A New Approach for Increasing Efficiency of Agricultural Tractors and Implements

Project ID: **ace161**

2022 DOE Vehicle Technologies Office
Annual Merit Review

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Overview

Timeline

- Start date: October 2020
- End date: January 2024
- Percent complete (May 2022): 50%

Budget

- Total project funding: $3,125,773
  - DOE share: $2.5M
  - Contractor share: $625,773
- Funding for FY 2021: $1,051,586
  federal ($ 809,969)
- Funding for FY 2022: $1,018,224
  federal ($ 825,352)

Partners

- Purdue University – *project lead*
- Case New Holland Industrial (CNHi)
- Bosch Rexroth
- National Renewable Energy Laboratory (NREL)

Barriers and Technical Targets

Barriers

- Improving the efficiency of commercial agricultural vehicles can reduce fuel consumption and provide decreased operating costs for American farms.
- Many agricultural vehicles are reliant on fluid-power for their work and drive circuits due to their ability to supply high specific power density and tolerate harsh conditions. However, current fluid-power systems have poor efficiency.
- State of the art fluid power systems have excessive throttling losses.

Technical Targets

- increase (double) the energy efficiency of the overall hydraulic transmission system of tractors and their implements, by *reducing throttling loss*
- Achieve a payback period < 2 years

Relevance

- When an agricultural tractor is connected to a high-power demand implement (a planter, a bailer, etc.) the energy efficiency of the high-pressure system that powers the implement is as low as 20%!
- A re-design of the hydraulic control system leveraging cutting edge electro-hydraulic control technology can increase the above energy efficiency.
- Commercial success a new fluid power technology is ensured by meeting cost requirement, but also allow compatibility across tractors and implements of different brands and technologies.

Objectives

to develop and demonstrate a novel Multi Pressure Rail (MPR) concept for hydraulic control systems of agricultural tractors and their implements capable of:

- ✓ doubling the energy efficiency of the overall hydraulic transmission system of the tractor and implement
- ✓ reducing the energy consumption of the in-tractor fluid power (FP) functions by ≥15%
- ✓ achieve a payback period < 2 years
- ✓ preserve compatibility with state-of-the-art machines
- ✓ demonstrate the technology on a Cash Crop High tractor and a 16-row planter

Reduction of Energy Cost

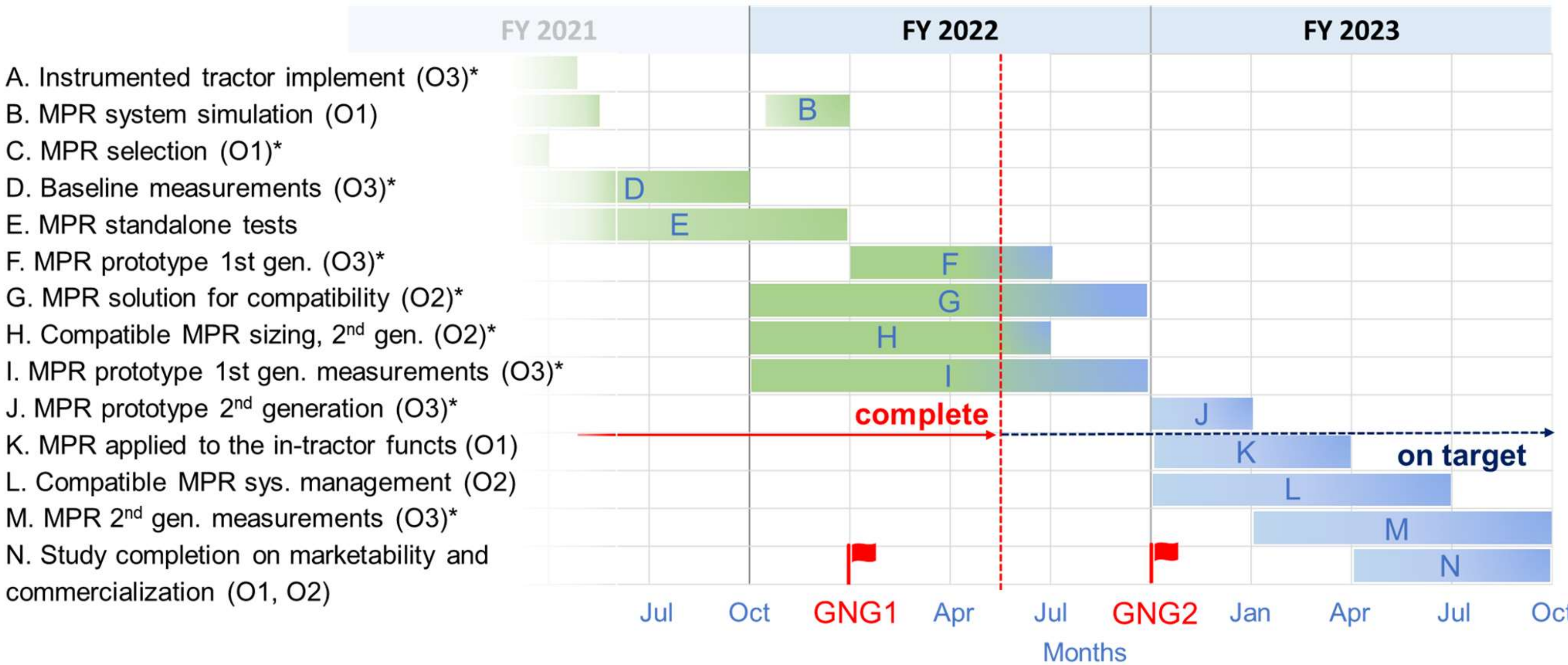
Cleaner Energy Technology

: focus of project activities in BP1, BP2

Milestones *(SMART Milestones denoted by *)*

Project activities occurs in three domains:

O1. MPR Configuration. To determine the configuration of the MPR system (optimizing energy efficiency)
O2. MPR Compatibility. To develop cost-effective methods for MPR machines compatible with traditional technology
O3. Technology Demonstration. To establish proof-of-concept MPR systems and demonstrate the energy efficiency advantage

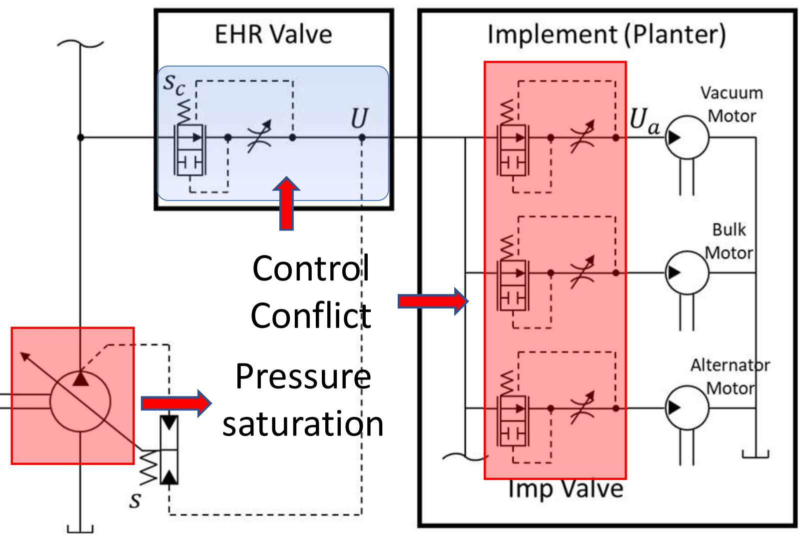


Go/No-Go (GNG) 1: The simulated MPR system delivers >60% higher efficiency than the baseline machine.*
GNG2: The measured MPR system overall energy efficiency MPR system >40% of the baseline configuration.*

