Volvo SuperTruck 2

Pathway to Cost-Effective Commercialized Freight Efficiency

Project ID: ACE101

Pascal Amar (PI)

Jian Li (PM Powertrain)

Volvo Group North America

DOE Annual Merit Review

June 4, 2020

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Project Overview

Objectives

Demonstrate >**100% improvement** in vehicle ton-miles per gallon compared with a 'best in class' 2009 truck, with a **stretch goal of 120%.**

Demonstrate **55% Brake Thermal Efficiency** on an engine dynamometer.

Develop technologies that are commercially cost effective in terms of a simple payback.

Barriers

Manage technology trade-offs during complete system integration

Develop complex systems concurrently

Push limits of laws of Thermodynamics

Timeline

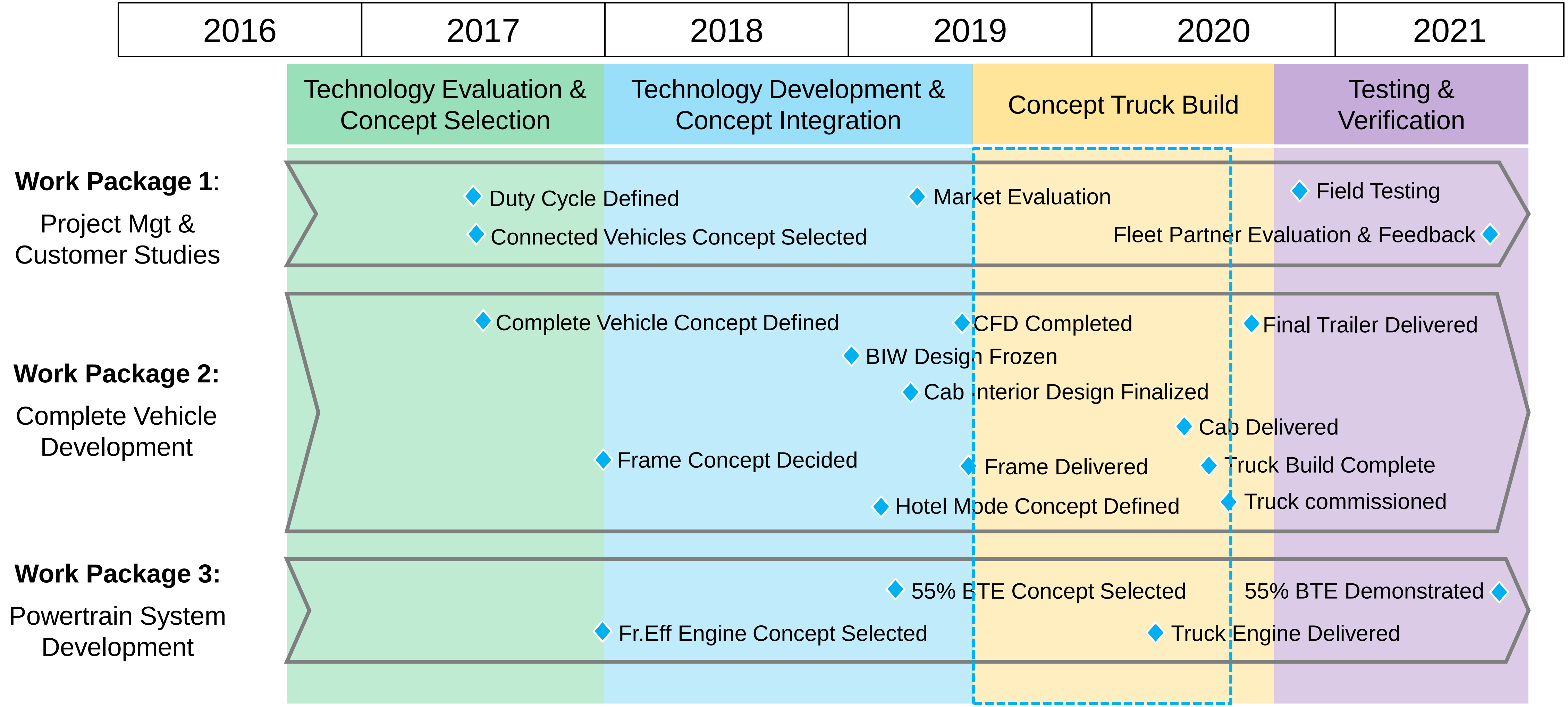
70%

Oct. 2016 — Sep. 2021

Funding

- Total project cost > $50 M
  - DOE funds $20 M
- FY2019 funding: $5,010,316
- FY2020 funding: $3,991,644

