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SIMULATION OF A HYBRID PROPULSION SYSTEM WITH A FLYWHEEL ENERGY STORAGE SYSTEM IN AN ARMY TACTICAL VEHICLE

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ABSTRACT

The next generation of military vehicles will require new and improved power systems. As fuel prices continue to rise and as power draws become greater on tactical wheeled vehicles, the performance and efficiency of the power system becomes more important. Up to 40% of vehicular traffic in combat theater is dedicated to fuel and water logistics. Reduction in fuel consumption will result in less traffic and reduced exposure to IED's as well as gains in cost efficiency. Advances in powertrain and vehicle systems are required to achieve these gains. Hybrid propulsion systems have been proven in passenger automobiles as well as some commercial applications. This technology enables fuel economy improvements upwards of 25%. Hybrid systems can also provide export power and silent watch capability for military vehicles. Duty cycle and environmental demands are more severe in military applications and current energy storage devices are not robust. Several hybrid military platforms have been demonstrated, but durability and performance concerns outweigh the benefits. Specifically, electrochemical energy storage systems are limited by operating temperature, and life cycle. Improved energy storage devices are needed and one potential device is the high speed flywheel. Advances in materials and controls have led to more efficient and more powerful systems. This paper explores the application of current flywheel technology to a tactical vehicle using modeling simulations and compares with existing energy storage devices.

INTRODUCTION

Models of the hybrid-electric XM1124 HMMWV and its conventional baseline HMMWV were developed and compared for their relative advantages and disadvantages using both the PSAT and Matlab/Simulink software. The modeling predictions were obtained for these vehicles using a variety of powertrain components and configurations. These modeling predictions were compared to experimental data obtained for prototype vehicles run over several courses at the Aberdeen Proving Ground. These models were also used to identify areas where the power train can be improved to enhance the vehicle's fuel consumption performance.

VEHICLE MODELS

PSAT Modeling Tool

The first step in the process was the selection of the PSAT tool, shown in Figure 1, for the modeling of the HMMWV and XM1124 vehicles. This software was selected because it enabled quick model building, contained a fairly wide selection of powertrain configurations and components in its libraries, included many standard driving cycles, and utilized nominal vehicle controllers. The software also provided a convenient GUI that accessed Matlab/Simulink and StateFlow modeling tools, and provided extensive simulation output information such as side-by-side vehicle fuel economy and performance details. The software was not without its challenges however as it provided minimal feedback on errors, had limited utility in the creation of new components and especially new architectures, and required licenses for the Mathworks products used. PSAT was deemed sufficient for the analysis since the models could be edited and run independently with Matlab.

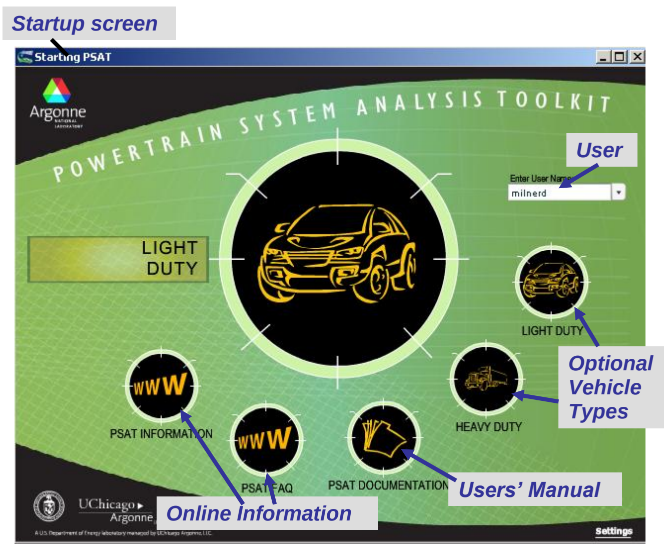

Figure 1: PSAT Modeling Tool Startup Screen

Model Design: Vehicle Model

The models were initially constructed using the PSAT toolset, but were subsequently converted for sole setup and simulation in Matlab/Simulink. The Matlab/Simulink versions of the models were configured to be run independently of the latter toolset. Figure 2 shows the top level of this HMMWV vehicle model. This level shows the vehicle driver, powertrain controller, component controller, powertrain model, and Matlab Workspace management.