Approach

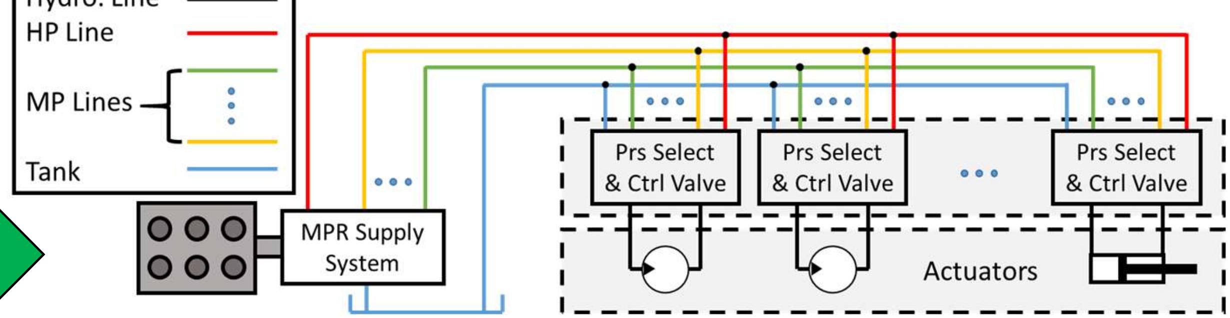
Basic Idea

Commercial solution



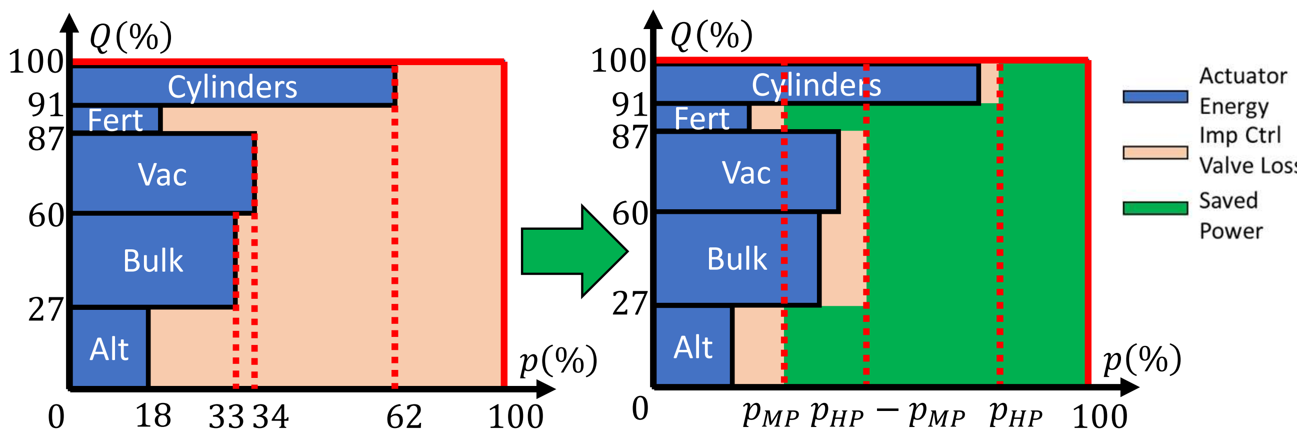
- valve redundancy
- conflict among flow control valves
- over-pressurization of supply flow

Proposed MPR system



conflict-free pressure control logic

From field test measurements on a tractor-planter, MPR can reduce power loss to allow double energy efficiency

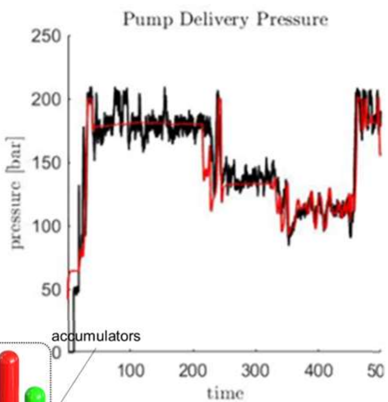


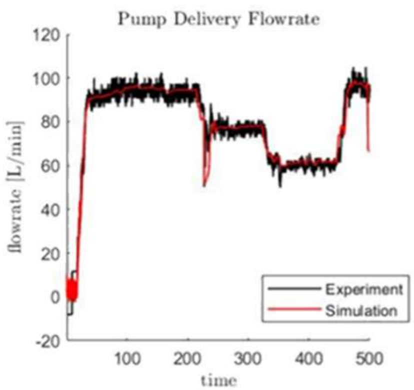
Previous work

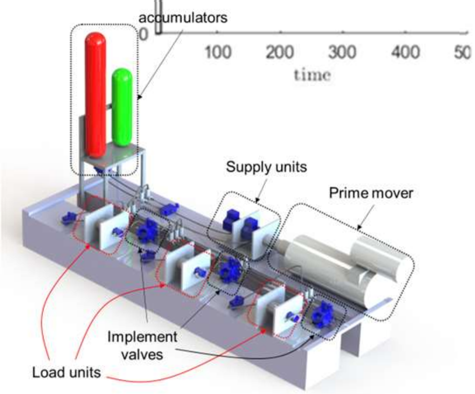
- **Reference vehicles (O3)**. Selected with inputs from Case New Holland. Instrumented at Purdue for power and efficiency measurements.
- **Baseline tests definition (O3)**. Definition of reference duty cycles (absence of standard to follow). These are indicated with “normal”, “low speed” and “high speed”. Stationary tests performed in lab conditions.

CNH T8.435 Tractor

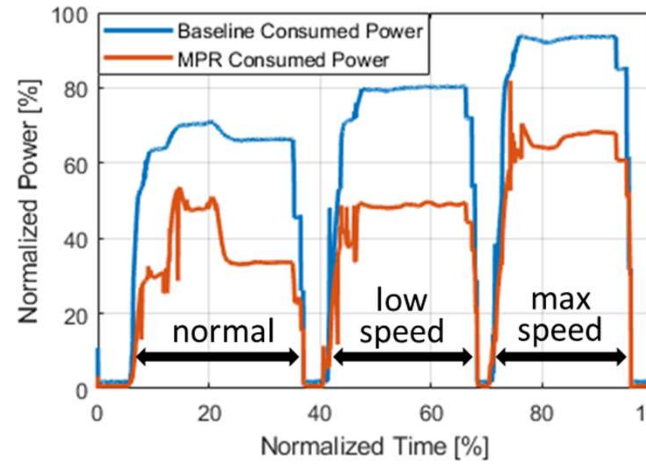
Case IH Early Riser 2150 Planter







- **Simulation model (O1)**. An Amesim model was formulated and validated against the stationary tests. The model allows for detailed analyses of energy flows and system efficiency
- **MPR design (O1)**. A MPR system with 3 pressure rail was identified as best compromise between energy efficiency and cost. The simulated power consumption of the MPR system is close to 50% of the baseline solution



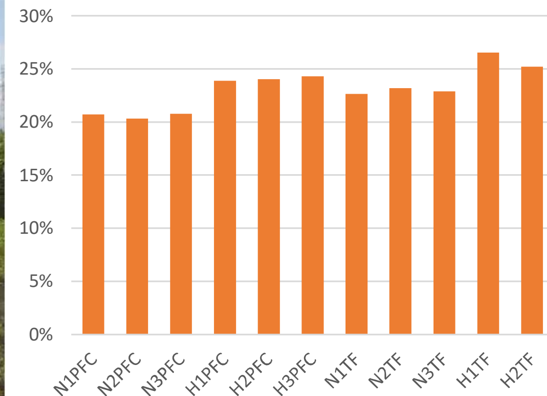
- **Stand alone test rig design (O3).** Preliminary design of a test rig to be implemented at Purdue to test MPR components and control strategies

Technical Accomplishments

Field tests (O3)

- Test performed at a Purdue Farm (Purdue Animal Science Research Center - ASREC) on instrumented reference vehicles

- Test plan based on two planter working conditions (N/H), three engine speeds (1/2/3), two tractor remote circuits (PFC/TF)



Overall system efficiency from field tests

Efficiency of hydraulic system downstream the pump (PFC)