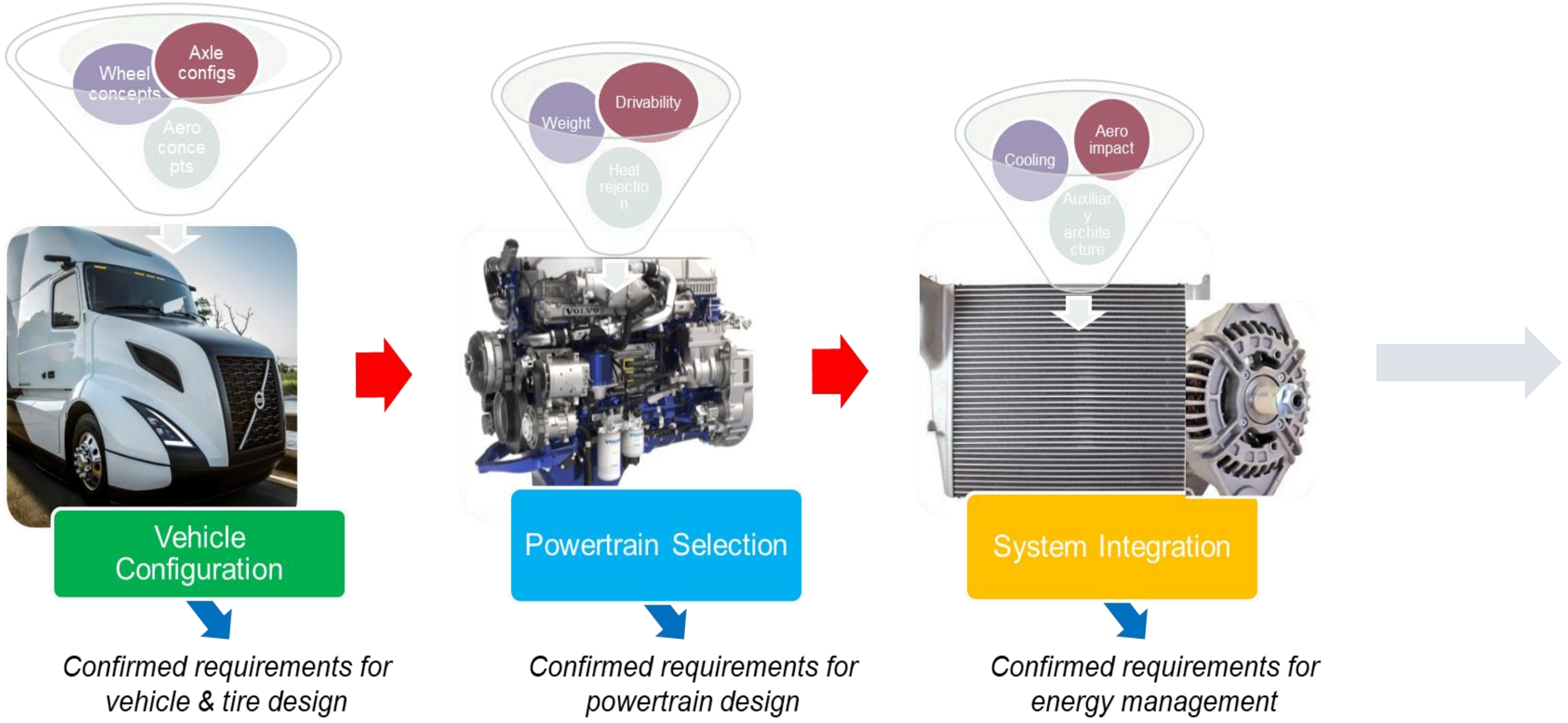
Approach & Milestones



Approach & Concept Overview

Vision: a super-efficient vehicle optimized for 65,000 lbs. and designed for the long-haul drivers of the future

Design criteria for each subsystem were derived from the program goals and broken down into individual targets or requirements.



Summary of the concept selected

4x2 axle configuration

19.5" wheels

Shorter cab w/ optimal interior configuration

<u>27,000 lbs. curb weight</u>

<u>15% better aero than ST 1</u>

325HP 11L powertrain

48V electrification & mild hybrid

All-electric HVAC

Multiple concepts were evaluated using complete vehicle simulations over a variety of duty cycles representing highway fleet operation.

Relevance & Approach: Data Driven Design / Fleet Studies

- Partnered with the **North American Council for Freight Efficiency** to:
  - Collect Voice of Customer on efficiency pain points & opportunities
  - Collect data from partner fleets to guide development of ST2 technologies

ABSTRACT: This report focuses on evaluating the potential viability of intentionally pairing tractors and trailers by model in freight system management based on performance factors to achieve improved fleet fuel efficiency. The report provides details and sources for more accurately modeling factors for optimizing freight system routing to include tractor and trailer performance metrics.

- Completed a first study on intentional **pairing of aerodynamic tractors & trailers**
  - Report evaluates viability of concept and provides modeling factors for optimizing freight system routing to include tractor/trailer metrics
  - See https://nacfe.org/report-library/intentional-pairing/

- On-going study: **increasing adoption of cruise control** to maximize real-world fuel savings & **improving future cruise control design**
  - Interviewed fleets to understand how well the functionality and benefits of the various cruise control offerings are understood by operators and fleet managers.
  - Currently collecting input from fleets to identify key parameters to cruise control utilization.
  - Next: refine development & implementation requirements to maximize fuel economy impact of cruise control.

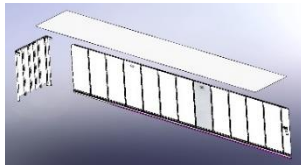
Accomplishments – Trailer Weight Reduction

Baseline trailer 13,390 lbs

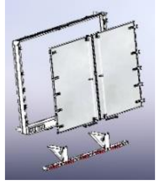
Total Savings **-1,992 lbs**

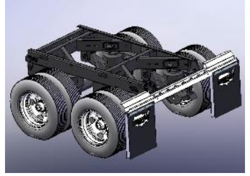
~15% weight reduction

Sidewalls	-457 lbs
Nose	-13 lbs
Roof	-27 lbs

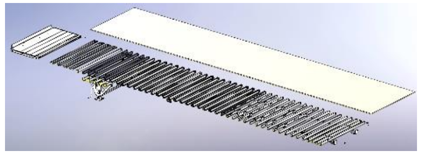


Rear Frame	-19 lbs
Susp. Components	-771 lbs





Floor System	-663 lbs
Al. Landing Gear	-42 lbs



The trailer walls are made up of laminated Cell Core panels –no more rivets.

