2019 DOE VEHICLE TECHNOLOGIES OFFICE
ANNUAL MERIT REVIEW PRESENTATION

EFFICIENT, COMPACT, AND SMOOTH VARIABLE PROPULSION MOTOR

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Project ID: ft083

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Overview

Timeline

- Project start date: 5/1/2018
- Project end date: 4/30/2021
- Percent complete: 30%

Budget

- Total project funding: $1,856k
  - DOE share: $1,484k
  - Contractor share: $372k
- Funding for FY2018: $637k
  - DOE share: $509k
  - Contractor share: $128k
- Funding for FY2019: $596k
  - DOE share: $472k
  - Contractor share: $123k

Barriers Addressed

- Efficient fluid power components/systems
- Reduce peak loads
- Advanced system controls

Partners

- University of Minnesota: Lead
- Milwaukee School of Engineering
- Poclain Hydraulics Inc.
- Bobcat/Doosan

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Relevance

Objectives:

- Efficiency >90% above 15% displacement
- Reduce fuel consumption 30%
- Power density >5 kW/kg
- Torque ripple <5% of the mean torque
- Cost <$4/kW

Go / No Go This Period (Simulation):

✓ Efficiency >97% above 15% displacement

✓ Torque ripple = 2.8%

Value Propositions:

- Motor Efficiency:
  - Saves fuel, increases power
- Variable Displacement Motor:
  - Increases transport speed and higher system efficiency
- Low Torque Ripple:
  - Improves control and productivity
- Scalable Motor:
  - Applicable to wide variety of off-highway vehicles

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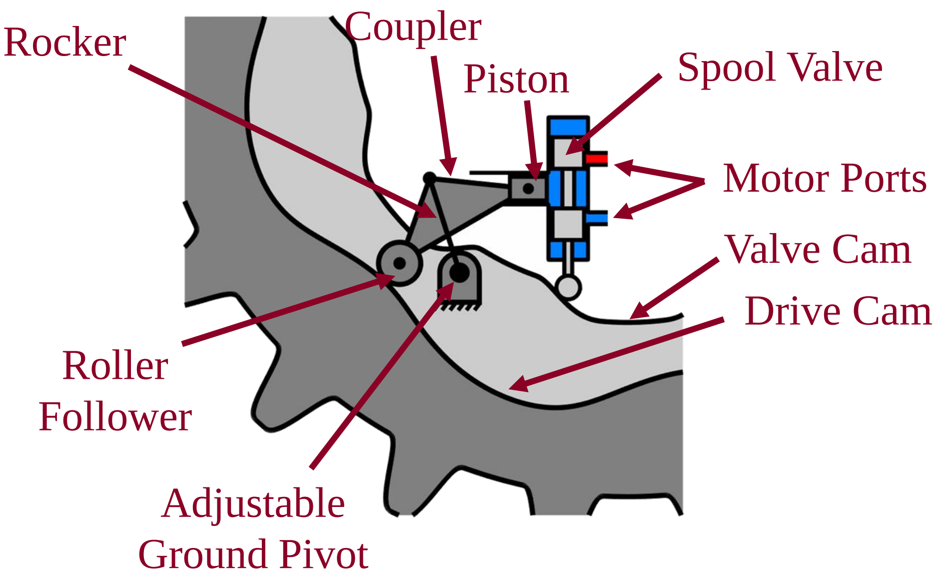
Milestones

	BP1				BP2			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Hydraulic motor kinematic and kinetic model complete.								
Hydraulic motor tribology model complete.								
Complete hydraulic motor drivetrain simulation complete.								
Preliminary business case complete.								
Model predicts total efficiency exceeds 90% at motor displacements above 15% and torque ripple is less than 5% of the mean output torque at full displacement.								
Single cylinder prototype design completed								
Single cylinder prototype operational								
Single cylinder prototype performance map complete								
Single cylinder prototype model validated								
Experimentally validated motor model predicting potential for total efficiency greater than 90% at displacements above 15%.								

