OPTIMIZATION AND EVALUATION OF ENERGY SAVINGS FOR CONNECTED AND AUTONOMOUS OFF-ROAD VEHICLES

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2022 DOE Vehicle Technologies Office Annual Merit Review

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Overview

Timeline

- Project Start: Sept. 2020
- Project end: Dec. 2023
- Percent complete: 50%

Budget

- Total project funding: $1,738,118
  - DOE: $1,670,000
  - Cost share: $68,118

- Funding for BP1: $559,135
- Funding for BP2: $584,738

Barriers

- Architecture complexity. For off-road vehicles, there exist both the drivetrain and the work circuit. There are complex dynamic interactions between them in real time.
- Operator inefficiency. The complex dynamics of the powertrain and its response time make operator control challenging, resulting in lower efficiency and productivity.

Partners

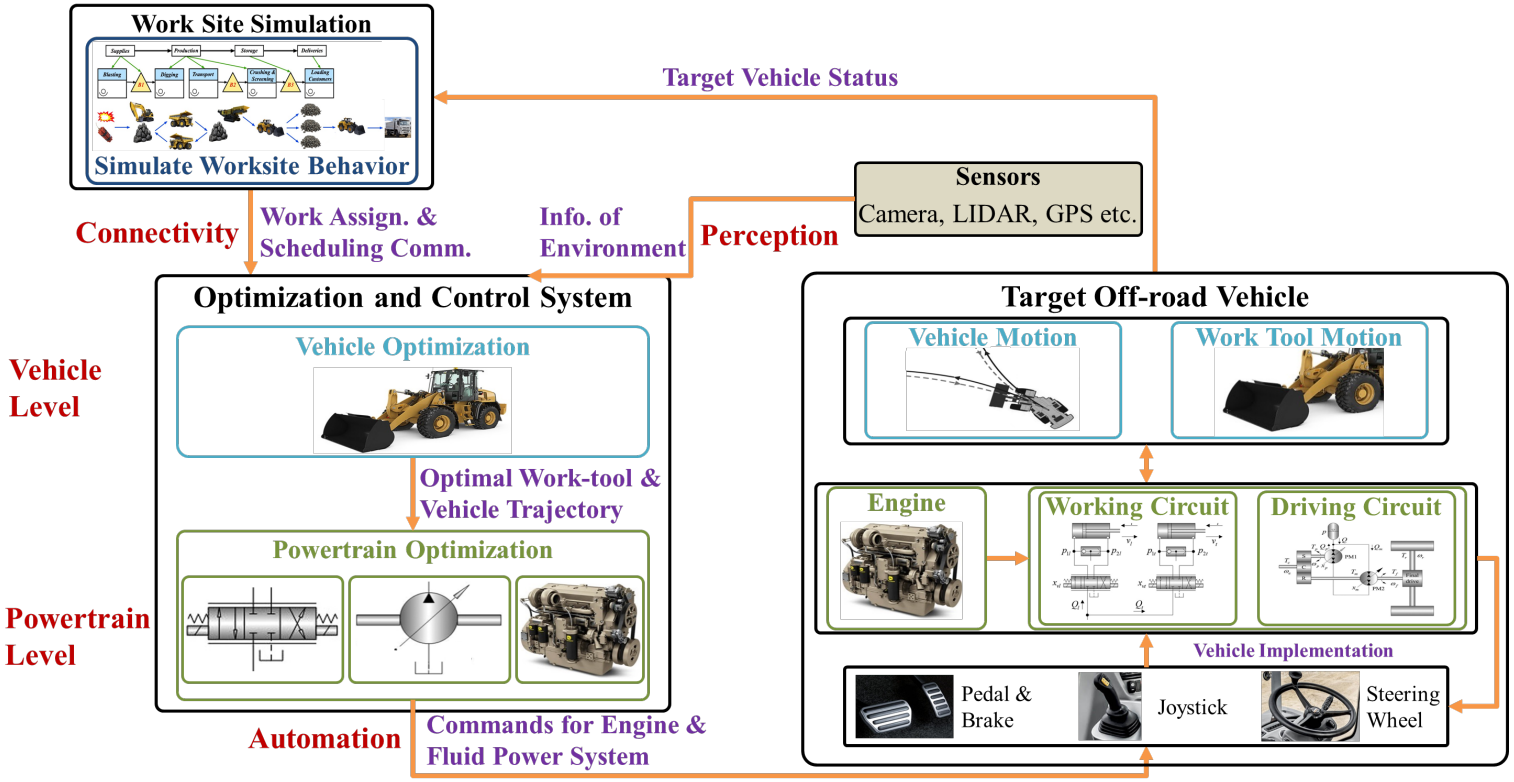
- University of Minnesota
- Texas A&M University
- CNH Industrial

Relevance

We aim to use connectivity and automation to reduce energy consumption and increase productivity for off-road vehicles.

Proposed Objectives:

- Develop systematic optimization and control methods for connected and autonomous off-road vehicles to achieve significant energy savings (20-40%) with improved productivity.
- Develop a hardware-in-the-loop (HIL) testbed to evaluate energy savings of connected and autonomous off-road vehicles in a time efficient, safe and cost-effective fashion.

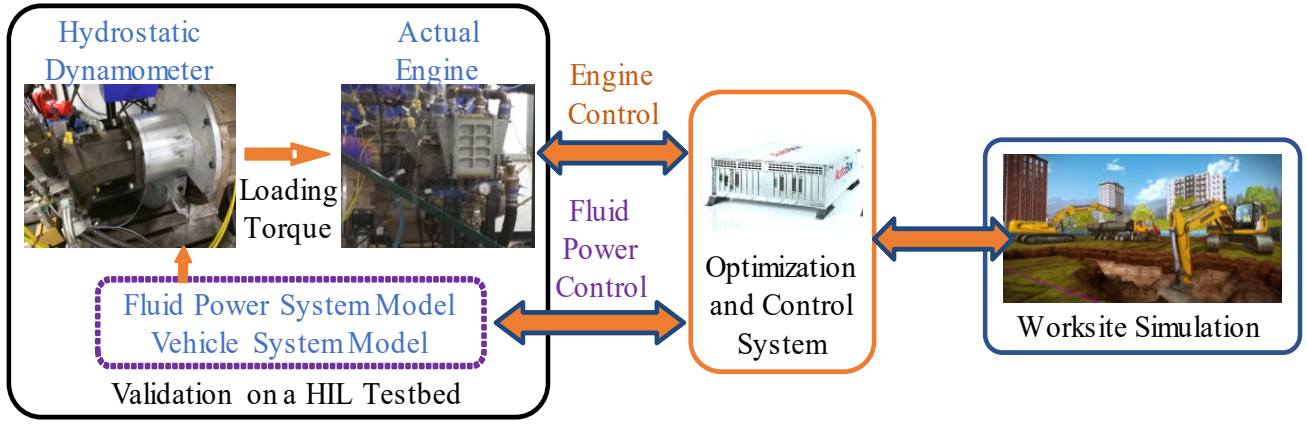


Milestones

Time	Description	Status
Sept. 2021	Optimization problem is formulated (Cost function and constraint equations available)	Complete
Dec. 2021	Vehicle model is developed (Root Mean Square error <5%)	Complete
March 2022	Communication system is developed (Communication latency < 100 milliseconds with no missing data)	Complete
June 2022	Solution to the optimization developed (Computation time < 80% of duty cycle; Efficiency gain > 20%)	On schedule
Sept. 2022	HIL testbed is fully integrated	On schedule

Approach

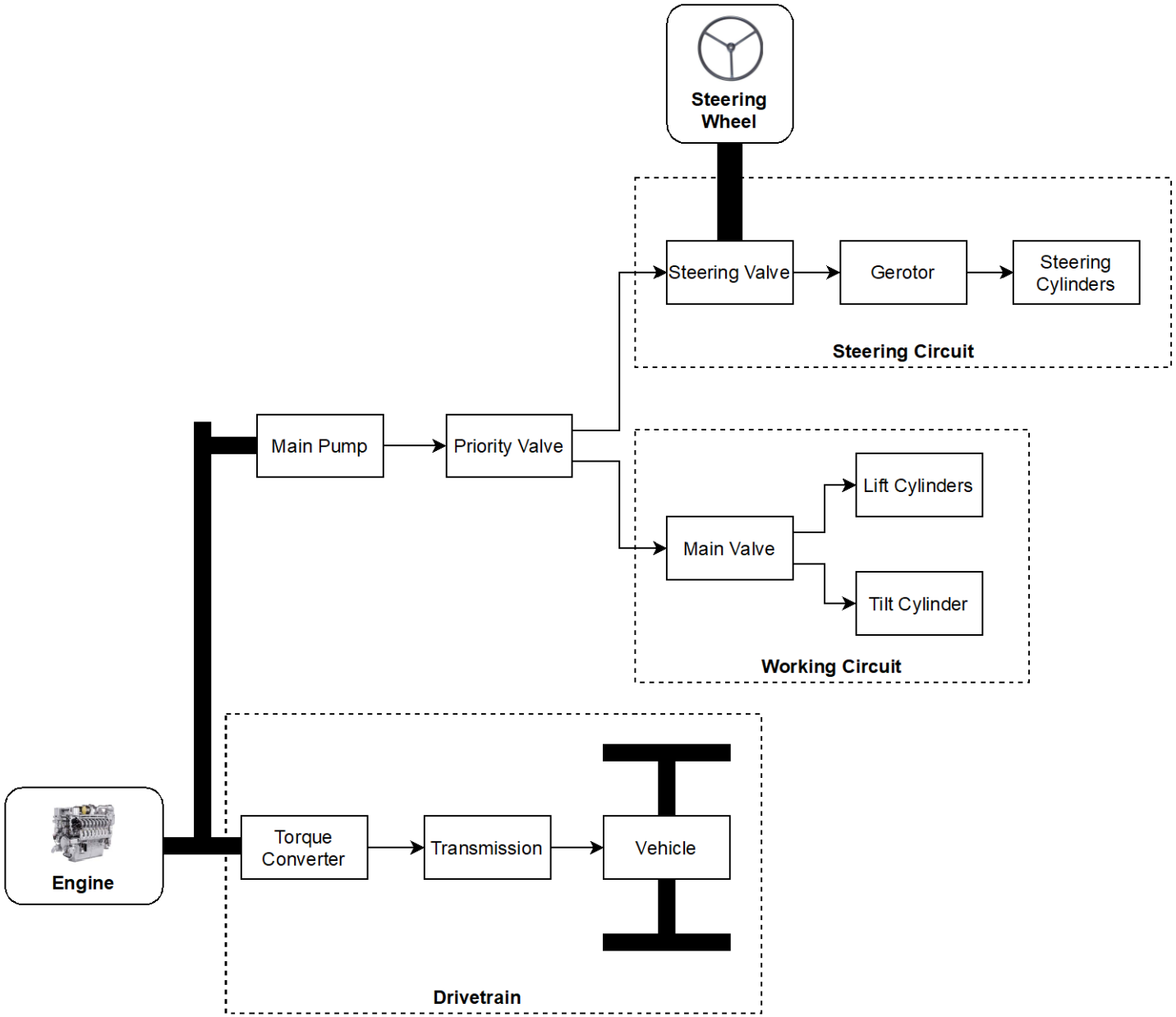
- **Optimization and Control of Off-road Vehicles:** The control system will perform co-optimization of vehicle speed and tool motion, fluid power system and the engine through automation. To formulate the model-based optimization problem, the target off-road vehicle model will be developed. Efficient numerical methods will be applied to solve the optimization.
- **HIL Testbed Development:** A HIL testbed will be developed to evaluate energy savings of the control and co-optimization system. The HIL testbed has an actual engine loaded by a hydrostatic dynamometer based on real-time simulation of work and drive circuits of the target off-road vehicle.
- **Evaluation and Testing of Off-road Vehicle Energy Savings with the HIL Testbed:** The HIL testbed will be used to evaluate the fuel economy and emissions benefits of the optimization and control with laboratory instruments and benchmark with baseline field data. The performance of the optimal control system will be evaluated at different levels of automation for the selected off-road application.



