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

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University of Minnesota

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Project ID: ace160

2021 DOE Vehicle Technologies Office Annual Merit Review

Overview

Timeline

- Project Start: Sept. 2020
- Project end: Dec. 2023
- Percent complete: 20%

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

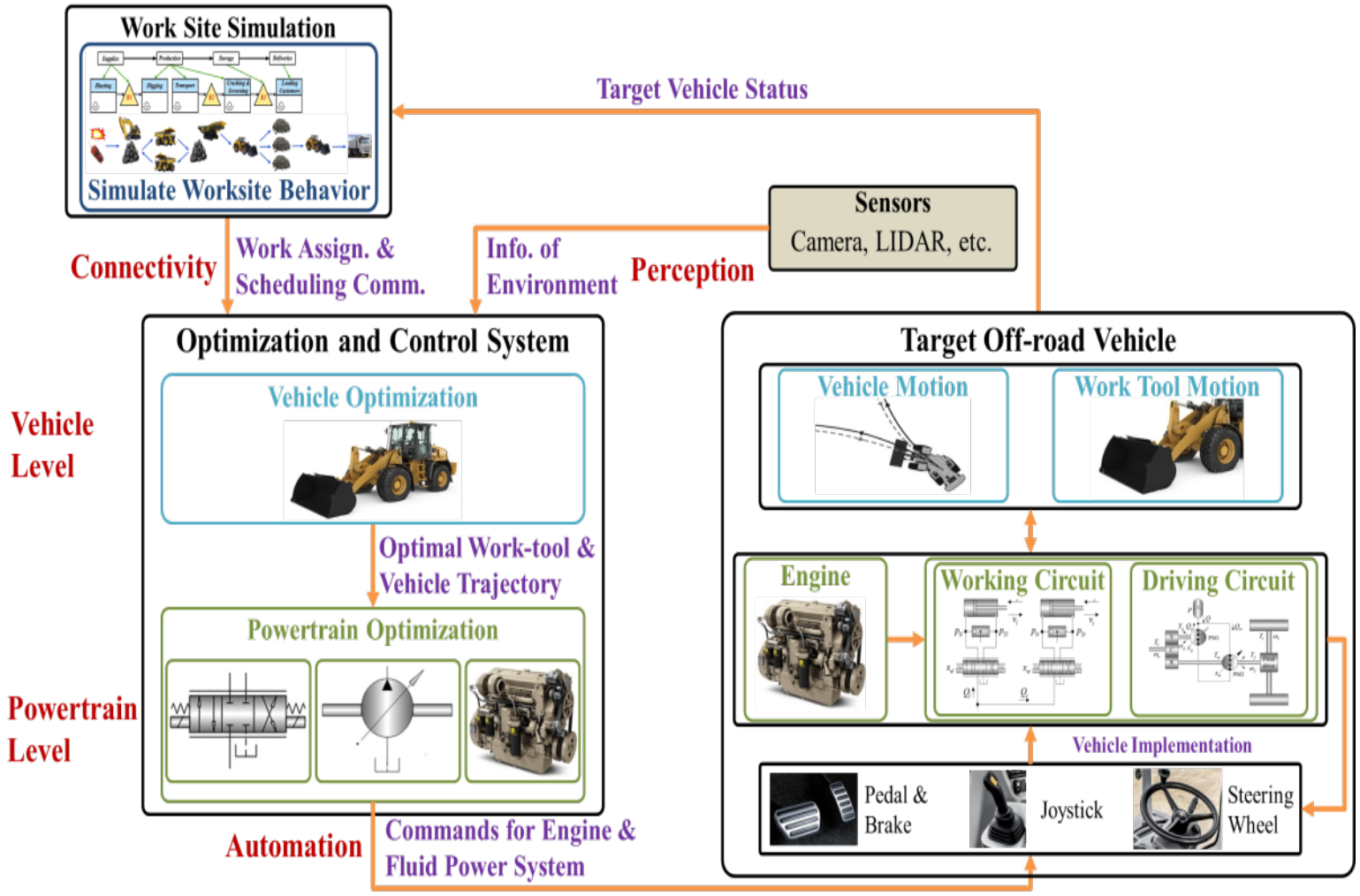
- University of Minnesota
- Texas A&M University
- CNH Industrial

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.