Approach



Variable displacement mechanism

- Low friction roller bearings
- Low piston side-load
- Multiple strokes per revolution

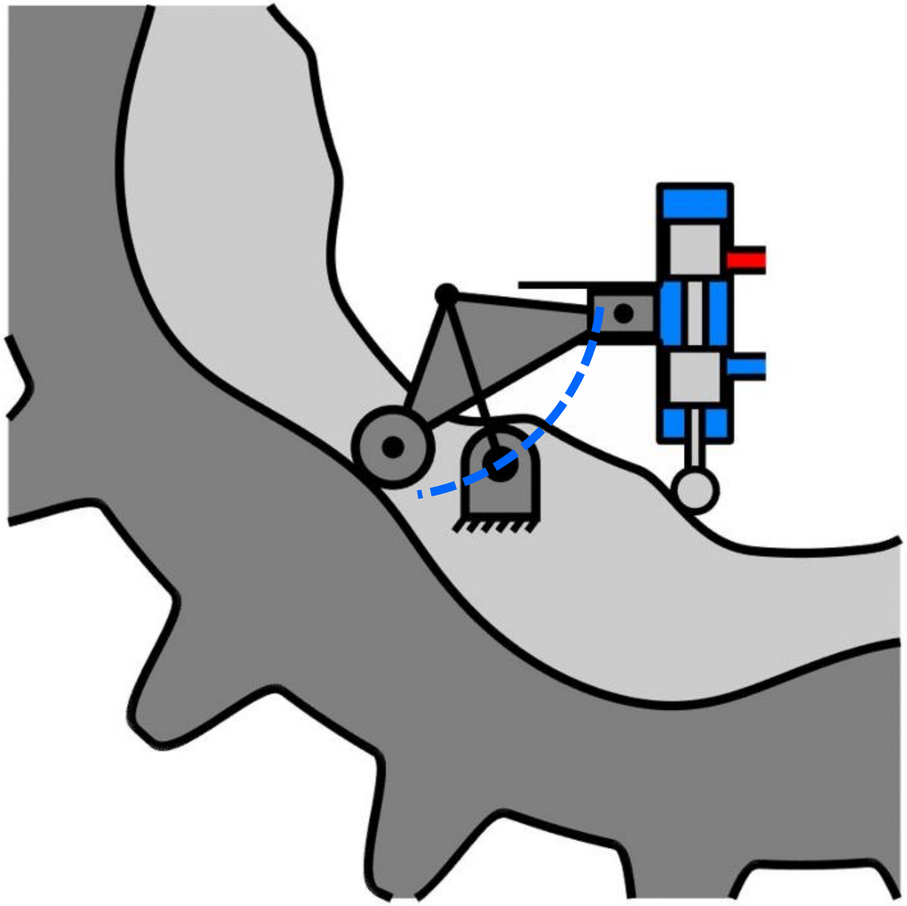
Benefits:

- High efficiency across wide range
- Low starting friction
- Low leakage
- High torque density
- Low torque ripple

Research approach:

- Dynamic model
  - Mechanism kinematics & kinetics
  - Friction in tribological surfaces
  - Cylinder pressure dynamics
- Parameter optimization
- Model validation: 1 cyl prototype
- Demonstration & HIL testing: multi-cylinder prototype

Technical Accomplishments: Kinematics



- Vary displacement by adjusting ground pivot of linkage driving cam
- Inverse cam design
  - Specify piston trajectory
  - Solve for cam profile

