VII.K.9 Research and Development for Off-Road Fuel Cell Applications

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The Toro Company
University of California, Davis
Donaldson Corporation

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Project Objective

This DOE funded project, with team members: The Toro Company, Donaldson, and U.C. Davis, will determine the effects of off-road air quality, shock, and vibration, on a fuel cell and reformer system.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section of the 2005 Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- A. Durability

Technical Targets

This project is designed to evaluate the operation of fuel cell and reformer systems in an off-road (lawn tractor, greens keeping, farm, construction, and industrial equipment) environment, including a focus on shock, vibration, air quality, and system integration.

Load profiles have been addressed for off-road fuel cell utilization, including typical load profiles, including drive train and power take-off (PTO) devices. Information has been gathered on the air contaminants that may have an effect on fuel cell operation. Test systems to evaluate air contaminants effects have been designed, and the parts have been ordered to construct the test systems. Additionally, a Toro Workman lawn tractor has been equipped to operate on DC voltages and has been equipped with accelerometers to evaluate shock and vibration interaction with the fuel cell system.

Approach

This project will utilize both existing and experimental data to generate information pertaining to the operation of a fuel cell system in an off-road environment. Specifically the project will address and identify:

- Load profiles for existing off-road equipment
- Impulse and vibration information for existing off-road equipment, as well as for an experimental data from a Toro Workman
- Cathode contaminants that are typical in an off-road environment
- Fuel cell test apparatus that will identify the effects of the contaminants on the operation of a fuel cell system
- Design of mitigation for impulse, vibration, and air contaminants
- Testing and validation of mitigation strategies

Accomplishments

Identification of a variety of load profiles for off-road vehicles (agricultural tractors) and air contaminants has been accomplished, including:

- Engine power and torque, PTO, and drawbar power (the power required to pull an implement at a uniform speed).
- Distribution of hours of tractor use by operations (average of 340 hours for 25 tractors).
- A Toro Workman 3000 tractor has been fitted with accelerometers, and is awaiting installation of the electric motor for load profile evaluation.
- A fuel cell hybrid Workman e2050 was operated at Farmlinks Golf Course in Alabama, and generated data for operating speeds, motor current, and hybrid voltage stability. The Workman was also tied to a global position system (GPS), to allow for synchronization of collected data, the vehicle activity, and location.
- An air contaminant database is under construction; this database will identify contaminants for investigation in the eight, single cell, test systems.
  - Sourced from:
    - Literature search internal and external to Donaldson
    - On-site air sampling of select off-road environments (mining, construction, airport, agriculture, grounds care)
- Fuel cell air quality test systems designed, and components ordered. The test systems are currently under construction.

Future Directions

During the remainder of the project, the following tasks will be accomplished:

Prepare source identification graph (vibration & impulse)	07/05
Impulse & vibration testing	10/05
Provide impact and vibration testing results	11/05
Test fuel cell system, post vibration testing	12/05
Delivery of air purifying and noise dampening solution	04/06
A Toro Workman will be provided for testing	04/06
List recommended air purification practices	06/06

Build an implement dampening system	09/06
Design validation testing	07/07
Fuel Cell System Specification	12/07

Introduction

The effect of operating a fuel cell power generation system in off-road conditions is not well understood. There are multiple issues that need to be examined to develop methods for proper design of such a fuel cell system, including:

- Understanding load profiles
- Identifying and quantifying possible air contaminants
- Shock and vibration profiles
- Design of mitigation strategies

An understanding of the effects of air contaminants, and specific shock and vibration sources, along with the design of mitigation strategies will provide valuable information for increasing the lifetime of fuel cell systems in off-road applications.

Approach

This project will utilize existing databases concerning operation of fuel cell systems in off-road conditions, including load profiles, shock and vibration analysis, and typical air contaminants. Where data does not exist, research will be done to fill in gaps, presenting a comprehensive overall picture of off-road conditions, as pertaining to a fuel cell system.

Mitigation strategies for deleterious conditions will be designed and tested, including vibration dampening, hybridized system design for load leveling, and air filtration.

Results

Usage of fuel cell systems for off-road applications, such as farming, construction, forestry and military present a number of challenges. The nature of the terrain surface profile typically induces low frequency high amplitude vibration to the vehicle as opposed to high frequency low amplitude vibration induced by the engine and other moving parts [1]. The mechanical stresses developed by such excitations can cause adverse effects on the fuel cell system in terms of longevity and safety of the system. Although there are a number of available citations discussing the safety considerations in the design of hydrogen-powered vehicles due to the unique flammability and migration properties of hydrogen [2], not much documented information is available on the effect of vibration and shock in terms of longevity of the fuel cell system.

Motion in many off-road vehicles consists of vibration and occasional or repeated mechanical shocks [3]. Due to the above mention terrain irregularities, bumps, and the vehicle's power source, vibration and shock are induced into the off-road vehicles [4]. In forestry vehicles the vibrations apart from the terrain also originate from the vehicle driving over logs [5]. These various sources of shock and vibration excite the vehicles both in translation (longitudinal, transverse and vertical) modes and rotational (roll, pitch and yaw) modes.

