Project ID: ace154

Heavy-Duty Hybrid Diesel Engine with Front-End Accessory Drive-Integrated Energy Storage

Chad P. Koci

Caterpillar Inc.

June 4th, 2020

2020 DOE Vehicle Technologies Office Annual Merit Review

CATERPILLAR®

Overview

Timeline

- Start date: May 2019
- End date: June 2022
- ~35% Complete

Budget

- Total Funding: $7.32M
  - DOE share: $3.44M
  - Industrial share: $3.88M
- 2019: $3.23M
- 2020: $2.16M

Barriers

- High-capability air handling equipment required for further engine downsizing
- Waste heat recovery and reduction in parasitic losses at reasonable costs
- Hybrid powertrain systems integration complexity and lack of modularity

Partners

- SuperTurbo Technologies
- University of Texas at Austin
- Project lead: Caterpillar

Relevance

- Objective
  - Research, develop, and demonstrate a heavy-duty hybrid diesel (H2D2) engine system for off-road applications
  - Performance Targets:
    - ***<u>17 (+/-2) % more fuel efficient than current Tier 4 diesel engine</u>***
    - Equivalent transient response vs. baseline diesel engine
    - Achieves Tier 4-Final Exhaust Emissions Levels

- Impact
  - Proposed improvements applied to off-road product range would save more than 25 million barrels of oil over 10 years
  - A crucial reduction in customer Total Cost of Ownership (TCO)

Milestones

Date/Time	Description of Milestone or Go/No-Go	Status
May 2019	Project launch and kick-off meeting	Complete
December 2019	Hybrid Concept Finalized	Delayed, no impact to Go/No-Go #1
January 2020	Baseline system CAD completed	Complete
April 2020	Baseline Thermofluid Simulation completed	Complete
June 2020 **Go/No-Go #1**	IF 1D system level simulation validates that the target total fuel consumption reduction AND Tier IV Final emissions AND the power system can be packaged in to target off-road machines; THEN proceed	On Schedule
October 2020	Thermofluid, Structural & Dynamic Simulation Complete	On Schedule
December 2020 **Go/No-Go #2**	IF the structural, dynamics simulations show that the target 12,000 hour durability can be achieved AND the subsystems demonstrate required performance on bench tests; THEN proceed	On Schedule

Approach & Strategy

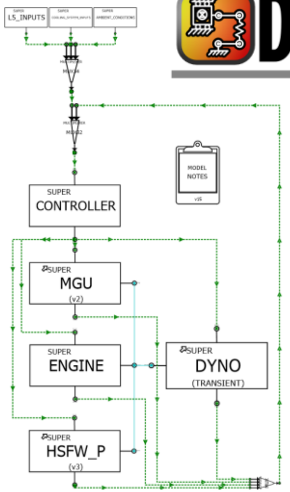
- Add hybrid power and energy aspects to enable:
  - Engine Downsizing
    - Transient load assist to *maintain machine productivity*
  - Energy Recovery
  - Start/Stop (or Anti-Idle)

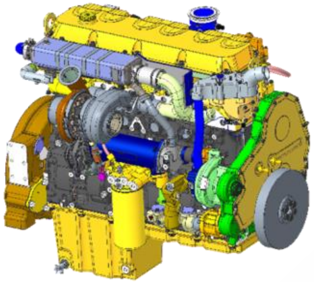
- We will design a high-efficiency powersystem with a 13L concept engine - downsized from 18L – for use in off-road machine applications. The powersystem will have a hybrid front-end accessory drive (FEAD) that incorporates:
  - High-Speed Flywheel (HSFW)
  - Mechanical-drive Turbocharger (SuperTurbo)
  - Motor-Generator Unit (MGU)

Approach & Strategy

- Concept Design & Simulation
  - Systems-level modeling of hybrid powersystem concept
    - Define concept trade-offs & provide performance predictions
- Major Subsystem Analysis & Specification
  - 1D & 3D Thermofluid, Structural & Dynamic simulations
    - Address durability, performance, & modularity
- Phase 1 Concept Demonstrator Engine
  - Validate engine-only performance predictions
- Phase 2 Hybrid Engine System Validation
  - Complete powersystem validation in transient test cell
- Technoeconomic Analysis
  - Address cost barriers & provide TCO value assessment

