.

Volvo SuperTruck Combustion System Explained

Optical inspection of the combustion event in the baseline piston vs piston with WAVE bumps

Notice the more complete burn at end of combustion with the WAVE piston as the fuel reaches the oxygen rich environment during re-entry.



Conditions:
1100rpm
50% load

Identical fuel injection parameters

Video camera located at cylinder wall between injector nozzle, above WAVE

Still shot near end of combustion

Volvo SuperTruck Combustion System Explained

The Volvo designed WAVE piston returns

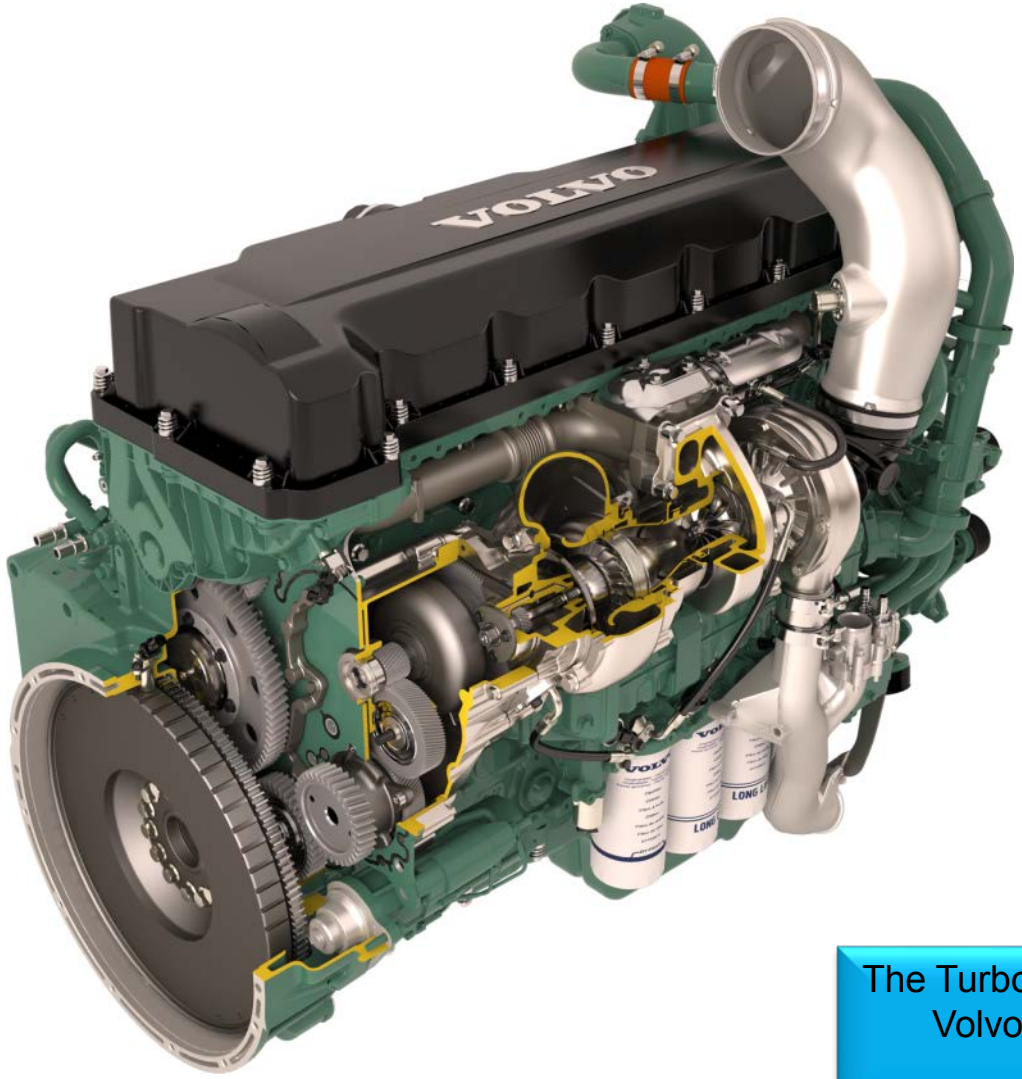
~2% fuel economy improvement
~90% reduction in soot

Relevant for all customer applications.

