Improved Efficiency of Off-Road Material Handling Equipment through Electrification

Project ID: ace162

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Advanced Power Systems Research Center (APS LABS)

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Michigan Tech 1885 APS LABS PETTIBONE

Overview

Timeline

- Project Start: October 2019
- Project End: March 31st 2024
- Percent Complete: 30%

Budget

- Total Project Value: $3.6M
  - Federal: $2.5M
  - Contractor Share: $1.1M

Partners

- Michigan Tech (APS LABS)
  - Project Lead
- Pettibone
  - Manufacturer Partner
- Dana, Parker, Terzo
  - Interactions / collaborations

Barriers

- Off-Road equipment has significant diversity of system architecture and end use
- Measuring baseline & incremental system level changes is difficult due to a lack of standardized operating cycles and in-use data
- Additional electrification components may drive initial cost up to the point of sacrificing customer acceptance

Relevance

- Material handling is critical at ports, truck / rail yards, manufacturing plants, construction sites, etc.
- Intermittent power demand (propulsion & material engagement) and material potential energy, make this machine type well suited for electrification

Project Goal:

Align with DOE VTO goals by demonstrating a >20% reduction in fuel consumption while maintaining emissions compliance, performance requirements, minimizing increases in cost, and maximizing customer acceptance

Key Project Objectives (BP1):

- Instrument production machine, establish operating cycles, and quantify baseline performance
- Develop & Validate a high-fidelity model of the baseline machine
- Identify electrification architectures having the potential to meet project goals

Key Project Objectives (BP2 & BP3):

- Identify optimal electrification architecture through modeling & experimentation
- Build a prototype electrified machine and demonstrate program goals are met

Milestones

Milestone	DOE FY	Description	Status
M1.1	FY21	SOPO Finalized	Complete
M1.2	FY21	Sub-Contracts Finalized	Complete
M1.3	FY22	Component Selection For Analysis	Complete
M1.4	FY22	Machine Baselining Complete	Complete
M1.5	FY22	Baseline Model Validated	Complete
G/NG1	FY22	Baseline complete, model complete, reasonable architectures identified	Complete
M2.1	FY22	Model Comprehends Electrified Architectures	In-Process, On-Track
M2.2	FY23	Electrification Architectures Simulated / Analyzed	In-Process, On-Track
M2.3	FY23	Electrification Architecture Determined	In-Process, On-Track
G/NG2	FY23	An Architecture & BOM that meets project goals has been identified	In-Process, On-Track
M3.1	FY23	Designs complete for integration	Not Started
M3.2	FY24	Hardware assembled	Not Started
M3.3	FY24	Controls & Calibration Complete	Not Started

Approach

- Baseline performance assessment while developing operating cycles representative of real-world utilization (Complete)
- Develop and calibrate a unified model representative of the baseline propulsion and fluid power systems (Complete)
- Synthesize & Analyze ***multiple architectures*** based on ***commercially available*** electrification components, and determine optimal architecture to meet project goal, within the constraints of the key barriers (diversity of machines & application, and customer sensitivity to function, reliability, and cost)
- Design the required integration hardware & assemble the prototype machine
- Develop and calibrate a supervisory controls architecture
- On-Track & real-world demonstration that the electrified machine meets project goals

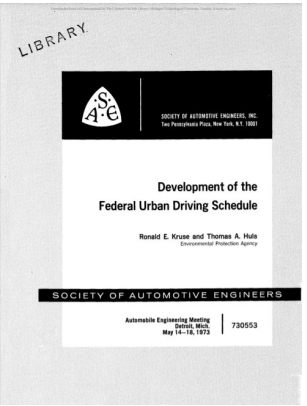
Technical Accomplishments and Progress (Past Year)

A test course, ***emulating known high usage scenarios,*** was developed at APS LABS to enable ***repeatable, and on-demand,*** testing throughout the project

Technical Accomplishments and Progress (Past Year)

Standard Operating Cycles established for key usage scenarios:

- Material Load & Material Unload
- High-Precision Material Movement
- Machine Transport


LIBRARY

SOCIETY OF AUTOMOTIVE ENGINEERS, INC.
Two Pennsylvania Plaza, New York, N.Y. 10001

Development of the
Federal Urban Driving Schedule

Ronald E. Kruse and Thomas A. Huls
Environmental Protection Agency

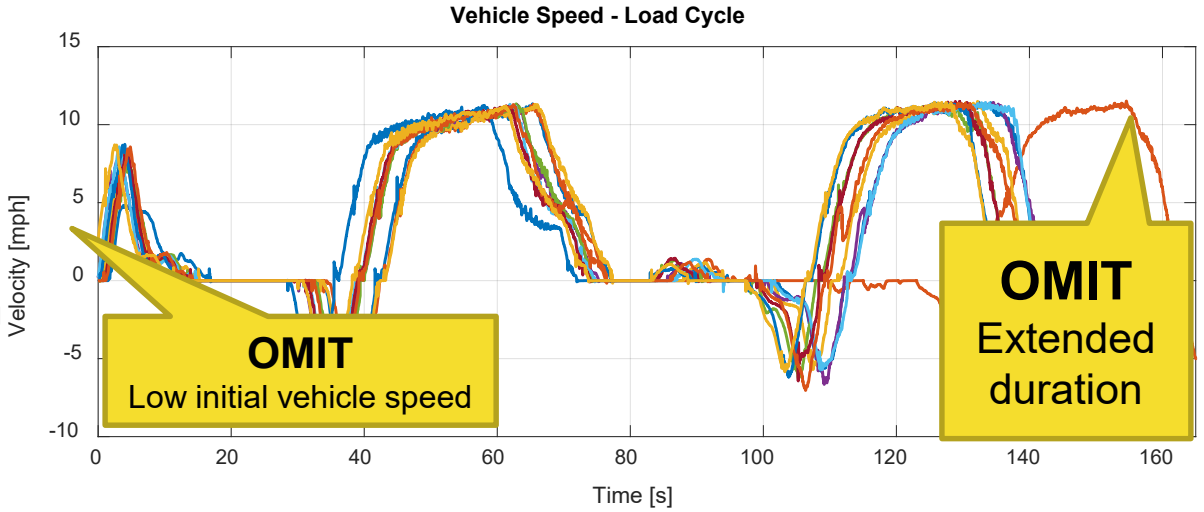
SOCIETY OF AUTOMOTIVE ENGINEERS

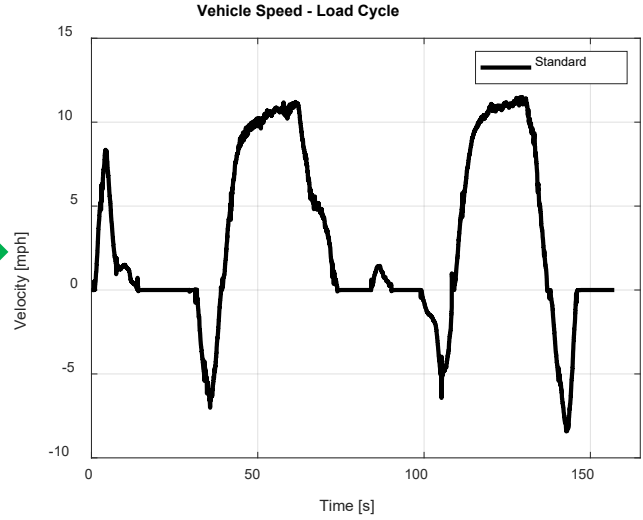
Automobile Engineering Meeting
Detroit, Mich.
May 14–18, 1973