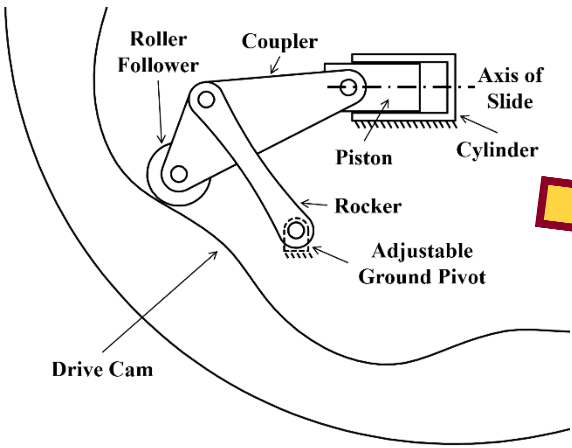
Technical Accomplishments: Kinetics

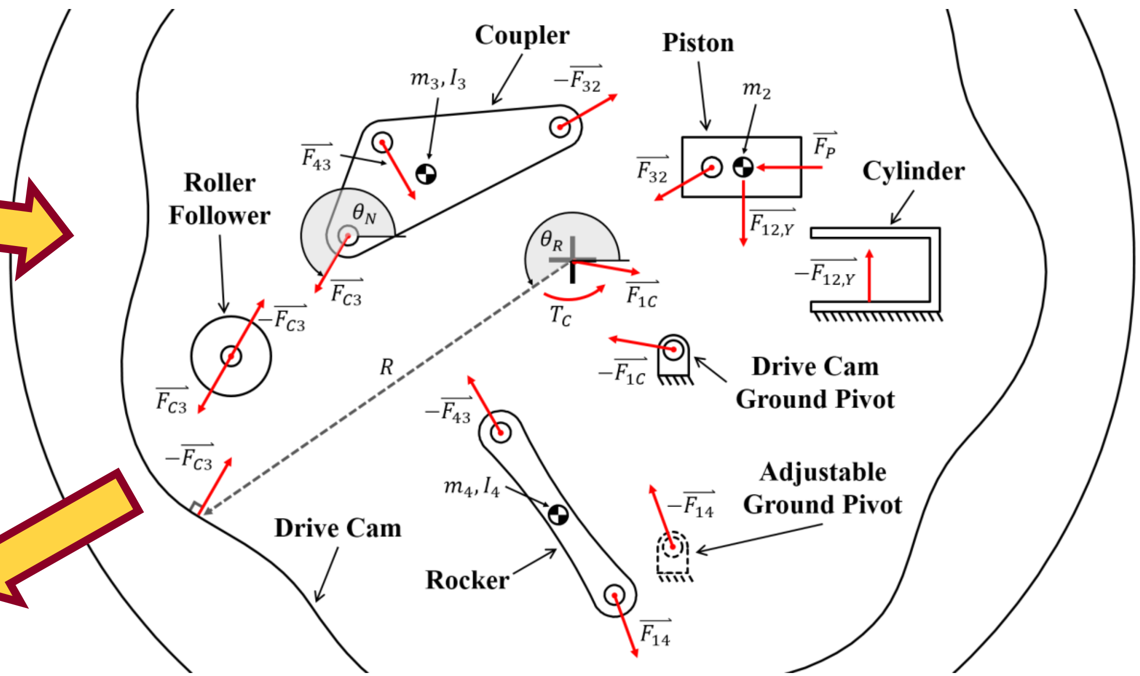
Static Force Balance
- Pressure is the only external force

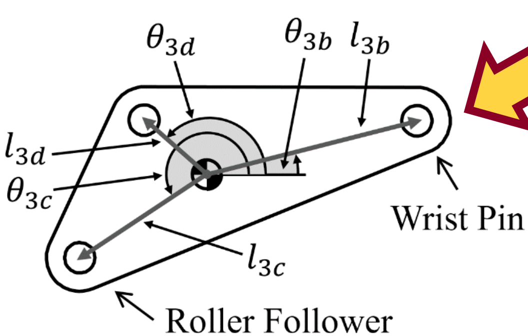
Size Bearings