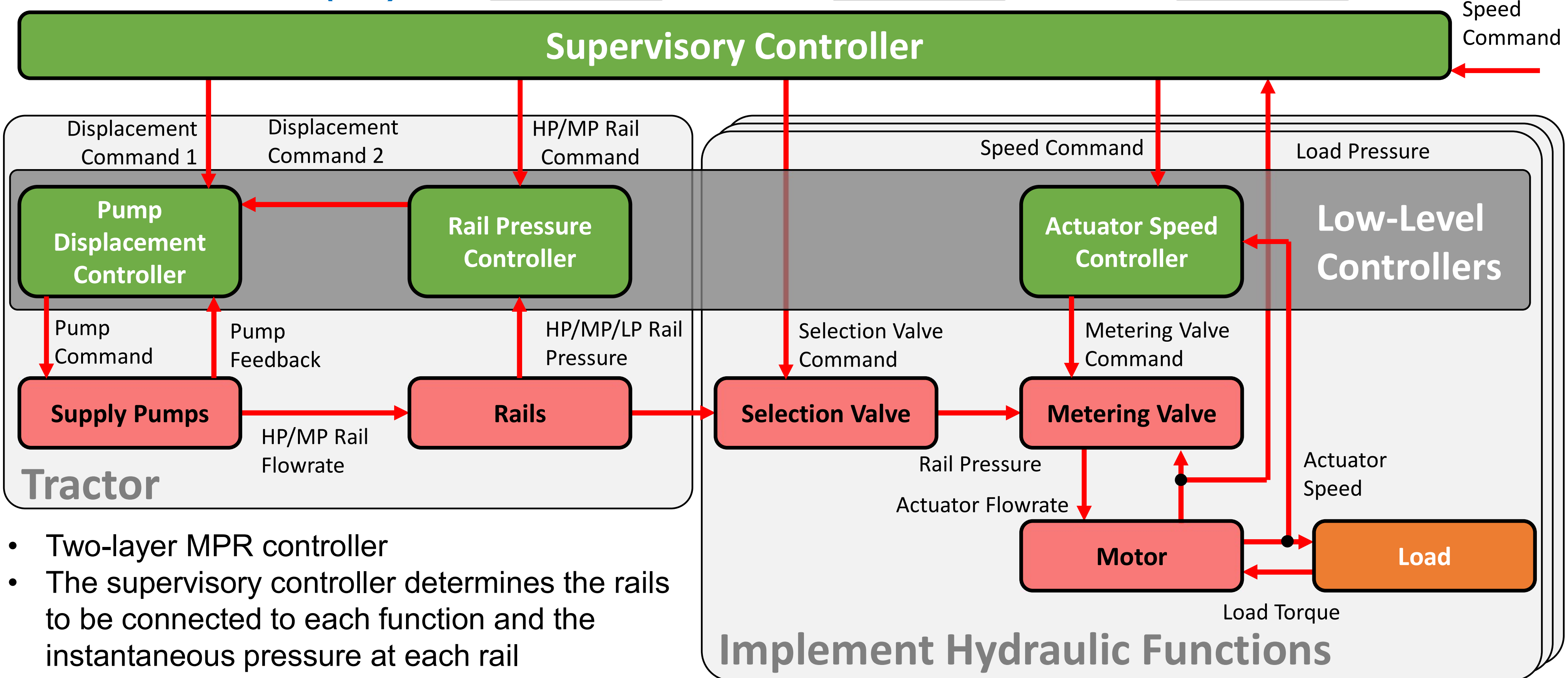
Sys. Eff.	Normal	High Spd.
T1 PFC	20.6%	24.1%
T1 TF	22.9%	25.9%
Overall	23.0%	

- Field tests permitted:
  - ✓ additional model validation
  - ✓ to characterize the power flow within the hydraulic system and identify the main source of power loss

Technical Accomplishments

MPR Controller (O1)

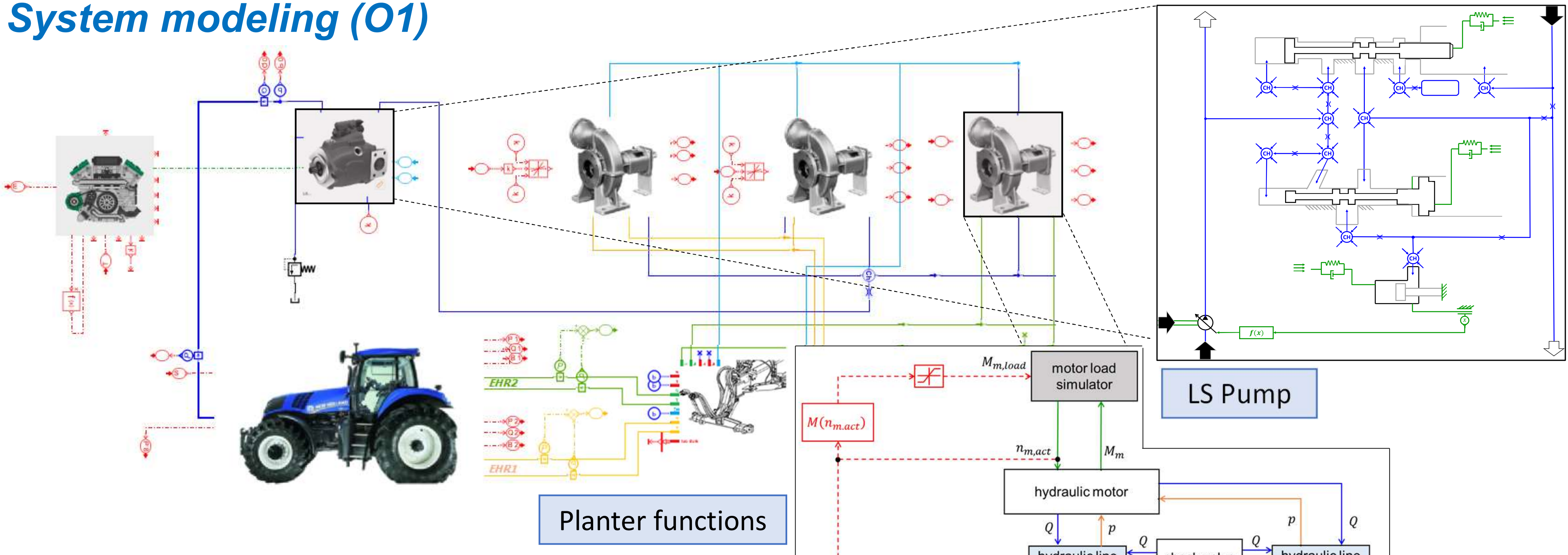
Controller | Hydraulic | Mechanical

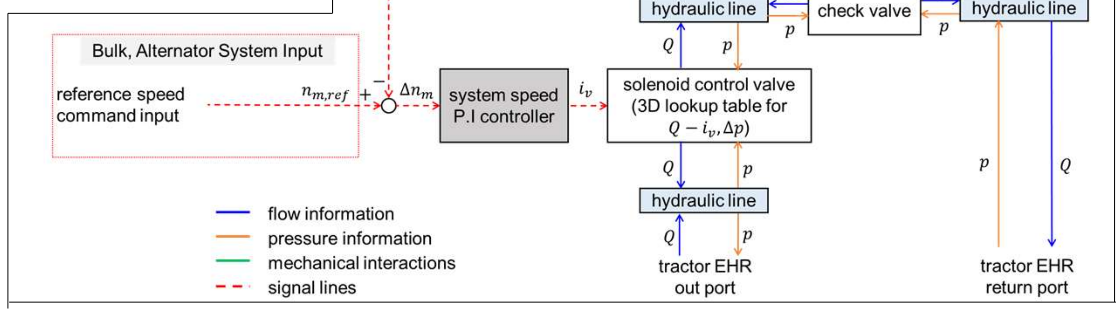


- Two-layer MPR controller
- The supervisory controller determines the rails to be connected to each function and the instantaneous pressure at each rail
- The low-level controllers acts on the pumps and on the actuator to meet the velocity commands

Technical Accomplishments

System modeling (O1)





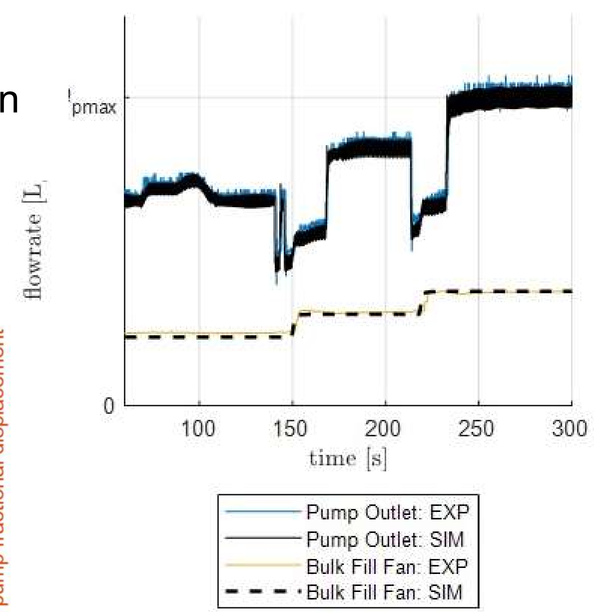
- A detailed lumped parameter model has been developed for the complete reference tractor – implement hydraulic control system, inclusive of the prime mover (engine)