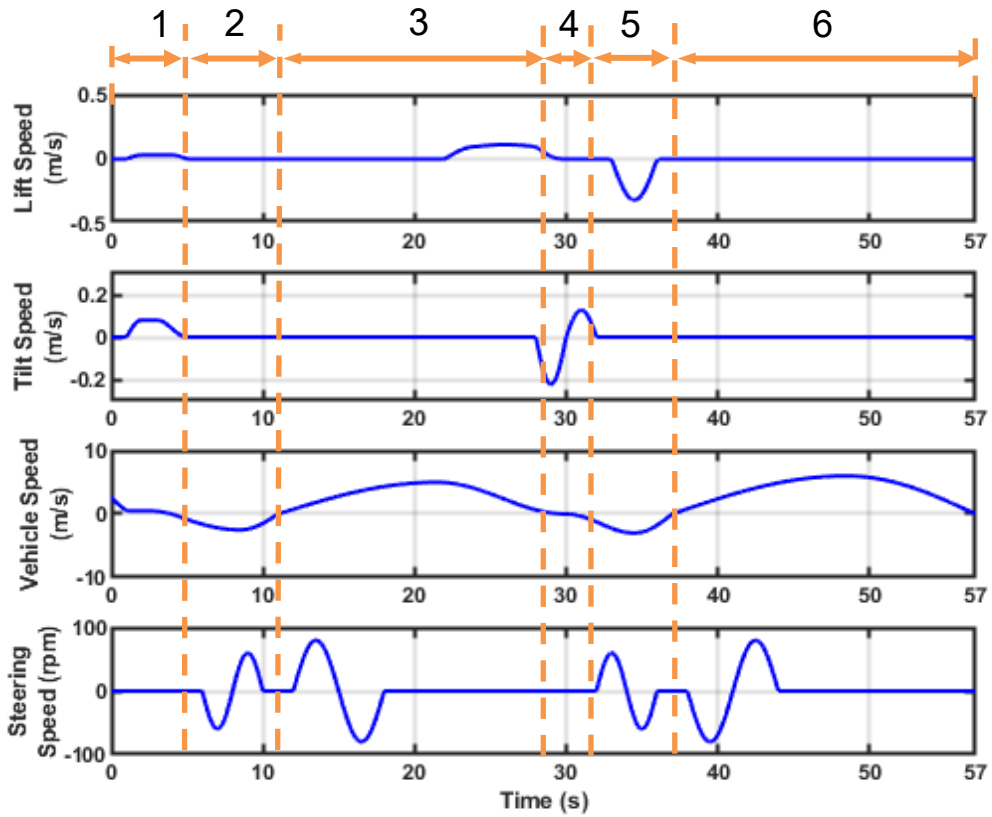
Technical Accomplishments

A full vehicle model for a wheel loader is developed and validated.

- Model Development
  - Drivetrain model
  - Work circuit model
  - Steering circuit model
- Model Calibration
  - Drivetrain model
  - Work circuit converter
  - Steering circuit model
- Model Validation
  - *Less than 5% of RMS error has been achieved comparing the model with the field data.*
  - *Fuel consumption discrepancy is within 2.3%*



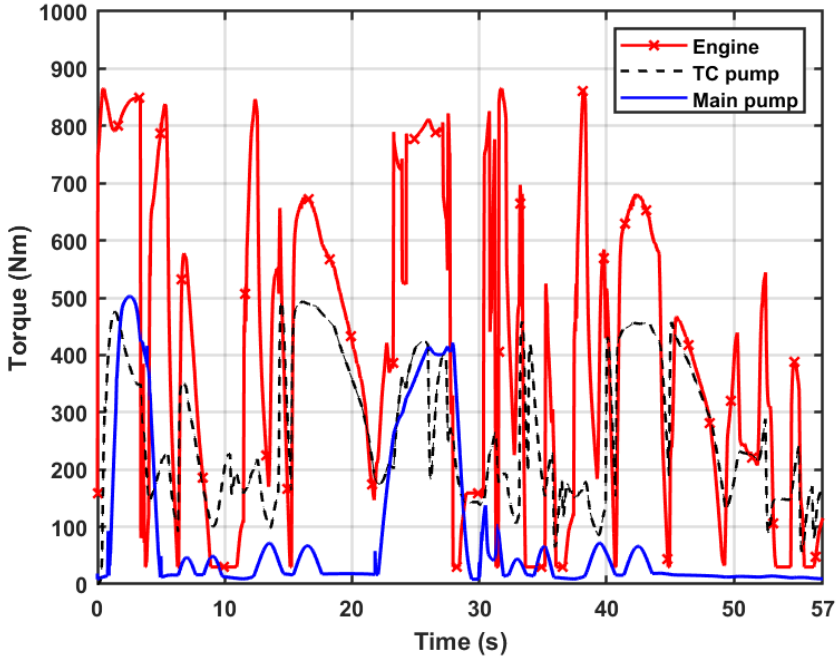
Technical Accomplishments: Vehicle model simulation



Six Phases in Long Cycle:

Phase 1 : Digging; ***Phase 2*** : Reverse 1; ***Phase 3*** : Forward 1;

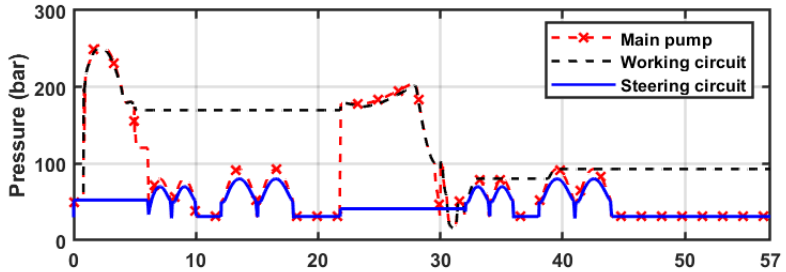
Phase 4 : Dumping; ***Phase 5*** : Reverse 2; ***Phase 6*** : Forward 2;



Engine torque

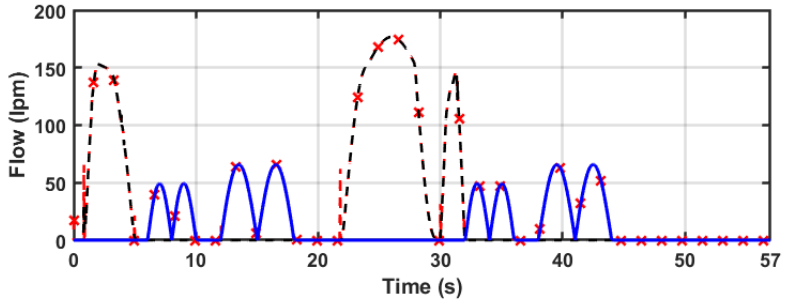
TC input torque

Hydraulic pump torque



Pressure and flow rate for:

