CENTER FOR COMPACT AND EFFICIENT FLUID POWER

A National Science Foundation Engineering Research Center

Challenges and Opportunities for Electrifying Off-Road Vehicles

Workshop Report

Center for Compact and Efficient Fluid Power

University of Minnesota

June 2023

Preface

A workshop titled “Challenges and Opportunities for Electrifying Off-Road Vehicles” was held on November 1-2, 2022, at the University of Minnesota. Participants from industry, government and academia attended the workshop. Three keynote speeches were presented giving an overview of transportation electrification, electrical motors and power electronics, and power management for off-road vehicles. Attendees were then engaged in group discussions on challenges and opportunities for battery systems, electrical systems, and power management. This report captures and summarizes the feedback collected during those discussions.

I would like to thank all attendees for their participation and feedback, especially Dr. Michael Weismiller from DOE and Prof. Eric Severson from UW- Madison for their keynote speeches.

Zongxuan Sun

Frank Rowley Professor of Mechanical Engineering

Director, Center for Compact and Efficient Fluid Power

University of Minnesota

I. Introduction

Off-road vehicles including construction machines and agriculture equipment account for about 10% of total transportation energy consumption in the US [1]. It is also a significant sector of the national and global economy and has a critical impact on infrastructure and agriculture. Diesel engines have been used as the prime mover for off-road vehicles because of their efficiency and high torque capacity. Fluid power has been widely used in off-road vehicles for both working and driving functions due to its power density, flexibility, and durability. Given the global challenges in energy consumption, emissions, and the environmental impact, electrification, hydrogen, and sustainable liquid fuels have been proposed for the off-road segment to address those challenges [1]. Roadmaps for sustainable aviation fuels have also been published by federal agencies [2-3]. Within this context, this workshop is focused on identifying the challenges and opportunities for electrifying off-road vehicles.

Unlike on-road vehicles, off-road vehicles often have both driving and working functions. For the driving function, the diesel engine propels the vehicle through a transmission. Various transmission technologies have been used, including automatic transmissions, hydrostatic transmissions, hydro-mechanical transmissions, etc. For the working functions, an engine driven pump is used to produce high pressure fluid to supply hydraulic cylinders and motors. Control of off-road vehicles today is often done by human operators. The operator must control both the driving and working functions simultaneously which makes it difficult and exhausting. Off-road vehicles often need to interact with the environment, for example, when scooping material. Overall, off-road vehicles have complex powertrain systems and perform difficult tasks and interact with the environment.

Off-road vehicles cover a large spectrum of applications, such as construction, agriculture, mining, material handling, etc. There are many different vehicle architectures and duty cycles. The volume for each type of vehicle is often low compared with on-road vehicles. These factors make it challenging to have electrification solutions that can cover the whole segment of off-road vehicles.

Electricity is an energy carrier, not an energy source. A key advantage of electrical systems is that electricity can be produced from various sources, including renewable sources. Electrification offers a pathway to introduce renewable energy into this segment with high efficiency. However, electrification for off-road vehicles needs to address several critical technical challenges. First, the requirements of battery energy and power density. The weight of the vehicle is crucial for its performance, also affecting the ability for quick recharge and discharge. Second, the integration of the electrical drive with fluid power. For off-road vehicles, the working functions often require linear motion. Hydraulic cylinders are ideal for such motion because of force density, load holding capability, and durability. Integrating electrical motors

with hydraulic pumps and cylinders is needed. Electro-hydraulic actuators (EHA) are one such example. Third, control of the EHA system. The working function often faces sudden and large force transients due to the varying environments, making motion control of the EHA system for off-road vehicles challenging.

It is exciting to consider the benefits and new capabilities electrification can bring to off-road vehicles. To achieve these benefits, collaboration among industry, academia and government is required. Skill sets from multiple disciplines including power generation, energy conversion, fluid power, system modeling, sensing and control are needed. Education of the next generation of researchers and engineers for off-road vehicles will ensure the continued success of this industry.

II. Current Status and Challenges

Electrification for on-road vehicles has been ongoing for more than two decades, including hybrid electric vehicles, plug-in hybrid, and battery electric vehicles. In recent years, the competition in EVs has intensified and many automotive OEMs have offered a wide array of electrified vehicles as shown below [4].

Table 1. Hybrid Electric and Electric Vehicles on US Market

Vehicle Type	**Powertrain Architecture**	**Engine Power(kW)**	**Transmission**	**Battery Size(kWh)**	**Motor Power(kW)**
Hybrid Electric Vehicle (102)	Parallel HEV / Power Split HEV	77.6-441	e-CVT/CVT DCT/AT/AMT	0.15 -5.04	1-174 **Note**: Most HEVs have one motor.
Plugin Hybrid Electric Vehicle (35)	Parallel HEV	71-574	e-CVT/CVT DCT/AT/AMT	7.9-24	53-348 **Note:** Most PEVs have one /two motors.
Battery Electric Vehicle (64)	2WD/4WD AWD/RWD	None	Automatic/Fixed Gear	32.6-125	107-829 **Note:** Most BEVs have two motors.

In recent years, electrification for off-road vehicles has also gained more attention. Many off-road vehicle OEMs have started offering electrified off-road vehicles. In general, those vehicles are concentrated in the small power range (10kw-60kw continuous). Applications include scissor lift, boom lift, turf, compact loader, and mini excavator. One motivation for the electrified off-road vehicles is the zero-emission requirement in cities where the vehicles are also closer to charging stations.