ST2 base trailer ~11,400 lbs

Aero devices 671 lbs

ST2 aero trailer **~12,070 lbs**

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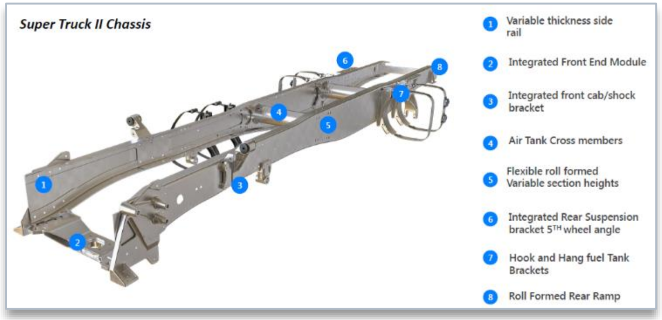
Accomplishments – Tractor Weight Reduction

Team proudly unveiling the completed lightweight ST2 frame assembly in August 2019

- Metalsa delivered a **tractor frame assembly >35% lighter** than the comparable configuration using a mix of technologies and materials
  - Variable rail thickness focused on high stress areas
  - Component integration to improve weight, cost & packaging



Successful proof of concept:
Aluminum air tank cross-member

- ST2 tractor curb weight is expected to be <**15,000 lbs target** thanks to a vehicle configuration focused on freight efficiency:
  - Shorter cab & chassis → lower curb weight
  - Smaller wheels & 4x2 → less weight & better aero
  - Better aero → less power & less fuel needed
  - Less power → less heat rejection
  - Less heat rejection → better aero
  - Less fuel / smaller tanks → less weight
  - ….

Example of the 'system approach':

even the front wheels are **optimized for low aero drag and low weight.**

(- 5 lbs vs. baseline Al. wheel)

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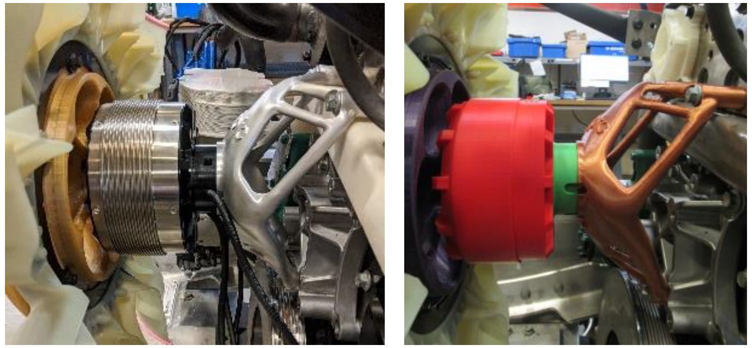
Accomplishments: Generative Design

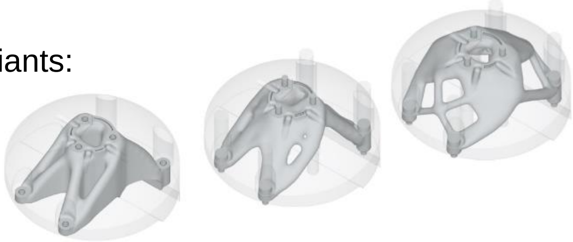
- **Generative design delivered significant weight reductions** & time savings
  - Design approach minimizes stress so new materials can be used
  - Very good match for additive manufacturing processes
  - Rapid & low-cost design iterations, including mock-ups
  - Ideal for fast design of new lightweight brackets in tight spaces

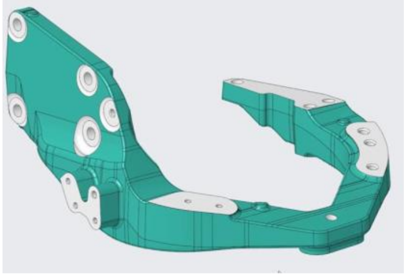
Printed engine ‘bridge bracket’



This generative design was optimized for machining
(left: final part / right: printed mock-up)

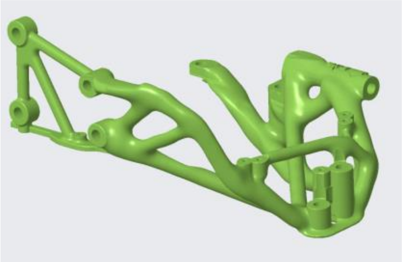
Design Variants:





Original Design
Material: Iron (cast)
Weight: 20.36 kg

Multiple design iterations of ST2 front engine mount



Generative Design
Material: Al 356 (cast)
Weight Reduction: 75%

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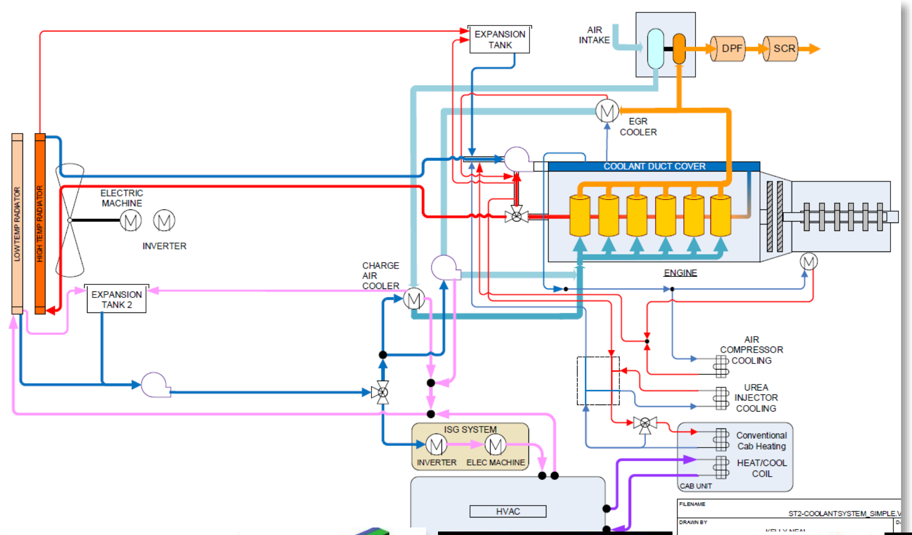
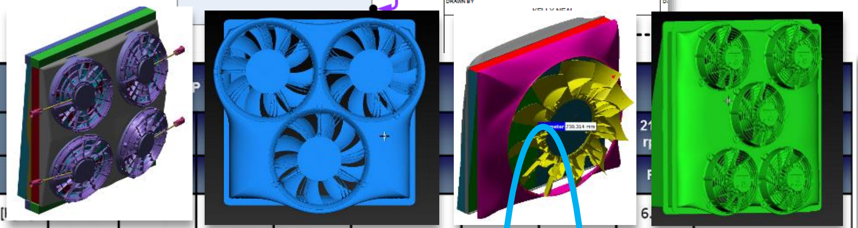
Accomplishment: Cooling Package Design & Installation