The WAVE piston will be in all Volvo and Mack 11 and 13 liter 2017 Model year engines in North America

Technology to Customer

Turbocompounding Explained



Energy and pressure are available in post-turbine exhaust. This normally wasted energy is delivered to a second turbine which is mechanically connected to the engine crankshaft.

The Volvo proprietary Turbocompound unit was carefully designed to match our downsped powertrain. This system approach enabled significant fuel economy improvement with increased torque while maintaining emissions compliance.

The TurboCompound will be in premium Volvo and Mack 13 liter 2017 Model year engines in North America

Technology to Customer

AfterTreatment Explained

Baseline (2010-2016) EATS unit

Moving from a separate DOC/DPF and SCR/ASC to a serviceable One-box packaged aftertreatment brought a 17 lbs. weight reduction.

2017+ EATS unit

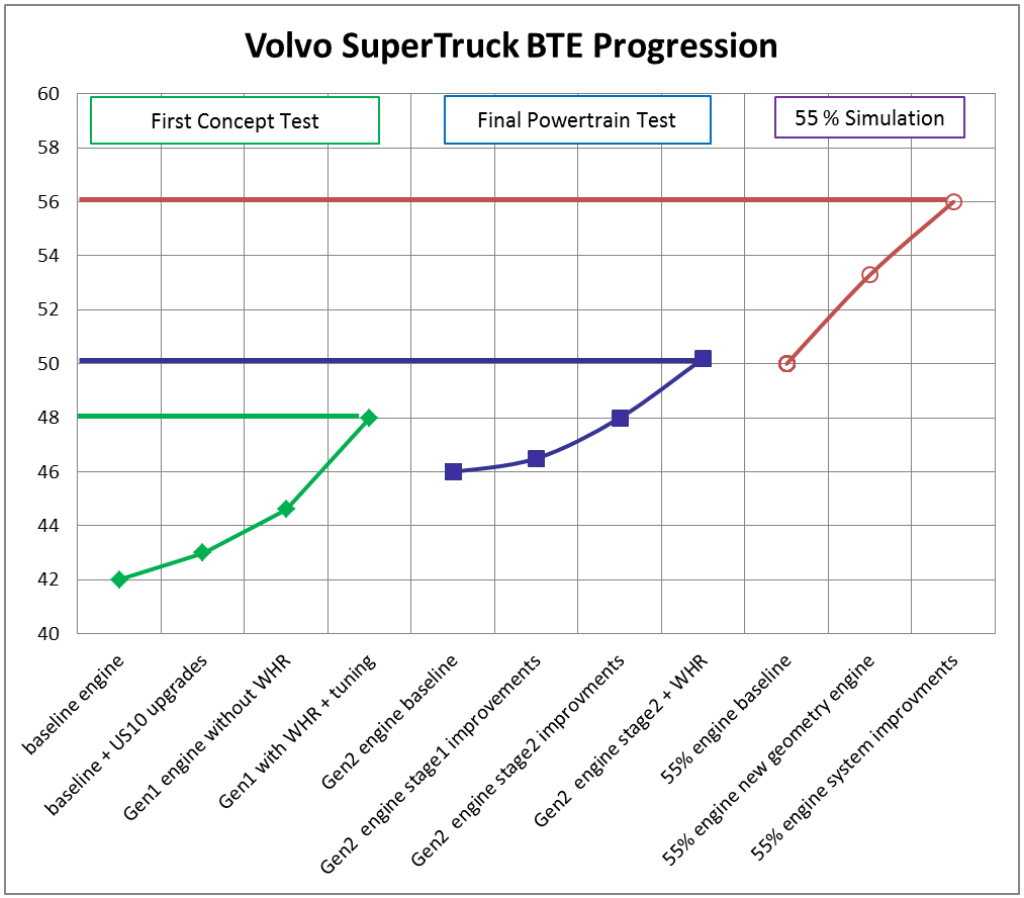
Improved thermal retention and changing from Iron to Copper based zeolite SCR enabled improved low temperature conversion efficiency.

