Improving Efficiency of Off-Road Vehicles by Novel Integration of Electric Machines and Advanced Combustion Engines

PI: Sage Kokjohn

University of Wisconsin – Madison

Engine **R**esearch **C**enter

June 24, 2021

Program Managers: John Terneus and Michael Weismiller

Award Number: DE-EE0008801

Project ID #: ACE164

Overview

Timeline

- Start: October 2019
- End: March 2023
- Completion 35%

Budget

- Total project funding $3.96M
- DOE: $2.70M
- Cost share: $1.26M

Partners

- Purdue University
- John Deere

Barriers

- Off-road vehicles account for 8% of the total energy consumed in the U.S. transportation sector and are a substantial source of harmful emissions, including nitrogen oxides and fine particulate matter.
- Full electrification of these applications is challenging due to the remote and harsh environments where these vehicles operate.
- Emissions, efficiency, and cost/complexity of hybrid diesel powertrains suitable for off-road applications are not well understood
- Cost effective, durable, low emissions, high efficiency approaches are needed for the off-road sector.
- A comprehensive strategy is required to explore ways to improve engine efficiency while lowering emissions (i.e., NOx, GHG, etc.)

Relevance

Relevance

- Modern off-road equipment will increasingly rely on electrified implements, but an onboard reciprocating engine is expected to remain the primary energy converter → **energy storage is expected to be available, but reducing the ICE's fuel consumption is paramount to enable GHG and cost reductions.**
- Addition of energy storage opens opportunities to improve efficiency while reducing emissions
- The goal of this work is to evaluate how the extra flexibility that an enhanced electrical system provides can be best used to enable high efficiency, low emissions off-road vehicles

Objective of Budget Period 1

- Perform system level modeling to identify a powertrain configuration capable of achieving a greater than 8% increase in efficiency over the current production powertrain

Full Program Objective

- Demonstrate a greater than 10% improvement in efficiency by utilizing electrification to enable
  1. engine downsizing
  2. increased air-handling flexibility
  3. optimized combustion process
  4. full hybridization

Milestones

Today

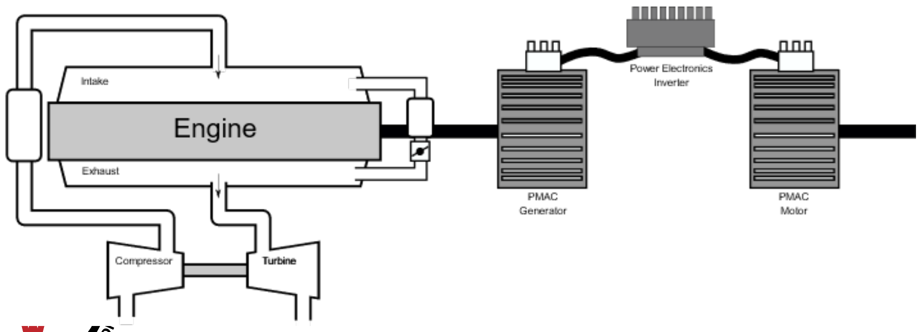
			BP1						BP2				BP3			
Name	**Description**	**Status**	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**	**Q8**	**Q9**	**Q10**	**Q11**	**Q12**	**Q13**	**Q14**
Model Validation	Model reproduces measured Brake Mean Effective Pressure (BMEP) and Brake Thermal Efficiency (BTE) to within 10% over the Non-Road Transient Cycle (NRTC).	Complete		M												
Baseline Model Evaluation	Constant speed load acceptance and transient response of the 4.5 L engine are compared to the 6.8 L engine. Identify deficiencies Areas showing performance deficiencies greater than 10% are documented.	Complete			M											
Engine Controller	Experimental results will show capability of controlling the start of combustion and the intake oxygen mass fraction to within 1 crank angle and 1%, while maintaining engine-out temperatures in excess of 225 deg. C.	Complete						M								
System Optimization	Optimized system using conventional diesel combustion with an efficiency improvement of greater than 8% over the Non-Road Transient Cycle (NRTC) is identified	Complete						G/NG								
Model Validation	Machine model reproduces measured efficiency to within 10%.	On-Track								M						
LTC Engine Calibration	Optimized multi-mode engine calibration generated for a system using each of the electrified air handling systems	On-Track								M						
Engine Mode Transitions	Demonstrate LTC-to-CDC and CDC-to-LTC mode transitions on engine with LTC combustion timing maintained within 4 degrees of desired values.	On-Track										M				
System Level Validation	A greater than 10% efficiency improvement over the baseline engine is demonstrated over the representative drive cycle.	On-Track										G/NG				
Supervisory Control	Refine algorithms and implement/test in Off-Road Demo Vehicle	Future													M	
Transient	Mode switching demonstrated over transient conditions.	Future												M		
Experimental Demonstration	An experimental demonstration of a greater than 10% efficiency improvement in a demo vehicle. The final system evaluation will provide a quantitative assessment of the potential of powertrain hybridization for off-highway vehicles.	Future														Final

Approach

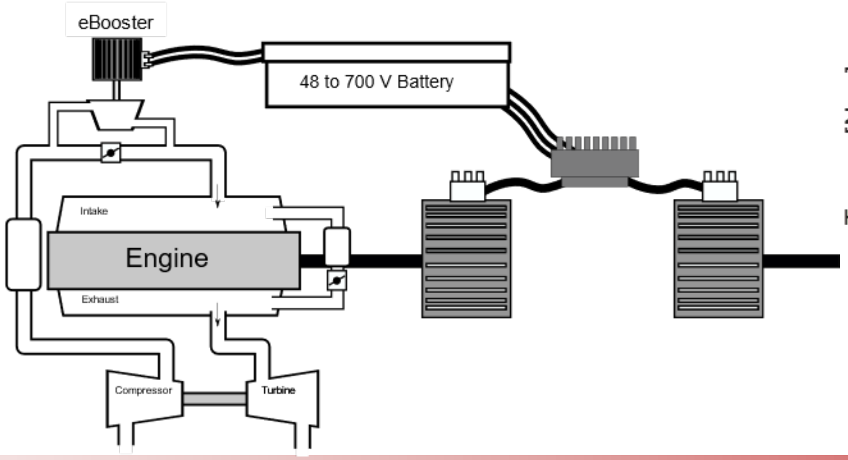
- Couple system level modeling, engine experiments, and vehicle testing to develop an optimized powertrain to take advantage of increased electrification to improve efficiency
- Demonstration vehicle is the John Deere 644K Hybrid Diesel Series Electric Three Speed (STSE) Front End Loader
  - Current configuration uses a series electric drivetrain and 6.8L engine **without energy storage**
  - Current effort will identify a pathway to downsize to 4.5L by incorporating the optimal level of energy storage

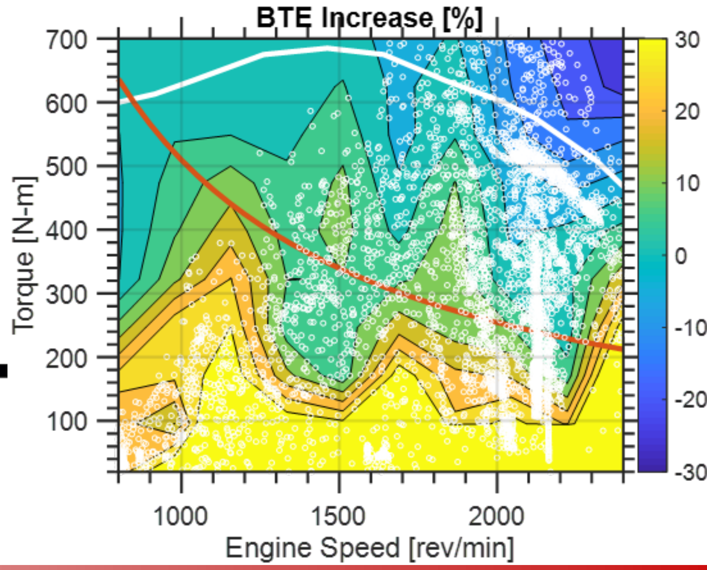
Brake Thermal Efficiency (BTE) increase compares 6.8 L engine and 4.5 L engine producing equal torque (points show drive cycle for 6.8 L engine)

Baseline Powertrain
(6.8 L Engine without energy storage)



Proposed Powertrain
(4.5 L Engine with energy storage)