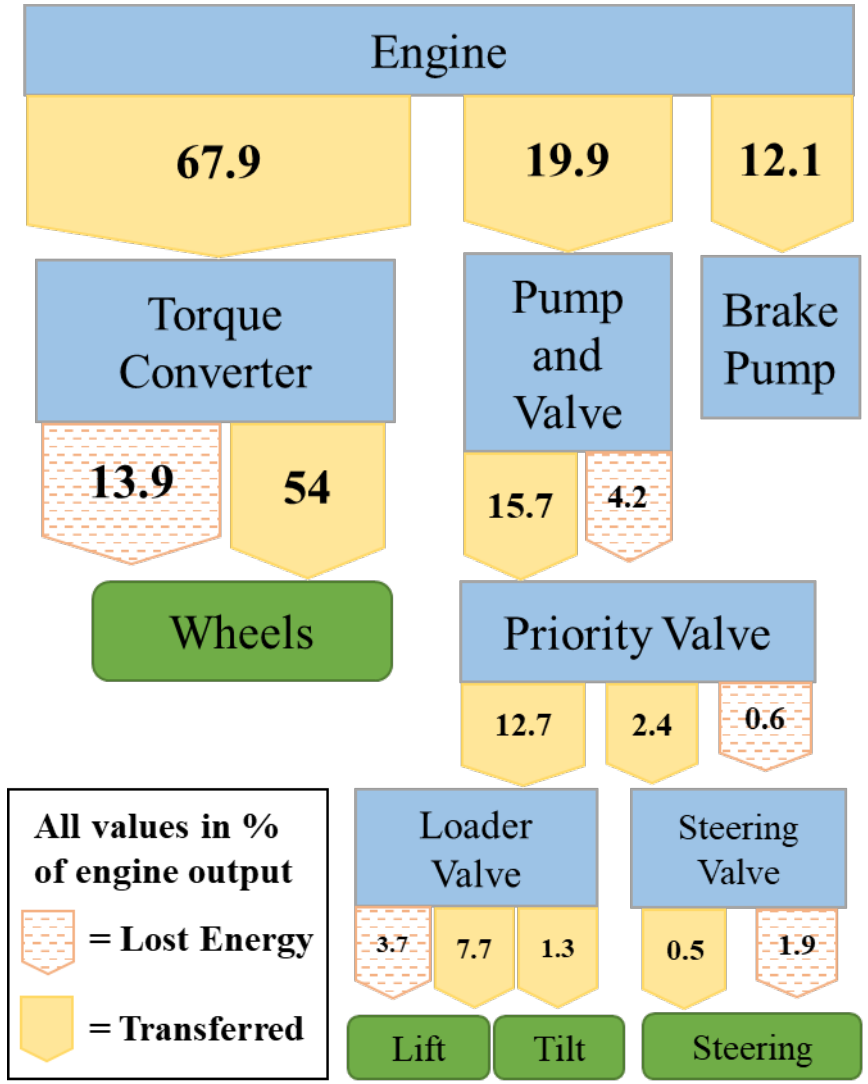
Hydraulic pump



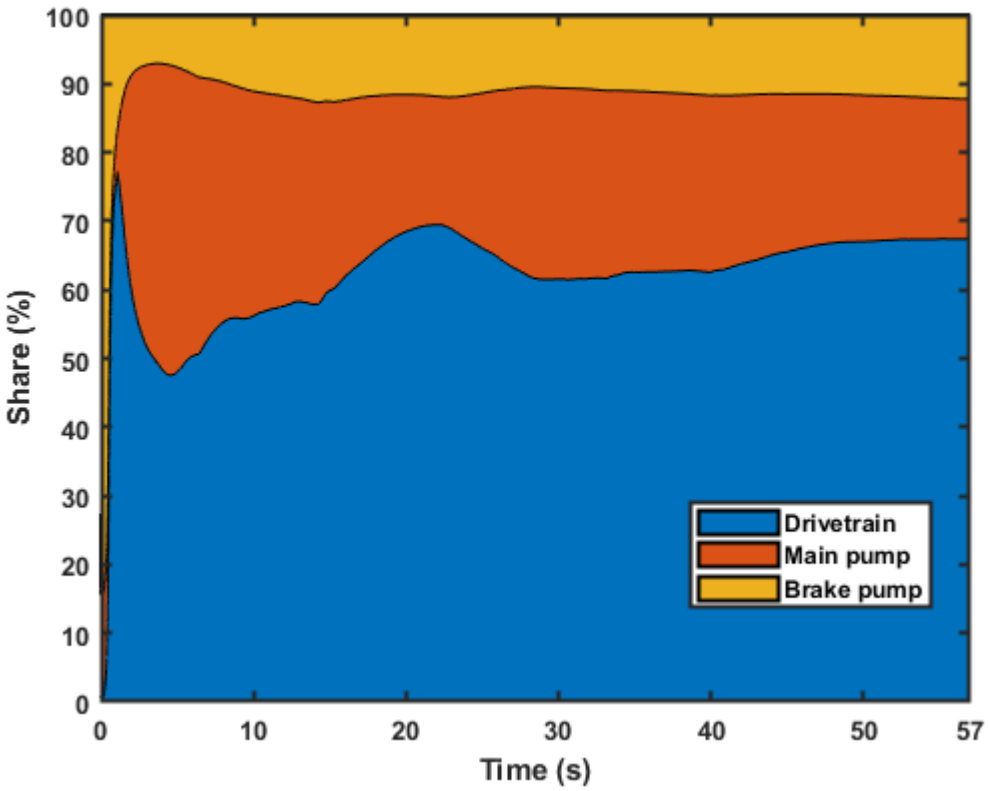
Working circuit

Steering circuit

Technical Accomplishments: Energy analysis



Energy usage breakdown

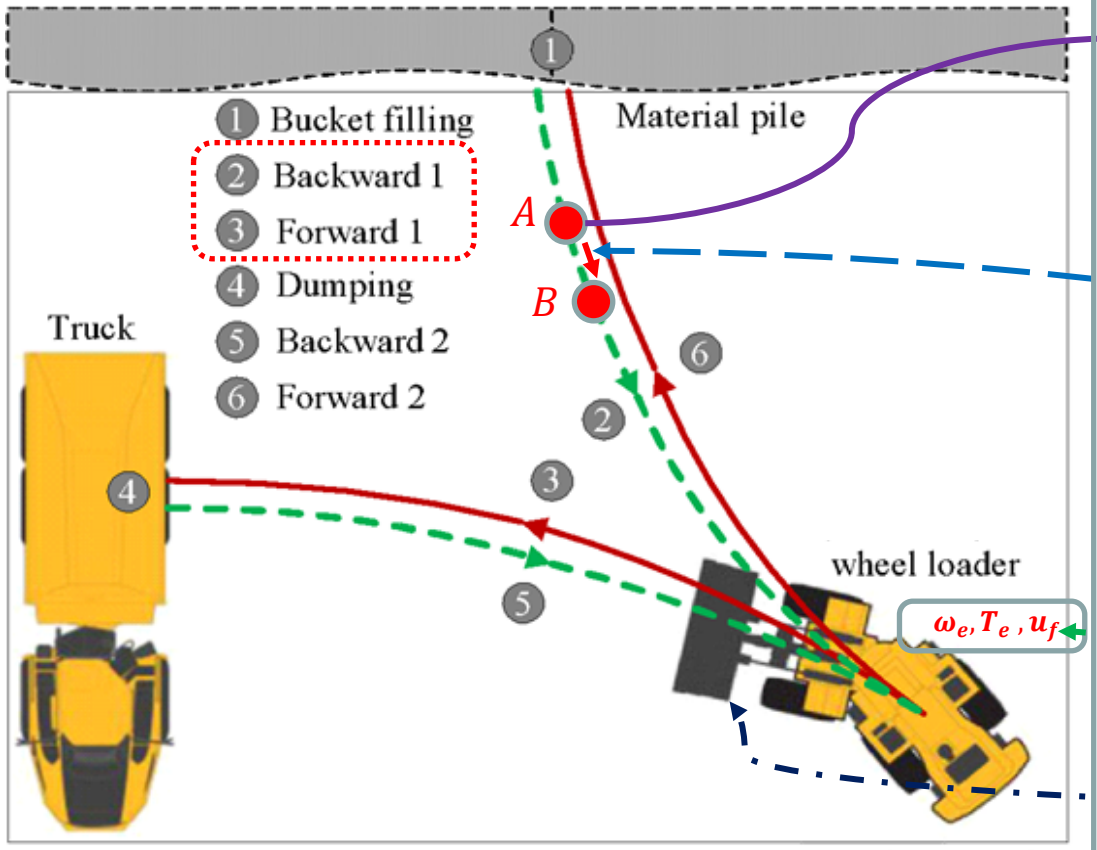


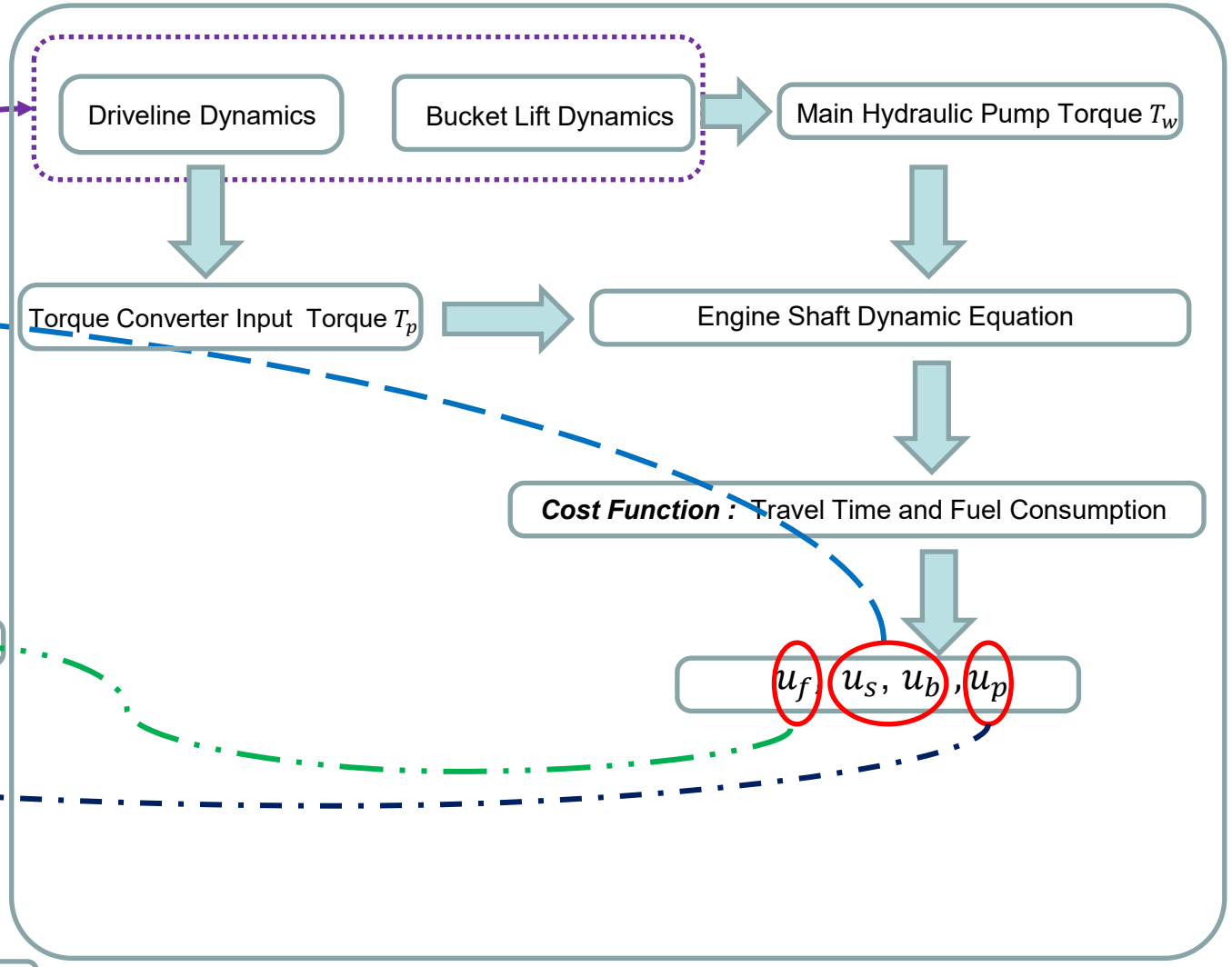
Energy flow during the cycle