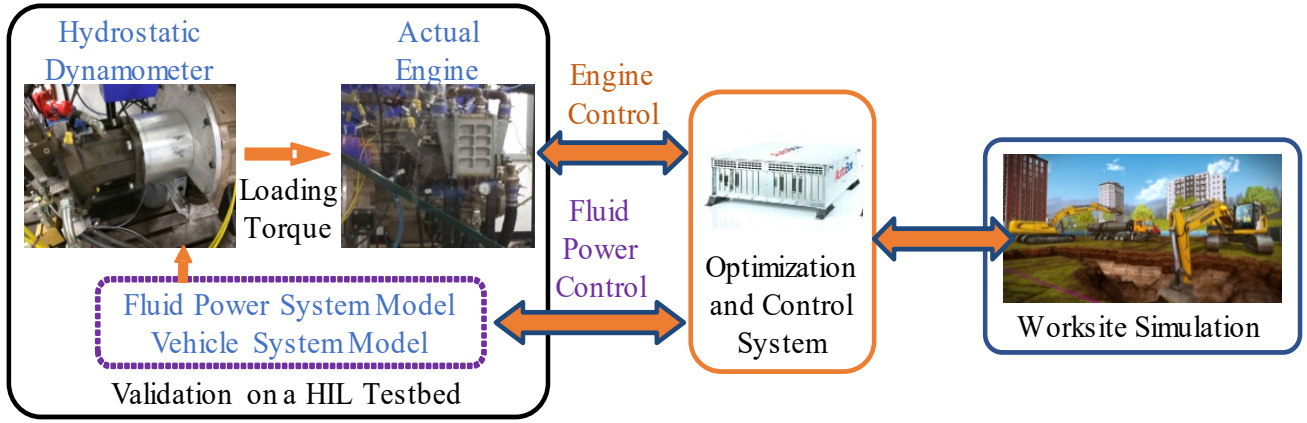


Milestones

Time	Description	Status
Dec. 2020	Off-road vehicle model is developed (Root Mean Square error < 5%)	Complete
March 2021	Model order is reduced (Order reduced by 30% or more)	Complete
June 2021	Worksite simulation is developed	On schedule
Sept. 2021	Optimization problem is formulated (Cost function and constraint equations available)	On schedule

Approach

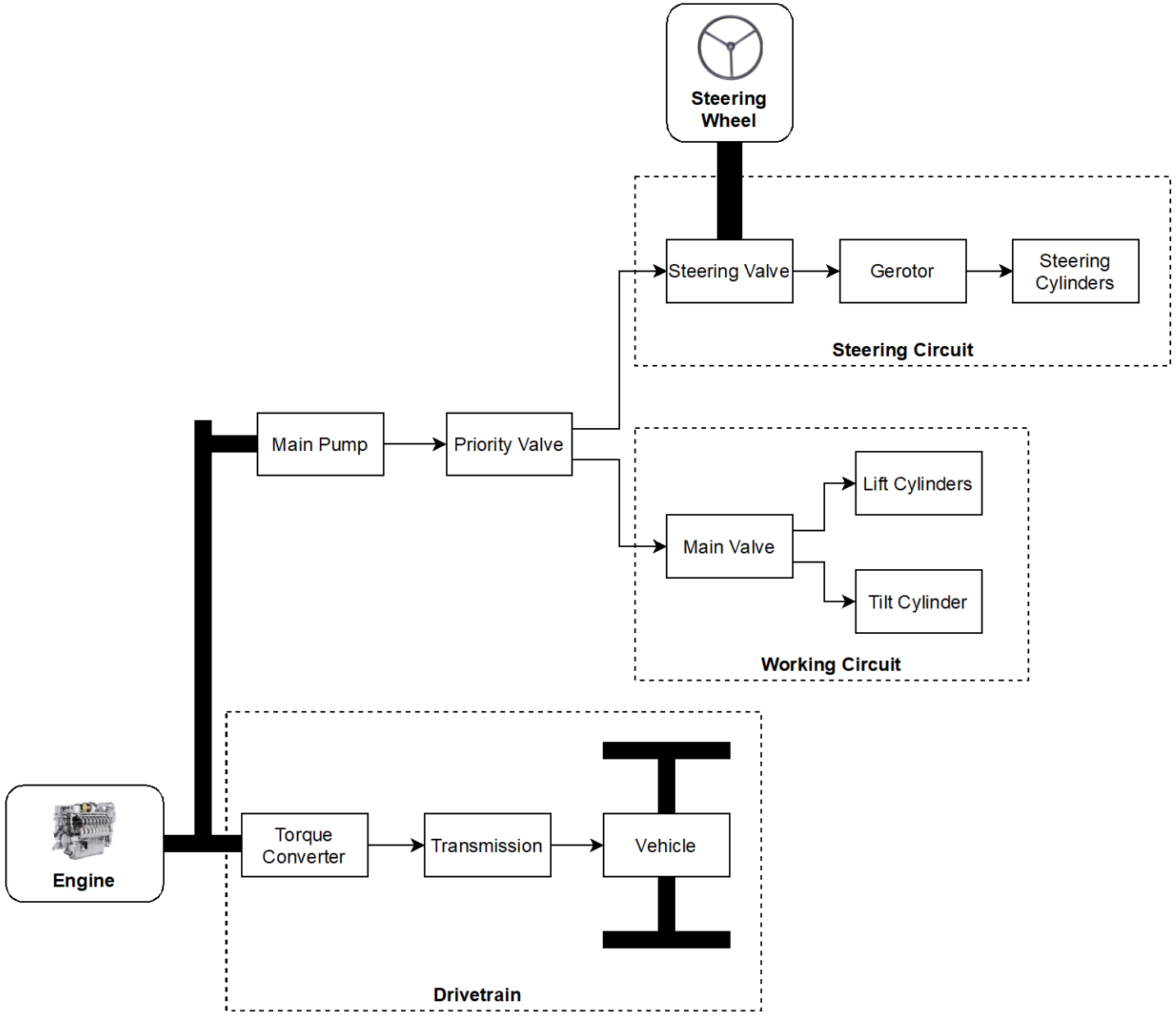
- **Optimization and Control of Off-road Vehicles:** The control system will perform co-optimization of vehicle speed and tool motion, fluid power system and the engine through automation. To formulate the model-based optimization problem, the target off-road vehicle model will be developed. Efficient 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.*