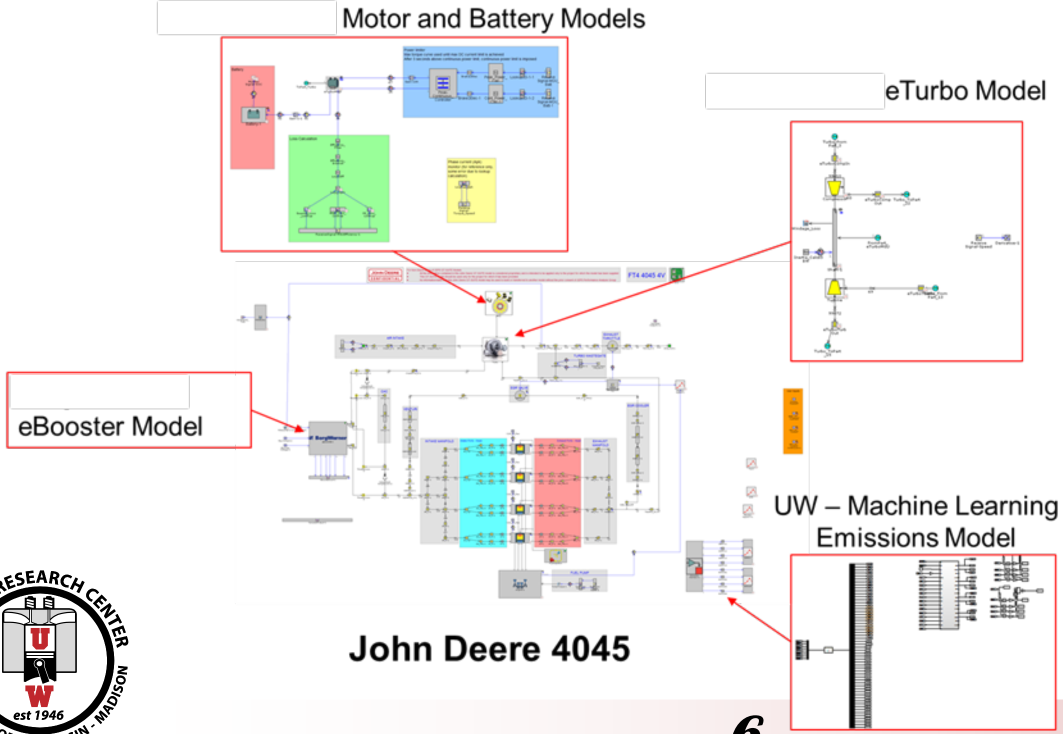


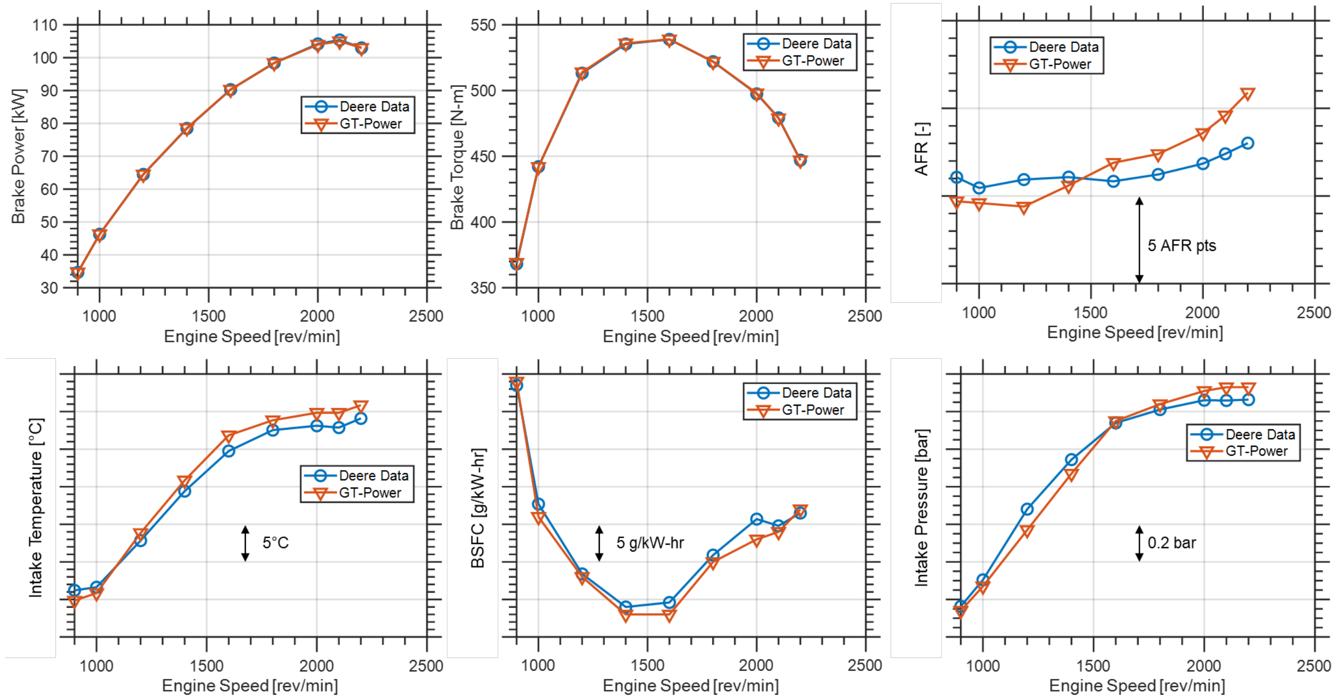


Technical Accomplishments and Progress

Accomplishments

- System-level models constructed to evaluate hybrid powertrain
- Model includes
  - Engine
  - Electrified air handling
  - Machine learning based emissions model derived from ~3000 computational fluid dynamics (CFD) simulations





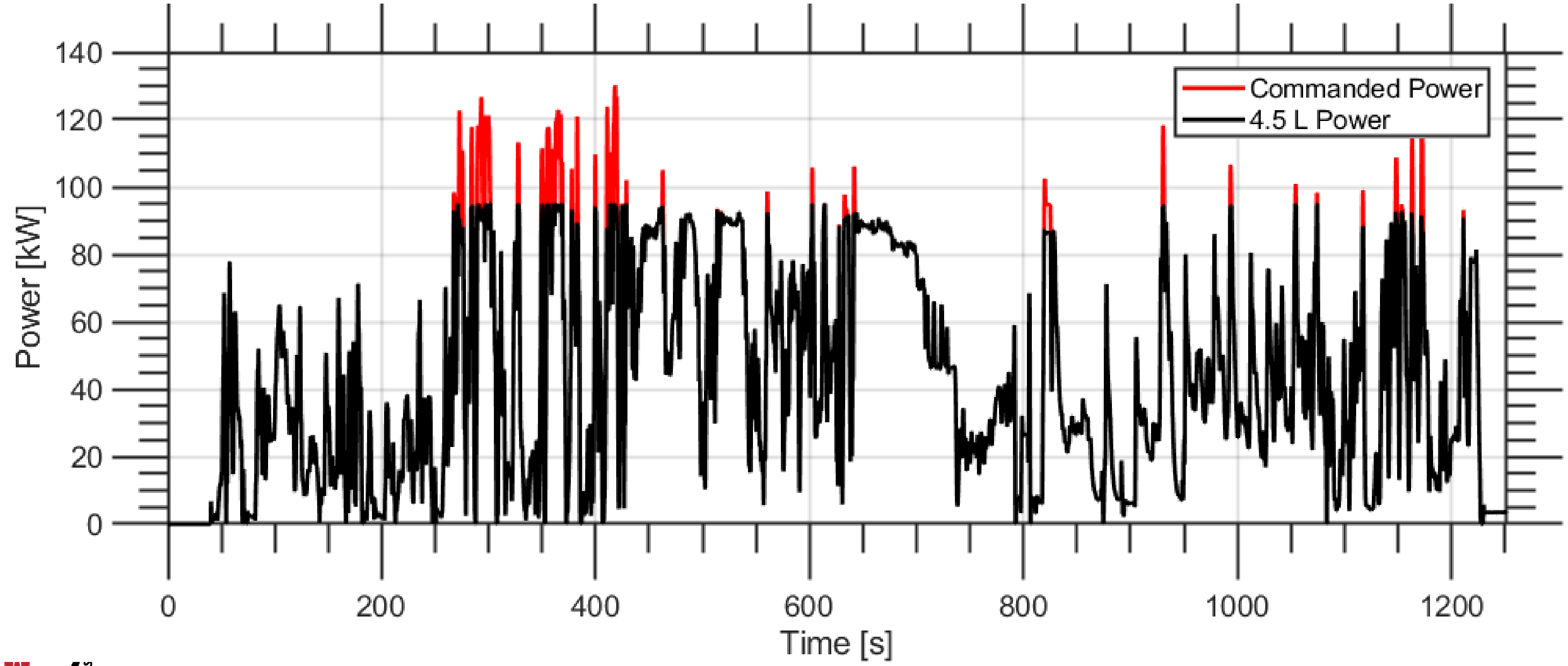
Validation performed through comparisons with John Deere supplied data → excellent prediction of flow and efficiency (e.g., maximum fuel consumption error ~2%)

Takeaway: System level models have been developed and validated for hardware selection

Technical Accomplishments and Progress

Model exercised to identify areas where the downsized engine cannot meet targets

- Non-road transient drive cycle (NTRC) shows short periods where 4.5 L is unable to reach power targets
- Can powertrain electrification be used to allow downsizing and improve efficiency?
- Preferred approach is to use single-turbo version of 4.5 L to offset cost of electrification to ensure market acceptance



Takeaway: downsized engine requires expanded load range to replace 6.8 L engine

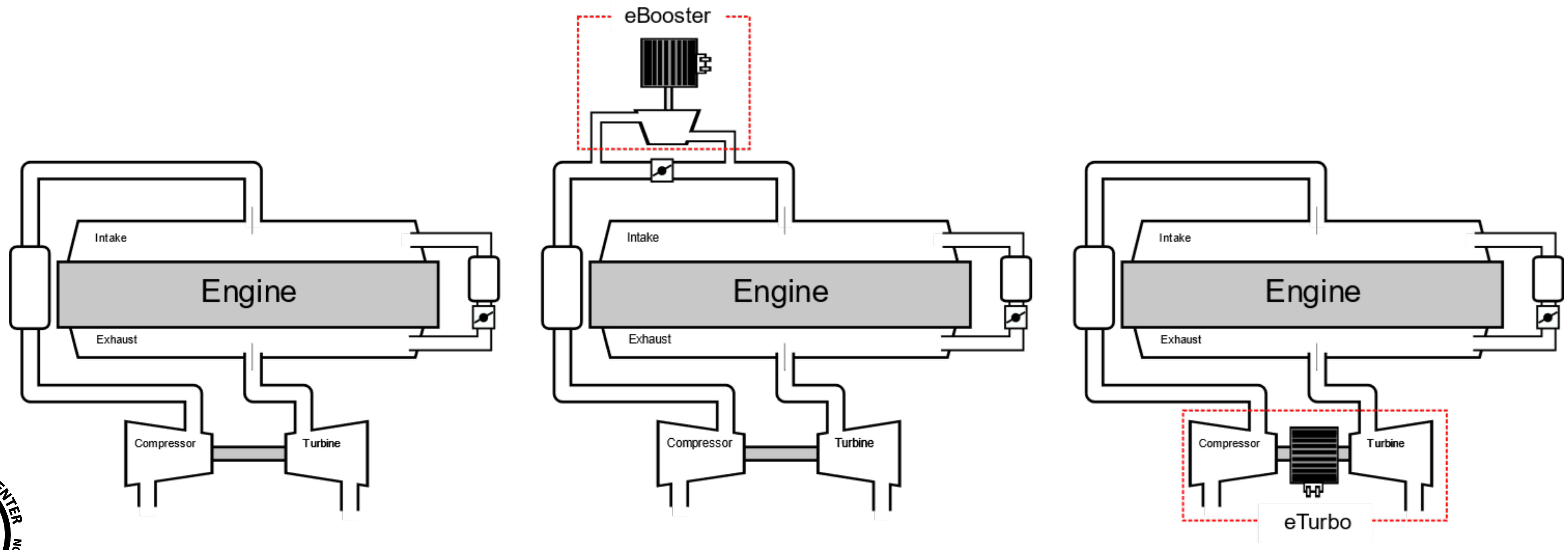
Technical Accomplishments and Progress

- Two electrified air system options evaluated
  - eBooster: Electric supercharger
  - eTurbo: Electric turbocharger (high speed motor on turboshaft)
- Both systems are 48 V (peak power near ~15 kW) → higher voltage systems were assessed, but found to be unnecessary for the present application