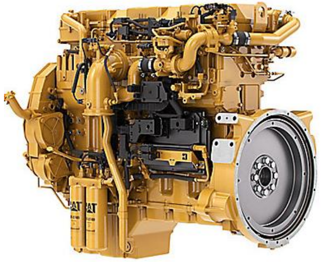
Dynasty





Technical Accomplishments & Progress

30% Increase
in Power
Density



Cat® C18 ACERT™
370 – 400kW

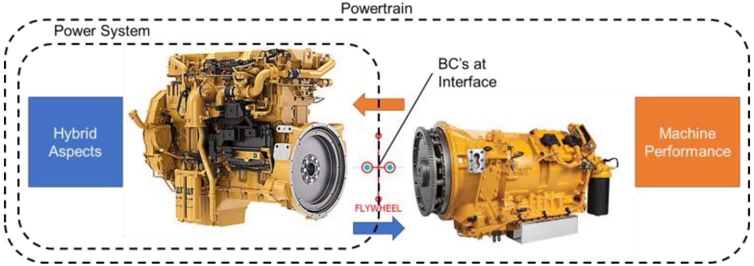
Concept ~13L
400kW

- 30% Downsized engine capability confirmed
- 3 off-road applications identified
- Baseline performance targets and comparisons completed
- Powersystem boundary conditions defined