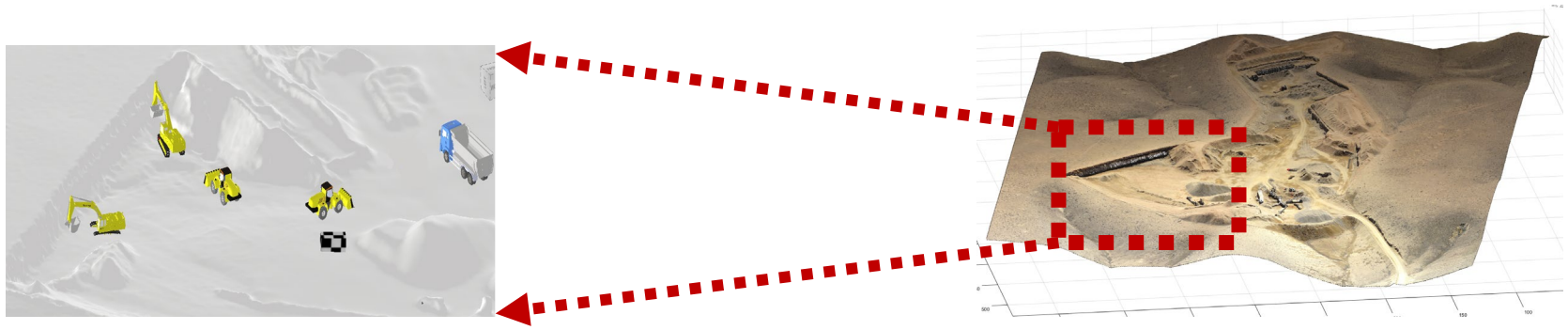
Technical Accomplishments (continued)

A reduced order model has been developed to facilitate the optimization and control system design.

- Steering circuit: order reduced from 9 to 6.
- Working circuit: order reduced from 8 to 6.
- Driveline: order reduced from 3 to 2.
- *Total order is reduced from 20 to 14, a 30% reduction*
- *Reduced order model matches the full order model within 1% error*

A worksite simulation is being constructed

- Construction of worksite simulation using MATLAB m-Script with Object Oriented Programming.
- Simulate operation of a fleet of autonomous off-road vehicles. Determine start/end location and time of working cycles.
- Outputs of worksite simulation are inputs to the vehicle level controller.



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.