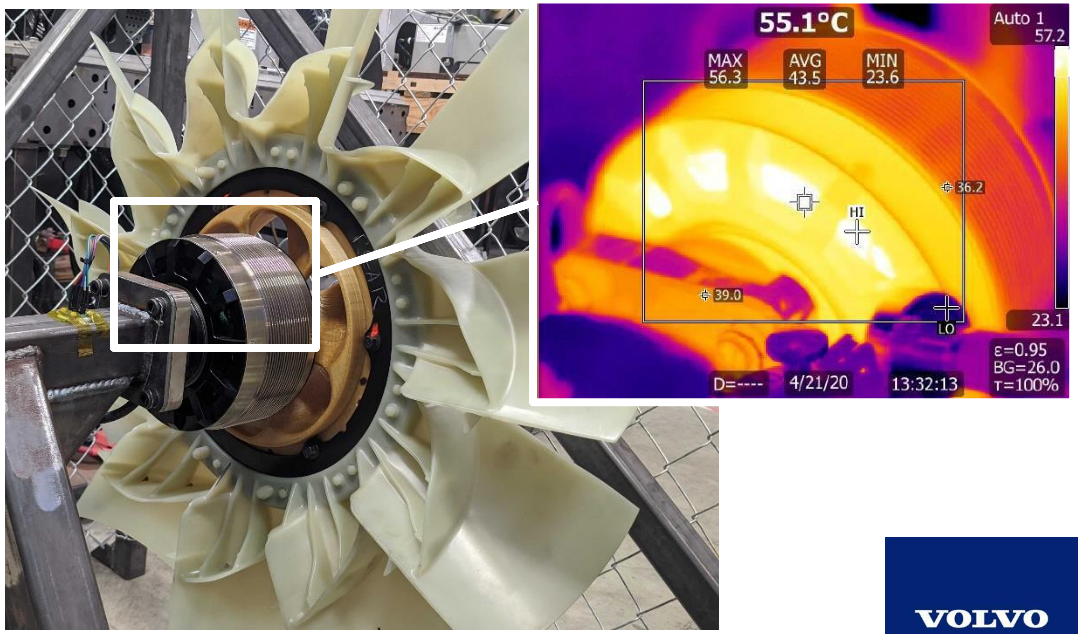




Grille Airflow		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
HTR	Top Tank	[°C]	89.6	137.2	119.5	107.3	119.7	130.3	110.9	99.0	125.3
	Air Mass Flow	[kg/s]	1.95	1.77	**2.28**	**2.79**	**2.26**	[illegible]	**2.62**	3.30	2.31
	Entry Air Temp	[°C]	32.0	32.0	32.0	32.0	32.0	[illegible]	[illegible]	32.0	51.9
LTR	Top Tank	[°C]	56.6	83.5	79.8	77.5	79.7	[illegible]	[illegible]	76.2	81.0
	Air Mass Flow	[kg/s]	2.07	1.98	2.50	3.03	2.51	[illegible]	[illegible]	3.57	2.25
	Entry Air Temp	[°C]	32.0	32.0	32.0	32.0	32.0	[illegible]	[illegible]	32.0	32.1
	LAT *HTR*	[°C]	49.4	1.8	**19.5**	**31.7**	**19.3**	[illegible]	**28.1**	40.0	13.7
	IMTD (?) *LTR*	[°C]	24.6*	51.5*	47.8*	45.5*	47.7*	[illegible]	46.1*	44.2*	49.0
FAN	**Power Draw**	[kW]	NA	3.2	6.5	11.6	5.4	5.0	[illegible]	18.9	1.7
	Vol. Flow Rate	[m³/s]		3.02	4.79	5.70	5.12	4.78	[illegible]	7.08	

Evaluation matrix – ST2 cooling package configurations

- Multiple cooling package configurations were evaluated to optimize the trade-off between heat rejection / aero drag / weight / energy consumption
- The concept selected consists of
  - **710mm fan driven by 48V air-cooled motor**
  - **Low-restriction radiator cores**
  - **Dual (HT/LT) loop cooling system with electric pumps**



Selected fan solution during rig performance testing.

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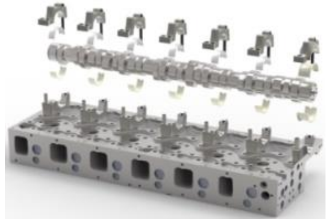
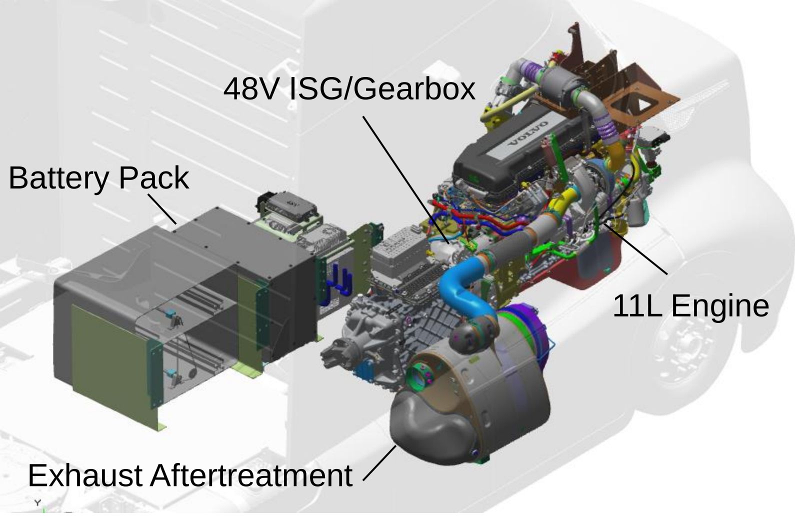
Approach – Freight Efficiency Optimized Powertrain