Note: series eTurbo configuration was also evaluated but eliminated from consideration due to cost

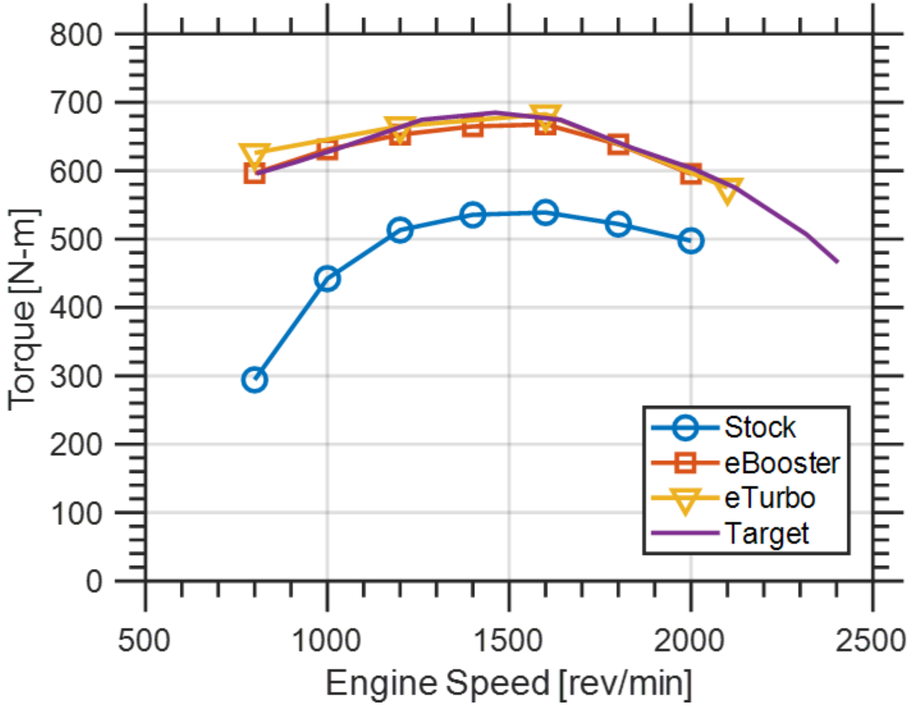
Note: multiple combinations of compressor and turbine geometry and technology assessed to meet targets. Only the most promising results are presented here.

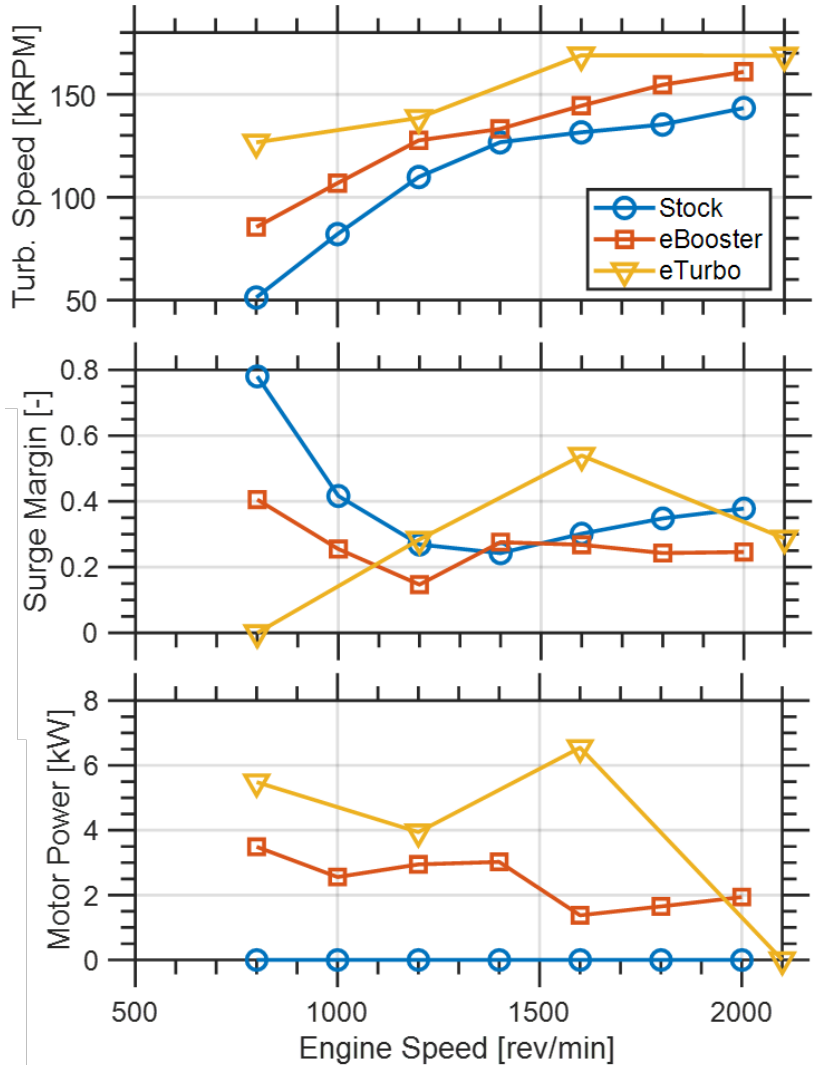
Stock **eBooster** **eTurbo**



Technical Accomplishments and Progress

- Both the eBooster and eTurbo can meet the torque targets
  - The eBooster meets torque targets easily
  - The eTurbo is near surge at the low speed high torque point → two stage boosting is needed

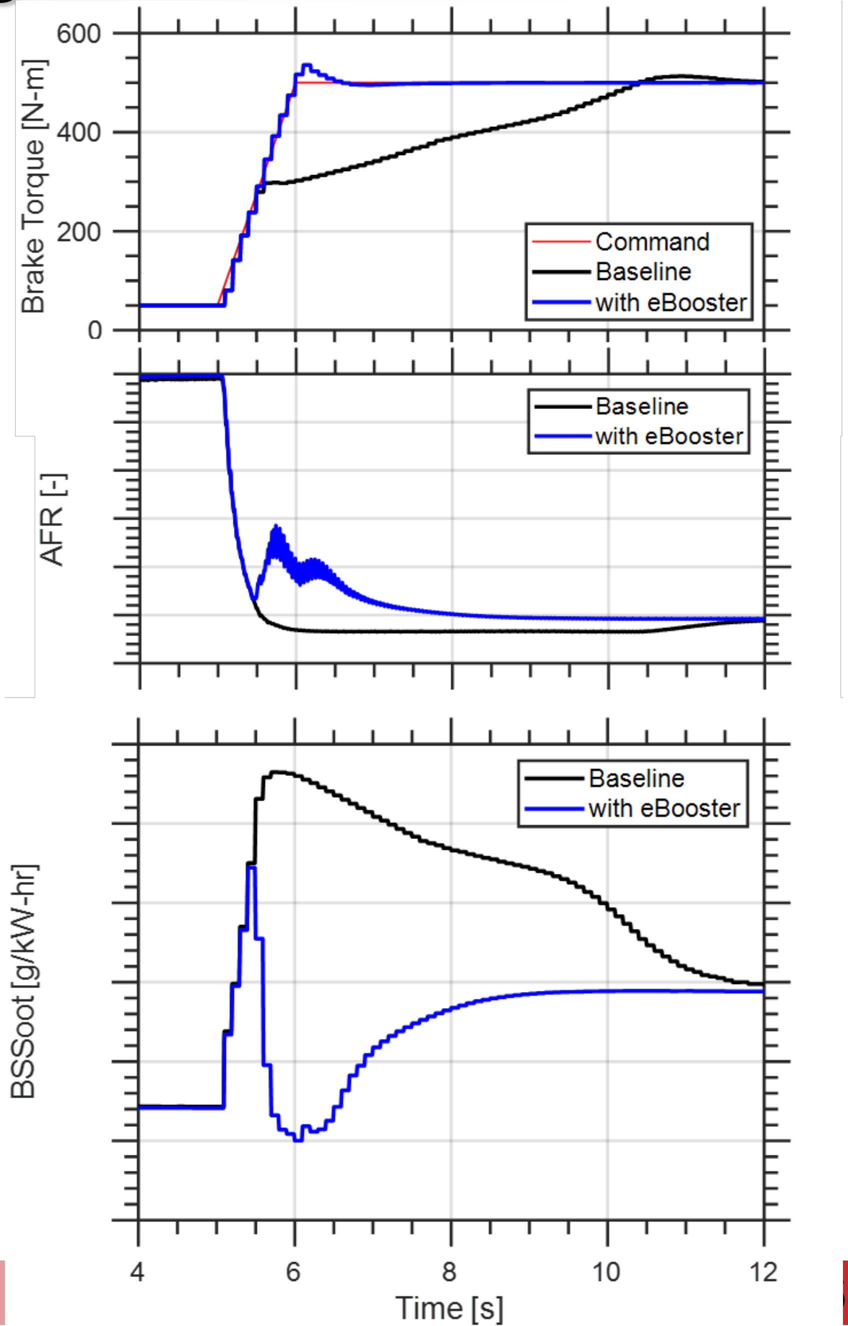




Takeaway: Electrification of air handling can enable downsizing while meeting low-speed torque targets, but two-stage compression (e.g., eBooster) will likely be needed to avoid surge