730553

https://doi.org/10.4271/730553

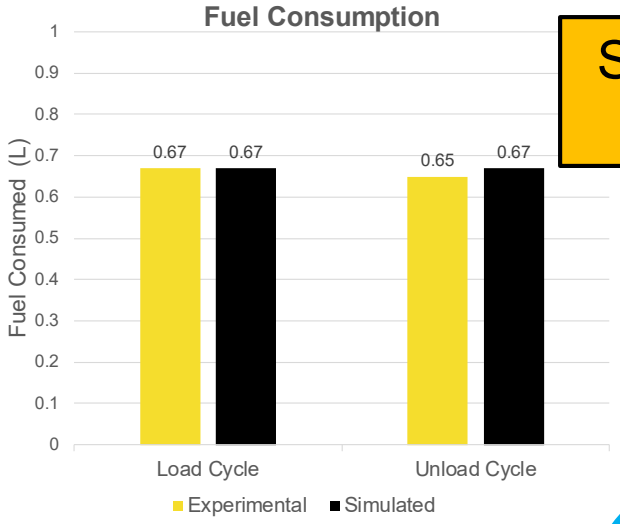
- The team followed methods utilized in developing Federal regulatory cycles
  - Statistically significant samples
  - Remove outlier cycles
  - Representative cycle is the closest to average runtime
  - Digital Filtering for a smooth target trace
  - Manual adjustments to maintain real-world representation



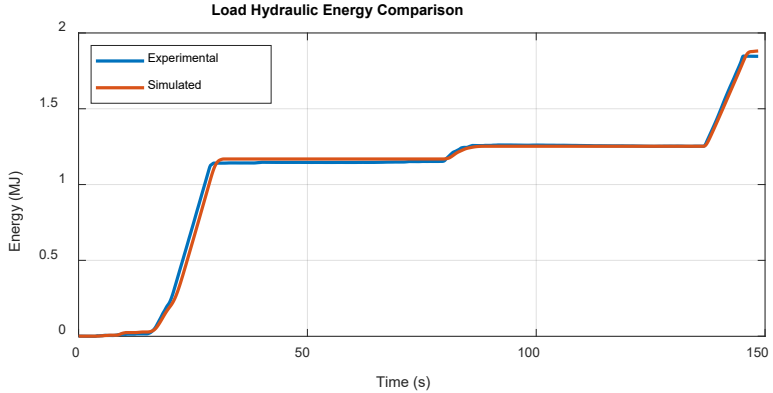


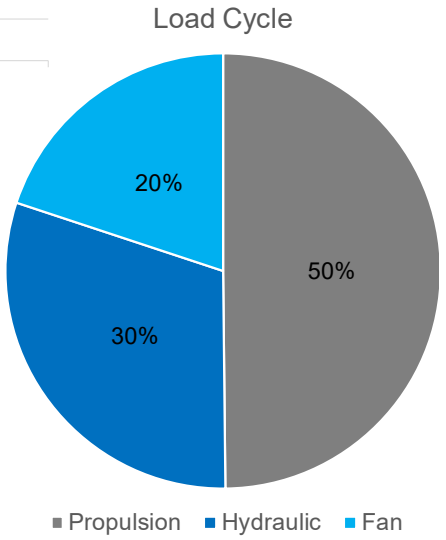
Technical Accomplishments and Progress (Past Year)

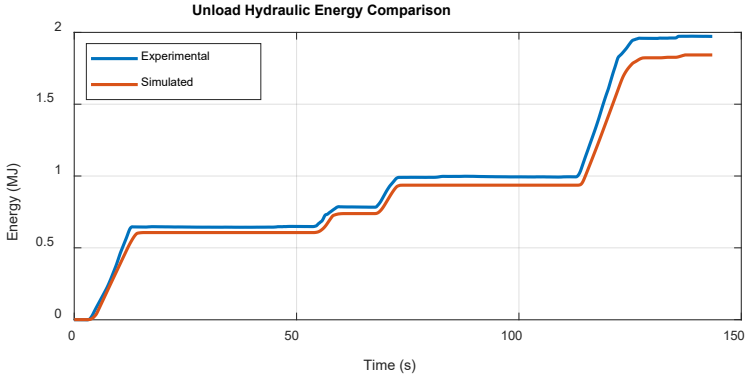
By analyzing experimental & simulated baseline results the team can better understand energy distribution and make informed electrification decisions



Simulated & Experimental results match well







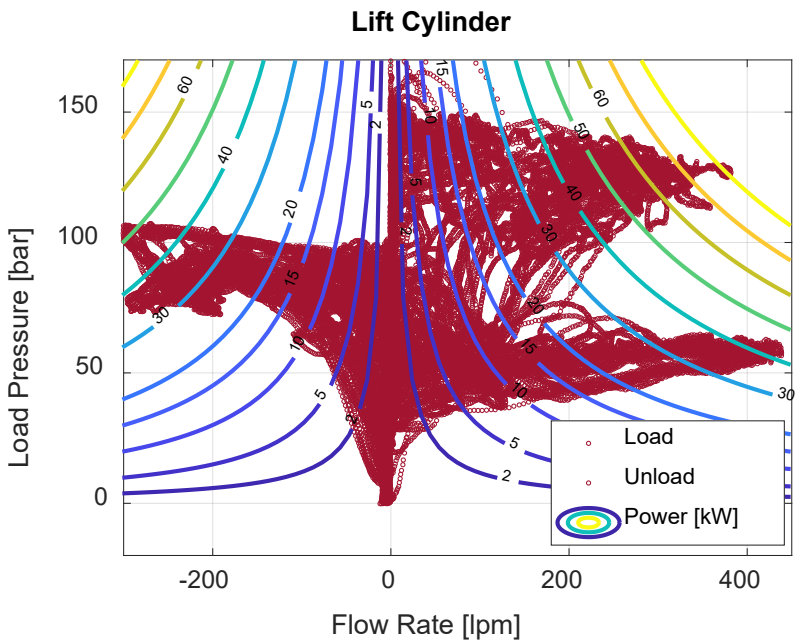
Fan consumes 20% of the brake energy: rigid coupling & sized for worse case