Energy analysis reveals that dynamic coupling between drivetrain and work circuit represents a key challenge and opportunity for energy saving.

Technical Accomplishments: Transport phase optimization

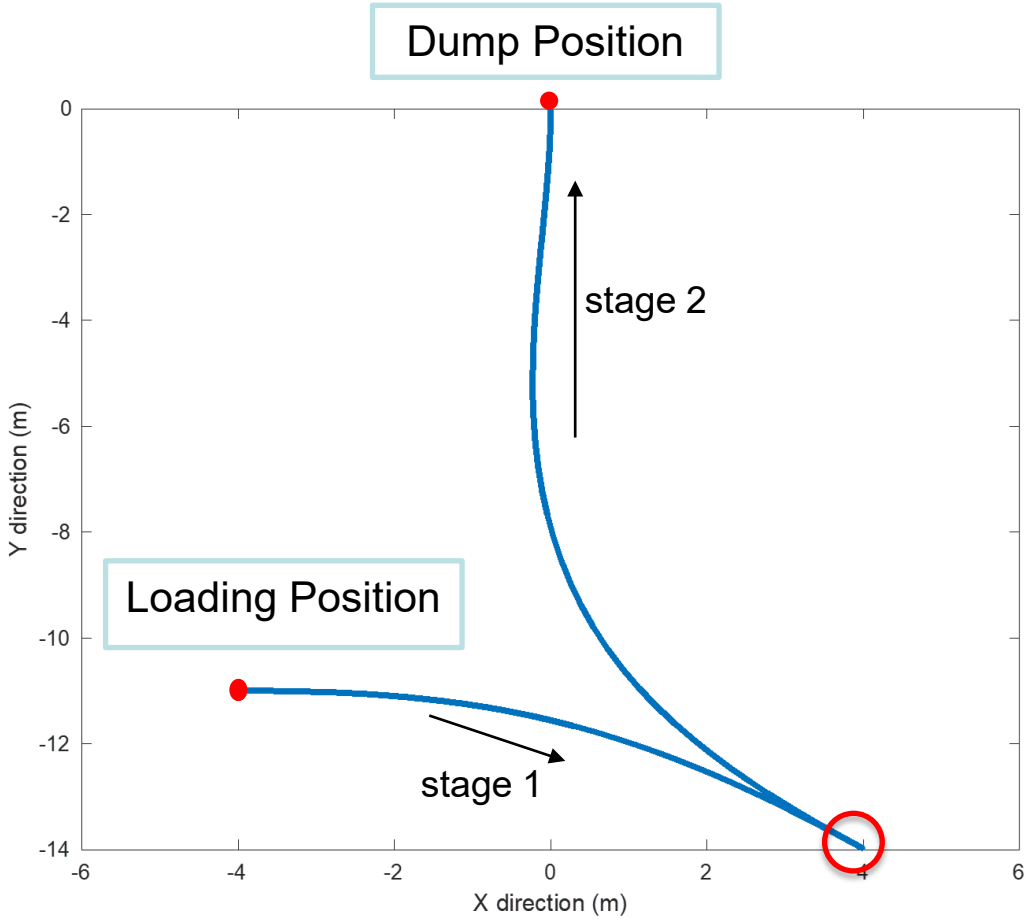
Objective: *optimize the energy consumption and productivity for the transport and lifting phase of the V-shaped loading cycle*

