Final Report

Project Title: Research and Development for Off-Road Fuel Cell Applications
U.S. Department of Energy Grant DE-FG36-04GO14303

Project Period: September 1, 2004 – September 30, 2012
Date of Report: April 2013
Recipient: IdaTech, LLC.
Award Number: DE-FG36-04GO14303


Contact: Mike Hicks, (541) 322-1040, mike.hicks@h2powertech.com

U.S. DOE Managers: David Peterson, DOE Golden Field Office
# Table of Contents

PROJECT OBJECTIVES ........................................................................................................... vi
BACKGROUND ......................................................................................................................... vi
OVERVIEW ............................................................................................................................... vi

## TASK 1: SYSTEM STUDY OF LAWN TRACTOR LOAD PROFILES

INTRODUCTION ......................................................................................................................... 1
LOAD PROFILES ....................................................................................................................... 2
  Testings ............................................................................................................................. 2
  Case Studies ..................................................................................................................... 3
  Implement Power Draw ..................................................................................................... 14

## VEHICLE REQUIREMENTS

  Traction Requirements ....................................................................................................... 15
  Power Train Configurations .............................................................................................. 16
  Prime Mover Torque ........................................................................................................... 16
  Vehicle Speed and Acceleration ....................................................................................... 16
  Power Profiles .................................................................................................................... 17
  Typical PTO by Class ........................................................................................................ 17
  Typical Hydraulic Actuator Requirements by Class ....................................................... 17
  Combine Harvesters ......................................................................................................... 18

## OPERATING REQUIREMENTS FOR A FUEL CELL POWER UNIT

  Power Train Differences Required to Accommodate the Fuel Cell ................................. 19
  Dealing with Transients .................................................................................................... 20

## VEHICLE ARCHITECTURE RECOMMENDATIONS

  Properties Of Diesel Engines Vs. Fuel Cell / Electric Motors ........................................... 20
  Vehicle Recommendations ............................................................................................. 21

## CONCLUSION AND RECOMMENDATIONS

CONCLUSION AND RECOMMENDATIONS ........................................................................... 23
APPENDIX ............................................................................................................................... 24
REFERENCES ......................................................................................................................... 37

## TASK 2: IMPULSE AND VIBRATION STUDY

INTRODUCTION ....................................................................................................................... 40
SUMMARY ................................................................................................................................ 40

### TASK 2A: SOURCE IDENTIFICATION OF VIBRATION AND SHOCK ON OFF-ROAD VEHICLES

SUMMARY ................................................................................................................................ 40
AGRICULTURE MACHINERY ................................................................................................... 42
  Vehicle 1 – Tractor ............................................................................................................. 42
  Vehicle 2 – Tractor ............................................................................................................. 42
  Vehicle 3 – Tractor ............................................................................................................. 43
  Vehicle 4 – Tractor ............................................................................................................. 43
  Vehicle 5 – Tractor ............................................................................................................. 44
  Vehicle 6 – Tractor ............................................................................................................. 44
  Vehicle 7 – Tractor ............................................................................................................. 45
  Vehicle 8 – Tractor/Implement ......................................................................................... 45
  Vehicle 9 – Tractor ............................................................................................................. 45
FORESTRY MACHINERY ....................................................................................................... 47
  Vehicle 10 – Skidder ........................................................................................................ 47
Vehicle 11 – Skidder ................................................................. 47
Vehicle 12 – Skidder ................................................................. 48
Vehicle 13 – Skidder/Loader/Bulldozer ........................................ 48
MILITARY MACHINERY ............................................................. 48
Vehicle 14 – Tank .................................................................... 48
Vehicle 15 – Wheel Hub ............................................................ 49
Vehicle 16 – JTEV ................................................................. 49
Vehicle 17 – Fuel Cell Truck ..................................................... 50
Vehicle 18 – Tank .................................................................... 51
Vehicle 19 – Mobile Shelters ................................................... 51
OFF-ROAD MACHINERY ......................................................... 51
Vehicle 20 – Dump Truck/Military Tank/Hovercraft .................. 51
Vehicle 21 – Air and Ground Transportation Vehicles ............... 52
Vehicle 22 – Mini-Baja ............................................................ 52
Vehicle 23 – Mobile Construction Machinery ........................... 52
MISCELLANEOUS ................................................................. 53
Mining ...................................................................................... 53
Vehicle 24 – Truck ................................................................. 53
Vehicle 25 – Mining Vehicles .................................................. 53
Vehicle 26 – Haul Truck .......................................................... 53
Hovercraft .............................................................................. 53
Vehicle 27 – Hovercraft .......................................................... 53
Earthmoving Machinery ......................................................... 53
Vehicle 28 – Excavator ............................................................ 53
Recreation Vehicles / ATVs ....................................................... 54
Vehicle 29 – ATV ................................................................. 54
Vehicle 30 – ATV ................................................................. 54
Toro’s Study ........................................................................... 54
Vehicle 31 – Workman Vehicle ............................................... 54
VIBRATION AND SHOCK SUMMARY BY VEHICLE CATEGORY .... 56
Agricultural Machinery: Vehicles 1-9 ....................................... 56
Forestry Machinery: Vehicles 10-13 ........................................ 57
Military Machinery: Vehicles 14-19 ......................................... 58
Typical Off-Road Machinery: Vehicles 20-23 .......................... 59
Miscellaneous Machinery: Vehicles 24-30 ............................. 60
REFERENCES ............................................................................ 61
TASK 2B. FUEL CELL SYSTEM VIBRATION AND SHOCK SPECTRUM
TESTING ................................................................................... 64
INTRODUCTION ........................................................................... 64
SUMMARY .................................................................................. 64
TEST PROCEDURE ..................................................................... 69
Hardware ................................................................................ 69
Software ................................................................................ 69
Setup ..................................................................................... 69
Process ................................................................................ 71
TEST RESULTS ........................................................................... 72
Data ............................................................................................................. 72
Day One, Run One ................................................................................... 72
  MEScope Data ................................................................................... 72
  Accelerometer Data ........................................................................... 77
Day One, Run Two ................................................................................... 89
  Accelerometer Data ............................................................................ 89
Day One, Run Three .............................................................................. 101
  Accelerometer Data ............................................................................ 101
Day One, Run Four ................................................................................ 113
  Accelerometer Data ............................................................................ 113
Day Two, Run One ................................................................................. 125
  MEScope Data ................................................................................... 125
  Accelerometer Data ............................................................................ 130
Day Two, Run Two ................................................................................ 146
  Accelerometer Data ............................................................................ 146
Day Two, Run Three .............................................................................. 162
  Accelerometer Data ............................................................................ 162
Day Two, Run Four ................................................................................ 178
  Accelerometer Data ............................................................................ 178
CONCLUSION .............................................................................................. 194

TASK 3 – AIR QUALITY STUDY ...................................................................... 195

TASK 3.A - CHARACTERIZATION OF AIR CONTAMINATION IN OFF ROAD
APPLICATIONS FOR FUEL CELL VEHICLES ................................................ 195
INTRODUCTION ........................................................................................... 195
LITERATURE SEARCH ................................................................................ 197
  Particulate Contaminants ........................................................................ 197
  Chemical Contaminants ........................................................................... 199
    Basic make Up of Air ........................................................................... 199
    Measuring Contaminants ..................................................................... 199
    Reported Levels of Various Contaminants ......................................... 199
Conclusion ................................................................................................. 204
ANALYTICAL METHODS ............................................................................. 205
  Particulate Contaminants ........................................................................ 205
  Chemical Contaminants ........................................................................... 205
APPENDIX A: US CONTAMINANT CONCENTRATION FOR SELECTED
CONTAMINANT BY COUNTY ...................................................................... 207
APPENDIX B: DEFINITIONS ........................................................................ 212
REFERENCES .............................................................................................. 214

TASK 3.C – AIR FILTER TESTING ................................................................. 215
INTRODUCTION ........................................................................................... 215
EXPERIMENTAL SET-UP ........................................................................... 215
  Schematic ............................................................................................. 215
  Controls ................................................................................................. 221
TEST PLAN: ................................................................................................. 224
  Phase I: Initial Shakedown .................................................................... 227
  Phase II: Tests ....................................................................................... 227
DATA ................................................................................................................................. 227
Equipment Calibration .................................................................................................... 227
Air Filter Pressure Drop Test .......................................................................................... 228
ISSUES AND RECOMMENDATIONS .............................................................................. 231

TASK 4: DESIGN, ASSEMBLE, AND TEST TWO TORO WORKMAN™ MID DUTY UTILITY VEHICLE WITH AN IDATECH FCS 3000 LIQUID FUELED FUEL CELL SYSTEM ................................................................................................................................. 233
TEST VEHICLE 1 (TV-1) ................................................................................................. 233
TEST VEHICLE 2 (TV-2) ................................................................................................. 243
LESSONS LEARNED AND CORRECTIVE ACTIONS .................................................... 248
PROJECT OBJECTIVES
To determine the effects of off-road air quality, shock, and vibration, on an advanced Proton Exchange Membrane (PEM) fuel cell and reformer subsystems and its integration with a Toro Workman™ Lawn Tractor.

BACKGROUND
The program originally consisted of the following four tasks
1. System Study of Lawn Tractor Load Profiles
2. Impulse and Vibration Study
   a. Source Identification of Vibration and Shock on-Off Road Vehicles
3. Air Quality Study
   a. Fuel Cell Air Contaminants
   b. Air Filter Development
4. Fuel Cell Specification

The program began in September 2004, was suspended in 2005 and was restarted in November 2007. During the suspension, Donaldson and Toro independently completed some of the tasks that were proposed under this program:
- A database of airborne fuel cell contaminants was generated (Task 3a)
- Air filter development was completed (Task 3b)
- Load profiles and power requirements for a Toro Workman™ were generated (Task 4)
- IdaTech under a US Navy program (Subcontract to HoKu, Program ID 06UJ9A00008B) developed a portable liquid fueled fuel cell system (FCS3000) of the size required for this program

After work resumed on this program in 2007 and as a result of the work independently completed during the suspension, Task 4 was modified to the following:

Additionally, due to the fact that there was leftover money as a result of some of the tasks being completed during the suspension and that Donaldson decided not to produce the fuel cell air filter designed in Task 3b, Task 3c - Air Filter Testing, was added in 2010 in order to evaluate available filters.

From the original task list, two items will not be included in the final report since they were paid for by their respective companies during the suspension. Those items are Task 3b – Air Filter Development and Task 4 – Fuel Cell Specification.

OVERVIEW
This program has addressed the load profiles for off-road PEM fuel cell utilization, including typical load profiles and drive train and power take off
devices. The program has also gathered information on the air contaminants that may have an effect on fuel cell operation and performance degradation. Toro has developed the Workman Model e2065 mid-duty truck equipped to operate on DC voltages, and had accelerometers installed and evaluated shock and vibration under this grant.
TASK 1: SYSTEM STUDY OF LAWN TRACTOR LOAD PROFILES

Investigation of Load Profiles for Agricultural Tractors and Fuel Cell Power Train Recommendations

University of California, Davis

Michael Beerman, Graduate Student
Uriel A. Rosa, Assistant Professor
Bryan Jenkins, Professor
Paul Erickson, Assistant Professor

INTRODUCTION
The modern Agricultural tractor has many uses. Each of those uses has a different power demand. The purpose of this investigation is to determine load profiles for different classes of off-road equipment using predominantly existing information from agricultural, military and other equipment testing programs (e.g. Nebraska Tractor Testing Laboratory, Aberdeen Test Center, OECD and OEM data). This effort focuses on agricultural applications where such information is available. Agricultural equipment to be considered includes lighter-duty general-purpose 2-wheel and 4-wheel drive tractors, which are considered to be primary targets for adapting fuel cell power units in the near term.

An investigation has been conducted on tractor requirements for traction, power train, prime mover torque, speed and acceleration, power profiles, typical power take-off (PTO) and hydraulic actuators. Operating requirements and changes in the power train required to facilitate a fuel cell power unit to accommodate functional differences, and differences in the transient response of the fuel cell compared with internal combustion engines are discussed. Finally recommendations are made regarding the power train design of three power classes of tractors <20 kW, 20 to 200 kW, and >200 kW, as well as for the prototype vehicle to be field-tested.

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.

The data collected are representative of North American agricultural tractors, in that there are different economic and social demands for farm equipment in different countries. Gasoline or diesel internal combustion engines power current tractors on the market in North America. Although there have been electric tractor (Alcock, 1983; Vik et al., 1984; Thoreson et al., 1986) and Fuel cell tractor
(Ihrig, 1960) prototypes made, none of these has made it into widespread use.

**LOAD PROFILES**

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 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).

**Testings**

Tractor testing is performed internationally at several OECD approved testing centers where market ready tractors are tested to find their operational limits and fuel efficiencies at different loads (OECD ; SAE, 1999). First the tractor is allowed a run-in period where a representative from the manufacturer is allowed to run the tractor and make any tuning modifications. During the tractor test the engine power and torque are measured by a dynamometer bench attached to the PTO at several different speeds (the rated engine speed, the standard PTO speed 540 or 1000 rpm, and at various different engine speeds). Torque, engine speed and hourly fuel consumption are recorded on the bench tests, and the tractor is field driven to determine drawbar performance.

Drawbar power is defined as the power actually required to pull, or move, an implement at a uniform speed. Drawbar power is not only a function of engine power, but also of tractive efficiency, which is dependent on weight distribution, field conditions, and the tires.

The Power Take Off (PTO) is a shaft that can be accessible usually either at the front or rear of the tractor (or at both) in which a mounted or pulled implement can receive mechanical power to perform an operation. For example a pick up baler is an implement, which is hitched to the tractor and connected to the PTO drive. As the tractor pass through the field of cut-dry hay the baler uses the power supplied by the PTO to pick up the hay, compress it, bind it with twine and then push the bound bale out of the machine to start a new bale.

If we evaluate the power demand on the engine during an operation such as baling we have the following to consider. The tractive power demand on the engine should be fairly constant (assuming a dry field, and slow speeds), and the PTO power used to bale the hay fluctuates due to the changing operation of the implement as can be seen in Figure 1.
Figure 1: Torque meter charts with a slip clutch (Hansen, M., 1952)

Case Studies
While searching for load profiles a search was performed to find traces similar to those used to evaluate automotive performance (velocity and grade vs. time). Since the use of tractors is fundamentally different from automobiles as a result they are not evaluated in the same manner. In order to determine what kind of loads the engine of a tractor will experience, torque and power traces were then sought after. It is possible to obtain maximum power and torque measurements recorded by the Nebraska Tractor Test facility at their web site

http://tractortestlab.unl.edu/testreports.htm

For tractors sold outside the US one can see the test reports posted by the OECD at

http://www2.oecd.org/agr-coddb/index_en.asp

One significant addition to the OECD reports are the engine maps of torque and power vs speed. However, neither of these tells us how the load that a tractor might experience varies over time. To obtain these data, research papers have been evaluated and several illustrative studies are mentioned as follows.

In a study of torsional loads on nine separate tractors the loads imposed on the PTO shafts were analyzed during different operations. Table 1 shows the torsional properties of eight of the nine tractors evaluated. Table 2 displays the findings of the variation in the torque during different operations. In this analysis it is found that there are three factors that play a large roll in the magnitude of peak PTO torsional loads. The first is the amount of kinetic energy stored in the rotating parts of the tractor, the second the moment of inertia of the rotating parts in the implement, and third the amount of resilience in the drive between the heavy rotating parts of the tractor and the rotating parts of the driven implement. Figure 2 shows the oscillatory nature of the implement loads on the PTO shaft.
due to the misalignment of the universal joint connecting the implement to the
PTO shaft.

Table 1: Kinetic energy of rotating parts and torsional properties of PTO drives of
current tractor models (Hansen, 1952)

<table>
<thead>
<tr>
<th>Tractor Make and Model</th>
<th>Approx Max. hp of Tractor</th>
<th>I of Rotating Parts (lb-ft/sec²)</th>
<th>E or Rotating Parts at Rated Speed (ft-lb)</th>
<th>Torsional Deflection of PTO Train at Y.P. (Degrees)</th>
<th>Torsional Yield Strength of PTO Train (lb-in)</th>
<th>Energy PTO Drive Will Absorb at Y.P. (ft-lb)</th>
<th>Ratio E in Rotating Parts to PTO Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35</td>
<td>2.33</td>
<td>12,120</td>
<td>20</td>
<td>17,600</td>
<td>256</td>
<td>47.3</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>1.32</td>
<td>11,300</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>35</td>
<td>3.23</td>
<td>16,820</td>
<td>37</td>
<td>28,000</td>
<td>1753</td>
<td>22.2</td>
</tr>
<tr>
<td>4</td>
<td>45</td>
<td>6.17</td>
<td>33,700</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>35</td>
<td>1.034</td>
<td>11,900</td>
<td>20</td>
<td>28,000</td>
<td>407</td>
<td>29.2</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2: Torque meter charts showing the effect of universal joint misalignment
while transmitting an average load of approximately 30  (Hansen, 1952)
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>35</td>
<td>Ensilage Harvester A</td>
<td>Spec. Slip</td>
<td>4900 - 6400</td>
<td>10800 - 15370</td>
<td>4680 - 6390</td>
<td>5450 - 7140</td>
<td></td>
<td>Chopping Heavy Drilled Corn</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>40</td>
<td>Ensilage Harvester A</td>
<td>Standard</td>
<td>3520 - 3820</td>
<td>3960 - 7630*</td>
<td>2390</td>
<td></td>
<td></td>
<td>Chopping Heavy Drilled Corn</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>35</td>
<td>Ensilage Harvester B</td>
<td>Standard</td>
<td>8660</td>
<td>6025 - 6865</td>
<td>3200</td>
<td></td>
<td></td>
<td>Chopping Heavy Drilled Corn</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>35</td>
<td>Forage Harvester C</td>
<td>Standard</td>
<td>14600</td>
<td>6370 - 7200</td>
<td>2870</td>
<td></td>
<td></td>
<td>Chopping Green Alfalfa</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>35</td>
<td>Forage Harvester C</td>
<td>Standard</td>
<td>9800 - 7530*</td>
<td>6100 - 8700</td>
<td>3270</td>
<td></td>
<td></td>
<td>Chopping Green Alfalfa</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>35</td>
<td>Forage Harvester C</td>
<td>Standard</td>
<td>12500 - 10900</td>
<td>9500</td>
<td>3600</td>
<td></td>
<td></td>
<td>Chopping Green Alfalfa</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>35</td>
<td>Forage Harvester C</td>
<td>Standard</td>
<td>21400</td>
<td>727</td>
<td></td>
<td></td>
<td></td>
<td>Attempting to Start a Plugged Machine</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>35</td>
<td>Corn Picker D</td>
<td>Standard</td>
<td>1570 - 1740</td>
<td>3990</td>
<td>727</td>
<td></td>
<td></td>
<td>Picking Corn</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>35</td>
<td>Baler E</td>
<td>Standard</td>
<td>18300 - 20600</td>
<td>5860 - 7470</td>
<td>1140</td>
<td></td>
<td></td>
<td>Baling Alfalfa</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>35</td>
<td>Baler E</td>
<td>Standard</td>
<td>13100</td>
<td>6550 - 8140</td>
<td>1545</td>
<td></td>
<td></td>
<td>Recheck of</td>
</tr>
<tr>
<td>---------</td>
<td>---------------</td>
<td>--------------------------</td>
<td>--------------------------</td>
<td>-----------------------</td>
<td>-------------------------------------------------------</td>
<td>-------------------------------------------------------</td>
<td>--------------------------------------------------</td>
<td>--------------------------------------------------</td>
<td>---------------------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>12</td>
<td>1 35 Baler E</td>
<td>Spec. Slip</td>
<td>10700 - 12100*</td>
<td>10700 - 12100*</td>
<td>7250 - 8920</td>
<td>11500 - 13300*</td>
<td>2250</td>
<td>Baling Alfalfa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>1 35 Baler E</td>
<td>Spec. Slip</td>
<td>10100*</td>
<td></td>
<td>5600 - 11100</td>
<td>10350 - 12600</td>
<td>1580</td>
<td>Baling Straw</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>9 40 Baler E</td>
<td>Standard</td>
<td>12250</td>
<td></td>
<td>7749 - 10945</td>
<td>10960 - 12095</td>
<td>1938</td>
<td>Baling Alfalfa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1 35 Baler E</td>
<td>Standard And Universal Joints Aligned</td>
<td>4501 - 5867</td>
<td></td>
<td></td>
<td></td>
<td>1383</td>
<td>Baling Alfalfa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>1 35 Baler F</td>
<td>Standard</td>
<td>16500</td>
<td></td>
<td>8600</td>
<td>22700</td>
<td></td>
<td>Baling Alfalfa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>1 35 Combine G</td>
<td>Spec. Slip</td>
<td>5000*</td>
<td>5000*</td>
<td>5000*</td>
<td>5000*</td>
<td>Baling Alfalfa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>1 35 Combine G</td>
<td>Standard</td>
<td>10100 - 16600*</td>
<td>3760</td>
<td>9380</td>
<td>1890</td>
<td>Combining Windrows</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>1 35 Combine G</td>
<td>Spec. Slip</td>
<td>7150</td>
<td>7760 - 9130</td>
<td>1700</td>
<td>Combining Windrows</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1 35 Combine G</td>
<td>Spec. Slip</td>
<td>7350 - 8650</td>
<td>4160 - 4200</td>
<td>7470</td>
<td>1600</td>
<td>Straight Combining</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>2 25 Hammer Mill H</td>
<td>Standard</td>
<td>9030</td>
<td>17500 - 20150</td>
<td>4145</td>
<td>7270</td>
<td>2700</td>
<td>Grinding Ear Corn</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>1 35 Hammer Mill H</td>
<td>Standard</td>
<td>6130</td>
<td>3740</td>
<td>14900</td>
<td>2140</td>
<td>Grinding Ear Corn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>1 35 Hammer Mill H</td>
<td>Spec. Slip</td>
<td>8230*</td>
<td>8230*</td>
<td>6920</td>
<td>4210</td>
<td>Grinding Ear Corn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>4 45 Hammer Mill J</td>
<td>Standard</td>
<td>10150</td>
<td>25800</td>
<td>7800</td>
<td>13000</td>
<td>5450</td>
<td>Grinding Ear Corn</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Safety Clutch in PTO Line Slipped Limiting Torsional Load to This Value
In a study on engine loading, an AC D-17 tractor was instrumented and used for several different tasks (Ricketts and Weber, 1961). The test tractor was used on twelve different farms and the recorded data (figures 3 through 6) show the range of engine power and speed in which each task was performed. Figure 7 shows a breakdown of the number of hours that a typical farm tractor is used over a varying number of tasks. The data were compiled from the yearly log of 25 different farmers near the University of Illinois, Urbana.

**Figure 3:** Range of engine horsepower and speed requirements for corn picking, subsoiling, field cultivating and soil packing (Ricketts, 1961)

**Figure 4:** Range of engine horsepower and speed requirements for planting, mowing, chopping, rotary hoeing and plowing (Ricketts, 1961)
Figure 5: Range of engine horsepower and speed requirements for cultivating, combining, applying anhydrous ammonia, and spike- and springtooth harrowing (Ricketts, 1961)

Figure 6: Range of engine horsepower and speed requirements for raking, crushing, crushing and mowing, and disking (Ricketts, 1961)
Figure 7: Distribution of hours of tractor use by operation – average of 340 hours for 25 tractors (Ricketts, 1961)

A paper presenting the functionality of a portable instrumentation package that was designed for tractors can give us an idea of load variation. Figure 8 shows both the vehicle speed and the draft power required for chisel plowing with a John Deere 3020 tractor.

Figure 8: Data from chisel plowing in dewey oats stubble (Strange et al., 1984)

In a different case a Cockshutt 30 hp (22kW) tractor was fitted with a torque meter on the shaft connecting the clutch to the transmission. Figure 9 shows the variable load of an implement (Gerlach, 1966).
In the interest of directly mapping the power demand on a tractor a study was performed to observe which regions of the engine map were most commonly used during various operations. A turbo-charged Ford 6610 AC (50 hp, 37kW) was fitted with data acquisition equipment, and was used by different operators and different tasks to show the change in engine usage. The change in engine usage then translates into a change in fuel consumption (Hansen et al., 1986). The Z-axis in figures 11 through 16 shows a percent time spent at that point. A number is specified at the origin to represent the amount of time at idle. The idle time was not plotted because it would have made the rest of the data difficult to be visualized.
Figure 11: Surface of field time data for operator 1 using a moldboard plow (Hansen et al., 1986)

Figure 12: Surface of field time data for operator 2 using a moldboard plow (Hansen et al., 1986)
Figure 13: Surface of field time data for operator 3 using a moldboard plow (Hansen et al., 1986)

Figure 14: Surface of field time data for a disk harrowing operation (Hansen et al., 1986)
Figure 15: Surface of field time data for a ripping operation (Hansen et al., 1986)

Figure 16: Surface of field time data for a haulage operation (Hansen et al., 1986)
Figures 17 and 18 show plotted torque vs. time for a tilling operation. The only differences between these two conditions were the tiller blade shapes and rotation direction. The operation was performed in Bangkok clay soil. The PTO speed was 540 rpm (Salokhe and Ramalingam, 2002).

**Figure 17**: Torque signals measured for the scoop blades on reverse-rotary tiller (Salokhe and Ramalingam, 2002)

**Figure 18**: Torque signals recorded for C-blade rotary tiller with forward rotation (conventional) (Salokhe and Ramalingam, 2002)

**Implement Power Draw**
Because agricultural tractors are designed to perform a myriad of tasks, the American Society of Agricultural Engineers has developed equations for calculating the draft and rotary power for agricultural implements (ASAE, 2003). These equations and tables of coefficients yield an average value of the power required for each operation taking into account the dimensions of the implement and the conditions of the soil. As has been shown these power draws do vary significantly with time depending on the operation. However, the variations are periodic and can be predicted.
VEHICLE REQUIREMENTS
For fuel cell powered tractors to be considered viable competitors to diesel powered tractors they need to show similar performance. The information that follows discusses performance ranges for three groups of agricultural tractors in order to obtain performance set points for a fuel cell tractor. In each case three groups of tractors were evaluated based on their PTO power. The first group consisted of tractors with PTO power of up to 20 kW, the next group with PTO power between 20 and 200 kW, and finally tractors with a PTO power greater than 200 kW.

Traction Requirements
Tractors were originally designed around the basis of creating greater traction for vehicles used in off road work. Thus this topic has been studied in great depth. Presented below is only a slight mention of the overall subject. Traction has been defined as “the force derived from the interaction between a device and a medium that can be used to facilitate a desired motion over the medium” (Gill, 1986). The net traction for a tractor drive wheel is determined by Equations 1 and 2 below (ASAE, 2003).

\[
NT = W \left( 0.88 \left( 1 - e^{-0.1B_n} \right) \left( 1 - e^{-7.5s} \right) - \frac{1}{B_n} - \frac{0.5s}{\sqrt{B_n}} \right)
\]

\[
B_n = \left( \frac{CI bd}{W} \right) \left( \frac{1 + \frac{\delta}{h}}{1 + 3 \frac{b}{d}} \right)
\]

Where:
- \( S \) = Slip
- \( W \) = Dynamic wheel load in force units normal to the soil surface
- \( CI \) = Cone index for the soil
- \( b \) = Unloaded tire section width
- \( d \) = Unloaded tire diameter
- \( h \) = Tire section height
- \( \delta \) = Tire deflection

As can be seen by the equations above, traction is directly related to weight. Larger tractors can develop greater traction resulting in larger drawbar power. It is also important to realize in agricultural applications that traction improvements should not be accomplished at the detriment of the soil structure. Larger tractors might develop greater traction, but may also compact the soil, reducing aeration and causing erosion. Even before the engine power is available to the wheels, limited transmission efficiencies, which range between 82% and 87%, cut into the available power (ASAE, 2003). Wheel slip also plays a large role in the overall efficiency of the tractor accounting for an additional 7% to 12% (Ryu et al., 2003). The design for maximum efficiency requires sizing the available drawbar power to meet the net traction of the tractor.
Power Train Configurations
There are several variations of tractor drive train configurations especially when evaluating the differences between wheeled, tracked and articulated tractors. Figure 19 shows a block diagram of a standard tractor drive train.

![Block diagram of tractor power train]

Depending upon the vehicle a tractor transmission can transmit power to the rear drive wheels, the front drive wheels, as well as the front and rear PTOs. The transmission is vital to the effectiveness of the tractor since torque requirements can demand large variations during operation, and most often the maximum amount of engine power is required as has been shown. The transmissions are generally very costly due to the number of gears, and the high stress present under low RPM and high torque work.

Prime Mover Torque
The measure of prime mover torque is the moment that a vehicle can continuously exert through the drive wheels. The torque at the wheels is increased by the use of gear reduction, but the amount of torque available to the transmission is dependent on the engine characteristics. If the maximum torque the vehicle can supply is insufficient to meet the load the engine will stall. Thus with current tractor design it is important to have a sufficient torque reserve (or torque back-up) (Culpin, 1992). When an engine has a higher torque at an engine speed slower than that corresponding to the maximum power it is said to have a torque reserve. When operating at maximum power if a higher torque is required the engine speed drops and the torque increases to meet the demand.

From the data collected from the Nebraska tractor tests and OEM data it is seen that there is a large range of vehicles with different available torques. For tractors in between 20 to 200 kW the maximum torque output varied from 96 to 953 Ft Lb. For tractors with PTO power greater than 200 kW the maximum torque ranged from 901 to 1757 Ft Lb. In every case the tractors evaluated had a torque reserve. (There was no torque available for the tractors with less than 20 kW of PTO power).

Vehicle Speed and Acceleration
Generally speaking tractors are not evaluated on the time it takes to accelerate from 0 to 60 mph. That is because most tractors are not designed to work at 60 mph. Although acceleration is not a key factor in agricultural vehicles for a
comparison of a fuel cell tractor to a traditional tractor acceleration should be similar. It would be useful to have a simulation to predict the acceleration of a tractor with changes made to the drive train. However, for an evaluation we can look at the laws of physics starting with Equation 3.

\[ F = ma \quad \text{EQ. 3} \]

If the mass of the tractor stays the same and the forces on the tractor are equivalent in the case of the fuel cell tractor and the internal combustion engine tractor than the acceleration should be the same. By making the torque equivalent the acceleration should also be equivalent.

The vehicle speed \( V \) is equal to the angular velocity of the wheels times the effective rolling radius of the wheels running on a particular soil. The angular velocity of the wheels depends on the torque supplied to the wheel and the tractive efficiency of the wheel (Zoz et al., 2002).

**Power Profiles**

A more detailed analysis of power profiles is given in the beginning of this report with data focusing mostly on field operations. It is believed that the power requirements, although transient in nature and dependent on the operation, are less variable for medium to large-scale tractors. For smaller tractors it is expected that the average use of the tractor will be chore work implying vast transient operations.

**Typical PTO by Class**

Max PTO power recorded at 540 RPM and 1000RPM was collected from the Nebraska tractor test reports, and when not available from the manufacturers. The data collected were divided into three tables: one for tractors with up to 20 kW of PTO power, next for tractors with PTO power between 20 kW and 200 kW and finally for tractors with PTO power greater than 200 kW, all of which can be seen in Appendix A. For each of the three groups examined there is a broad range of PTO powers available enabling a tractor choice for almost any power level, which is very different from the automobile market where distinct classes exist. It is the authors recommendation that if the goal is to build a prototype to compare with the 20 kW group of compact tractors that the highest power rating of 20 kW be chosen. However, with the broad ranges of available tractors it is difficult to give a general PTO requirement for each of these three groups.

**Typical Hydraulic Actuator Requirements by Class**

For the 20 kW tractor group the hydraulic power ranged from 4.1 to 9.4 kW. For the 20 to 200 kW group the hydraulic power ranged from 7.8 to 50.6 kW, and for the 200 kW and up group the hydraulic power varied from 26 to 51 kW (can be seen in Appendix A). It is also worthy to note that several tractors came with the option of an upgraded hydraulic pump yielding higher hydraulic power. In general it is difficult to choose a general hydraulic power requirement for each of these groups since the spread of possibilities is so vast just as in the case of PTO.
power. For the traditional tractors it was found that the hydraulic pump was powered by a mechanical connection to the engine. Although hydraulic power was recorded, the performance of the hydraulic systems can be very different in nature despite similar power. This is due to different uses, flow rates and pressures. Once again if a comparison was to be made it would be advisable to use a hydraulic system with similar specifications to the control tractor.

**Combine Harvesters**

Limited amount of information was available on the power profiles of combine harvesters. Table 3 shows power specifications for several combines collected from OEM data sheets. The combines are high power, and during the harvest are generally run continuously until the harvest is complete. Due to the number of functions taking place on the harvesters, and the current method of mechanical power transmission, it has been shown that the use of electric motors could prove advantageous in increasing overall efficiency and optimizing the use of space (Bernhard, 2003).

**Table 3**: Power specifications of combine harvesters

<table>
<thead>
<tr>
<th>Make</th>
<th>Model</th>
<th>Power</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>hp</td>
<td>kW</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>8680</td>
<td>260.0</td>
<td>193.9</td>
</tr>
<tr>
<td>John Deere</td>
<td>9560 STS</td>
<td>265.0</td>
<td>197.6</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>9690</td>
<td>285.0</td>
<td>212.5</td>
</tr>
<tr>
<td>Challenger</td>
<td>CH660</td>
<td>285.0</td>
<td>212.5</td>
</tr>
<tr>
<td>New Holland</td>
<td>CR940</td>
<td>295.0</td>
<td>220.0</td>
</tr>
<tr>
<td>New Holland</td>
<td>CX840</td>
<td>295.0</td>
<td>220.0</td>
</tr>
<tr>
<td>John Deere</td>
<td>9660 STS</td>
<td>305.0</td>
<td>227.4</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>9790</td>
<td>330.0</td>
<td>246.1</td>
</tr>
<tr>
<td>New Holland</td>
<td>CR960</td>
<td>330.0</td>
<td>246.1</td>
</tr>
<tr>
<td>New Holland</td>
<td>CX860</td>
<td>330.0</td>
<td>246.1</td>
</tr>
<tr>
<td>John Deere</td>
<td>9760 STS</td>
<td>340.0</td>
<td>253.5</td>
</tr>
<tr>
<td>Challenger</td>
<td>CH670</td>
<td>350.0</td>
<td>261.0</td>
</tr>
<tr>
<td>New Holland</td>
<td>CR970</td>
<td>370.0</td>
<td>275.9</td>
</tr>
<tr>
<td>New Holland</td>
<td>CX880</td>
<td>370.0</td>
<td>275.9</td>
</tr>
<tr>
<td>John Deere</td>
<td>9860 STS</td>
<td>375.0</td>
<td>279.6</td>
</tr>
<tr>
<td>Case IH</td>
<td>AFX8010</td>
<td>375.0</td>
<td>279.6</td>
</tr>
</tbody>
</table>
OPERATING REQUIREMENTS FOR A FUEL CELL POWER UNIT

Fuel cells have their highest efficiency at high voltages corresponding to lower loads through the cell polarization curve (Larminie, 2003). An equation for efficiency based on cell voltage can be seen in Equation 4.

\[
\text{Efficiency} = u \times \left( \frac{V_c}{1.48} \right) \times 100
\]

The typical power demand in agricultural vehicles is constant and high. Compared to current engine ratings, they are operated close to max RPM. To maintain a high efficiency the fuel cell stack would need to be oversized so that it would be able to run at an optimum power level. Since medium to large scale tractors are not subject to the constant unexpected variable loads seen by urban automobiles, and do not require heavy breaking, large scale hybridization would not be of much benefit (Schuller, 2002).

Power Train Differences Required to Accommodate the Fuel Cell

It is expected that due to the current series plate construction of fuel cell stacks that the vibration seen in off-road applications could be detrimental.

Temperature will also play a role for fuel cell tractors to be used in Midwest farming during the winter. Stack heaters and insulation will be required to protect the electrolyte and shorten start up times in severe cold. Depending on the operational temperature of the type of stack used cooling can also become an issue. PEM stacks currently used in automotive application have an operation range of 30-80°C. Unless cooling is to come from a source other than a water circulated radiator a very large surface area is going to be required especially on hot summer days.

Air purity is yet another concern for fuel cell systems since the poisoning of cell catalyst is the greatest current threat to operating stacks. A series of advanced air clean up devices should be required to ensure that the stack is not polluted by particulate matter.

Aside from the effects of vibration, temperature and air purity, the concept of a fuel cell powered tractor offers greater flexibility in power train layout since the components are not mechanically linked. This would enable the designers to place the components such that the overall vehicle has the weight distributed for optimum traction. A block diagram of a fuel cell powered tractor power train can be seen in Figure 20.
Dealing with Transients
The transient response of the fuel cell stack itself is not a limiting factor. It has been shown that a PEM fuel cell can reach 90% production within 1 second (Yan et al., 2005). Turbocharged Diesel response times have been shown to be on the order of 1.7 sec (Katrasnik et al., 2003). When dealing with fuel cell systems, the fuel processor has proven to be the limiting mechanism. It has been shown that the limiting process in the indirect liquid-fueled fuel cell power train is the slow response of the fuel reformer, which can take up to 20 seconds to ramp up to 99% of the flow demand (Emonts et al., 2000; Betts, 2002; Beckhaus et al., 2004).