The workshop attendees are divided into three groups and rotate among them: battery systems, electrical systems, and power management.

Battery

- **Design/Operation challenges**
    - Robustness of battery packs in uncertain working conditions
        - Temperature
        - Vibration
        - Dust
        - Corrosive liquids
    - Thermal management of batteries
        - Thermal management requirements
        - Preconditioning batteries for use in extreme thermal conditions (cold winters, hot summers)
    - Tradeoff between battery size, weight constraints, and charging time.
        - Large battery pack: long operation, long recharging time
        - Small battery pack: short operation, short recharging time
        - The duration of a battery charge, time of recharging, and its impact on productivity in different applications
    - Cost of ownership vs. cost of operation
        - Acceptable payback periods range from 2-5 years.
    - Different requirements that will involve fluid characteristics (conductivity, additives, etc.) and filtration.
- **Diversity, Standardization challenges**
    - Diversity of the industry with applications
        - Large OEMs vs. small niche market providers
        - Different duty cycles and power requirements
    - Standardization
        - Materials

        - Choice of voltage, DC vs. AC, single vs. multiple phase
        - Off the shelf options for batteries, motors, power electronics, etc.
- **Procurement, Manufacturing, End of life challenges**
    - The high carbon footprint associated with manufacturing batteries.
    - Scarcity and security challenges of acquiring battery materials.
    - Recycling batteries

Electrical System

- Overall system cost and payback time, educating on the value proposition, resale value, fear of the unknown
- Safety and reliability throughout an expected 10-year life. Rebuild for another 10 years.
- The amount of time (duty cycle) that off-road machines must operate per day.
- Size, packaging, weight
- Understanding new kinds of failure modes
- Durable electrical solutions that can handle extreme motion, shock loads, etc.
- Lack of consistency of voltage selection, component selection, availability.
- Linear actuator devices are lagging rotating devices with respect cost, packaging and reliability.

Power management

- What different level of electrification should we have for off-road vehicles? Do we understand what should be electrified?
- Need to match the current vehicle performance, better if can exceed the current performance.
- Don’t sacrifice reliability and durability.
- Rethink the architecture for off-road vehicles with electrified off-road vehicles, evaluation of different architectures.
- Can we scale the technology?

- Operate under all environments.
- Currently following the on-road development, but too many applications
- How to tie the electrification with automation?
- Training needed to ensure safety.

Based on the feedback collected in the three areas (batteries, electrical systems, power management), we find some common themes that identify the challenges for electrifying off-road vehicles:

- There is a need for an off-road vehicles' electrification roadmap.
- Cost of electrifying off-road vehicles is still too high, but it is getting better.
- Off-road vehicles have a wide variety of operating duty cycles and requirements that complicate electrification.
- Long operating profiles place even greater emphasis on energy storage systems than for on-road vehicles.
- Safety, robustness, and reliability must be accounted for when electrifying off-road vehicles.
- Educating the talent required to meet the electrification challenge is a major obstacle to overcome.
- Standards and a greater offering of products/subsystems are needed.

III. Opportunities

The workshop attendees also discussed the potential opportunities for solving the challenges listed in the previous section.

- Develop and publish pre-competitive research roadmap.
- Develop universal standards and guidelines, including duty cycles.
- Workforce development, especially multidisciplinary education (electrical & mechanical, even chemical)
- Encourage and educate a systems mindset
- Attract the best students with better promotion.

- Clear strategy from industry, government, and academia
- Possible cross industry collaboration
- Data mining for the vehicle and on the vehicle
- The university/industry team offers a lot of benefits for pre-competitive research and education.

References

1. The US national blueprint for transportation decarbonization, DOE/EE-2674, January 2023
2. Sustainable Aviation Fuel Grand Challenge Roadmap, DOE, DOT, USDA, EPA, 2022
3. Sustainable Aviation Fuel, review of technical pathway, DOE/EE-2041, 2020
4. Electrified vehicle technical information, ANL, 2023

UNIVERSITY OF MINNESOTA
Driven to Discover℠

CCEFP WORKSHOP

Center for Compact and Efficient Fluid Power (CCEFP)

Fall 2022 Workshop: ***The Opportunities and Challenges of Electrifying Off-road Vehicles***

Agenda: November 1-2nd, 2022

DAY 1: Tuesday, November 1st

4:00pm - WELCOME /Introduction, ME1130

4:10pm – UMN Mechanical Engineering Lab Tours

6:00pm - CASUAL DINNER - University of Minnesota Campus Club

DAY 2: Wednesday, November 2nd, ME1130

7:45 AM -8:00 AM WELCOME – UMN College of Science & Engineering Dean Prof Andrew Alleyne

SESSION I: Invited presenters

8:00 - 10:00 AM

- *Electrifying Off-Road Vehicles– Dr. Michael Weismiller, VTO, DOE (60min)*

- *Electrical Components and Subsystems Requirements for Off-Road Vehicles – Prof Eric Severson, UW Madison (60 min)*

10:00-10:15 break

10:15-11:15AM

- *Unique Challenges regarding Power Management of Off-road Vehicles – Prof Zongxuan Sun (60min)*

SESSION II: Facilitated breakout sessions

11:15 - 12:15 PM

- *Batteries & charging systems*
- *Electrical systems*
- *Power Management*

12:15-1:15 PM LUNCH

SESSION III: Reporting back of discussions

1:15 - 2:45 PM

- *Batteries & charging systems*
- *Electrical systems*
- *Power Management*

Wrap up/Q&A/Next Steps