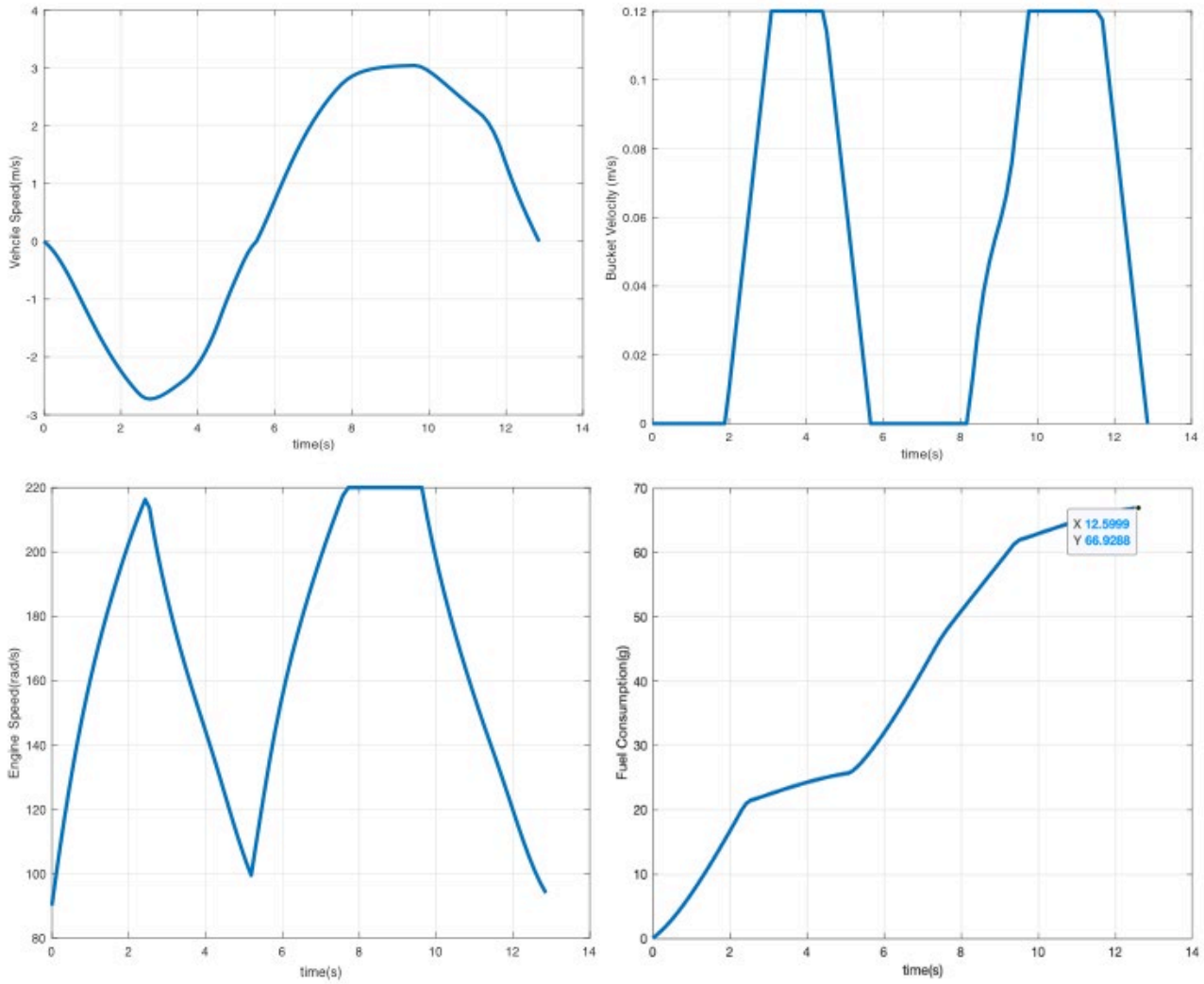




requires a complete stop; determined by the optimization algorithm automatically

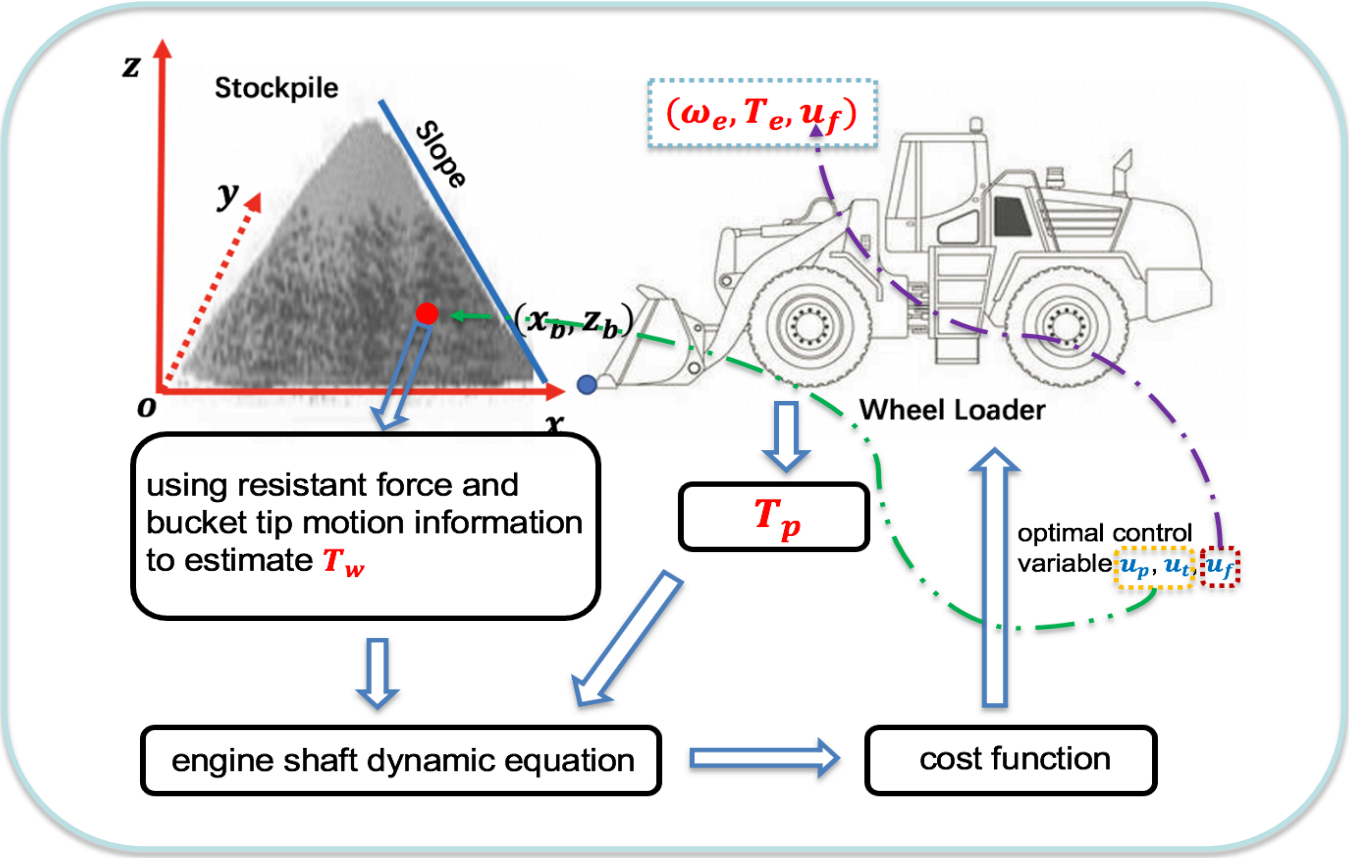
Technical Accomplishments: Optimal transport trajectory





Optimal result shows a 16% decrease in fuel consumption compared with the human-driven cycle.
27.9% fuel benefit can be achieved with more aggressive steering.

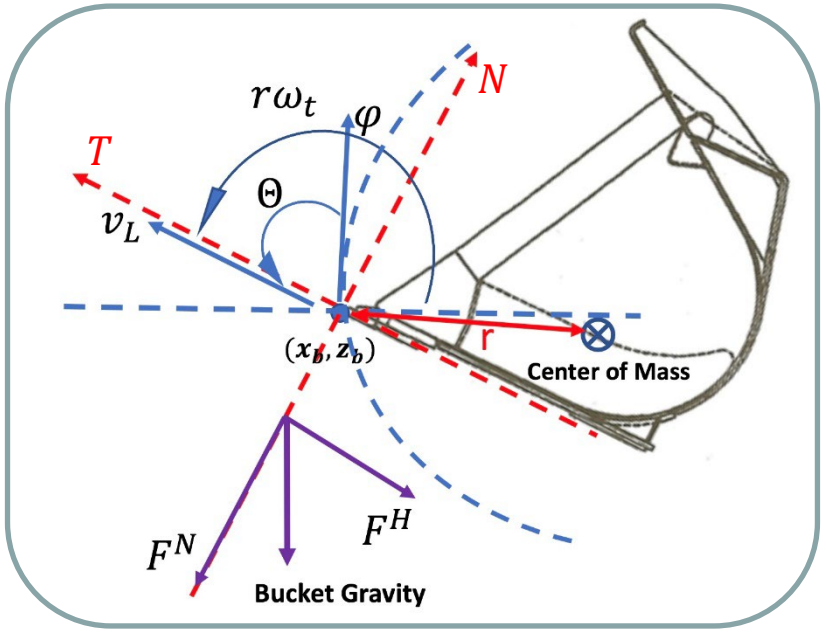
Technical Accomplishments: Digging phase optimization



Working Scenario Setting

- The bucket move only inside $x - z$ plane without having motion in y direction.
- The bucket tip position and orientation angle is used to represent the the bucket motion.
- Resistance force is calculated at the bucket tip.
- The work done by the bucket is mapped into the main hydraulic pump.
- Cost function is fuel consumption.

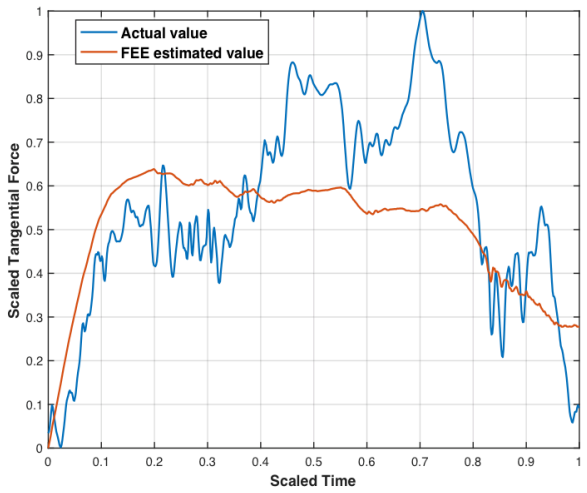
Technical Accomplishments: Resistance Force Estimation

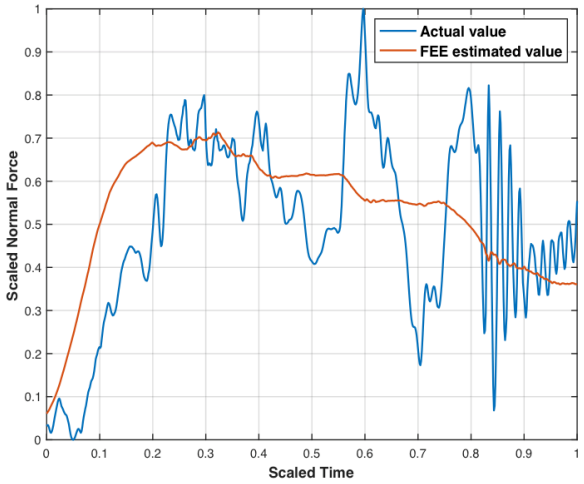


1. *Resistance Force is estimated by the Fundamental Earthmoving Equation (FEE) model.*

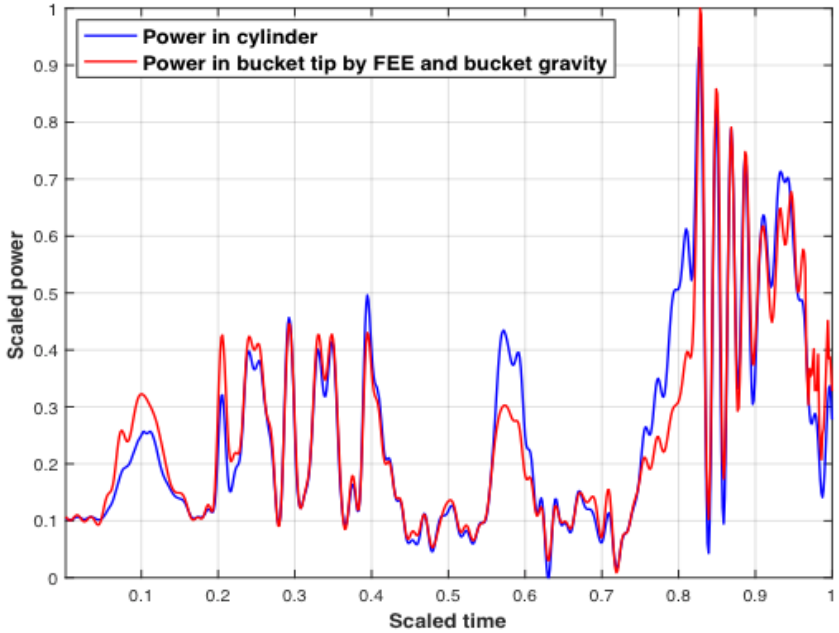
2. F^N *and* F^H *are Resistance Force along the tangential and normal directions (red dash lines).*