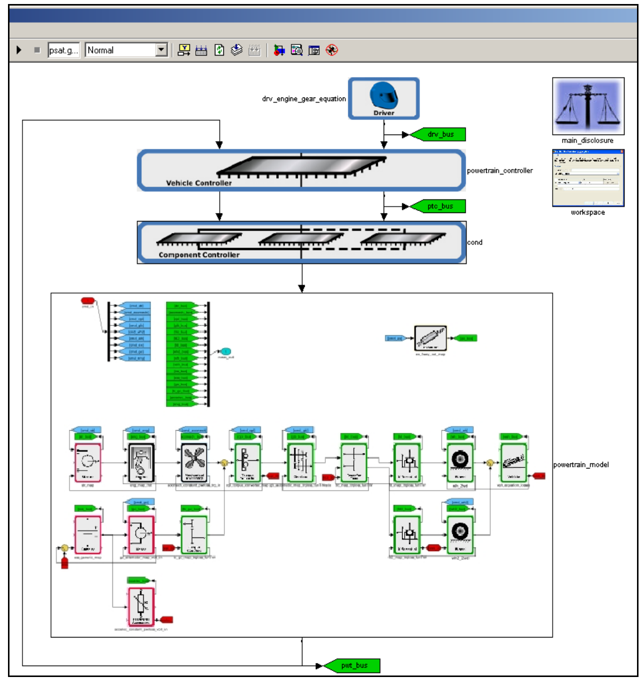

Figure 2: HMMWV Vehicle Model Top-View in Matlab/Simulink

This view shows the driver, powertrain controller, and, most prominently, the powertrain models. The models for the other vehicles appear similar to this layout with small variations visible in the powertrain model. The most notable difference for the XM1124 is the presence of the large battery for energy storage and the presence of a pair of traction motors, one for each wheel axle, for vehicle propulsion. The XM1124 powertrain is shown in Figure 3.

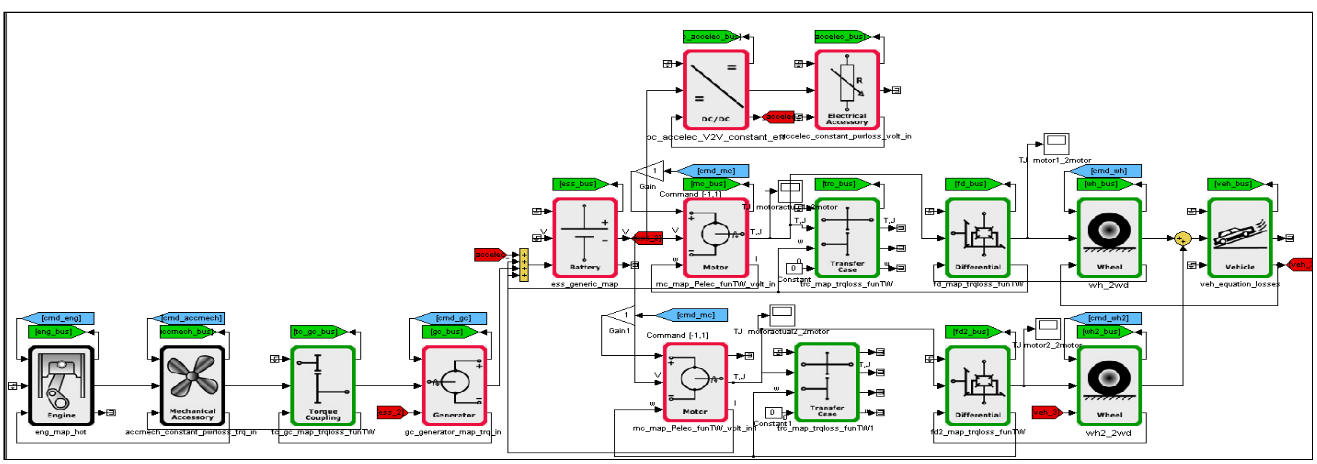

Figure 3: XM1124 Powertrain Model in Matlab/Simulink

The vehicle models were defined with specific powertrain architectures and components per details of the actual vehicles. There were four primary powertrains utilized: the HMMWV, the HMMWV with a flywheel energy storage system, the XM1124 with two motors, and the XM1124 with one motor. The details for these vehicle models are listed in Table 1. Some architectures utilized various components, such as Pb-Acid batteries for some simulations, and $LiFePO_4$[1,2] batteries for other simulations, so these architectures are annotated with both systems accordingly.