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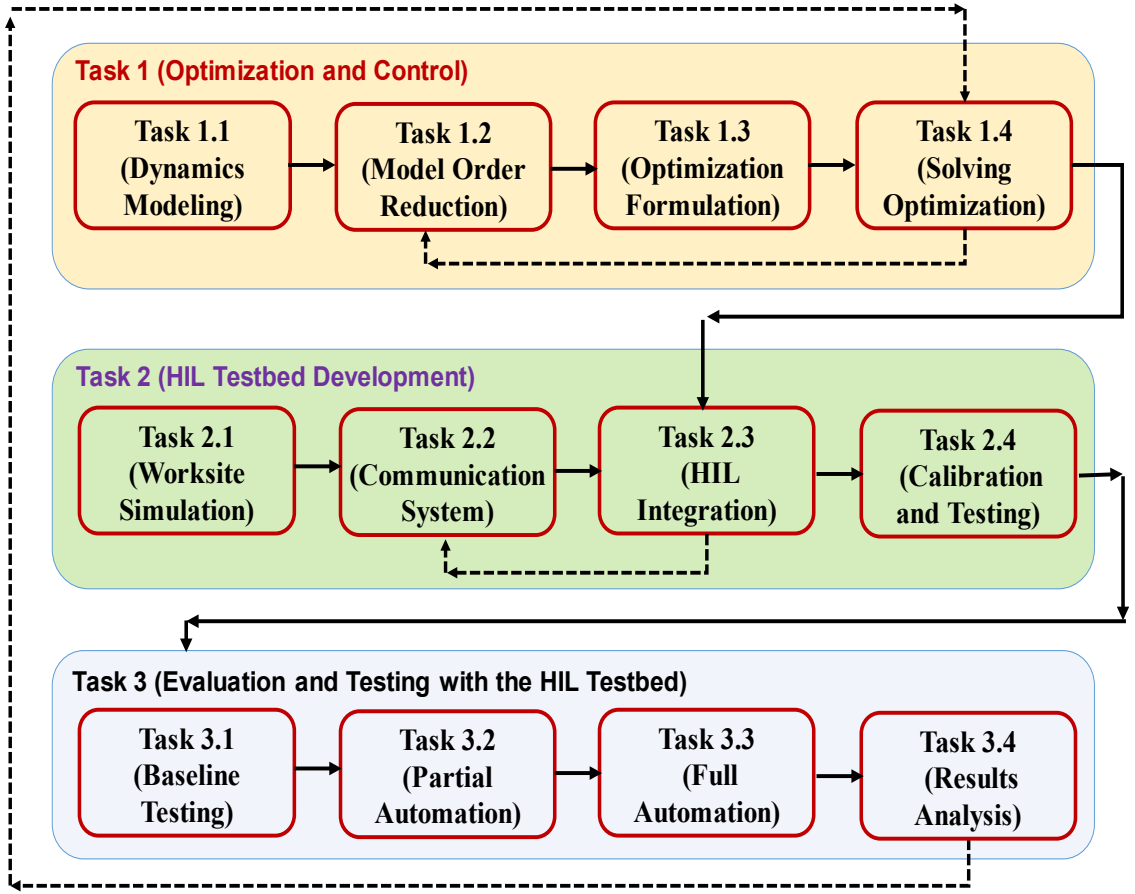
Proposed Future Research

- Formulate the optimization problem based on the developed model including cost function and constraints based on field operation (9/2021)
- Develop solution to the optimization including both analytical approach and numerical approach (Computation time < 80% of duty cycle; Efficiency gain > 20%) (6/2022)
- Finish the worksite simulation development (6/2021)
- Develop the communication system (Communication latency < 100 milliseconds with no missing data) (3/2022)
- Integrate the system model, optimization and control, worksite simulation, and communication with the HIL testbed (9/2022)