48V hybrid system recovers kinetic energy
- Integrated starter / generator on rear PTO
- 2-speed gearbox for optimal torque/RPM
- 14 kWh Li-Ion battery system for energy storage

Improved air handling system
- EGR pump maximizes expansion
- Re-optimized fixed turbo system
- Miller camshaft enables more pumping reduction



Parasitic loss reduction with improved base engine
- Synthetic overlay Bearings
- Long Con rod
- Short CH piston
- Low friction ring pack
- Variable oil pump



Redesigned Aftertreatment system
- low back pressure with short DPF/SCR
- Low restriction exhaust diffuser design
- Electrically heated catalyst

Combustion efficiency improvement
- 20:1 compression ratio wave bowl
- 250 bar peak cylinder pressure
- Optimized heat release w/ improved common rail
- Thermal barrier coated pistons & liners

More parasitic loss reduction enabled by 48V hybridization
- Front Engine Accessory Belt removal
- Electric coolant pumps (*left*)
- Electric radiator fan
- Electric EGR pump

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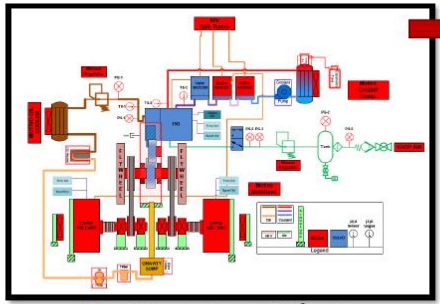
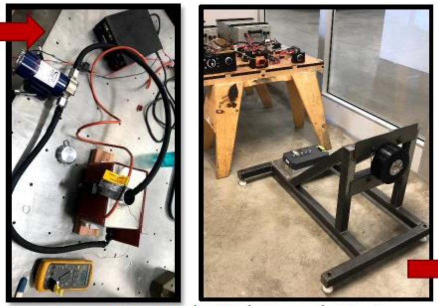
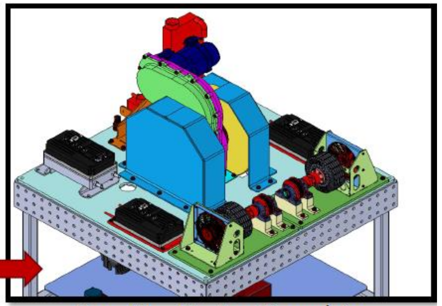
Accomplishments - 48V Mild Hybrid System Development



Day 14 – System Definition

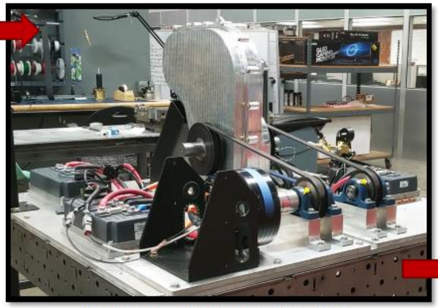


Day 35 – High-Risk Bench Tests



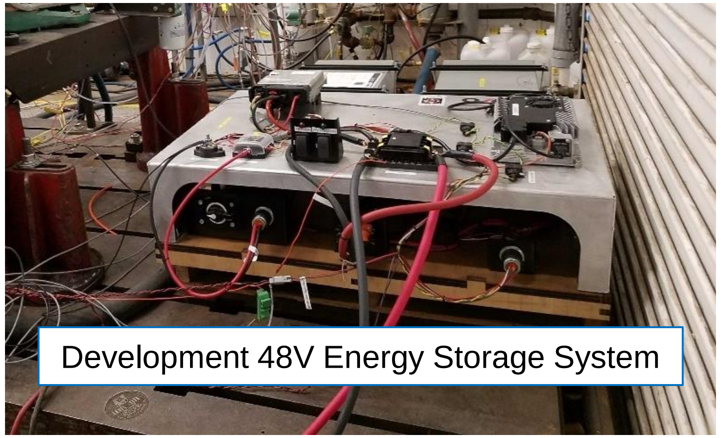
Day 49 – Design Complete

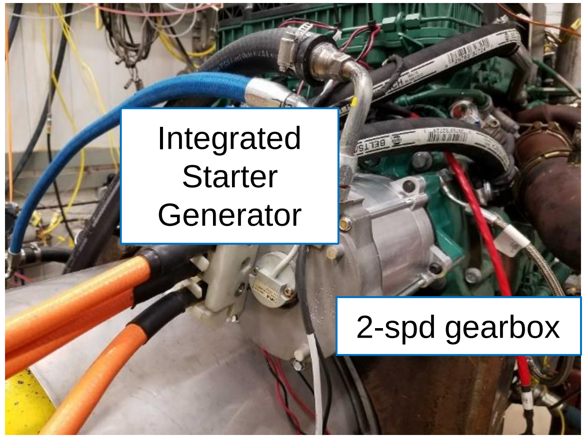
Day 76 – System Dry Fit



Day 88 – Initial Spin Test

Day 100 – Dyno Commissioned





- **Designed & built a custom dynamometer** at Motivo
- **Characterized ISG/Gearbox functionality & performance**
- **Characterize/validate ESS performance**
  - Validate architecture, software & calibrations
- **Mild Hybrid System installed on 11L engine** at SWRI for integration testing, software debug, calibration & characterization of the complete powertrain. including
  - High Temp (HT) / Low Temp (LT) electric coolant pumps
  - Liquid / Air Charge Air Cooler (CAC)
  - 48V Integrated Starter Generator (ISG)
  - 2-speed Gbx to connect ISG to REPTO
  - Energy Storage System (ESS)
- **Validated mild-hybrid Powertrain installed in ST2 chassis**