Attributes	HMMWV	HMMWV with Flywheel	XM1124 with Two Motors	XM1124 with One Motor
Purpose	Baseline	Compare (new concept) with baseline	Compare (tested concept) with baseline	Compare (PSAT version of model) with baseline
Architecture	Conventional Diesel 4-wheel drive	Diesel Mech. Hybrid 4-wheel drive	Diesel Hybrid 4-wheel drive	Diesel Hybrid 4-wheel drive
Energy Storage	None	Flywheel (carbon filament)	Battery (Pb-Acid or LiFePO4)	Battery (Pb-Acid or LiFePO4)
Vehicle Total Mass (unloaded)	2794 kg	3194 kg (2794 kg + Mass flywheel x # flywheels)	3719 kg Pb-Acid; 2794 kg lightened Pb-Acid; 3171 kg $LiFePO_4$	3719 kg Pb-Acid; 2794 kg lightened Pb-Acid; 3171 kg $LiFePO_4$
Engine	6.5 L (142 kW)	6.5 L (142 kW)	2.2 L (100 kW)	2.2 L (100 kW)
Traction Motor	0 kW	0 kW	2x 100 kW UQM PM	200 kW UQM PM
Battery	6 Ah	6 Ah	3 kW-hr SAFT Pb-Acid; 5 kW-hr A123_26650 $LiFePO_4$	3 kW-hr SAFT Pb-Acid; 5 kW-hr A123_26650 $LiFePO_4$
Transmission	4 gear auto	4 gear auto	N/A	N/A
Driver	K_p=1000 P K_i=0.5	K_p=1000 P K_i=0.5	K_p=1000 P K_i=0.5	K_p=1000 P K_i=0.5
Hotel Loads	5600 W (mech.)	5600 W (mech.)	5600 W (elec.)	5600 W (elec.)

Table 1: Vehicle Model Attributes

Furthermore, the models were modified to include variable rolling resistance coefficients to allow for various rolling resistances on courses. Another significant addition was the inclusion of a flywheel model in an alternative version of the HMMWV; this would be used for comparisons between the conventional HMMWV and potential new versions incorporating one or more advanced flywheels.

The vehicle models were each identically set to gross vehicle weights of 5,216 kg (11,500 lb). However, each vehicle architecture has a uniquely sized powertrain and thus a unique payload capacity to achieve this weight. Table 2 shows the payload weight available for each of the principal vehicle designs studied.

Vehicle	Payload (kg)	Unloaded Mass (kg)
HMMWV baseline	2422.3	2794.0
HMMWV (Flywheels)	2022.3	3194.0
XM1124 (Pb-Acid)	1497.3	3719.0
XM1124 ($LiFePO_4$)	2045.3	3171.0

Table 2: Vehicle Model Payloads for 5216 kg GVW

As observed, the baseline HMMWV has the largest payload capacity at 2422.3 kg, the XM1124 with $LiFePO_4$ battery and the HMMWV with sixteen 60 kW flywheels have nearly comparable payload capacities with 2022.3 and 2045.3 kg respectively, and the XM1124 with Pb-Acid battery has the small payload capacity with 1497.3 kg.

Model Design: Flywheel Model

Recent advances in high-speed carbon filament flywheel technology inspired an investigation of the utility of these flywheel systems as energy storage systems for military vehicles. A model of a high-speed flywheel was therefore created, debugged, and integrated with the models to determine the applicability of this technology for this purpose. The flywheel model is shown integrated between the gearbox and the transfer case in the conventional diesel architecture. The flywheel model is shown in Figure 4.