- Pick smallest bearing that is rated above joint load

Size Links
- Links must fit bearings, plus extra support material

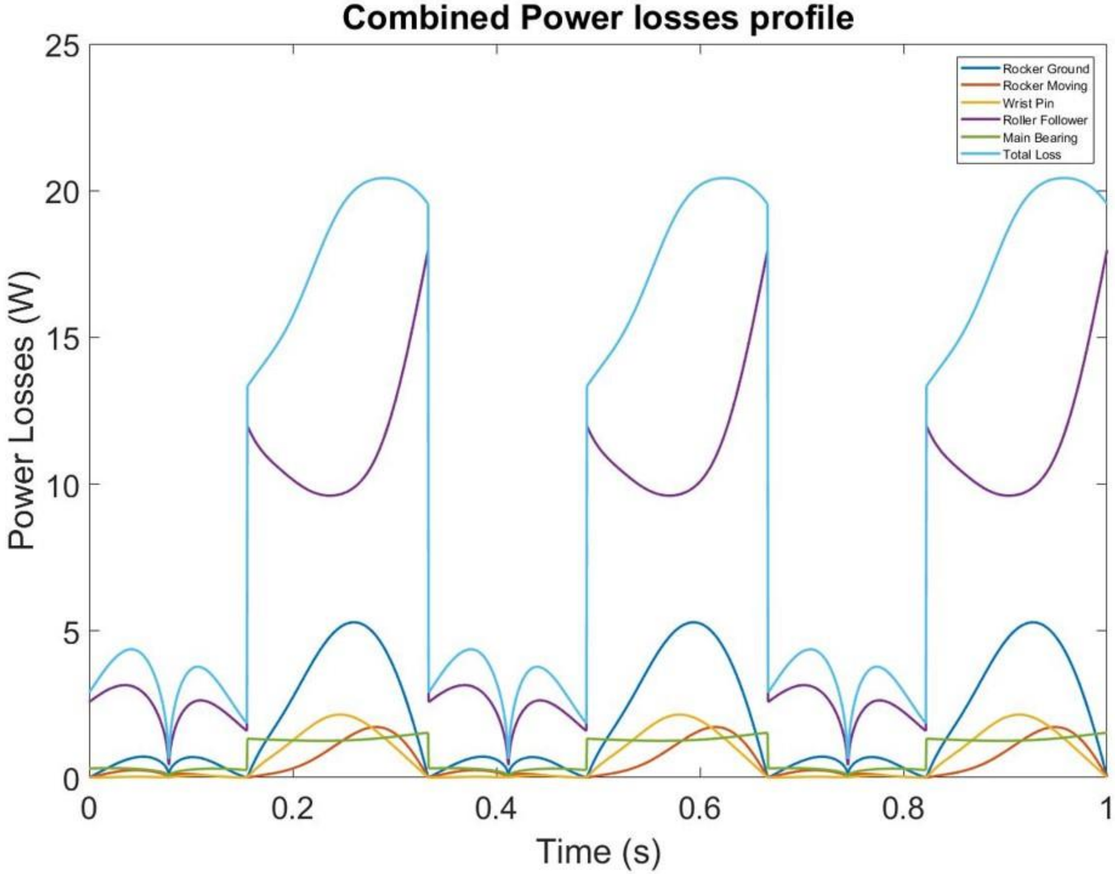
Dynamic Force Balance w/ Friction
- Tribological models
- Non-linear → iterative solution