→ *ready for road testing to begin summer 2020*

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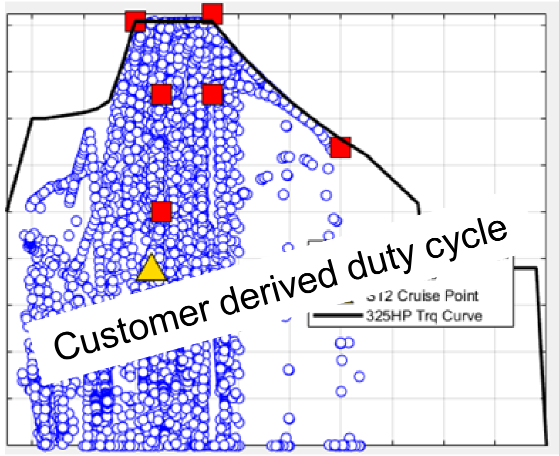
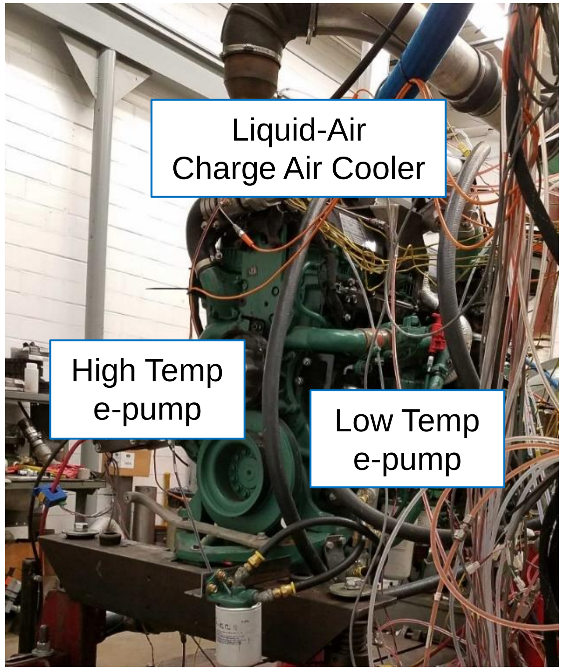
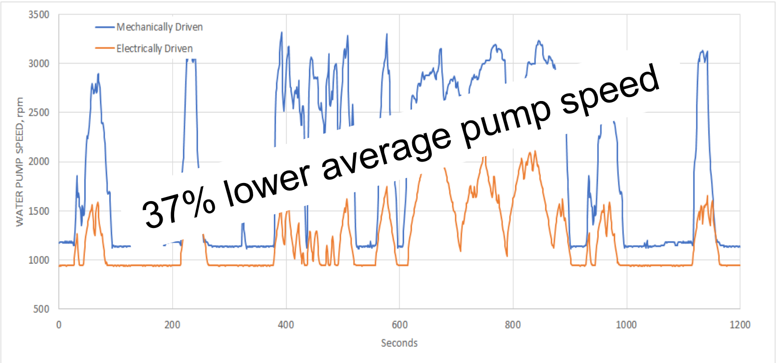
Accomplishments: Powertrain Electrification

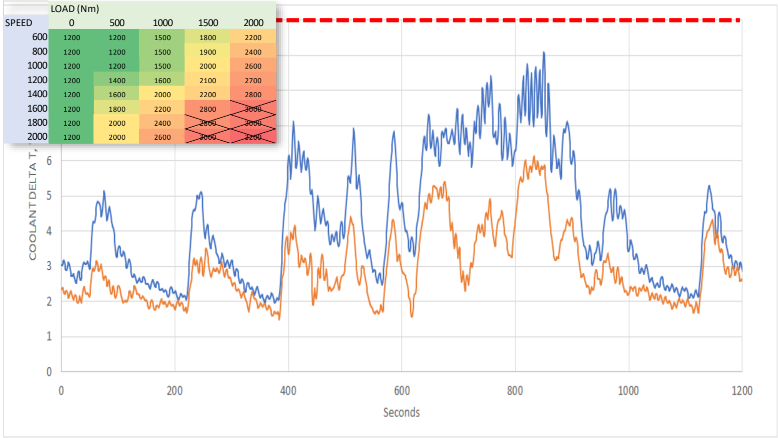




- New components on the new ST2 dual-loop cooling system were validated on an engine dynamometer at the **Southwest Research Institute**, including
  - Electric High Temp (HT) coolant pump
  - Electric Low Temp (LT) coolant pump
  - Liquid / Air Charge Air Cooler (CAC)
- Cooling performance and energy consumption were measured on a variety of road cycles
- Control logic and base calibrations for the e-pumps were validated
- Back-to-back testing of belt driven vs. electrified pumps confirmed **of +0.5 ~ 0.7% BTE** from friction reduction
- **>1% Fuel Eco improvement on ST2 road cycle**



Belt-driven vs. electric coolant pump speed over FTP



SPEED	LOAD (Nm) 0	500	1000	1500	2000
600	1200	1200	1500	1800	2200
800	1200	1200	1500	1900	2400
1000	1200	1200	1500	2000	2600
1200	1200	1400	1600	2100	2700
1400	1200	1600	2000	2200	2800
1600	1200	1800	2200	2800	~~3000~~
1800	1200	2000	2400	~~2800~~	~~3000~~
2000	1200	2000	2600	~~3000~~	~~3200~~