The improved aftertreatment system will be in production in 2017 → Technology to Customer

Accomplishments towards 50% BTE (Objective 1a)

The 50% BTE powertrain system development is complete, with 50% BTE measured in test cell and installed in chassis.

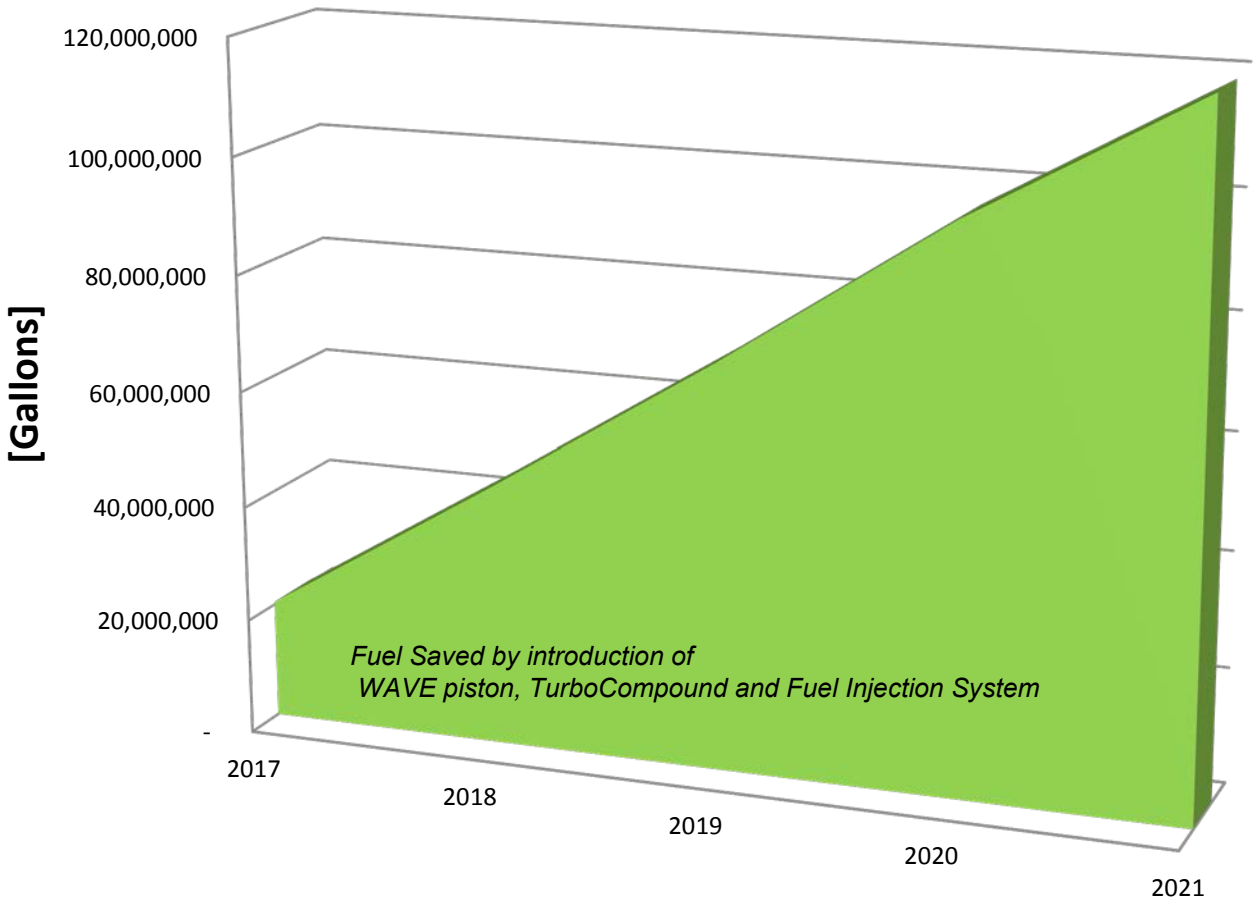
The 5-stage Axial Steam Turbine for WHR was successfully tested in the 50% BTE system.