The strategy behind a hybrid power train is to allow for the downsizing of the power plant by compensating with some other form of stored energy. This is a great strategy for vehicles that rarely run at full power such as cars, or an example found of a hybrid electric forest vehicle (Carlini et al., 1997). However, as can be seen by Figures 11 through 16 agricultural tractors are often run at full power for extended periods of time. Even in the case of the medium to large scale tractors some degree of hybridization is recommended. By designing a hybrid fuel cell system the advantage would be that you would be able to quickly provide power for any oscillatory demands, as well as be able to exceed the rated power for a short duration to overcome any abnormal obstacles.

VEHICLE ARCHITECTURE RECOMMENDATIONS
It is important to note that the basis of this study is on an analysis of power demand and load profiles only. Presented below is a comparison showing that the use of electric motors is well suited to the torque demands of agricultural work. Also discussed is recommendations by the author for fuel cell tractor prototypes in each of the three pre-designated groups.

Properties Of Diesel Engines Vs. Fuel Cell / Electric Motors
As previously mentioned several electric tractors have been developed. Their greatest shortcoming has been battery life, limiting the tractors to chore usage. If a fuel cell was used to power the electric tractor the strength of an electric tractor

---

**Figure 20**: Block diagram of fuel cell tractor power train

The electric transmission of power affords the elimination of costly transmissions and uncouples the power generation from the usage.
could be fully realized, which is the electric motor. One of the important factors in tractor engine design is having a torque reserve so that, for example, when a plow hits a tree root, or a large stone, the engine output increases in torque as the speed drops, otherwise in the case of an IC engine it will stall. As can be seen Figure 21 electric motors are great in this regard (the electric motor in Figure 21 is a series wound DC traction motor). If we also compare the efficiency plot in Figure 21 back to the usage plots in Figures 11 through 16 we can see that if an electric motor was being used that the motor efficiency would almost always be at maximum.

![Figure 21: Comparison between electric and diesel motor characteristics, which have identical power ratings (Christianson, 1984)](image)

During the literature review it was found that several computer models have been created to evaluate tractive efficiency of tractors as well as the draft of pulled implements (Sonnen, 1969; Clark, 1981; Dwyer, 1987). As mentioned previously implement draft can be found using the ASAE standards if soil composition is known (ASAE, 2003). There have also been several models developed to evaluate tractive efficiency and vehicle performance on an economic scale (Al-Janobi, 2002). It is recommended that a more comprehensive model be developed to evaluate possible drive train design taking into account the often variable nature of the load profile with outputs such as vehicle performance, efficiency and fuel consumption. ADVISOR is one example of a simulation program developed to evaluate different automobile power train configurations including fuel cells (Markel et al., 2002; Maxoulis et al., 2004).

**Vehicle Recommendations**

Without a detailed computational analysis it is difficult to determine what architecture would yield the best performance. However, from the data collected on the uses of different sized tractors and the response times of fuel processors. The following is recommended.

For small tractors to be used for personal or chore usage which would currently fall into the category of less than 20 kW it is recommended that a slightly larger
fuel cell stack of 25 kW be used with a direct drive electric motor. Compressed hydrogen would yield the fast transient response times required, and a moderate level of hybridization should be used to recoup the energy that would otherwise be lost by frequent stops and starts. Aside from the main drive motor, an additional hydraulic pump motor should be used to provide hydraulic power. An additional motor designed to operate at 540 rpm could be used to supply PTO power and enable the motor to be optimized for operation at that speed.

For medium scale tractors that currently utilize 20 to 200 kW of power the load profiles have shown to be relatively constant with predictable transients. For this class of vehicles it is also recommended that the fuel cell stack be slightly larger than the current compression engine counterpart. Studies have shown that the vehicles are most often operated at maximum power, and to obtain the highest possible efficiency out of the fuel cell stack it would be ideal to operate the stack at partial power. For ease of operation and longer hours of operation it is recommended that vehicles of this class use on board liquid fuel reformers, with a small degree of hybridization to handle unexpected transients. Since the load profiles of the operations performed by these vehicles is fairly predictable and generally continues for many hours at a time the liquid fuel option is well suited.

For ease of implementation a single electric motor could directly replace the internal combustion engine on a current tractor chassis retaining the use of the transmission. If implementation costs are not an issue there could be separate motors used for prime motive force, the hydraulic pump and each PTO connection.

The largest class of agricultural tractor evaluated is those that are over 200 kW. These vehicles would be best suited to a similar architecture as the medium scale tractors.

It is anticipated that for fuel cell vehicles to be used in agricultural applications, eventually, drawn implements that currently use PTO power could be fitted with their own electric motor(s), and a cable could be run to the implement to supply power. This would yield overall increases in efficiency since the fuel conversion of the fuel cell is greater than that of the internal combustion engine, and the efficiency of the electric motor is generally higher than that of the transmission of power through the mechanical transmission, universal joint(s) of the PTO and mechanical transmission of the implement. The elimination of the universal joints connecting the PTO outlet to the implement would also afford a greater degree of flexibility in operation.

If fuel cells were to be tested for use in large scale tractors it is recommended that combine harvesters be a starting point. The elimination of the numerous mechanical transmissions of power from the engine to the individual processes could result in much greater efficiencies. Also the size of combines would easily comply with the requirements of an indirect liquid fueled fuel cell.
CONCLUSION AND RECOMMENDATIONS
As has been shown the electric motors are a good match to the power characteristics required by agricultural work. On the basis of load profiles alone the authors would highly recommend the use of a hybrid fuel cell power train for medium to large agricultural tractors (Carlini et al., 1997).

It is recommended that further studies be performed to research the effect of energy density in tractor systems to determine if the size and weight of acceptable fuel cell systems are compatible with off road use. A vehicle simulation should be made to facilitate a parametric evaluation of possible power trains and their economical impacts.
### APPENDIX

#### Table A1: Tractor data for small tractors with up to 20 kW of PTO power

<table>
<thead>
<tr>
<th>Make</th>
<th>Drive</th>
<th>Model</th>
<th>Weight (kg)</th>
<th>Weight (LB)</th>
<th>Power at 540 PTO RPM (kW)</th>
<th>Power at 540 PTO RPM (hp)</th>
<th>Hydraulic power at 540 PTO RPM (kW)</th>
<th>Hydraulic power at 540 PTO RPM (hp)</th>
<th>Hitch Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massey Ferguson</td>
<td>Std.</td>
<td>MF 1417-4</td>
<td>645</td>
<td>1422</td>
<td>9.9</td>
<td>13.3</td>
<td>4.1</td>
<td>5.4</td>
<td>1</td>
</tr>
<tr>
<td>Case-IH</td>
<td>Std.</td>
<td>DX18E</td>
<td>596</td>
<td>1314</td>
<td>10.2</td>
<td>13.7</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>New Holland</td>
<td>Std.</td>
<td>TZ18DA</td>
<td>595</td>
<td>1311</td>
<td>10.2</td>
<td>13.7</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>John Deere</td>
<td>4WD</td>
<td>4010</td>
<td>644</td>
<td>1420</td>
<td>10.4</td>
<td>14.0</td>
<td>4.9</td>
<td>6.6</td>
<td>1</td>
</tr>
<tr>
<td>Case-IH</td>
<td>Std.</td>
<td>DX22E</td>
<td>596</td>
<td>1314</td>
<td>12.7</td>
<td>17.0</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>New Holland</td>
<td>Std.</td>
<td>TZ22DA</td>
<td>599</td>
<td>1320</td>
<td>12.7</td>
<td>17.0</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Case-IH</td>
<td>Std.</td>
<td>DX23</td>
<td>722</td>
<td>1592</td>
<td>13.0</td>
<td>17.5</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>John Deere</td>
<td>4WD</td>
<td>2210</td>
<td>635</td>
<td>1400</td>
<td>13.2</td>
<td>17.7</td>
<td>4.7</td>
<td>6.3</td>
<td>1</td>
</tr>
<tr>
<td>New Holland</td>
<td>Std.</td>
<td>TC23DA</td>
<td>722</td>
<td>1592</td>
<td>13.8</td>
<td>18.5</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>4WD</td>
<td>1523</td>
<td>695</td>
<td>1532</td>
<td>13.9</td>
<td>18.7</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>AGCO</td>
<td>4WD</td>
<td>ST24A</td>
<td>710</td>
<td>1565</td>
<td>14.2</td>
<td>19.0</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Case-IH</td>
<td>Std.</td>
<td>DX25E</td>
<td>600</td>
<td>1323</td>
<td>14.2</td>
<td>19.0</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>New Holland</td>
<td>Std.</td>
<td>TZ25DA</td>
<td>599</td>
<td>1320</td>
<td>14.2</td>
<td>19.0</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>AGCO</td>
<td>Std.</td>
<td>ST25</td>
<td>720</td>
<td>1588</td>
<td>14.5</td>
<td>19.5</td>
<td>5.1</td>
<td>6.9</td>
<td>1</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>Std.</td>
<td>MF 1423-4</td>
<td>679</td>
<td>1498</td>
<td>14.5</td>
<td>19.5</td>
<td>5.1</td>
<td>6.9</td>
<td>1</td>
</tr>
<tr>
<td>AGCO</td>
<td>4WD</td>
<td>ST22A</td>
<td>620</td>
<td>1367</td>
<td>14.7</td>
<td>19.7</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Case-IH</td>
<td>Std.</td>
<td>DX26</td>
<td>726</td>
<td>1600</td>
<td>14.7</td>
<td>19.7</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>New Holland</td>
<td>Std.</td>
<td>TC26DA</td>
<td>726</td>
<td>1600</td>
<td>15.3</td>
<td>20.5</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>Std.</td>
<td>MF 1429-4</td>
<td>1240</td>
<td>2734</td>
<td>17.2</td>
<td>23.0</td>
<td>8.1</td>
<td>10.9</td>
<td>1</td>
</tr>
<tr>
<td>Case-IH</td>
<td>Std.</td>
<td>DX29</td>
<td>1122</td>
<td>2474</td>
<td>17.6</td>
<td>23.6</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>790</td>
<td>975</td>
<td>2150</td>
<td>17.9</td>
<td>24.0</td>
<td>5.0</td>
<td>6.7</td>
<td>1</td>
</tr>
<tr>
<td>AGCO</td>
<td>Std.</td>
<td>ST30x</td>
<td>1147</td>
<td>2528</td>
<td>18.3</td>
<td>24.5</td>
<td>6.9</td>
<td>9.3</td>
<td>1</td>
</tr>
<tr>
<td>AGCO</td>
<td>4WD</td>
<td>ST28A</td>
<td>1000</td>
<td>2205</td>
<td>18.3</td>
<td>24.5</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>4WD</td>
<td>MF 1428V-2/4</td>
<td>1064</td>
<td>2345</td>
<td>18.3</td>
<td>24.5</td>
<td>6.9</td>
<td>9.3</td>
<td>1</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>4WD</td>
<td>1528</td>
<td>1099</td>
<td>2423</td>
<td>18.3</td>
<td>24.5</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>4WD</td>
<td>1531</td>
<td>1099</td>
<td>2423</td>
<td>18.3</td>
<td>24.5</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>New Holland</td>
<td>Std.</td>
<td>TC29DA</td>
<td>1122</td>
<td>2474</td>
<td>18.6</td>
<td>25.0</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>AGCO</td>
<td>Std.</td>
<td>ST32</td>
<td>1198</td>
<td>2642</td>
<td>19.3</td>
<td>25.9</td>
<td>7.2</td>
<td>9.7</td>
<td>1</td>
</tr>
<tr>
<td>AGCO</td>
<td>4WD</td>
<td>ST33A</td>
<td>1000</td>
<td>2205</td>
<td>19.3</td>
<td>25.9</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Make</td>
<td>Drive</td>
<td>Model</td>
<td>Weight (kg)</td>
<td>Weight (LB)</td>
<td>Power at 540 PTO RPM (kW)</td>
<td>Power at 540 PTO RPM (hp)</td>
<td>Hydraulic power (kW)</td>
<td>Hydraulic power (hp)</td>
<td>Hitch Class</td>
</tr>
<tr>
<td>-----------------</td>
<td>-------</td>
<td>----------</td>
<td>-------------</td>
<td>-------------</td>
<td>---------------------------</td>
<td>--------------------------</td>
<td>----------------------</td>
<td>----------------------</td>
<td>--------------</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>Std.</td>
<td>MF 1431-4</td>
<td>1069</td>
<td>2356</td>
<td>19.3</td>
<td>25.9</td>
<td>7.2</td>
<td>9.7</td>
<td>1</td>
</tr>
<tr>
<td>AGCO</td>
<td>4WD</td>
<td>ST34A</td>
<td>1290</td>
<td>2844</td>
<td>19.4</td>
<td>26.0</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>4WD</td>
<td>1533</td>
<td>1290</td>
<td>2844</td>
<td>19.4</td>
<td>26.0</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Challenger</td>
<td>4WD</td>
<td>MT265B</td>
<td>1422</td>
<td>3136</td>
<td>19.4</td>
<td>26.0</td>
<td>9.4</td>
<td>12.6</td>
<td>1</td>
</tr>
</tbody>
</table>

Note: All of the data presented is from the manufacturers, since the Nebraska tests do not give results for compact tractors. Hence, max drawbar pull and max torque were unavailable.
Table A2: Tractor data for medium scale tractors with PTO power ratings between 20 kW and 200 kW

<table>
<thead>
<tr>
<th>Make</th>
<th>Drive</th>
<th>Model</th>
<th>Weight (kg)</th>
<th>Power at 540 PTO RPM (kW)</th>
<th>Power at 1000 PTO RPM (kW)</th>
<th>Hydraulic power Hitch Class</th>
<th>Hitch Class</th>
<th>Max draw bar pull unballasted (lb)</th>
<th>Max torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case-IH</td>
<td>Std.</td>
<td>DX33</td>
<td>1122</td>
<td>20.1</td>
<td>26.9</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>AGCO</td>
<td>Std.</td>
<td>ST35</td>
<td>1437</td>
<td>20.1</td>
<td>27.0</td>
<td>8.4</td>
<td>11.3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>AGCO</td>
<td>Std.</td>
<td>ST35x</td>
<td>1399</td>
<td>20.1</td>
<td>27.0</td>
<td>8.4</td>
<td>11.3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>Std.</td>
<td>MF 1433-4</td>
<td>1275</td>
<td>20.1</td>
<td>27.0</td>
<td>8.4</td>
<td>11.3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>Std.</td>
<td>MF 1433V-4</td>
<td>1265</td>
<td>20.1</td>
<td>27.0</td>
<td>8.4</td>
<td>11.3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>New Holland</td>
<td>Std.</td>
<td>TC33DA</td>
<td>1122</td>
<td>21.3</td>
<td>28.6</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>John Deere</td>
<td>4WD</td>
<td>4410</td>
<td>1284</td>
<td>21.6</td>
<td>29.0</td>
<td>15.0</td>
<td>20.1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Case-IH</td>
<td>Std.</td>
<td>D/DX35</td>
<td>1497</td>
<td>21.7</td>
<td>29.1</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>New Holland</td>
<td>Std.</td>
<td>TC35DA</td>
<td>1523</td>
<td>21.7</td>
<td>29.1</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>New Holland</td>
<td>Std.</td>
<td>TC35A</td>
<td>1466</td>
<td>22.1</td>
<td>29.6</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>AGCO</td>
<td>4WD</td>
<td>ST41A</td>
<td>1310</td>
<td>23.1</td>
<td>31.0</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>4WD</td>
<td>1540</td>
<td>1310</td>
<td>23.1</td>
<td>31.0</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Challenger</td>
<td>4WD</td>
<td>MT275B</td>
<td>1437</td>
<td>23.1</td>
<td>31.0</td>
<td>9.4</td>
<td>12.6</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>AGCO</td>
<td>Std.</td>
<td>ST40</td>
<td>1507</td>
<td>24.2</td>
<td>32.4</td>
<td>8.4</td>
<td>11.3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>AGCO</td>
<td>Std.</td>
<td>ST40x</td>
<td>1442</td>
<td>24.2</td>
<td>32.4</td>
<td>8.4</td>
<td>11.3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>Std.</td>
<td>MF 1440-4</td>
<td>1361</td>
<td>24.2</td>
<td>32.4</td>
<td>8.4</td>
<td>11.3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>Std.</td>
<td>MF 1440V-4</td>
<td>1331</td>
<td>24.2</td>
<td>32.4</td>
<td>8.4</td>
<td>11.3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Case-IH</td>
<td>Std.</td>
<td>D/DX40</td>
<td>1531</td>
<td>24.8</td>
<td>33.2</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>New Holland</td>
<td>Std.</td>
<td>TC40DA</td>
<td>1557</td>
<td>24.8</td>
<td>33.2</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>New Holland</td>
<td>Std.</td>
<td>TC40A</td>
<td>1544</td>
<td>26.1</td>
<td>35.0</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>AGCO</td>
<td>Std.</td>
<td>ST45</td>
<td>2018</td>
<td>27.6</td>
<td>37.0</td>
<td>9.6</td>
<td>12.9</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>Std.</td>
<td>MF1445-4</td>
<td>1753</td>
<td>27.6</td>
<td>37.0</td>
<td>9.3</td>
<td>12.5</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Case-IH</td>
<td>Std.</td>
<td>D/DX45</td>
<td>1648</td>
<td>28.2</td>
<td>37.8</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>New Holland</td>
<td>Std.</td>
<td>TC45DA</td>
<td>1696</td>
<td>28.2</td>
<td>37.8</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>AGCO</td>
<td>4WD</td>
<td>ST47A</td>
<td>1585</td>
<td>28.3</td>
<td>38.0</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>4WD</td>
<td>1547</td>
<td>1585</td>
<td>28.3</td>
<td>38.0</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Challenger</td>
<td>4WD</td>
<td>MT285B</td>
<td>1660</td>
<td>28.3</td>
<td>38.0</td>
<td>11.0</td>
<td>14.8</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>DX48</td>
<td>1957</td>
<td>28.8</td>
<td>38.6</td>
<td>8.6</td>
<td>11.5</td>
<td>1</td>
<td>96</td>
</tr>
<tr>
<td>Make</td>
<td>Drive</td>
<td>Model</td>
<td>Weight (kg)</td>
<td>Power at 540 PTO RPM (kW)</td>
<td>Power at 1000 PTO RPM (kW)</td>
<td>Hydraulic power (kW)</td>
<td>Hitch Class</td>
<td>Max draw bar pull unballasted (lb)</td>
<td>Max torque (lb ft)</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-------</td>
<td>------------------------</td>
<td>-------------</td>
<td>----------------------------</td>
<td>----------------------------</td>
<td>----------------------</td>
<td>-------------</td>
<td>-----------------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>New Holland FWA TC 48DA - New</td>
<td></td>
<td></td>
<td>1957</td>
<td>28.8</td>
<td>8.6</td>
<td>1</td>
<td>96</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>New Holland Std. TC45A</td>
<td></td>
<td></td>
<td>1567</td>
<td>29.5</td>
<td>12.5</td>
<td>1</td>
<td>96</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>Case-IH FWA CX 50/C50</td>
<td></td>
<td></td>
<td>3445</td>
<td>30.5</td>
<td>12.0</td>
<td>2</td>
<td>7990</td>
<td>121</td>
<td>164</td>
</tr>
<tr>
<td>AGCO 4WD ST52A</td>
<td></td>
<td></td>
<td>1625</td>
<td>30.6</td>
<td>12.0</td>
<td>1</td>
<td>96</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>Massey Ferguson 4WD 1552</td>
<td></td>
<td></td>
<td>1585</td>
<td>30.6</td>
<td>12.0</td>
<td>1</td>
<td>96</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>Challenger 4WD MT295B</td>
<td></td>
<td></td>
<td>1690</td>
<td>30.6</td>
<td>12.0</td>
<td>1</td>
<td>96</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>Case-IH FWA JX 55</td>
<td></td>
<td></td>
<td>2756</td>
<td>31.6</td>
<td>12.2</td>
<td>2</td>
<td>3680</td>
<td>115</td>
<td>156</td>
</tr>
<tr>
<td>Massey Ferguson FWA 243</td>
<td></td>
<td></td>
<td>2327</td>
<td>31.7</td>
<td>12.2</td>
<td>2</td>
<td>4310</td>
<td>133</td>
<td>180</td>
</tr>
<tr>
<td>New Holland FWA TN 55D</td>
<td></td>
<td></td>
<td>2901</td>
<td>31.8</td>
<td>12.5</td>
<td>2</td>
<td>5030</td>
<td>136</td>
<td>185</td>
</tr>
<tr>
<td>White FWA 6045</td>
<td></td>
<td></td>
<td>2216</td>
<td>32.9</td>
<td>10.5</td>
<td>1</td>
<td>5115</td>
<td>132</td>
<td>179</td>
</tr>
<tr>
<td>Case-IH FWA JX 55 series II - New</td>
<td></td>
<td></td>
<td>2756</td>
<td>33.7</td>
<td>12.2</td>
<td>2</td>
<td>5180</td>
<td>133</td>
<td>181</td>
</tr>
<tr>
<td>AGCO Std. ST55</td>
<td></td>
<td></td>
<td>2004</td>
<td>34.0</td>
<td>12.8</td>
<td>1</td>
<td>96</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>Massey Ferguson Std. MF 1455-4</td>
<td></td>
<td></td>
<td>1720</td>
<td>34.0</td>
<td>12.8</td>
<td>1</td>
<td>96</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>Massey Ferguson Std. MF 1455V-2/4</td>
<td></td>
<td></td>
<td>1615</td>
<td>34.0</td>
<td>12.8</td>
<td>1</td>
<td>96</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>John Deere FWA 5210/5220</td>
<td></td>
<td></td>
<td>2300</td>
<td>34.4</td>
<td>11.9</td>
<td>1</td>
<td>130</td>
<td>176</td>
<td></td>
</tr>
<tr>
<td>Massey Ferguson FWA 2210</td>
<td></td>
<td></td>
<td>2506</td>
<td>34.5</td>
<td>13.0</td>
<td>2</td>
<td>133</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>John Deere Std. 5105 (late)</td>
<td></td>
<td></td>
<td>2041</td>
<td>35.2</td>
<td>10.4</td>
<td>1</td>
<td>133</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>Case-IH FWA JX 65</td>
<td></td>
<td></td>
<td>2781</td>
<td>35.6</td>
<td>9.5</td>
<td>2</td>
<td>3680</td>
<td>129</td>
<td>176</td>
</tr>
<tr>
<td>Case-IH FWA DX55</td>
<td></td>
<td></td>
<td>2125</td>
<td>35.6</td>
<td>9.2</td>
<td>1</td>
<td>122</td>
<td>165</td>
<td></td>
</tr>
<tr>
<td>New Holland FWA TC 55 DA - New</td>
<td></td>
<td></td>
<td>2125</td>
<td>35.6</td>
<td>9.2</td>
<td>1</td>
<td>122</td>
<td>165</td>
<td></td>
</tr>
<tr>
<td>Massey Ferguson FWA 263</td>
<td></td>
<td></td>
<td>2318</td>
<td>36.7</td>
<td>11.6</td>
<td>2</td>
<td>4520</td>
<td>161</td>
<td>219</td>
</tr>
<tr>
<td>John Deere FWA 5205 (late)</td>
<td></td>
<td></td>
<td>2161</td>
<td>37.8</td>
<td>11.0</td>
<td>2</td>
<td>0.00</td>
<td>142</td>
<td></td>
</tr>
<tr>
<td>New Holland FWA TN-65</td>
<td></td>
<td></td>
<td>2549</td>
<td>38.6</td>
<td>12.5</td>
<td>2</td>
<td>7155</td>
<td>146</td>
<td>199</td>
</tr>
<tr>
<td>New Holland FWA TN 65D</td>
<td></td>
<td></td>
<td>2930</td>
<td>39.1</td>
<td>12.5</td>
<td>2</td>
<td>6785</td>
<td>151</td>
<td>206</td>
</tr>
<tr>
<td>Massey Ferguson FWA 4225</td>
<td></td>
<td></td>
<td>3461</td>
<td>39.8</td>
<td>11.5</td>
<td>2</td>
<td>7680</td>
<td>174</td>
<td>237</td>
</tr>
<tr>
<td>Make</td>
<td>Drive</td>
<td>Model</td>
<td>Weight</td>
<td>Power at 540 PTO RPM</td>
<td>Power at 1000 PTO RPM</td>
<td>Hydraulic power</td>
<td>Hitch Class</td>
<td>Max draw bar pull unballasted</td>
<td>Max torque</td>
</tr>
<tr>
<td>---------------------------</td>
<td>-------</td>
<td>---------------------------------------</td>
<td>--------</td>
<td>----------------------</td>
<td>-----------------------</td>
<td>-----------------</td>
<td>-------------</td>
<td>--------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(kg) (LB)</td>
<td></td>
<td>(kW) (hp)</td>
<td>(kW) (hp)</td>
<td>(kW) (hp)</td>
<td></td>
<td>(lb) (kN) (lb ft) (Nm)</td>
<td></td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>4325 (also 4225)</td>
<td>3461</td>
<td>7630</td>
<td>39.8 53.4</td>
<td>11.5 15.4</td>
<td>2</td>
<td>7680 34.16</td>
<td>174.7 237</td>
</tr>
<tr>
<td>Challenger</td>
<td>FWA</td>
<td>MT 425</td>
<td>3461</td>
<td>7630</td>
<td>39.8 53.4</td>
<td>11.5 15.4</td>
<td>2</td>
<td>7680 34.16</td>
<td>174.7 237</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>CX 60/C60</td>
<td>3450</td>
<td>7605</td>
<td>41.0 55.0</td>
<td>11.8 15.8</td>
<td>2</td>
<td>9160 40.75</td>
<td>161 218</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>5310/5320</td>
<td>2336</td>
<td>5150</td>
<td>41.7 55.9</td>
<td>12.1 16.2</td>
<td>2</td>
<td>0.00 168</td>
<td>228</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>JX 75</td>
<td>3073</td>
<td>6775</td>
<td>42.0 56.3</td>
<td>9.5 12.8</td>
<td>2</td>
<td>3930 17.48</td>
<td>153.3 208</td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TL 70D</td>
<td>3740</td>
<td>8245</td>
<td>42.1 56.5</td>
<td>11.6 15.6</td>
<td>2</td>
<td>9065 40.32</td>
<td>170.4 231</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>2220</td>
<td>2245</td>
<td>4950</td>
<td>42.8 57.3</td>
<td>9.7 13.0</td>
<td>2</td>
<td>169 229</td>
<td></td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>JX 65 series II - New</td>
<td>2781</td>
<td>6130</td>
<td>44.6 59.8</td>
<td>10.6 14.2</td>
<td>2</td>
<td>4625 20.57</td>
<td>172.5 234</td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TN 70D</td>
<td>2570</td>
<td>5665</td>
<td>44.6 59.8</td>
<td>12.5 16.7</td>
<td>2</td>
<td>7375 32.81</td>
<td>179.2 243</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>JX 75 series II - New</td>
<td>3307</td>
<td>7290</td>
<td>47.3 63.4</td>
<td>11.0 14.7</td>
<td>2</td>
<td>6190 27.53</td>
<td>153.3 208</td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TN 75D</td>
<td>2930</td>
<td>6460</td>
<td>47.5 63.7</td>
<td>15.2 20.4</td>
<td>2</td>
<td>2438 10.84</td>
<td>202.2 274</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>4233</td>
<td>3146</td>
<td>6935</td>
<td>48.3 64.8</td>
<td>50.7 68.0</td>
<td>2</td>
<td>6970 31.00</td>
<td>197.5 268</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>4335 (also 4233)</td>
<td>3146</td>
<td>6935</td>
<td>48.3 64.8</td>
<td>50.7 68.0</td>
<td>2</td>
<td>6970 31.00</td>
<td>197.5 268</td>
</tr>
<tr>
<td>Challenger</td>
<td>FWA</td>
<td>MT 445</td>
<td>3146</td>
<td>6935</td>
<td>48.3 64.8</td>
<td>50.7 68.0</td>
<td>2</td>
<td>6970 31.00</td>
<td>197.5 268</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>JX 80U</td>
<td>3699</td>
<td>8155</td>
<td>48.5 65.0</td>
<td>14.7 19.7</td>
<td>2</td>
<td>9105 40.50</td>
<td>186.4 253</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>4235</td>
<td>3713</td>
<td>8185</td>
<td>48.6 65.2</td>
<td>49.7 66.6</td>
<td>2</td>
<td>8545 38.01</td>
<td>211.5 287</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>5410/5420</td>
<td>2624</td>
<td>5785</td>
<td>48.8 65.4</td>
<td>16.3 21.9</td>
<td>2</td>
<td>204 277</td>
<td></td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>JX 85</td>
<td>3173</td>
<td>6995</td>
<td>49.1 65.8</td>
<td>9.5 12.8</td>
<td>2</td>
<td>4460 19.84</td>
<td>169.7 230</td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TL 80D</td>
<td>3740</td>
<td>8245</td>
<td>49.2 66.0</td>
<td>11.6 15.6</td>
<td>2</td>
<td>9195 40.90</td>
<td>188.4 255</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>6110 PQ</td>
<td>4300</td>
<td>9480</td>
<td>51.8 69.4</td>
<td>25.2 33.8</td>
<td>2</td>
<td>10145 45.13</td>
<td>231 313</td>
</tr>
<tr>
<td>Challenger</td>
<td>FWA</td>
<td>MT 455</td>
<td>3731</td>
<td>8225</td>
<td>55.6 74.5</td>
<td>57.8 77.5</td>
<td>2</td>
<td>8950 39.81</td>
<td>241.3 327</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>4245 and 4243</td>
<td>3731</td>
<td>8225</td>
<td>55.8 74.8</td>
<td>57.8 77.5</td>
<td>2</td>
<td>8950 39.81</td>
<td>241.3 327</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>5510/5520</td>
<td>2885</td>
<td>6360</td>
<td>56.9 76.2</td>
<td>16.6 22.3</td>
<td>2</td>
<td>236 320</td>
<td></td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>JX 85 series II - New</td>
<td>3484</td>
<td>7680</td>
<td>57.0 76.4</td>
<td>13.5 18.1</td>
<td>2</td>
<td>6520 29.00</td>
<td>239.8 325</td>
</tr>
<tr>
<td>Make</td>
<td>Drive</td>
<td>Model</td>
<td>Weight (kg)</td>
<td>Power at 540 PTO RPM (kW)</td>
<td>Power at 1000 PTO RPM (kW)</td>
<td>Hydraulic power (kW)</td>
<td>Hitch Class</td>
<td>Max draw bar pull unballasted (lb)</td>
<td>Max torque (Nm)</td>
</tr>
<tr>
<td>---------------</td>
<td>-------</td>
<td>------------------------</td>
<td>-------------</td>
<td>---------------------------</td>
<td>---------------------------</td>
<td>----------------------</td>
<td>-------------</td>
<td>----------------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>JX 90U</td>
<td>3951</td>
<td>60.3</td>
<td>80.9</td>
<td>14.7</td>
<td>2</td>
<td>9285</td>
<td>213.5</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>JX 95 series II - New</td>
<td>3454</td>
<td>60.6</td>
<td>81.3</td>
<td>11.9</td>
<td>2</td>
<td>6500</td>
<td>219.7</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>JX 95</td>
<td>3454</td>
<td>60.9</td>
<td>81.7</td>
<td>9.5</td>
<td>2</td>
<td>4115</td>
<td>206.4</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>JX 100U</td>
<td>3951</td>
<td>62.0</td>
<td>83.1</td>
<td>14.7</td>
<td>2</td>
<td>9510</td>
<td>243.8</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>4253 and 4255</td>
<td>3824</td>
<td>62.1</td>
<td>83.3</td>
<td>64.7</td>
<td>2</td>
<td>9170</td>
<td>269.4</td>
</tr>
<tr>
<td>Challenger</td>
<td>FWA</td>
<td>MT 465</td>
<td>3824</td>
<td>62.1</td>
<td>83.3</td>
<td>64.7</td>
<td>2</td>
<td>9170</td>
<td>269.4</td>
</tr>
<tr>
<td>AGCO Allis</td>
<td>FWA</td>
<td>5650</td>
<td>2141</td>
<td>64.7</td>
<td>86.7</td>
<td>11.1</td>
<td>2</td>
<td>4385</td>
<td>218</td>
</tr>
<tr>
<td>AGCO Allis</td>
<td>FWA</td>
<td>5660</td>
<td>2350</td>
<td>64.7</td>
<td>86.7</td>
<td>11.1</td>
<td>2</td>
<td>4795</td>
<td>218</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>CX 70/C70</td>
<td>3749</td>
<td>64.7</td>
<td>86.7</td>
<td>11.1</td>
<td>2</td>
<td>9485</td>
<td>185</td>
</tr>
<tr>
<td>McCormick</td>
<td>FWA</td>
<td>CX-70</td>
<td>3749</td>
<td>64.7</td>
<td>86.7</td>
<td>11.1</td>
<td>2</td>
<td>9485</td>
<td>185</td>
</tr>
<tr>
<td>McCormick</td>
<td>FWA</td>
<td>CX-75</td>
<td>3749</td>
<td>64.7</td>
<td>86.7</td>
<td>11.1</td>
<td>2</td>
<td>9485</td>
<td>185</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>MX 80C</td>
<td>4799</td>
<td>64.7</td>
<td>86.7</td>
<td>11.1</td>
<td>2</td>
<td>11080</td>
<td>231</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>6120 SP</td>
<td>4241</td>
<td>64.7</td>
<td>86.7</td>
<td>11.1</td>
<td>2</td>
<td>7395</td>
<td>231</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>CX 80/C80</td>
<td>3690</td>
<td>64.7</td>
<td>86.7</td>
<td>11.1</td>
<td>2</td>
<td>9530</td>
<td>231</td>
</tr>
<tr>
<td>McCormick</td>
<td>FWA</td>
<td>CX-80</td>
<td>3690</td>
<td>64.7</td>
<td>86.7</td>
<td>11.1</td>
<td>2</td>
<td>9530</td>
<td>231</td>
</tr>
<tr>
<td>McCormick</td>
<td>FWA</td>
<td>CX-85</td>
<td>3690</td>
<td>64.7</td>
<td>86.7</td>
<td>11.1</td>
<td>2</td>
<td>9530</td>
<td>231</td>
</tr>
<tr>
<td>AGCO</td>
<td>Std.</td>
<td>LT70</td>
<td>3617</td>
<td>55.8</td>
<td>74.9</td>
<td>9.5</td>
<td>2</td>
<td>235</td>
<td>192</td>
</tr>
<tr>
<td>AGCO Allis</td>
<td>Std.</td>
<td>8745 (Cummins engine)</td>
<td>3617</td>
<td>55.8</td>
<td>74.9</td>
<td>9.5</td>
<td>2</td>
<td>235</td>
<td>192</td>
</tr>
<tr>
<td>White</td>
<td>Std.</td>
<td>6410</td>
<td>3617</td>
<td>55.8</td>
<td>74.9</td>
<td>9.5</td>
<td>2</td>
<td>235</td>
<td>192</td>
</tr>
<tr>
<td>AGCO Allis</td>
<td>Std.</td>
<td>8745</td>
<td>3536</td>
<td>56.2</td>
<td>75.3</td>
<td>9.1</td>
<td>2</td>
<td>240</td>
<td>192</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>MX 90C</td>
<td>5080</td>
<td>56.2</td>
<td>75.4</td>
<td>19.8</td>
<td>3</td>
<td>11935</td>
<td>236</td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TS 90 24 speed</td>
<td>4314</td>
<td>56.6</td>
<td>75.9</td>
<td>16.7</td>
<td>2</td>
<td>10330</td>
<td>239.5</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>6210 PQ</td>
<td>4359</td>
<td>56.7</td>
<td>76.0</td>
<td>16.7</td>
<td>2</td>
<td>10695</td>
<td>249</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>6220 PQ</td>
<td>4345</td>
<td>56.9</td>
<td>76.3</td>
<td>16.7</td>
<td>2</td>
<td>8115</td>
<td>252</td>
</tr>
<tr>
<td>AGCO</td>
<td>FWA</td>
<td>LT75 New</td>
<td>4354</td>
<td>58.9</td>
<td>79.0</td>
<td>15.9</td>
<td>2</td>
<td>240</td>
<td>192</td>
</tr>
<tr>
<td>Make</td>
<td>Drive</td>
<td>Model</td>
<td>Weight (kg)</td>
<td>Power at 540 PTO RPM (kW)</td>
<td>Power at 1000 PTO RPM (kW)</td>
<td>Hydraulic power Hitch Class</td>
<td>Hitch Class</td>
<td>Max draw bar pull unballasted (lb)</td>
<td>Max draw bar pull unballasted (kN)</td>
</tr>
<tr>
<td>--------------------</td>
<td>-------</td>
<td>-------------------------</td>
<td>-------------</td>
<td>---------------------------</td>
<td>-----------------------------</td>
<td>----------------------------</td>
<td>-------------</td>
<td>------------------------------------</td>
<td>-------------------------------------</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>6245</td>
<td>4230</td>
<td>59.3 79.5</td>
<td>16.2 21.7</td>
<td>2</td>
<td>7890</td>
<td>35.10 230.1</td>
<td>312</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>CX 90/C90</td>
<td>3976</td>
<td>60.5 81.1</td>
<td>14.2 19.1</td>
<td>2</td>
<td>9220</td>
<td>41.01 235</td>
<td>319</td>
</tr>
<tr>
<td>McCormick</td>
<td>FWA</td>
<td>CX-90 and CX-95</td>
<td>3706</td>
<td>60.5 81.1</td>
<td>14.2 19.1</td>
<td>2</td>
<td>9220</td>
<td>41.01 235</td>
<td>319</td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TL90D</td>
<td>3819</td>
<td>60.6 81.2</td>
<td>11.6 15.6</td>
<td>2</td>
<td>9285</td>
<td>41.30 215.6</td>
<td>292</td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TL 100D</td>
<td>3989</td>
<td>61.1 81.9</td>
<td>10.1 13.5</td>
<td>2</td>
<td>9525</td>
<td>42.37 244.7</td>
<td>332</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>6255</td>
<td>4454</td>
<td>62.1 83.3</td>
<td>16.2 21.7</td>
<td>2</td>
<td>8970</td>
<td>39.90 252.8</td>
<td>343</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>6310 PQ</td>
<td>4416</td>
<td>62.1 83.3</td>
<td>21.7 29.1</td>
<td>2</td>
<td>9415</td>
<td>41.88 267</td>
<td>362</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>6310 SP</td>
<td>4354</td>
<td>62.4 83.7</td>
<td>25.5 34.2</td>
<td>2</td>
<td>10090</td>
<td>44.88 273</td>
<td>370</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>6320 PQ</td>
<td>4550</td>
<td>63.9 85.7</td>
<td>31.7 42.5</td>
<td>2</td>
<td>9450</td>
<td>42.04 265</td>
<td>359</td>
</tr>
<tr>
<td>AGCO Allis</td>
<td>FWA</td>
<td>8765</td>
<td>3921</td>
<td>65.0 87.2</td>
<td>8.2 11.0</td>
<td>2</td>
<td>280</td>
<td>380</td>
<td>380</td>
</tr>
<tr>
<td>AGCO Allis</td>
<td>FWA</td>
<td>CX 100/C100</td>
<td>3756</td>
<td>65.0 87.2</td>
<td>13.9 18.7</td>
<td>2</td>
<td>9160</td>
<td>40.75 268</td>
<td>363</td>
</tr>
<tr>
<td>McCormick</td>
<td>FWA</td>
<td>CX-100 and CX-105</td>
<td>3756</td>
<td>65.0 87.2</td>
<td>13.9 18.7</td>
<td>2</td>
<td>9160</td>
<td>40.75 268</td>
<td>363</td>
</tr>
<tr>
<td>AGCO</td>
<td>FWA</td>
<td>LT90</td>
<td>4454</td>
<td>65.4 87.7</td>
<td>16.6 22.2</td>
<td>2</td>
<td>322</td>
<td>437</td>
<td>373</td>
</tr>
<tr>
<td>AGCO</td>
<td>Std.</td>
<td>LT85</td>
<td>3833</td>
<td>65.5 87.9</td>
<td>10.4 14.0</td>
<td>2</td>
<td>275</td>
<td>373</td>
<td>373</td>
</tr>
<tr>
<td>AGCO Allis</td>
<td>Std.</td>
<td>8765 (Cummins engine)</td>
<td>3833</td>
<td>65.5 87.9</td>
<td>10.4 14.0</td>
<td>2</td>
<td>275</td>
<td>373</td>
<td>373</td>
</tr>
<tr>
<td>White</td>
<td>Std.</td>
<td>6510</td>
<td>3833</td>
<td>65.5 87.9</td>
<td>10.4 14.0</td>
<td>2</td>
<td>275</td>
<td>373</td>
<td>373</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>6403</td>
<td>3969</td>
<td>65.7 88.1</td>
<td>13.9 18.6</td>
<td>2</td>
<td>7636</td>
<td>33.97 266</td>
<td>361</td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TS 100</td>
<td>4300</td>
<td>66.0 88.5</td>
<td>18.9 25.4</td>
<td>2</td>
<td>9780</td>
<td>43.50 276.4</td>
<td>375</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>6415</td>
<td>4300</td>
<td>67.6 90.7</td>
<td>18.3 24.5</td>
<td>2</td>
<td>9065</td>
<td>40.32 265</td>
<td>359</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>6410 PQ</td>
<td>4391</td>
<td>69.0 92.5</td>
<td>23.3 31.2</td>
<td>2</td>
<td>9480</td>
<td>42.17 293</td>
<td>397</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>4360 (also 4260, 4263)</td>
<td>4119</td>
<td>69.1 92.7</td>
<td>11.9 15.9</td>
<td>2</td>
<td>9420</td>
<td>41.90 270.2</td>
<td>366</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>6265</td>
<td>4781</td>
<td>70.5 94.5</td>
<td>16.2 21.7</td>
<td>2</td>
<td>10515</td>
<td>46.77 290.9</td>
<td>394</td>
</tr>
<tr>
<td>FENDT</td>
<td>FWA</td>
<td>410</td>
<td>5525</td>
<td>70.6 94.7</td>
<td>22.7 30.4</td>
<td>3</td>
<td>12730</td>
<td>56.63 333</td>
<td>451</td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TM 115</td>
<td>5334</td>
<td>70.7 94.8</td>
<td>30.3 40.7</td>
<td>2</td>
<td>11690</td>
<td>52.00 310.9</td>
<td>422</td>
</tr>
</tbody>
</table>
### Power at 540 PTO RPM