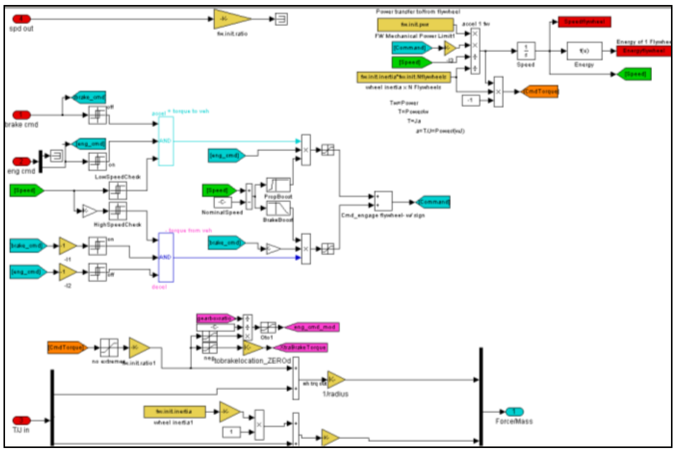

Figure 4: Flywheel Model

The flywheel was defined as a simplified version of the flybrid[3,4,5] system with base parameters set initially for 60 kW maximum power per flywheel, a 0.026 kg-m^2 moment of inertia, and a gear ratio of 20 to the transfer case. The number, power, inertia and other parameters of the flywheels are adjustable per the simulation setup. The model fundamentally determines torque and inertia sent from the flywheel down the powertrain by resolving acceleration and deceleration commands based directly upon the engine and brake commands sent to the vehicle's engine and brakes respectively, but with adjustments based upon the current speed of the flywheel with respect to the limits of the flywheel's operational speed.

The flywheel model currently follows the following steps:

- *Determines the desired sign and magnitude of torque to provide*
  - *Checks the 'eng_cmd' and 'brake_cmd' inputs to get sign and magnitude*
  - *Checks the current speed of flywheel to confirm it can provide the requested torque*
  - *Makes certain speed is not too high when requested to provide negative torque and thus be sped up, or that speed is not too low when requested to provide positive torque and thus be sped down*
- *Calculates the acceleration of one flywheel, a, per Equation 1.*

$$a = -C \cdot \frac{P_{\max}}{J \cdot N \cdot \omega} \qquad (1)$$

  - *Where P_{max} is the flywheel's max power of the flywheel, J is the flywheel's moment of inertia, N is the number of flywheels, and ω is flywheel speed.*
  - *C is the sign of the command signal for transmitting torque to the drivetrain, and thus the negative of the sign of torque that is accelerating/decelerating the flywheel.*
  - *ω, flywheel speed, is calculated by integrating a.*
- *Calculates the torque from all flywheels to the drivetrain per Equation 2*

$$T = -a \cdot J \cdot N \cdot g \qquad (2)$$

  - *Where g is the gear ratio of the flywheel.*
- *Calculates the energy of the flywheel per Equation 3*

$$E = \frac{1}{2} \cdot J \cdot \omega^2 \qquad (3)$$

- *Calculates the amount to reduce the commands to the power system's engine and brakes proportionally to the amount of torque that is added or subtracted respectively by the flywheel. This takes into account the equivalent gear ratio from the flywheel to those respective systems.*
  - *Propulsion Torque command from the flywheel is divided by the gear ratio of the gear box, and by the maximum torque of the engine. This amount is reduced from the engine command.*
  - *Braking Torque from the flywheel is multiplied by flywheel gear ratio, transfer case gear ratio, and final drive gear ratio. This amount is reduced from the commanded brake torque.*

Model Simulation: Flywheel Number

The flywheels were anticipated to provide ample power density for brief mobility demands, but to provide insufficient energy density for silent watch demands unless a considerable number of flywheels were used. Compared with the energy density of Lithium Ion batteries at 60-200 kW-hr/kg, or even Lead Acid batteries at ~20 kW-hr/kg, the energy density requirements of silent watch would be difficult to meet with flywheels. In fact, it was calculated that the number of flywheels, at ~5.7 kW-hr/kg, required for the energy density necessary for silent watch activities would number around 16 or more flywheels. The models developed for this investigation could be updated and utilized to predict the viability of such flywheels in various numbers and design assuming the packaging of such systems in such numbers could be accomplished by the manufacturer.

Model Simulation: Fuel Economy Calculations

The fuel economy measured in simulations had to be adjusted for the battery state-of-charge (SOC) change from beginning to end of a given course. To account for this, the calculation for fuel economy was calculated as the distance traveled divided by the volume of fuel used and the equivalent volume of fuel used in terms of energy pulled from the battery. Equation 4 shows the calculation for fuel economy and the integral of battery energy change.

$$FE = \frac{D}{\left(V_{gas}\right) + \left(\frac{E^{ESS}_{stored}}{\eta_{mot} \cdot \eta_{gen} \cdot \eta_{eng} \cdot Elec_{DieselEq}}\right)} \quad (4)$$

Where D is the distance traveled, V_{gas} is the volume of diesel fuel used, E^{ESS}_{stored} is the energy transferred to/from the battery during the simulation, $Elec_{DieselEq}$ is the equivalent amount of fuel used per change in battery SOC, and η_{mot}, η_{gen}, and η_{eng} are the efficiencies of the motor, generator, and engine respectively. $Elec_{DieselEq}$ was nominally 137.7 MJ/gal, and the values for η_{mot}, η_{gen}, and η_{eng} were nominally 0.94, 0.94, and 0.41 respectively. Equation 5 is energy transferred to and from the battery.

$$E^{ESS}_{stored} = \int_0^{time} I^{ESS}_{out}(t)dt \cdot V^{ESS}_{OC} \quad (5)$$

Where I^{ESS}_{out} is the current out of the battery, and V^{ESS}_{OC} is voltage of the battery.