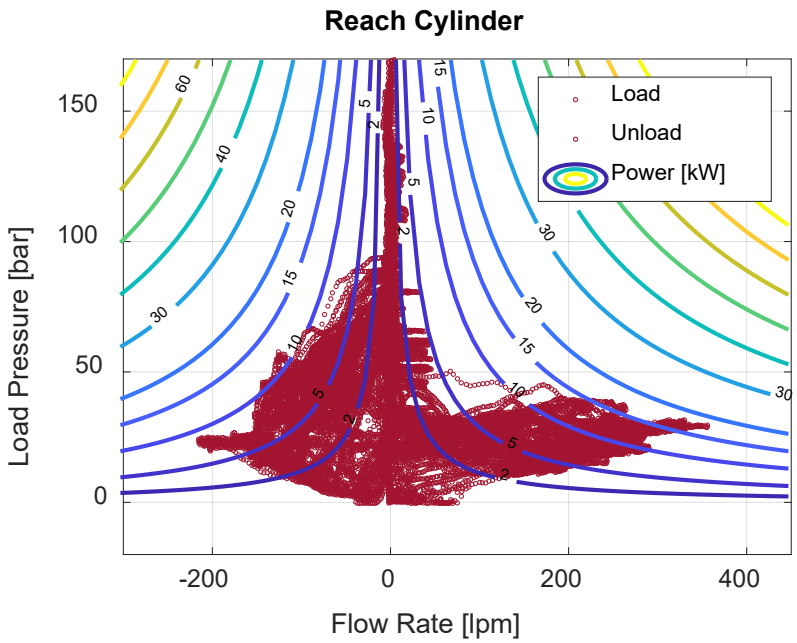
Despite a Net Change in material PE between the load / unload cycles, the fluid power system consumes the same energy

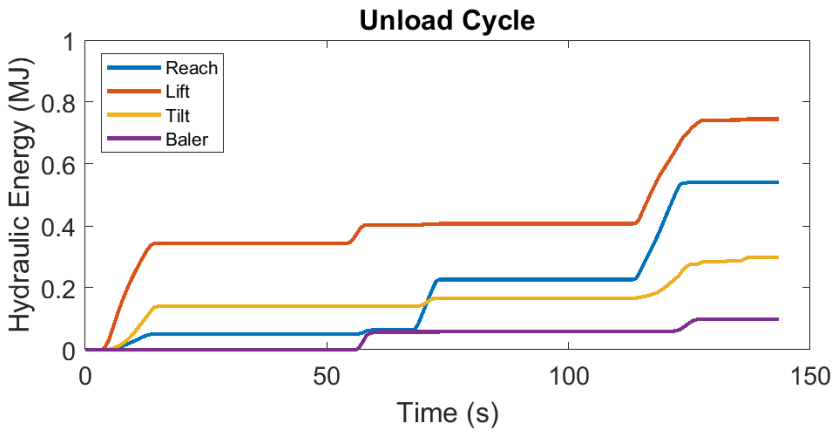
Technical Accomplishments and Progress (Past Year)

- Each hydraulic actuation was analyzed to determine the fluid power electrification requirements & what functions to group in a distributed electrified architecture
- Total fluid energy requirements factor into HV battery sizing

Lift functions require significantly more peak power than reach (80 kW vs 20 kW), but little difference in total cycle energy







Technical Accomplishments and Progress (Past Year)