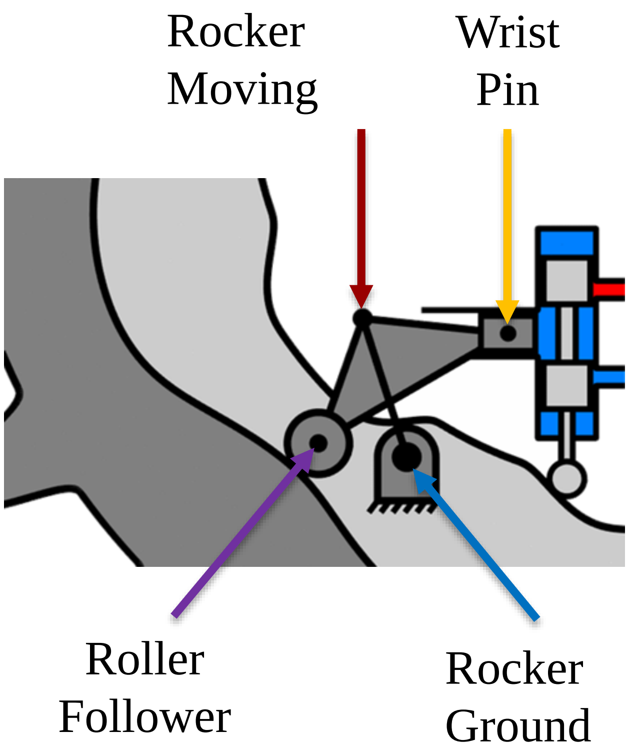






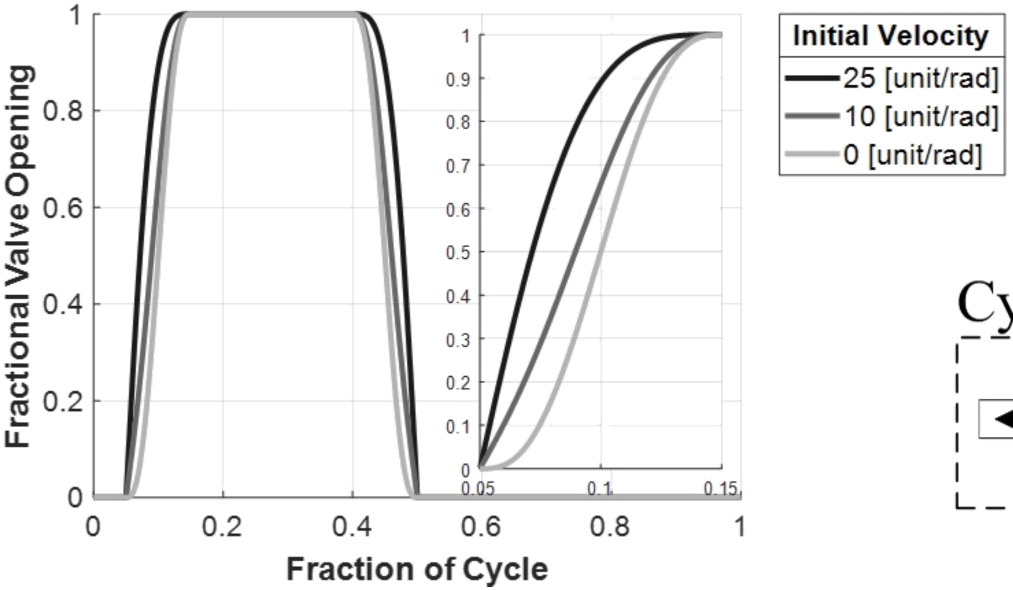
Technical Accomplishment: Tribology

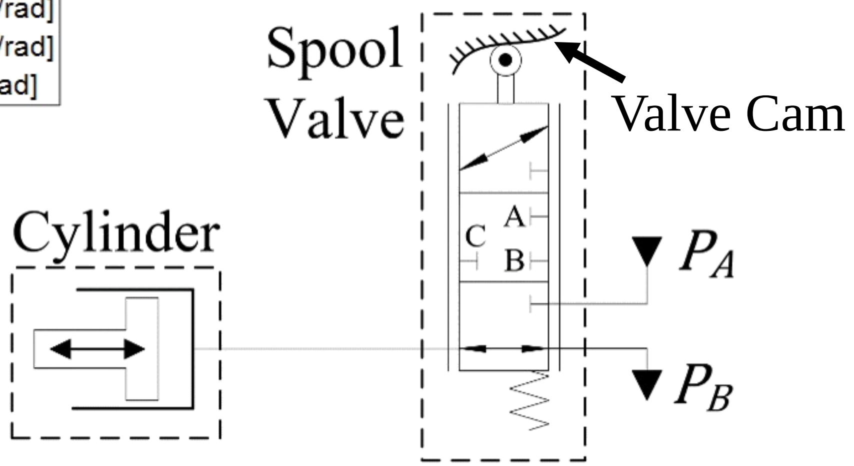




- Predicting fluid film thickness and friction in all joints
- Frictional power loss is very low