The addition of flywheels requires a similar adjustment to the adjusted fuel economy of vehicles as do batteries. The adjusted fuel economy for the HMMWV model including the flywheel was thus calculated considering the energy level in the flywheel with respect to time as shown in Equation 6.

$$FE = \frac{D}{\left(V_{gas}\right) + \left(\frac{E^{ESS}_{stored}}{\eta_{mot} \cdot \eta_{gen} \cdot \eta_{eng} \cdot Elec_{DieselEq}}\right)\left(\frac{E^{FW}_{stored}}{\eta_{eng} \cdot Elec_{DieselEq}}\right)} \quad (6)$$

Where E^{FW}_{stored} is the amount of energy lost or gained in the flywheel in the simulation. This flywheel energy is defined by equation 7.

$$E^{FW}_{stored} = \left[E_t - E_i\right] \cdot N \quad (7)$$

Where E_t is the energy of the flywheel at a given time per equation 3, E_i is the flywheel's initial energy when the simulation is started, and N is the number of flywheels.

Model Validation

The models were compared with experimental data obtained by TACOM on the 11500 lb (5216.3 kg) HMMWV and XM1124 vehicles in 2008. This was again for the three Aberdeen courses: Churchville, Hartford, and Munson. The revisions for these simulations included aggressive driver gains on all courses. This was done to accommodate the potential higher average rolling resistances for larger truck tires and the presence of some non-concrete surfaces on the courses. The Munson course was noted as having portions of gravel[6]. The fuel economy results were compared as shown in Tables 3 and 4 for the HMMWV and XM1124 respectively. Note that the driver gain k_p was 20000 for these simulations, and the rolling resistance coefficients were:

- *Churchville: RR1= 0.0300 , RR2=0.00060*
- *Hartford: RR1= 0.0200 , RR2=0.00040*
- *Munson: RR1= 0.0225 , RR2=0.00045*

	Fuel Economy (MPG)		
Vehicle	Churchville (~14 mph)	Hartford (~ 45 mph)	Munson (~25 mph)
Simulated HMMWV	5.7	9.7	11.6
Experimented HMMWV	5.6	9.6	10.9

Table 3: Fuel Economy of HMMWV Model vs. Experimental Vehicle

	Fuel Economy (MPG)		
HMMWV (Modeled)	Churchville (~14 mph)	Hartford (~ 45 mph)	Munson (~25 mph)
Simulated XM1124 ($LiFePO_4$)	7.0	11.4	13.0
Experimented XM1124 (Li-Ion)	6.0	10.9	11.1

Table 4: Fuel Economy of XM1124 Model vs. Experimental Vehicle

The HMMWV model matched well with the experimental results only for the Churchville course with a difference of less than 2%. The model differed from the experimental results by about 1% and 6% for the Hartford and Munson courses respectively. The XM1124 model had a 17%, 5%, and 17% variation from the experimental data for the Churchville, Hartford, and Munson courses respectively.

Therefore, the models provided fairly precise matching with experimental data for the HMMWV utilizing an aggressive driver k_p=20000 and the new values for course rolling resistances. There were some small differences between the simulated and tested XM1124 fuel economy. The team shall endeavor to resolve the discrepancies as the project progresses.

Results

The vehicle models were rerun with at vehicle masses of 11500 lb (5216.3 kg) for all vehicles as before, but with a more aggressive driver gain and increased rolling resistances for the Hartford and Munson courses. These simulations provided results shown in Figures 5-10.