988K Large Wheel Loader

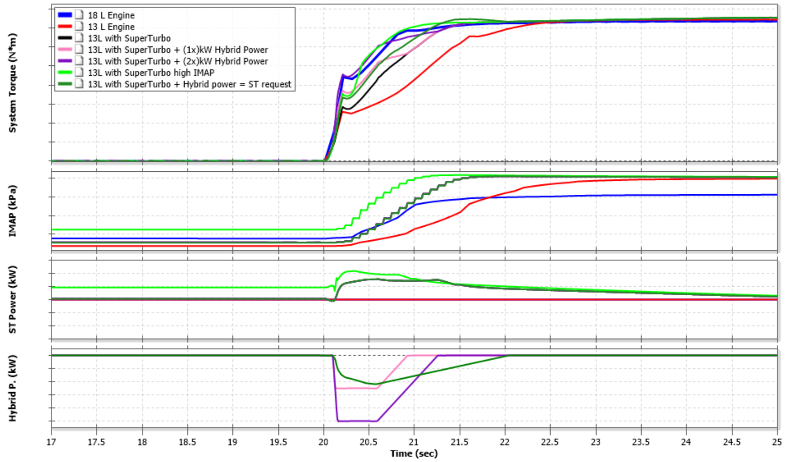
390F Hydraulic Excavator

745 Articulated Truck

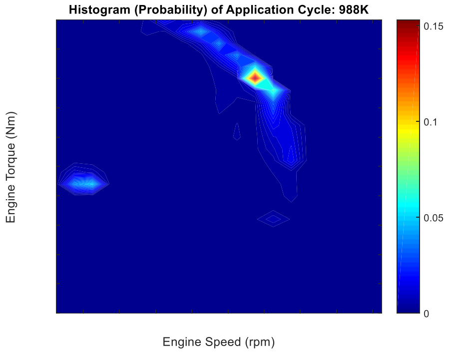


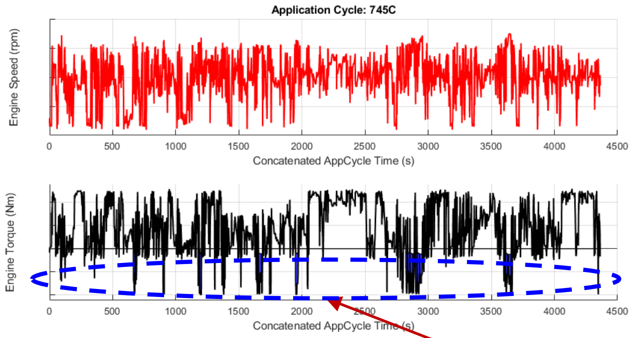
CATERPILLAR

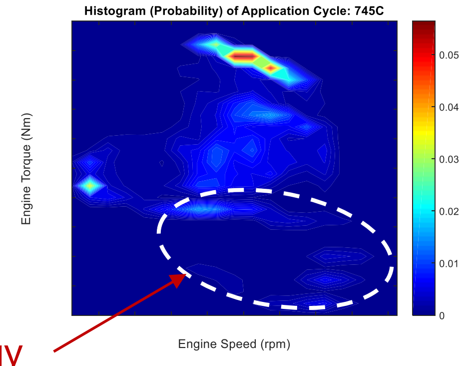
Technical Accomplishments & Progress

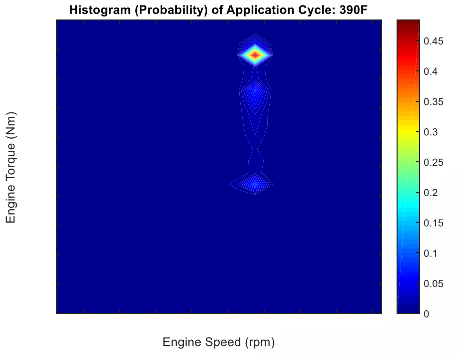


- Histograms, Application cycles, & energy recovery defined
- Transient load response critical focus on hybrid system definition









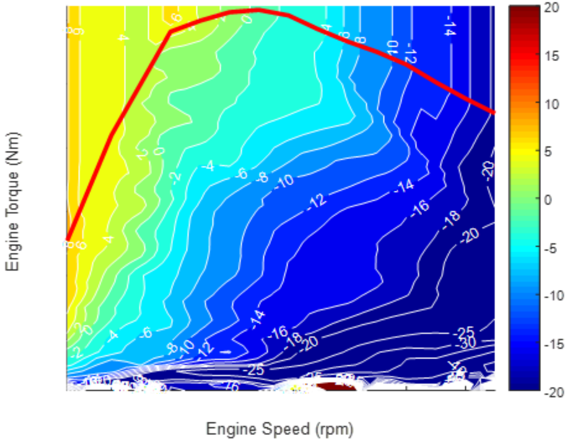
Recoverable Energy

CATERPILLAR®

Technical Accomplishments & Progress

- Concept Engine Accomplishments
  - Performance simulated
  - Initial calibration generated
  - Preliminary design completed
  - Phase 1 engine build completed

13L-18L BSFC, Percent Difference (%)



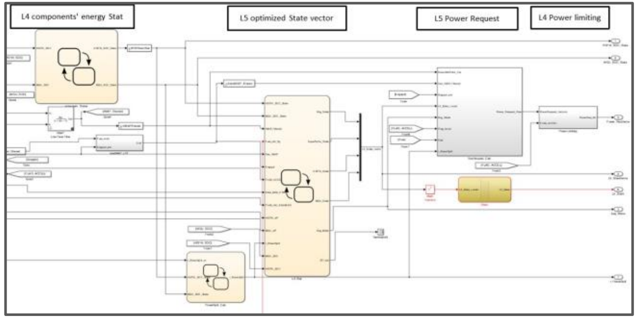
- High Efficiency Building Blocks
  - Increased Peak Cylinder Pressure (PCP)
  - Higher CR
  - Lower friction
  - Improved combustion
  - Improved breathing
  - Optimized cooling
  - Reduced aftertreatment restriction

CATERPILLAR

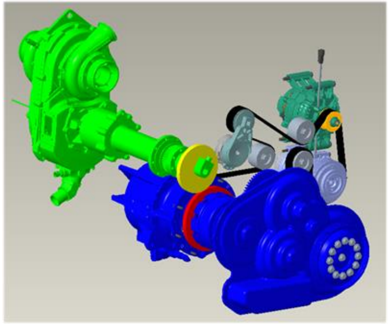
Technical Accomplishments & Progress

- Powersystem Accomplishments
  - Supervisory control structure developed
  - Hybrid concept definition narrowed
  - Hybrid device size/power/capability identified
  - Start/stop benefit range identified
  - Go/No-Go #1 input compiled