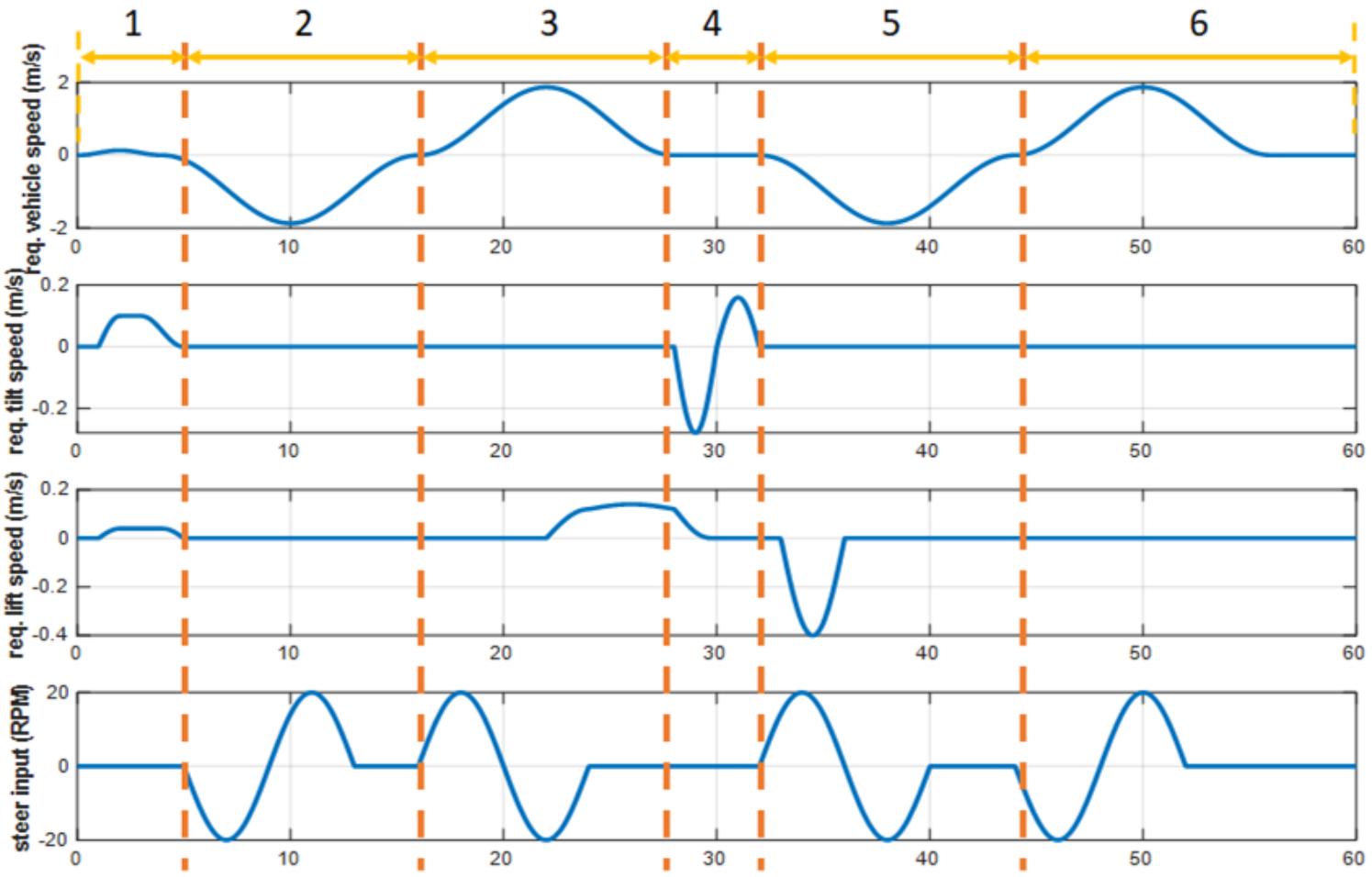
Any proposed future work is subject to change based on funding levels.

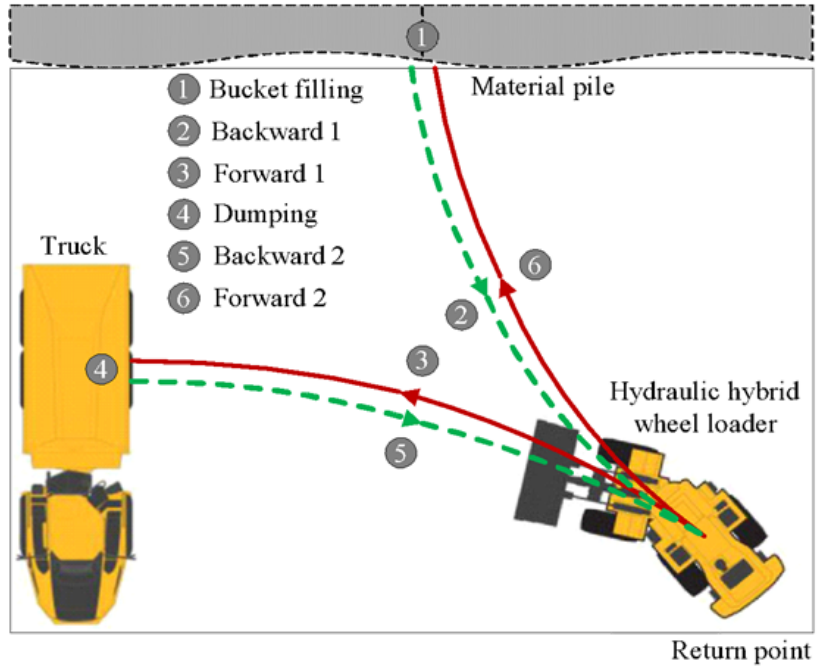
Summary

- 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.
- The first two quarters of the project are focused on system model development. The dynamics of the developed models have been validated with field data provided by CNH with high accuracy.
- The current focus is to formulate the optimization and control problem based on the developed model.