27 Performance & Design Attributes

59 Architecture permutations

	Engine Off Stationary	Engine Off Creep & Low Load	KE Recovery	PE Recovery	Plug-in Benefit	Opportunity Charging Efficiency	Low Load / Low Duty Cycle Efficiency	High Load / High Duty Cycle Efficiency	Propulsion System Efficiency	Hydraulic System Efficiency	Range	Center of Gravity Shift	Mass	Powertrain Packaging	Hydraulic Packaging	Battery Packaging	Serviceability	Reliability	Cost of Operating	Usage of COTS Components	Number of new parts	In-Use Flexibility	Program Time Risk	Cost of Production Machine	Cost of Prototype	Prototyping: Controls Complexity	Prototyping: Hardware Complexity	Total Weighted Scores
Descriptions- See more in Descriptions tab	-2 = no shut off, 0 = no shut off hyd	-2 = no creep, +2 = good creep ability	2 = no KE, 2 good KE	-2 = no PE recovery, +2 is best PE recovery	-2 = no benefit, +2 = most benefit	-2 = no ability, +2 = best opp charging eff.	-2 = least efficient, +2 = most efficient	-2 = least efficient, +2 = most efficient	-2 = baseline, +2 = most efficient	-2 = baseline, 0 = EH, +2 is EH+	-2 = BEV, +2 = best	Too early for ranking	-2 = BEV, +2 = baseline	-2 = difficult packaging, +2 = easy packaging	-2 = difficult packaging, +2 = easy packaging	-2 = BEV, +2 = baseline	0 = baseline	+2 = baseline	0 = baseline	-2 = least COTS , +2 = most COTS	-2 = most new parts, +2 = fewest new parts	-2 = least flexible, +2 = most flexible	-2 = most risk, +2 = least risk	-2 = most expensive, +2 = least expensive	-2 = most expensive, +2 = least expensive	-2 = most complex, +2 = least complex	-2 = most complex, +2 = least complex	
Weighting Factor	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	
P1	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	0	0	2	2	2	2	0	2	0	2	2	-2	2	2	2	2	2	
P0	0	-2	-2	-2	-1	2	-2	-2	-2	-2	0	0	2	2	2	1	0	1	1	2	2	-1	2	2	2	2	2	36
P0 EF	0	-2	-2	-2	-1	2	-2	-2	-2	-2	0	0	2	2	2	1	0	1	1	2	2	-1	2	2	2	2	2	36
P0 EH	2	-2	-2	-2	0	2	-1	1	-2	0	1	0	2	2	1	1	0	0	1	2	2	0	2	2	2	2	2	47
P0 EFH	2	-2	-2	-2	0	2	0	1	-2	0	1	0	2	2	1	1	0	0	1	2	2	0	2	2	2	2	2	47
P0 EH+	2	-2	-2	-2	0	2	0	1	-2	2	1	0	2	2	1	1	0	0	1	2	1	0	1	1	1	1	2	41
P0 EFH+	2	-2	-2	-2	0	2	0	1	-2	2	1	0	2	2	1	1	0	0	1	2	1	0	1	1	1	1	2	41
P1	0	-2	-2	-2	-1	2	-2	-2	-2	-2	0	0	2	1	2	1	0	1	1	0	2	-1	2	2	2	2	1	25
P1 EF	0	-2	-2	-2	-1	2	-2	-2	-2	-2	0	0	2	1	2	1	0	1	1	0	2	-1	2	2	2	2	1	25
P1 EH	2	-2	-2	-2	0	2	-1	1	-2	0	1	0	2	1	1	1	0	0	1	0	2	0	2	2	2	2	1	36
P1 EFH	2	-2	-2	-2	0	2	-1	1	-2	0	1	0	2	1	1	1	0	0	1	0	2	0	2	2	2	2	1	36
P1 EH+	2	-2	-2	-2	0	2	0	1	-2	2	1	0	2	1	1	1	0	0	1	0	1	0	1	1	1	1	1	30
P1 EFH+	2	-2	-2	-2	0	2	0	1	-2	2	1	0	2	1	1	1	0	0	1	0	1	0	1	1	1	1	1	30
P2	2	2	-2	-2	1	2	-1	2	-1	-2	1	0	2	0	2	0	0	1	1	0	1	0	1	1	1	1	0	33
P2 EF	2	2	-2	-2	1	2	-1	2	-1	-2	1	0	2	0	2	0	0	1	1	0	1	0	1	1	1	1	0	33
P2 EH	2	2	-2	-2	2	2	0	1	-1	0	2	0	2	0	1	1	0	0	1	0	1	1	1	1	1	1	0	38
P2 EFH	2	2	-2	-2	2	2	0	1	-1	0	2	0	2	0	1	1	0	0	1	0	1	1	1	1	1	1	0	38
P2 EH+	2	2	-2	-2	2	2	1	1	-1	2	2	0	2	0	1	0	0	0	1	0	0	1	0	0	0	0	0	32
P2 EFH+	2	2	-2	-2	2	2	1	1	-1	2	2	0	2	0	1	0	0	0	1	0	0	1	0	0	0	0	0	32
P3	-2	2	2	-2	1	-2	0	2	0	-2	1	0	1	1	2	-1	0	1	0	0	2	-1	1	1	1	2	1	27
P3 EF	-2	2	2	-2	1	-2	0	2	0	-2	1	0	1	1	2	-1	0	1	0	0	2	-1	1	1	1	2	1	27
P3 EH	-2	2	2	-2	2	-2	1	1	0	0	2	0	1	1	1	-1	0	0	0	0	2	0	1	1	1	2	1	32
P3 EFH	-2	2	2	-2	2	-2	1	1	0	0	2	0	1	1	1	-1	0	0	0	0	2	0	1	1	1	2	1	32
P3 EH+	-2	2	2	-2	2	-2	2	1	0	2	2	0	1	1	1	-1	0	0	0	0	1	0	0	0	0	1	1	26
P3 EFH+	-2	2	2	-2	2	-2	2	1	0	2	2	0	1	1	1	-1	0	0	0	0	1	0	0	0	0	1	1	26
P3 + P0	0	2	2	-2	1	2	0	2	1	-2	1	0	1	1	2	-1	0	0	1	0	1	0	0	0	1	1	1	31
P3 + P0 EF	0	2	2	-2	1	2	0	2	1	-2	1	0	1	1	2	-1	0	0	1	0	1	0	0	0	1	1	1	31
P3 + P0 EH	2	2	2	-2	2	2	1	1	1	0	2	0	1	1	1	-1	0	-1	1	0	1	1	0	0	1	1	1	42
P3 + P0 EFH	2	2	2	-2	2	2	1	1	1	0	2	0	1	1	1	-1	0	-1	1	0	1	1	0	0	1	1	1	42
P3 + P0 EH+	2	2	2	-2	2	2	2	1	1	2	2	0	1	1	1	-1	0	-1	1	0	0	1	-1	-1	0	0	1	36
P3 + P0 EFH+	2	2	2	-2	2	2	2	1	1	2	2	0	1	1	1	-1	0	-1	1	0	0	1	-1	-1	0	0	1	36
P4	-2	2	2	-2	1	-2	0	2	0	-2	1	0	1	2	2	-1	0	1	0	-2	2	-1	-2	1	0	2	-1	5
P4 EF	-2	2	2	-2	1	-2	0	2	0	-2	1	0	1	2	2	-1	0	1	0	-2	2	-1	-2	1	0	2	-1	5
P4 EH	-2	2	2	-2	2	-2	1	1	0	0	2	0	1	2	1	-1	0	0	0	-2	2	0	-2	1	0	2	-1	10
P4 EFH	-2	2	2	-2	2	-2	1	1	0	0	2	0	1	2	1	-1	0	0	0	-2	2	0	-2	1	0	2	-1	10
P4 EH+	-2	2	2	-2	2	-2	2	1	0	2	2	0	1	2	1	-1	0	0	0	-2	1	0	-2	0	-1	1	-1	7
P4 EFH+	-2	2	2	-2	2	-2	2	1	0	2	2	0	1	2	1	-1	0	0	0	-2	1	0	-2	0	-1	1	-1	7
P4 + P0	0	2	2	-2	1	2	0	2	1	-2	1	0	1	2	2	-1	0	0	1	-2	1	0	-2	0	0	1	-1	12
P4 + P0 EF	0	2	2	-2	1	2	0	2	1	-2	1	0	1	2	2	-1	0	0	1	-2	1	0	-2	0	0	1	-1	12
P4 + P0 EH	2	2	2	-2	2	2	1	1	1	0	2	0	1	2	1	-1	0	-1	1	-2	1	1	-2	0	0	1	-1	23
P4 + P0 EFH	2	2	2	-2	2	2	1	1	1	0	2	0	1	2	1	-1	0	-1	1	-2	1	1	-2	0	0	1	-1	23
P4 + P0 EH+	2	2	2	-2	2	2	2	1	1	2	2	0	1	2	1	-1	0	-1	1	-2	0	1	-2	-1	-1	0	-1	20
P4 + P0 EFH+	2	2	2	-2	2	2	2	1	1	2	2	0	1	2	1	-1	0	-1	1	-2	0	1	-2	-1	-1	0	-1	20
Series w/ base trans	2	2	-2	-2	1	2	1	-2	1	-2	1	0	-1	-2	2	-1	-2	0	0	0	-2	1	-2	-2	0	-1	-1	-20
Series EF w/ base trans	2	2	-2	-2	1	2	1	-2	1	-2	1	0	-1	-2	2	-1	-2	0	0	0	-2	1	-2	-2	0	-1	-1	-20
Series EH w/ base trans	2	2	-2	-2	2	2	2	-2	1	0	2	0	-1	-2	1	-1	-2	-1	0	0	-2	2	-2	-2	0	-1	-1	-13
Series EFH w/ base trans	2	2	-2	-2	2	2	2	-2	1	0	2	0	-1	-2	1	-1	-2	-1	0	0	-2	2	-2	-2	0	-1	-1	-13
Series EH+ w/ base trans	2	2	-2	-2	2	2	0	-2	1	2	2	0	-1	-2	1	-1	-2	-1	0	0	-2	2	-2	-2	-1	-2	-1	-13
Series EFH+ w/ base trans	2	2	-2	-2	2	2	2	-2	1	2	2	0	-1	-2	1	-1	-2	-1	0	0	-2	2	-2	-2	-1	-2	-1	-13
Series EH w/ base axles	2	2	2	-2	2	2	2	-2	2	0	2	0	0	-1	1	-1	0	-1	0	0	0	2	-1	-2	0	0	-1	11
Series EFH w/ base axles	2	2	2	-2	2	2	2	-2	2	0	2	0	0	-1	1	-1	0	-1	0	0	0	2	-1	-2	0	0	-1	11
Series EH+ w/ base axles	2	2	2	-2	2	2	2	-2	2	2	2	0	0	-1	1	-1	0	-1	0	0	-1	2	-2	-2	-1	-1	-1	[illegible]
Series EFH+ w/ base axles	2	2	2	-2	2	2	2	-2	2	2	2	0	0	-1	1	-1	0	-1	0	0	-1	2	-2	-2	-1	-1	-1	[illegible]
Series- Parallel EH w/ base axles	2	2	2	-2	2	2	2	2	2	0	2	0	0	-2	1	-1	-2	-1	2	-2	-1	2	-2	-2	-2	-2	-2	[illegible]
Series- Parallel EFH w/ base axles	2	2	2	-2	2	2	2	2	2	0	2	0	0	-2	1	-1	-2	-1	2	-2	-1	2	-2	-2	-2	-2	-2	[illegible]
Series- Parallel EH+ w/ base axles	2	2	2	-2	2	2	2	2	2	2	2	0	0	-2	1	-1	-2	-1	2	-2	-2	2	-2	-2	-2	-2	-2	[illegible]
Series- Parallel EFH+ w/ base axles	2	2	2	-2	2	2	2	2	2	2	2	0	0	-2	1	-1	-2	-1	2	-2	-2	2	-2	-2	-2	-2	-2	[illegible]
BEV EH w/ base axles	2	2	2	-2	2	-2	2	0	2	0	-2	0	-2	2	1	-2	2	0	1	0	0	0	0	-2	-2	0	0	[illegible]
BEV EH+ w/ base axles	2	2	2	-2	2	-2	2	0	2	2	-2	0	-2	2	1	-2	2	0	1	0	-1	0	-1	-2	-2	-1	0	[illegible]