<table>
<thead>
<tr>
<th>Make</th>
<th>Drive</th>
<th>Model</th>
<th>Weight (kg)</th>
<th>Power at 540 PTO RPM (kW)</th>
<th>Power at 1000 PTO RPM (kW)</th>
<th>Hydraulic power Hitch Class (kW)</th>
<th>Hitch Class (hp)</th>
<th>Hitch Class (lb)</th>
<th>Hitch Class (kN)</th>
<th>Hitch Class (lb ft)</th>
<th>Hitch Class (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>6420 AQ</td>
<td>5039</td>
<td>71.6</td>
<td>31.6</td>
<td>42.4</td>
<td>2</td>
<td>9915</td>
<td>44.10</td>
<td>326</td>
<td>442</td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TS 110 24 speed</td>
<td>4443</td>
<td>72.9</td>
<td>17.4</td>
<td>23.3</td>
<td>2</td>
<td>10375</td>
<td>46.15</td>
<td>323.4</td>
<td>438</td>
</tr>
<tr>
<td>AGCO Allis</td>
<td>FWA</td>
<td>8775</td>
<td>4976</td>
<td>73.2</td>
<td>30.0</td>
<td>40.2</td>
<td>2</td>
<td>8807</td>
<td>39.18</td>
<td>298</td>
<td>404</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>6603</td>
<td>4266</td>
<td>73.4</td>
<td>17.0</td>
<td>22.8</td>
<td>2</td>
<td>8807</td>
<td>39.18</td>
<td>298</td>
<td>404</td>
</tr>
<tr>
<td>AGCO</td>
<td>FWA</td>
<td>RT95</td>
<td>5042</td>
<td>74.7</td>
<td>30.6</td>
<td>41.0</td>
<td>2</td>
<td>324</td>
<td>439</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AGCO Allis</td>
<td>FWA</td>
<td>8775</td>
<td>5042</td>
<td>74.7</td>
<td>30.6</td>
<td>41.0</td>
<td>2</td>
<td>324</td>
<td>439</td>
<td></td>
<td></td>
</tr>
<tr>
<td>White</td>
<td>FWA</td>
<td>6710</td>
<td>5042</td>
<td>74.7</td>
<td>30.6</td>
<td>41.0</td>
<td>2</td>
<td>324</td>
<td>439</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>4370 (also 4270)</td>
<td>4130</td>
<td>75.2</td>
<td>11.0</td>
<td>14.7</td>
<td>2</td>
<td>9330</td>
<td>41.50</td>
<td>316.6</td>
<td>429</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>7220</td>
<td>5366</td>
<td>75.2</td>
<td>29.4</td>
<td>39.4</td>
<td>2</td>
<td>11834</td>
<td>52.64</td>
<td>330</td>
<td>447</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>6270</td>
<td>4781</td>
<td>77.2</td>
<td>16.2</td>
<td>21.7</td>
<td>2</td>
<td>9690</td>
<td>43.10</td>
<td>316.1</td>
<td>429</td>
</tr>
<tr>
<td>Challenger</td>
<td>FWA</td>
<td>MT 535</td>
<td>4781</td>
<td>77.2</td>
<td>30.6</td>
<td>41.0</td>
<td>2</td>
<td>9690</td>
<td>43.10</td>
<td>316.1</td>
<td>429</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>6615</td>
<td>4840</td>
<td>77.2</td>
<td>18.9</td>
<td>25.3</td>
<td>2</td>
<td>9875</td>
<td>43.93</td>
<td>311</td>
<td>422</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>MXM 120</td>
<td>5366</td>
<td>77.6</td>
<td>30.6</td>
<td>41.0</td>
<td>2</td>
<td>12320</td>
<td>54.80</td>
<td>372.2</td>
<td>505</td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TM 120</td>
<td>5366</td>
<td>77.6</td>
<td>30.6</td>
<td>41.0</td>
<td>2</td>
<td>12320</td>
<td>54.80</td>
<td>372.2</td>
<td>505</td>
</tr>
<tr>
<td>FENDT</td>
<td>FWA</td>
<td>411</td>
<td>5525</td>
<td>79.2</td>
<td>30.6</td>
<td>41.0</td>
<td>3</td>
<td>13375</td>
<td>59.49</td>
<td>367</td>
<td>498</td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>4WD, Articulated TV 140 and TV 145</td>
<td>6675</td>
<td>81.3</td>
<td>30.6</td>
<td>41.0</td>
<td>2</td>
<td>11010</td>
<td>48.97</td>
<td>395</td>
<td>536</td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TM 125</td>
<td>5337</td>
<td>81.8</td>
<td>29.3</td>
<td>39.3</td>
<td>2</td>
<td>11870</td>
<td>52.80</td>
<td>371.4</td>
<td>504</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>MXM 130</td>
<td>5405</td>
<td>84.1</td>
<td>31.2</td>
<td>41.9</td>
<td>2</td>
<td>12550</td>
<td>55.83</td>
<td>348</td>
<td>472</td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TM 130</td>
<td>5405</td>
<td>84.1</td>
<td>31.2</td>
<td>41.9</td>
<td>2</td>
<td>12550</td>
<td>55.83</td>
<td>348</td>
<td>472</td>
</tr>
<tr>
<td>FENDT</td>
<td>FWA</td>
<td>412</td>
<td>5525</td>
<td>85.5</td>
<td>30.6</td>
<td>41.0</td>
<td>3</td>
<td>12370</td>
<td>55.02</td>
<td>408</td>
<td>553</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>7510 PQ</td>
<td>6024</td>
<td>85.8</td>
<td>27.4</td>
<td>36.7</td>
<td>2</td>
<td>13818</td>
<td>61.47</td>
<td>395</td>
<td>536</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>7320</td>
<td>5899</td>
<td>86.0</td>
<td>29.4</td>
<td>39.4</td>
<td>2</td>
<td>13130</td>
<td>58.41</td>
<td>353</td>
<td>479</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>7420</td>
<td>5847</td>
<td>86.9</td>
<td>29.2</td>
<td>39.2</td>
<td>2</td>
<td>12802</td>
<td>56.95</td>
<td>414</td>
<td>561</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>6280</td>
<td>5185</td>
<td>87.2</td>
<td>16.2</td>
<td>21.7</td>
<td>2</td>
<td>11535</td>
<td>51.31</td>
<td>362.9</td>
<td>492</td>
</tr>
<tr>
<td>AGCO Allis</td>
<td>FWA</td>
<td>8785</td>
<td>5647</td>
<td>87.3</td>
<td>28.2</td>
<td>37.8</td>
<td>2</td>
<td>388</td>
<td>526</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Make</td>
<td>Drive</td>
<td>Model</td>
<td>Weight</td>
<td>Power at 540 PTO RPM</td>
<td>Power at 1000 PTO RPM</td>
<td>Hydraulic power</td>
<td>Hitch Class</td>
<td>Max draw bar pull unballasted</td>
<td>Max torque</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>-------</td>
<td>---------</td>
<td>---------</td>
<td>----------------------</td>
<td>----------------------</td>
<td>------------------</td>
<td>-------------</td>
<td>--------------------------------</td>
<td>------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>White</td>
<td>FWA</td>
<td>6810</td>
<td>5772</td>
<td>12725</td>
<td>87.9</td>
<td>117.8</td>
<td>32</td>
<td>2</td>
<td>11925</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TM 135</td>
<td>6130</td>
<td>13515</td>
<td>88.0</td>
<td>118.0</td>
<td>29.5</td>
<td>3</td>
<td>16375</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FENDT</td>
<td>FWA</td>
<td>712 - New</td>
<td>6720</td>
<td>14815</td>
<td>88.1</td>
<td>118.1</td>
<td>24.5</td>
<td>3</td>
<td>15025</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AGCO</td>
<td>FWA</td>
<td>RT115</td>
<td>5851</td>
<td>12900</td>
<td>89.8</td>
<td>120.4</td>
<td>24.2</td>
<td>3</td>
<td>10630</td>
<td></td>
<td></td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>7610 PQ</td>
<td>6595</td>
<td>14540</td>
<td>90.0</td>
<td>120.7</td>
<td>26.3</td>
<td>3</td>
<td>14933</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>MXM 140</td>
<td>5867</td>
<td>12935</td>
<td>90.1</td>
<td>120.8</td>
<td>30.5</td>
<td>2</td>
<td>13895</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TM 140</td>
<td>5867</td>
<td>12935</td>
<td>90.1</td>
<td>120.8</td>
<td>30.5</td>
<td>2</td>
<td>13895</td>
<td></td>
<td></td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>7520 IVT</td>
<td>6024</td>
<td>13280</td>
<td>93.8</td>
<td>125.8</td>
<td>32.0</td>
<td>3</td>
<td>13634</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>6290</td>
<td>5169</td>
<td>11395</td>
<td>94.1</td>
<td>126.2</td>
<td>16.2</td>
<td>2</td>
<td>10925</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Challenger</td>
<td>FWA</td>
<td>MT 545</td>
<td>5169</td>
<td>11395</td>
<td>94.1</td>
<td>126.2</td>
<td>29.5</td>
<td>2</td>
<td>10925</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TM 150</td>
<td>6332</td>
<td>13960</td>
<td>94.5</td>
<td>126.7</td>
<td>29.6</td>
<td>2</td>
<td>14430</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FENDT</td>
<td>FWA</td>
<td>714 - New</td>
<td>6720</td>
<td>14815</td>
<td>99.1</td>
<td>132.9</td>
<td>24.5</td>
<td>3</td>
<td>15215</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>MXM 155</td>
<td>5860</td>
<td>12920</td>
<td>99.6</td>
<td>133.6</td>
<td>30.8</td>
<td>2</td>
<td>13915</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TM 155</td>
<td>5860</td>
<td>12920</td>
<td>99.6</td>
<td>133.6</td>
<td>30.8</td>
<td>2</td>
<td>13915</td>
<td></td>
<td></td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>7710 PQ</td>
<td>6836</td>
<td>15070</td>
<td>102.8</td>
<td>137.9</td>
<td>28.3</td>
<td>3</td>
<td>15820</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AGCO</td>
<td>FWA</td>
<td>RT130</td>
<td>7271</td>
<td>16030</td>
<td>105.1</td>
<td>140.9</td>
<td>27.4</td>
<td>3</td>
<td>12950</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>8220</td>
<td>7210</td>
<td>15895</td>
<td>105.3</td>
<td>141.2</td>
<td>26.7</td>
<td>3</td>
<td>14705</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AGCO</td>
<td>CVT / FWA</td>
<td>RT135 New</td>
<td>7042</td>
<td>15525</td>
<td>105.9</td>
<td>142.1</td>
<td>34.9</td>
<td>3</td>
<td>13536</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TM 165</td>
<td>6557</td>
<td>14455</td>
<td>110.2</td>
<td>147.8</td>
<td>31.2</td>
<td>2</td>
<td>14615</td>
<td></td>
<td></td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>7720</td>
<td>7473</td>
<td>16475</td>
<td>112.3</td>
<td>150.6</td>
<td>29.0</td>
<td>3</td>
<td>16440</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>MX 180</td>
<td>8718</td>
<td>19220</td>
<td>112.6</td>
<td>151.0</td>
<td>35.4</td>
<td>3</td>
<td>19501</td>
<td></td>
<td></td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>7810 IVT</td>
<td>7344</td>
<td>16190</td>
<td>112.7</td>
<td>151.1</td>
<td>28.6</td>
<td>3</td>
<td>16698</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>8240</td>
<td>7396</td>
<td>16305</td>
<td>113.8</td>
<td>152.6</td>
<td>26.7</td>
<td>3</td>
<td>13945</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Challenger</td>
<td>FWA</td>
<td>MT 565</td>
<td>7396</td>
<td>16305</td>
<td>113.8</td>
<td>152.6</td>
<td>30.1</td>
<td>3</td>
<td>13945</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FENDT</td>
<td>FWA</td>
<td>716 - New</td>
<td>6720</td>
<td>14815</td>
<td>114.1</td>
<td>153.0</td>
<td>24.5</td>
<td>3</td>
<td>15635</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AGCO</td>
<td>FWA</td>
<td>RT 145</td>
<td>7582</td>
<td>16715</td>
<td>114.3</td>
<td>153.3</td>
<td>30.1</td>
<td>3</td>
<td>15069</td>
<td></td>
<td></td>
</tr>
<tr>
<td>White</td>
<td>FWA</td>
<td>8410</td>
<td>7582</td>
<td>16715</td>
<td>114.3</td>
<td>153.3</td>
<td>30.1</td>
<td>3</td>
<td>15069</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>MXM 175</td>
<td>7164</td>
<td>15795</td>
<td>115.0</td>
<td>154.2</td>
<td>29.7</td>
<td>2</td>
<td>16455</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Final Report DE-FG36-04GO14303
<table>
<thead>
<tr>
<th>Make</th>
<th>Drive</th>
<th>Model</th>
<th>Weight (kg)</th>
<th>Power at 540 PTO RPM</th>
<th>Power at 1000 PTO RPM</th>
<th>Hydraulic power Hitch Class Max draw bar pull unballasted</th>
<th>Max torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TM 175 - New</td>
<td>7164</td>
<td>115.0 (154.2)</td>
<td>29.7 (39.8)</td>
<td>2</td>
<td>16455 (73.20)</td>
</tr>
<tr>
<td>AGCO</td>
<td>FWA</td>
<td>RT150 New</td>
<td>7446</td>
<td>115.7 (155.2)</td>
<td>35.0 (47.0)</td>
<td>3</td>
<td>14253 (63.40)</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>8250</td>
<td>8194</td>
<td>121.7 (163.2)</td>
<td>29.8 (40.0)</td>
<td>3</td>
<td>16235 (72.22)</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>8110</td>
<td>8775</td>
<td>123.3 (165.4)</td>
<td>29.8 (39.9)</td>
<td>3</td>
<td>19272 (85.73)</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>MXM 190</td>
<td>7924</td>
<td>124.8 (167.4)</td>
<td>27.5 (36.9)</td>
<td>2</td>
<td>17465 (77.69)</td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TM 190 - New</td>
<td>7924</td>
<td>124.8 (167.4)</td>
<td>27.5 (36.9)</td>
<td>2</td>
<td>17465 (77.69)</td>
</tr>
<tr>
<td>AGCO</td>
<td>FWA</td>
<td>DT 160</td>
<td>8623</td>
<td>125.5 (168.3)</td>
<td>29.5 (39.6)</td>
<td>3</td>
<td>19010 (84.56)</td>
</tr>
<tr>
<td>AGCO Allis</td>
<td>FWA</td>
<td>9755 (Cummins engine)</td>
<td>8623</td>
<td>125.5 (168.3)</td>
<td>29.5 (39.6)</td>
<td>3</td>
<td>17894 (79.60)</td>
</tr>
<tr>
<td>White</td>
<td>FWA</td>
<td>8510</td>
<td>8623</td>
<td>125.5 (168.3)</td>
<td>29.5 (39.6)</td>
<td>3</td>
<td>17894 (79.60)</td>
</tr>
<tr>
<td>AGCO Allis</td>
<td>FWA</td>
<td>9755</td>
<td>8700</td>
<td>126.0 (168.9)</td>
<td>26.5 (35.6)</td>
<td>3</td>
<td>17894 (79.60)</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>MX 200</td>
<td>8918</td>
<td>127.4 (170.8)</td>
<td>33.5 (44.9)</td>
<td>3</td>
<td>19863 (88.35)</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>7820</td>
<td>7815</td>
<td>127.5 (171.0)</td>
<td>29.2 (39.1)</td>
<td>3</td>
<td>17061 (75.89)</td>
</tr>
<tr>
<td>Challenger</td>
<td>FWA</td>
<td>MT 635</td>
<td>8528</td>
<td>127.8 (171.4)</td>
<td>26.5 (35.6)</td>
<td>3</td>
<td>561 (761)</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>8245</td>
<td>8528</td>
<td>127.8 (171.4)</td>
<td>26.5 (35.6)</td>
<td>3</td>
<td>561 (761)</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>8120</td>
<td>9099</td>
<td>128.4 (172.1)</td>
<td>29.9 (40.1)</td>
<td>3</td>
<td>18768 (83.48)</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>MX 210</td>
<td>9160</td>
<td>128.7 (172.5)</td>
<td>46.2 (62.0)</td>
<td>3</td>
<td>19579 (87.09)</td>
</tr>
<tr>
<td>FENDT</td>
<td>FWA</td>
<td>918</td>
<td>8555</td>
<td>131.8 (176.8)</td>
<td>31.7 (42.5)</td>
<td>3</td>
<td>19535 (86.90)</td>
</tr>
<tr>
<td>Massey Ferguson</td>
<td>FWA</td>
<td>8260</td>
<td>8548</td>
<td>137.1 (183.9)</td>
<td>29.8 (39.9)</td>
<td>3</td>
<td>589 (799)</td>
</tr>
<tr>
<td>Challenger</td>
<td>FWA</td>
<td>MT 645</td>
<td>8548</td>
<td>137.1 (183.9)</td>
<td>29.8 (39.9)</td>
<td>3</td>
<td>589 (799)</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>7920</td>
<td>8149</td>
<td>138.4 (185.6)</td>
<td>30.8 (41.3)</td>
<td>3</td>
<td>17373 (77.28)</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>8210</td>
<td>8777</td>
<td>139.7 (187.3)</td>
<td>29.8 (39.9)</td>
<td>3</td>
<td>19515 (86.81)</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>Tracked 8210T</td>
<td>11517</td>
<td>140.3 (188.1)</td>
<td>28.6 (38.4)</td>
<td>3</td>
<td>24479 (108.89)</td>
</tr>
<tr>
<td>FENDT</td>
<td>FWA</td>
<td>920</td>
<td>8555</td>
<td>141.6 (189.9)</td>
<td>31.7 (42.5)</td>
<td>3</td>
<td>19210 (85.45)</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>MX 220</td>
<td>9076</td>
<td>141.9 (190.3)</td>
<td>34.4 (46.1)</td>
<td>3</td>
<td>20650 (91.86)</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>8220</td>
<td>9092</td>
<td>142.6 (191.2)</td>
<td>29.9 (40.1)</td>
<td>3</td>
<td>18291 (81.36)</td>
</tr>
<tr>
<td>AGCO Allis</td>
<td>FWA</td>
<td>9765</td>
<td>8700</td>
<td>143.0 (191.8)</td>
<td>26.5 (35.6)</td>
<td>3</td>
<td>641 (869)</td>
</tr>
<tr>
<td>Make</td>
<td>Drive</td>
<td>Model</td>
<td>Weight (kg)</td>
<td>Power at 540 PTO RPM (kW)</td>
<td>Power at 1000 PTO RPM (kW)</td>
<td>Hydraulic power Hitch (kW)</td>
<td>Hitch Class</td>
</tr>
<tr>
<td>-----------------------</td>
<td>-------</td>
<td>------------------------</td>
<td>-------------</td>
<td>---------------------------</td>
<td>---------------------------</td>
<td>---------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Case-IH FWA MX230</td>
<td></td>
<td>9117 20100</td>
<td></td>
<td>143.2 192.0</td>
<td>46.6 62.5</td>
<td>3 19628 87.31</td>
<td>778</td>
</tr>
<tr>
<td>New Holland FWA TG 210</td>
<td></td>
<td>9278 20455</td>
<td></td>
<td>144.2 193.3</td>
<td>46.5 62.4</td>
<td>3 20092 89.37</td>
<td>679</td>
</tr>
<tr>
<td>AGCO FWA DT 180</td>
<td></td>
<td>8838 19485</td>
<td></td>
<td>149.1 200.0</td>
<td>30.0 40.2</td>
<td>3 18618 82.82</td>
<td>633</td>
</tr>
<tr>
<td>AGCO Allis FWA 9765</td>
<td></td>
<td>8838 19485</td>
<td></td>
<td>149.1 200.0</td>
<td>30.0 40.2</td>
<td>3 18618 82.82</td>
<td>633</td>
</tr>
<tr>
<td>White FWA 8610</td>
<td></td>
<td>8838 19485</td>
<td></td>
<td>149.2 200.1</td>
<td>30.0 40.2</td>
<td>3 18618 82.82</td>
<td>633</td>
</tr>
<tr>
<td>Challenger Tracked MT 735</td>
<td></td>
<td>12705 28010</td>
<td></td>
<td>149.6 200.7</td>
<td>49.4 66.3</td>
<td>3 26200 116.54</td>
<td>720</td>
</tr>
<tr>
<td>John Deere Tracked 8310T</td>
<td></td>
<td>11775 25960</td>
<td></td>
<td>153.9 206.3</td>
<td>28.6 38.4</td>
<td>3 25919 115.29</td>
<td>729</td>
</tr>
<tr>
<td>John Deere FWA 8310</td>
<td></td>
<td>9008 19860</td>
<td></td>
<td>154.5 207.3</td>
<td>29.8 39.9</td>
<td>3 18508 82.33</td>
<td>741</td>
</tr>
<tr>
<td>Massey Ferguson FWA 8270 (also 8170)</td>
<td></td>
<td>9795 21595</td>
<td></td>
<td>158.3 212.3</td>
<td>26.5 35.6</td>
<td>3 20765 92.37</td>
<td>710</td>
</tr>
<tr>
<td>Challenger FWA MT 655</td>
<td></td>
<td>9795 21595</td>
<td></td>
<td>158.3 212.3</td>
<td>26.5 35.6</td>
<td>3 20765 92.37</td>
<td>710</td>
</tr>
<tr>
<td>Case-IH FWA MX 240</td>
<td></td>
<td>9410 20745</td>
<td></td>
<td>159.1 213.4</td>
<td>34.3 46.0</td>
<td>3 20928 93.09</td>
<td>810</td>
</tr>
<tr>
<td>New Holland FWA TG 230</td>
<td></td>
<td>9226 20340</td>
<td></td>
<td>159.3 213.6</td>
<td>47.4 63.5</td>
<td>3 19826 88.19</td>
<td>754</td>
</tr>
<tr>
<td>AGCO Allis FWA 9775</td>
<td></td>
<td>9002 19845</td>
<td></td>
<td>160.9 215.8</td>
<td>29.8 40.0</td>
<td>3 19799 80.05</td>
<td>716</td>
</tr>
<tr>
<td>John Deere Tracked 8320T</td>
<td></td>
<td>12127 26735</td>
<td></td>
<td>162.3 217.6</td>
<td>29.5 39.6</td>
<td>3 26656 118.57</td>
<td>780</td>
</tr>
<tr>
<td>John Deere FWA 8320</td>
<td></td>
<td>9085 20030</td>
<td></td>
<td>163.0 218.5</td>
<td>29.9 40.1</td>
<td>3 19460 86.56</td>
<td>760</td>
</tr>
<tr>
<td>Case-IH FWA MX 255</td>
<td></td>
<td>9775 21550</td>
<td></td>
<td>163.4 219.2</td>
<td>46.2 62.0</td>
<td>3 21234 94.45</td>
<td>879</td>
</tr>
<tr>
<td>Challenger Tracked MT 745</td>
<td></td>
<td>12710 28020</td>
<td></td>
<td>164.7 220.8</td>
<td>49.7 66.6</td>
<td>3 26433 117.58</td>
<td>804</td>
</tr>
<tr>
<td>AGCO FWA DT 200</td>
<td></td>
<td>8904 19630</td>
<td></td>
<td>165.1 221.4</td>
<td>28.8 38.6</td>
<td>3 17996 80.05</td>
<td>716</td>
</tr>
<tr>
<td>AGCO Allis FWA 9775 (Cummins engine)</td>
<td></td>
<td>8904 19630</td>
<td></td>
<td>165.1 221.4</td>
<td>28.8 38.6</td>
<td>3 17996 80.05</td>
<td>716</td>
</tr>
<tr>
<td>White FWA 8710</td>
<td></td>
<td>8904 19630</td>
<td></td>
<td>165.1 221.4</td>
<td>28.8 38.6</td>
<td>3 17996 80.05</td>
<td>716</td>
</tr>
<tr>
<td>FENDT FWA 924</td>
<td></td>
<td>8555 18860</td>
<td></td>
<td>167.4 224.5</td>
<td>33.1 44.4</td>
<td>3 19625 87.30</td>
<td>657</td>
</tr>
<tr>
<td>New Holland 4WD, Articulated 9282 (also 9184)</td>
<td></td>
<td>11251 24805</td>
<td></td>
<td>170.8 229.0</td>
<td>40.2 53.9</td>
<td>4 25020 111.29</td>
<td>746</td>
</tr>
<tr>
<td>Massey Ferguson 8280</td>
<td></td>
<td>9770 21540</td>
<td></td>
<td>172.5 231.3</td>
<td>26.5 35.6</td>
<td>3 20925 93.08</td>
<td>801</td>
</tr>
<tr>
<td>Challenger FWA MT 665</td>
<td></td>
<td>9770 21540</td>
<td></td>
<td>172.5 231.3</td>
<td>26.5 35.6</td>
<td>3 20925 93.08</td>
<td>801</td>
</tr>
<tr>
<td>Make</td>
<td>Drive</td>
<td>Model</td>
<td>Weight</td>
<td>Power at 540 PTO RPM</td>
<td>Power at 1000 PTO RPM</td>
<td>Hydraulic power</td>
<td>Hitch Class</td>
</tr>
<tr>
<td>---------------</td>
<td>-------</td>
<td>---------------</td>
<td>--------</td>
<td>-----------------------</td>
<td>------------------------</td>
<td>-----------------</td>
<td>-------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(kg)</td>
<td>(LB)</td>
<td>(kW)</td>
<td>(hp)</td>
<td></td>
</tr>
<tr>
<td>AGCO</td>
<td>FWA</td>
<td>DT 225</td>
<td>8956</td>
<td>19745</td>
<td>174.0</td>
<td>233.4</td>
<td>29.4</td>
</tr>
<tr>
<td>AGCO Allis</td>
<td>FWA</td>
<td>9785</td>
<td>8956</td>
<td>19745</td>
<td>174.0</td>
<td>233.4</td>
<td>29.4</td>
</tr>
<tr>
<td>White</td>
<td>FWA</td>
<td>8810</td>
<td>8956</td>
<td>19745</td>
<td>174.0</td>
<td>233.4</td>
<td>29.4</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>8420</td>
<td>10786</td>
<td>23780</td>
<td>175.6</td>
<td>235.5</td>
<td>29.9</td>
</tr>
<tr>
<td>John Deere</td>
<td>Tracked</td>
<td>8410T and 8420T</td>
<td>11966</td>
<td>26380</td>
<td>176.5</td>
<td>236.8</td>
<td>28.6</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>8410</td>
<td>9271</td>
<td>20440</td>
<td>176.6</td>
<td>236.8</td>
<td>29.8</td>
</tr>
<tr>
<td>Case-IH</td>
<td>4WD, Articulated</td>
<td>STX 275</td>
<td>14417</td>
<td>31785</td>
<td>178.2</td>
<td>238.9</td>
<td>36.9</td>
</tr>
<tr>
<td>Case-IH</td>
<td>4WD, Articulated</td>
<td>TJ 275</td>
<td>14417</td>
<td>31785</td>
<td>178.2</td>
<td>238.9</td>
<td>36.9</td>
</tr>
<tr>
<td>Case-IH</td>
<td>FWA</td>
<td>MX 285</td>
<td>9811</td>
<td>21630</td>
<td>180.6</td>
<td>242.2</td>
<td>47.7</td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>MX 270</td>
<td>9480</td>
<td>20900</td>
<td>181.3</td>
<td>243.2</td>
<td>34.3</td>
</tr>
<tr>
<td>New Holland</td>
<td>FWA</td>
<td>TG 255</td>
<td>9639</td>
<td>21250</td>
<td>183.4</td>
<td>246.0</td>
<td>45.6</td>
</tr>
<tr>
<td>John Deere</td>
<td>Tracked</td>
<td>8520T</td>
<td>12374</td>
<td>27280</td>
<td>190.9</td>
<td>256.0</td>
<td>29.5</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>8520</td>
<td>10796</td>
<td>23800</td>
<td>191.3</td>
<td>256.5</td>
<td>29.9</td>
</tr>
<tr>
<td>Challenger</td>
<td>Tracked</td>
<td>MT 755</td>
<td>13320</td>
<td>29365</td>
<td>191.9</td>
<td>257.3</td>
<td>50.6</td>
</tr>
<tr>
<td>John Deere</td>
<td>FWA</td>
<td>9120</td>
<td>16046</td>
<td>35375</td>
<td>196.1</td>
<td>263.0</td>
<td>26.8</td>
</tr>
<tr>
<td>FENDT</td>
<td>FWA</td>
<td>926</td>
<td>8555</td>
<td>18860</td>
<td>196.6</td>
<td>263.6</td>
<td>31.7</td>
</tr>
</tbody>
</table>
### Table A3: Tractor data for large tractors with a PTO power rating in excess of 200 kW

<table>
<thead>
<tr>
<th>Make</th>
<th>Drive</th>
<th>Model</th>
<th>Weight</th>
<th>Power at 1000 PTO RPM</th>
<th>Hydraulic power</th>
<th>Hitch Class</th>
<th>Max draw bar pull unballasted</th>
<th>Max torque</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(kg)</td>
<td>(kW)</td>
<td>Hitch Class</td>
<td></td>
<td>Hitch pull unballasted</td>
<td>Torque</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(LB)</td>
<td>(hp)</td>
<td>Hitch Class</td>
<td></td>
<td>Hitch pull unballasted</td>
<td>Torque</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(kW)</td>
<td>(kW)</td>
<td>Hitch Class</td>
<td></td>
<td>Hitch pull unballasted</td>
<td>Torque</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(hp)</td>
<td>(hp)</td>
<td>Hitch Class</td>
<td></td>
<td>Hitch pull unballasted</td>
<td>Torque</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(lb)</td>
<td>(kN)</td>
<td>Hitch Class</td>
<td></td>
<td>Hitch pull unballasted</td>
<td>Torque</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(lb ft)</td>
<td>(Nm)</td>
<td>Hitch Class</td>
<td></td>
<td>Hitch pull unballasted</td>
<td>Torque</td>
</tr>
<tr>
<td>New Holland 4WD, Articulated</td>
<td>9482</td>
<td></td>
<td>13608</td>
<td>30000</td>
<td>204.1</td>
<td>273.7</td>
<td>43.6</td>
<td>56.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Holland FWA</td>
<td>TG 285</td>
<td></td>
<td>9605</td>
<td>21175</td>
<td>204.9</td>
<td>274.8</td>
<td>46.7</td>
<td>62.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case-IH 4WD, Articulated</td>
<td>STX 325</td>
<td></td>
<td>14481</td>
<td>31925</td>
<td>210.1</td>
<td>281.8</td>
<td>36.9</td>
<td>49.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Holland 4WD, Articulated</td>
<td>TJ 325</td>
<td></td>
<td>14481</td>
<td>31925</td>
<td>210.1</td>
<td>281.8</td>
<td>36.9</td>
<td>49.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Challenger Tracked</td>
<td>MT 765</td>
<td></td>
<td>13311</td>
<td>29345</td>
<td>211.0</td>
<td>283.0</td>
<td>49.5</td>
<td>66.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>John Deere FWA</td>
<td>9200</td>
<td></td>
<td>14959</td>
<td>32980</td>
<td>221.5</td>
<td>297.0</td>
<td>27.7</td>
<td>37.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Holland 4WD, Articulated</td>
<td>9684</td>
<td></td>
<td>13894</td>
<td>30630</td>
<td>224.7</td>
<td>301.3</td>
<td>41.9</td>
<td>56.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>John Deere FWA</td>
<td>9220</td>
<td></td>
<td>16558</td>
<td>36505</td>
<td>237.1</td>
<td>318.0</td>
<td>26.6</td>
<td>35.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Holland 4WD, Articulated</td>
<td>9682</td>
<td></td>
<td>14454</td>
<td>31865</td>
<td>238.5</td>
<td>319.8</td>
<td>45.2</td>
<td>60.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Challenger Tracked</td>
<td>MT 835</td>
<td></td>
<td>18690</td>
<td>41205</td>
<td>244.9</td>
<td>328.4</td>
<td>49.3</td>
<td>66.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>John Deere Tracked</td>
<td>9400T</td>
<td></td>
<td>19253</td>
<td>42445</td>
<td>247.5</td>
<td>332.0</td>
<td>29.8</td>
<td>39.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>John Deere Tracked</td>
<td>9420T and 9300T</td>
<td></td>
<td>19253</td>
<td>42445</td>
<td>247.5</td>
<td>332.0</td>
<td>29.8</td>
<td>39.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case-IH 4WD, Articulated</td>
<td>STX 375</td>
<td></td>
<td>17060</td>
<td>37610</td>
<td>252.0</td>
<td>337.9</td>
<td>36.9</td>
<td>49.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Holland 4WD, Articulated</td>
<td>TJ 375</td>
<td></td>
<td>17060</td>
<td>37610</td>
<td>252.0</td>
<td>337.9</td>
<td>36.9</td>
<td>49.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>John Deere FWA</td>
<td>9420T</td>
<td></td>
<td>16895</td>
<td>37246</td>
<td>256.1</td>
<td>343.4</td>
<td>44.6</td>
<td>59.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>John Deere Tracked</td>
<td>9520T</td>
<td></td>
<td>19690</td>
<td>43410</td>
<td>266.6</td>
<td>357.5</td>
<td>30.6</td>
<td>41.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>John Deere Tracked</td>
<td>9320T</td>
<td></td>
<td>19432</td>
<td>42840</td>
<td>267.7</td>
<td>359.0</td>
<td>29.9</td>
<td>40.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>John Deere FWA</td>
<td>9520T</td>
<td></td>
<td>17379</td>
<td>38315</td>
<td>267.8</td>
<td>359.1</td>
<td>26.4</td>
<td>35.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>John Deere Tracked</td>
<td>9620T New</td>
<td></td>
<td>19677</td>
<td>43380</td>
<td>271.1</td>
<td>363.5</td>
<td>28.6</td>
<td>38.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>John Deere FWA</td>
<td>9320</td>
<td></td>
<td>16583</td>
<td>36560</td>
<td>272.1</td>
<td>364.9</td>
<td>26.8</td>
<td>36.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Challenger Tracked</td>
<td>MT 845</td>
<td></td>
<td>18897</td>
<td>41660</td>
<td>272.4</td>
<td>365.3</td>
<td>48.2</td>
<td>64.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>John Deere FWA</td>
<td>9620</td>
<td></td>
<td>17735</td>
<td>39100</td>
<td>276.4</td>
<td>370.7</td>
<td>28.5</td>
<td>38.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case-IH 4WD, Articulated</td>
<td>STX 440 and 450 Quadtrac</td>
<td></td>
<td>23294</td>
<td>51355</td>
<td>297.6</td>
<td>399.1</td>
<td>36.9</td>
<td>49.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case-IH 4WD, Articulated</td>
<td>STX 440 and 450</td>
<td></td>
<td>17838</td>
<td>39325</td>
<td>298.8</td>
<td>400.6</td>
<td>38.0</td>
<td>50.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Holland 4WD, Articulated</td>
<td>TJ 450</td>
<td></td>
<td>17838</td>
<td>39325</td>
<td>298.8</td>
<td>400.6</td>
<td>38.0</td>
<td>50.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Challenger Tracked</td>
<td>MT 855</td>
<td></td>
<td>19842</td>
<td>43745</td>
<td>319.4</td>
<td>428.3</td>
<td>50.6</td>
<td>67.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Challenger Tracked</td>
<td>MT 865</td>
<td></td>
<td>20058</td>
<td>44220</td>
<td>366.1</td>
<td>491.0</td>
<td>50.6</td>
<td>67.9</td>
</tr>
</tbody>
</table>
REFERENCES


ASAE (2003). "ASAE D497.4 FEB03 Agricultural Machinery Management Data."