Technical Accomplishment: Valve Timing



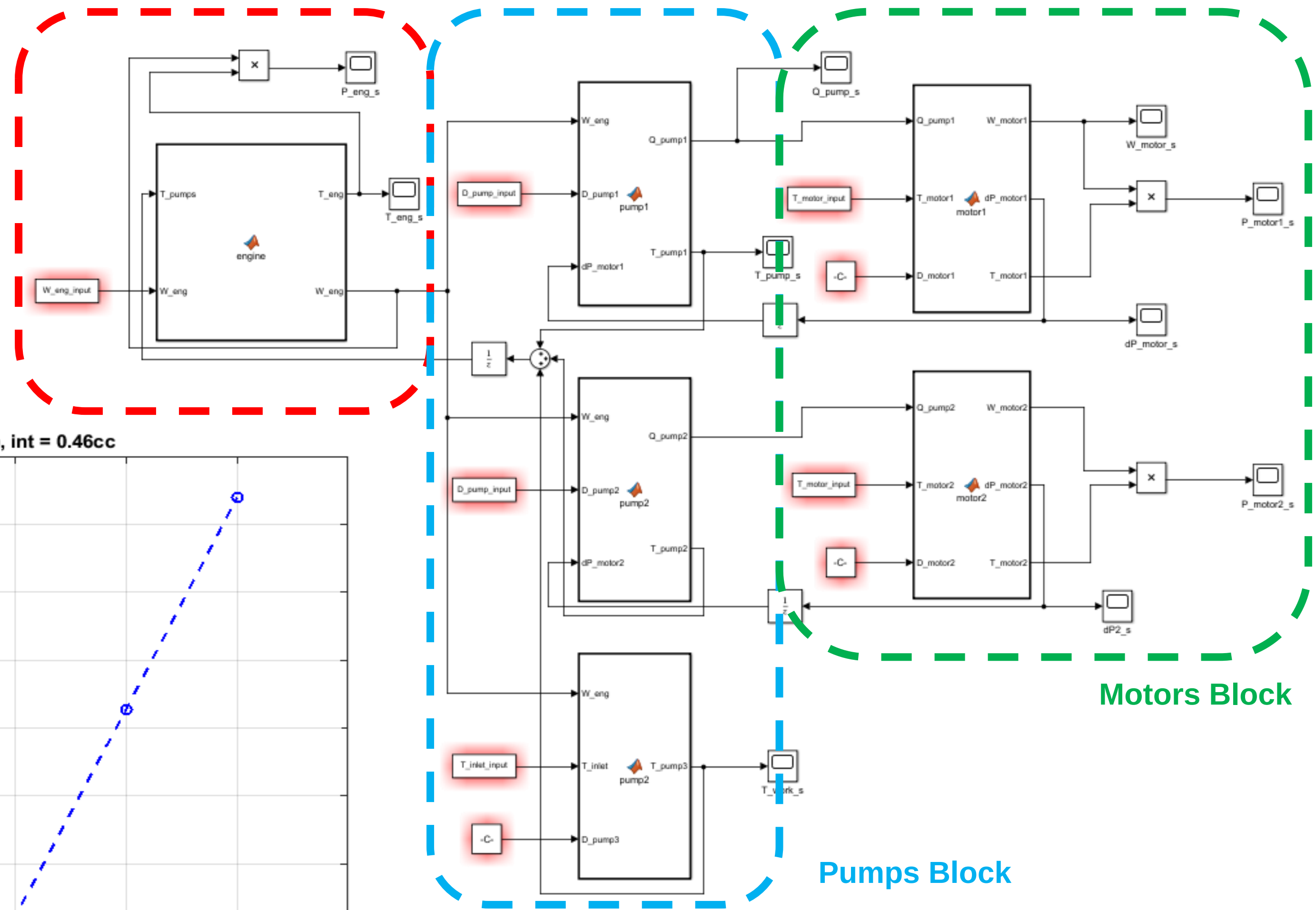


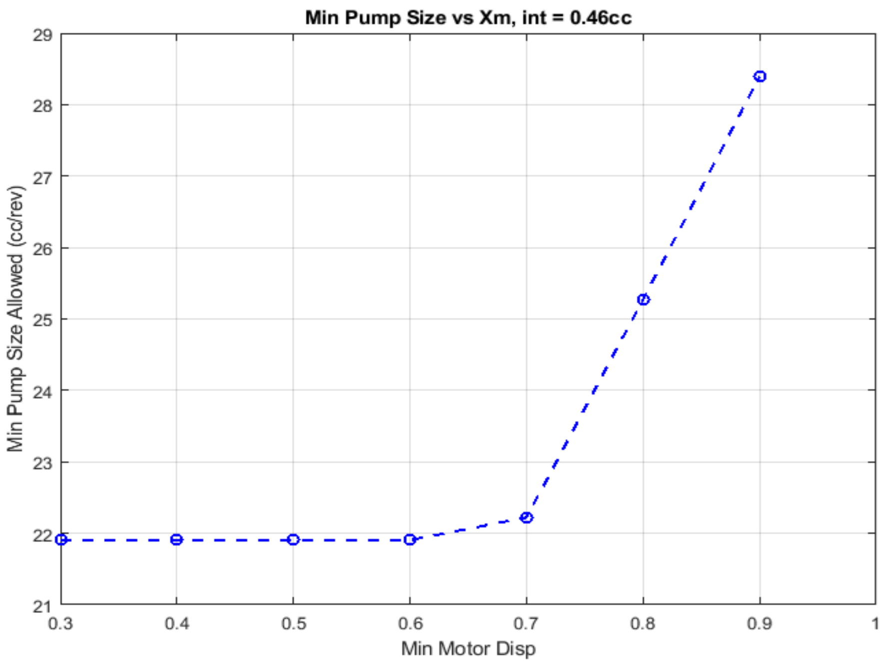
Findings:

- Valve timing critical to efficiency via “pre/de-compression”
- Valve area slope important to efficiency across wide range of speed, pressure, and displacement

Technical Accomplishment: System Model

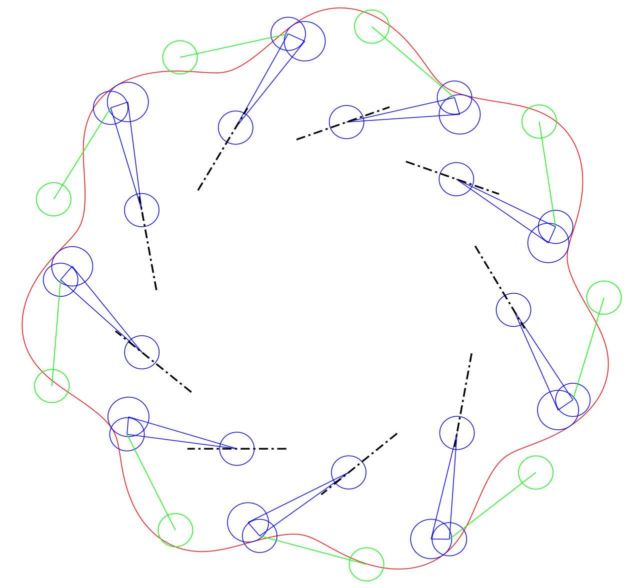
Finding: Variable Motor allows 2X pump downsizing