Simple control table keeps coolant within specs

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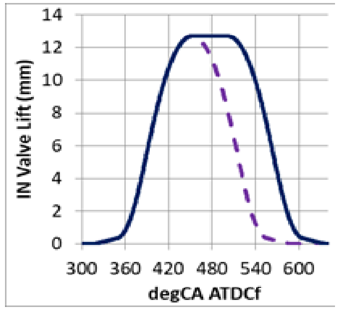
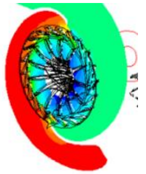
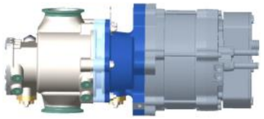
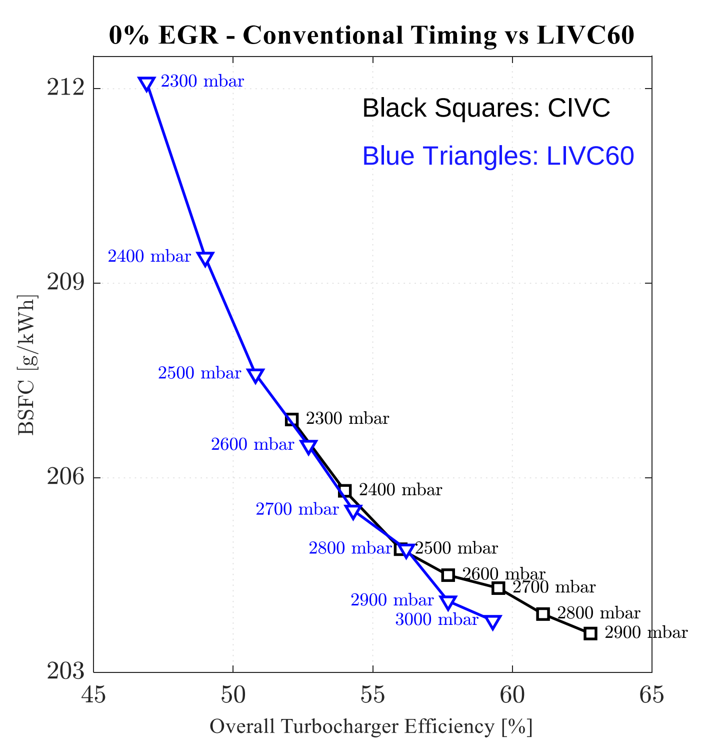
Accomplishments: Advanced Combustion

- **EGR Pump + Twin Entry FGT: +0.5 ~ 0.9 BTE %**
    - Allows re-optimization of fixed geometry turbo
    - High Air-fuel ratio improves combustion rate
    - Positive pumping work
- **20:1 Compr. Ratio: +0.3 BTE %**
    - Improved gross Indicated Thermal Efficiency
- **Miller cam: +0.3 ~ 0.7 BTE %**
    - High expansion ratio at moderated effective CR
    - Open cycle eff. improved despite vol. eff. drop
    - Lower NOx allows reduced EGR
    - Reduced cyl. pressure allows better combustion
- **Combustion system integrated on 11L engine → →**
- **Performance verification is complete**









Studies at UMich using SCRE equipped with VVA system found that LIVC using Miller cycle begin to show slight advantage over conv. valve timing at higher turbo efficiencies

UNIVERSITY OF MICHIGAN

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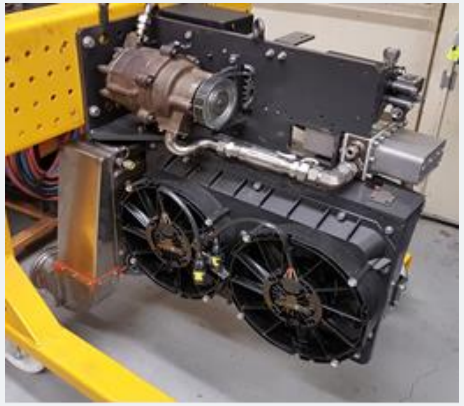
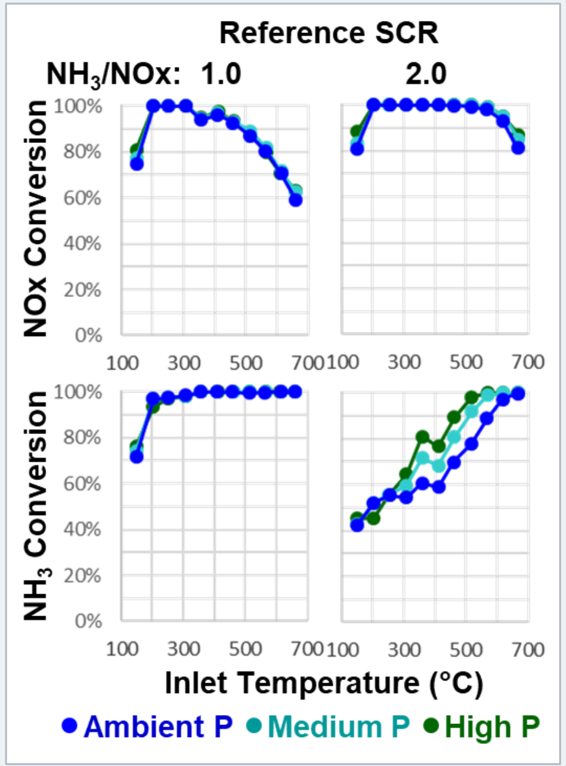
Progress – Advanced Powertrain