INTRODUCTION
The literature review for identifying the nature and strength of the off-road vibration levels is an on-going process. Not much literature that has been published is readily available on the levels of vibrations present on the chassis of an off-road vehicle. Literature is available in the form of ride comfort, where many have studied the vibration levels on the seat of a vehicle or on the frame below the seat. The data presented in this process do not truly represent the extreme nature of the vibration levels present on the vehicles as the seat placement is usually chosen in a place (CG) where the vertical vibrations are small. Even though these levels do not truly represent the entirety of the vibration levels, they provide an indication of extreme levels and would help as an input to the experimental design for the vibrational testing on the fuel cells.

SUMMARY
The data obtained from the literature review supplemented by part of Toro’s data obtained on the Workman vehicle are summarized in this report to have an understanding on the vibration levels. In presenting the summary of the data acquired through literature review and Toro’s experimentation, each contribution was treated as an individual vehicle; i.e., every paper that was summarized in this report was treated as one vehicle. A brief summary of various literatures is presented to aid the understanding on how the data was generated in a specific study that was used to compile this report. The reviewed data were summarized into six categories:

Agricultural Machinery: Vehicles 1-9
Forestry Machinery: Vehicles 10-13
Military Machinery: Vehicles 14-19
Typical Off-road Machinery: Vehicles 20-23
Miscellaneous Machinery: Vehicles 24-30
Toro Workman Vehicle: Vehicles 31

Figure 1 and 2 shown in the next page are the identified peak and rms vertical acceleration found in the literature. The complete numerical summary of the various categories of vehicles is also presented in this report.
**Figure 1:** Peak acceleration Values of the Vehicles Researched

**Figure 2:** RMS Acceleration Values of the Vehicles Researched
AGRICULTURE MACHINERY

Vehicle 1 – Tractor

In his study of farm tractors J. Matthews [1] studied the vibration levels on the driver’s seat for two models of pneumatic-tired tractor over a variety of farm surfaces and presents the excitation frequencies and amplitudes of the recorded ride characteristics. He presented measured values of peak and mean vibration levels felt in the three translational directions in a table that shown below. The vibration levels were measured while driving the tractors on five different surfaces.

Over track and pasture he reported that vertical vibrations on the two models were seen in the frequency range of 3-5 Hz and transverse vibrations at approximately 2 Hz. Over deep ploughed land (ground surface is severely undulated) vertical vibrations were seen over the range of 2-6 Hz and high levels of longitudinal vibration between 1-2 Hz were reported. Over track and rough pasture sustained oscillations at 4 Hz in pitch plane and at 2Hz in roll plane were also reported. The table below gives the strength of these induced vibrations in terms of the acceleration amplitudes.

Table 1: Measured linear and rotational vibrations of four-wheel drive tractor on unmetalled track (8 mile/hr)

<table>
<thead>
<tr>
<th>Component</th>
<th>Acceleration amplitude, $g$</th>
<th>Tractor</th>
<th>Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>Mean 0.10</td>
<td>0.16</td>
<td>160%</td>
</tr>
<tr>
<td></td>
<td>Maximum 0.5</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Longitudinal</td>
<td>Mean 0.06</td>
<td>0.07</td>
<td>120%</td>
</tr>
<tr>
<td></td>
<td>Maximum 0.3</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Transverse</td>
<td>Mean 0.10</td>
<td>0.05</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>Maximum 0.6</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>

Pitch: Just noticeable 2-3 c/s oscillation of $<1$ amplitude. Max. displacement 1°

Roll: Max. frequency 2 c/s (not continuous). Max. angular displacement 1°

Vehicle 2 – Tractor

In the study by B. K. Huang et al [2] accelerations at seat and chassis were measured to quantify the vibration level in all three translation modes. It is stated that “The results indicated that for each operation the tractor acceleration in vertical, longitudinal, and transverse directions became larger with increased tractor speed, and the highest acceleration occurred at a higher frequency. In transverse vibrations, little difference was observed among the maximum acceleration verses frequency curves for different types of farm operations”. For the vertical direction the frequency distribution curves indicated the vibration presence in the range of 1.5-5.5 Hz for the chassis and between
2.5-6.5 Hz for the seat. The amplitude of the vertical vibration was seen to be as high as 2g at 4 mph.

The analysis of the field data indicated that the longitudinal and transverse vibrations were much smaller than the vertical vibration. For the longitudinal the maximum acceleration was less than 1.2 g and the frequencies were distributed from 1.5-5.0 Hz with the highest concentration at 2 and 3 Hz. For the transverse vibration the maximum acceleration was less than 0.5 g and the frequencies were distributed from 1 to 4.5 Hz.

**Vehicle 3 – Tractor**

In their study towards improving the ride comfort by using passive seat suspension S. Rakheja et al [3] measured the vibration levels in both translation modes and rotational modes on a seat that is rigidly fixed to the cab on a tractor. They reported that the resonant frequencies of the tractor predominated at around 2.6 Hz in vertical direction, 1 Hz in transverse, 1.5-4.5 Hz in longitudinal, 1 Hz in roll and 1.5-4.5 Hz in pitch. Below are the PSD representations of their work.

![Figure 3: PSD functions of the different modes of vibration](image)

**Vehicle 4 – Tractor**

In their study of roll and pitch vibration characteristics on off-road vehicles Young et al [4] measured the accelerations at seat-chassis attachment point on a pneumatic tired farm tractor. It was showed that roll accelerations in general were higher than the pitch
acceleration levels and both pitch and roll vibrations subsided after 5 Hz. It was reported that the study of J Matthew [1] addressed sustained vibration at 2 Hz in roll and at 4 Hz in pitch.

In conclusion Young et al [4] stated that, “Roll acceleration levels on a farm tractor are in general, appreciably greater than pitch acceleration levels. Acceleration levels for both roll and pitch subside remarkably for frequencies above 5 Hz. The occurrence of multiple acceleration peaks below 6 Hz for both roll and pitch probably indicates resonant frequencies in the rotational modes of multiple degree-of-freedom system with a non-constant tire spring rate characteristic of unsprung off-road vehicles”.

**Vehicle 5 – Tractor**

In their study of the ride vibration transfer functions of tractors, Lines et al [5] used two tractors MF 575 and MF 590 to compare between the measured and predicted responses on the tractors using simulation and field data. Though not much data was presented in terms of accelerations, he presented a plot of measured PSDs of vibration in the 3 translational directions for the tractor speed of 12 km/hr. From the plot it can be observed that, the dominant frequencies are between 0-5Hz and the vibration level in the vertical direction is the maximum among the three translational directions, followed by longitudinal and then lateral.

**Vehicle 6 – Tractor**

In their study titled, “Tractor Vibrations at the operator’s”, Gerke and Hoag [6] measured the vibration levels at the man seat interface on a tractor in various working conditions. All the data recorded was presented in frequency domain as weighted rms accelerations according to the ISO 2631 standard. Vibration levels were presented for all three translational directions. Below table summaries observations from the plots provided in the study.

**Table 2: Summary from Gerke and Hoag [6]**

<table>
<thead>
<tr>
<th>Working condition</th>
<th>Vehicle speed (m/s)</th>
<th>Direction</th>
<th>Peak rms acceleration (m/s²)</th>
<th>Dominant frequency / band (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chisel Plowing soybean ground</td>
<td>2.3</td>
<td>Vertical</td>
<td>0.25</td>
<td>2.5</td>
</tr>
<tr>
<td>Chisel Plowing soybean ground</td>
<td>2.3</td>
<td>Lateral</td>
<td>0.4</td>
<td>40</td>
</tr>
<tr>
<td>Chisel Plowing corn ground</td>
<td>2.3</td>
<td>Fore-aft</td>
<td>0.4</td>
<td>40</td>
</tr>
<tr>
<td>Chisel Plowing corn ground</td>
<td>2.1</td>
<td>Vertical</td>
<td>0.22</td>
<td>2.5</td>
</tr>
<tr>
<td>Chisel Plowing corn ground</td>
<td>2.1</td>
<td>Lateral</td>
<td>0.4</td>
<td>40</td>
</tr>
<tr>
<td>Chisel Plowing corn ground</td>
<td>2.1</td>
<td>Fore-aft</td>
<td>0.4</td>
<td>40</td>
</tr>
<tr>
<td>Disking chisel-plowed ground</td>
<td>2.8</td>
<td>Vertical</td>
<td>0.7</td>
<td>2.5</td>
</tr>
<tr>
<td>Disking chisel-plowed ground</td>
<td>2.8</td>
<td>Lateral</td>
<td>0.4</td>
<td>2.5</td>
</tr>
<tr>
<td>Disking chisel-plowed ground</td>
<td>2.8</td>
<td>Fore-aft</td>
<td>0.4</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Vehicle 7 – Tractor
In their study of the effects of the implements free-play on tractor vibration, Bukta et al [7] placed a accelerometer below the driver’s seat on the tractor frame and measure the vibration with and without the implements connected to the tractor’s three-point hitch. A mathematical model was also developed to predict the same as mentioned above when the vehicle was moving at a speed of 6.5 km/h.

Both the measured and predicted values look to be in good agreement. From the plots of the vertical vibrations presented and from the results it is seen that the maximum peak-to-peak values of vertical vibration are 4.2 g and 3 g for the with-implement and without-implement conditions respectively. The dominant frequency was found to be the same in both cases equal to 3 Hz which was also equal to the forcing frequency.

Vehicle 8 – Tractor/Implement
In their study of vibration in cover crop rollers, Raper et al [8] measured vertical vibration levels on three kinds of alternate roller designs aimed at lowering the vibration levels felt on the roller. The plot shown below is directly taken from the study. The three different types mentioned as Long straight, Short Staggered and Curved are the three alternate designs that were looked at in the study.

![Figure 4: Vertical vibration level of various roller designs](image)

As observed above on the cover crop the implement sees as high as 8 g of vertical vibration for the Long straight type of design.

Vehicle 9 – Tractor
In their study titled, “Ride vibration on tractor-implement system”, Mehta et al [9] studied the effect off vehicle speed on the vibration level felt on the tractor at the seat driver interface in all the three translational axes. The vibration levels were measured independently for with and without the implement conditions. For tractor alone (without the implement), the vehicle was driven over three different surfaces: Tar macadam road, Farm road and Untilled field.
Ride vibrations were presented individually for both with and without the implement conditions. The plots below are directly taken from the study for the without the implement condition.

Figure 5: Variation of acceleration level with forward speed: (a) Longitudinal, (b) Lateral, (c) Vertical, (d) Sum

For the implement condition, measurements were recorded for four different situations: Tractor with MB plough (Transport), Tractor with MB plough (Ploughing), Tractor with Disc Harrow (Transport) and Tractor with Disc Harrow (Harrowing).

It is stated in the results that, “The weighted r.m.s. acceleration levels in longitudinal axis (ax) during harrowing operation, in lateral axis (ay) during transport mode and ploughing operation and in vertical axis (az) during transport mode and harrowing operation were insignificant (less than 0.01 m/s2) and therefore not recorded here. The ride vibration levels in longitudinal axis were slightly damped for tractor with MB plough and significantly (40-70%) damped for tractor with disc harrow during transport mode, as compared to tractor alone on untilled field. Because the implement damped tractor pitch motion, and since the driver was not seated at the centre of pitch, his motion in the
longitudinal axis was affected. On the untilled field, no conclusive difference in longitudinal vibration levels was found during transport mode of tractor alone and tractor with MB plough during ploughing operation. The longitudinal vibration levels during harrowing operation were insignificant." The plot below is copied from the study for the implement condition.

Figure 6: Variation of acceleration level with forward speed: (a) Longitudinal, (b) Lateral, (c) Vertical, (d) Sum

FORESTRY MACHINERY
Vehicle 10 – Skidder
In his study of forestry vehicles, Rummer [10] developed a mathematical model to simulate the vibration levels that are felt on a typical forestry vehicle. The terrain profile was generated from the study of Aho and Katto (1971). The studied model was of a clam­-bunk skidder. Masses for each of the components and the inertial properties were estimated from the manufactures literature. Peak vertical acceleration levels were estimated to be 1.5 g – 1.75 g @ 1 Hz at a traveling speed of 1.3 m/sec. No other kinds of vibrational data were documented.

Vehicle 11 – Skidder
In his further study of forestry vehicles Rummer [11] evaluates the computer model
developed in his previous work by comparing the results to measured acceleration values on a test track. In this work Rummer stated that “The typical prime mover for forestry applications is a rubber tired, frame-steered vehicle with the axels solidly attached to the frame”. In this paper Rummer compares measured and predicted vector-sum acceleration values under the seat location. The presented values are in g rms.

Figure 4 illustrates the comparison of the vector-sum accelerations for one of the mathematical models. The predicted values are higher than the measured values. The highest vector-sum acceleration for both predicted and measured values were observed at 1.8 Hz and are equal to 1.3 g rms and 1 g rms respectively.

**Vehicle 12 – Skidder**
In their study titled “Vibration attenuation performance of suspension seats for off-road forestry vehicles”, P. E. Boileau and S. Rakheja [12] reported a resonant frequency in the vertical direction at 1.8 Hz. It is stated in their study that, “Terrain-induced vibrations of forestry vehicles predominate in the frequency range of 0.5-5.0 Hz.

In their study Boileau et al provided a frequency spectrum of the vertical vibration measured on the cab floor of a skidder operating under typical conditions. The dominant frequency was measured to be in the 2.5 Hz frequency band and the maximal vertical acceleration was approximately 0.5 g.

**Vehicle 13 – Skidder/Loader/Bulldozer**
In their study Wilson et al [13] presented measurements both vertical and lateral vibrations in forestry vehicles for more effectively isolating operators from such vibrations. In the study Wilson et al presented recent measurements on four different forestry vehicles: Clark 667 Scarifying Skidder, Caterpillar 980 Loader, Komatsu D85 Bulldozer and Clark 664 Skidder (empty). The measurements were taken by placing accelerometers on the vehicle frame directly under the operator seat pad. All acceleration data is presented in the form of PSDs for all three directions of transverse vibrations. Wilson et al stated that “of particular significance is the relatively high level of lateral vibration compared to those in the vertical direction”.

From the figure of the PSDs presented it can be observed that in all cases the spikes PSDs are between 1.0-3.0 Hz except on the bulldozer which has a spike in the vertical direction at 6 Hz.

**MILITARY MACHINERY**
**Vehicle 14 – Tank**
In their study El-Demerdash et al [14] studied the ride performance of multi-axles combat vehicles driven at various speeds over terrain profile. Three different vehicle models were developed to study the vertical vibration and the pitching vibration levels. The terrain considered was rigid and is presented as a PSD of Gaussian stationary random process.

The PSD of the vertical vibration and the pitching vibration were shown in plots. The maximum rms accelerations felt were: Vertical acceleration was approximately .2g (two
axle model) and pitching acceleration was 1.02 rad/sec^2 (three axle model). From the PSD plots shown it is seen that the significant frequencies for both vertical and pitch vibration are between 1-2 Hz. The data was simulated for a speed of 10 m/s.

**Vehicle 15 – Wheel Hub**

In their study Triche et al [15] conducted a set of simulations and full-scale experiments to determine suitable shock load design requirements for in-hub (wheel) propulsion motors for hybrid and all-electric combat vehicles. It is stated that “The test was designed to represent severe on- and off-road situations that are realistic but not overly improbable, as described above”.

The summary from the study as it is are replicated below.

“Drop test results are summarized by the following:

- For low speed travel with off-road tire pressures (10 to 20 psi, or 69 to 138 kPa), shock loads of 25 to 55 g's are experienced.
- For low speed travel with on-road tire pressures (20 to 30 psi or 138 to 207 kPa), the shock loads from a drop impact increase to 35 to 55 g's.
- For on- or off-road cases where the run flat is engaged (0 psi, 0 kPa), drop impacts result in shock loads >20 g's.

Curb test results are summarized by the following:

- For cross-country travel with off-road tire pressures (69 to 138 kPa, or 10 to 20 psi), shock loads of around 60 g's are experienced.
- For on-road travel with on-road tire pressures (138 to 207 kPa, or 20 to 30 psi), the shock loads from a curb impact increase to 60 to 95 g's.
- For on- or off-road cases where the run flat is engaged (0 kPa or 0 psi), curb impacts result in shock loads > 90 g's.

Pothole test results are summarized by the following:

- For cross-country travel with off-road tire pressures (69 to 138 kPa, or 10 to 20 psi), shock loads of 60 to 90 g's are experienced.
- For on-road travel with on-road tire pressures 138 to 207 kPa (20 to 30 psi), the shock loads from a pothole increase to 80 to 100 g's.”

**Vehicle 16 – JTEV**

The study, “Development of a hybrid electric vehicle for the US Marine Corps” by LaPlante et al [16] intended at developing a JTEV for US Marine Corp. The study goal included extremely high ability and high speed over rough terrain. These factors influenced the design of both the mechanical and electrical system in the areas of waterproofing, material selection, vibration hardening and isolation of components. The suspension and chassis were designed to withstand the shock and vibration in the extreme conditions.

In the design of the chassis it is mentioned that by FISA specification it is designed to withstand crash imposed loads of 1.5 g lateral, 5.5 g longitudinal and 7.5 g vertical.
Vehicle 17 – Fuel Cell Truck
In their work Maturia et al [17] studied the vibration and shock considerations in the design of a truck mounted fuel cell APU system for on and off road conditions. In the work it is stated that, “there are two types of excitation sources that can affect the durability and structural integrity of the APU system: (i) tire-road dynamic interaction and (ii) engine vibration. Based on the field measurement results, the tire-road interaction is typically the more severe of these two excitations. Consequently, the design of a vibration isolation system is primarily concerned with isolating the APU and truck frame dynamics under the on-the-road vehicle operating conditions.”

The developed mathematical model was studied for various aspects including the vibration prediction spectrum based on 4 g of uniform base excitation input per SAE J1455 standard titled “Joint SAE/TMC Recommended Environmental Practices for electronic equipment Design (Heavy-Duty Trucks)”. Below are the plots from the above study showing the predicted steady-sated response of the APU system.

![Prediction spectra](image)

**Figure 7**: Predicted steady state responses for APU system per SAE J1455

The peak values in the translational vibration can be observed to be between 90-250 g occurring predominantly in the 10-60 Hz frequency band. The peak values in the rotational vibration can be observed to be approximately 2000 rad/sec2 occurring...
predominantly in the 10-80 Hz frequency band.

**Vehicle 18 – Tank**
In their study titled, “Analysis and conceptual design of a semi-active suspension system for the M5551 tank”, Margolis and Krasnicki [18] studied the feasibility of semi-active suspensions applied to a M5551 tank. As a part of their study they reported simulated values of the change in the rms vertical and pitch accelerations with respect to speed at the CG location of the tank. For the plots presented in the study it can be seen that the peak rms values at a speed of 40 mph are: vertical – 4.5 g and pitch – 24 rad/sec².

**Vehicle 19 – Mobile Shelters**
In their study titled, “Blast induced shock testing on mobile communication shelters”, Polk et al [19] measured vibration levels on the walls of the mobile shelters and reported of maximum acceleration levels sometimes exceeding 1500 g’s. Upon certain shock isolation systems, the measured results were still as high as 390 g’s in the horizontal and 292 g’s in the vertical directions.

**OFF-ROAD MACHINERY**

**Vehicle 20 – Dump Truck/Military Tank/Hovercraft**
In his study titled, “Vibration and dynamics of off-road vehicles”, Craighead [20] investigated three different off road vehicles: a 25 tonne articulated dump truck manufactured by DJB Engineering Limited, a Vickers Mk 3b/3 battle tank and a small hovercraft designed for agricultural use for vibration levels through simulations. He further validated the model by comparing the simulated values to actual measured values on the prototype vehicle mentioned above.

The results of the simulation and experimental measurements were presented for the vertical and pitch acceleration about the CG of the vehicles. Plots were also to compare the results. The observations from the plots and the results presented in the study are summarized below.

<table>
<thead>
<tr>
<th>Vehicle Suspension</th>
<th>Mode of Vibration</th>
<th>Peak Acceleration</th>
<th>rms Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Truck</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>Vertical (g)</td>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Pitch (rad/sec²)</td>
<td>13.0</td>
<td>4.7</td>
</tr>
<tr>
<td>No</td>
<td>Vertical (g)</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Pitch (rad/sec²)</td>
<td>10.0</td>
<td>3.6</td>
</tr>
<tr>
<td><strong>Tank</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torsion Bar</td>
<td>Vertical (g)</td>
<td>0.7</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>Pitch (rad/sec²)</td>
<td>2.0</td>
<td>1.12</td>
</tr>
<tr>
<td>Hydrogen Gas</td>
<td>Vertical (g)</td>
<td>0.4</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>Pitch (rad/sec²)</td>
<td>2.0</td>
<td>1.25</td>
</tr>
</tbody>
</table>
Vehicle 21 – Air and Ground Transportation Vehicles
In his study titled, “Review of measured vibration and noise environments experienced by passengers in aircraft and in ground transportation systems”, Stephens [21] conducted comprehensive experimental measurements on aircrafts and various ground transportation vehicles and presented them in plots showing the comparison between various limits of vibration levels felt on these vehicles. The plots below are directly taken from his study. The descriptors used in the plots are as follows:
gp: Peak acceleration in g’s associated with a particular time history.
grms: Over all rms acceleration in g’s associated with a particular time history.

Vehicle 22 – Mini-Baja
In their study titled, “Experimental and Numerical Analysis of an off-road vehicle suspension” Buarque et al [22] presented vertical acceleration levels felt on a Mini-Baja vehicle suspension when subjected to a sinusoidal bump input. The vehicle was instrumented with a strain gauge type accelerometer mounted on the suspension and was driven over the bump at a low speed of 2.0 m/sec. The maximum vertical acceleration at such low speed was measured to be 2 g.

Vehicle 23 – Mobile Construction Machinery
In his study titled, “Survey of technical preventative measures to reduce whole-body vibration effects when designing mobile machinery”, Donati [23] presented a plot summarizing the vertical weighted rms acceleration seen on a number of mobile machinery. The plot is below is taken from his study.

![Figure 8](image)

The data was recorded on the seats of these vehicles. It can be seen from the plot that some of the vehicles see a vibration level as high as 0.3 g rms.
MISCELLANEOUS

Mining
Vehicle 24 – Truck
In their study Remington et al [24] studied the exposure of vibration in mining workers. Field measurements were conducted on 61 surface coal mining vehicles by placing a tri-axial accelerometer on the seats of the vehicles. No data was presented in terms of accelerations.

Vehicle 25 – Mining Vehicles
In their study John Gniady and John Bauman stated that in construction and mining vehicles the amplitudes of vibration can be as high as 1.5 g and the typical frequencies of interest are 0-20 Hz.

Vehicle 26 – Haul Truck
In his study of a Mine haul truck, Hans modeled the stuck to simulate the vehicle dynamics. He reported that the vertical acceleration of the mainframe’s CG for travel at 50Km/h is generally below 0.1 g with an occasional excursion to 0.2 g. The dominant frequency is about 1 Hz, consistent with the bounce frequency measured on haul trucks in various studies.

Hovercraft
Vehicle 27 – Hovercraft
In his study of Hovercraft ride Lovesey compared the peak vibration levels on floor of a launch (28 knot) and a small hovercraft (45 knot). The levels indicated that the ride on the hovercraft is much smoother than the launch.

The different vibration levels were summarized for the peak values and the associated frequencies on the 2 vehicles. The values presented are summarized below.

<table>
<thead>
<tr>
<th>Motion</th>
<th>Frequency (Hz)</th>
<th>Acceleration (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heave</td>
<td>1.3</td>
<td>0.14</td>
</tr>
<tr>
<td>Sway</td>
<td>12.5</td>
<td>0.05</td>
</tr>
<tr>
<td>Shunt</td>
<td>4.7</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Earthmoving Machinery
Vehicle 28 – Excavator
In their study Dong-wook Lee et al evaluated the operator exposure to shock and vibration in the cabin of the excavator design. The study included two different aspects which are internal vibration caused by the engine and vibration caused due to external disturbances. The external disturbances were further classified into bucket shock, traveling shock and rock braking. In the present report the values of the older design are considered to give the extreme values that the excavator cabin can feel.

Bucket shock: Peak value is approximately 2 g and the vital frequency band is 5-25 Hz
Traveling shock: It is reported in the study that this shock locates in the frequency range
of 10-20 Hz
Rock Breaking: Peak value is approximately 1 g and the vital frequency band is 30-40 Hz

**Recreation Vehicles / ATVs**

**Vehicle 29 – ATV**
In his study Breen provides an overview on the design of ATVs. In the study Breen reports that ATVs in operation are more than critically damped. From the figures presented the accelerations could get to 8 g on a vertical drop.

**Vehicle 30 – ATV**
In his study Sushinsky measured vertical accelerations on 14 different ATVs. He quotes that, “The vertical acceleration vector was viewed as the most important quantity in this investigation because it could be directly linked to forces acting on the target areas. In this study, the peak acceleration range was defined the sum of the peak magnitudes of negative and positive accelerations. The appropriateness of using the acceleration ranges was drawn from an examination of the acceleration profiles. The positive and the negative peak acceleration characteristically followed each other within 0.4 sec time increment”.

The accelerations were measured on eight different locations, four on the vehicle and four on the driver. The four vehicle locations and the corresponding peak values are as follows:

- Front Axle: 8.7 g (Vehicle 6)
- Frame: 8.0 g (Vehicle 6)
- CG: 6.1 g (Vehicle 5 & 6)
- Rear Axle: 10.0 g (Vehicle 6)

**Toro’s Study**

**Vehicle 31 – Workman Vehicle**
The data acquired by Toro has been shared with UC Davis to help in the design of an experimental plan for the fuel cell vibration and shock testing.
The study by Toro was done on the new Fuel Cell Hybrid Workman e2050 golf cart prototype vehicle. Vibration data was collected at Midland Hills CC, Minnesota. Various possible terrain induced excitation inputs while performing golf course or other turf maintenance such as driving over speed bumps, potholes e.t.c., were identified. The vehicle was mounted with nine tri-axial accelerometers for acquiring the vibrational data. Four accelerometers were placed on the four corners of the main frame (bed area) of the workman chassis, with a fifth one located at an approximate likely location for such a vehicle’s fuel cell (mid-mount, low, under the bed). Another four accelerometers were placed near the wheel spindles.

The data was acquired at 6 different speeds with further variability added by the load and suspension conditions. The data was collected under with and without suspension condition for each of the 6 speeds and under each suspension condition further
variability was added by empty and full load conditions.

The inputs from the five accelerometers on the frame were used to compute the vibration level at any location of the vehicle. For this the vehicle was assumed to be a rigid body. Initial analysis was done on the CG location under five different dynamic conditions, which are: Vehicle full braking (panic stop), Vehicle tree root impacts, Vehicle typical trip, Vehicle driveway curb impact and Vehicle speed bump impact. The peak translational acceleration values were identified under the above mentioned five dynamic conditions and the FFT were plotted to identify the corresponding frequency distribution.

**Table 5: Peak Acceleration of the Toro Workman Vehicle**

<table>
<thead>
<tr>
<th>Dynamic Condition</th>
<th>Type of Load</th>
<th>Longitudinal</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Peak</td>
<td>Dominant Frequency</td>
<td>Peak Acceleration</td>
<td>Dominant Frequency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Acceleration</td>
<td>(Hz)</td>
<td>(G's)</td>
<td>(Hz)</td>
</tr>
<tr>
<td>Vehicle full braking (panic stop)</td>
<td>Shock</td>
<td>1.8</td>
<td>0-5</td>
<td>-</td>
<td>-0.6</td>
</tr>
<tr>
<td>Vehicle tree root impacts</td>
<td>Oscillation</td>
<td>2.1</td>
<td>0-10</td>
<td>2.0</td>
<td>0-30</td>
</tr>
<tr>
<td>Vehicle typical trip</td>
<td>Oscillation</td>
<td>1.9</td>
<td>0-10</td>
<td>-3.0</td>
<td>0-10</td>
</tr>
<tr>
<td>Vehicle driveway curb impact</td>
<td>Shock</td>
<td>2.3</td>
<td>0-10</td>
<td>1.9</td>
<td>0-10</td>
</tr>
<tr>
<td>Vehicle speed bump impact</td>
<td>Shock</td>
<td>3.0</td>
<td>0-10</td>
<td>-1.7</td>
<td>0-10</td>
</tr>
</tbody>
</table>
# Vibration and Shock Summary by Vehicle Category

## Agricultural Machinery: Vehicles 1-9

### Transitional Acceleration

<table>
<thead>
<tr>
<th>Vehicle Number</th>
<th>Author</th>
<th>Type of Load</th>
<th>Vertical</th>
<th>Longitudinal</th>
<th>Lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Peak Acceleration (G’s)</td>
<td>RMS Acceleration (G’s)</td>
<td>Dominant Frequency (Hz)</td>
</tr>
<tr>
<td>1</td>
<td>Matthews</td>
<td>Vibration</td>
<td>1.20</td>
<td>-</td>
<td>2-6</td>
</tr>
<tr>
<td>2</td>
<td>Haung</td>
<td>Vibration</td>
<td>2.00</td>
<td>-</td>
<td>1.5-6.5</td>
</tr>
<tr>
<td>3</td>
<td>Rekheja</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>2.60</td>
</tr>
<tr>
<td>4</td>
<td>Young</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>Lines</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>0-5</td>
</tr>
<tr>
<td>6</td>
<td>Gerke</td>
<td>Vibration</td>
<td>-</td>
<td>0.07</td>
<td>0-3</td>
</tr>
<tr>
<td>7</td>
<td>Bukta</td>
<td>Vibration</td>
<td>4.20</td>
<td>-</td>
<td>3.00</td>
</tr>
<tr>
<td>8</td>
<td>Reper</td>
<td>Implement Vibration</td>
<td>19.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>Mehta</td>
<td>Vibration</td>
<td>-</td>
<td>0.25</td>
<td>-</td>
</tr>
</tbody>
</table>

### Rotational Acceleration

<table>
<thead>
<tr>
<th>Vehicle Number</th>
<th>Author</th>
<th>Type of Load</th>
<th>Vertical</th>
<th>Roll</th>
<th>Yaw</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Peak Acceleration (rad/s²)</td>
<td>Peak Acceleration (rad/s²)</td>
<td>Dominant Frequency (Hz)</td>
</tr>
<tr>
<td>1</td>
<td>Matthews</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Haung</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Rekheja</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Young</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>Lines</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>Gerke</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>Bukta</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>0-5</td>
</tr>
<tr>
<td>8</td>
<td>Reper</td>
<td>Implement Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>Mehta</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
## Forestry Machinery: Vehicles 10-13

### Transitional Acceleration

<table>
<thead>
<tr>
<th>Vehicle Number</th>
<th>Author</th>
<th>Type of Load</th>
<th>Vertical</th>
<th>Longitudinal</th>
<th>Lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Peak Acceleration (G's)</td>
<td>RMS Acceleration (G's)</td>
<td>Dominant Frequency (Hz)</td>
</tr>
<tr>
<td>10</td>
<td>Rummer</td>
<td>Vibration</td>
<td>1.5-1.75</td>
<td>-</td>
<td>1.00</td>
</tr>
<tr>
<td>11</td>
<td>Rummer</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>Boileau</td>
<td>Vibration</td>
<td>0.50</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>13</td>
<td>Wilson</td>
<td>Vibration</td>
<td>-</td>
<td>0.20</td>
<td>0-10</td>
</tr>
</tbody>
</table>

### Rotational Acceleration

<table>
<thead>
<tr>
<th>Vehicle Number</th>
<th>Author</th>
<th>Type of Load</th>
<th>Pitch</th>
<th>Roll</th>
<th>Yaw</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Peak Acceleration (rad/s²)</td>
<td>RMS Acceleration (rad/s²)</td>
<td>Dominant Frequency (Hz)</td>
</tr>
<tr>
<td>10</td>
<td>Rummer</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>Rummer</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>Boileau</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>Wilson</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
## Military Machinery: Vehicles 14-19

### Transitional Acceleration

<table>
<thead>
<tr>
<th>Vehicle Number</th>
<th>Author</th>
<th>Type of Load</th>
<th>Vertical</th>
<th></th>
<th>Longitudinal</th>
<th></th>
<th>Lateral</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Peak Acceleration (G's)</td>
<td>RMS Acceleration (G's)</td>
<td>Dominant Frequency (Hz)</td>
<td>Peak Acceleration (G's)</td>
<td>RMS Acceleration (G's)</td>
</tr>
<tr>
<td>14</td>
<td>Demerdash</td>
<td>Vibration</td>
<td></td>
<td>100.00</td>
<td>0.20</td>
<td>1-2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>Triche</td>
<td>Shock</td>
<td></td>
<td>7.50</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>16</td>
<td>LaPlante</td>
<td>Vibration</td>
<td></td>
<td>250.00</td>
<td>-</td>
<td>5.50</td>
<td>-</td>
<td>1.50</td>
</tr>
<tr>
<td>17</td>
<td>Mathurai</td>
<td>Vibration</td>
<td></td>
<td>-</td>
<td>10-80</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>18</td>
<td>Margolis</td>
<td>Vibration</td>
<td></td>
<td>-</td>
<td>4.50</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>19</td>
<td>Polk</td>
<td>Shock</td>
<td></td>
<td>292.00</td>
<td>-</td>
<td>390.00</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### Rotational Acceleration