Technical Accomplishments and Progress

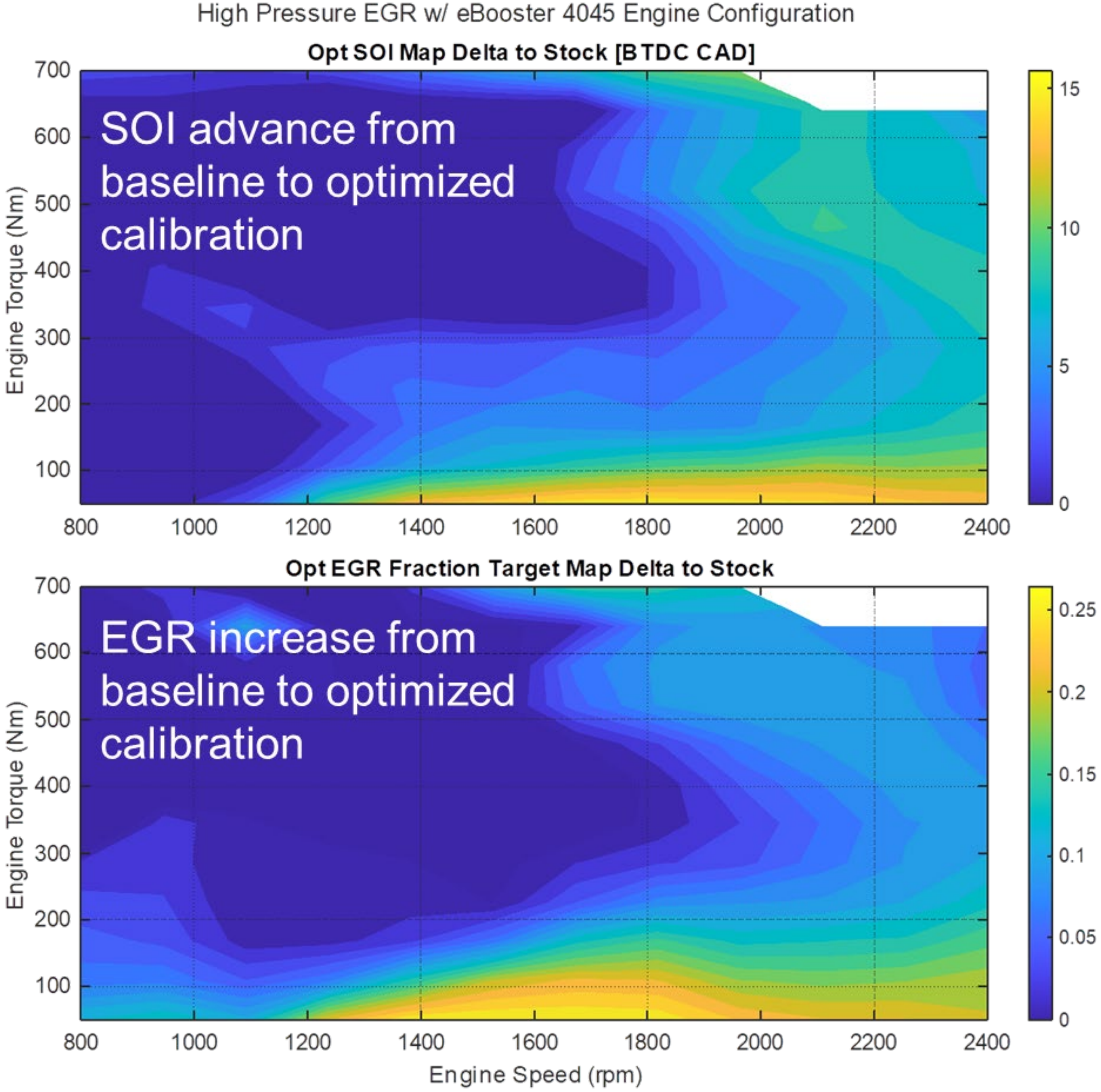
- eBooster shows substantial control over airflow → can this be used to reduce transient soot while improving transient response?
- Simulated load step from 50 N-m to 500 N-m at 1200 rev/min
- Fuel controller reduces fueling if air-fuel ratio (AFR) decreases below 17
- PID controller on eBooster to keep exhaust AFR above 19 (simulate wide band lambda sensor)
- Peak soot reduced by 21%
- Cumulative soot reduced from 0.196 g/kW-hr to 0.119 g/kW-hr (39% reduction) with substantially improved transient response



Takeaway: Electrification of air handling can enable substantial transient soot reductions

Technical Accomplishments and Progress

- Improved AFR control enabled by the use of an eBooster allows re-optimization of EGR / SOI to control NOx and maximize efficiency.
- System level model exercised to identify changes in SOI timings and EGR that maximizes efficiency while meeting emissions targets when using eBooster
  - Optimization targeted maximum brake thermal efficiency at NOx levels equal to or lower than the baseline calibration
- EGR increased by up to 25% and SOI timing advanced by up to 14 degrees → the largest differences occur at mid/high speed and low load where sufficient back pressure exists to drive EGR



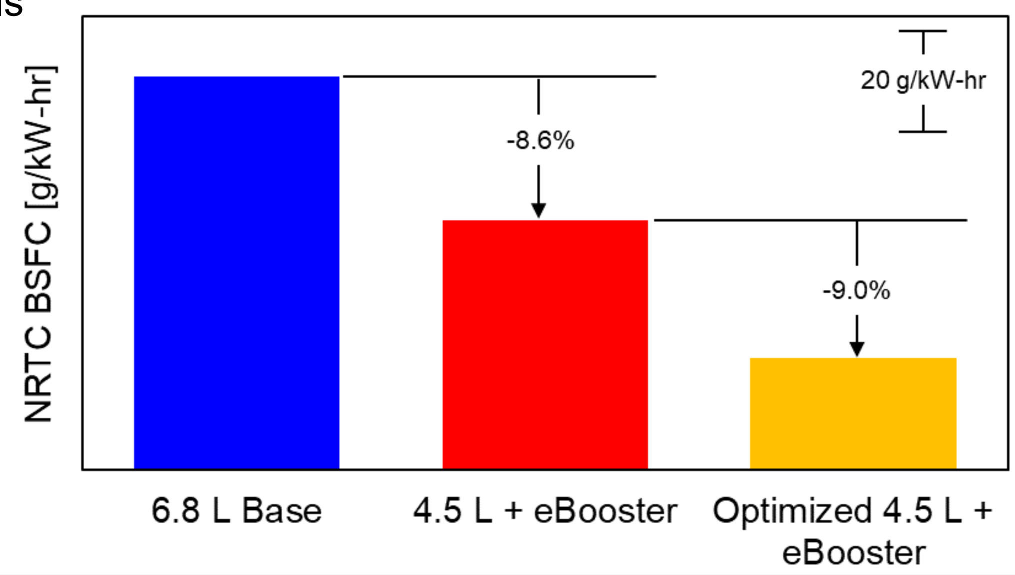
Takeaway: System can be re-optimized to improve efficiency when control over air-handling is improved