The 50% BTE system includes the previously mentioned technologies and many more improvements to reduce friction and pumping losses, and items such as Rankine WHR.

Powertrain Project Results

Anticipated Gallons of Fuel Saved by Customers due to SuperTruck Powertrain Technology Introduction



In the next 5 years …

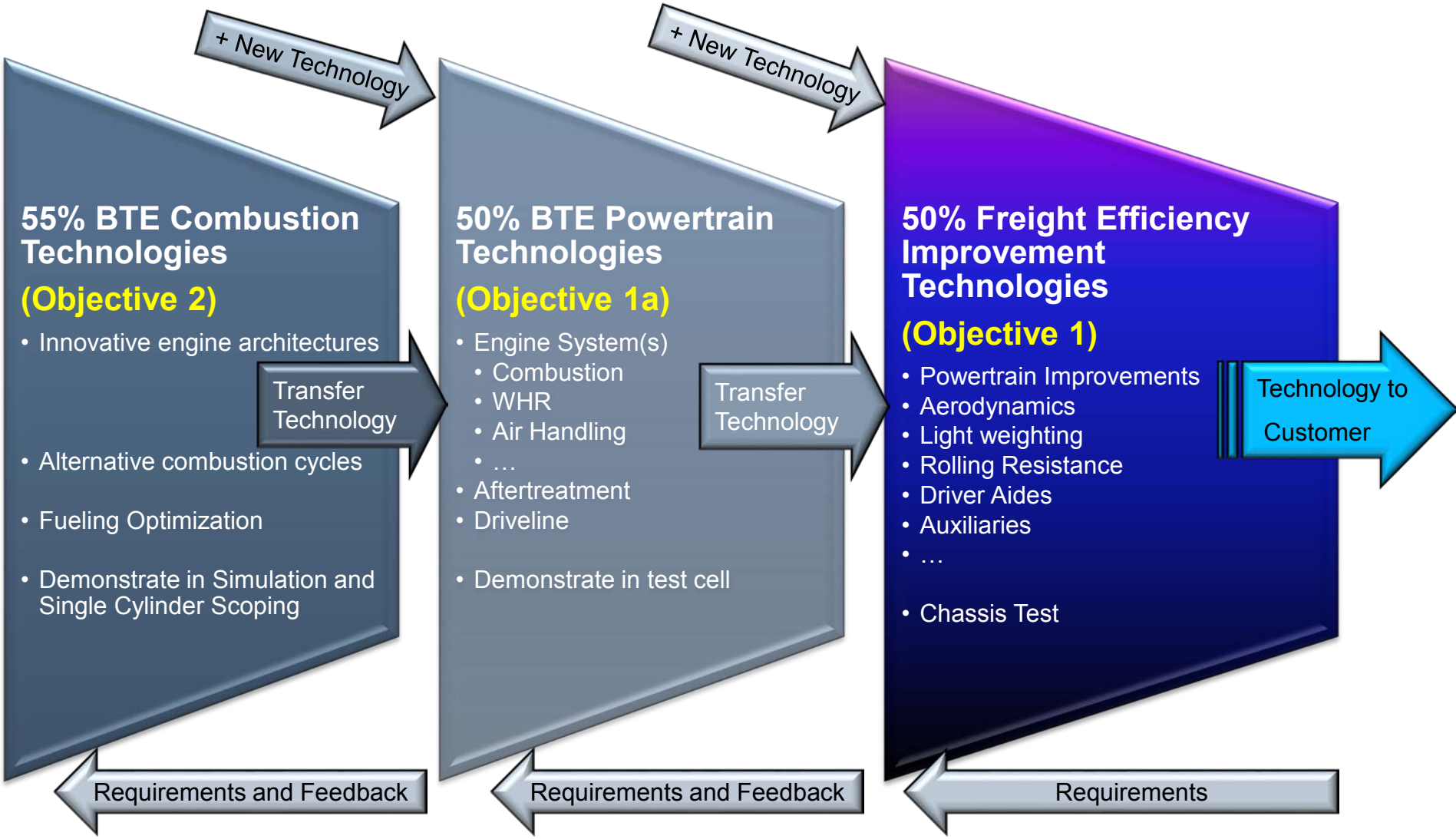
Powertrain* Technology matured in SuperTruck will save Volvo Group customers approximately