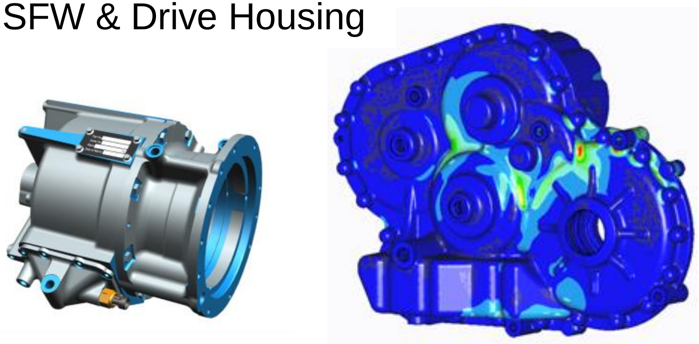
Controls



Hybrid FEAD Packaging and CAD Layout



HSFW & Drive Housing

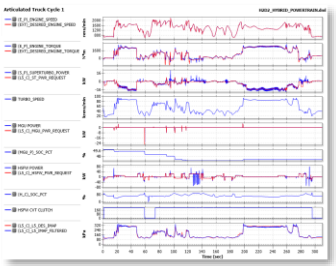


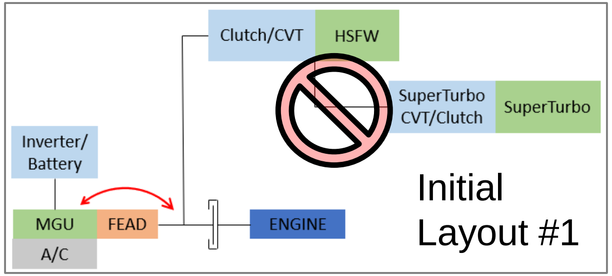
CATERPILLAR®

Technical Accomplishments & Progress

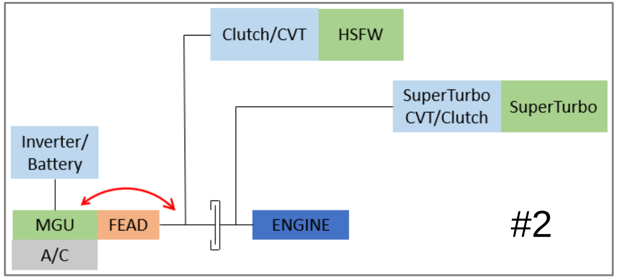
- Concept Definition Phase has reduced complexity and narrowed hybrid concept

Dynasty

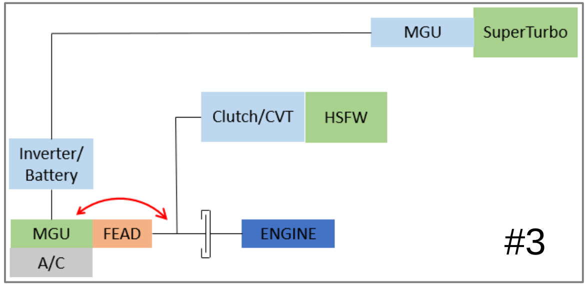




Initial Layout #1



#2



#3

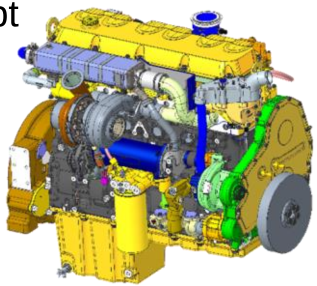
#n

…Final

Technical Accomplishments & Progress

- Powersystem efficiency prediction range overlaps the program goal range of 17 (+/-) 2%

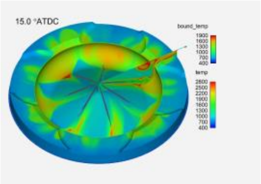
Concept Engine



SuperTurbo

Flywheel

TBC



Transient Response Also Enables Engine Eff.