<table>
<thead>
<tr>
<th>Vehicle Number</th>
<th>Author</th>
<th>Type of Load</th>
<th>Vertical</th>
<th></th>
<th>Longitudinal</th>
<th></th>
<th>Lateral</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Peak Acceleration (rad/s²)</td>
<td>RMS Acceleration (rad/s²)</td>
<td>Dominant Frequency (Hz)</td>
<td>Peak Acceleration (rad/s²)</td>
<td>RMS Acceleration (rad/s²)</td>
</tr>
<tr>
<td>14</td>
<td>Demerdash</td>
<td>Vibration</td>
<td></td>
<td>-</td>
<td>1.02</td>
<td>1-2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>Triche</td>
<td>Shock</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>16</td>
<td>LaPlante</td>
<td>Vibration</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>17</td>
<td>Mathurai</td>
<td>Vibration</td>
<td></td>
<td>200.00</td>
<td>-</td>
<td>10-80</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>18</td>
<td>Margolis</td>
<td>Vibration</td>
<td></td>
<td>-</td>
<td>24.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>19</td>
<td>Polk</td>
<td>Shock</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
### Typical Off-Road Machinery: Vehicles 20-23

**Transitional Acceleration**

<table>
<thead>
<tr>
<th>Vehicle Number</th>
<th>Author</th>
<th>Type of Load</th>
<th>Vertical</th>
<th>Longitudinal</th>
<th>Lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Peak Acceleration (G's)</td>
<td>RMS Acceleration (G's)</td>
<td>Dominant Frequency (Hz)</td>
</tr>
<tr>
<td>20</td>
<td>Craighead</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Truck</td>
<td></td>
<td>1.00</td>
<td>0.30</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Tank</td>
<td></td>
<td>0.70</td>
<td>0.42</td>
<td>-</td>
</tr>
<tr>
<td>21</td>
<td>Stephens</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>22</td>
<td>Buarque</td>
<td>Shock</td>
<td>2.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>23</td>
<td>Donati</td>
<td>Vibration</td>
<td>-</td>
<td>0.30</td>
<td>-</td>
</tr>
</tbody>
</table>

**Rotational Acceleration**

<table>
<thead>
<tr>
<th>Vehicle Number</th>
<th>Author</th>
<th>Type of Load</th>
<th>Vertical</th>
<th>Longitudinal</th>
<th>Lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Peak Acceleration (rad/s²)</td>
<td>RMS Acceleration (rad/s²)</td>
<td>Dominant Frequency (Hz)</td>
</tr>
<tr>
<td>20</td>
<td>Craighead</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Truck</td>
<td></td>
<td>13.00</td>
<td>4.70</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Tank</td>
<td></td>
<td>2.00</td>
<td>1.25</td>
<td>-</td>
</tr>
<tr>
<td>21</td>
<td>Stephens</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>22</td>
<td>Buarque</td>
<td>Shock</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>23</td>
<td>Donati</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
### Miscellaneous Machinery: Vehicles 24-30

#### Transitional Acceleration

<table>
<thead>
<tr>
<th>Vehicle Number</th>
<th>Author</th>
<th>Type of Load</th>
<th>Vertical</th>
<th></th>
<th>Longitudinal</th>
<th></th>
<th>Lateral</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Peak Acceleration (G's)</td>
<td>RMS Acceleration (G's)</td>
<td>Dominant Frequency (Hz)</td>
<td>Peak Acceleration (G's)</td>
<td>RMS Acceleration (G's)</td>
<td>Dominant Frequency (Hz)</td>
</tr>
<tr>
<td>24</td>
<td>Remington</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>25</td>
<td>Gniady</td>
<td>Vibration</td>
<td>1.50</td>
<td>-</td>
<td>0-20</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>26</td>
<td>Prem</td>
<td>Vibration</td>
<td>0.20</td>
<td>-</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>27</td>
<td>Lovesey</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>28</td>
<td>Wook Lee</td>
<td>Vibration</td>
<td>2.00</td>
<td>-</td>
<td>5-40</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>29</td>
<td>Breen</td>
<td>Shock</td>
<td>8.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>30</td>
<td>Sushinsky</td>
<td>Shock</td>
<td>10.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

#### Rotational Acceleration

<table>
<thead>
<tr>
<th>Vehicle Number</th>
<th>Author</th>
<th>Type of Load</th>
<th>Pitch</th>
<th></th>
<th>Roll</th>
<th></th>
<th>Yaw</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Peak Acceleration (rad/s²)</td>
<td>RMS Acceleration (rad/s²)</td>
<td>Dominant Frequency (Hz)</td>
<td>Peak Acceleration (rad/s²)</td>
<td>RMS Acceleration (rad/s²)</td>
<td>Dominant Frequency (Hz)</td>
</tr>
<tr>
<td>24</td>
<td>Remington</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>25</td>
<td>Gniady</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>26</td>
<td>Prem</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>27</td>
<td>Lovesey</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>28</td>
<td>Wook Lee</td>
<td>Vibration</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>29</td>
<td>Breen</td>
<td>Shock</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>30</td>
<td>Sushinsky</td>
<td>Shock</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
REFERENCES


whole-body vibration effects when designing mobile machinery. 2nd International Conference on Whole-Body Vibration Injuries, Nov 7-9 2000, Siena, Italy, Academic Press.
TASK 2B. FUEL CELL SYSTEM VIBRATION AND SHOCK SPECTRUM TESTING

Richard Lawrence
IdaTech

INTRODUCTION
The purpose of these vibration and shock spectrum experiments was to test operating conditions of the IdaTech fuel cell in the Toro Workman™ off-road vehicle. The tests focused on movement of the rear compartment where the fuel cell is mounted. The results do not reflect direct movements or impacts on the fuel cell itself.

SUMMARY
Upon observation of the data, it appears that the rear compartment of the vehicle does not sustain any g-force short time impacts greater than 117.2g. The measured g-force varies greatly depending on whether measured at accelerometers at the back of the vehicle or the front of the vehicle. The back of the vehicle sustains higher g-force on average than the front. The data can be viewed in detail for each test in the Time Domain Data graphs in the appended data section of this document. When looking at the back two accelerometers (A and D) the high g-forces can be observed in all three axis, but only for brief periods of time.

Analysis of the Average Spectrum data suggests that the vehicle does not sustain any vibrations that exceed 1g. The vibrations at the higher frequencies (above 800Hz) may be attributed to noise vibrations generated from the electric motor and generator on the vehicle. These vibrations should not be of any concern in terms of operation of the fuel cell. The frequencies originated from the terrain are considered within the range of 1-20Hz and this range is where the highest g-forces were measured. Data taken during day 2 gives more detail as a result of two additional frequencies at vibration frequencies are utilized for all 15 inputs.

Analysis of the FRF data was largely done in MEScope. The data was used to generate the vibrating modes of the storage compartment at the various measured frequencies. These were obtained from the FRF processed from recorded accelerometers data. The results of the simulations between day one and day two tests seem to vary which is most likely due to the fact that average spectrum data was only gathered for input three (the input used as a reference for the FRF analysis.) All of the day two runs have Average spectrum data for all 15 inputs.

The results from day one suggest that several of the frequencies result in vibrations in all directions, but predominantly in the z-direction. There were also vibrations in both the x and y directions, but, for the most part, these were much
smaller than the vibrations in the z-direction.

Day two’s results do not match up with day one’s results as expected. The results of the analysis with MEScope suggest that the majority of the vibrations occur in the horizontal directions (x-direction and y-direction) and not as much in the z-direction. It appears that the data and analysis are correct. The most likely cause for the differences in results between day one and day two is due to the lack of all the Average spectrum data for day one.

Tables 1, 2, and 3 summarize the results for the day 1 and day 2 tests. The max and minimum values were generated via observation of the time domain data. Table 1 corresponds to data from day 1. Tables 2 and 3 correspond to data taken from day 2.
### Table 1: Measured acceleration and frequency data measured on Day 1 of the tests

<table>
<thead>
<tr>
<th>Run</th>
<th>Surface</th>
<th>Speed</th>
<th>Section</th>
<th>Acc. Location</th>
<th>X-direction (g)</th>
<th>Y-direction (g)</th>
<th>Z-direction (g)</th>
<th>Peak Amplitude between 0-20Hz</th>
<th>RMS Vibration Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Min.</td>
<td>Min.</td>
<td>Min.</td>
<td>(Hz)</td>
<td>(g)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td>Run 1</td>
<td>grass, pavement</td>
<td>var.</td>
<td>Top 9</td>
<td>See fig. 2</td>
<td>-56.93</td>
<td>-7.83</td>
<td>-0.40</td>
<td>-32.05</td>
<td>-7.73</td>
</tr>
<tr>
<td>Run 1</td>
<td>grass, pavement, gravel</td>
<td>var.</td>
<td>Bottom 9</td>
<td>See fig. 2</td>
<td>-20.35</td>
<td>-5.21</td>
<td>-0.03</td>
<td>-30.10</td>
<td>-5.63</td>
</tr>
<tr>
<td>Run 2</td>
<td>grass, pavement</td>
<td>var.</td>
<td>Bottom 9</td>
<td>See fig. 2</td>
<td>-37.42</td>
<td>-1.06</td>
<td>-0.09</td>
<td>-25.97</td>
<td>-7.18</td>
</tr>
<tr>
<td>Run 2</td>
<td>grass, pavement, gravel</td>
<td>var.</td>
<td>Bottom 9</td>
<td>See fig. 2</td>
<td>-38.50</td>
<td>-6.22</td>
<td>-0.45</td>
<td>-59.08</td>
<td>-7.81</td>
</tr>
<tr>
<td>Run 3</td>
<td>grass, pavement</td>
<td>var.</td>
<td>Bottom 9</td>
<td>See fig. 2</td>
<td>-42.02</td>
<td>-86.56</td>
<td>-17.46</td>
<td>-50.36</td>
<td>-98.39</td>
</tr>
<tr>
<td>Run 3</td>
<td>grass, pavement, gravel</td>
<td>var.</td>
<td>Bottom 9</td>
<td>See fig. 2</td>
<td>-17.68</td>
<td>-36.24</td>
<td>-3.76</td>
<td>-18.55</td>
<td>-38.24</td>
</tr>
<tr>
<td>Run 4</td>
<td>grass, pavement</td>
<td>var.</td>
<td>Bottom 9</td>
<td>See fig. 2</td>
<td>-24.81</td>
<td>-45.62</td>
<td>-10.14</td>
<td>-36.28</td>
<td>-55.06</td>
</tr>
<tr>
<td>Run 4</td>
<td>grass, pavement, gravel</td>
<td>var.</td>
<td>Bottom 9</td>
<td>See fig. 2</td>
<td>-40.92</td>
<td>-46.72</td>
<td>-9.44</td>
<td>-56.80</td>
<td>-68.62</td>
</tr>
</tbody>
</table>

**Notes:**
- ND indicates not determined.

---

**Figure:**
- Run 1: Top 9, See fig. 2
- Run 2: Bottom 9, See fig. 2
- Run 3: Bottom 9, See fig. 2
- Run 4: Bottom 9, See fig. 2

**Legend:**
- A: Min. Amplitude
- B: Max. Amplitude
- C, D, E: Other parameters related to vibration.
Table 2: Measured acceleration and frequency data measured on Day 2 of the tests

<table>
<thead>
<tr>
<th>Surface</th>
<th>Speed</th>
<th>Section</th>
<th>Acc. Location</th>
<th>X-direction (g)</th>
<th>Y-direction (g)</th>
<th>Z-direction (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>grass, pavement</td>
<td>var.</td>
<td>Top 9</td>
<td>See fig. 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>grass, pavement, gravel</td>
<td>var.</td>
<td>Top 9</td>
<td>See fig. 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>grass, pavement</td>
<td>var.</td>
<td>Top 9</td>
<td>See fig. 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>grass, pavement</td>
<td>var.</td>
<td>Bottom 9</td>
<td>See fig. 2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Min. | A  | B  | C  | D  | E  | A  | B  | C  | D  | E  | A  | B  | C  | D  | E  |
Max. | A  | B  | C  | D  | E  | A  | B  | C  | D  | E  | A  | B  | C  | D  | E  |

X-direction (g) | A  | B  | C  | D  | E  | A  | B  | C  | D  | E  | A  | B  | C  | D  | E  |
Min. | -76.79 | -0.81 | -6.92 | -49.61 | -7.88 | 114.80 | 0.13 | 0.95 | 117.20 | 2.89 |
Max. | -7.88 | 114.80 | 0.13 | 0.95 | 117.20 | 2.89 |

Y-direction (g) | A  | B  | C  | D  | E  | A  | B  | C  | D  | E  | A  | B  | C  | D  | E  |
Min. | -80.65 | -14.49 | -74.67 | -44.59 | -76.95 | 116.80 | 11.74 | 105.50 | 113.90 | 110.50 |
Max. | -76.95 | 116.80 | 11.74 | 105.50 | 113.90 | 110.50 |

Z-direction (g) | A  | B  | C  | D  | E  | A  | B  | C  | D  | E  | A  | B  | C  | D  | E  |
Min. | -5.26 | -8.62 | -58.80 | -52.45 | -89.45 | 113.80 | 8.11 | 48.25 | 116.50 | 68.59 |
Max. | -5.26 | -89.45 | 113.80 | 8.11 | 48.25 | 116.50 | 68.59 |
Table 3: Measured acceleration and frequency data measured on Day 2 of the tests

<table>
<thead>
<tr>
<th>Run</th>
<th>Peak Amplitude between 0-20Hz</th>
<th>Other Peak Vibration Frequencies (Hz)</th>
<th>RMS Vibration Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A (Hz)</td>
<td>B (Hz)</td>
<td>C (Hz)</td>
</tr>
<tr>
<td>Run 1</td>
<td>4.00</td>
<td>0.07</td>
<td>4.00</td>
</tr>
<tr>
<td>Run 2</td>
<td>4.00</td>
<td>0.01</td>
<td>4.00</td>
</tr>
<tr>
<td>Run 3</td>
<td>4.00</td>
<td>0.16</td>
<td>4.00</td>
</tr>
<tr>
<td>Run 4</td>
<td>4.00</td>
<td>0.64</td>
<td>4.00</td>
</tr>
<tr>
<td>Run 1</td>
<td>4.00</td>
<td>0.05</td>
<td>4.00</td>
</tr>
<tr>
<td>Run 2</td>
<td>4.00</td>
<td>0.01</td>
<td>4.00</td>
</tr>
<tr>
<td>Run 3</td>
<td>4.00</td>
<td>0.42</td>
<td>4.00</td>
</tr>
<tr>
<td>Run 4</td>
<td>4.00</td>
<td>1.00</td>
<td>4.00</td>
</tr>
</tbody>
</table>
The RMS data fluctuates between runs for the day two data. This is most likely due to the inconsistent stops made during the test runs. During these stops data were still being sampled. It may be possible to obtain more accurate RMS values for the vibration frequencies by further cropping of the data to remove the periods where the vehicle was stopped.

The fuel cell is located closest to accelerometer 5, so vibrations and impacts measured at accelerometer 5 (E) are most reflective of vibrations and impacts occurring to the fuel cell.

TEST PROCEDURE

Hardware
The following hardware was used for these tests:
- Toro Workman™ Off-Road Vehicle
- Oros R36 DSP Analyzer Unit
- 3 Axis Dytran Accelerometers x5
- 350W DC-AC Converter
- Dell Laptop

Software
The following software was used for analysis of the data:
- NVGate v5.1.00017
- MEScope v5.0.2008.1031

Setup
The Accelerometers were attached to the rear compartment of Toro vehicle; one accelerometer at each corner and one at the center of the compartment towards the front of the vehicle. Figure 1 is a table of the accelerometer names, references, Oros input channels, and respective axis labels. Figure 2 is a diagram of the physical locations and orientations of the accelerometers on the Toro Off-Road Vehicle. Figure 3 is a photograph of the back of the Toro Off-Road Vehicle with the location of the accelerometers circled.
<table>
<thead>
<tr>
<th>Accelerometer</th>
<th>Reference Letter</th>
<th>Oros Inputs</th>
<th>Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>67</td>
<td>A</td>
<td>1</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Z</td>
</tr>
<tr>
<td>68</td>
<td>B</td>
<td>4</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>Z</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>Y</td>
</tr>
<tr>
<td>69</td>
<td>C</td>
<td>7</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>Z</td>
</tr>
<tr>
<td>70</td>
<td>D</td>
<td>10</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
<td>Z</td>
</tr>
<tr>
<td>71</td>
<td>E</td>
<td>13</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14</td>
<td>Z</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>Y</td>
</tr>
</tbody>
</table>

**Figure 1:** Table of Accelerometer Names

**Figure 2:** Diagram of the Physical Locations and Orientations of the Accelerometers
In Figure 2, the numbers on each axis correspond to the axis number for that accelerometer. The numbers within the parenthesis represents the Oros channel number used for that accelerometer axis.

A couple of things to note about the accelerometer setup:

1. Accelerometer B’s axis 3 is in the –y direction
2. Accelerometer E’s axis 2 is in the –z direction

Because these two accelerometers had to be mounted in a fashion that resulted in them being oriented in the negative direction for one of their axis, the data for those axis will be inverted compared to the rest of the data.

The Oros and the laptop were both powered by the 350W DC-AC converter for all the tests. The DC-AC converter was connected to the vehicle batteries. Each accelerometer was attached to the Oros via a 3 channel cable. The vehicle was manned by two persons at all times; one to drive, and the other to monitor the equipment and data sampling.

**Process**
The Oros was started at the beginning of each run. It would only be stopped at the end
each run. At the end of each run the data set was saved and a new one was setup for the next run. Data was taken over the course of two days. The data sets are broken up into runs based on which set of holes on the golf course was being traveled. The course was broken up into two sections for these tests:

- Top 9 (holes 1 through 9)
- Bottom 9 (holes 10 through 18)

There were four sets of data taken each day for a total of eight data sets gathered from the course. Data was gathered throughout the duration of travel for each of the sets of holes traveled. Voice notes were recorded during day two to mark suspected points of interest and spots where the vehicle was stopped.

All data analysis was done post gathering and was done in NVGate.

**TEST RESULTS**

**Data**

The data in this section will be broken up in the order that the data were taken. There are two sections of data:

1. Day One
2. Day Two

In each of these sections there are four sets of data. The Data Set Title is the name that was given to the data set at the time of sampling. It can be used to access the appropriate set of data from within NVGate if necessary.

**Day One, Run One**

Driver: Richard Lawrance
Equipment Operator: Robert Dailey
Data Set Title: Morning Run 1 Holes 1 through 9, Robert and Richard

**MEScope Data**

The stress points of the vehicle compartment are shown below. There are two or more sets of pictures associated with each frequency being observed. These pictures represent each peak of the oscillation at that frequency. In each picture there are the following views (in order from top left and then clockwise around the image):

- Z-axis view
- 3D view
- Y-axis view
- X-axis View

The frequencies chosen to be displayed here where based of the peaks seen in the g-forces measured in the average spectrum data. Not all of the peaks are displayed.
Figure 4: 3.2Hz
Figure 5: 73.6Hz
Figure 6: 106Hz
Figure 7: 669Hz
Accelerometer Data
Unless otherwise noted, the scaling for the graphs is as follows:

Time domain graph scale:
- X-axis: 6:14:43am to 6:31:06am
- Y-axis: +80g to -60g

FRF data graph scale:
- Top Graph
  - X-axis 0Hz to 1.4kHz
  - Y-axis: 0 to 10 no units
- Bottom Graph
  - X-axis 0Hz to 1.4kHz
  - Y-axis: -720° to 720°

Average spectrum graph scale:
- X-axis: 0Hz to 1.4kHz
- Y-axis: 0g to 0.006g
TIME Domain Data

Figure 8: Accelerometer 1(#67, Reference A)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- Blue: Input 3 (z axis)
Average Spectrum Data

**Figure 9:** Accelerometer 1(#67, Reference A). This data is for the average spectrum for input 3. No other average spectrum data was gathered on day one of testing.

The graph scale data for the average spectrum data is as follows:
- x-scale 0Hz to 1.6kHz
- y-scale: 0g to 7E-3g
FRF Data

Figure 10: Accelerometer 1(#67, Reference A)

The colors are assigned as follows:

- Orange: Input 1(x axis)
- Green: Input 2 (y axis)
- No blue for this set because there is no FRF data for input 3
- Reference Input: Input 3

The graph scale data for the FRF data is as follows:

- Top Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 8 no units
- Bottom Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 11: Accelerometer 2 (#68, Reference B)

The colors are assigned as follows:
- Orange: Input 4 (x axis)
- Green: Input 5 (z axis)
- Blue: Input 6 (y axis) *note that this data set is inverted from the rest of them
FRF Data

The colors are assigned as follows:
- Orange: Input 4 (x axis)
- Green: Input 5 (z axis)
- Blue: Input 6 (y axis) *note that this data set is inverted from the rest of them
- Reference Input: Input 3

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 250 no units
- Bottom Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: -720° to 720°
Time Domain Data

**Figure 13**: Accelerometer 3 (#69, Reference C)

The colors are assigned as follows:

- Orange: Input 7 (x axis)
- Green: Input 8 (y axis)
- Blue: Input 9 (z axis)
**FRF Data**

![Graphs](image)

**Figure 14: Accelerometer 3 (#69, Reference C)**

The colors are assigned as follows:
- Orange: Input 7 (x axis)
- Green: Input 8 (y axis)
- Blue: Input 9 (z axis)
- Reference Input: Input 3

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 550 no units
- Bottom Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: $-720^\circ$ to $720^\circ$
Time Domain Data

Figure 15: Accelerometer 4 (#70, Reference D)

The colors are assigned as follows:
- Orange: Input 10 (x axis)
- Green: Input 11 (y axis)
- Blue: Input 12 (z axis)
FRF Data

Figure 16: Accelerometer 4 (#70, Reference D)

The colors are assigned as follows:
- Orange: Input 10 (x axis)
- Green: Input 11 (y axis)
- Blue: Input 12 (z axis)
- Reference Input: Input 3

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 15 no units
- Bottom Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 17: Accelerometer 5(#71, Reference E)

The colors are assigned as follows:
- Orange: Input 13 (x axis)
- Green: Input 14 (z axis) *note that this data set is inverted from the rest of them
- Blue: Input 15 (y axis)
FRF Data

Figure 18: Accelerometer 5(#71, Reference E)

The colors are assigned as follows:
- Orange: Input 13 (x axis)
- Green: Input 14 (z axis) *note that this data set is inverted from the rest of them
- Blue: Input 15 (y axis)
- Reference Input: Input 3

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 600 no units
- Bottom Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: -720° to 720°
Day One, Run Two

Driver: Richard Lawrance
Equipment Operator: Robert Dailey
Data Set Title: Morning Run 1 Holes 10 through 18, Robert and Richard

Accelerometer Data

Unless otherwise noted, the scaling for the graphs is as follows:

Time domain graph scale:
- X-axis: 7:04:54 to 7:17:41
- Y-axis: +30g to -30g

FRF data graph scale:
- Top Graph
  - X-axis 0Hz to 1.4kHz
  - Y-axis: 0 to 10 no units
- Bottom Graph
  - X-axis 0Hz to 1.4kHz
  - Y-axis: -720° to 720°

Average spectrum graph scale:
- X-axis: 0Hz to 1.4kHz
- Y-axis: 0g to 0.006g

Notes
This run was ended prematurely due to the batteries needing to have time to recharge. The data does not reflect a complete run through the bottom 9 holes of the golf course.
**Time Domain Data**

**Figure 19**: Accelerometer 1(#67, Reference A)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- Blue: Input 3 (z axis)
Average Spectrum Data

Figure 20: Accelerometer 1(#67, Reference A)

Scale Information
- X-axis: 0Hz to 1.25kHz
- Y-axis: 0g to 25E-3g
FRF Data

Figure 21: Accelerometer 1(#67, Reference A)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- No data for input 3

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 4.5 no units
- Bottom Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: -720° to 720°
Time Domain Data

![Graph showing Time Domain Data]

**Figure 22**: Accelerometer 2 (#68, Reference B)

The colors are assigned as follows:
- Orange: Input 4 (x axis)
- Green: Input 5 (z axis)
- Blue: Input 6 (y axis) *note that this data set is inverted from the rest of them
**Figure 23**: Accelerometer 2 (#68, Reference B)

The colors are assigned as follows:
- Orange: Input 4 (x axis)
- Green: Input 5 (z axis)
- Blue: Input 6 (y axis) *note that this data set is inverted from the rest of them

The graph scale data for the FRF data is as follows:
- **Top Graph**
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 150 no units
- **Bottom Graph**
  - x-scale 0Hz to 1.25kHz
  - y-scale: -720° to 720°
Time Domain Data

![Graph showing acceleration data over time]

**Figure 24:** Accelerometer 3 (#69, Reference C)

The colors are assigned as follows:
- Orange: Input 7 (x axis)
- Green: Input 8 (y axis)
- Blue: Input 9 (z axis)
The colors are assigned as follows:
- Orange: Input 7 (x axis)
- Green: Input 8 (y axis)
- Blue: Input 9 (a axis)

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 325 no units
- Bottom Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: -720° to 720°
Time Domain Data

**Figure 26:** Accelerometer 4 (#70, Reference D)

The colors are assigned as follows:
- Orange: Input 10 (x axis)
- Green: Input 11 (y axis)
- Blue: Input 12 (z axis)
FRF Data

Figure 27: Accelerometer 4 (#70, Reference D)

The colors are assigned as follows:
- Orange: Input 10 (x axis)
- Green: Input 11 (y axis)
- Blue: Input 12 (z axis)

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 3 no units
- Bottom Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 28: Accelerometer 5 (#71, Reference E)

The colors are assigned as follows:
- Orange: Input 13 (x axis)
- Green: Input 14 (z axis) *note that this data set is inverted from the rest of them
- Blue: Input 15 (y axis)
FRF Data

Figure 29: Accelerometer 5 (#71, Reference E)

The colors are assigned as follows:
- Orange: Input 13 (x axis)
- Green: Input 14 (z axis) *note that this data set is inverted from the rest of them
- Blue: Input 15 (y axis)

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 250 no units
- Bottom Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: -720° to 720°
Day One, Run Three

Driver: Richard Lawrance  
Equipment Operator: Robert Dailey  
Data Set Title: Morning Run 1 Holes 10 through 18 (second try,) Robert and Richard

Accelerometer Data

Unless otherwise noted, the scaling for the graphs is as follows:

Time domain graph scale:
- X-axis: 9:55:08am to 10:13:15am
- Y-axis: +90g to -50g

FRF data graph scale:
- Top Graph
  - X-axis 0Hz to 1.4kHz
  - Y-axis: 0 to 10 no units
- Bottom Graph
  - X-axis 0Hz to 1.4kHz
  - Y-axis: -720° to 720°

Average spectrum graph scale:
- X-axis: 0Hz to 1.4kHz
- Y-axis: 0g to 0.006g

Notes
This run was a repeat of run two in order to get a full set of data for holes 10 through 18.
Time Domain Data

Figure 30: Accelerometer 1(#67, Reference A)

The colors are assigned as follows:

- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- Blue: Input 3 (z axis)
Average Spectrum Data

Figure 31: Accelerometer 1(#67, Reference A)

Scale Information
- X-axis: 0Hz to 1.25kHz
- Y-axis: 0g to 50E-3g
FRF Data

Figure 32: Accelerometer 1(#67, Reference A)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- No data for input 3

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 4 no units
- Bottom Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 33: Accelerometer 2 (#68, Reference B)

The colors are assigned as follows:
- Orange: Input 4 (x axis)
- Green: Input 5 (z axis)
- Blue: Input 6 (y axis) *note that this data set is inverted from the rest of them
FRF Data

Figure 34: Accelerometer 2 (#68, Reference B)

The colors are assigned as follows:
- Orange: Input 4 (x axis)
- Green: Input 5 (z axis)
- Blue: Input 6 (y axis) *note that this data set is inverted from the rest of them

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 180 no units
- Bottom Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 35: Accelerometer 3 (#69, Reference C)

The colors are assigned as follows:
- Orange: Input 7 (x axis)
- Green: Input 8 (y axis)
- Blue: Input 9 (z axis)
FRF Data

Figure 36: Accelerometer 3 (#69, Reference C)

The colors are assigned as follows:
- Orange: Input 7 (x axis)
- Green: Input 8 (y axis)
- Blue: Input 9 (z axis)

The graph scale data for the FRF data is as follows:
- **Top Graph**
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 475 no units
- **Bottom Graph**
  - x-scale 0Hz to 1.25kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 37: Accelerometer 4 (#70, Reference D)

The colors are assigned as follows:
- Orange: Input 10 (x axis)
- Green: Input 11 (y axis)
- Blue: Input 12 (z axis)
FRF Data

Figure 38: Accelerometer 4 (#70, Reference D)

The colors are assigned as follows:
- Orange: Input 10 (x axis)
- Green: Input 11 (y axis)
- Blue: Input 12 (z axis)

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 4 no units
- Bottom Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 39: Accelerometer 5 (#71, Reference E)

The colors are assigned as follows:
- Orange: Input 13 (x axis)
- Green: Input 14 (z axis) *note that this data set is inverted from the rest of them
- Blue: Input 15 (y axis)
FRF Data

Figure 40: Accelerometer 5 (#71, Reference E)

The colors are assigned as follows:
- Orange: Input 13 (x axis)
- Green: Input 14 (z axis) *note that this data set is inverted from the rest of them
- Blue: Input 15 (y axis)

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 275 no units
- Bottom Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: -720° to 720°
Day One, Run Four

Driver: Richard Lawrance  
Equipment Operator: Robert Dailey  
Data Set Title: Morning Run 1 Holes 10 through 18, Robert and Richard

Accelerometer Data
Unless otherwise noted, the scaling for the graphs is as follows:

Time domain graph scale:
- X-axis: 10:35:43am to 10:52:00am
- Y-axis: +90g to -50g

FRF data graph scale:
- Top Graph
  - X-axis 0Hz to 1.4kHz
  - Y-axis: 0 to 10 no units
- Bottom Graph
  - X-axis 0Hz to 1.4kHz
  - Y-axis: -720° to 720°

Average spectrum graph scale:
- X-axis: 0Hz to 1.4kHz
- Y-axis: 0g to 0.006g

Notes
This was the final run of the day. It is a repeat of the bottom 9 holes.
Time Domain Data

Figure 41: Accelerometer 1(#67, Reference A)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- Blue: Input 3 (z axis)
Average Spectrum Data

Figure 42: Accelerometer 1(#67, Reference A)

Scale Information
- Y-axis: 0g to 450E-3g
- Y-axis: 0Hz to 1.25kHz
FRF Data

Figure 43: Accelerometer 1 (#67, Reference A)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- *No data for input 3*

The graph scale data for the FRF data is as follows:
- **Top Graph**
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 4.5 no units
- **Bottom Graph**
  - x-scale 0Hz to 1.25kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 44: Accelerometer 2 (#68, Reference B)

The colors are assigned as follows:
- Orange: Input 4 (x axis)
- Green: Input 5 (z axis)
- Blue: Input 6 (y axis) *note that this data set is inverted from the rest of them
FRF Data

Figure 45: Accelerometer 2 (#68, Reference B)

The colors are assigned as follows:
- Orange: Input 4 (x axis)
- Green: Input 5 (z axis)
- Blue: Input 6 (y axis) *note that this data set is inverted from the rest of them

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 300 no units
- Bottom Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 46: Accelerometer 3 (#69, Reference C)

The colors are assigned as follows:

- Orange: Input 7 (x axis)
- Green: Input 8 (y axis)
- Blue: Input 9 (z axis)
FRF Data

Figure 47: Accelerometer 3 (#69, Reference C)

The colors are assigned as follows:
- Orange: Input 7 (x axis)
- Green: Input 8 (y axis)
- Blue: Input 9 (z axis)

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 700 no units
- Bottom Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 48: Accelerometer 4 (#70, Reference D)

The colors are assigned as follows:

- Orange: Input 10 (x axis)
- Green: Input 11 (y axis)
- Blue: Input 12 (z axis)
FRF Data

Figure 49: Accelerometer 4 (#70, Reference D)

The colors are assigned as follows:
- Orange: Input 10 (x axis)
- Green: Input 11 (y axis)
- Blue: Input 12 (z axis)

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 3 no units
- Bottom Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 50: Accelerometer 5 (#71, Reference E)

The colors are assigned as follows:
- Orange: Input 13 (x axis)
- Green: Input 14 (z axis) *note that this data set is inverted from the rest of them
- Blue: Input 15 (y axis)
FRF Data

Figure 51: Accelerometer 5 (#71, Reference E)

The colors are assigned as follows:
- Orange: Input 13 (x axis)
- Green: Input 14 (z axis) *note that this data set is inverted from the rest of them
- Blue: Input 15 (y axis)

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: 0 to 350 no units
- Bottom Graph
  - x-scale 0Hz to 1.25kHz
  - y-scale: -720° to 720°
Day Two, Run One

Driver: Richard Lawrance
Equipment Operator: Robert Dailey
Data Set Title: Morning Run 1 Holes 1 through 9, Uriel and Richard

MEScope Data

The stress points of the vehicle compartment are shown below. There are two or more sets of pictures associated with each frequency being observed. These pictures represent each peak of the oscillation at that frequency. In each picture there are the following views (in order from top left and then clockwise around the image):

- Z-axis view
- 3D view
- Y-axis view
- X-axis View

The frequencies chosen to be displayed here where based of the peaks seen in the g-forces measured in the average spectrum data. Not all of the peaks are displayed.
Figure 52: 4Hz
Figure 53: 72Hz
Figure 54: 104Hz
Figure 55: 668Hz
Accelometer Data
Unless otherwise noted, the graph scales are as follows
Time domain graph scale:
  • X-axis: 6:21:56am to 6:37:50am
  • Y-axis: +80g to -80g

FRF data graph scale:
  • Top Graph
    o X-axis 0Hz to 1.6kHz
    o Y-axis: 0 to 3.5 no units
  • Bottom Graph
    o X-axis 0Hz to 1.6kHz
    o Y-axis: -720° to 720°

Average spectrum graph scale:
  • X-axis: 0Hz to 1.6kHz
  • Y-axis: 0g to 0.001g
Time Domain Data

Figure 56: Accelerometer 1(#67, Reference A)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- Blue: Input 3 (z axis)
Average Spectrum Data

Figure 57: Accelerometer 1(#67, Reference A)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- Blue: Input 3 (z axis)
**FRF Data**

![FRF Data Chart]

**Figure 58: Accelerometer 1(#67, Reference A)**

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- *No FRF data for input 3*
Time Domain Data

Figure 59: Accelerometer 2 (#68, Reference B)

The colors are assigned as follows:
- Orange: Input 4 (x axis)
- Green: Input 5 (z axis)
- Blue: Input 6 (y axis) *note that this data set is inverted from the rest of them
Average Spectrum Data

Figure 60: Accelerometer 2 (#68, Reference B)

The colors are assigned as follows:
- Orange: Input 4 (x axis)
- Green: Input 5 (z axis)
- Blue: Input 6 (y axis) *note that this data set is inverted from the rest of them

Scale information:
- X-axis: 0 to 1.6k
- Y-axis: 0 to 0.6E-3
FRF Data

Figure 61: Accelerometer 2 (#68, Reference B)

The colors are assigned as follows:
- Orange: Input 4 (x axis)
- Green: Input 5 (z axis)
- Blue: Input 6 (y axis) *note that this data set is inverted from the rest of them
• **Time Domain Data**

![Time Domain Data](image)

**Figure 62**: Accelerometer 3 (#69, Reference C)

The colors are assigned as follows:
- Orange: Input 7 (x axis)
- Green: Input 8 (y axis)
- Blue: Input 9 (z axis)
Average Spectrum Data

![Graph of Accelerometer 3 (#69, Reference C)](image)

**Figure 63:** Accelerometer 3 (#69, Reference C)

The colors are assigned as follows:
- Orange: Input 7 (x axis)
- Green: Input 8 (y axis)
- Blue: Input 9 (z axis)
FRF Data

Figure 64: Accelerometer 3 (#69, Reference C)

The colors are assigned as follows:
- Orange: Input 7 (x axis)
- Green: Input 8 (y axis)
- Blue: Input 9 (z axis)
Time Domain Data

![Graph of Time Domain Data]

**Figure 65: Accelerometer 4 (#70, Reference D)**

The colors are assigned as follows:
- Orange: Input 10 (x axis)
- Green: Input 11 (y axis)
- Blue: Input 12 (z axis)
Average Spectrum Data

**Figure 66**: Accelerometer 4 (#70, Reference D)

The colors are assigned as follows:

- Orange: Input 10 (x axis)
- Green: Input 11 (y axis)
- Blue: Input 12 (z axis)
FRF Data

Figure 67: Accelerometer 4 (#70, Reference D)

The colors are assigned as follows:

- Orange: Input 10 (x axis)
- Green: Input 11 (y axis)
- Blue: Input 12 (z axis)
Time Domain Data

Figure 68: Accelerometer 5 (#71, Reference E)

The colors are assigned as follows:
- Orange: Input 13 (x axis)
- Green: Input 14 (z axis) *note that this data set is inverted from the rest of them
- Blue: Input 15 (y axis)
Average Spectrum Data

Figure 69: Accelerometer 5 (#71, Reference E)

The colors are assigned as follows:
- Orange: Input 13 (x axis)
- Green: Input 14 (z axis) *note that this data set is inverted from the rest of them
- Blue: Input 15 (y axis)

Scale Information:
- Y-axis 0g to 1.5E-3g
FRF Data

Figure 70: Accelerometer 5 (#71, Reference E)

The colors are assigned as follows:
- Orange: Input 13 (x axis)
- Green: Input 14 (z axis) *note that this data set is inverted from the rest of them
- Blue: Input 15 (y axis)
Day Two, Run Two

Driver: Richard Lawrance  
Equipment Operator: Uriel Rosa  
Data Set Title: Morning Run 1 Holes 1 through 9, Uriel and Richard

Accelerometer Data  
Unless otherwise noted, the graph scales are as follows  
Time domain graph scale:  
  • X-axis: 7:16:22am to 7:33:15am  
  • Y-axis: +90g to -50g  

FRF data graph scale:  
  • Top Graph  
    o X-axis 0Hz to 1.6kHz  
    o Y-axis: 0 to 5 no units  
  • Bottom Graph  
    o X-axis 0Hz to 1.6kHz  
    o Y-axis: -720° to 720°

Average spectrum graph scale:  
  • X-axis: 0Hz to 1.6kHz  
  • Y-axis: 0g to 0.04g

Notes  
This was the final run of the day. It is a repeat of the bottom 9 holes.
Figure 71: Accelerometer 1(#67, Reference A)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- Blue: Input 3 (z axis)
Average Spectrum Data

**Figure 72**: Accelerometer 1(#67, Reference A)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (axis)
- Blue: Input 3 (z axis)
FRF Data

Figure 73: Accelerometer 1(#67, Reference A)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- No data for input 3

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: 0 to 5 no units
- Bottom Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 74: Accelerometer 2 (#68, Reference B)

The colors are assigned as follows:
- Orange: Input 4 (x axis)
- Green: Input 5 (z axis)
- Blue: Input 6 (y axis) *note that this data set is inverted from the rest of them
Average Spectrum Data

Figure 75: Accelerometer 2 (#68, Reference B)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (z axis)
- Blue: Input 3 (y axis) *note that this data set is inverted from the rest of them
FRF Data

Figure 76: Accelerometer 2 (#68, Reference B)

The colors are assigned as follows:
- Orange: Input 4 (x axis)
- Green: Input 5 (z axis)
- Blue: Input 6 (y axis) *note that this data set is inverted from the rest of them

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: 0 to 700 no units
- Bottom Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 77: Accelerometer 3 (#69, Reference C)

The colors are assigned as follows:
- Orange: Input 7 (x axis)
- Green: Input 8 (y axis)
- Blue: Input 9 (z axis)
Figure 78: Accelerometer 3 (#69, Reference C)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- Blue: Input 3 (z axis)

Scale information:
- X-axis: 0Hz to 1.6kHz
- Y-axis: 0g to 70E-3
**FRF Data**

![FRF Data Graph](image)

**Figure 79: Accelerometer 3 (#69, Reference C)**

The colors are assigned as follows:
- Orange: Input 7 (x axis)
- Green: Input 8 (y axis)
- Blue: Input 9 (z axis)

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: 0 to 200 no units
- Bottom Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 80: Accelerometer 4 (#70, Reference D)

The colors are assigned as follows:
- Orange: Input 10 (x axis)
- Green: Input 11 (y axis)
- Blue: Input 12 (z axis)
Average Spectrum Data

Figure 81: Accelerometer 4 (#70, Reference D)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- Blue: Input 3 (z axis)

Scale Information:
- Y-axis: 0g to 80E-3g
- X-axis: 0Hz to 1.6kHz
FRF Data

Figure 82: Accelerometer 4 (#70, Reference D)

The colors are assigned as follows:
- Orange: Input 10 (x axis)
- Green: Input 11 (y axis)
- Blue: Input 12 (z axis)

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: 0 to 6 no units
- Top Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: -720° to 720°
**Time Domain Data**

![Graph](image)

**Figure 83**: Accelerometer 5 (#71, Reference E)

The colors are assigned as follows:

- Orange: Input 13 (x axis)
- Green: Input 14 (z axis) *(note that this data set is inverted from the rest of them)*
- Blue: Input 15 (y axis)
Figure 84: Accelerometer 5 (#71, Reference E)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- Blue: Input 3 (z axis)

Scale Information:
- X-axis: 0Hz to 1.6kHz
- Y-axis: 0g to 30E-3g
FRF Data

Figure 85: Accelerometer 5 (#71, Reference E)

The colors are assigned as follows:
- Orange: Input 13 (x axis)
- Green: Input 14 (z axis) *note that this data set is inverted from the rest of them
- Blue: Input 15 (y axis)

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: 0 to 200 no units
- Bottom Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: -720° to 720°
Day Two, Run Three

Driver: Richard Lawrance
Equipment Operator: Robert Dailey
Data Set Title: Morning Run 1 Holes 10 through 18, Robert and Richard

Accelerometer Data
Unless otherwise noted, the graph scales are as follows
Time domain graph scale:
  • X-axis: 8:29:19am to 8:44:47am
  • Y-axis: +90g to -50g

FRF data graph scale:
  • Top Graph
    o X-axis 0Hz to 1.4kHz
    o Y-axis: 0 to 10 no units
  • Bottom Graph
    o X-axis 0Hz to 1.4kHz
    o Y-axis: -720° to 720°

Average spectrum graph scale:
  • X-axis: 0Hz to 1.4kHz
  Y-axis: 0g to 0.006g

Notes
This was the final run of the day.
Time Domain Data

The colors are assigned as follows:

- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- Blue: Input 3 (z axis)

Figure 86: Accelerometer 1(#67, Reference A)
Average Spectrum Data

Figure 87: Accelerometer 1(#67, Reference A)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (axis)
- Blue: Input 3 (z axis)

Scale Information:
- X-axis: 0Hz to 1.6kHz
- Y-axis: 0g to 20E-3g
Figure 88: Accelerometer 1(#67, Reference A)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- No data for input 3

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: 0 to 1.5 no units
- Bottom Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 89: Accelerometer 2 (#68, Reference B)

The colors are assigned as follows:
- Orange: Input 4 (x axis)
- Green: Input 5 (z axis)
- Blue: Input 6 (y axis) *note that this data set is inverted from the rest of them
Average Spectrum Data

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (z axis)
- Blue: Input 3 (y axis) *note that this data set is inverted from the rest of them

Scale Information:
- X-axis: 0Hz to 1.6kHz
- Y-axis: 0g to 1.5E-3g

Figure 90: Accelerometer 2 (#68, Reference B)
FRF Data

**Figure 91: Accelerometer 2 (#68, Reference B)**

The colors are assigned as follows:
- Orange: Input 4 (x axis)
- Green: Input 5 (z axis)
- Blue: Input 6 (y axis) *note that this data set is inverted from the rest of them

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: 0 to 237 no units
- Bottom Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: -720° to 720°
Time Domain Data

**Figure 92**: Accelerometer 3 (#69, Reference C):

The colors are assigned as follows:
- Orange: Input 7 (x axis)
- Green: Input 8 (y axis)
- Blue: Input 9 (z axis)
Average Spectrum Data

Figure 93: Accelerometer 3 (#69, Reference C)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (axis)
- Blue: Input 3 (z axis)

Scale Information:
- X-axis: 0Hz to 1.6kHz
- Y-axis: 0g to 2E-3g
FRF Data

Figure 94: Accelerometer 3 (#69, Reference C)

The colors are assigned as follows:
- Orange: Input 7 (x axis)
- Green: Input 8 (y axis)
- Blue: Input 9 (z axis)

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: 0 to 80 no units
- Bottom Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 95: Accelerometer 4 (#70, Reference D)

The colors are assigned as follows:
- Orange: Input 10 (x axis)
- Green: Input 11 (y axis)
- Blue: Input 12 (z axis)
Figure 96: Accelerometer 4 (#70, Reference D)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (axis)
- Blue: Input 3 (z axis)

Scale Information:
- X-axis: 0Hz to 1.6kHz
- Y-axis: 0g to 25E-3g
FRF Data

The colors are assigned as follows:
- Orange: Input 10 (x axis)
- Green: Input 11 (y axis)
- Blue: Input 12 (z axis)

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: 0 to 2 no units
- Bottom Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 98: Accelerometer 5 (#71, Reference E)

The colors are assigned as follows:
- Orange: Input 13 (x axis)
- Green: Input 14 (z axis) *note that this data set is inverted from the rest of them
- Blue: Input 15 (y axis)
Average Spectrum Data

**Figure 99**: Accelerometer 5 (#71, Reference E)

The colors are assigned as follows:

- Orange: Input 1 (x axis)
- Green: Input 2 (axis)
- Blue: Input 3 (z axis)

Scale Information:

- X-axis: 0Hz to 1.6kHz
- Y-axis: 0g to 5E-3g
FRF Data

Figure 100: Accelerometer 5 (#71, Reference E)

The colors are assigned as follows:
- Orange: Input 13 (x axis)
- Green: Input 14 (z axis) *note that this data set is inverted from the rest of them
- Blue: Input 15 (y axis)

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: 0 to 94 no units
- Bottom Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: -720° to 720°
Day Two, Run Four

Driver: Richard Lawrance
Equipment Operator: Robert Dailey
Data Set Title: Morning Run 1 Holes 1 through 9, Robert and Richard

Accelerometer Data
Unless otherwise noted, the graph scales are as follows
Time domain graph scale:
- X-axis: 10:35:43am to 10:52:00am
- Y-axis: +90g to -50g

FRF data graph scale:
- Top Graph
  - X-axis 0Hz to 1.4kHz
  - Y-axis: 0 to 10 no units
- Bottom Graph
  - X-axis 0Hz to 1.4kHz
  - Y-axis: -720° to 720°

Average spectrum graph scale:
- X-axis: 0Hz to 1.4kHz
- Y-axis: 0g to 0.006g

Notes
This was manned by Robert and Richard. The top nine holes were repeated.
Time Domain Data

Figure 101: Accelerometer 1(#67, Reference A)

The colors are assigned as follows:

- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- Blue: Input 3 (z axis)
Average Spectrum Data

Figure 102: Accelerometer 1(#67, Reference A)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- Blue: Input 3 (z axis)

Scale Information:
- X-axis: 0Hz to 1.6kHz
- Y-axis: 0g to 20E-3g
FRF Data

Figure 103: Accelerometer 1(#67, Reference A)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (y axis)
- No data for input 3

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: 0 to 3 no units
- Bottom Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: -720° to 720°
Figure 104: Accelerometer 2 (#68, Reference B)

The colors are assigned as follows:

- Orange: Input 4 (x axis)
- Green: Input 5 (z axis)
- Blue: Input 6 (y axis) *note that this data set is inverted from the rest of them
Average Spectrum Data

Figure 105: Accelerometer 2 (#68, Reference B)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (z axis)
- Blue: Input 3 (y axis) *note that this data set is inverted from the rest of them

Scale Information:
- X-axis: 0Hz to 1.6kHz
- Y-axis: 0g to 1.2E-3g
FRF Data

Figure 106: Accelerometer 2 (#68, Reference B)

The colors are assigned as follows:
- Orange: Input 4 (x axis)
- Green: Input 5 (z axis)
- Blue: Input 6 (y axis) *note that this data set is inverted from the rest of them

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: 0 to 430 no units
- Bottom Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 107: Accelerometer 3 (#69, Reference C)

The colors are assigned as follows:
- Orange: Input 7 (x axis)
- Green: Input 8 (y axis)
- Blue: Input 9 (z axis)
Average Spectrum Data

Figure 108: Accelerometer 3 (#69, Reference C)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (axis)
- Blue: Input 3 (z axis)

Scale Information:
- X-axis: 0Hz to 1.6kHz
- Y-axis: 0g to 5E-3g
The colors are assigned as follows:
- Orange: Input 7 (x axis)
- Green: Input 8 (y axis)
- Blue: Input 9 (z axis)

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: 0 to 308 no units
- Bottom Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 110: Accelerometer 4 (#70, Reference D)

The colors are assigned as follows:
- Orange: Input 10 (x axis)
- Green: Input 11 (y axis)
- Blue: Input 12 (z axis)
Average Spectrum Data

Figure 111: Accelerometer 4 (#70, Reference D)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (axis)
- Blue: Input 3 (z axis)

Scale Information:
- X-axis: 0Hz to 1.6kHz
- Y-axis: 0g to 30E-3g
Figure 112: Accelerometer 4 (#70, Reference D)

The colors are assigned as follows:
- **Orange:** Input 10 (x axis)
- **Green:** Input 11 (y axis)
- **Blue:** Input 12 (z axis)

The graph scale data for the FRF data is as follows:
- **Top Graph**
  - x-scale: 0Hz to 1.6kHz
  - y-scale: 0 to 4 no units
- **Bottom Graph**
  - x-scale: 0Hz to 1.6kHz
  - y-scale: -720° to 720°
Time Domain Data

Figure 113: Accelerometer 5 (#71, Reference E)

The colors are assigned as follows:
- Orange: Input 13 (x axis)
- Green: Input 14 (z axis) *note that this data set is inverted from the rest of them
- Blue: Input 15 (y axis)
Average Spectrum Data

Figure 114: Accelerometer 5 (#71, Reference E)

The colors are assigned as follows:
- Orange: Input 1 (x axis)
- Green: Input 2 (axis)
- Blue: Input 3 (z axis)

Scale Information:
- X-axis: 0 Hz to 1.6 kHz
- Y-axis: 0 g to 9E-3 g
FRF Data

Figure 115: Accelerometer 5 (#71, Reference E)

The colors are assigned as follows:
- Orange: Input 13 (x axis)
- Green: Input 14 (z axis) *note that this data set is inverted from the rest of them
- Blue: Input 15 (y axis)

The graph scale data for the FRF data is as follows:
- Top Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: 0 to 270 no units
- Bottom Graph
  - x-scale 0Hz to 1.6kHz
  - y-scale: -720° to 720°
CONCLUSION

The conclusion that can be drawn data is that the vibration effects from the vehicle driving off road are fairly small overall. It appears that the brief impacts over time may be of more concern than the vibrations caused on the vehicle. This conclusion is drawn from the fact that while they were brief, there were impacts that resulted in measurements of more than 117.2g-force. On the other hand, the vibrations never seem to have a magnitude greater than 1g-force. Vibrations that were attributed to road travel were between the 0Hz and 20Hz range. While vibrations could be measured in all three axis, the amplitude of these vibrations were very small, the max being 9.97E-01 in the z axis during run 4 on day two.

It may also be beneficial to add some additional angle braces in the compartment of the vehicle. This may assist in reducing the horizontal vibrations measured. While the fuel cell stack could benefit from being mounted on vibration isolators to minimize the transfer of the horizontal vibrations into the structure of the stack, it does not seem to be of great concern if the stack is tightly attached to the chassis.
INTRODUCTION
When ambient air is used as a source of oxygen for the cathode in fuel cells, the life, durability and performance of the fuel cells are affected by air quality. The cathode catalyst and the electrolyte can be temporarily or permanently poisoned or damaged by contaminants that are present in the atmosphere such as sub-micrometer particulate matter, sulfur compounds, volatile organic compounds (VOCs), salts and oxides of nitrogen (NOx) etc. The concentration and type of these atmospheric contaminants vary with location, time of day and season. The removal of these contaminants is beyond the capability of current air contamination control systems (particulate filters) used in power plants such as engines and gas turbines. Therefore to maximize the performance, life and durability of PEM fuel cells, a new class of air contamination control is required.

The contamination of the cathode side of a PEM fuel cell can be divided into two main categories. The first category is poisoning of the catalyst by compounds that adsorb to the catalyst and occupy sites. Examples are VOCs and carbon monoxide. These compounds would be oxidized at elevated temperatures, but the operating temperature of most PEM fuel cells is about 80-120°C, thus preventing oxidation. The second category is either local or uniform contamination of the cathode/membrane interface by contaminant ions. Examples of contaminant ions are sodium, potassium, calcium, copper, zinc and magnesium. It has been found that contamination of the cathode side of a PEM fuel cell is even more serious than that of the anode side. The electrolyte in PEM fuel cells is acidic, and base gases and particles such as ammonia, salts and limestone etc. may be harmful to the electrolyte. In general, the contamination issue for fuel cells is very different than that of traditional power systems such as internal combustion engines and gas turbines. Large particulate matter is filtered out of the combustion air in engines to prevent wear, but CO and VOCs are not of concern as they are fuels for the combustion process. Sub-micron particulate matter and chemicals are not filtered from the combustion air in engines, as they are harmless. If the same level of filtration is applied to the cathode air in PEM fuel cells, contaminant ions and chemicals may permanently degrade the fuel cell.

Air contaminants vary with location in both composition and magnitude. Particulate matter for example, varies nine orders of magnitude in concentration from calm days over the ocean to a windy day in the desert. In addition, the size distribution of the particulates varies depending on the source of the particulate matter. Figure 1 describes in general terms how the contaminants vary with environmental conditions and
### Table 1: Types of Contaminants vs. Geographic Area

<table>
<thead>
<tr>
<th>Location</th>
<th>Urban Major metropolitan areas with heavy industry and motor vehicles</th>
<th>Rural/Arctic Forest, tundra and agriculture</th>
<th>Off-shore and Maritime</th>
<th>Desert</th>
<th>Tropical</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Environment Conditions</strong></td>
<td>Rain, fog, smog, snow. 28°F to 100°F (-2°C to +38°C). Corrosive chemicals, VOCs, SO2, gummy soot particles, NOx, NH3, and dried salts.</td>
<td>Snow, freezing rain, frost. -40°F to 90°F (-40°C to +32°C). Dry, noncorrosive fibrous particles, ammonia, SO2, and blowing dust.</td>
<td>Wet and dry salt, corrosive particles. 0°F to 90°F (-18°C to +32°C). Blowing rain, salts, sea spray, fog, snow and ice.</td>
<td>Dry, sunny. 32°F to 122°F (0°C to +50°C). Sandstorms, whirlwinds, dry, corrosive particles, clays and salts.</td>
<td>Heavy rainfall. 40°F to 122°F (+5°C to 50°C). Fibrous noncorrosive particles, molds and insects.</td>
</tr>
<tr>
<td><strong>Particle Concentration (μg/m³)</strong></td>
<td>50 – 175</td>
<td>&lt;150</td>
<td>&lt;135</td>
<td>&gt;350,000</td>
<td>&lt;135</td>
</tr>
<tr>
<td><strong>Particle Size Range (Micrometers)</strong></td>
<td>0.01 – 30</td>
<td>0.01 – 75</td>
<td>0.01 – 10</td>
<td>0.01 – 500</td>
<td>0.01 – 10</td>
</tr>
</tbody>
</table>

**Figure 1**: Types of Contaminants vs. Geographic area

Volatile Organic Compounds (VOCs) such as unburned hydrocarbon emissions from internal combustion engines vary greatly in concentration depending on location and the sources of emissions. Urban areas in cold climates experience days with significantly elevated levels of VOCs due to cold started internal combustion engines. Areas where two cycle internal combustion engines are operated have high concentrations of carbon monoxide and VOCs. A city can have relatively low average concentrations of VOCs, but have local areas where the concentrations are elevated. Sulfur compounds in the air are found wherever fuels containing sulfur are combusted, agricultural areas such as hog farms or industrial sources such as pulp mills. Typical average concentrations of a few select pollutants in various cities listed in Figure 2 illustrates the variation that can occur between locations. In extreme situations such as in battlefields, warfare gases and other pollutants can be present in the air in concentrations listed in Figure 3."
<table>
<thead>
<tr>
<th>Location</th>
<th>SO2 (ppb)</th>
<th>PM10 (μg/m^3)</th>
<th>Benzene (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perth, Australia</td>
<td>2.0</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>London, UK</td>
<td>11.0</td>
<td>29</td>
<td>1.8</td>
</tr>
<tr>
<td>Rome, Italy</td>
<td>1.0</td>
<td>52</td>
<td>3.7</td>
</tr>
<tr>
<td>Paris, France</td>
<td>5.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Berlin, Germany</td>
<td>6.0</td>
<td>31</td>
<td>2.8</td>
</tr>
<tr>
<td>Shanghai, China</td>
<td>20.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delhi, India</td>
<td>9.0</td>
<td>162</td>
<td></td>
</tr>
<tr>
<td>Taipei, Taiwan</td>
<td>4.0</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>Moscow, Russia</td>
<td>41.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cairo, Egypt</td>
<td>26.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stockholm, Sweden</td>
<td>2.0</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>New York, US</td>
<td>9.0</td>
<td>17</td>
<td>3.0</td>
</tr>
<tr>
<td>Los Angeles, US</td>
<td>2.0</td>
<td>139</td>
<td>1.0</td>
</tr>
<tr>
<td>Houston, US</td>
<td>2.6</td>
<td>29</td>
<td>0.8</td>
</tr>
<tr>
<td>Minneapolis, US</td>
<td>9.8</td>
<td>25</td>
<td>0.5</td>
</tr>
<tr>
<td>Vancouver, Canada</td>
<td>2.0</td>
<td>14</td>
<td>0.7</td>
</tr>
<tr>
<td>Mexico City, Mexico</td>
<td>28.0</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>Sao Paulo, Brazil</td>
<td>16.0</td>
<td>54</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2:** Average ambient air contaminants vs. Location

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Concentration (PPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Monoxide</td>
<td>20</td>
</tr>
<tr>
<td>Sulfur Dioxide</td>
<td>0.5</td>
</tr>
<tr>
<td>Benzene</td>
<td>50</td>
</tr>
<tr>
<td>Propane</td>
<td>90</td>
</tr>
<tr>
<td>Nitrogen Dioxide</td>
<td>0.4</td>
</tr>
<tr>
<td>Cyanogan Chloride (CNCL)</td>
<td>780-1560</td>
</tr>
<tr>
<td>Hydrogen Cyanide (HCN)</td>
<td>1780-3560</td>
</tr>
<tr>
<td>Sulfur Mustard</td>
<td>15</td>
</tr>
<tr>
<td>Sarin</td>
<td>170-340</td>
</tr>
</tbody>
</table>

**Figure 3:** Concentrations of Contaminants in a Battlefield

**LITERATURE SEARCH**

**Particulate Contaminants**

Particulate matter (PM) is typically in the size range of 10 nanometers to 100 micrometers in diameter. PM_{2.5} refers to the concentration of “fine” particles that are less than 2.5 microns. PM_{10} refers to the concentration of “coarse” particles, less than 10 microns in diameter. Particulate matter can also be classified as primary or secondary particles. Primary particles, such as dust from roads or elemental carbon (soot) from diesel fuel or wood combustion, are emitted directly into the air. Secondary particles are formed in the atmosphere from gaseous emissions such as sulfates formed from SO2, or nitrates formed from NOx emissions from automobiles, power plants and other industrial combustin sources. The USEPA has reported the average concentration in ambient environments of PM_{10} ranges from 20-40 μg/m^3. Much higher
Concentrations are found in more polluted urban environments. In addition, off road vehicles are subject to higher concentration from road or soil dust.

Barris\(^3\) reported an average ambient range of 10-139 \(\mu g/m^3\). Paved roads ranged from 139 \(\mu g/m^3\) to 57 mg/m\(^3\), and dirt roads from 139 \(\mu g/m^3\) to 6113 mg/m\(^3\).

<table>
<thead>
<tr>
<th>Condition</th>
<th>Dust Concentration (mg/m3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Ambient</td>
<td>0.010-0.139</td>
</tr>
<tr>
<td>95th % Ambient</td>
<td>0.089</td>
</tr>
<tr>
<td>99th % Ambient</td>
<td>0.112</td>
</tr>
<tr>
<td>Paved Roads</td>
<td>0.139-57</td>
</tr>
<tr>
<td>Dirt Roads</td>
<td>0.139-6113</td>
</tr>
<tr>
<td>Dust Storms</td>
<td>0.1-176</td>
</tr>
<tr>
<td>Worst Dust Storm</td>
<td>3000</td>
</tr>
<tr>
<td>0 Visibility</td>
<td>883</td>
</tr>
<tr>
<td>20x0 Visibility</td>
<td>17657</td>
</tr>
</tbody>
</table>

**Table 1:** Range of Dust Concentrations in Various Engine Environments

Besse\(^4\) studied the particle size distribution as a function of height above a dirt road traveled by Light Armored Vehicles (LAVs). A sampling system was set up to take samples from 1-3 meters above the ground at 0.3 meter intervals. The stand was located 2 meters from the road. They found that there was only a minor shift toward the smaller particles as height increased (Table 2). As expected, the weight percent at each height decreased with increasing height (Table 3). The increase at 1.6 meters was attributed to air currents caused by the vehicles body configuration or exhaust system.

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>330</td>
<td>222</td>
<td>178</td>
<td>139</td>
<td>107</td>
<td>87.9</td>
<td>74.2</td>
<td>47.3</td>
<td>23</td>
</tr>
<tr>
<td>1</td>
<td>435</td>
<td>278</td>
<td>222</td>
<td>173</td>
<td>134</td>
<td>109</td>
<td>72.5</td>
<td>48.9</td>
<td>29.9</td>
</tr>
<tr>
<td>1.3</td>
<td>434</td>
<td>265</td>
<td>229</td>
<td>179</td>
<td>140</td>
<td>115</td>
<td>71.1</td>
<td>51.9</td>
<td>31.8</td>
</tr>
<tr>
<td>1.6</td>
<td>463</td>
<td>322</td>
<td>257</td>
<td>199</td>
<td>153</td>
<td>124</td>
<td>103</td>
<td>52</td>
<td>30.6</td>
</tr>
<tr>
<td>2</td>
<td>486</td>
<td>329</td>
<td>204</td>
<td>200</td>
<td>159</td>
<td>126</td>
<td>107</td>
<td>54.4</td>
<td>32.7</td>
</tr>
<tr>
<td>2.3</td>
<td>476</td>
<td>307</td>
<td>246</td>
<td>191</td>
<td>148</td>
<td>121</td>
<td>101</td>
<td>53.6</td>
<td>32.8</td>
</tr>
<tr>
<td>2.6</td>
<td>461</td>
<td>318</td>
<td>253</td>
<td>187</td>
<td>152</td>
<td>124</td>
<td>104</td>
<td>55.1</td>
<td>33.6</td>
</tr>
<tr>
<td>3</td>
<td>514</td>
<td>348</td>
<td>280</td>
<td>217</td>
<td>166</td>
<td>134</td>
<td>112</td>
<td>55.8</td>
<td>32.8</td>
</tr>
</tbody>
</table>

**Table 2:** Particle size distribution as a function of height

<table>
<thead>
<tr>
<th>Height, m</th>
<th>Percentage, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.8</td>
</tr>
<tr>
<td>1.3</td>
<td>14.5</td>
</tr>
<tr>
<td>1.6</td>
<td>18.4</td>
</tr>
<tr>
<td>2</td>
<td>13.5</td>
</tr>
<tr>
<td>2.3</td>
<td>10.7</td>
</tr>
<tr>
<td>2.6</td>
<td>9.4</td>
</tr>
<tr>
<td>3</td>
<td>9.7</td>
</tr>
<tr>
<td>3.3</td>
<td>3.0</td>
</tr>
</tbody>
</table>

**Table 3:** Weight percentage of total airborne particulate at each height
Chemical Contaminants

Basic make Up of Air
Air is widely established to contain 78.03-78.08% nitrogen, 20.95-20.99% oxygen, 0.94% argon, 0.03-0.04% carbon dioxide, 0.001-0.002% neon, 0.0005% helium, 0.0001% krypton, 0.00005% hydrogen, and 0.000009% xenon, and this basic composition is relatively constant. Other compounds maybe present and the concentrations and nature of these compounds can vary widely from location to location and in a specific location from day to day based on atmospheric conditions and local activity.

Measuring Contaminants
Chemical contaminants are usually reported as either mass per volume of air such as micrograms per cubic meter (μg/m³), or part per billion by volume (ppb). Part per billion is defined as the volume of the gaseous contaminant divided by the volume of air times one billion.

\[ ppb = \frac{V_c}{V_a} \times 10^9 \]

The number of molecules in a given volume of air at constant temperature and pressure will always be constant. This concept is known as Avogadro's law. Most Chemical detectors are concentration dependant and measure the number of molecules of a particular species in a given volume. The concentration is then reported as part per billion or part per million. This measurement is useful for determining the relative amount of one contaminant to the next. The value of the measurement in ppb will also be independent of temperature and pressure since the volume of both the contaminant and air will increase proportionally with increased temperature and decrease proportionally with increased pressure.

The ideal gas law further describes the relationship between a volume (V) of gas at a given temperature (T), and pressure (P), and the number of molecules or moles (n).

\[ PV = nRT \]

R is the ideal gas constant and is dependent on the units of measurement. The mass (m) of a contaminant can be calculated from the number of moles divided by the molecular weight (M).

\[ n = \frac{m}{M} \]

Therefore,

\[ PV = \frac{mR}{M} \]

The mass of a contaminant in a specific volume is then dependant on pressure, temperature, and the molecular weight of the contaminant. The value is usually assumed to be at standard temperature and pressure, 760 mmHg, and 25°C. At this temperature and pressure, ppb can be converted to μg/m³ with the equation:

\[ \mu g/m^3 = \frac{C_{ppb}M}{24.5} \]

Reported Levels of Various Contaminants
Chemical contaminants in the air can be divided up in to three classes 1) acid gases 2)
base gases 3) volatile organic compounds (VOCs). Acid gases are gases that will form acids when mixed with water. Common examples are sulfur dioxide (SO₂) which will form sulfuric acid (H₂SO₄) when dissolved in water, and nitrogen oxide (NO) or nitrogen dioxide (NO₂) which will form nitrous acid (HNO₂) and nitric acid (HNO₃) when dissolved in water. Nitrogen oxide and nitrogen dioxide are often combined and referred to as oxides of nitrogen and represented as NOₓ. Base gases are gases that will form base solutions with water such as ammonia (NH₃) which forms ammonium (NH₄OH) when dissolved in water. Acid and base gases can also combine to form salts and can agglomerate to form secondary particles. Organic compounds are a broad class of compounds containing carbon chains or rings and hydrogen, and often also contain other elements such as oxygen, nitrogen, sulfur, etc. Volatile organic compounds are compounds that readily evaporate under room temperature and pressure. VOCs are common and ubiquitous. They are solvents used in paints and building materials, aerosols, fuels such as gasoline and diesel fuel, petroleum distillates and other industrial products. They are also emitted from plants and animals by off gassing or respiration. Acid gases and VOCs have been found to be particularly detrimental to fuel cell performance.

The USEPA² has set national air quality standards for six principal air pollutants: nitrogen dioxide (NO₂), ozone (O₃), sulfur dioxide (SO₂), particulate matter (covered in section 2.1), carbon monoxide (CO), and lead (Pb). Typical concentrations, as given by the EPA are given in Table 4.

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Concentration in ppb (µg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen dioxide</td>
<td>10-40 (19-75)</td>
</tr>
<tr>
<td>Sulfur dioxide</td>
<td>1.0-10 (2.6-26)</td>
</tr>
<tr>
<td>Ozone</td>
<td>50-200 (98-391)</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>2-6 (2.3-6.8)</td>
</tr>
<tr>
<td>Lead</td>
<td>0-0.1 (0.8)</td>
</tr>
</tbody>
</table>

Table 4: Average Annual Concentration of Principal Air Pollutants

The EPA defines toxic air pollutants as those compounds that may cause serious health problems⁶. Typical examples of toxic air pollutants are benzene, perchloroethylene, and methylene chloride. Most toxic air pollutants, like those listed, are anthropogenic, but some are also released from natural sources such as forest fires. The Clean Air Act identifies 188 compounds from industrial sources. The EPA and state agencies monitor selected compounds and have compiled data to establish risk assessments and create maps that model ambient concentrations for a given compound across the nation. Table 5 shows some compounds of interest with the highest, median, and lowest concentrations. Concentration maps, shown in Appendix A, illustrate how widespread common VOCs are in the atmosphere. All of these compounds could adversely affect fuel cell performance.
### Table 5: Concentrations of common pollutants as measured by the EPA

Jacobson\(^7\) reported concentrations of variable gases in polluted and clean troposphere.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Highest ppb (µg/m(^3))</th>
<th>Media ppb (µg/m(^3))</th>
<th>Lowest ppb (µg/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetaldehyde</td>
<td>2.6 (4.75)</td>
<td>0.07 (0.13)</td>
<td>0.0006 (0.001)</td>
</tr>
<tr>
<td>Acrolein</td>
<td>0.26 (0.6)</td>
<td>0.15 (0.34)</td>
<td>6.6x10(^{-5}) (1.5x10(^{-4}))</td>
</tr>
<tr>
<td>Benzene</td>
<td>1.5 (4.76)</td>
<td>0.2 (0.65)</td>
<td>0.15 (0.48)</td>
</tr>
<tr>
<td>Carbon tetrachloride</td>
<td>0.15 (0.94)</td>
<td>0.14 (0.88004)</td>
<td>0.14 (0.88000)</td>
</tr>
<tr>
<td>Ethylene dichloride</td>
<td>0.035 (0.14)</td>
<td>0.015 (0.062002)</td>
<td>0.015 (0.062000)</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>5.6 (6.81)</td>
<td>0.38 (0.46)</td>
<td>0.20 (0.25)</td>
</tr>
<tr>
<td>Methylene chloride</td>
<td>0.85 (2.94)</td>
<td>0.045 (0.17)</td>
<td>0.043 (0.15)</td>
</tr>
<tr>
<td>Perchloroethylene</td>
<td>0.20 (1.39)</td>
<td>0.022 (0.149)</td>
<td>0.020 (0.140)</td>
</tr>
<tr>
<td>Tetrachloroethane</td>
<td>0.16 (1.08)</td>
<td>0.012 (0.084)</td>
<td>0.012 (0.0810)</td>
</tr>
</tbody>
</table>

### Table 6: Concentration of variable gases in clean and polluted troposphere in ppb (µg/m\(^3\))

Data obtained from the World Health Organization are in agreement with Jacobson's report and show that, as expected heavily populated urban areas have very high concentrations of carbon monoxide.

Cross\(^8\) reported on data from a literature search on ambient pollutants in urban, rural and military battlefield environments. He found that in urban and rural environments eight pollutants accounted for over 99.9% of all measured pollutants. The most common pollutants found in urban and rural environments were carbon monoxide (CO), particulate matter less than 10 microns in size (PM\(_{10}\)), SO\(_2\), toluene, ozone, NO\(_2\), particulate matter less than 2.5 microns in size (PM\(_{2.5}\)) and formaldehyde. In urban
environments CO was the most prevalent pollutant due to automobile exhaust; in rural environments PM$_{10}$ was the most prevalent due to road dust and blown dirt. In heavily polluted battlefield environments there were fifteen chemicals accounting for over 99.5% of the pollutants. Carbon monoxide was again the most prevalent, aluminum oxide and other airborne particle were the next highest followed by hydrogen chloride, VOCs, NO$_x$, NH$_3$, hydrogen sulfide and hydrogen cyanide. Other chemical warfare agents such as sarin, sulfur mustard and cyanogen chloride may be present, but studies of their concentrations are classified. Moore and coworkers studied the effect of chemical warfare agents and pollutants and found that some cause a depression in fuel cell performance.