Weighted & Summed total score ranks the architectures

3 iterations of a Pugh style decision matrix were completed to determine the optimal electrification architecture

Technical Accomplishments and Progress (Past Year)

All selected architectures

P0 | P1 | P2 | P3+P0 | Series with Base Transmission | Series with Base Axles | BEV

Top 25% of hybrid architecture analysis

Other architectures of research interest

Performance requirements

P0 | P1 | P2 | P3+P0 | Series with Base Transmission | Series with Base Axles | BEV

Fail | Marginal | Pass

Low confidence these will reach 20% fuel consumption reduction

Unable to meet torque requirements

Unable to operate for long periods of time

Hybrid architecture scores

P0	P1	P2	P3+P0	Series with Base Transmission
47	36	38	43	-13

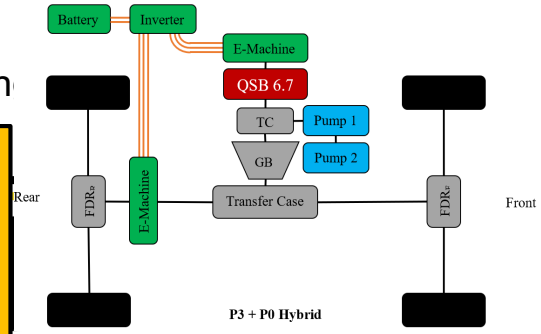
Bottom 5% of architecture scores

Most likely architectures

P0 | P1 | P2 | P3+P0

Low Confidence

Most promisin



P3 + P0 w/ Distributed Electrified Hydraulics is the most likely to meet fuel consumption and performance requirements

Responses to Previous Year Reviewer Comments

Summary of Concern(s)	Review Area	Response
Limited parameterization data, schematics, etc. and lack of machine application data will make modeling difficult	Approach	Indeed modeling was very challenging, however, as shown in this presentation we know have a high fidelity model with good agreement to baseline data.
It would have been helpful to have seen more clearly the type of electrification envisioned	Approach	The objective of BP2 (current BP) is to determine the electrification architecture & major components
Delays in subcontracting, baseline machine availability, etc. put project completion at risk	Accomplishments	All contracts are now signed, and we have had the baseline machine for almost 1 year
Pre-existing field data is not available	Collaboration	Agreed. We were aware of this so our plan was to obtain field data during summer of BP1, however this was delayed due to machine arrival 6 months out of phase, and lack of willing end-users. Workarounds were implemented, and field data will be collected at multiple users, summer of BP2.
The team should consider applications beyond material handling	Future Research	Good suggestion. We will do that.
No details given about electrification circuits & components	Future Research	The objective of BP2 (current BP) is to determine the electrification architecture & major components
% complete for the project does not seem to line up with milestone completion	Future Research	Thanks for bringing this to our attention. Not all milestones require the same effort to complete, so the % project complete doesn't scale linearly with number of complete milestones. We'll examine more carefully in the future.
Limited pre-existing information and data will be a challenge	Resources	Agreed. We have developed plans to address this and the OEM partner is very supportive of all project activities

Collaboration & Coordination

Institution	Relationship / Type	Contributions
Michigan Tech / APS LABS	Prime / University	Project Management, Coordination, Testing, Modeling, Prototype Build, Controls
PETTIBONE	Sub / Industry	Engineering Expertise, Machine Technical Specifications, schematics, CAD, etc., Machine Performance Requirements, Voice of Customer, etc. Pathway to commercialization and US Manufacturing
DANA	Key Vendor / Industry	Engineering Expertise, Sub-System & Component Technical Specifications
BorgWarner	Key Vendor / Industry	Engineering Expertise, Sub-System & Component Technical Specifications
Parker	Key Vendor / Industry	Engineering Expertise, Sub-System & Component Technical Specifications
TERZO	Key Vendor / Industry	Engineering Expertise, Sub-System & Component Technical Specifications
EMP POWERING THE FUTURE	Key Vendor / Industry	Engineering Expertise, Sub-System & Component Technical Specifications
PUKALL LUMBER COMPANY	End-User / Industry	Voice of the Customer, End-User Field Testing
DURA-BOND PIPE	End-User / Industry	Voice of the Customer, End-User Field Testing

Remaining Challenges & Barriers

Challenge / Barrier	Risk	Contingency
Lead Time on electrification components are proving to be long and unpredictable	High	Select alternative architecture or components based on COTS availability.
Material potential energy recovery will be difficult due to safety measures that must be included in the production machine	Low	Proceed w/o PE Recovery. PE recovery is a benefit, but small compared to other opportunities.
Hardware integration challenges (packaging, adaptions, etc.)	Medium	Select alternative architecture or components that resolve integration issues.
Controls integration challenges (usability, etc.)	Medium	Select alternative architecture or components that resolve integration issues.

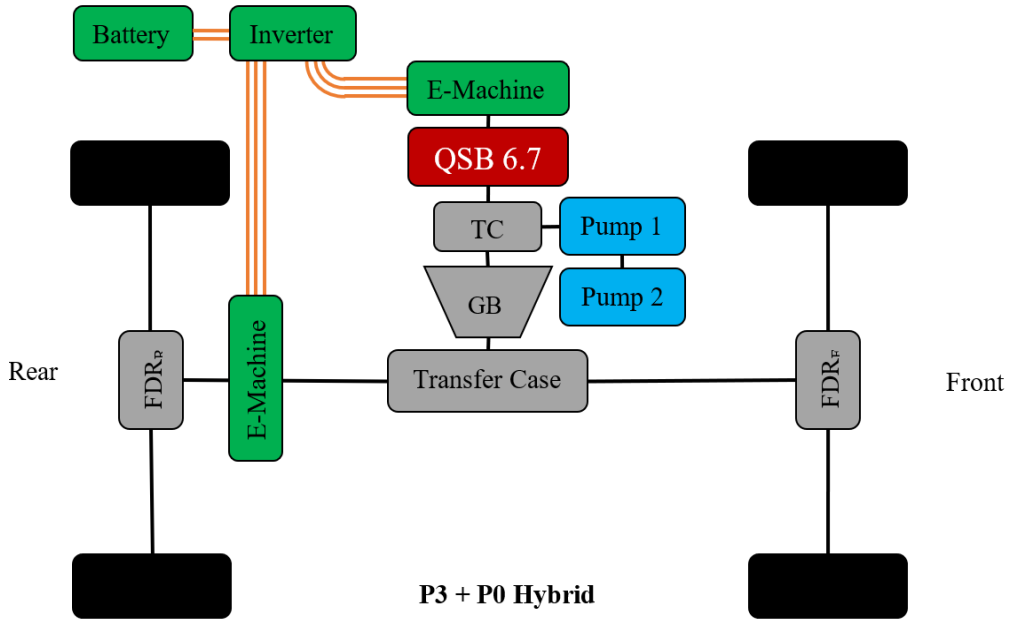
Proposed Future Research

- FY22
  - Finalize architecture selection and sub-system and major component BOM
  - Order long-lead items
  - Sub-System Laboratory Testing
- FY23
  - Integration Design (brackets, enclosures, house & wiring, etc.)
  - Hardware Fabrication & Assembly
  - Development of supervisory controls algorithms
  - Controls calibration
  - On-Track & Real-World performance evaluation