Resistance Force Validation

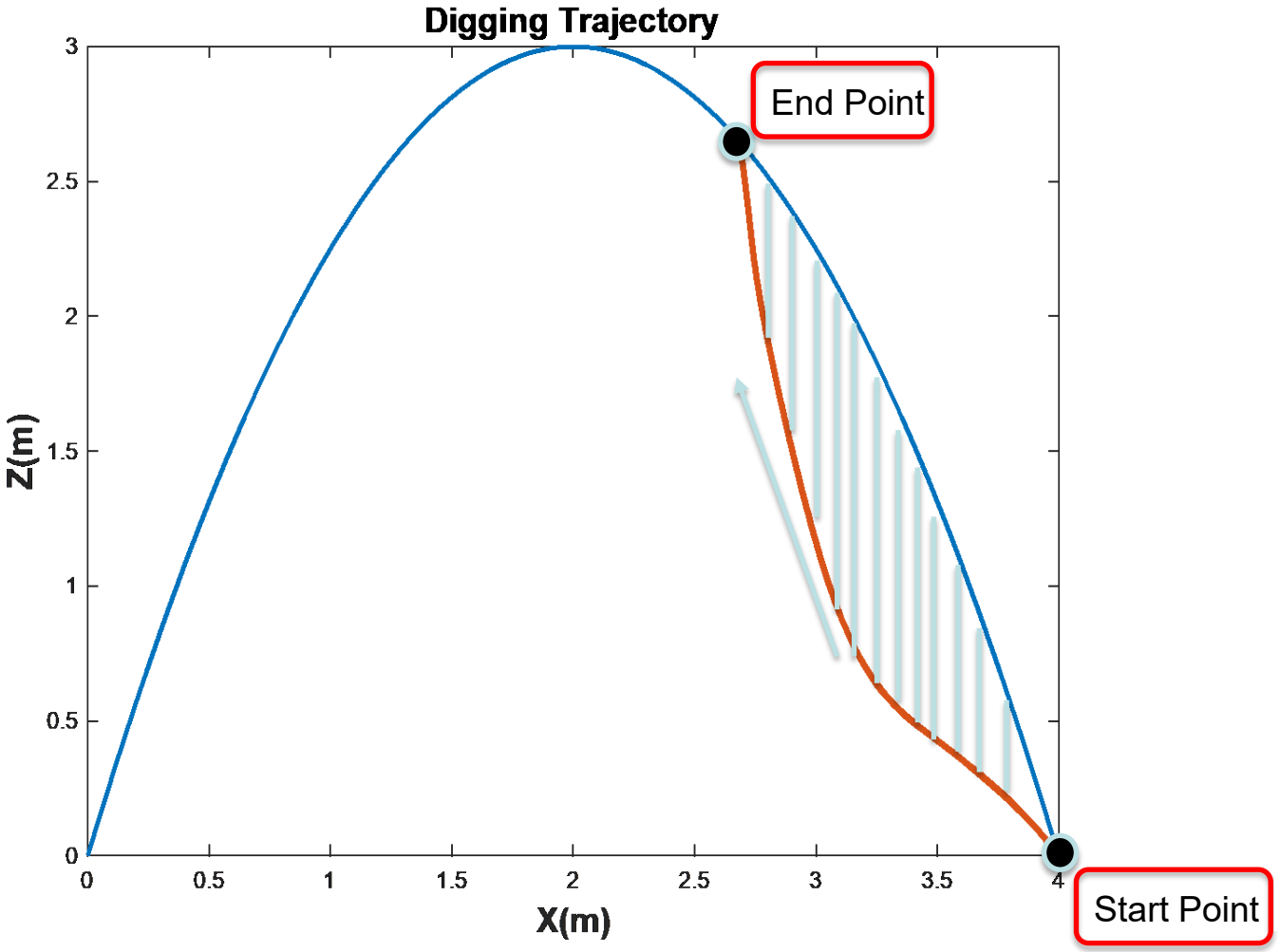


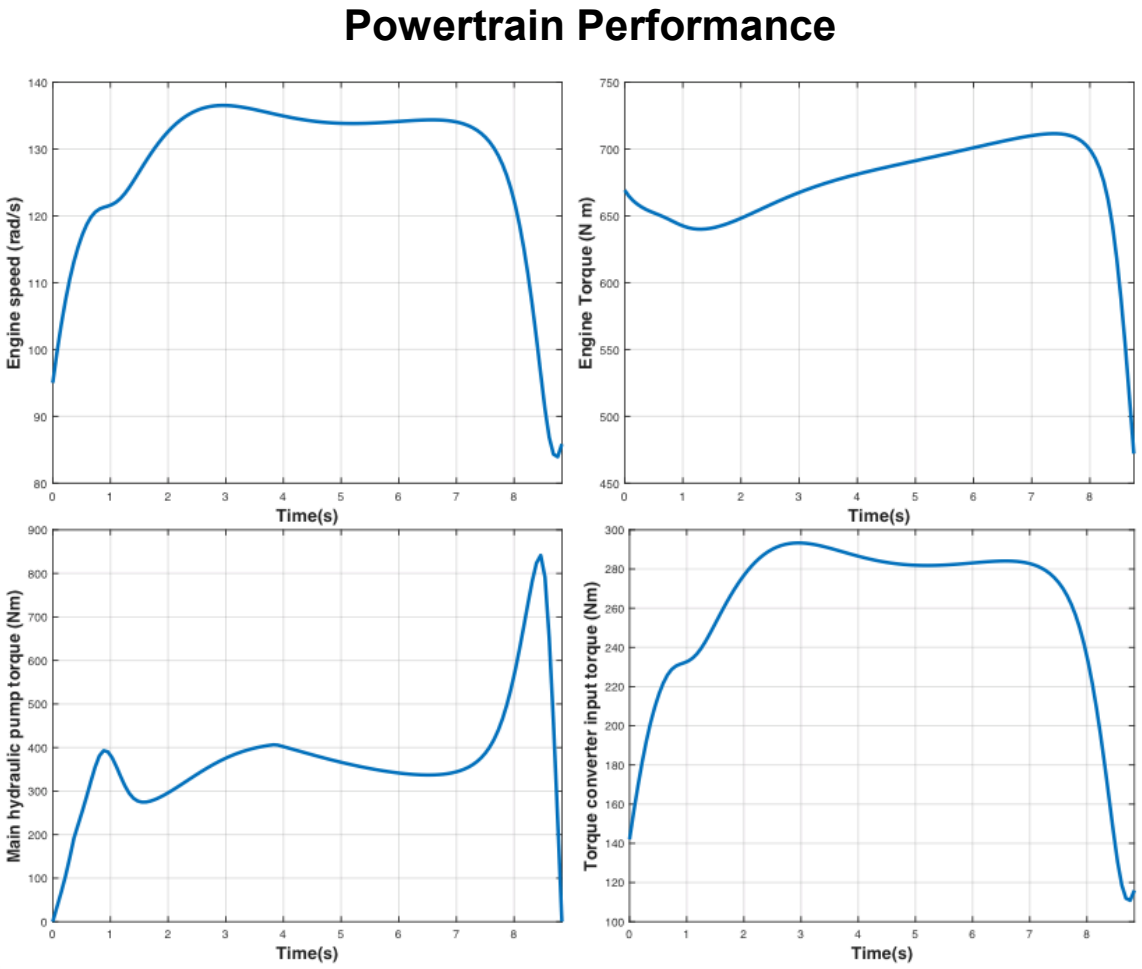


Power Validation at the bucket and at the hydraulic cylinder



Technical Accomplishments: Optimal digging profile

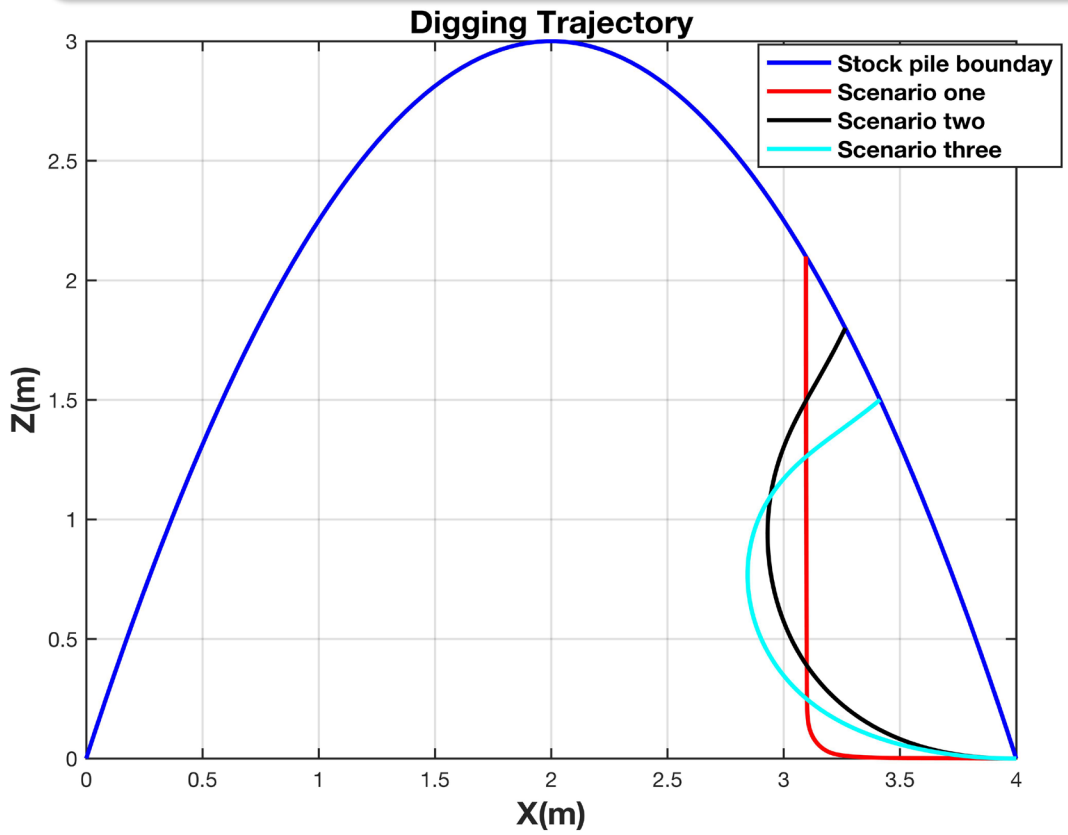




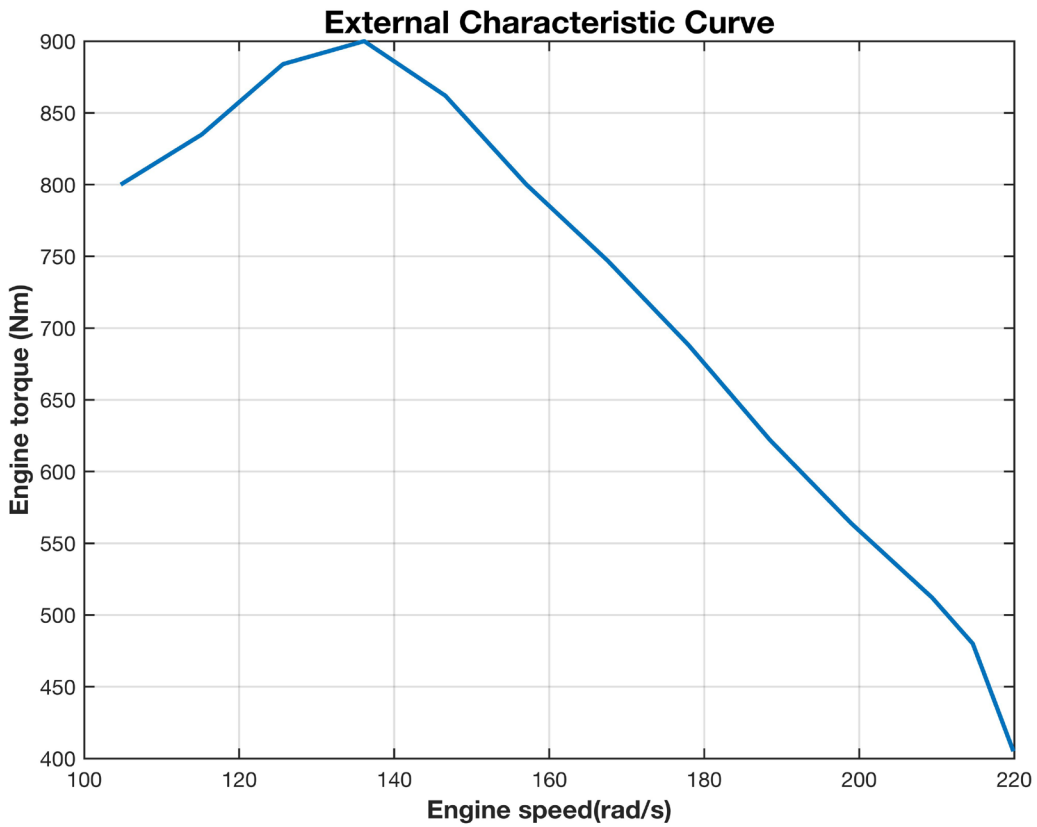
Fuel consumption is 48.23 g with time duration of 8.756s

Technical Accomplishments: Comparison with human operation

Imitate bucket trajectory of human driver's loading operation



Mimic human driver's operation with 100% throttle during bucket loading

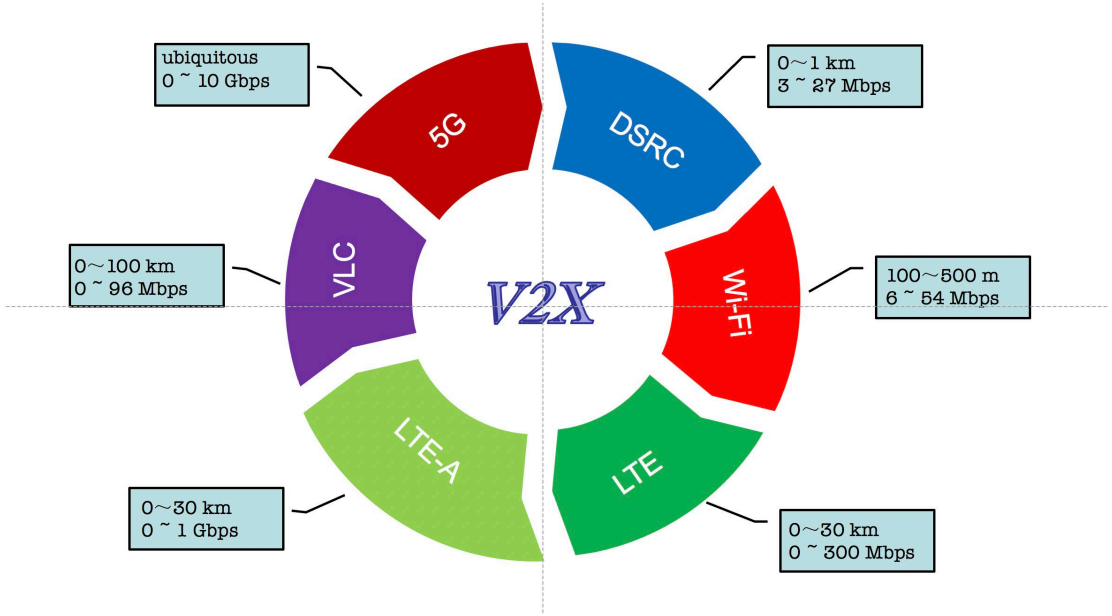


Scenario	One	Two	Three
Fuel Consumption(g)	69.7222	69.0363	68.8094

Fuel Benefit is around 30%

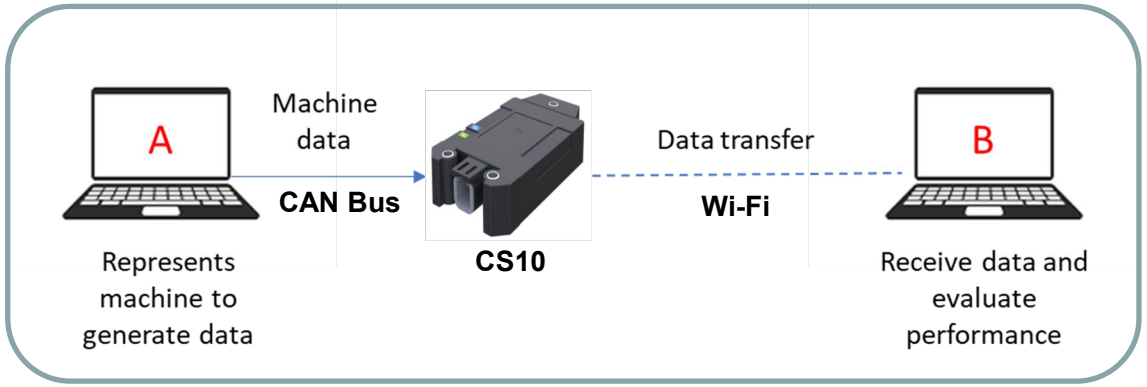
Technical Accomplishments: Communication system

Vehicle Communication Overview



Device	Danfoss CS10 wireless gateway	Danfoss CS100 cellular gateway	Danfoss CS500 IoT gateway
Communication Methods	Via Wi-Fi or Bluetooth	Via LTE Cat.M1 and 2G	Via 4G LTE, 3G UMTS/HSPA+, and 2G GSM/GPRS/EDGE

Experimental Setup



Experimental Performance

Interval	1000 ms		100 ms		10 ms		1 ms	
	T	R	T	R	T	R	T	R
Total Messages	19	19	40	40	246	246	2655	2655
Accuracy	100%		100%		100%		100%	

Responses to Previous Year Reviewers' Comments

- *One challenge with taking off-road vehicle performance and correlating it with a good vehicle model is the soft soil portion of the analysis.*

FEE based resistance force model has been developed. It has been validated with field data. A real-time adaptive force model has also been developed and an IP has been filed for this model.