Technical Accomplishments

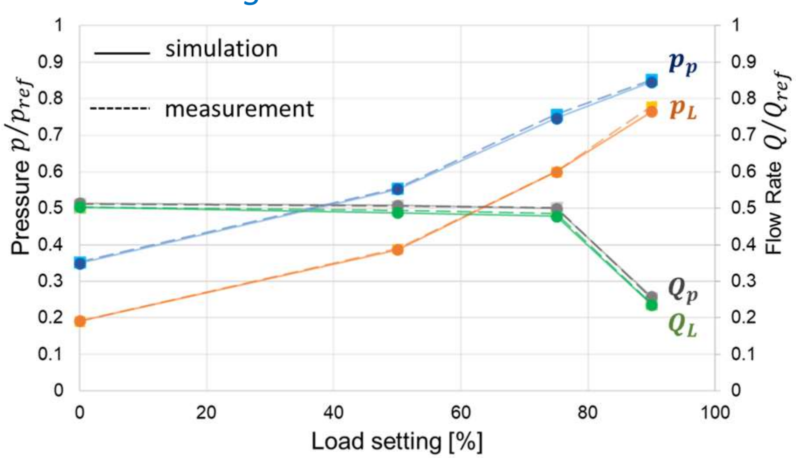
Model validation (O1)

- The simulation model was validated from tests performed on the tractor, as stand alone (tests on hydraulic remotes), as well as on tests on the complete tractor-planter system
- The model achieves good matching with respect to experimental results (always > 95% accuracy) in both steady state as well as dynamic conditions (such as pump transients)
- The model can be considered accurate enough to be used for advances studies on the energy efficiency and control design on the MPR system

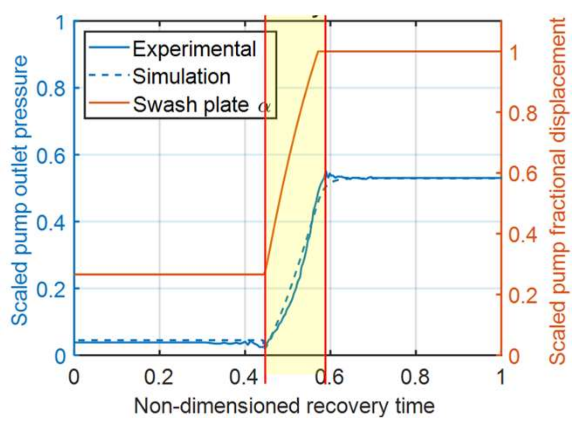
Flow on hydraulic remote during planter operation



Single Remote Tractor Test

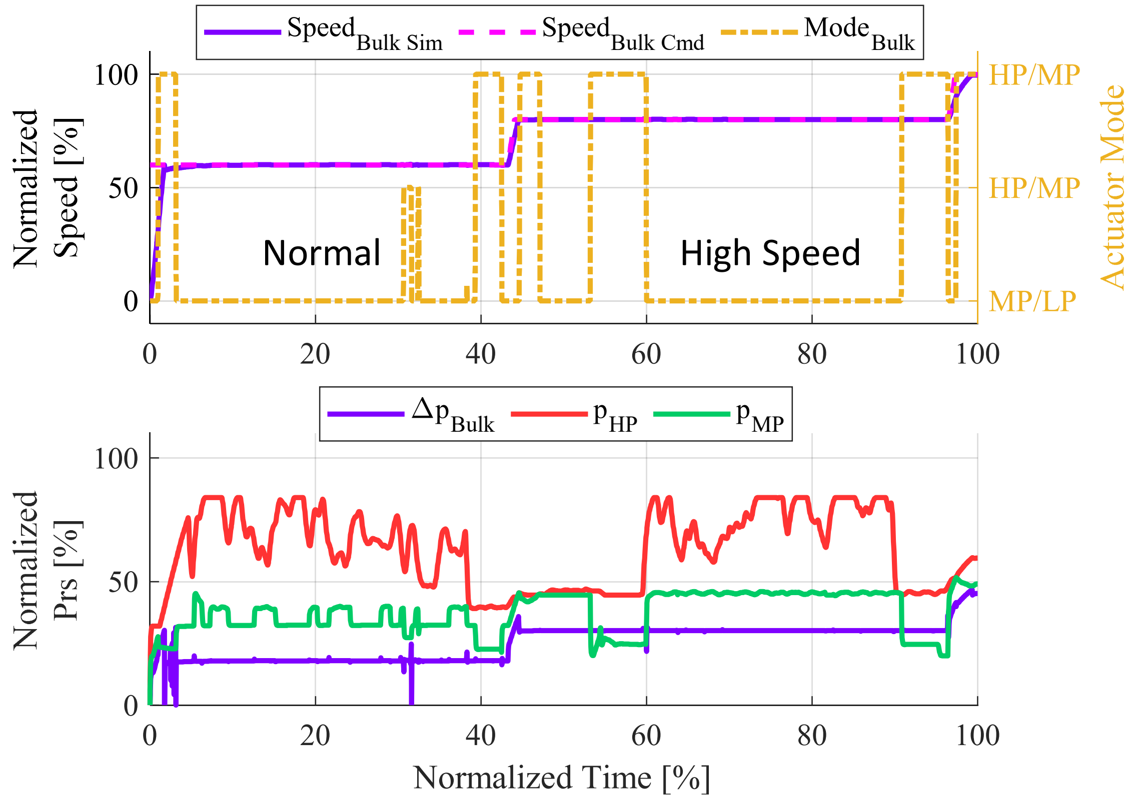


Pump Dynamic Response



Technical Accomplishments

MPR predicted performance (O1)



MPR simulation – example of one function (bulk motor) in realistic drive cycle conditions

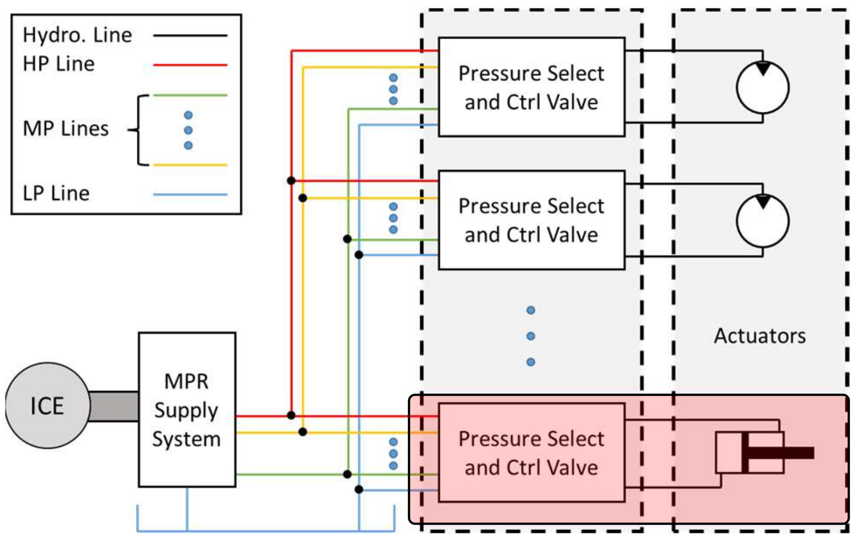
- Drive cycles collected from experiments were input to the simulation model for testing the MPR performance, considering all hydraulic functions
- Despite the high dynamic requirements of the downforce cylinder in the planter, the proposed controller achieves good command tracking, replicating the same dynamic performance of the commercial baseline solution
- The supervisory controller engages all possible operating modes for the hydraulic functions (i.e. possible combinations of connections with pressure rails) and varies the rail pressure to minimize the power loss

Technical Accomplishments

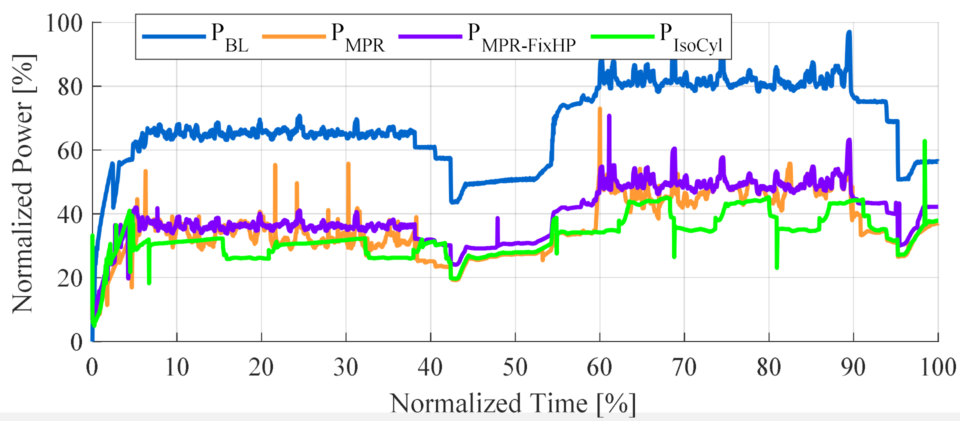
MPR predicted performance (O1)

- Different architectures for the hydraulic system and the controller were explored for the MPR, involving the control of the instantaneous rail pressure, as well as a method for separating the downforce cylinder system.