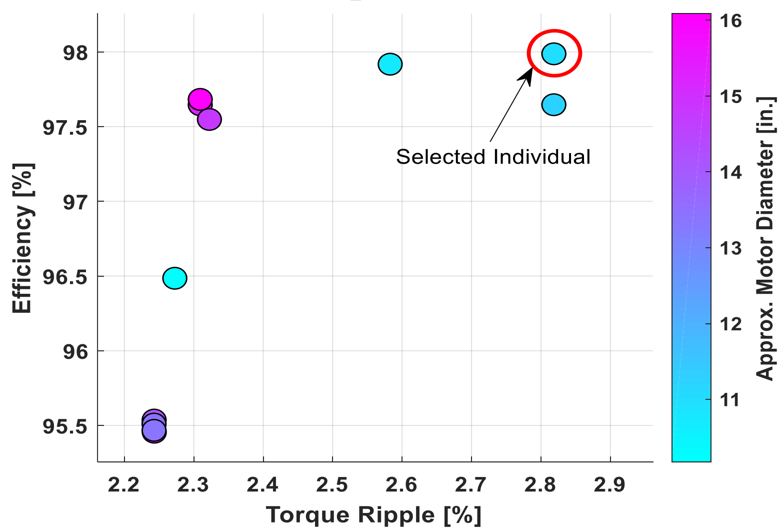


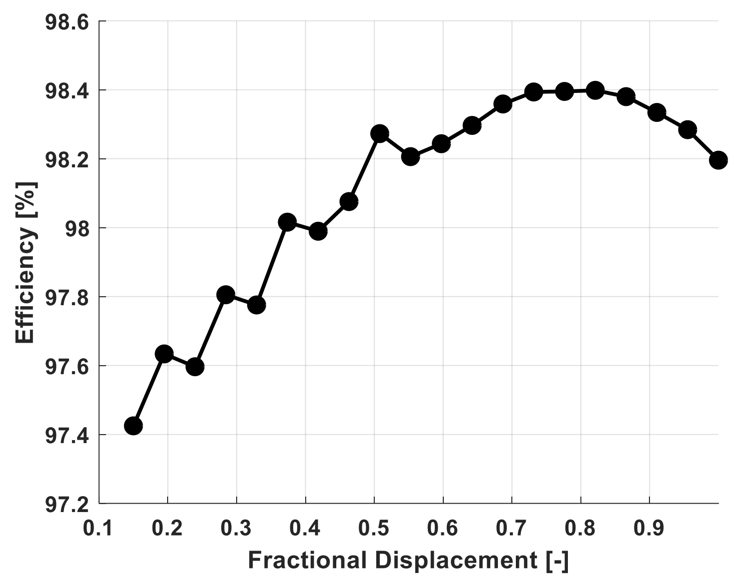
Technical Accomplishment: Motor Optimization

Example Optimal Mechanism



Pareto Optimal Front





<u>Met Go/No Go Decision:</u>

- Efficiency >97% above 15% displacement
- Torque ripple 2.8 %

Responses to Previous Year Reviewers' Comments

- This project is nearing completion of BP1
- No previous reviews

Partners/Collaborators

University of Minnesota	Lead institution. Responsible for mechanical design aspects of the project including motor modeling, optimization, motor design and prototyping.
MSOE University	Responsible for tribological aspects of the project including friction modeling and single & multi piston prototype tests.
Bobcat	OEM track steer manufacturer. Responsible for vehicle system requirements, duty cycle requirements and customer value propositions.
POCLAIN Hydraulics	Hydraulic components manufacturer. Responsible for providing baseline motor requirements, developing business case and prototype assistance.
Consultants	1. Retired hydraulic industry VP of research. Responsible for overall project management 2. VDLM co-inventor. Responsible for guiding motor modeling and design. 3. Retired hydraulic industry master designer. Responsible for CAD design of prototypes.