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

Summary

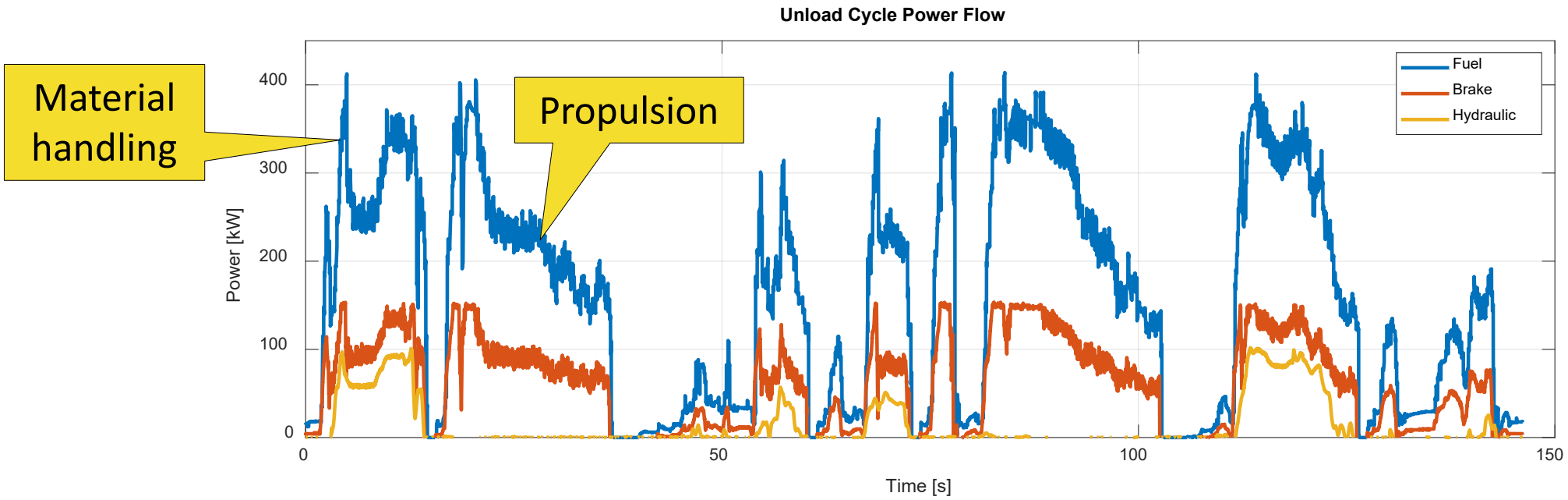
- Baseline testing is complete
- Model is complete and validated
- P0+P3 Propulsion Architecture with Distributed Electrified Hydraulics is the most likely electrification architecture from an efficiency & performance perspective
- Major next steps will include:
  - Hardware integration design
  - Controls & software



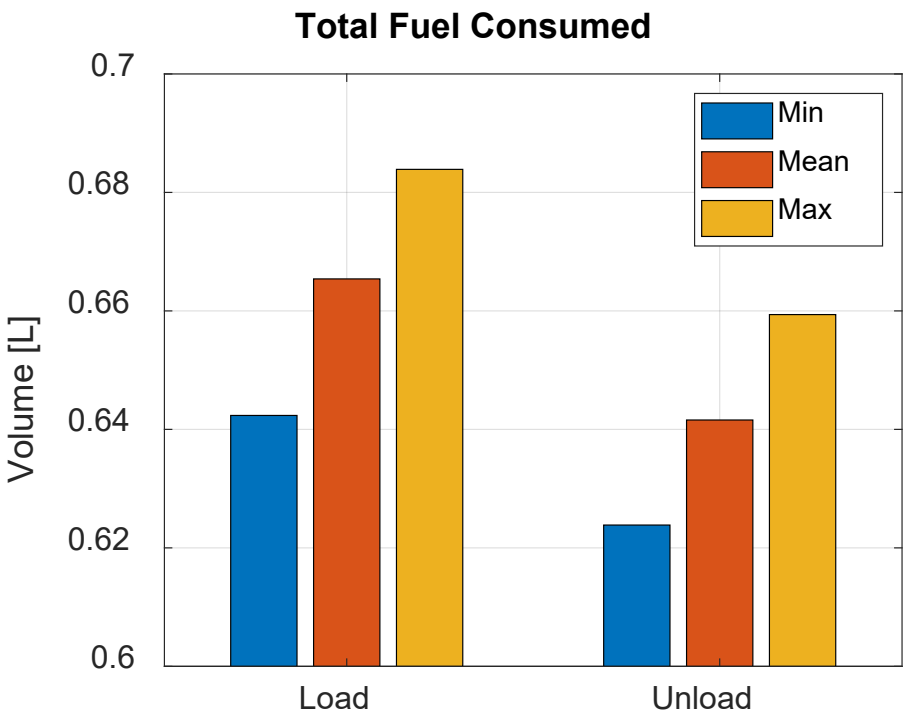
Technical Back-Up Slides

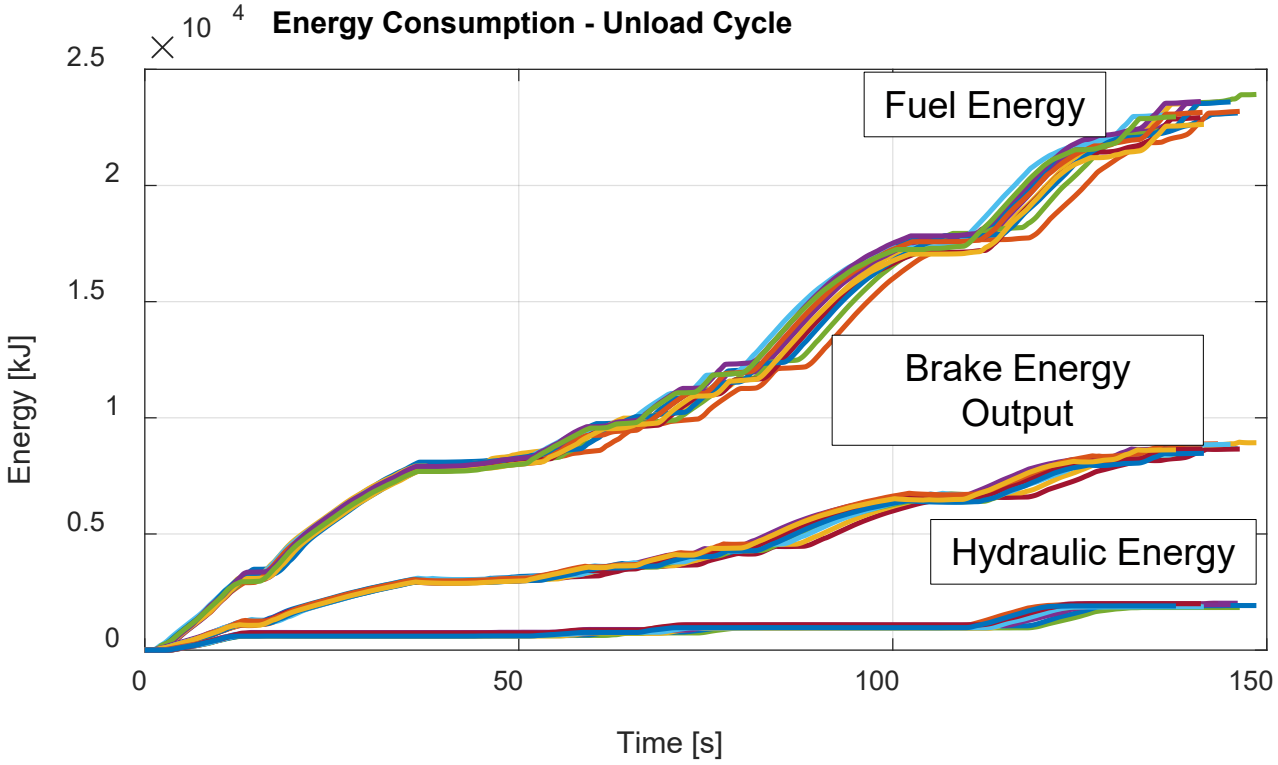
Technical Accomplishments and Progress (Past Year)