An investigation has been conducted on tractor requirements for traction, power train, prime mover torque, speed and acceleration, power profiles, typical PTO and hydraulic actuators. This review indicates that electric motors provide favorable characteristics for agricultural applications and that uncoupling the mechanical power from the load may increase efficiency allowing the power supply to operate at peak efficiency while the electric motor provides the time varying torque.

Agricultural Drive Cycles

Tractor testing is performed internationally at several testing centers where market ready tractors are tested to find their operational limits and fuel efficiencies at different loads [5, 6]. Initially the tractor is allowed a run-in period where a representative from the manufacturer is allowed to operate the tractor and make any tuning modifications. During the tractor test the engine

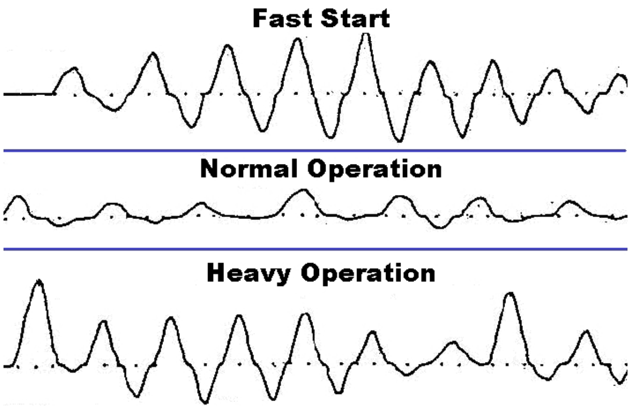

Figure 1. PTO Fluctuations

power and torque is measured by a dynamometer bench attached to the PTO at several different speeds (the rated engine speed, the standard PTO speed 540 or 1,000 rpm, and at various different engine speeds). From the bench tests torque, engine speed and hourly fuel consumption are recorded.

If we evaluate the power demand on the engine during an operation such as hay baling we have the power demand on the engine for motive force, which should be, fairly constant (assuming a uniform field, and slow speeds), however the PTO power fluctuates due to the changing operation of the implement as can be seen in Figure 1.

There are different profiles expected for different vehicles. For small vehicles it is expected that the power demand will be much more transient. Whereas for large vehicles that are used to work large fields, it is expected that the load profile will be fairly steady with oscillations occurring only when abnormalities are encountered (such as rocks in plowing or equipment malfunction).

The data collection exercise of a FC-hybrid Workman e2050 at Farmlinks Golf Course in Alabama was largely successful (Figure 2). Many aspects of that particular application, such as operating speeds, motor current (load), and hybrid voltage stability are better understood. The activity was also largely successful at obtaining and synching GPS-mapping data. Unfortunately, instrumentation problems were encountered with the accelerometer installed for the test, and no acceleration data was obtained.

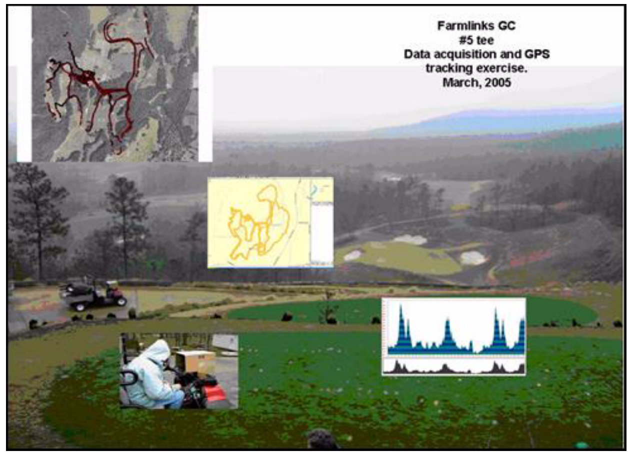

Figure 2. Toro Workman Field Testing

The systems for determining the effects of cathode air quality on an off-road fuel cell system has been designed, with the major components identified in house.

This schematic is a representation of one of eight test systems that will be built. The contaminants to be studied will be provided by Donaldson, based upon their databases of contaminant levels that could apply to off-road conditions discussed in this project.

Conclusions

- The use of a hybrid fuel cell power train for off-road systems is highly recommended. As has been shown, the electric motors are a good match to the power characteristics. It is recommended that a battery pack be used to meet spikes in the power demand.
- The main two factors that govern the strength and nature of vibration on off-road vehicles are the conditions of the terrain and the speed of the vehicle.
- Assuming speeds lower than 10 mph the terrain induced vibrations mainly range between 0-10 Hz. With increase in speeds the vibration amplitude and frequency range increase correspondingly. The vibration in the vertical direction dominates and can be as high as 2g. The amplitude of the vibration levels could be much higher depending upon the design of the vehicle. Owing to the complex nature of the off-road vehicle dynamics occasional or repetitive shock is induced into the vehicle. High

frequency vibrations are also present due to the vehicle power source and induced transient vibrations

- An extended literature review is still required for complete understanding of this task subject, and it is currently in progress.

FY 2005 Publications/Presentations

1. DOE Quarterly Technical Report and Presentation

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