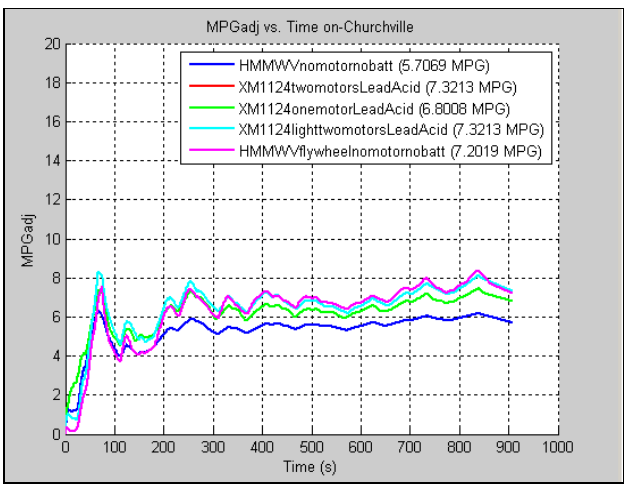

Figure 5: HMMWV on Churchville

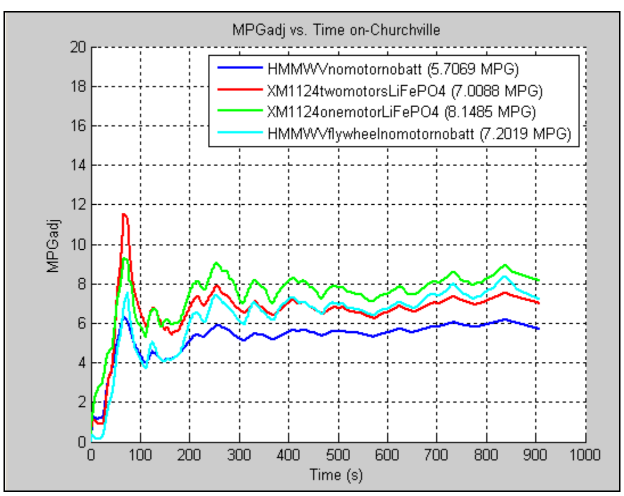

Figure 6: XM1124 on Churchville

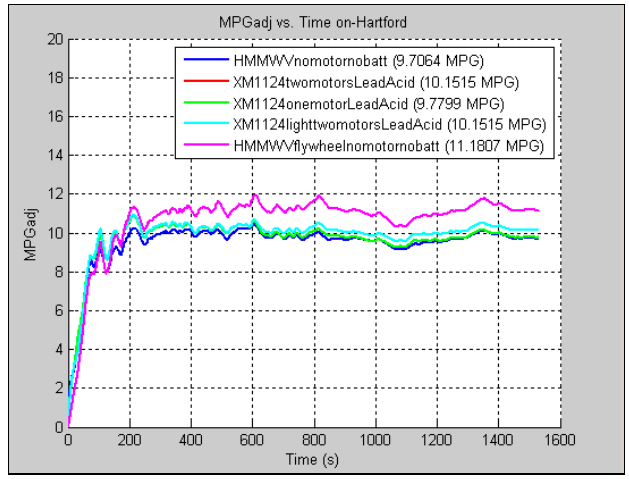

Figure 7: HMMWV on Harford

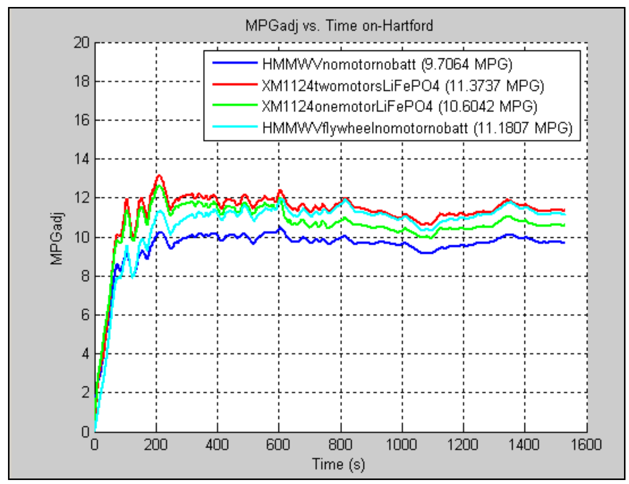

Figure 8: XM1124 on Harford

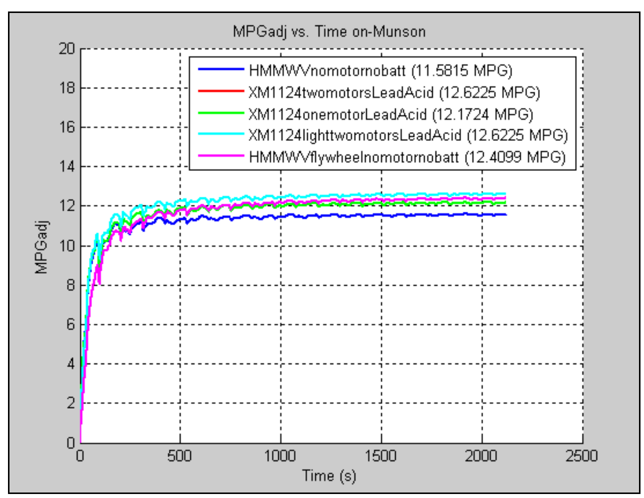

Figure 9: HMMWV on Munson

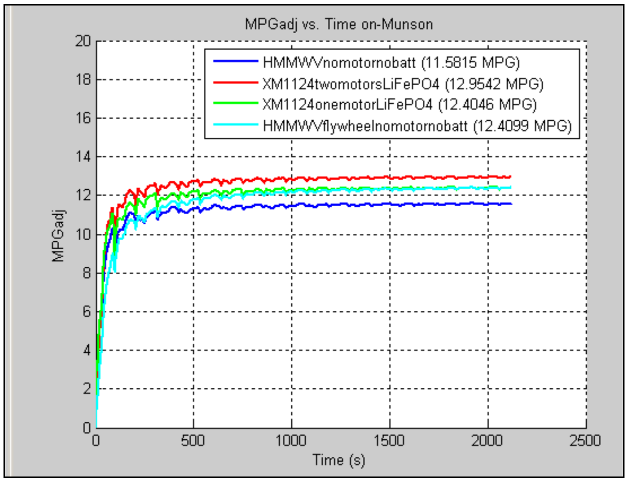

Figure 10: XM1124 on Munson

The fuel economy numbers for each simulation are shown in Table 5 by vehicle and course. It was determined the relative (%) numbers should be used for the comparison, so Table 6 was created to show the relative performance of each vehicle on the same courses. The model using 16 flybrid flywheels had the most consistent improvement in fuel economy over the baseline HMMWV, though the difference was most significant for the Churchville course at 26%. The gains on the Hartford and Munson courses were 15% and 7% gains respectively. The XM1124 hybrid vehicles with $LiFePO_4$ batteries and two motors performed better than the HMMWV with the best gains for the Churchville course at 23%, but was lower at 18% and 12% gains on the Hartford and Munson courses respectively. The two-motor Pb-Acid vehicles also performed better than the HMMWV vehicle over Churchville at 28%, but performed with only minor gains at 5% and 8% for the Hartford and Munson courses respectively.

HMMWV	Churchville (MPG)	Hartford (MPG)	Munson (MPG)