- Baseline testing shows multiple levels of power flow from fuel input to brake output and the hydraulic system.
  - Multiple levels of power flow necessary for finding the possible fuel consumption reduction



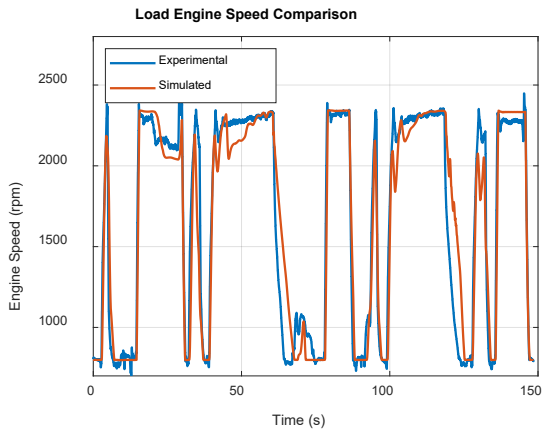
Technical Accomplishments and Progress (Past Year)

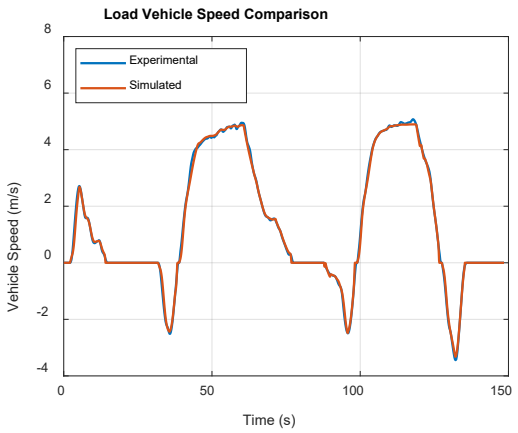


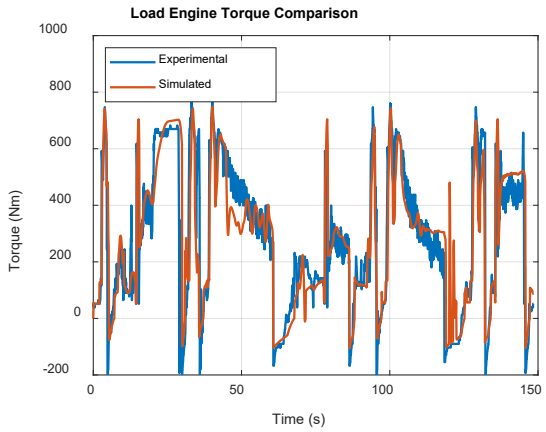


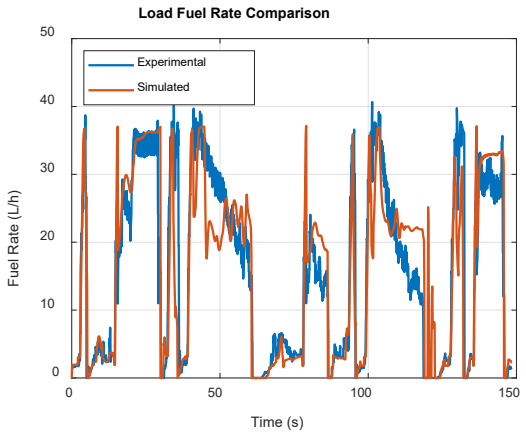
Simulation Results

Load Cycle

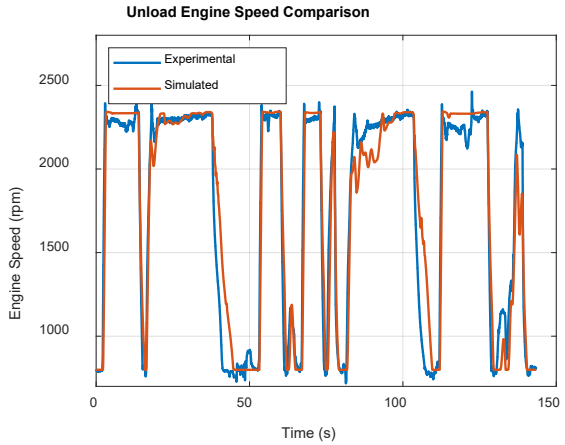


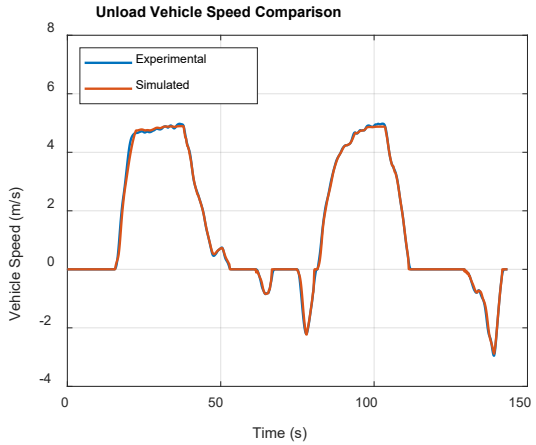


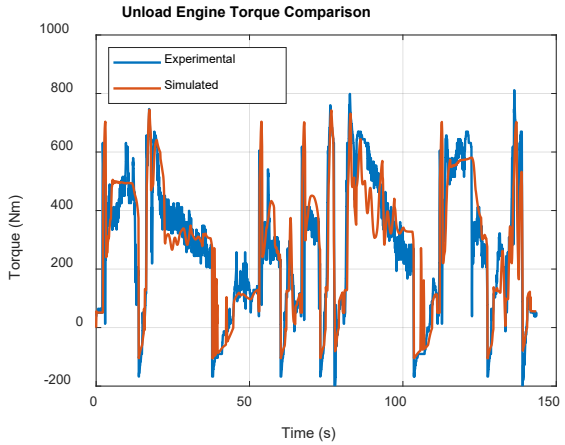


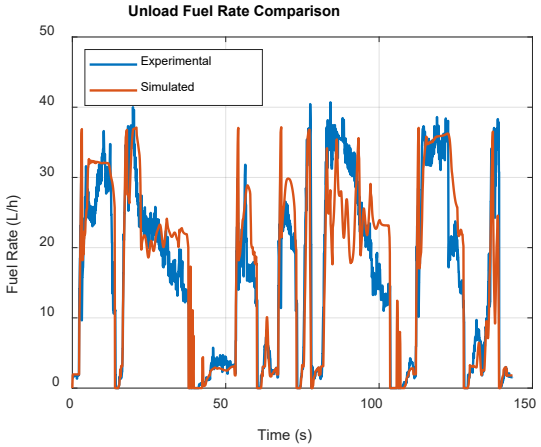


Unload Cycle



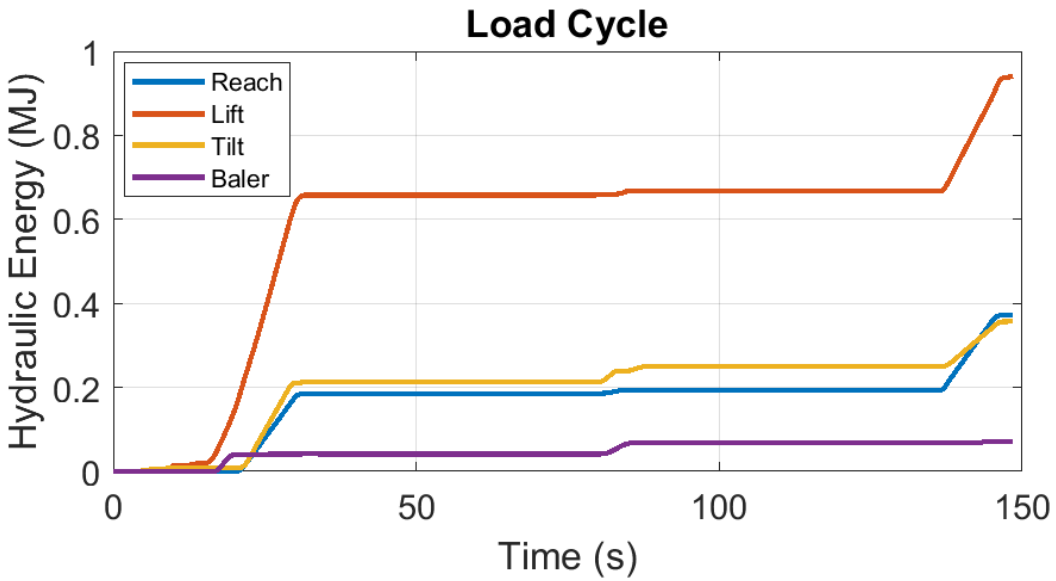


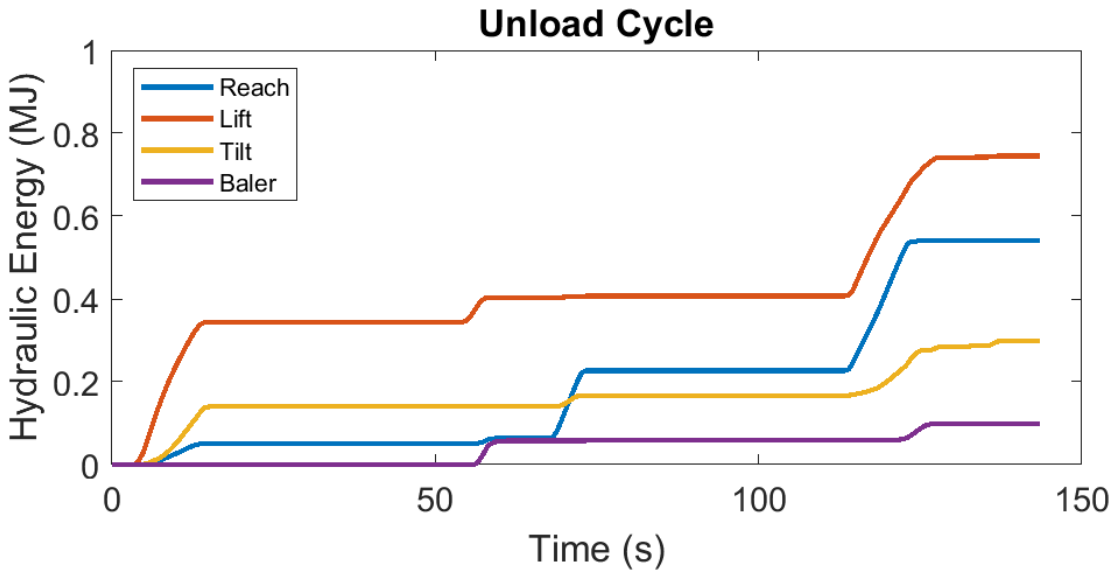




Technical Accomplishments and Progress (Past Year)

- Model allows insight into hydraulic functions individual energy consumption
- Cylinders indicated in figure to right





Technical Accomplishments and Progress (Past Year)

Detailed example of a small subset of the decision matrix