- *It was not clear to the reviewer how the tool part of the machine will be evaluated in the HIL.*

Based on the trajectories of the driveline and the work tool, the load on the engine will be calculated using the validated system model. This load will be applied in real-time to the engine through the HIL testbed. Fuel consumption will be measured to evaluate the effect of different trajectories.

- *The reviewer asked two questions. Firstly, can the team describe how this optimization will interact with the machine operator? Secondly, will the controls detect what is desired and dampen, limit, or alter the operator input somehow or will there be periods of automation that the operator can choose to enable somehow? How this really gets implemented in an operator and dynamic work environment was not yet clear to the reviewer.*

The optimization results can be implemented as driver assistance, partial automation (either drivetrain or work tool automation), and full automation. Effect of different levels of automation will be evaluated with the HIL testbed.

Collaboration and Coordination

- University of Minnesota: Lead the overall project. Develop and validate full vehicle model for off-road vehicles including the fluid power system, build the HIL testbed, implement the co-optimization control and conduct energy savings evaluation using the HIL testbed.

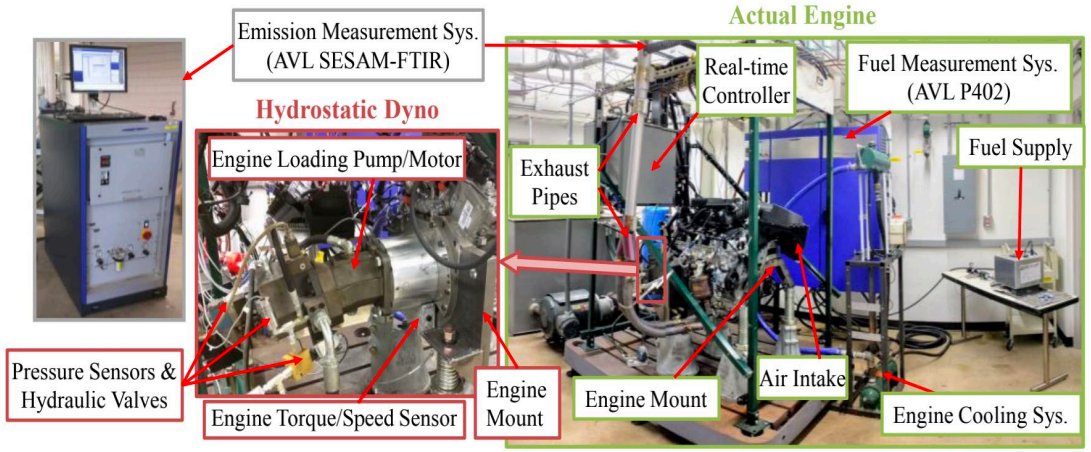
- Texas A&M University: Develop and validate the reduced order model, construct the worksite simulation, develop the co-optimization of vehicle dynamics and powertrain operation.