Table 7: Effect of Military Pollutants on Fuel Cell Performance

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Concentration</th>
<th>Percentage of original output during challenge</th>
<th>Percentage of original output during recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon monoxide</td>
<td>20 ppm</td>
<td>96%</td>
<td>100%</td>
</tr>
<tr>
<td>Nitrogen dioxide</td>
<td>400 ppb</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Sulphur dioxide</td>
<td>500 ppb</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Benzene</td>
<td>50 ppm</td>
<td>95% (50 mA/cm$^2$)</td>
<td>93% (100 mA/cm$^2$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>72% (200 mA/cm$^2$)</td>
</tr>
<tr>
<td>Propane</td>
<td>90 ppm</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>HCN</td>
<td>1780 ppm</td>
<td>13%</td>
<td>45%</td>
</tr>
<tr>
<td>HCN</td>
<td>3560 ppm</td>
<td>9%</td>
<td>35%</td>
</tr>
<tr>
<td>CCl$_3$</td>
<td>780 ppm</td>
<td>11%</td>
<td>32%</td>
</tr>
<tr>
<td>CCl$_3$</td>
<td>1560 ppm</td>
<td>12%</td>
<td>30%</td>
</tr>
<tr>
<td>Sulphur mustard</td>
<td>15 ppm</td>
<td>13%</td>
<td>13%</td>
</tr>
<tr>
<td>Sarin</td>
<td>170 ppm</td>
<td>30%</td>
<td>30%</td>
</tr>
<tr>
<td>Sarin</td>
<td>340 ppm</td>
<td>23%</td>
<td>23%</td>
</tr>
</tbody>
</table>

Off road applications will offer unique chemical contamination challenges. Vehicles driving on fields or in forested areas will be subject to a variety of biogenic volatile organic compounds. Forest trees have been shown to emit significant amounts of isoprene and monoterpenes. Kristine studied the emissions of VOCs from pasture and found emissions of oxygenated species including methanol, ethanol, propanone, butanone, and ethanal with only a small amount of isoprene and monoterpenes. Fluxes as high as 23,000 μg (carbon) m$^{-2}$ h$^{-1}$ were measured, with clover emitting more VOCs than grass. Emission rates after mowing increased dramatically with clover emissions increasing 80 times and grass emissions increasing 180 times. These emissions included the above compounds plus higher levels of (Z)-3-hexenal, (E)-2-hexenal, (Z)-2-hexen-1-ol, (Z)-3-hexen-1-ol, and (Z)-hexenyl acetate.

Concentrations of VOCs from cut grass and clover were measured by de Gouw who found that as the grass dries the VOC emissions increase. The concentrations of methanol and (Z)-3-hexenal rose immediately after cutting both grass and clover. After approximately 200 minutes the VOC emissions started to rise again. Concentrations of (Z)-3-hexenal and acetaldehyde peaked at approximately 1 PPM 400 minutes after cutting grass. Concentration of (Z)-3-hexenal peaked at 0.1 PPM and acetone peaked at 2 PPM 300 minutes after cutting clover.
Grass  Clover

<table>
<thead>
<tr>
<th>Compound</th>
<th>Grass</th>
<th>Clover</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>After cutting</td>
<td>Peak at 400 min</td>
</tr>
<tr>
<td>(Z)-3-hexenal</td>
<td>300</td>
<td>1000</td>
</tr>
<tr>
<td>(Z)-3-hexenol</td>
<td>200</td>
<td>90</td>
</tr>
<tr>
<td>Hexenyl acetate</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Methanol</td>
<td>300</td>
<td>200</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>200</td>
<td>1000</td>
</tr>
<tr>
<td>Butanone</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Acetone</td>
<td>400</td>
<td></td>
</tr>
</tbody>
</table>

**Table 8:** VOC concentrations (ppb) in air immediately after cutting and after drying

Pesticides are also present in low concentrations during application. Yeary\(^5\) studied the concentrations of various pesticides in the air during application. Pesticide concentrations were measured in the outdoor ambient air and at the applicator breathing zone. In most measurements the concentrations of pesticides were below the detectable limit of 1 μg/m\(^3\). Tables 9 and 10 show the results of their testing.

<table>
<thead>
<tr>
<th>Pesticide</th>
<th>Number of sample sites</th>
<th>No. Below detectable limit</th>
<th>TWA ppb (μg/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acephate</td>
<td>17</td>
<td>16</td>
<td>4.3 (32)</td>
</tr>
<tr>
<td>Ammonia</td>
<td>12</td>
<td>12</td>
<td>---</td>
</tr>
<tr>
<td>Carbaryl</td>
<td>28</td>
<td>15</td>
<td>1.6 (13)</td>
</tr>
<tr>
<td>Dicofel</td>
<td>53</td>
<td>52</td>
<td>0.5 (6)</td>
</tr>
<tr>
<td>Diazinon</td>
<td>34</td>
<td>32</td>
<td>0.3 (4)</td>
</tr>
<tr>
<td>Malathion</td>
<td>5</td>
<td>5</td>
<td>---</td>
</tr>
<tr>
<td>2,4-D</td>
<td>16</td>
<td>11</td>
<td>2.8 (25)</td>
</tr>
<tr>
<td>Xylene</td>
<td>30</td>
<td>30</td>
<td>---</td>
</tr>
</tbody>
</table>

**Table 9:** Outdoor ambient air during pesticide application

<table>
<thead>
<tr>
<th>Pesticide</th>
<th>Number of sample sites</th>
<th>No. Below detectable limit</th>
<th>TWA μg/m(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atrasine</td>
<td>22</td>
<td>16</td>
<td>0.1 (1)</td>
</tr>
<tr>
<td>Bensulide</td>
<td>10</td>
<td>10</td>
<td>---</td>
</tr>
<tr>
<td>Chlorpyrifos</td>
<td>17</td>
<td>9</td>
<td>0.35 (5)</td>
</tr>
<tr>
<td>2,4-D</td>
<td>76</td>
<td>61</td>
<td>0.4 (4)</td>
</tr>
<tr>
<td>Dacthal</td>
<td>2</td>
<td>2</td>
<td>---</td>
</tr>
<tr>
<td>Diazinon</td>
<td>20</td>
<td>7</td>
<td>1.1 (14)</td>
</tr>
<tr>
<td>MCPA</td>
<td>25</td>
<td>25</td>
<td>---</td>
</tr>
<tr>
<td>Pendimethalin</td>
<td>8</td>
<td>8</td>
<td>---</td>
</tr>
</tbody>
</table>

**Table 10:** Applicator breathing zone air monitoring
Conclusion
Air quality is affected by many factors and can vary widely between locations and even from day to day. Particulate levels generally average from 0.01-0.14 mg/m$^3$ but are frequently higher in off road situations such as dirt roads where the level may be as high as 6000 mg/m$^3$. In addition, small particles, 0.01-5.0 μm, can have a detrimental effect on fuel cell cathodes. Particles of this size are often secondary particles containing sulfur dioxide and oxides of nitrogen which are detrimental to fuel cell performance. Typical filters for internal combustion engines are not as effective at removing these small particles. HEPA grade filtration is most likely necessary to achieve maximum performance for fuel cells.

Chemical contaminants also vary widely in composition and concentration depending on location and time. The wide range of chemical contaminants should be considered in the fuel cell filtration design. The filter should be able to remove acid gases, base gases and a broad range of volatile organic compounds.

ANALYTICAL METHODS
Donaldson will conduct field testing of air quality, with Toro’s assistance, by fitting a Heavy Duty Workman® utility vehicle with air monitoring and sampling devises. Air samples will be taken at a golf course specified by Toro in St. Paul, MN. The goal of the sampling is to determine types and concentrations of contaminants that may be encountered in an off road fuel cell vehicle. This data will be used to test possible contaminants to determine their affect on fuel cell performance and design filter systems. Particulate and chemical contaminant data will be collected. Samples will be collected at various locations around the course and in as many different conditions as possible, i.e. morning, afternoon, during mowing or fertilizing etc. There are numerous methods for measuring contaminant concentrations in air. The USEPA, NIOSH and OSHA all have libraries of methods for general testing and testing for specific chemicals. Methods usually involve using a sample pump to draw air through an adsorbent devise or filter paper, then analyzing the adsorbent. Air samples will be taken at the back of the vehicle (A), in between the box and the cab (B), and on the front of the vehicle (C). Sample location A will allow us to collect contaminant data caused by the vehicle as it disturbs the soil. Sample location B will collect contaminant data near the potential air inlet for the fuel cell. Sample location C will collect contaminant data from the undisturbed environment.
Particulate Contaminants
Particulate analysis will focus on PM$_{10}$ and will be conducted in accordance with NIOSH method 0600. These particles will adversely affect the performance of fuel cells and are not removed very well by typical IC engine filtration.

Sampling of particulates will use a pump with an impactor used to remove large particles from the air. Particles smaller than 10 microns will be collected on a pre-weighed filter paper to determine the mass of particles in the air. A scanning electron microscope will also be used to try to determine the size distribution and electron dispersion spectroscopy will be used to try to determine the chemical make up of the particles.

Chemical Contaminants
Sampling and measurement will focus on acid gases, specifically sulfur dioxide and oxides of nitrogen, base gases, specifically ammonia, and volatile organic compounds. Sampling and analysis of acid gases will be conducted in accordance with NIOSH methods 6004 for SO$_2$ and/or NIOSH method 6014 for NO$_x$. Base gas analysis will be conducted in accordance with NIOSH method 6016 for ammonia. In these analyses, a sample pump will be fitted with adsorbent tubes. The flow rate through each tube is calibrated and the sample time measured and recorded. The adsorbent material in each tube is extracted with de-ionized water. The water sample is then concentrated and analyzed by ion chromatography. Contaminants can then be identified and quantified.
Sampling of VOCs will be conducted in accordance with EPA Compendium Method TO-17, “Determination of Volatile Organic Compounds in Ambient Air Using Active Sampling onto Sorbent Tubes”. In this analysis a pump will again be used to draw air through adsorbent tubes to collect the contaminants for analysis by thermal desorption/gas chromatography/mass spectroscopy. We will use two different adsorbents for VOC sampling. Carbosieve® is used for the collection of light organic compounds typically with boiling points from -60°C to 80°C, and Tenax® TA is used for collection of higher molecular weight organics typically with boiling points from 100°C to 400°C. Typical flow rates and sampling times will be 0.1-1.0 Liters/minute, and 1-4 hours respectively. Samples will be returned to Donaldson’s Corporate Technology laboratory for analysis.
APPENDIX A: US CONTAMINANT CONCENTRATION FOR SELECTED CONTAMINANT BY COUNTY
These maps illustrate the modeled ambient concentration of air toxics by county in 1996. Map colors indicate ranges of median concentration values, and each county is colored according to its value relative to the rest of the country. The concentration value displayed in maps is the median. Pollutant concentration is expressed in micrograms per cubic meter of air (µg/m³).
APPENDIX B: DEFINITIONS

Acid gas: Gas that will form acids when mixed with water. Common examples are sulfur dioxide (SO₂) which will form sulfuric acid (H₂SO₄) when dissolved in water, and nitrogen oxide (NO) or nitrogen dioxide (NO₂) which will form nitrous acid (HNO₂) and nitric acid (HNO₃) when dissolved in water.

Anthropogenic: Relating to, or resulting from the influence of human beings on nature.

Base gas: Gas that will form base solutions with water such as ammonia (NH₃) which forms ammonium (NH₄OH) when dissolved in water.

Biogenic Compounds: Compounds produced by the actions of living organisms.

Chromatography: A series of related techniques for the separation of a mixture of compounds by their distribution between two phases. In gas-liquid chromatography the distribution is between a gaseous and a liquid phase. In column chromatography the distribution is between a liquid and a solid phase.

Hydrocarbon: Compounds containing only carbon and hydrogen. Petroleum products are a common example of hydrocarbons.

Ion chromatography: A form of liquid chromatography that uses ion-exchange resins to separate atomic or molecular ions based on their interaction with the resin.

Mass spectroscopy: Mass spectrometry is a technique for separating ions by their mass-to-charge (m/z) ratios in order to identify a compound or a molecular structure.

Organic compound: Chemical compounds based on carbon chains or rings and also containing hydrogen, with or without oxygen, nitrogen, and other elements.

Oxides of nitrogen: A mixture of nitrogen oxide (NO) and nitrogen dioxide (NO₂) greenhouse gases produced as by-products in combustion engines and many industrial processes; NO x in the atmosphere are converted to nitric acid (HNO₃) which falls as acid rain.

PM₂.₅: Refers to the concentration of “fine” particles that are less than 2.5μm in diameter.

PM₁₀: Refers to the concentration of “course” particles, less than 10μm in diameter.

Thermal desorption: A method for vaporizing and introducing volatile and semi-volatile compounds present in a sample into an analytical instrument by means of thermal energy.

Troposphere: The portion of the earth’s atmosphere from the surface to the tropopause; that is, the lowest 10-20 km of the atmosphere. The troposphere is characterized by decreasing temperature with height, and is the layer of the atmosphere containing most
clouds and other common weather phenomena

Volatile organic compounds (VOCs): Compounds that vaporize (become a gas) at room temperature. Common sources which may emit VOCs include housekeeping and maintenance products, building and furnishing materials, gasoline, kerosene, diesel fuel, industrial solvents, and plants and animals.
REFERENCES
2. US EPA website, *National Air Quality 2001 Status and Trends*
6. US EPA website, *Toxic Air Pollutants*
INTRODUCTION
Fuel cell systems for back-up power are best suited for use in regions where the grid is unstable. These regions tend to be in the developing world where air quality is often poor to unhealthy. In order for a fuel cell system to operate successfully in these regions, contaminants in the ambient air must be removed or greatly reduced before supplying oxygen to the cathode. As a result, air filters are routinely used to filter the air to remove particulates and contaminants. However, no real data on air filter efficacy and lifetime exists for fuel cell applications. It is the objective of this research to determine efficacy and longevity of air filters with respect to removing NO\textsubscript{x} and SO\textsubscript{x} contaminants, two contaminants that are routinely found in high levels in the developing world.

EXPERIMENTAL SET-UP
Schematic
A simple schematic of the experimental apparatus is shown in Figure 1 and a P&ID is provided in Figure 2. The test system can be further separated into the following subsystems:

- **Air delivery (Figure 3):** Consists of the air compressor, the air tank, the dryer and the chiller.
- **Humidification (Figure 4):** Consists of the humidification tank which has an inlet valve for water which is controlled by P&ID through Labview.
- **Pollutant injection system (Figure 5):** Consists of Mass Flow Controllers (MFCs) which operate in the mSLPM range of interest for NO\textsubscript{2} and SO\textsubscript{2}.
- **Gas heating (Figure 6).** Consists of the heaters and the thermocouples controlled by P&ID through Labview.
- **Filter testing (Figure 6):** Consists of the assembly that has been built to house the filters in a manner that isolates them from the ambient.
- **Gas sampling (Figure 7):** Consists of a series of Mass flow controllers (MFCs) which regulate the air flow rates through each of the filters during the test.
**Figure 1:** Test set-up schematic
Figure 2: P&ID
Figure 3: Air Delivery

Figure 4: Humidification
Figure 5: Pollution gas flow control

Figure 6: Filter housings and heater control
The air compressor, dryer, and chiller provide cold, dry air for the system to operate (Figure 3). Solenoids at the beginning of each channel allow air to flow for testing. This also allows channels to be shut off individually without interrupting flow to the other channels. Mass flow meters following the solenoids measure inlet air flow and also meters pollutant concentrations.

A first set of heaters brings the air to test temperature for each channel. The humidification system (Figure 4) follows consisting of a chamber to allow mixing of air and water. The system pumps water into the chambers through misting nozzles. Water flow is controlled with variable control valves. Closed loop feedback for humidification control is provided by the humidity sensor downstream.

This temperature and humidity controlled air then passes into the pollutant injection system which meters flow of SO\textsubscript{2} and NO\textsubscript{2} into the air stream. Solenoid valves must open before the pollutant is allowed to flow and are shut off when no pollutant is needed. An air purge solenoid introduces clean air upstream of the pollutant mass flow controllers to clear any trapped pollutant during shutdown (Figure 5).

After the pollutant injection, the flow of each channel is split into three sub-channels and mass flow meters control flow of polluted air to the different filters (Figure 6). A final heating stage heats each sub-channel to offset any heat lost since the initial heaters. Filtered air is sampled and passes through to a common exhaust manifold and expelled from the experimental area.

The sampling system consists of 12 solenoid valves and a manifold (Figure 7) to the gas analyzer. Each channel has an upstream sample and three downstream samples; one for each type of filter. The upstream sample is a short distance downstream of pollution injection and will act as error signal to pollution concentration control as well as
test data for the filters. The downstream samples will read pollution levels after the filter to assess filter performance. The sampling system will open one solenoid while keeping the other 11 closed. The Horiba gas analyzer will draw from the sampling system long enough to clear the tube of previous samples as well as attain a stable reading. This results in long periods between samples of each filter.

The system has emergency release solenoids which vent all gas from each channel during the event of an emergency. These solenoids are normally open and must be energized to close. In the event of a power failure, these solenoids will automatically open causing the entire system to vent.

During the actual test, the test parameters including air flow rate, pollutant flow rates, temperature and humidity are set to the desired values noted in the experimental plan. All of these parameters as well as the solenoid valves are controlled from Labview and are recorded against a date and time stamp. Each test will continue until filter failure. Once a filter fails, the filter will be replaced and the test repeated with a new set of values from the full factorial of the experiment.

Controls
Custom software was written using Labview to control all the test equipment. P&ID loops were written to control the air temperature and air humidity. Code for test data saving is included in the control software. By this means, an excel spreadsheet containing readings for flow rate, temperature and humidity is continuously storing data while the control program is running.

In order to achieve integrated data acquisition, we used a NI systems as detailed in Table 1.

<table>
<thead>
<tr>
<th>DAC cards</th>
<th>Number of AI</th>
<th>Number of AO</th>
<th>Number of DIO</th>
<th>Counters</th>
</tr>
</thead>
<tbody>
<tr>
<td>NI PXI 6723</td>
<td>0</td>
<td>32</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>NI PXie 6363</td>
<td>32</td>
<td>4</td>
<td>48</td>
<td>4</td>
</tr>
<tr>
<td>NI 4353 PXie</td>
<td>32</td>
<td>0</td>
<td>8</td>
<td>0</td>
</tr>
</tbody>
</table>

|               | (thermocouple) |             |               |          |
|               | 32/32          | 36           | 56            | 4        |

Table 1: Table detailing the data cards being used for P&ID control

The acquired data is then processed through Labview to achieve P&ID control. The Labview interface (Figure 8) allows for real time display of the parameter that is being
controlled thereby ensuring that the gains may be manually changed if the control system fails to achieve the desired value.

![User interface on Labview for P&ID control of temperature and humidity](image)

**Figure 8:** User interface on Labview for P&ID control of temperature and humidity

Due to the fact that there is only one gas analyzer per pollutant and several sampling points in the system, proper multi-point pollutant monitoring can only be achieved by implementing a sampling sequence. For that purpose, separate Labview testing sequence code (Figure 9) was developed in order to get an automated sampling sequence. The code creates a testing sequence in which sampling valves throughout the system are opened one at a time while the rest of the valves are kept closed. The software also allows one to select between manual and automatic valve command and to indicate the sampling time during which the valves remain open until steady readings are achieved in the analyzers. The sampling data containing the status of the valves (open or closed) for each time, is stored on an excel spreadsheet that can be merged with the gas concentration data from the analyzers.
Figure 9: Labview user interface showing the sampling sequence involving the upstream sample and the three filter samples. The sampling time can be set in such a manner that a steady value can be obtained for each sample.

Lastly, software to merge the Labview data and the Horiba data into one master data file was created. The testing experiments deal with three different sources of data. The first source is the output from Labview, which generates two separate files, and the other two sources are the Horiba gas analyzers. Since time is the common variable in all the data files, it is possible to merge them into one file. In order to do this, a Windows application was developed, which generates a single output file from the four mentioned inputs. The user interface for the software is shown in Figure 10. The intent is to generate one master data file for each day of testing.
Figure 10: User interface for data merge software

TEST PLAN:
In discussions with air filter companies, the critical factors for determining air filter performance are:

- Contaminant concentration
- Gas flow rate
- Temperature
- Humidity level

With this in mind, we selected the following ranges for the key variables:

- NO₂ – 100 and 170 μg/m³
- SO₂ – 25 and 100 μg/m³
- Gas flow rate – 100 and 300 slpm
- Temperature – 10°C and 40°C
- Relative humidity – 25% and 70%

Since the interactions between the key variables are not known, we decided to perform a factorial design of experiments, the details of which are provided in Table 2 and Table 3.
<table>
<thead>
<tr>
<th>Test Number</th>
<th>NO₂ (μg/m³)</th>
<th>SO₂ (μg/m³)</th>
<th>Flow (slpm)</th>
<th>Temp. (°C)</th>
<th>Relative Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>25</td>
<td>100</td>
<td>10</td>
<td>25%</td>
</tr>
<tr>
<td>2</td>
<td>170</td>
<td>25</td>
<td>100</td>
<td>10</td>
<td>25%</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>10</td>
<td>25%</td>
</tr>
<tr>
<td>4</td>
<td>170</td>
<td>100</td>
<td>100</td>
<td>10</td>
<td>25%</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>25</td>
<td>300</td>
<td>10</td>
<td>25%</td>
</tr>
<tr>
<td>6</td>
<td>170</td>
<td>25</td>
<td>300</td>
<td>10</td>
<td>25%</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>100</td>
<td>300</td>
<td>10</td>
<td>25%</td>
</tr>
<tr>
<td>8</td>
<td>170</td>
<td>100</td>
<td>300</td>
<td>10</td>
<td>25%</td>
</tr>
<tr>
<td>9</td>
<td>100</td>
<td>25</td>
<td>100</td>
<td>40</td>
<td>25%</td>
</tr>
<tr>
<td>10</td>
<td>170</td>
<td>25</td>
<td>100</td>
<td>40</td>
<td>25%</td>
</tr>
<tr>
<td>11</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>40</td>
<td>25%</td>
</tr>
<tr>
<td>12</td>
<td>170</td>
<td>100</td>
<td>100</td>
<td>40</td>
<td>25%</td>
</tr>
<tr>
<td>13</td>
<td>100</td>
<td>25</td>
<td>300</td>
<td>40</td>
<td>25%</td>
</tr>
<tr>
<td>14</td>
<td>170</td>
<td>25</td>
<td>300</td>
<td>40</td>
<td>25%</td>
</tr>
<tr>
<td>15</td>
<td>100</td>
<td>100</td>
<td>300</td>
<td>40</td>
<td>25%</td>
</tr>
<tr>
<td>16</td>
<td>170</td>
<td>100</td>
<td>300</td>
<td>40</td>
<td>25%</td>
</tr>
<tr>
<td>17</td>
<td>100</td>
<td>25</td>
<td>100</td>
<td>10</td>
<td>70%</td>
</tr>
<tr>
<td>18</td>
<td>170</td>
<td>25</td>
<td>100</td>
<td>10</td>
<td>70%</td>
</tr>
<tr>
<td>19</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>10</td>
<td>70%</td>
</tr>
<tr>
<td>20</td>
<td>170</td>
<td>100</td>
<td>100</td>
<td>10</td>
<td>70%</td>
</tr>
<tr>
<td>21</td>
<td>100</td>
<td>25</td>
<td>300</td>
<td>10</td>
<td>70%</td>
</tr>
<tr>
<td>22</td>
<td>170</td>
<td>25</td>
<td>300</td>
<td>10</td>
<td>70%</td>
</tr>
<tr>
<td>23</td>
<td>100</td>
<td>100</td>
<td>300</td>
<td>10</td>
<td>70%</td>
</tr>
<tr>
<td>24</td>
<td>170</td>
<td>100</td>
<td>300</td>
<td>10</td>
<td>70%</td>
</tr>
<tr>
<td>25</td>
<td>100</td>
<td>25</td>
<td>100</td>
<td>40</td>
<td>70%</td>
</tr>
<tr>
<td>26</td>
<td>170</td>
<td>25</td>
<td>100</td>
<td>40</td>
<td>70%</td>
</tr>
<tr>
<td>27</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>40</td>
<td>70%</td>
</tr>
<tr>
<td>28</td>
<td>170</td>
<td>100</td>
<td>100</td>
<td>40</td>
<td>70%</td>
</tr>
<tr>
<td>29</td>
<td>100</td>
<td>25</td>
<td>300</td>
<td>40</td>
<td>70%</td>
</tr>
<tr>
<td>30</td>
<td>170</td>
<td>25</td>
<td>300</td>
<td>40</td>
<td>70%</td>
</tr>
<tr>
<td>31</td>
<td>100</td>
<td>100</td>
<td>300</td>
<td>40</td>
<td>70%</td>
</tr>
<tr>
<td>32</td>
<td>170</td>
<td>100</td>
<td>300</td>
<td>40</td>
<td>70%</td>
</tr>
</tbody>
</table>
Table 3: Gas Flow Rates

<table>
<thead>
<tr>
<th>Test #</th>
<th>MFC NO2 g</th>
<th>MFC SO2 g</th>
<th>Horiba NO2 ppm</th>
<th>Horiba SO2 ppm</th>
<th>MFM Slpm Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.8844142</td>
<td>0.3719336</td>
<td>0.0048643</td>
<td>0.0486</td>
<td>0.0008740</td>
</tr>
<tr>
<td>2</td>
<td>1.5035041</td>
<td>0.3719336</td>
<td>0.0082693</td>
<td>0.0827</td>
<td>0.0008740</td>
</tr>
<tr>
<td>3</td>
<td>0.8844142</td>
<td>1.4877345</td>
<td>0.0048643</td>
<td>0.0486</td>
<td>0.0034962</td>
</tr>
<tr>
<td>4</td>
<td>1.5035041</td>
<td>1.4877345</td>
<td>0.0082693</td>
<td>0.0827</td>
<td>0.0034962</td>
</tr>
<tr>
<td>5</td>
<td>2.6532425</td>
<td>1.1158009</td>
<td>0.0145928</td>
<td>0.0486</td>
<td>0.0026221</td>
</tr>
<tr>
<td>6</td>
<td>4.5105123</td>
<td>1.1158009</td>
<td>0.0248078</td>
<td>0.0827</td>
<td>0.0026221</td>
</tr>
<tr>
<td>7</td>
<td>2.6532425</td>
<td>4.4632035</td>
<td>0.0145928</td>
<td>0.0486</td>
<td>0.0104885</td>
</tr>
<tr>
<td>8</td>
<td>4.5105123</td>
<td>4.4632035</td>
<td>0.0248078</td>
<td>0.0827</td>
<td>0.0104885</td>
</tr>
<tr>
<td>9</td>
<td>0.8844142</td>
<td>0.3719336</td>
<td>0.0048643</td>
<td>0.0486</td>
<td>0.0008740</td>
</tr>
<tr>
<td>10</td>
<td>1.5035041</td>
<td>0.3719336</td>
<td>0.0082693</td>
<td>0.0827</td>
<td>0.0008740</td>
</tr>
<tr>
<td>11</td>
<td>0.8844142</td>
<td>1.4877345</td>
<td>0.0048643</td>
<td>0.0486</td>
<td>0.0034962</td>
</tr>
<tr>
<td>12</td>
<td>1.5035041</td>
<td>1.4877345</td>
<td>0.0082693</td>
<td>0.0827</td>
<td>0.0034962</td>
</tr>
<tr>
<td>13</td>
<td>2.6532425</td>
<td>1.1158009</td>
<td>0.0145928</td>
<td>0.0486</td>
<td>0.0026221</td>
</tr>
<tr>
<td>14</td>
<td>4.5105123</td>
<td>1.1158009</td>
<td>0.0248078</td>
<td>0.0827</td>
<td>0.0026221</td>
</tr>
<tr>
<td>15</td>
<td>2.6532425</td>
<td>4.4632035</td>
<td>0.0145928</td>
<td>0.0486</td>
<td>0.0104885</td>
</tr>
<tr>
<td>16</td>
<td>4.5105123</td>
<td>4.4632035</td>
<td>0.0248078</td>
<td>0.0827</td>
<td>0.0104885</td>
</tr>
<tr>
<td>17</td>
<td>0.8844142</td>
<td>0.3719336</td>
<td>0.0048643</td>
<td>0.0486</td>
<td>0.0008740</td>
</tr>
<tr>
<td>18</td>
<td>1.5035041</td>
<td>0.3719336</td>
<td>0.0082693</td>
<td>0.0827</td>
<td>0.0008740</td>
</tr>
<tr>
<td>19</td>
<td>0.8844142</td>
<td>1.4877345</td>
<td>0.0048643</td>
<td>0.0486</td>
<td>0.0034962</td>
</tr>
<tr>
<td>20</td>
<td>1.5035041</td>
<td>1.4877345</td>
<td>0.0082693</td>
<td>0.0827</td>
<td>0.0034962</td>
</tr>
<tr>
<td>21</td>
<td>2.6532425</td>
<td>1.1158009</td>
<td>0.0145928</td>
<td>0.0486</td>
<td>0.0026221</td>
</tr>
<tr>
<td>22</td>
<td>4.5105123</td>
<td>1.1158009</td>
<td>0.0248078</td>
<td>0.0827</td>
<td>0.0026221</td>
</tr>
<tr>
<td>23</td>
<td>2.6532425</td>
<td>4.4632035</td>
<td>0.0145928</td>
<td>0.0486</td>
<td>0.0104885</td>
</tr>
<tr>
<td>24</td>
<td>4.5105123</td>
<td>4.4632035</td>
<td>0.0248078</td>
<td>0.0827</td>
<td>0.0104885</td>
</tr>
<tr>
<td>25</td>
<td>0.8844142</td>
<td>0.3719336</td>
<td>0.0048643</td>
<td>0.0486</td>
<td>0.0008740</td>
</tr>
<tr>
<td>26</td>
<td>1.5035041</td>
<td>0.3719336</td>
<td>0.0082693</td>
<td>0.0827</td>
<td>0.0008740</td>
</tr>
<tr>
<td>27</td>
<td>0.8844142</td>
<td>1.4877345</td>
<td>0.0048643</td>
<td>0.0486</td>
<td>0.0034962</td>
</tr>
<tr>
<td>28</td>
<td>1.5035041</td>
<td>1.4877345</td>
<td>0.0082693</td>
<td>0.0827</td>
<td>0.0034962</td>
</tr>
<tr>
<td>29</td>
<td>2.6532425</td>
<td>1.1158009</td>
<td>0.0145928</td>
<td>0.0486</td>
<td>0.0026221</td>
</tr>
<tr>
<td>30</td>
<td>4.5105123</td>
<td>1.1158009</td>
<td>0.0248078</td>
<td>0.0827</td>
<td>0.0026221</td>
</tr>
<tr>
<td>31</td>
<td>2.6532425</td>
<td>4.4632035</td>
<td>0.0145928</td>
<td>0.0486</td>
<td>0.0104885</td>
</tr>
<tr>
<td>32</td>
<td>4.5105123</td>
<td>4.4632035</td>
<td>0.0248078</td>
<td>0.0827</td>
<td>0.0104885</td>
</tr>
</tbody>
</table>
The experimental plan consists of two phases:

**Phase I: Initial Shakedown**
During the initial shakedown, equipment is tested for functionality and accuracy. During this phase, we:

- Tested control loops on heaters and humidifiers. These tests were conducted with dry runs (no pollutants) to ensure accurate control and stability of environmental systems.
- Checked for leaks and proper pressure drops.
- Calibrated the gas analyzers and pollution injection systems.

After initial shakedown, the first test run may commence along with any additional troubleshooting.

**Phase II: Tests**
The test plan entails using the above setup to run a range of tests as shown in the full factorial (Tables 2 and 3). The data for the performance of the fuel cell will be measured by the gas analyzers. This data can be plotted against time and the results from the various tests can be combined and assessed based upon a number of parameters. Of particular interest are the lifetime performance curves of the filters. We intend to get two data points under each set of conditions. Due to numerous issues detailed in the “Issues and Recommendations” section, no Phase II test data was collected.

**DATA**

**Equipment Calibration**
The calibration of the Horiba gas analyzers involves a procedure which includes first zeroing the device and then calibrating at a determined span value. The Horiba NO analyzer achieved near zero NO readings with ambient air which allowed the zero setting for the analyzer to be set. For effective calibration of the Horibas, the actual reading on the gas analyzers must be in the vicinity of the actual theoretically expected values. This was achieved both for low range and high range calibration (Table 4 and Figure 11).

<table>
<thead>
<tr>
<th>Air Flow Rate (SLPM)</th>
<th>NO Flow Rate (mSLPM)</th>
<th>Theoretically Expected NO Reading on Gas Analyzer (ppm)</th>
<th>Actual Value on Gas Analyzer (ppm)</th>
<th>Within Satisfactory Calibration Range based on Horiba Manual</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>7.5</td>
<td>0.075</td>
<td>~0.071</td>
<td>Yes</td>
</tr>
<tr>
<td>1.2</td>
<td>8</td>
<td>0.133</td>
<td>~0.16</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**Table 4**: Theoretical and actual values for NO concentrations during gas analyzer calibration.
Figure 11: Graph showing stable readings in the vicinity of the expected values. The sudden changes at the span set show the successful calibration to actual values.

A similar calibration was performed on the SO$_2$ analyzer.

**Air Filter Pressure Drop Test**

For the initial shakedown, the three channels of the system were operated running dry air (no pollutant content) through it. During this phase, mass flow meters and controllers were calibrated and tested using the LabView interphase. Air heaters were tested using the feedback given by the different thermocouples. Similarly, the humidity equipment was tested for different water flow rates using feedback from the humidity sensors.

As part of the initial shakedown, pressure drop tests were conducted for channel 1. For that purpose, an analog differential pressure gauge was connected at each filter inlet and outlet. Using the LabView interphase, the mass flow controllers of each sub-channel (1-A, 1-B and 1-C) were regulated in order to test different flow rate working values (100 to 300 slpm). For each value of flow rate considered, 3 independent measurements of pressure drop were taken. The three filters and their corresponding pressure drop results are shown in Figures 12 to 15.
Figure 12: Filter A

Figure 13: Filter B

Figure 14: Filter C
The above results show values of pressure drop between 0.7 and 9.7 in H$_2$O, with filter A having the highest pressure drop and filter C the lowest. As expected, pressure drop increases with increasing values of flow rate. For all three filters, the measured filter pressure drop is well within the fuel cell system requirements.

**Figure 15:** Pressure drop test results
ISSUES AND RECOMMENDATIONS
Several major setbacks were encountered in the collection of data which are still ongoing. Many of these issues stem from a design which would operate continuously with dangerous gases. The safety requirements of the university necessitated that the entire system be housed externally and this remote operation requirement for safety created further difficulty with system operation and integration. The problems encountered are inherent in trying to design a fully automatic full scale test for multiple filters. The major issues and recommendations are listed below.

1. The original design was intended for operation in a fume hood with poisonous gases being held external to the personnel area. A safety review required that the system be housed in a remote external area that further necessitated construction of a dedicated facility (outdoor cover). The delay and construction costs of building this cover became a major obstacle to the completion of the project. The original budget planned for an 18 month project. While personnel were overseeing construction of the cover, the budget for personnel was quickly consumed during the delay. The construction also delayed the project significantly such that continuity of personnel was not maintained.

2. Continuity of personnel became a major issue for this project as volunteer researchers were relied upon as the personnel budget was spent in the first 18 months of the project. Generally, these researchers were looking for a project that could be completed quickly and thus recruitment of qualified personnel became a major issue. These researchers were required to learn a complicated system and code before progressing with data collection and analysis. Trouble shooting became major obstacles for those researchers as the original design changed and previous personnel associated with the design were unavailable for discussion. This was a failure of communication that is inherent in a university system.

3. Continuous operation was in the original design but this required complex safety controls and notifications. Integration of this remote continuous day and night operation required more time than it was designed to save. Although we are continuing the operation of this current system at our own expense, we suggest that the operation of the filters be run as a cumulative test in a daily discrete manner rather than a continuous test.

4. The humidifier tanks are designed to inject a water spray into the test air in order to bring the air to the desired relative humidity for a given test. In the original design, a water pump was used to pump water from the faucet into the electronic valve at the top of the humidifier tank. This electronic valve was designed to allow the right amount of water into the tank as per the test requirement. A feedback control loop used the data from a relative humidity sensor to control the opening of the valve. The water pump from the faucet was deemed necessary to provide water to the valve at its operating pressure. This water pump, however, proved to be too big for the purposes of the test and ruptured the water pipe because the electronic valve was not sufficiently open causing a pressure buildup in the pipe itself. This rupture caused some damage to electronic equipment in and around the humidifier tanks. Following this episode, we recently managed to successfully run the humidity control system using water directly from the faucet flowing into the electronic valve. As such, one key recommendation would be to do away with a pump in any future test.
5. We find that the chiller that we are using in our test is not delivering sufficiently cold air to run tests at temperatures as low as 10°C. We, therefore, recommend that any similar test in the future use a much more effective chiller than the one used in our test.

6. It has been reported that the pipe heater used in our test once turned red and ran a temperature in excess of 1000°C while being controlled using the feedback P&ID loop. We recommend finding a way of programming a safety limit into the heater control system.

7. Calibration of the gas analyzers at our operating range proved to be a major problem with no ready solution. The ranges of concentration of the SO₂ and NO₂ gases are near the limits of physical detection. As such, we recommend that the gas analyzers be thoroughly tested before designing the experimental matrix. The experimental matrix may then be designed in such a manner that we may be certain that the gas analyzers would be effective under the test parameters.

8. Integration of the analyzers for remote and continuous operation proved to be problematic. Dependence on solenoids for switching the flow to and from the analyzers to measure inputs and outputs from the various systems also created numerous problems with calibration. Since inputs and outputs need to be monitored, it is suggested that two sets of analyzers be purchased.

9. The air compressor originally procured proved insufficient for the purposes of our test. We, therefore, procured an additional compressor to allow greater capacity. The original budget did not include compressors for air delivery as building air was expected to be used. The removal of the system to a remote location required the compressors be purchased and a complex air delivery system to be installed and used.
TEST VEHICLE 1 (TV-1)
During the suspension of this program, Toro® determined that the IdaTech FCS 3000 fuel cell system (developed during the suspension under a separate contract to the US Navy as a subcontractor to Hoku; Program ID 06UJ9A00008B) matched the operational requirements of the Workman® Model e2065. As a result, a Toro® Workman® Model e2065 light-duty maintenance truck was received (Figure 1) and retrofitted to house an IdaTech FCS 3000 fuel cell system (Figure 2). The model e2065 unit was designated test vehicle-one (TV-1).