	Engine Off Stationary	Engine Off Creep & Low Load	KE Recovery	PE Recovery	Plug-in Benefit	Opportunity Charging Efficiency	Low Load / Low Duty Cycle Efficiency	High Load / High Duty Cycle Efficiency	Propulsion System Efficiency	Hydraulic System Efficiency	Range
Descriptions: See more in Descriptions tab	-2 = no shut off, 0 = no shut off hyd	-2 = no creep, +2 = good creep ability	-2 = no KE, 2 good KE	-2 = no PE recovery, +2 is best PE recovery	-2 = no benefit, +2 = most benefit	-2 = no ability, +2 = best opp. charging eff.	-2 = least efficient, +2 = most efficient	-2 = least efficient, +2 = most efficient	-2 = baseline, +2 = most efficient	-2 = baseline, 0 is EH, +2 is EH+	-2 = BEV, +2 = best
Weighting Factor	3	3	1	1	1	1	1	2	3	3	3
Base	-2	-2	-2	-2	-2	-2	-2	2	-2	-2	0
P0	0	-2	-2	-2	-1	2	-2	2	-2	-2	0
P0 EF	0	-2	-2	-2	-1	2	-2	2	-2	-2	0
P0 EH	2	-2	-2	-2	0	2	-1	1	-2	0	1
P0 EFH	2	-2	-2	-2	0	2	-1	1	-2	0	1
P0 EH+	2	-2	-2	-2	0	2	0	1	-2	2	1
P0 EFH+	2	-2	-2	-2	0	2	0	1	-2	2	1
P1	0	-2	-2	-2	-1	2	-2	2	-2	-2	0
P1 EF	0	-2	-2	-2	-1	2	-2	2	-2	-2	0
P1 EH	2	-2	-2	-2	0	2	-1	1	-2	0	1
P1 EFH	2	-2	-2	-2	0	2	-1	1	-2	0	1
P1 EH+	2	-2	-2	-2	0	2	0	1	-2	2	1
P1 EFH+	2	-2	-2	-2	0	2	0	1	-2	2	1

Top 25% move onto next stage of analysis