	Baseline		MPR		MPR FixHP		MPR IsoCyl	
	Normal	High-Speed	Normal	High-Speed	Normal	High-Speed	Normal	High-Speed
Total Power [%]	65.41	81.89	34.46	47.26	36.43	49.78	29.83	39.15
Reduction [%]	-	-	**47.32**	**42.28**	**44.30**	**39.22**	**54.40**	**52.19**
Efficiency [%]	20.19	27.89	38.33	48.33	36.25	45.88	44.28	58.34
Efficiency Gain [%]	-	-	**89.85**	**73.29**	**79.54**	**64.50**	**119.32**	**109.18**



Instantaneous power consumptions during a drive cycle

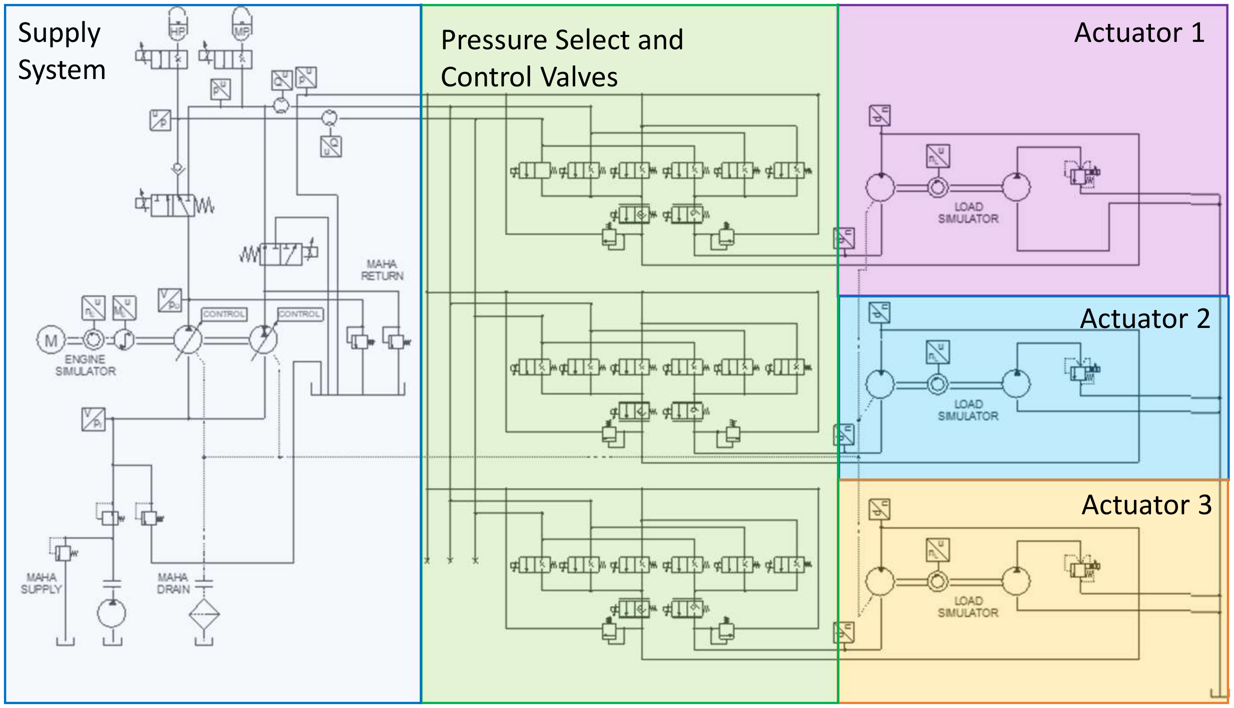


up to **54.40% reduction** in power consumption
up to **119.32% relative increase** in system efficiency ⇐ **GNG1**

Technical Accomplishments

MPR stand alone test rig (O3)

- A standalone flexible test rig was implemented at Purdue with novel Bosch Rexroth technology specifically designed for MPR
- Experiments needed to validate dynamic performance of the proposed control scheme particularly during mode switching logic



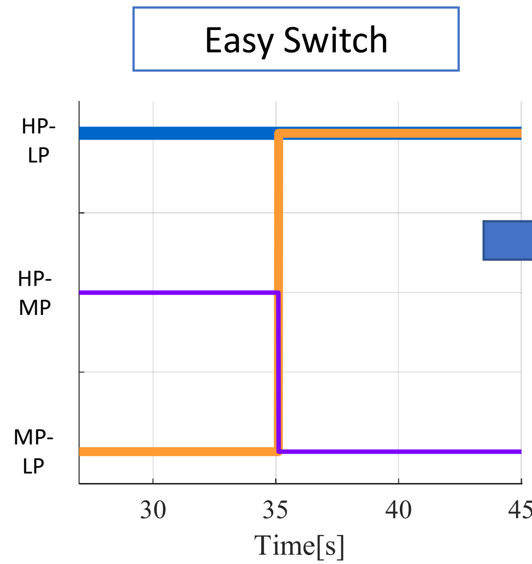
Hydraulic schematic and picture of the stand-alone test rig for MPR system implemented at the Maha Fluid Power Research Center of Purdue

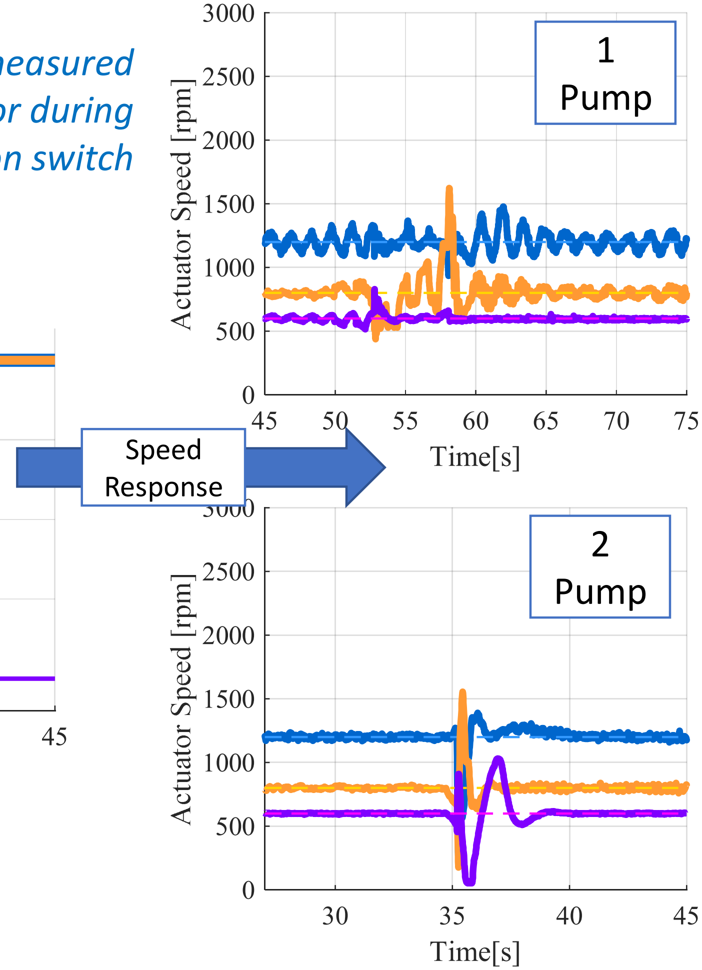
Technical Accomplishments

MPR stand alone test rig (O3)