Remaining Challenges and Barriers

- Motor detailed design
  - Complex packaging, critical tolerances, material selection, coating selection
- Validating subsystem models from full motor experiments
- Displacement actuation control
- System sizing and control
  - Varying pump displacement adds control degree-of-freedom
  - Complex trade-offs in component sizing and control

Proposed Future Research

FY19: Model Validation: Single Cylinder Prototype

- Optimize prototype parameters
- Detailed design of prototype
- Fabricate prototype
- Dynamometer testing and model validation
- Develop system control strategy

FY20: Performance Demonstration: Multi-Cylinder Prototype

- Optimize multi-cylinder prototype
- Detailed design: include displacement actuation
- Fabricate prototype
- Hardware-in-loop: controller evaluation and performance demonstration

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

Summary

- Balanced research team of academics, OEM vehicle, and OEM hydraulic motor
- Multi-domain dynamic motor model
  - Kinematics & kinetics: Design for low torque ripple
  - Tribology: Low friction forces
  - Fluid dynamics: Low valve transition losses
  - System model: Inform component sizing
  - Model integration and optimization
- Met milestones and Go/No Go criteria
  - Efficiency >90% above 15% displacement
  - Torque ripple <5%

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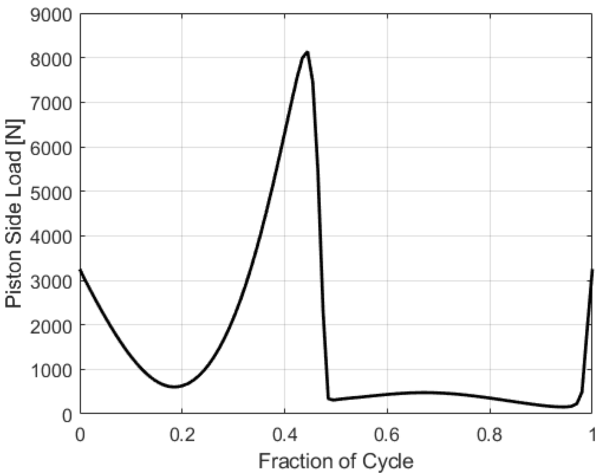
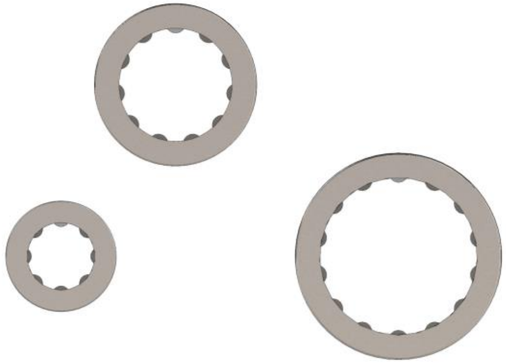
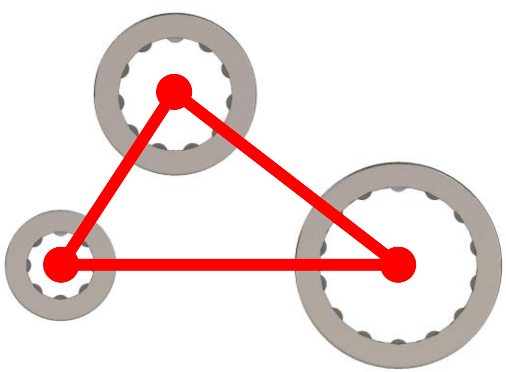
TECHNICAL BACKUP SLIDES

Automatic Bearing & Link Sizing



Bearing No.	Basic load ratings (kN) C_r	C_{0r}
K3X5X7TN	1.56	1.29
K4X7X7TN	1.83	1.32
K5X8X8TN	2.18	1.71
K5X8X10TN	3.04	2.63
K5X9X13TN	4.29	3.55
K6X9X8H	3.19	2.90
K6X9X8TN	2.47	2.07
K6X9X10TN	3.07	2.74
K7X10X8TN	2.74	2.44
K7X10X10TN	3.40	3.22
K7X11X15TN	6.44	6.24
K8X11X8FV	3.23	3.11
K8X11X8TN	2.34	2.05
K8X11X10H	4.57	4.89
K8X11X10FV	4.01	4.11
K8x11x10TN	3.84	3.91
K8x11x13TN	5.18	5.75
K8X11X13H	5.22	5.78
K9X12X10FH	4.27	4.60
K9X12X10FV	4.27	4.60
K9X12X13FH	5.57	6.47
K9X12X13FV	5.57	6.47
K9X13X8H	3.96	3.50
K10X13X10H	5.40	6.43
K10X13X10TN	4.29	4.77
K10X13X13	5.90	7.16





Optimization Flow Chart