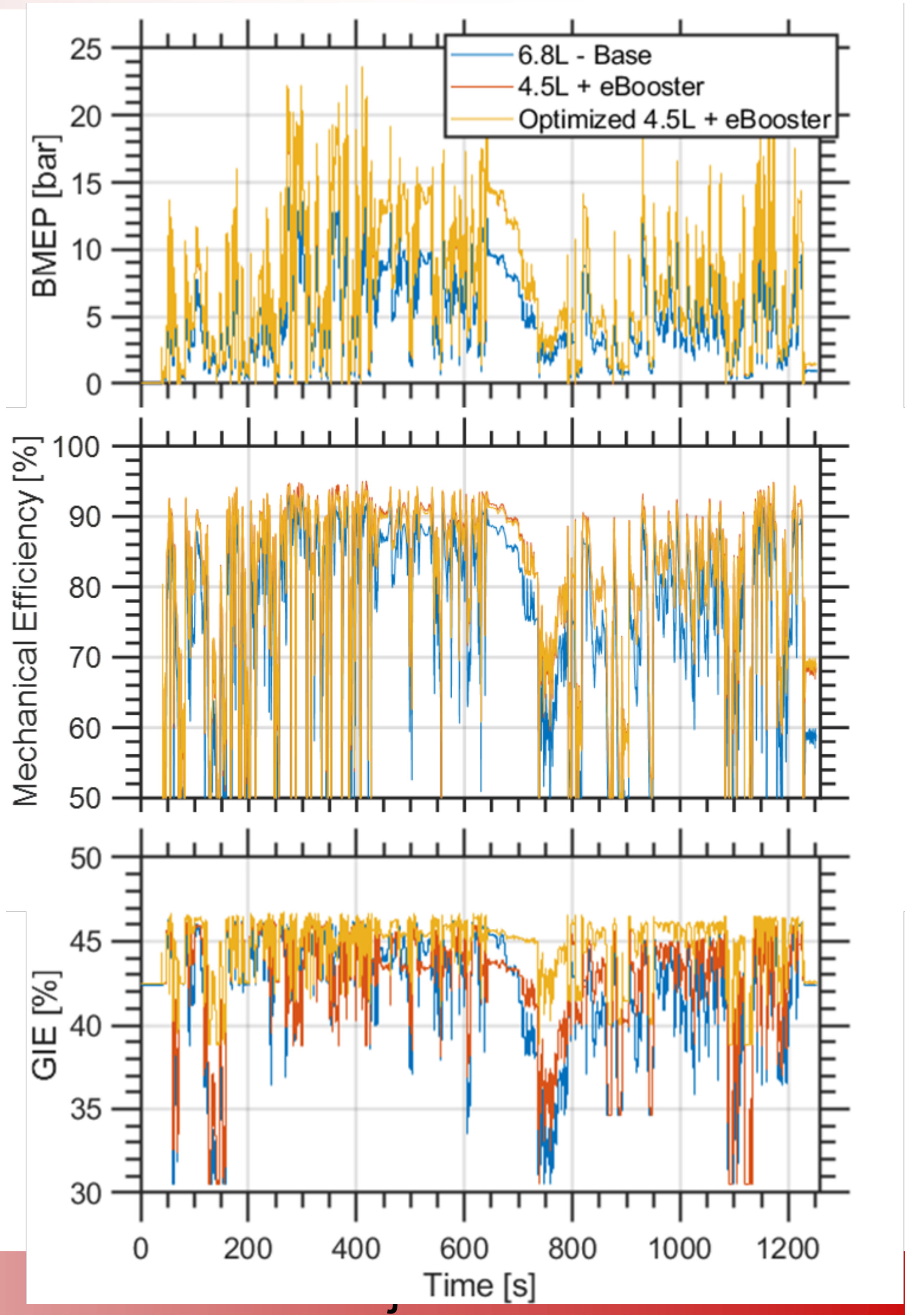
Technical Accomplishments and Progress

System level efficiency

- Baseline system compared to optimized system over the non-road transient cycle (NRTC) (simulation).
- Without optimized calibration, downsized engine with eBooster decreases brake specific fuel consumption (BSFC) by 8.6% over the NRTC due to improved mechanical efficiency (increased brake mean effective pressure (BMEP) reduces the relative contribution of friction)
- With optimized calibration, downsized engine with eBooster decrease BSFC by an additional 9% due to higher gross indicated efficiency (GIE) at equal NOx levels

Note: eBooster power consumption included in fuel consumption by adding alternator torque to ensure state-of-charge is maintained.

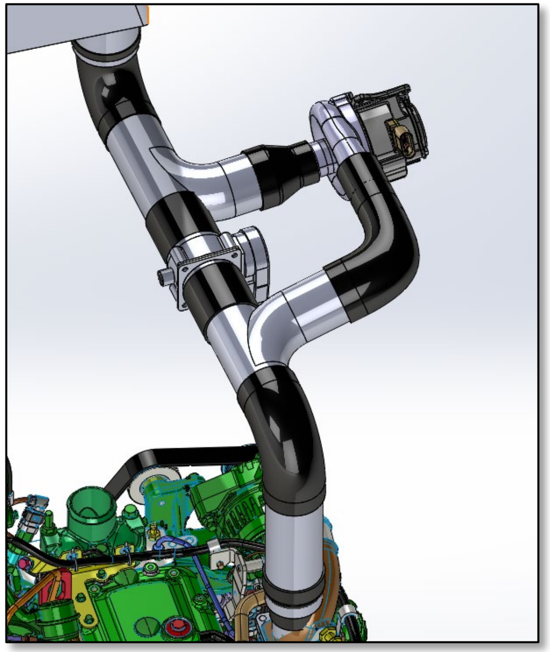




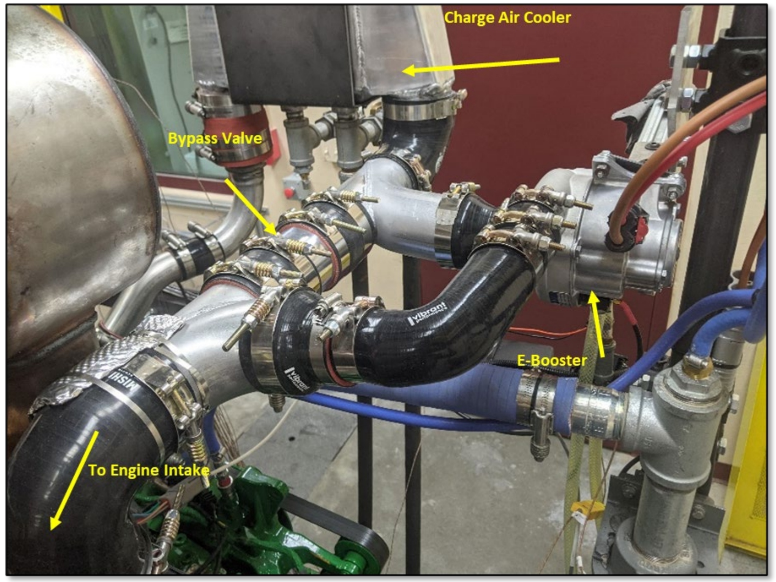
Takeaway: substantial improvements in brake efficiency are feasible in the present application

Technical Accomplishments and Progress

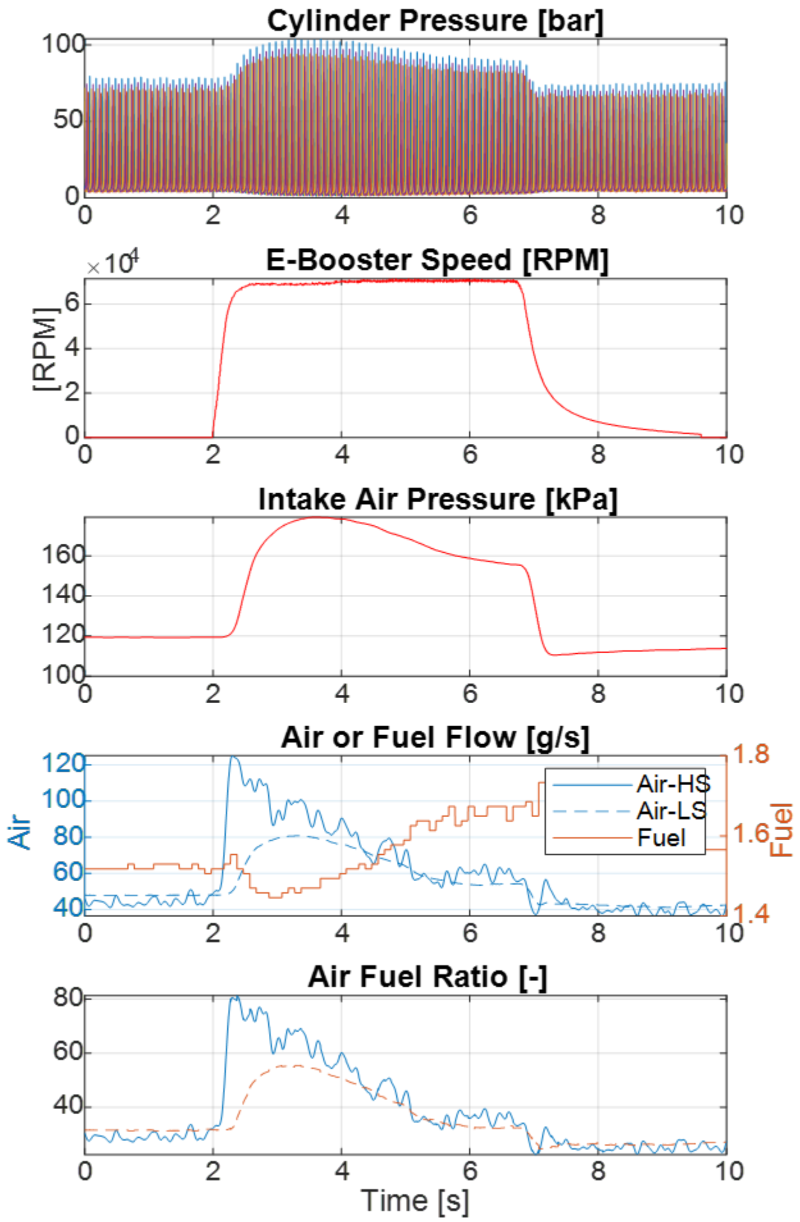
- Downsized engine with eBooster installed in UW-Madison hybrid test cell to enable engine-level evaluation in FY22



Intake system design to accommodate eBooster



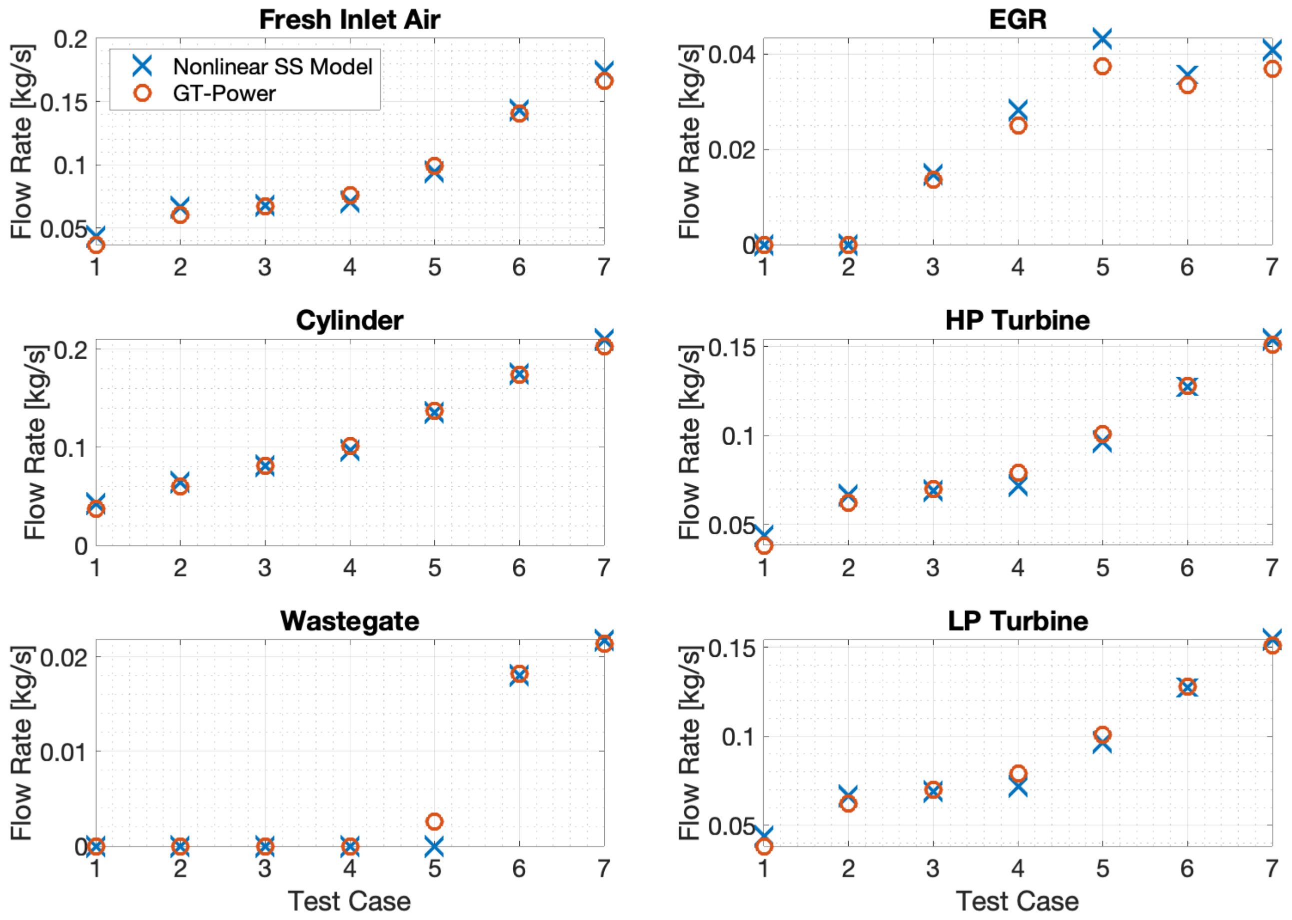
Modified intake system with e-Booster and added components