Technical Back-Up Slides

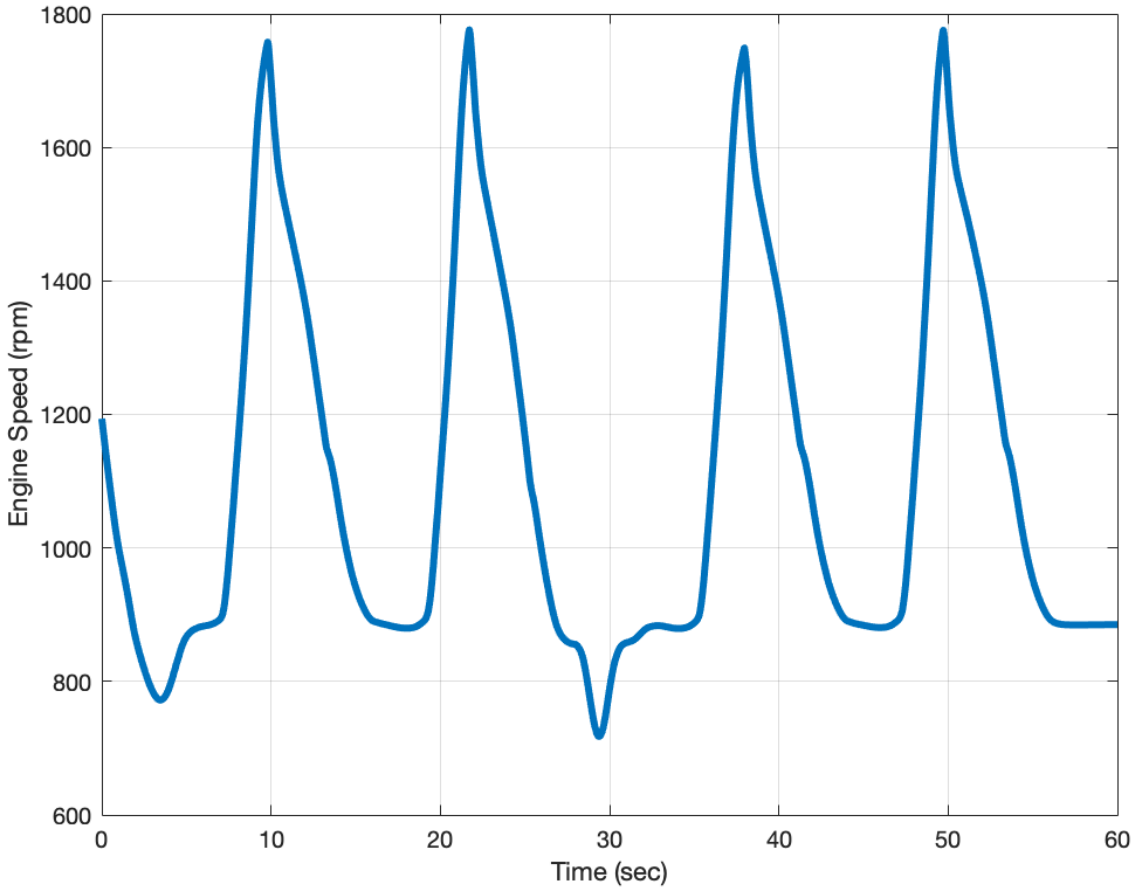
Overall System Simulation



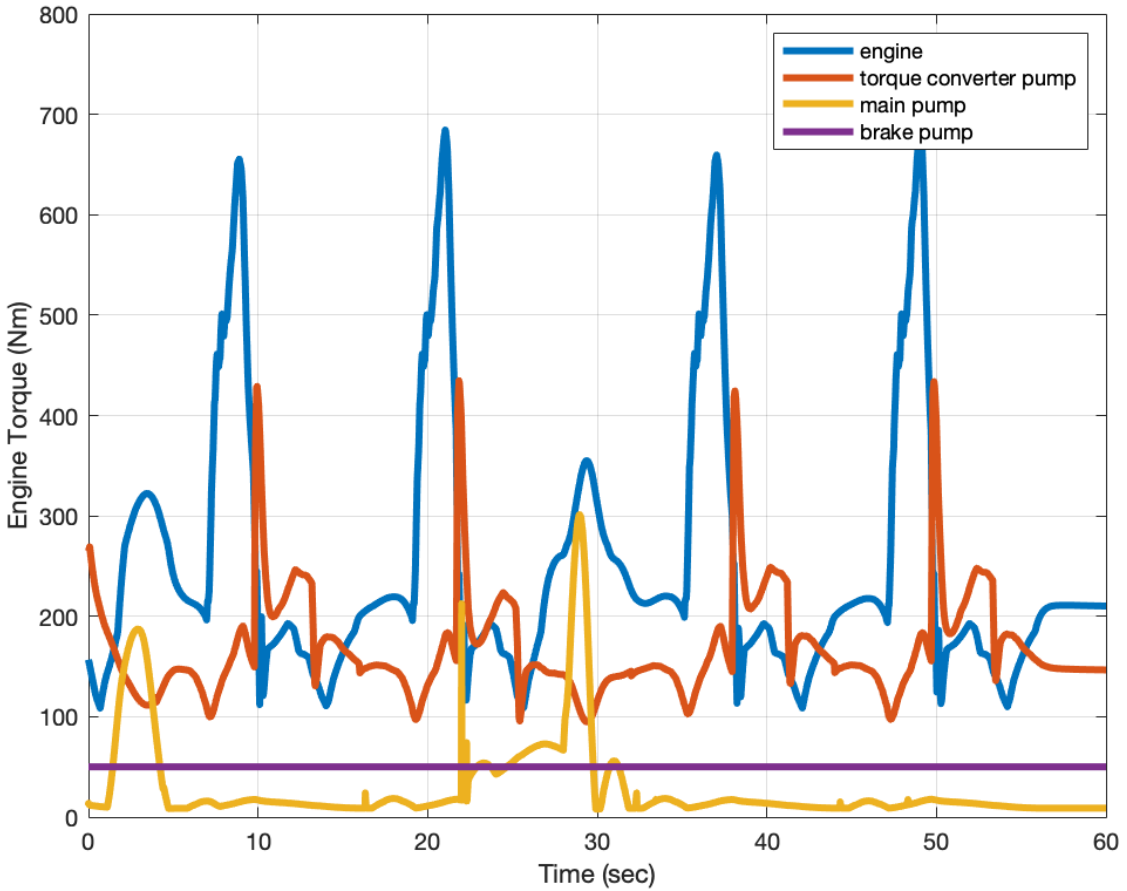