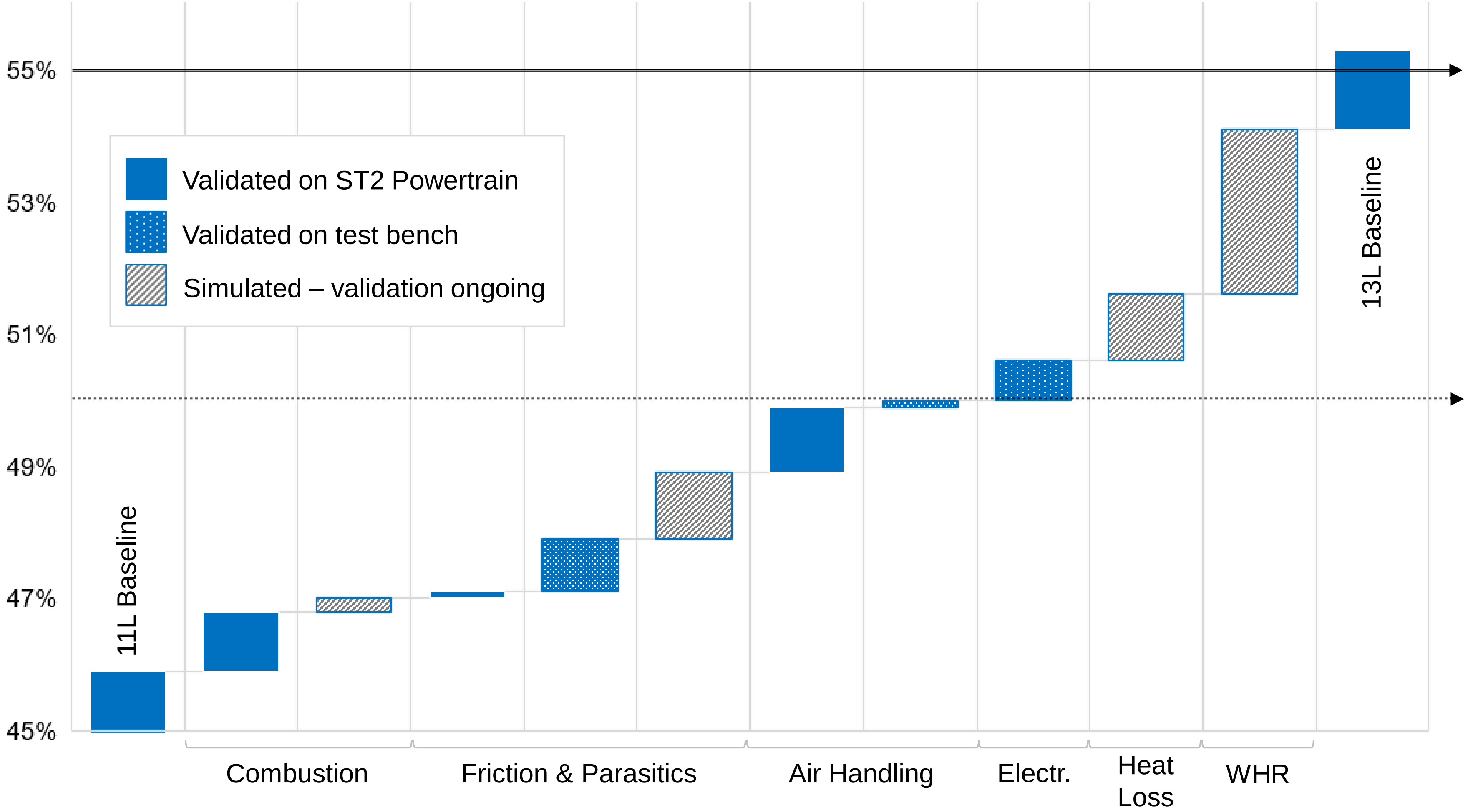
- **New Waste Heat Recovery System**
  - Dual loop design generates electricity
  - Captures exhaust & coolant energy
  - Connected to 48V mild-hybrid system
  - **2%~3% estimated combined BTE gain**
  - Working fluids: Cyclopentane & refrigerant
- Tailpipe WHR system being rebuilt
- Coolant WHR system in design



- **Challenge:** 55% BTE engine has lower exhaust temperatures, making emissions control more difficult. Placing catalysts upstream of the turbo yields higher temperatures, but impacts of elevated pressure on catalyst performance is largely unknown
- **Approach & Collaborations:** a new synthetic exhaust flow reactor at **ORNL** is used to run elevated pressure experiments on catalyst samples from **Johnson Matthey**, at relevant exhaust compositions, flows, and temperatures provided by **Volvo**.
- **Progress:**
  - SCR catalyst showed improved NOx and NH3 conversion with increasing pressure
  - High pressure operation helps prevent NH3 slip under overdosing conditions



Progress – Validation of Powertrain Technologies



CR 20:1
PCP 250 bar
Bowl optimization
Miller camshaft
New Common Rail

e-EGR pumping
Low friction rings
Long con.rod
low comp.height
Improved bearings
Low friction liners
Reduced piston cool.
Low viscosity oil

High Efficient CAC
Optimized EGR cool.
Low EATS restriction
Optimized turbo
EGR pumping

TBC bowl
High temp. piston
Cyl. head insulation
Exh. port insulation

Powertrain optimized for thermal efficiency
Engine Dyno Demo

Powertrain optimized for freight efficiency
Truck Demo

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Project Summary

- **Relevance**

  The goals of this project are aligned with the key barriers to higher fuel efficiency of highway transportation. Each task in the project scope addresses a specific technical challenge e.g. aerodynamic improvement, friction reduction.

- **Approach**

  Volvo's SuperTruck 2 program is currently in the third of four phases, which focuses on integrated the technologies selected and developed in previous phases. Phase II is on track to deliver designs and components to support the start of the complete vehicle build in the next phase.

- **Milestones & Technical Accomplishments**

  In this reporting period we successfully completed analysis and design iterations of new systems and have progressed to the testing phase on schedule. evaluation based on simulations. Bench testing of many components is now complete and integration is well underway for the complete vehicle demonstrator that will demonstrate >120% freight efficiency improvement. Development work continues for the technologies selected to achieve the 55% BTE engine goal.

- **Future Work**

  Complete build & commissioning of the ST2 demonstrator to begin road testing. Optimize the 48V mild-hybrid and energy management systems based on initial results. Continue to develop and integrate the technologies selected for the 55% BTE engine demonstration.

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

Thank you

See You Soon!

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Technical Backup Slides

ST2 Cooling System Overview – Presented at AMR 2019

Significant improvements in parasitic drag forces and combustion efficiency resulted in lower power demand and heat rejection. This provided new design freedom for the cooling system.

Multiple concepts were evaluated with regards to their impact on weight / cost / efficiency / packaging of the complete vehicle.

The solution chosen features:

1. High & low temperature loops
2. Electric pumps
3. 28” fan with electric drive
4. Liquid/Air charge air cooler
5. Low-restriction radiators