Takeaway: Hardware for engine-level validation is installed and functional

Technical Accomplishments and Progress

- Powertrain controls effort developing multiple input, multiple output (MIMO) architecture to maximize control authority of electrified air handling system
- Non-linear state-space model shows excellent agreement with system simulation results → architecture will be embedded on flexible ECU in FY22

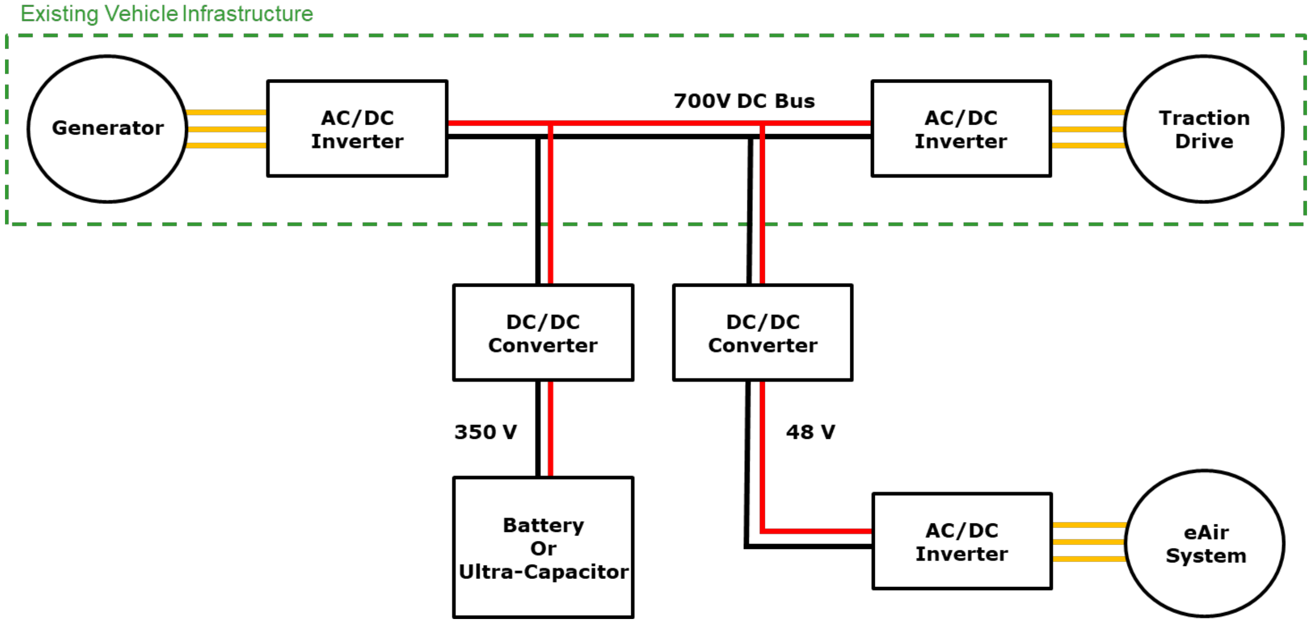


Takeaway: Non-linear state-space model suitable for ECU embedding can accurately capture system dynamics

Technical Accomplishments and Progress

- Vehicle procurement and electrical architecture layout is underway for vehicle level demonstration of optimized system

Electrical System Layout



Takeaway: Vehicle procurement and layout activities are proceeding for vehicle level testing of optimized hardware

Responses to Previous Year Reviewers' Comments

This is the first year that the project has been reviewed

Collaboration and Coordination

Team member	Location	Role in project
UW – Madison Engine Research Center	Madison, WI	Program Lead Combustion System Development
UW – Madison Wisconsin Electric Machines and Power Electronics Consortium	Madison, WI	Electric Machine Development
John Deere	Cedar Falls, IA	System Integration and Cost Assessment
Purdue University	West Lafayette, IN	Powertrain Controls

Remaining Challenges and Barriers

Main Barriers

- Balancing the cost, complexity, durability, and efficiency of a hybrid powertrain to enable market acceptance → a systematic assessment is required to provide pre-competitive data that can be widely applied to the off-road market

Technical Challenges

- System contains multiple components interacting at a wide range of time and length scales → modeling approach needs to be carefully considered to balance computational cost and accuracy
- Control of EGR needs to be carefully considered when eBooster is implemented to avoid transient NOx
- Implementation into full vehicle requires flexible electrical architecture to enable assessment of tradeoff between battery size / C-rate and operating mode

Proposed Future Research

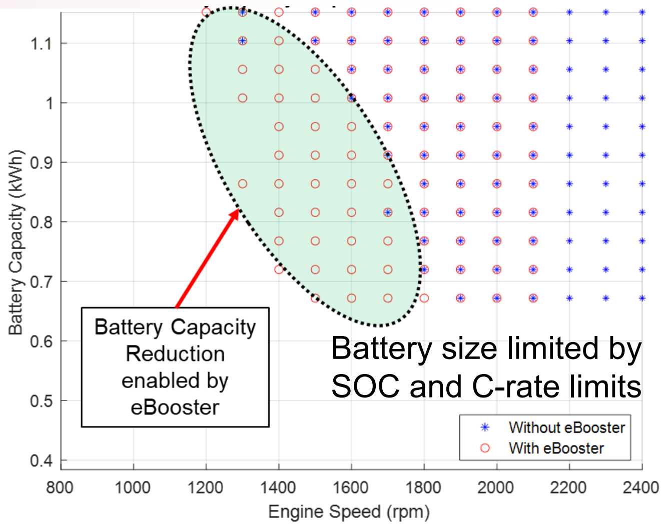
Future Work

FY21

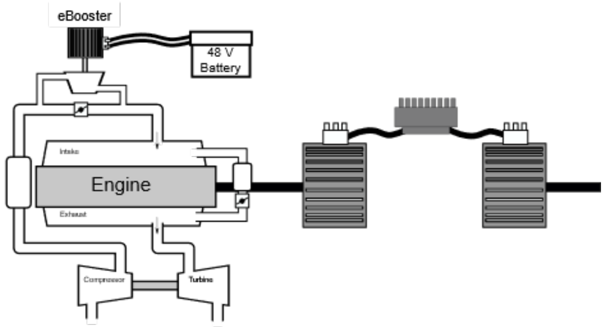
- Validate model-predicted engine level efficiency improvement using multi-cylinder engine testing
- Evaluate increased levels of hybridization to quantify battery sizing requirements using system level simulations and, if promising, powertrain experiments
- Develop supervisory control architecture for full powertrain
- Begin hardware implementation on test vehicle

FY22

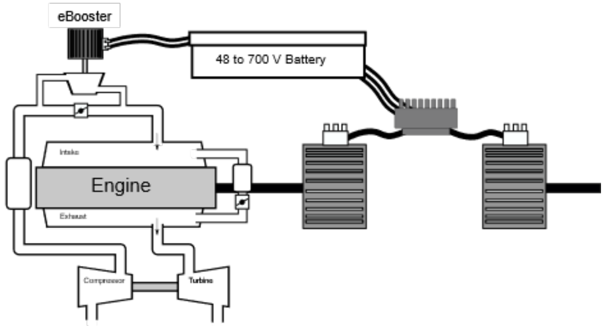
- Complete test vehicle hardware implementation
- Perform vehicle level testing to quantify efficiency gains of fully optimized system
- Quantify cost and efficiency tradeoffs of selected architecture



System optimized in BP1



System to be optimized in BP2



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

Summary

Accomplishments

- System level model constructed and validated to evaluate hybrid powertrain configurations
- Model exercised to identify a downsized engine with electrified air handling system capable of achieving an efficiency increase of over 15% compared to the baseline architecture
- Model setup to evaluate increased levels of electrification and assess battery sizing requirements
- Engine test cell setup to validate model predictions
- Control architecture developed for electrified air handling system
- Vehicle procurement and planning progressing for vehicle demonstration per program schedule