- Controller optimized to achieve best behavior during the switch of one function between different rails
- The two-pump architecture for the MPR was found as more capable to handle transients, thus selected for the tractor implementation

Example of measured dynamic behavior during MPR configuration switch





Technical Accomplishments

MPR stand alone test rig (O3)

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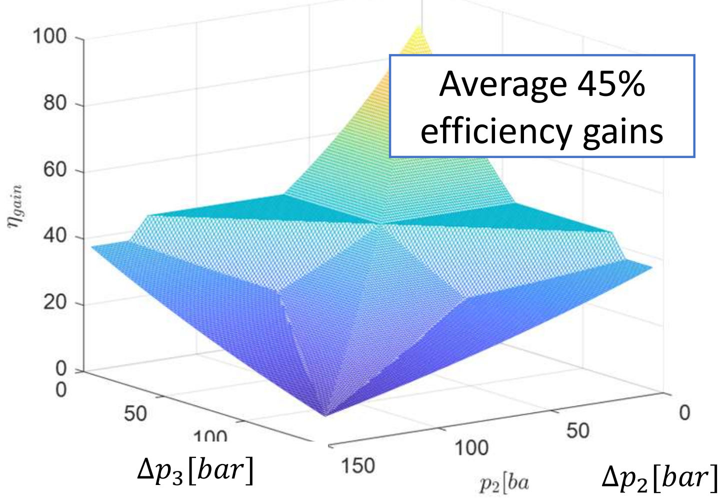
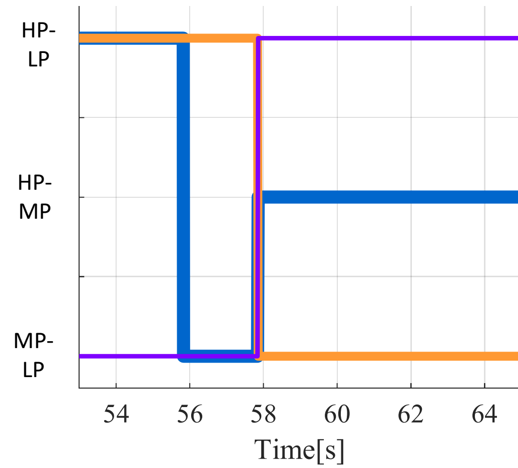
Example of measured dynamic behavior during MPR configuration switch

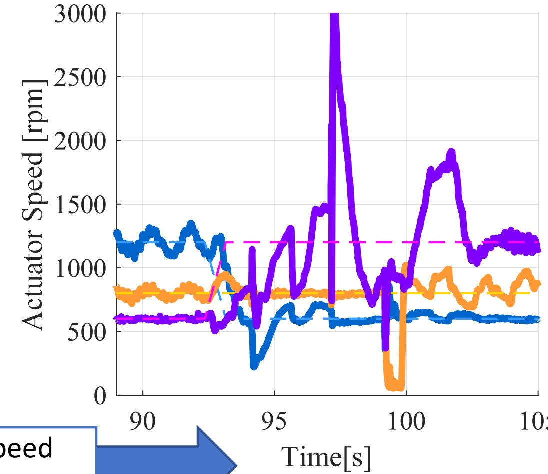
- The test rig allowed quantifying energy savings of MPR over state of the art hydraulic flow control technology



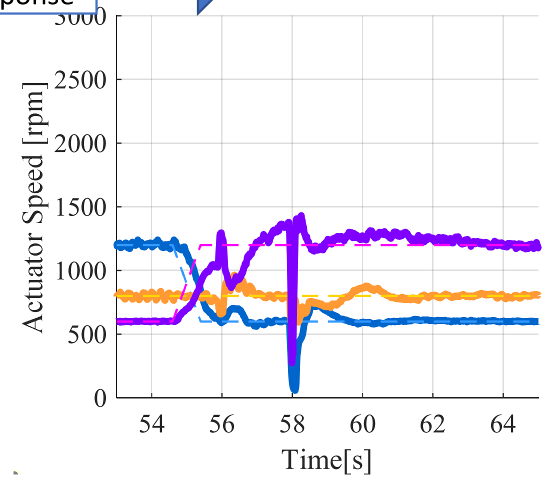
Hard Mode Switch



2 pump handles difficult switches better than 1 pump



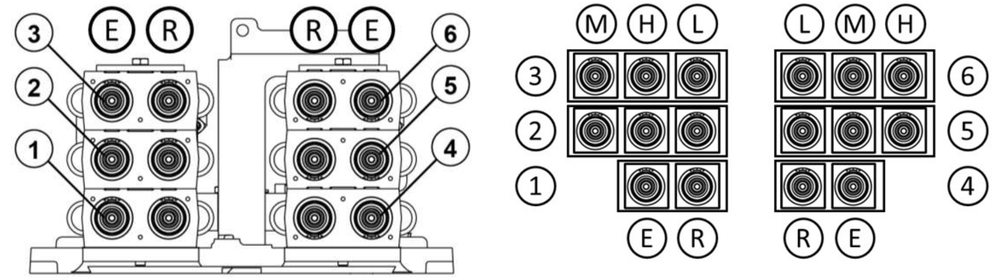
Speed Response



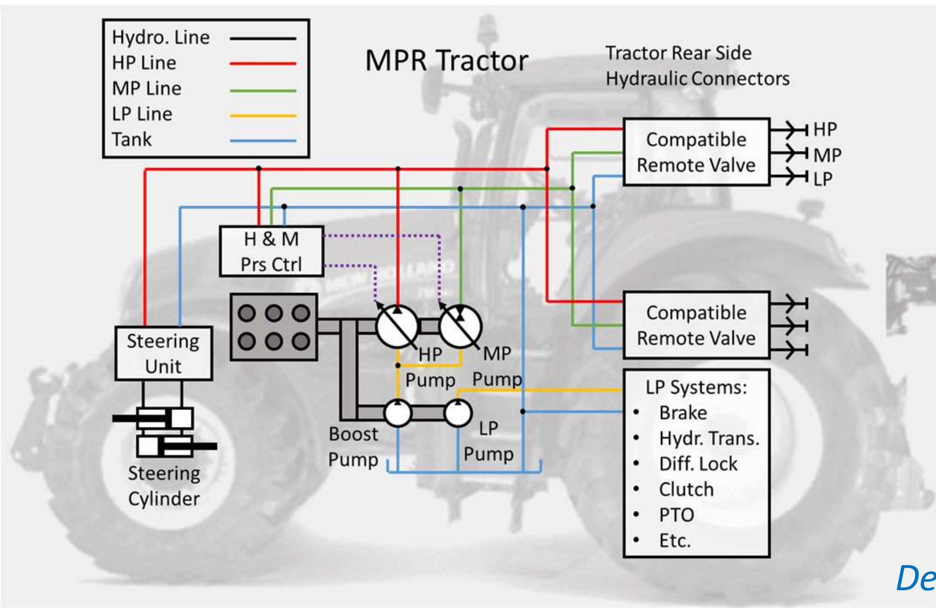
Technical Accomplishments

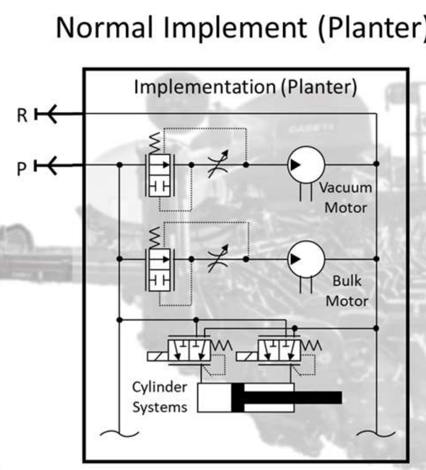
MPR compatibility (O2)

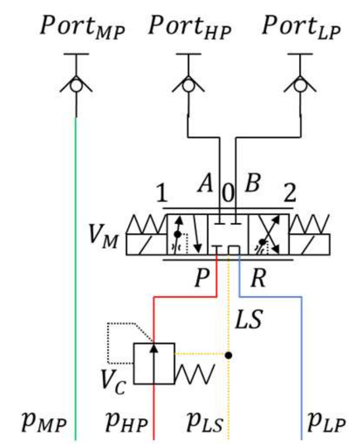
- The project analyzed possible scenarios for connecting a non-MPR tractor with a MPR implement (and viceversa)
- Minor modifications on the hydraulic schematic of the MPR systems are required on both the MPR tractor and MPR implement to allow compatibility
- Most effort to allow compatibility is on the system controller, and not on hardware modification