120 million gallons of fuel

**Not including SuperTruck vehicle improvements, some of which are already in production as well.*

Technology to Customer

Powertrain Workflow Approach / Strategy



Approach to Freight Efficiency Improvement

2011	2012	2013	2014	2015	2016

Phase I - Concept Selection

Baseline Tests

Techn. Development

Concepts Evaluation

engine bench

mule truck

Concept Truck

Model Development

Validation

Energy Management Dev.

Virtual Optimization

Phase II - Development & Integration

Techn. Refinement

Validation

engine bench

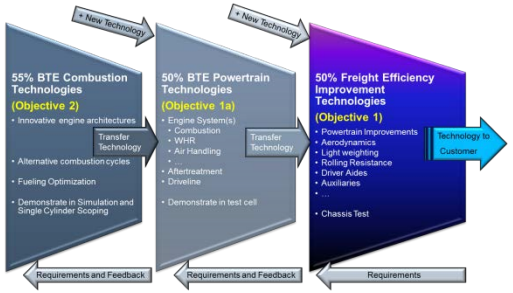
Integration

demonstrator chassis

Optimization

Demo Truck

Accomplishments towards 50% Freight Efficiency Improvement (Objective 1)



The Powertrain was delivered to the SuperTruck concept demonstrator with robust performance and has enabled an

88% Freight Efficiency improvement

measured during on-road testing

exceeding the 50% freight efficiency objective.

Collaborators / Partners

Partners have assisted in concept selections, simulation, integration and test phases, striving to deliver an optimized powertrain and chassis for maximum return on investment.

Specific focus on more academic development partners are listed below, but many thanks are due to other very involved suppliers whom are not listed.

Powertrain Collaborator / Partner	Focus
The Customer	Logged vehicle data was used from thousands of highway vehicles on the market to define drive cycles and requirements
Volvo Technology of America	Contract Management and Collaborator Integration
Volvo Group Trucks Technology	Engine, Transmission, Axles, Light weighting, Chassis Auxiliaries, Integration, Chassis Aerodynamics, …
Ricardo, Inc.	Rankine WHR Generation 1 Development
University of Michigan	55% BTE Simulation and Testing
Pennsylvania State University	55% BTE Simulation and Testing
Lund University	55% BTE Concept Development
Exxon Mobil	Advanced Fuels and Lubrications

Summary of Volvo Supertruck Project Status

- **Timeline:** Project complete
- **Budget:** Spent 100% to plan.
- **Relevance:** DOE program objectives relevant to this project are as follows: Develop more efficient highway transportation technologies, reduce petroleum consumption, reduce operating cost, improve environmental impact, and reduce time to market for high risk high complexity items (all have been achieved)
- **Approach:** Through simulation and testing, develop technologies that meet or exceed **55%** BTE scoping, **50%** BTE powertrain system in chassis, and **50%** Freight Efficiency improvement.
- **Technical Accomplishments:** Volvo has scoped a **56 %** BTE capable engine system, tested a **50%** BTE powertrain system in chassis and achieved **88%** Freight Efficiency improvement. ☑ ☑ ☑
- **Collaborations:** Suppliers and partners have developed technologies for improved fuel economy and freight efficiency and have delivered many improvements to the market already, with future product introductions planned. Academic partners have assisted in methods and tool development to achieve the BTE goals, and the program has assisted in the education of 6PhDs, 7MS, 4BS students.
- **Future Plans:** Technologies with good ROI promise will continue to be matured to deliver to customer. There remain major challenges to industrialize many 50% technologies, the most extreme example of Rankine WHR requiring much development effort to insure reliability and cost effectiveness. Considerations are being made to continue in the pursuit of 55% BTE.

The Volvo SuperTruck Project has met or exceeded all project criteria, with many technologies already delivered from the project to our customers, and more to come.

VOLVO