Figure 1: Toro’s Workman™ Model e2065
Three FC3000 fuel cell systems were assembled and all three passed operational testing. One fuel cell system, while sitting next to the vehicle, was used to charge the batteries. After successfully demonstrating that the fuel cell system could charge the batteries, the fuel cell system was reconfigured and installed into the vehicle (Figure 3).

TV-1 was deployed at River’s Edge Golf course in Bend, OR (Figure 4) during the summer of 2008. Figure 5 is a graph of the system parameters while the vehicle was driven on the golf course. The control method is for the fuel cell to maintain a battery voltage of 56 Vdc. which means that the fuel cell ramps up and down with battery voltage. In this case, the battery voltage was low at start-up so the fuel cell ramped up and charged the batteries to 56 Vdc. Afterwards, the fuel cell system ramped up and down with power usage and at the end of the run the batteries were at 56 Vdc
The unit did experience several shutdowns during the course of its summer operation, the details of which can be found in Table 1. During the winter an upgrade was performed on the fuel cell system. The upgrade consisted of new H2 recirculation pump mounting, improved cabin fan, new current sensor, improved fuel line routing, new
Table 1: TV-1 Daily Record on Golf Course, Summer 2008

<table>
<thead>
<tr>
<th>DATE</th>
<th>START</th>
<th>END</th>
<th>BARS</th>
<th>FUEL</th>
<th>MAINTENANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>14-Jul</td>
<td>3.7</td>
<td>5.1</td>
<td>2</td>
<td>FULL</td>
<td>RETURNED TO SHOP FC NOT ON BATTERY LOW</td>
</tr>
<tr>
<td>15-Jul</td>
<td>5.1</td>
<td>5.4</td>
<td></td>
<td>FULL</td>
<td>RETURNED TO RIVER'S EDGE</td>
</tr>
<tr>
<td>21-Jul</td>
<td>5.4</td>
<td>6.4</td>
<td></td>
<td></td>
<td>STARTED</td>
</tr>
<tr>
<td>23-Jul</td>
<td>6.4</td>
<td>6.7</td>
<td>7/8</td>
<td>FC COOLANT SW</td>
<td></td>
</tr>
<tr>
<td>24-Jul</td>
<td>6.7</td>
<td>8.7</td>
<td>3</td>
<td></td>
<td>REPLACED REFORMER FUEL PUMP</td>
</tr>
<tr>
<td>25-Jul</td>
<td>8.7</td>
<td>8.9</td>
<td>7</td>
<td>1/4</td>
<td>CHECKED FC 2X LOW H2 PSIG AND RAFF. FILLED TANK</td>
</tr>
<tr>
<td>25-Jul</td>
<td>8.7</td>
<td>8.9</td>
<td>7</td>
<td>1/4</td>
<td>CHECKED FC 2X LOW H2 PSIG AND RAFF. FILLED TANK</td>
</tr>
<tr>
<td>25-Jul</td>
<td>8.9</td>
<td>11</td>
<td>6</td>
<td>5/8</td>
<td>RETURN TO SHOP. WILL NOT START EMERGENCY SWITCH</td>
</tr>
<tr>
<td>28-Jul</td>
<td>8.9</td>
<td>11</td>
<td>6</td>
<td>5/8</td>
<td>OPERATOR ERROR</td>
</tr>
<tr>
<td>29-Jul</td>
<td>11.1</td>
<td>12</td>
<td>10</td>
<td>5/8</td>
<td>RAN 3 HOURS AT SHOP NO PROBLEM FULL TANK/FULL CHARGE</td>
</tr>
<tr>
<td>29-Jul</td>
<td>12.4</td>
<td>13</td>
<td>1</td>
<td></td>
<td>THEY RAN TRUCK</td>
</tr>
<tr>
<td>30-Jul</td>
<td>5:30</td>
<td>12</td>
<td>5</td>
<td>1</td>
<td>ON COURSE 1-9 5:30- 7:21</td>
</tr>
<tr>
<td>30-Jul</td>
<td>6:35</td>
<td>8</td>
<td>S/D</td>
<td>RESTARTED</td>
<td></td>
</tr>
<tr>
<td>30-Jul</td>
<td>6:44</td>
<td></td>
<td>S/D</td>
<td>RESTARTED</td>
<td></td>
</tr>
<tr>
<td>30-Jul</td>
<td>7:05</td>
<td></td>
<td>S/D</td>
<td>RESTARTED</td>
<td></td>
</tr>
<tr>
<td>30-Jul</td>
<td>7:20</td>
<td>13</td>
<td>8</td>
<td>OK</td>
<td></td>
</tr>
<tr>
<td>30-Jul</td>
<td>7:21</td>
<td>8</td>
<td>S/D</td>
<td>LEFT COURSE</td>
<td></td>
</tr>
<tr>
<td>30-Jul</td>
<td></td>
<td></td>
<td></td>
<td>MOST OF THE TIME KEY ON. LOTS OF STOPS.</td>
<td></td>
</tr>
<tr>
<td>30-Jul</td>
<td></td>
<td></td>
<td></td>
<td>IN 3 HOURS ACCUMULATED 4 HRS KEY ON</td>
<td></td>
</tr>
<tr>
<td>1-Aug</td>
<td>5:30</td>
<td>8:25</td>
<td>6</td>
<td>S/U</td>
<td></td>
</tr>
<tr>
<td>1-Aug</td>
<td>12.8</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BACK NINE</td>
<td>5:30</td>
<td></td>
<td>S/D</td>
<td>SAL IS DRIVER</td>
<td></td>
</tr>
<tr>
<td>1-Aug</td>
<td>6:06</td>
<td></td>
<td>S/D</td>
<td>SUPPLY UNDER VOLTAGE DURING ACCELERATION</td>
<td></td>
</tr>
<tr>
<td>DATE</td>
<td>START</td>
<td>END</td>
<td>BARS</td>
<td>FUEL</td>
<td>MAINTENANCE</td>
</tr>
<tr>
<td>-----------------</td>
<td>----------</td>
<td>--------</td>
<td>------</td>
<td>-----------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>6:30</td>
<td>FC ONLINE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6:39</td>
<td>LONG RUN 12-13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6:46</td>
<td>5 1/2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6:48</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6:52</td>
<td>S/D</td>
<td>LOW CELL VOLTAGE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6:53</td>
<td>S/U</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7:01</td>
<td>S/D</td>
<td>MANUAL WILL NOT RAMP UP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7:03</td>
<td>S/U</td>
<td>RAMPS UP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7:12</td>
<td>BOUNCING, DOWN HILL RUN</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7:17</td>
<td>15 7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7:23</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7:32</td>
<td>S/D</td>
<td>LOW CELL VOLTAGE WHILE ON RUN 17T-17G</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7:39</td>
<td>S/D</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7:50</td>
<td>9 7</td>
<td>BATTERY 52.7 V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8:25</td>
<td>10 10</td>
<td>STUCK ON COURSE BATTERY DEAD. FC WILL NOT S/U SUSPECT LOW VOLTAGE ATTACHED CHARGER</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-Aug</td>
<td>Saturday, August 02, 2008</td>
<td>10:05</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-Aug</td>
<td>Sunday, August 03, 2008</td>
<td>6:10</td>
<td>FULLY CHARGED</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-Aug</td>
<td>Monday, August 04, 2008</td>
<td>5:20</td>
<td>17 10 S/U</td>
<td>START SYSTEM</td>
<td></td>
</tr>
<tr>
<td>5-Aug</td>
<td>Tuesday, August 05, 2008</td>
<td>17.5</td>
<td>19 10 5/8</td>
<td>BED FULL OF SAND TOD ONBOARD S/D LOW CELL VOLTAGE</td>
<td></td>
</tr>
<tr>
<td>6-Aug</td>
<td>Wednesday, August 06, 2008</td>
<td>19:12</td>
<td>20 6 7/16</td>
<td>FC FAULT 3X</td>
<td></td>
</tr>
<tr>
<td>7-Aug</td>
<td>Thursday, August 07, 2008</td>
<td>4:30</td>
<td>FULL FUEL TANK</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8-Aug</td>
<td>Friday, August 08, 2008</td>
<td>5:30</td>
<td>S/U</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DATE</td>
<td>START</td>
<td>END</td>
<td>BARS</td>
<td>FUEL</td>
<td>MAINTENANCE</td>
</tr>
<tr>
<td>------------</td>
<td>--------</td>
<td>---------</td>
<td>-------</td>
<td>--------------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>9-Aug</td>
<td>6:17</td>
<td>FC ONLINE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6:19</td>
<td>FAULT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6:00</td>
<td>S/U</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7:10</td>
<td>S/D</td>
<td>LOW CELL VOLTAGE CELL-1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9-Aug</td>
<td>Saturday, August 09, 2008</td>
<td>6:10</td>
<td>S/U</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-Aug</td>
<td>Sunday, August 10, 2008</td>
<td>6:29</td>
<td>S/D</td>
<td>PUMP CYCLE UP AND DOWN</td>
<td></td>
</tr>
<tr>
<td>11-Aug</td>
<td>Monday, August 11, 2008</td>
<td>6:31</td>
<td>AUTO RESTART PUMP UO/DOWN THEN STEADY</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6:35</td>
<td>S/D</td>
<td>LOW CELL VOLTAGE CELL-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13-Aug</td>
<td>Wednesday, August 13, 2008</td>
<td>4:46</td>
<td>S/U IN SHOP</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5:20</td>
<td>FC ONLINE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5:44</td>
<td>MOVE TO RIVER'S EDGE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5:50</td>
<td>ON 10th TEE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20.3</td>
<td>21</td>
<td>10 F</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6:20</td>
<td>BACK NINE COMPLETED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6:24</td>
<td>1 HOLE REGEN MOTOR CONTROLLER S/D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6:51</td>
<td>COMPLETE FRONT NINE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>21.3</td>
<td>22</td>
<td>10 3/4</td>
<td>1.8 kW</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6:59</td>
<td>5 GAL</td>
<td>LEFT RUNNING</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8:00</td>
<td>S/U</td>
<td>FUEL CELL OFF. MAINTENCE CREW USING VEHICLE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14-Aug</td>
<td>Thursday, August 14, 2008</td>
<td>5:10</td>
<td>S/U</td>
<td>342.859 HR</td>
<td>FC ON LINE</td>
</tr>
<tr>
<td></td>
<td>5:52</td>
<td>FC ONLINE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DATE</td>
<td>START</td>
<td>END</td>
<td>BARS</td>
<td>FUEL</td>
<td>MAINTENANCE</td>
</tr>
<tr>
<td>-------</td>
<td>-------</td>
<td>------</td>
<td>------</td>
<td>--------------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>6:15</td>
<td>7</td>
<td>S/D</td>
<td>LCV CELL-1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6:38</td>
<td>S/D</td>
<td>LCV CELL-1 BATTERY DROP</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6:39</td>
<td>S/U</td>
<td>344.855 HR</td>
<td>11 TH G TO 12TH F</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7:02</td>
<td>S/D</td>
<td>LCV CELL-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7:03</td>
<td>S/U</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7:10</td>
<td></td>
<td></td>
<td>POWER DROP RAPIDLY</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7:12</td>
<td></td>
<td></td>
<td>MANUAL</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7:12</td>
<td></td>
<td></td>
<td>EMO</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7:20</td>
<td></td>
<td></td>
<td>WILL NOT RESTART INSTANT S/D</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7:58</td>
<td>S/U</td>
<td></td>
<td>STARTS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8:08</td>
<td></td>
<td></td>
<td>POWER OFF NO FAULT BOTH ON LINE ZAHN?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8:11</td>
<td>S/D</td>
<td></td>
<td>VERY HOT DAY</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8:17</td>
<td>S/U</td>
<td></td>
<td>BED OPEN WILL NOT RAMP</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8:24</td>
<td>24</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8:27</td>
<td>S/D</td>
<td></td>
<td>MANUAL</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9:04</td>
<td>S/U</td>
<td></td>
<td>FC ONLINE RAMPS UP</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11:13</td>
<td>10</td>
<td></td>
<td>SYSTEM OFF</td>
<td></td>
</tr>
<tr>
<td>16-Aug</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Saturday, August 16, 2008</td>
<td></td>
<td>2</td>
<td>PLACED ON CHARGER</td>
<td></td>
</tr>
<tr>
<td>17-Aug</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sunday, August 17, 2008</td>
<td></td>
<td>10</td>
<td>REMOVE CHARGER</td>
<td></td>
</tr>
<tr>
<td>18-Aug</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Monday, August 18, 2008</td>
<td></td>
<td>10</td>
<td>1/2 NOISE TEST RAIN THUNDER LIGHTING</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5:10</td>
<td></td>
<td></td>
<td>dB 80 MOWER</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>48 AMBIENT</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20' 68 CART</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>45 AMBIENT</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3' 46 START UP</td>
<td></td>
</tr>
<tr>
<td>DATE</td>
<td>START</td>
<td>END</td>
<td>BARS</td>
<td>FUEL</td>
<td>MAINTENANCE</td>
</tr>
<tr>
<td>------------</td>
<td>------------</td>
<td>---------</td>
<td>------</td>
<td>------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>19-Aug</td>
<td>6:05</td>
<td>S/D</td>
<td>57</td>
<td>ONLINE</td>
<td>COMPUTER DOESN'T STORE DATA CLOSED</td>
</tr>
<tr>
<td>Tuesday, August 19, 2008</td>
<td>5:25</td>
<td>S/U</td>
<td></td>
<td></td>
<td>ON COURSE HEAVY RAIN RETURN S/D UNKNOWN</td>
</tr>
<tr>
<td>19-Aug</td>
<td>5:51</td>
<td>S/D</td>
<td>57</td>
<td>SHUT COMPUTER</td>
<td></td>
</tr>
<tr>
<td>19-Aug</td>
<td>5:54</td>
<td>S/D</td>
<td>57</td>
<td>OPEN COMPUTER AND ITS ON</td>
<td></td>
</tr>
<tr>
<td>19-Aug</td>
<td>6:06</td>
<td>S/D</td>
<td>57</td>
<td>FC ONLINE THEN S/D</td>
<td></td>
</tr>
<tr>
<td>19-Aug</td>
<td>6:07</td>
<td>S/D</td>
<td>57</td>
<td>WILL NOT RESTART, REMOVE COMPUTER</td>
<td></td>
</tr>
<tr>
<td>19-Aug</td>
<td>6:13</td>
<td>S/D</td>
<td>57</td>
<td>MOVE TO YARD S/U</td>
<td></td>
</tr>
<tr>
<td>19-Aug</td>
<td>6:15</td>
<td>S/D</td>
<td>57</td>
<td>UNKNOWN CAUSE</td>
<td></td>
</tr>
<tr>
<td>25-Aug</td>
<td>5:25</td>
<td>S/U</td>
<td></td>
<td></td>
<td>NEW CATHODE AIR FILTER</td>
</tr>
<tr>
<td>Monday, August 25, 2008</td>
<td>5:51</td>
<td>S/D</td>
<td></td>
<td></td>
<td>NEW SHORTER CORRAGATED HOSE BURNER BLOWER</td>
</tr>
<tr>
<td>25-Aug</td>
<td>5:54</td>
<td>S/D</td>
<td></td>
<td></td>
<td>NEW H2 THREE WAY VALVE FOR ANOTHER SYSTEM</td>
</tr>
<tr>
<td>25-Aug</td>
<td>6:06</td>
<td>S/D</td>
<td></td>
<td></td>
<td>BURNER HEATER WIRE REROUTE</td>
</tr>
<tr>
<td>25-Aug</td>
<td>6:07</td>
<td>S/D</td>
<td></td>
<td></td>
<td>REROUTE METHANOL FEED LINE</td>
</tr>
<tr>
<td>25-Aug</td>
<td>6:13</td>
<td>S/D</td>
<td></td>
<td></td>
<td>BOLT DOWN REFORMER - ONE LEG</td>
</tr>
<tr>
<td>25-Aug</td>
<td>6:15</td>
<td>S/D</td>
<td></td>
<td></td>
<td>FIX CAPACITOR THAT BROKE OFF FROM REFORMER BOARD</td>
</tr>
<tr>
<td>2-Sep</td>
<td>7:39</td>
<td>29</td>
<td>FULL</td>
<td></td>
<td>S/U SYSTEM TRY NEW GUI FROM TOD NEEDS WORK</td>
</tr>
<tr>
<td>Tuesday, September 02, 2008</td>
<td>9:40</td>
<td>S/D</td>
<td></td>
<td></td>
<td>SYSTEM OPERATING FULLY CHARGE BATTERIES</td>
</tr>
<tr>
<td>2-Sep</td>
<td>14:40</td>
<td>31</td>
<td>1</td>
<td>3/4</td>
<td>MEET WITH DIR. MARKETING. VEHICLE RUNNING</td>
</tr>
<tr>
<td>2-Sep</td>
<td>14:56</td>
<td>S/D</td>
<td></td>
<td></td>
<td>S/D, S/U TAKE VEHICLE TO SHOP</td>
</tr>
<tr>
<td>2-Sep</td>
<td>5:20</td>
<td>S/U</td>
<td></td>
<td></td>
<td>FC OFF, S/U WILL NOT RAMP</td>
</tr>
<tr>
<td>3-Sep</td>
<td>5:20</td>
<td>S/U</td>
<td></td>
<td></td>
<td>MANUAL S/D AND S/U FC RAMPS 5 BAR S/D MANUAL NOISE SOUNDS LIKE COOLANT PUMP</td>
</tr>
<tr>
<td>3-Sep</td>
<td>5:20</td>
<td>S/U</td>
<td></td>
<td></td>
<td>S/U</td>
</tr>
<tr>
<td>DATE</td>
<td>START</td>
<td>END</td>
<td>BARS</td>
<td>FUEL</td>
<td>MAINTENANCE</td>
</tr>
<tr>
<td>--------------</td>
<td>-------</td>
<td>-----</td>
<td>------</td>
<td>-------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>4-Sep</td>
<td>6:08</td>
<td></td>
<td></td>
<td>FC ONLINE 500W AND RAMPING</td>
<td>LEAVE VEHICLE FOR CREW W/ COMPUTER CONNECTED</td>
</tr>
<tr>
<td></td>
<td>9:03</td>
<td></td>
<td></td>
<td>FC ONLINE TRY NEW GUI DOESN'T WORK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9:17</td>
<td></td>
<td></td>
<td>FC S/D LOW H2 PRESSURE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15:30</td>
<td>10</td>
<td></td>
<td>S/U 2 MINUTES 10 BARS</td>
<td></td>
</tr>
<tr>
<td>Thursday, September 04, 2008</td>
<td>10:40</td>
<td>1/2</td>
<td></td>
<td>FC ONLINE PORTABLE CAN'T LOG ON</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10:45</td>
<td>32.0</td>
<td>3/4</td>
<td>ADD 1 GAL FUEL, CREW LIKES VEHICLE BECAUSE IT IS QUIET</td>
<td></td>
</tr>
<tr>
<td>5-Sep</td>
<td>6:00</td>
<td>35</td>
<td>10  3/8</td>
<td>S/U</td>
<td></td>
</tr>
<tr>
<td>Friday, September 05, 2008</td>
<td>14:19</td>
<td>36</td>
<td>5   1/2</td>
<td>ADDED FUEL BURNER FLAME OUT SUCK UP FUEL</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6-Sep</td>
<td></td>
<td></td>
<td>S/U GUI STILL NOT WORKING</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7-Sep</td>
<td></td>
<td></td>
<td>REFORMER EXHAUST MELTED BED PLASTIC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6-Sep</td>
<td></td>
<td></td>
<td>FUEL CELL ON RUN 1/2 HOUR</td>
<td></td>
</tr>
<tr>
<td>Saturday, September 06, 2008</td>
<td>5:25</td>
<td>6</td>
<td></td>
<td>S/U VEHICLE TO COURSE</td>
<td></td>
</tr>
<tr>
<td>7-Sep</td>
<td>12:45</td>
<td>39</td>
<td>5   1/2</td>
<td>S/U INSTANT RED LIGHT</td>
<td></td>
</tr>
<tr>
<td>Sunday, September 07, 2008</td>
<td>5:20</td>
<td></td>
<td></td>
<td>S/U</td>
<td></td>
</tr>
<tr>
<td>8-Sep</td>
<td>6:10</td>
<td></td>
<td></td>
<td>F/C FAULT LOW H2 PRESSURE/LOW CELL</td>
<td></td>
</tr>
<tr>
<td>Monday, September 08, 2008</td>
<td>6:13</td>
<td></td>
<td></td>
<td>S/U</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6:15</td>
<td></td>
<td></td>
<td>FC ON LINE AND RAMPING LEFT RUNNING</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9:06</td>
<td>9   5/8</td>
<td>SYSTEM OFF</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9:09</td>
<td></td>
<td></td>
<td>S/U NEW GUI SAVES DATA ADDED FUEL</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9:21</td>
<td></td>
<td></td>
<td>S/D LOW H2 PRESSURE PRV?</td>
<td></td>
</tr>
<tr>
<td>Tuesday, September 09, 2008</td>
<td>40</td>
<td>1</td>
<td></td>
<td>PLACED ON CHARGER</td>
<td></td>
</tr>
<tr>
<td>9-Sep</td>
<td>16:00</td>
<td>41</td>
<td>3</td>
<td>FUEL ADDED 1.1 GAL ADDED COOLANT 1”</td>
<td></td>
</tr>
<tr>
<td>10-Sep</td>
<td>6:30</td>
<td>41</td>
<td>10</td>
<td>S/U DRIVE - BLOWER AND RECIRC NOT ON S/D</td>
<td></td>
</tr>
<tr>
<td>DATE</td>
<td>START</td>
<td>END</td>
<td>BARS</td>
<td>FUEL</td>
<td>MAINTENANCE</td>
</tr>
<tr>
<td>------------</td>
<td>-------</td>
<td>-----</td>
<td>------</td>
<td>--------------------</td>
<td>----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>11-Sep</td>
<td>12:00</td>
<td>41</td>
<td>9</td>
<td>S/U OK</td>
<td>S/U INTERMINT H2 RECIRC. THEN S/D PUT ON CHARGER</td>
</tr>
<tr>
<td>11-Sep</td>
<td>16:00</td>
<td>42</td>
<td>6</td>
<td>3/4</td>
<td>SYSTEM S/D</td>
</tr>
<tr>
<td>Thursday, September 11, 2008</td>
<td>15:30</td>
<td>43</td>
<td>4</td>
<td>3/4</td>
<td>READIED AND TRIED THREE TIME TO START S/D LOW CELL VOLTAGE RAMPS TO 50 AMPS? PREFERENCES FALL WITH Pfeed</td>
</tr>
<tr>
<td>15-Sep</td>
<td>15-Sep</td>
<td>43-</td>
<td>10</td>
<td>FULL</td>
<td>RETURN TORO TO IDATECH. CHECK REFORMER PREFERENCES PRV OK. SUSPECT ZAHN RAMPING TOO QUICK AND TOO HIGH 50 AMPS AT STACK. MAYBE FUEL PUMP, BUT H2 PRESSURE STAYS UP WHILE CELLS FALL</td>
</tr>
<tr>
<td>Wednesday, September 17, 2008</td>
<td>18-Sep</td>
<td>43-</td>
<td>10</td>
<td>FULL</td>
<td>FOUND WIRE WE REPAIRED IN FIELD FOR BLOWER WAS REVERSED, CONNECTOR #11 TO BLOWER RELAY. CHARGED BATTERY.</td>
</tr>
</tbody>
</table>
firmware, onboard data acquisition, dash meter to monitor battery charging current. The
new firmware increased the allowable fuel cell ramp rate and improved the maximum
net output from 2.2kW to 2.8kW peak. In addition, the new layout design is easier to
manufacture and maintain as the new design can be removed as one unit with minor
disconnects. The new layout is shown in Figure 6.

![Image](image_url)

**Figure 6**: Second generation integration of FCS3000 in TV-1

In all, the fuel cell system in TV-1 obtained the following statistics while operating on a
rough and highly terrain, during high ambient temperatures and being exposed to
several types of particulants – dirt, dust, grass clippings, fertilizer and sand.
- Total run time of 318 hrs
- Consumed 474 liters of HydroPlus™ fuel
- Produced 357 kW-hrs
- Experienced 172 thermal cycles
- kW-hrs/L = 0.753

**TEST VEHICLE 2 (TV-2)**
IdaTech installed a fuel cell and reformer into a second prototype, a Toro Workman
MDE battery-electric utility vehicle. The MDE is a newer version of the Workman e2065
used in TV-1. The new vehicle design incorporates front wheel shocks and an
accessible area under the front hood. The batteries were placed two in front and two in
the rear compartment which eliminated the “saddle bag” batteries external to the rear
compartment in the first vehicle. A photo of TV-2 in front of the High Desert Museum is
shown in Figure 7. The FCS design is the same as the upgraded version in TV-1
(Figure 6).
Figure 7: TV-2 at the High Desert Museum

TV-2 was deployed at the High Desert Museum during the summer of 2009. A typical drive cycle is shown in Figure 8 and the summer 2009 operational history is shown in Table 2.

Figure 8: Power output and battery voltage of TV-2 at the High Desert Museum
Table 2: TV-2 Daily Record at the High Desert Museum, Summer 2009

<table>
<thead>
<tr>
<th>DATE</th>
<th>TOD</th>
<th>HRS</th>
<th>BARS</th>
<th>FUEL</th>
<th>MAINTENANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-Jun Tuesday, June 02, 2009</td>
<td>6:30</td>
<td>2.1</td>
<td>10</td>
<td>3/4</td>
<td>S/U IN SHOP OK</td>
</tr>
<tr>
<td></td>
<td>7:30</td>
<td></td>
<td></td>
<td></td>
<td>FIRST DAY High Desert Museum (HDM) Difficult to get FC to kick on.</td>
</tr>
<tr>
<td></td>
<td>11:30</td>
<td></td>
<td></td>
<td></td>
<td>Call from Jeff S/Ds</td>
</tr>
<tr>
<td></td>
<td>12:04</td>
<td>2.8</td>
<td>10</td>
<td>1/2</td>
<td>Arrive FC ON fully charged. Why? 1/2 tank. Drive get S/D</td>
</tr>
<tr>
<td>3-Jun Wednesday, June 03, 2009</td>
<td>14:30</td>
<td>4.1</td>
<td>8</td>
<td>1/2</td>
<td>ADD FUEL 3/4 Comments: love vehicle, front battery needs brace fore aft.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Accelerator pedal to sensitive. Shocks bottom out they will adjust.</td>
</tr>
<tr>
<td>5-Jun Friday, June 05, 2009</td>
<td>14:30</td>
<td>4.6</td>
<td>9</td>
<td>5/8</td>
<td>ADDED FUEL 7/8 FOR WEEKEND</td>
</tr>
<tr>
<td>9-Jun Tuesday, June 09, 2009</td>
<td>14:16</td>
<td>8.8</td>
<td>9</td>
<td>1/4</td>
<td>ADDED FUEL 7/8 Add 1 pt coolant</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DCDC Converter loose</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.8kW LEFT ONLINE</td>
</tr>
<tr>
<td>19-Jun Friday, June 19, 2009</td>
<td>14:30</td>
<td>13.6</td>
<td>6</td>
<td>3/8</td>
<td>BED MELTED LOSE VENT REPLACE. ADDED FUEL 7/8</td>
</tr>
<tr>
<td>24-Jun Wednesday, June 24, 2009</td>
<td>14:30</td>
<td>14.6</td>
<td>10</td>
<td>7/8</td>
<td>NEW EXHAUST VENT. NEW DCDC CONVERTER SHEET METAL, SEPARATE METER WIRING,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FIX STEAM T/C. DELIVERED VEHICLE</td>
</tr>
<tr>
<td>25-Jun Thursday, June 25, 2009</td>
<td>7:30</td>
<td>14.6</td>
<td>10</td>
<td>7/8</td>
<td>PHOTOS OF VEHICLE IN FRONT OF MUSEUM</td>
</tr>
<tr>
<td>26-Jun Friday, June 26, 2009</td>
<td>10:40</td>
<td>15.1</td>
<td>8</td>
<td>7/8</td>
<td>PHOTOS OF VEHICLE SYSTEM</td>
</tr>
<tr>
<td>30-Jun Tuesday, June 30, 2009</td>
<td>10:10</td>
<td>19.4</td>
<td>1.5</td>
<td>7/8</td>
<td>BASICALLY DEAD, ADDED FUEL S/U</td>
</tr>
<tr>
<td>30-Jun Tuesday, June 30, 2009</td>
<td>15:10</td>
<td>19.5</td>
<td>5</td>
<td>7/8</td>
<td>1.4 Kew</td>
</tr>
<tr>
<td>2-Jul Thursday, July 02, 2009</td>
<td>14:51</td>
<td>21</td>
<td>10</td>
<td>1/4</td>
<td>FUEL ADDED TO 7/8, BATTERY WEDGE FELL OUT</td>
</tr>
<tr>
<td>7-Jul Tuesday, July 07, 2009</td>
<td>15:36</td>
<td>25.7</td>
<td>5</td>
<td>5/6</td>
<td>FUEL ADDED TO 7/8</td>
</tr>
<tr>
<td>15-Jul Wednesday, July 15, 2009</td>
<td>14:20</td>
<td>32.5</td>
<td>5</td>
<td>0</td>
<td>FUEL ADDED TO 7/8</td>
</tr>
<tr>
<td>DATE</td>
<td>TOD</td>
<td>HRS</td>
<td>BARS</td>
<td>FUEL</td>
<td>MAINTENANCE</td>
</tr>
<tr>
<td>------------</td>
<td>--------------</td>
<td>-----</td>
<td>------</td>
<td>------</td>
<td>----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>21-Jul</td>
<td>Tuesday, July 21, 2009</td>
<td>8:45</td>
<td>33.3</td>
<td>5</td>
<td>AT RIVERS EDGE WITH UC DAVIS FOR S&amp;V</td>
</tr>
<tr>
<td>21-Jul</td>
<td>Tuesday, July 21, 2009</td>
<td>10:37</td>
<td>33.3</td>
<td>10</td>
<td>AT RIVERS EDGE BACK 9-2 FRONT 9-1</td>
</tr>
<tr>
<td>22-Jul</td>
<td>Wednesday, July 22, 2009</td>
<td>5:30</td>
<td>33.3</td>
<td>10</td>
<td>AT RIVERS EDGE FRONT 9</td>
</tr>
<tr>
<td>23-Jul</td>
<td>Thursday, July 23, 2009</td>
<td>5:30</td>
<td>33.3</td>
<td>10</td>
<td>AT RIVERS EDGE FRONT 9-3 BACK 9-2</td>
</tr>
<tr>
<td>27-Jul</td>
<td>Monday, July 27, 2009</td>
<td>7:30</td>
<td>36</td>
<td>10</td>
<td>F DELEVER HDM</td>
</tr>
<tr>
<td>29-Jul</td>
<td>Wednesday, July 29, 2009</td>
<td>13:30</td>
<td>37.1</td>
<td>4</td>
<td>S/D LOOSE VOLTAGE TAPS</td>
</tr>
<tr>
<td>31-Jul</td>
<td>Friday, July 31, 2009</td>
<td>14:30</td>
<td>38.3</td>
<td>7</td>
<td>FILL TANK GET DATA CARD</td>
</tr>
<tr>
<td>4-Aug</td>
<td>Tuesday, August 04, 2009</td>
<td>14:20</td>
<td>40</td>
<td>0</td>
<td>CHARGER ON S/U BURNER FLAME OUT</td>
</tr>
<tr>
<td>5-Aug</td>
<td>Wednesday, August 05, 2009</td>
<td>14:20</td>
<td>40</td>
<td>0</td>
<td>REMOVE TV-2 AND DELIVER TV-1</td>
</tr>
<tr>
<td>17-Aug</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TROUBLESHOOT TV-2 TO NO AVAIL. REPLACE REFORMER W/ REFORMER FROM TV-1 THEN REPLACE REFORMER BOARD</td>
</tr>
<tr>
<td>19-Aug</td>
<td>Wednesday, August 19, 2009</td>
<td>7:20</td>
<td>40.1</td>
<td>10</td>
<td>DELIVER TO HDM</td>
</tr>
<tr>
<td>21-Aug</td>
<td>Friday, August 21, 2009</td>
<td>13:47</td>
<td>40.8</td>
<td>9</td>
<td>GOT DATA CARDS, FILLED TANK 7/8</td>
</tr>
<tr>
<td>25-Aug</td>
<td>Tuesday, August 25, 2009</td>
<td>7:37</td>
<td>43.6</td>
<td>7</td>
<td>FIX DAMAGED RADIATOR, GOT DATA CARDS, FILLED TANK 7/8</td>
</tr>
<tr>
<td>1-Sep</td>
<td>Tuesday, September 01, 2009</td>
<td>7:37</td>
<td>46.5</td>
<td>3</td>
<td>FILLED TANK 7/8. Don: SYSTEM DOESN'T CHARGE WHEN DRIVEN S/D</td>
</tr>
<tr>
<td>3-Sep</td>
<td>Thursday, September 03, 2009</td>
<td>15:00</td>
<td>47.4</td>
<td>10</td>
<td>FILLED TANK 7/8</td>
</tr>
<tr>
<td>8-Sep</td>
<td>Tuesday, September 08, 2009</td>
<td>14:34</td>
<td>48.7</td>
<td>10</td>
<td>FILLED TANK 7/8. S/D DRIVING</td>
</tr>
<tr>
<td>11-Sep</td>
<td>Friday, September 11, 2009</td>
<td>14:34</td>
<td>50</td>
<td>8</td>
<td>FILLED TANK 7/8.</td>
</tr>
<tr>
<td>15-Sep</td>
<td>Tuesday, September 15, 2009</td>
<td>15:03</td>
<td>52.1</td>
<td>8</td>
<td>FILLED TANK 7/8.</td>
</tr>
<tr>
<td>21-Sep</td>
<td>Monday, September 21, 2009</td>
<td>9:02</td>
<td>54.4</td>
<td>7</td>
<td>FILLED TANK 7/8.</td>
</tr>
<tr>
<td>25-Sep</td>
<td>Friday, September 25, 2009</td>
<td>9:02</td>
<td>57.2</td>
<td>7</td>
<td>FILLED TANK 7/8.</td>
</tr>
</tbody>
</table>

Abbreviations: S/U – Start Up; S/D – Shut Down; HDM – High Desert Museum; BARS: vehicle battery charge level on scale 0 to 10; TOD – Time Of Day; TV – Test Vehicle
Unlike the golf course, the High Desert Museum is a rough but flat terrain and extremely dusty and dirty. In only 57 hours of operation, the amount of dust and dirt build-up on the fuel cell system was significant. Compare the amount of dust in Figure 8 to the as build in Figure 6. However, even with the amount of dust and dirt build-up, the system still operated without issues. In all, the fuel cell system in TV-2 obtained the following statistics at the High Desert Museum:

- Total run time of 368 hrs
- Consumed 315 liters of HydroPlus™ fuel
- Produced 149 kW-hrs
- Experienced 63 thermal cycles
- kW-hrs/L = 0.473

**Figure 8:** TV-2 Prototype Fuel Cell Powered Vehicle at the High Desert Museum after 57.2 hours Exposure

A picture of TV-2 next to other vehicles at the High Desert Museums is shown in Figure 9. As you can see, TV-2 is approximately the same size as the other vehicles employed by the High Desert Museum.
LESSONS LEARNED AND CORRECTIVE ACTIONS

There were two main learning’s from the field trials: (1) need to restrain all wiring otherwise the vibrations from the off-road conditions will damage the wiring and connections and (2) off-road conditions are significantly more dirty and dusty the on-road conditions so sensitive equipment must be protected. A summary of the lesson learned is shown in Table 3.

Table 3: Issue and Corrective Actions

<table>
<thead>
<tr>
<th>Issue</th>
<th>Corrective Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>System overheat on hot days</td>
<td>Added additional cooling fans</td>
</tr>
<tr>
<td>Thermocouple shorted</td>
<td>Added restraint</td>
</tr>
<tr>
<td>Wires fell of coolant switch</td>
<td>Added restraint</td>
</tr>
<tr>
<td>Fuel pump slowed down from dirt build-up</td>
<td>Sealed pump gearbox opening</td>
</tr>
<tr>
<td>Fuel line dry</td>
<td>Remove tank dip tube and place tank connection on bottom</td>
</tr>
<tr>
<td>Inverter not ramping</td>
<td>Installed new inverter and firmware</td>
</tr>
<tr>
<td>Troubleshooting faults takes too much time</td>
<td>Added onboard data acquisition</td>
</tr>
<tr>
<td>Too many circuit boards increase likelihood of wiring breakage</td>
<td>Consolidation of circuit board recommended</td>
</tr>
</tbody>
</table>