Expected view of the compatible MPR tractor remote connections (right) compared to current technology (left)







Example of connection of MPR tractor with non-MPR implement

Design of the compatible remote valve based on traditional technology

Collaboration

Collaborators	Relationship	Extent of the collaboration
PURDUE UNIVERSITY *PI: Andrea Vacca*	**Prime** University Outside VTO	• Purdue leads the activities related to the MPR design, for both the compatible and non-compatible implementation. All the simulation and the testing activities on the tractor, the implement and the stationary test rig are performed at Purdue
CNH INDUSTRIAL *Gary Kassen*	Sub Industry Outside VTO	• CNHi supports the simulation, testing, and physical modifications of both the tractor and the implement systems to build working prototypes. Finally, CNH provides expert operators and guidance to identify the representative drive cycles for the reference vehicles
rexroth A Bosch Company *Enrique Busquets*	Sub Industry Outside VTO	• Bosch Rexroth leads activities related to the fabrication of the EH components for the MPR system. Rexroth helps in the implementation of the stand-alone test rigs and the vehicle prototypes, and in the design of the most suitable sensors and control strategies
NREL Transforming ENERGY *Chen Zhang*	Sub National Lab Outside VTO	• NREL participates in the experimental activities involving the reference vehicles. NREL derives control strategies for the proposed MPR technology through machine-learning methods to enable optimal energy savings for various tractor-implement configurations. NREL will also participate in cost analysis tasks

Proposed Future Research

	Remaining Challenges	Future Work
FY2022	• Measurements on reference MPR tractor-implement and comparisons against conventional technology	1. Vehicle modification (1st prototype - 70% completed) 2. Execute field tests according to test plan defined in BP1
FY2022	• Finalize compatible MPR configuration	1. Simulation of a MPR vehicle connected to a non-MPR one, evaluation of control aspects and energy efficiency
FY2022	• Control at saturation conditions (insufficient flow)	1. Control Design 2. Tests on stand-alone test rig
FY2022	• Market analysis	1. Marketability of MPR solutions
FY2023	• Implement and test the MPR compatible configuration found in BP2	1. 2nd tractor-implement prototype preparation 2. Field Tests according to test plan defined in BP1
FY2023	• Extension of MPR technology to the in-tractor functions (such as steering, suspensions, etc.)	1. Model extension to in-tractor functions 2. MPR vs std technology comparison (simulation)
FY2023	• Applicability of MPR technology to other implements	1. Application of data driven control strategy in simulation and in test conditions

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

Resources

Collaborators	Resources
PURDUE UNIVERSITY *PI: Andrea Vacca*	• The main project activities occur at the Purdue's Maha Fluid Power Research Center, which is the largest academic lab dedicated to fluid power research in the country. Besides lab facilities (test rigs and equipment to modify off road vehicles), access to Purdue owned Farms is provided for the field tests. Four Purdue PhD students are fully dedicated to this project, under the supervision of the project PI
CNH INDUSTRIAL *Gary Kassen*	• CNH contributes to the project through personnel in its main research facility at Burr Ridge. Following CNH teams are involved to the project activities: Advanced Technology & Innovation, Hydr. Components, Adv. Systems & Hydrostatic Drives, Simulations & Controls. CNH also provided the reference vehicles for the technology demonstration and expert operators to assist on the field tests
rexroth A Bosch Company *Enrique Busquets*	• Bosch Rexroth participates to the project with two engineers supervised by Dr. Busquets from the Mobile Hydraulic Group (Fountain Inn, SC). The team has access to all company global resources and has had capability to contributed to the project with specially designed components (such as the new EO pumps)
NREL Transforming ENERGY *Chen Zhang*	• NREL holds reputation as leader in conducting fleet field studies and identifying the applicability of low TRL energy saving technologies. One research engineer from the NREL's Center for Integrated Mobility Sciences is fully dedicated to this project

Summary

Accomplishments

- Baseline field tests designed by the Team were performed on the tractor-implement system fully instrumented in FY21
- Stand alone test rig for testing MPR technology completed
- Field tests and stand-alone tests allowed validating the simulation model used for MPR technology development
- Energy efficiency of the std tractor-implement technology found to be about 20% in most drive cycles
- The MPR control architecture first formulated in FY21 where improved to enable optimal energy efficiency while ensuring proper dynamic performance
- Different MPR architectures studied, all meeting the GNG1 goal, the most promising one double energy efficiency
- Solutions to ensure MPR compatibility proposed in FY22

Technical Highlights

- The proposed MPR technology is confirmed to doubles the energy efficiency of the overall tractor-implement hydraulic system
- Definition of drive cycles for testing the fluid power system of tractor-implements
- Experiments demonstrated the technology in a purposely design stand alone stationary test rig
- Experiments set for FY22 will demonstrate the technology on an actual agricultural system

Successful project management through weekly and monthly meetings. Expected milestones delivered on time.

Impact towards DOE-VTO Objectives

An opportunity for US industry to transform agricultural equipment technology through a high-efficient method that offers the advantage of being compatible with existing state-of-the-art technology

Collaborations

Close cooperation between an OEM, a tier 1 component supplier, a national lab and a University lab creates a unique platform for technology innovation

CNH INDUSTRIAL rexroth A Bosch Company NREL Transforming ENERGY

Technical Back-Up

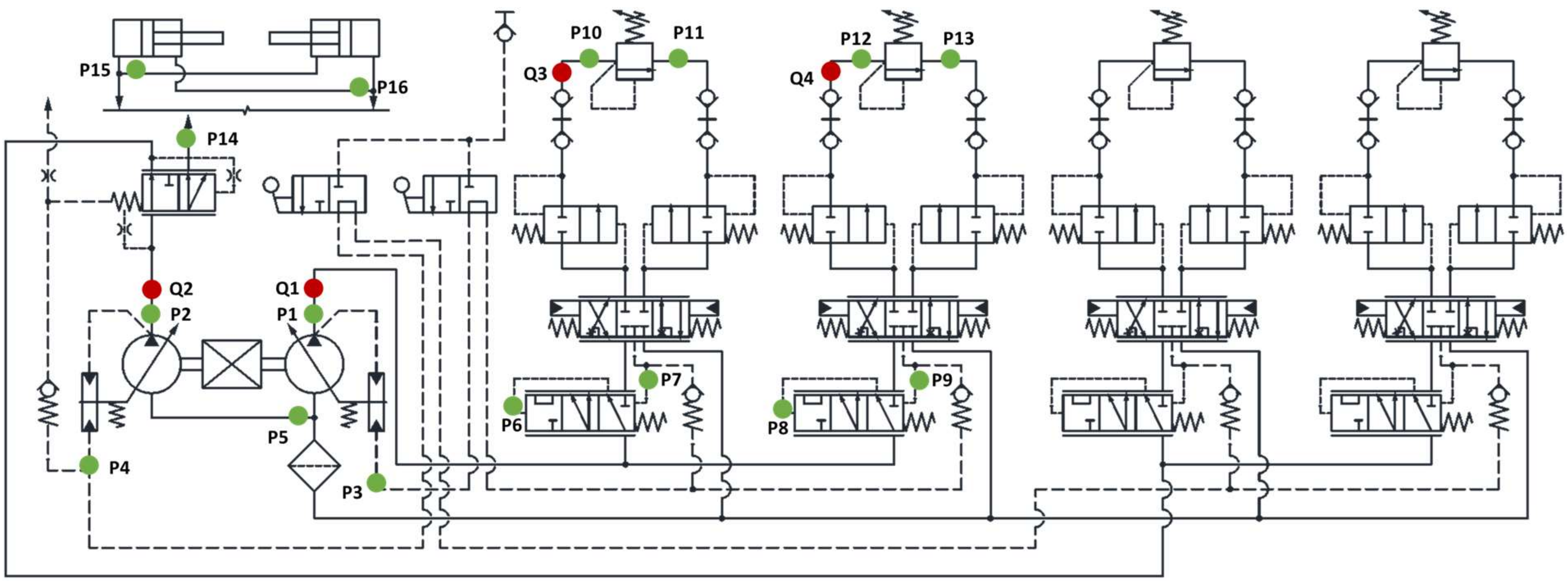
Technical Back-Up

Tractor instrumentation (O3)