Short loading cycle

Engine

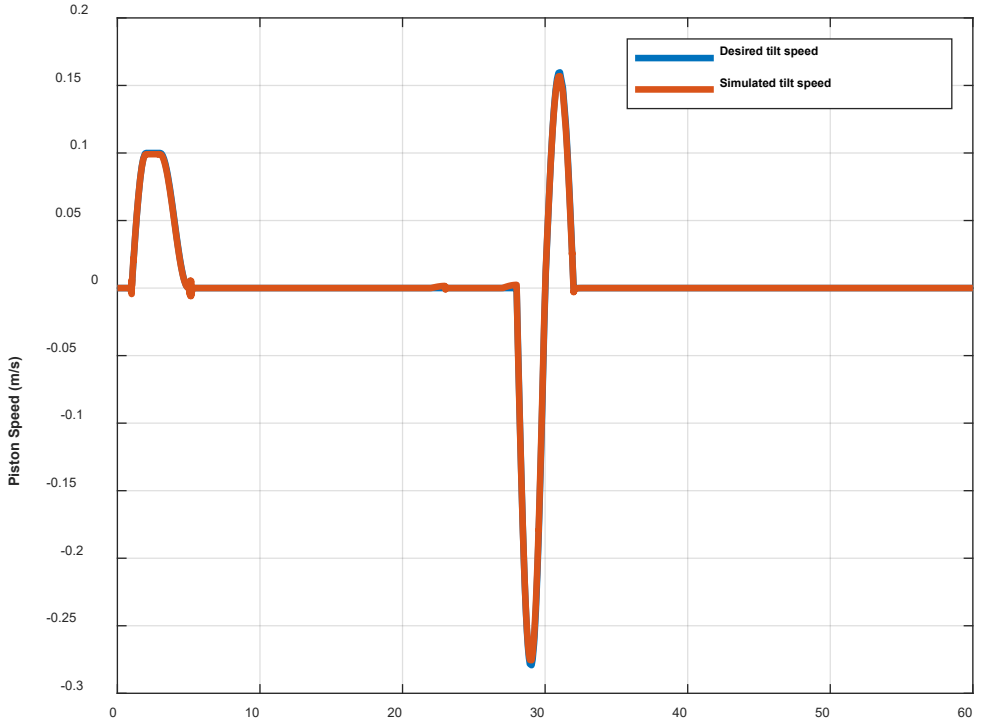


Engine speed

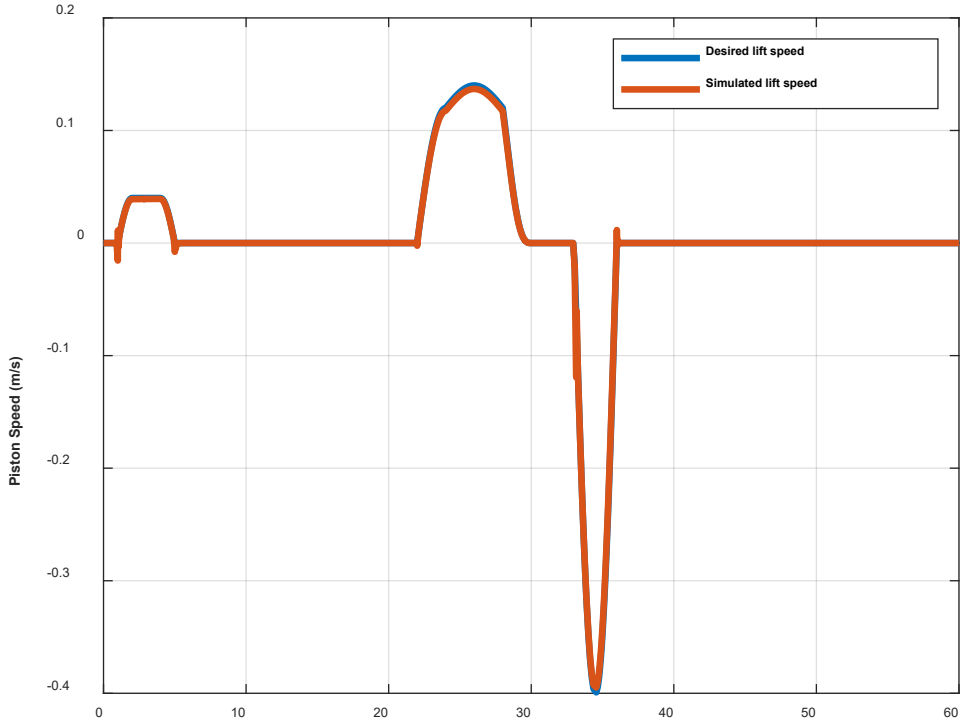


Engine and loading torques