Relevance toward VTO objectives

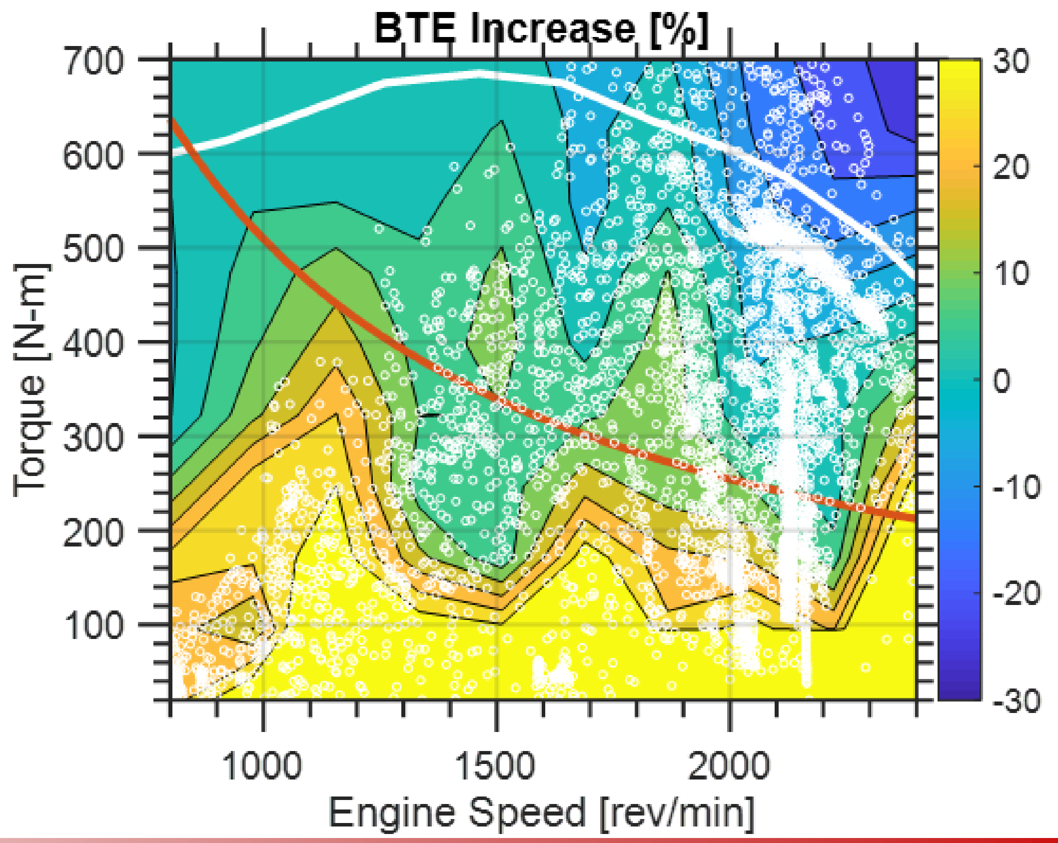
- This program seeks to use simulation, optimization, engine, powertrain and vehicle testing to support development of a hybrid architecture that is capable of reducing fuel consumption for a broad range of off-road vehicles. The program seeks to identify and quantify tradeoffs between system efficiency, complexity, cost, and customer acceptance to provide insight into future off-road powertrain options.

Technical Back-Up Slides

Approach

- **Why downsize?** 6.8 L engine spends a substantial amount of time at light-to-moderate loads that can be achieved with 4.5 L engine
- However, 4.5 L engine with a conventional air system is not able to meet low speed torque requirements (~800 rev/min) needed to allow downsizing
- Initial focus has been on electrification of the air-handling system to enable downsizing → necessary to reach low speed high torque conditions needed for loader cycle with 4.5 L engine

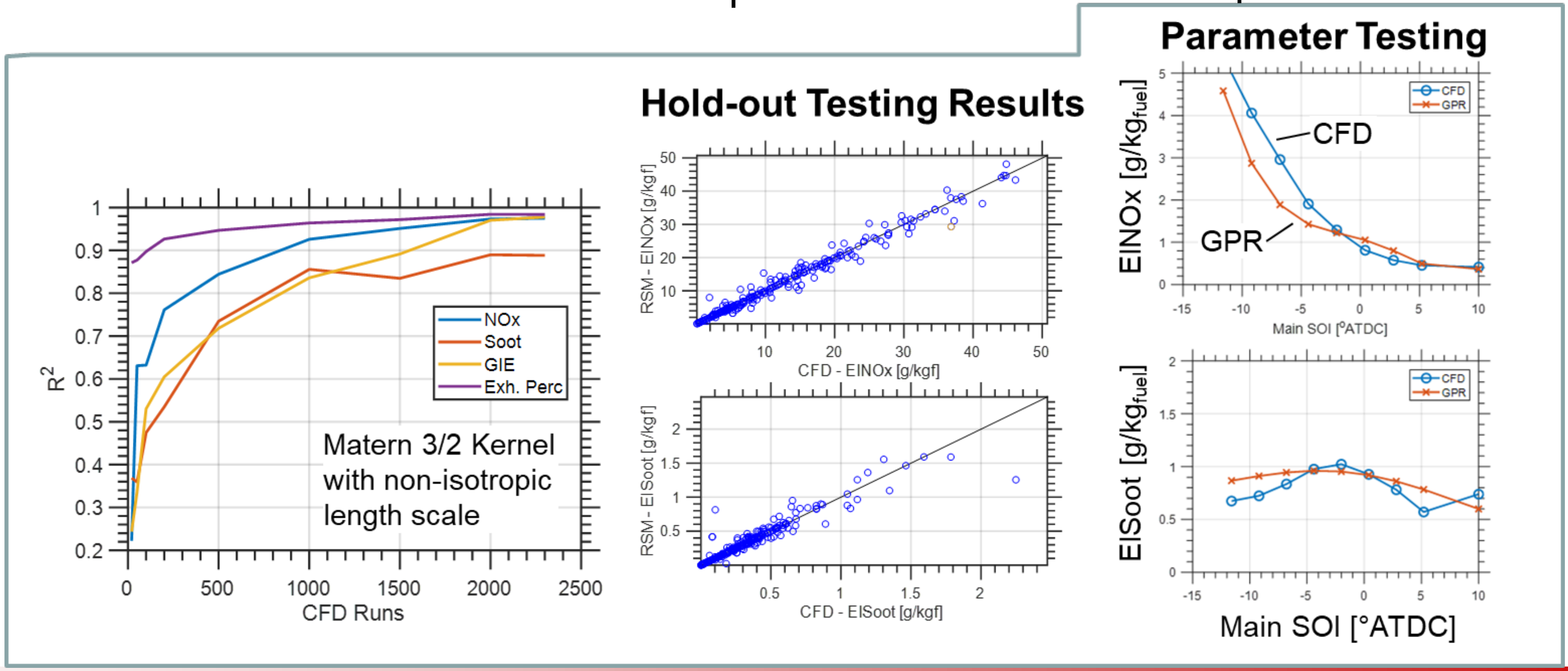
BTE increase compares 6.8 L engine and 4.5 L engine producing equal torque (points show NRTC for 6.8 L engine)



Technical Accomplishments and Progress

- Machine learning NOx and soot models developed from ~3000 CFD simulations covering operating space using Latin hypercube design of experiments performed varying 12 parameters to cover the full operating range including injection schedule
- Gaussian Process Regression (GPR) model trained to predict outputs as a function of inputs (e.g., $NOx = f(operating\ point, inj.schedule, IVC\ conditions))$
- The number of simulations required was quantified by sampling dataset and comparing to holdouts.
- Overall response is good at 1000 runs. Soot is the most difficult response → 2000+ runs is required to achieve an R^2 of 0.9

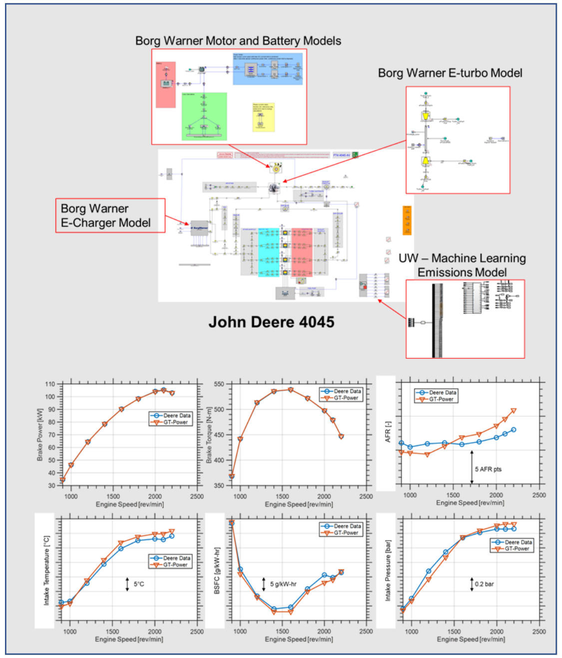
Takeaway: Approach developed to enable CFD-level accuracy of emissions prediction in cycle-simulation



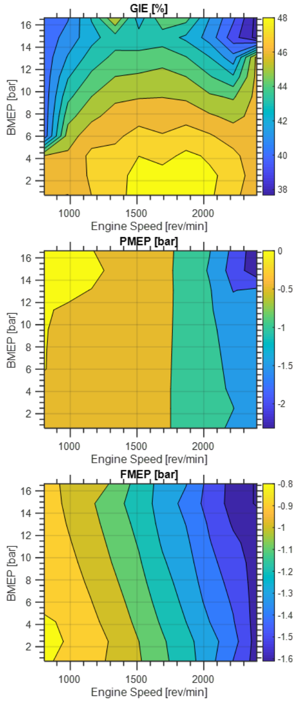
Technical Accomplishments and Progress

- System level efficiency evaluated using map-based approach validated through comparisons with both steady state and transient test data