Pressures	
Sensor Label	Location
P1	TF Pump Outlet
P2	PFC Pump Outlet
P3	TF Load Sense
P4	PFC Load Sense
P5	Filter Head Outlet
P6	EHR 5 P_int
P7	EHR 5 P_y
P8	EHR 6 P_int
P9	EHR 6 P_y
P10	EHR 5 Outlet
P11	EHR 5 Return
P12	EHR 6 Outlet
P13	EHR 6 Return
P14	SPV Outlet
P15	L Steering Cyl
P16	R Steering Cyl

Flows	
Sensor Label	Location
Q1	TF Pump Outlet
Q2	PFC Pump Outlet
Q3	EHR 5 Outlet
Q4	EHR 6 Outlet

Other Signals
Steering Angle Sensor
Synchronization Signal
Full CAN

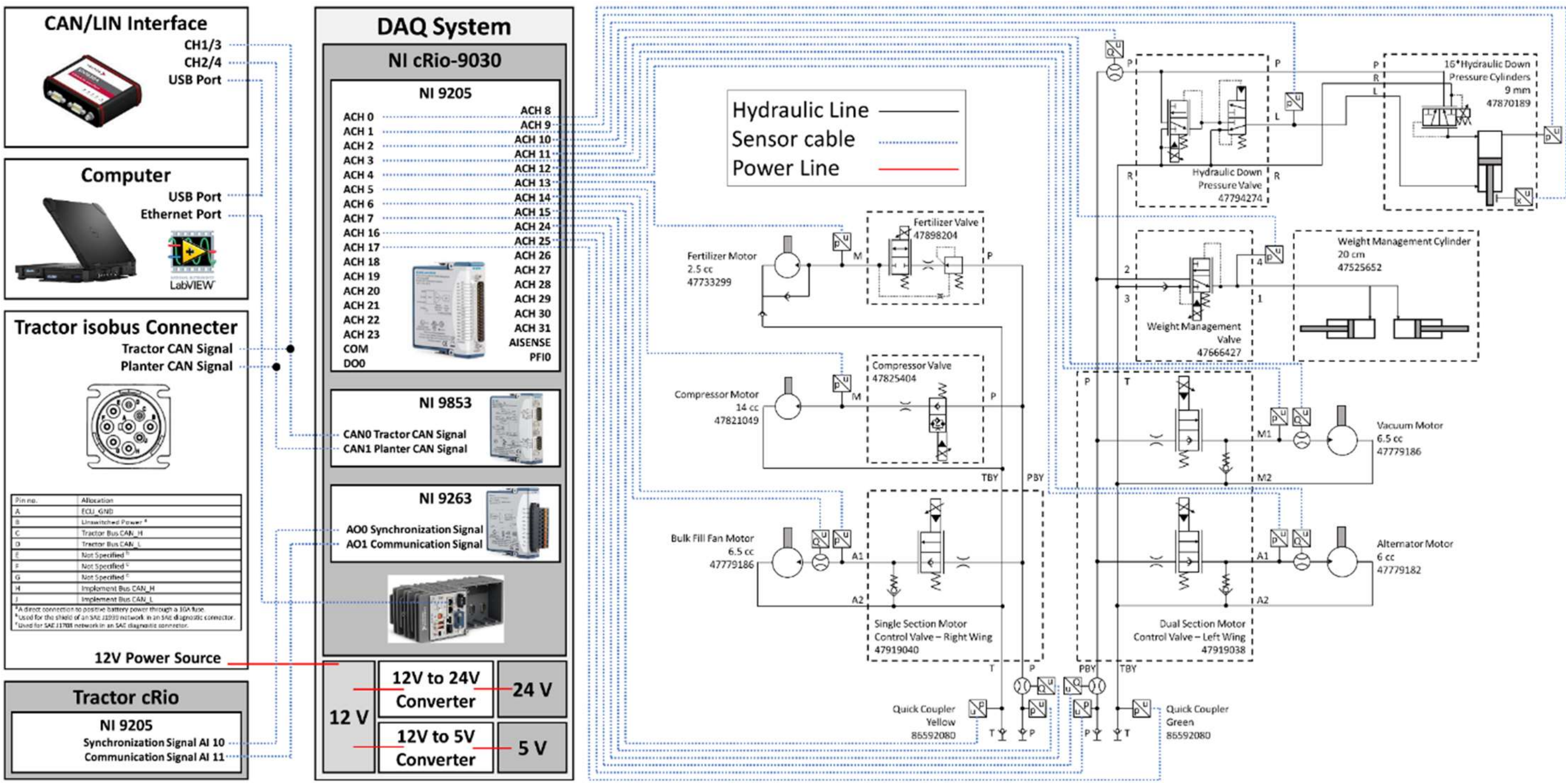


Pressure and flow meters give complete picture of power distribution

- Pump
- Steering
- Remote valves
- Return

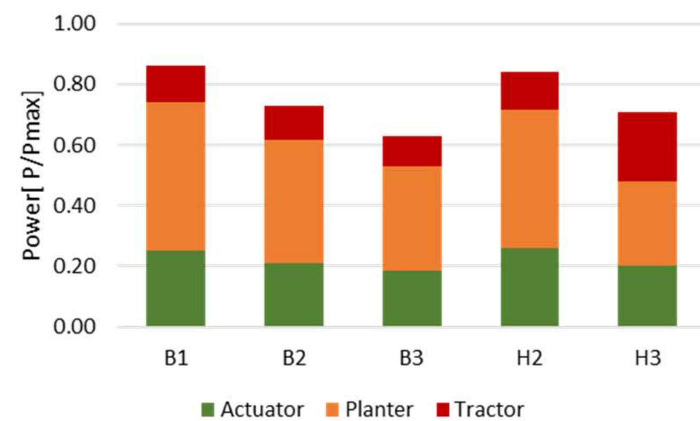
Technical Back-Up

Planter instrumentation and data acquisition system (O3)

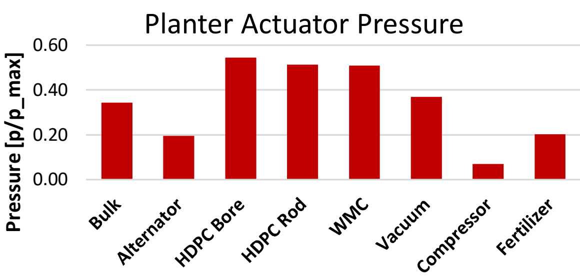


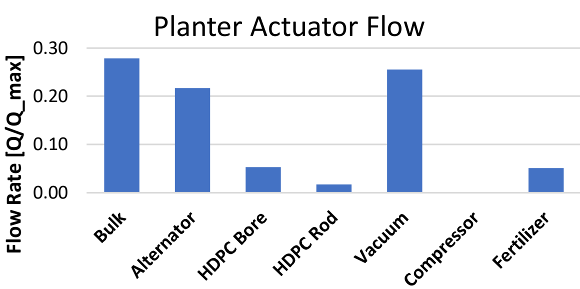
Field test – system power distribution (O3)

- Flow data are normalized against respective max measurement (p/p_{max}, Q/Q_{max}) for generality and to meet confidentiality requirements
- Pressure breakdown reveals poor energy efficiency performance of the standard load sensing system technology
- Lower pressure users experience more losses

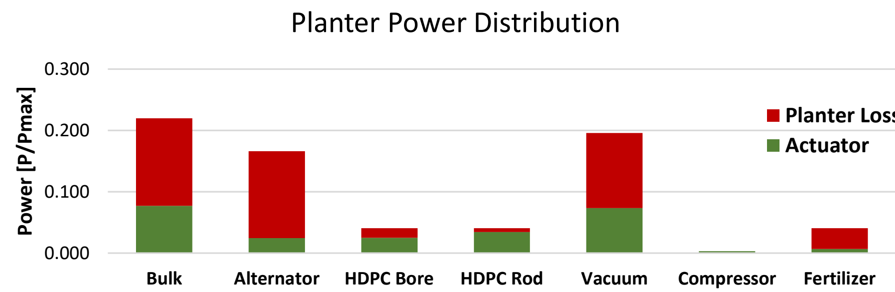


Power consumed depending on the test condition





Average flow, pressure and power values during one of the field tests with the baseline technology (load sensing)



Test stand data acquisition system (O3)