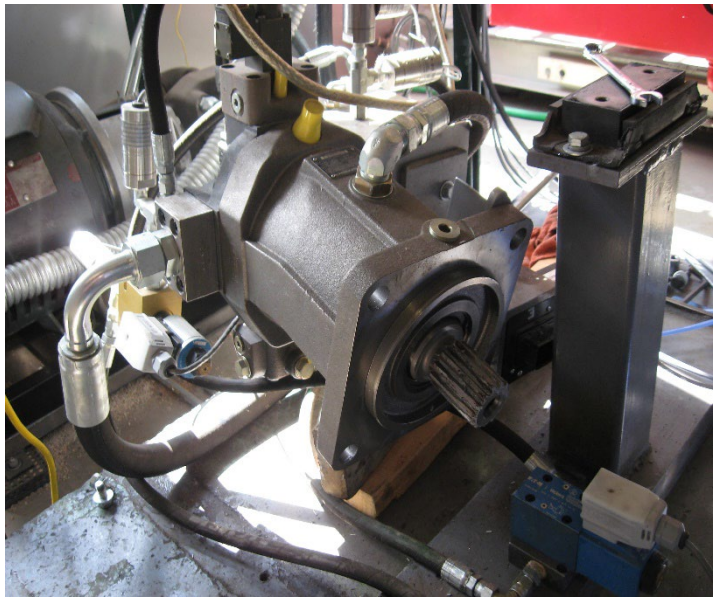
- CNH Industrial: define the representative off-road vehicle applications, coordinate actual vehicle testing at CNH, validate the off-road vehicle model and provide industrial feedback on the testing and optimization results.

To facilitate project coordination, we have weekly meetings for each university, bi-weekly meetings for two universities, and monthly meetings for the whole team.

Remaining Challenges and Barriers

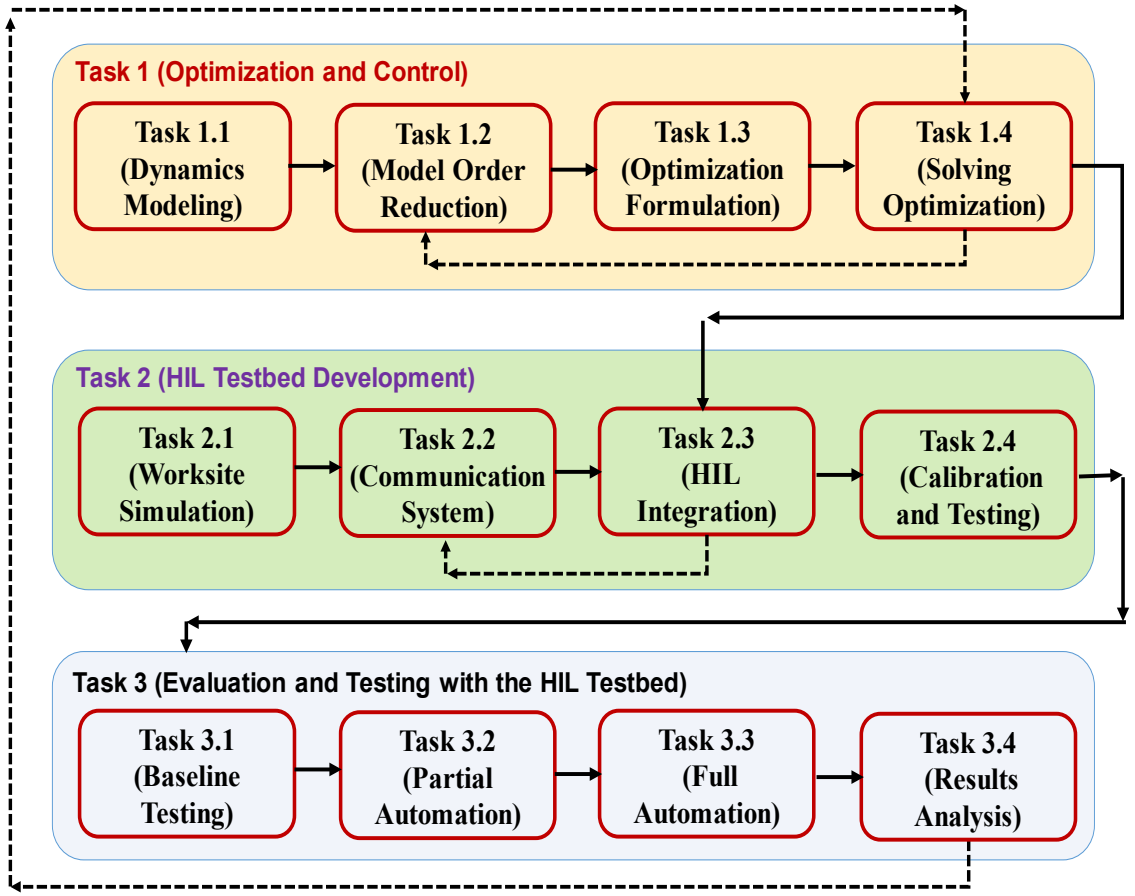
- Next step is to demonstrate the optimization and control on the HIL testbed.
- The validated system model will be integrated with the control system and the HIL testbed to evaluate the fuel benefits of the optimization.
- Currently we are in the process of installing a CNH 521 wheel loader engine for the HIL testbed.





Proposed Future Research

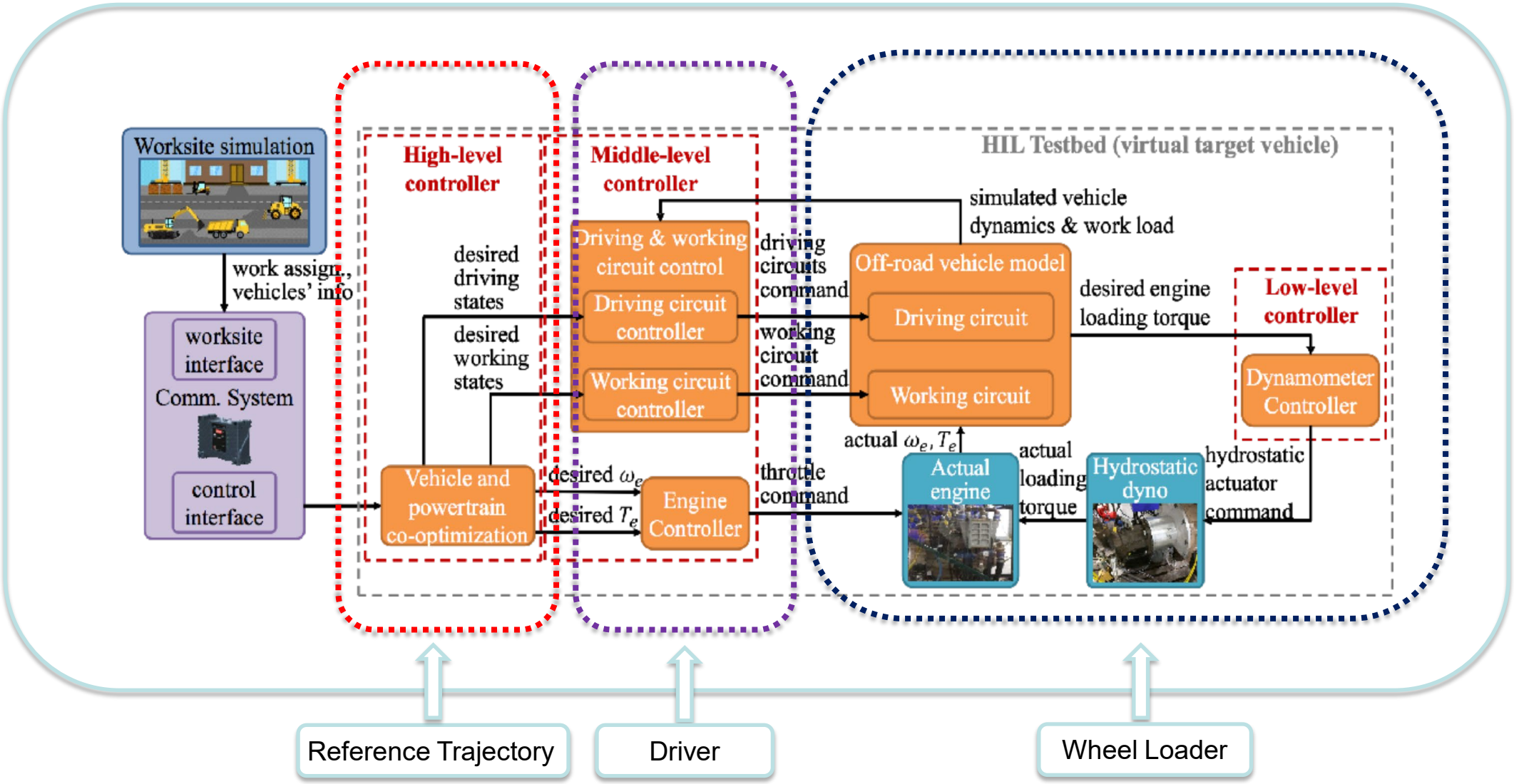
- Develop solution to the optimization including both analytical approach and numerical approach (Computation time < 80% of duty cycle; Efficiency gain > 20%) (6/2022)
- Integrate the system model, optimization and control, worksite simulation, and communication with the HIL testbed (9/2022)
- HIL testbed is well calibrated and real-time operational (Sampling time of 0.2 seconds; Discrepancy between measurements of HIL and actual wheel loader < 5%) (12/2022)
- HIL testbed baseline is documented (3/2023)
- Partial automation evaluation (6/2023)
- Full automation evaluation (9/2023)



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

Summary

- The objective of this project is to save energy and improve productivity for off-road vehicles through connectivity and automation.
- A wheel loader is selected as a representative example and will be evaluated using a hardware-in-the-loop testbed.
- A dynamic model for the wheel loader has been developed and validated with field data. Energy analysis based on the model reveals opportunities for fuel saving.
- Optimization has been formulated for both transport phase and digging phase. Significant energy benefits (more than 20%) have been obtained.
- Currently focusing on HIL testbed integration. Future work is to use the HIL testbed to evaluate the energy benefits of different levels of automation.

Technical Back-Up Slides

HIL Testbed Architecture