Working circuit

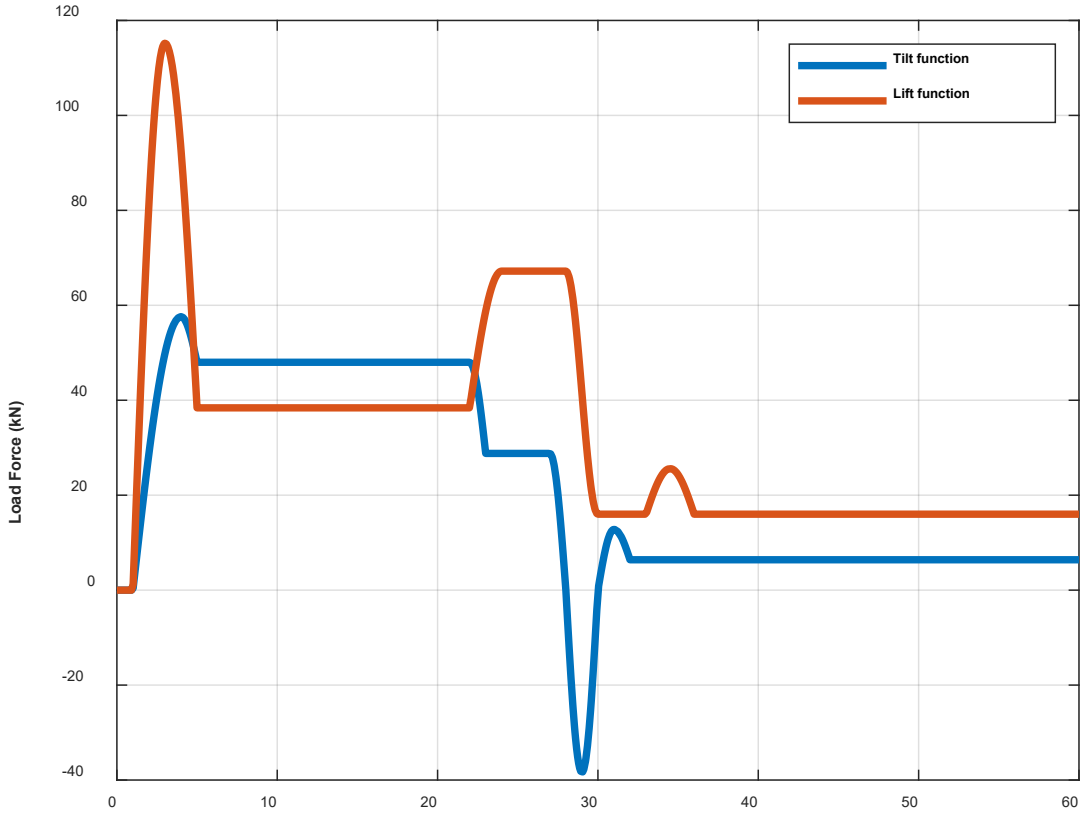


Tilt speed



Lift speed

Tilt and Lift force



Working circuit, tilt and lift load force