Nominal	5.7	9.7	11.6
With Flywheels	7.2	11.2	12.4
XM1124 (Pb-Acid)	Churchville (MPG)	Hartford (MPG)	Munson (MPG)
Two Motor	7.3	10.2	12.6
One Motor	6.8	9.8	12.2
XM1124 ($LiFePO_4$)	Churchville (MPG)	Hartford (MPG)	Munson (MPG)
Two Motor	7.0	11.4	13.0
One Motor	8.1	10.6	12.4

Table 5: Fuel Economy Results for HMMWV and XM1124 Models

HMMWV	Churchville (%)	Hartford (%)	Munson (%)
Nominal	--	--	--
With Flywheels	26.3	15.5	6.9
XM1124 (Pb-Acid)	Churchville (MPG)	Hartford (MPG)	Munson (MPG)
Two Motor	28.1	5.2	8.6
One Motor	19.3	1.0	5.2
XM1124 ($LiFePO_4$)	Churchville (MPG)	Hartford (MPG)	Munson (MPG)
Two Motor	22.8	17.5	12.1
One Motor	42.1	9.3	6.9

Table 6: Percent Relative Fuel Economy Results for HMMWV and XM1124 Models

CONCLUSIONS

Commercial flywheels using innovative carbon filament technology allows speeds in excess of 65,000 RPM which expand the energy and power capabilities of flywheels for tactical vehicles. Such flywheel systems can provide similar vehicle performance as electrochemical energy storage systems currently in development, but the flywheel systems do not share the same limitations in operating temperature and life cycle, making them potentially superior in many vehicular power cycling operations. Further, the technology is still being advanced with predictions that in 10 years flywheel performance will be a factor of greater than four higher than current performance[3].

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