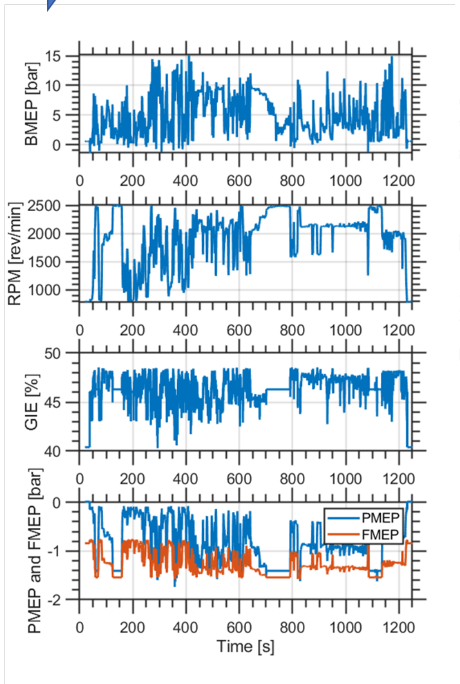
Validated GT-Power Model

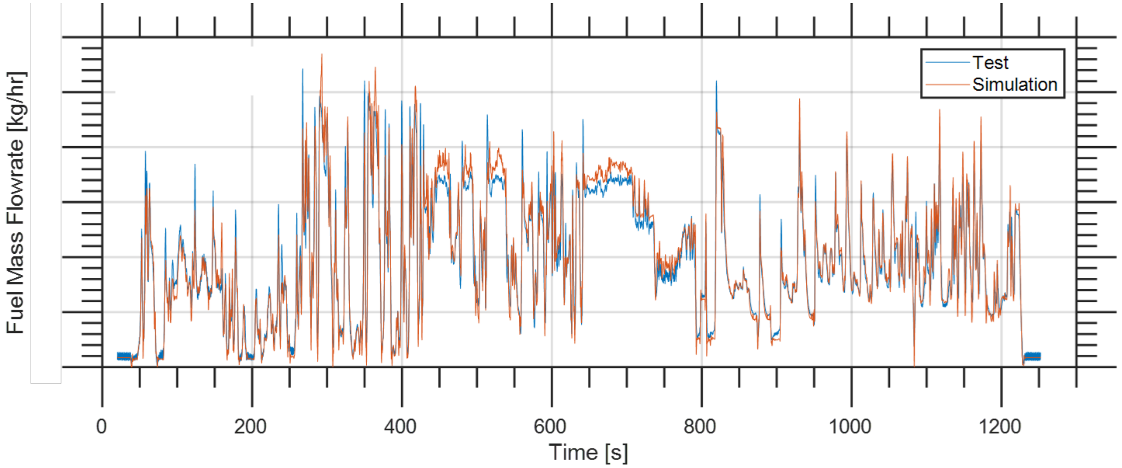


Maps of GIE, PMEP, and FMEP from GT model results



Drive Cycle Simulations



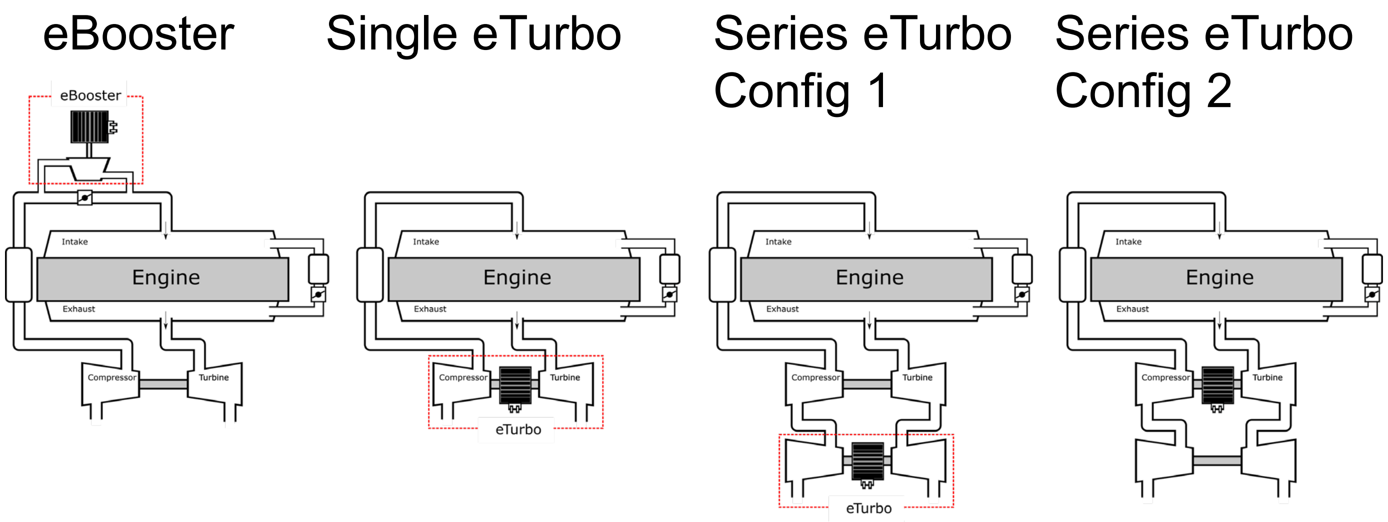


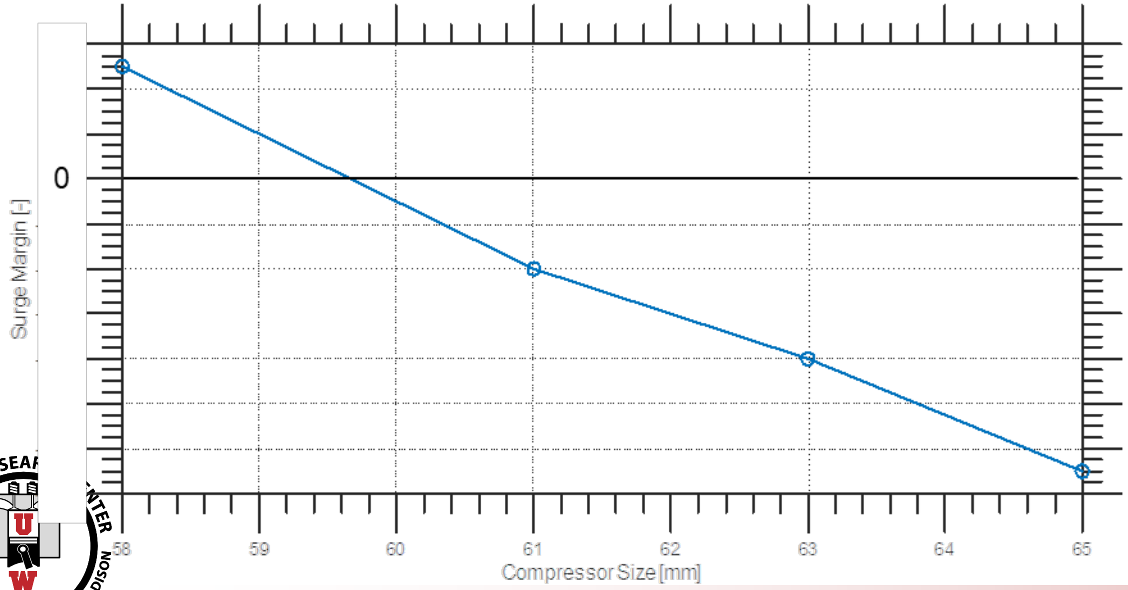
- Approach compared to NRTC test data supplied by John Deere
- Simulation reproduces test BSFC to within 2%
- Approach is acceptable to evaluate options and runs nearly instantaneously

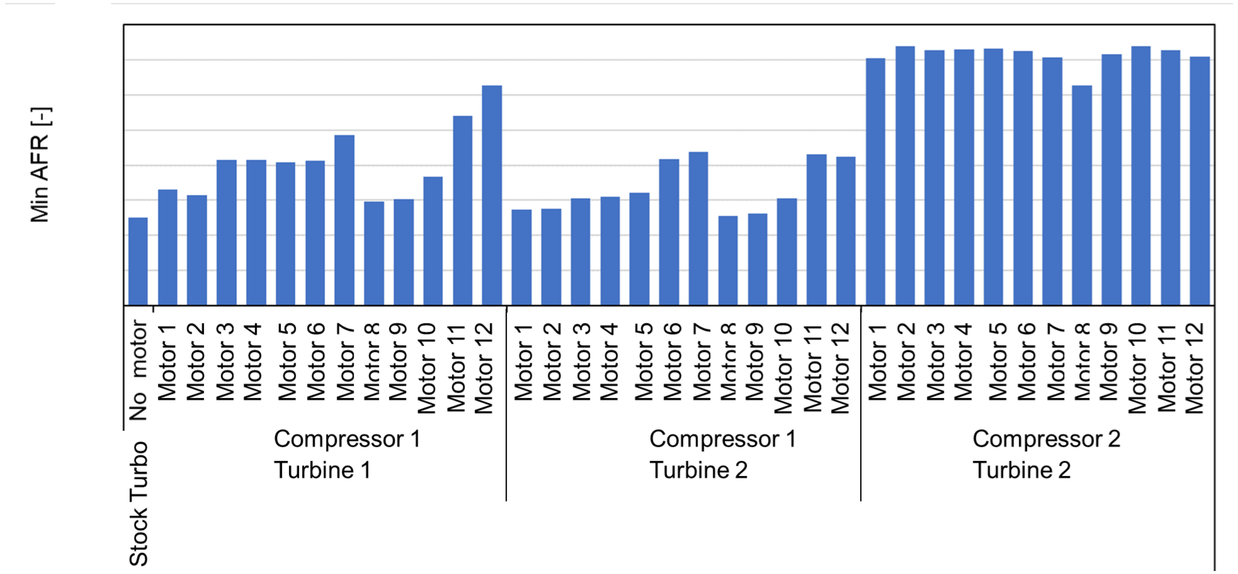
Air Handling Assessment

Accomplishments

- Multiple electrified air handling configurations assessed considering a range of:
  - Compressor sizes / trims
  - Turbine sizes / trims
  - Motor sizes and power levels
  - Compressor and turbine technology
- eBooster and series eTurbo meet requirements. Single eTurbo has surge and/or turbine speed challenges







Air-handling electrification

Accomplishments

- Energy flow for eBooster supplying 1.6 kW to eBooster
  - Increased airflow allows power to be increased by 25 kW at equal AFR
- 1.95 kW from battery
  - 1.25 kW of battery power directly added to brake power through pumping loop → 64% of supplied energy ends up producing work