Current predictions of high-level efficiency contributions over the baseline 18L engine powersystem

9.0-10.0%	13L Concept engine
1.5-2.5%	SuperTurbo Turbo-compounding
0.5-1.0%	High-Speed Flywheel (HSFW)
0.5-2.0%	Thermal Barrier Coatings (TBC)
2.0-4.0%	Start/stop implementation
13.5-19.5%	***Current Total***

Response to Previous Year Reviewers' Comments

- This is the first AMR for this project (launch date of May 2019)

Collaborations & Coordination

Partners

- Caterpillar
- SuperTurbo Technologies
- University of Texas at Austin

Vendors

- Bosch
- Punch Flybrid
- Borg Warner

https://punchflybrid.com/

https://www.borgwarner.com/technologies/electric

https://www.boschautoparts.com/en/auto/diesel-parts

Remaining Challenges and Barriers

- Replicating the snap torque of the larger engine requires significant hybrid assist power that must be transmitted near instantly. This has produced cascading hybrid power, actuator and controls requirements.
- Supervisory hybrid controls strategy refinement & early-benefit prediction is difficult due to uncertainties in plant model dynamics. This is driving extended concept simulation effort prior to the concept selection milestone.
- Packaging hybrid devices becomes complex as the interaction and power increase.
- Maintaining the same high-durability requirements for a 30% increased power density engine brings extensive analysis effort.
- Realizing & measuring (with statistical confidence) predicted improvements in areas of engine friction and heat transfer is historically difficult.

Proposed Future Research

- Finalize concept for Go/No-Go #1 Decision
- Phase 1 concept demonstrator engine-only validation testing
- Continue major subsystem analysis and specification toward Go/No-Go #2 Decision
- Begin hybrid system build and integration

				BP1							BP2				BP3			
				2018	2019				2020				2021				2022	
Item Title	**Item Description**	**Start Date**	**End Date**	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**	**Q8**	**Q9**	**Q10**	**Q11**	**Q12**	**Q13**	**Q14**	**Q15**
Contracting, Project Kick-off, Project Management		**10/1/2018**	**6/30/2022**															
Concept Design and Simulation		**6/1/2019**	**3/31/2021**															
Decision Point 1	*IF 1D system level simulation validates that the target total fuel consumption reduction AND Tier IV Final emissions AND the power system can be packaged in to target off-road machines; THEN proceed to Task 3.*		6/30/2020							♦								
Major Subsystem Analysis & Specification		**3/1/2019**	**12/31/2020**															
Decision Point 2	*IF the structural, dynamics simulations show that the target 12,000 hour durability can be achieved AND the subsystems demonstrate required performance on bench tests; THEN proceed to ST-3.1*		12/31/2020									♦						
Hybrid Engine System Build & Integration		**4/1/2020**	**12/31/2021**															
Hybrid Engine System Validation		**9/30/2021**	**6/30/2022**															
Technoeconomic Analysis and Documentation		**4/1/2022**	**6/30/2022**															

Proposed Future Research

- Finalize concept for Go/No-Go #1 Decision
  - Finalize hybrid concept layout and lock down main component specifications
- Phase 1 concept demonstrator engine-only validation testing
  - Confirm combustion, air system, and rating development direction
  - Provide engine-only preliminary validation data
- Continue major subsystem analysis and specification toward Go/No-Go #2 Decision
  - Develop Phase 2 hybrid concept powersystem component specifications
  - Confirm friction and heat transfer direction
  - Confirm 12,000hr durability
- Demonstrate 17 (+/-2)% efficiency improvement
  - Powersystem test cell build, hybrid system procurement and integration
  - Demonstrate fuel efficiency over the 3 key off-road applications

Program Summary

- Engine
  - The smaller concept engine development is on track
  - Significant engine downsizing and efficiency improvements are partially enabled by the transient response assist capabilities of the hybrid devices
- FEAD Hybrid Aspects
  - High-Speed Flywheel (HSFW) and Motor Generator Unit (MGU) development is on target
  - SuperTurbo development is proceeding speedily into the next specification phase
- Caterpillar is reasonably confident in this system achieving off-road efficiency improvements of 17 (+/-2)%

Technical Back-up

- Initial FEAD hybrid concept layout