2012 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
POWER AND MOBILITY (P&M) MINI-SYMPOSIUM
AUGUST 14-16, MICHIGAN

Quantitative Analysis of a Hybrid Electric HMMWV for Fuel Economy Improvement

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ABSTRACT

This paper presents a quantitative analysis and comparison of fuel economy and performance of a series hybrid electric HMMWV (High Mobility Multi-purpose Wheeled Vehicle) military vehicle with a conventional HMMWV of equivalent size. Hybrid vehicle powertrains show improved fuel economy gains due to optimized engine operation and regenerative braking. In this paper, a methodology is presented by which the fuel economy gains due to optimized engine are isolated from the fuel economy gains due to regenerative braking. Validated vehicle models as well as data collected on test tracks are used in the quantitative analysis. The regenerative braking of the hybrid HMMWV is analyzed in terms of efficiency from the kinetic energy at the wheels to the portion of regenerative power which is retrievable by the battery. The engine operation of both the series hybrid and conventional HMMWV are analyzed using a 2-D bin analysis methodology. Finally, the vehicle model is used to make recommendations on improving the fuel economy of the series hybrid as well as the conventional HMMWV.

Introduction

The US Army (Tank Automotive Research Development and Engineering Center (TARDEC) and National Automotive Center (NAC)) has acquired several hybrid platforms to assess the applicability of hybrid technology for typical military missions. These hybrid platforms include both series and parallel hybrid topologies [1]. This paper compares a conventional HMMWV M1113 with a series hybrid HMMWV XM1124 in terms of fuel economy improvements over three military drive cycles, namely: (a) Churchville drive cycle; (b) Munson drive cycle; (c) Harford drive cycle. The Churchville drive cycle is a 3.7 mile long, dirt course loop at Aberdeen Proving Grounds (APG) with hilly cross country terrain and varying grades. This loop is typically driven at a constant speed with complete stops at regular intervals. The Munson drive cycle is a 1.52 mile, compact gravel and paved loop at APG with varying grade. This drive cycle is typically driven at a constant speed with no stops. The Harford drive cycle is an 18.58 mile loop of paved public local highway with traffic lights, stops, and varying grades. In the Harford drive cycle, the vehicle is required to maintain an average of 42 mph, but stop at the designated traffic lights and stops on the road.

The attributes of the hybrid powertrain that help improve fuel economy of their conventional counterparts are more efficient engine operation and regenerative braking [1-4]. In a series hybrid topology, as in the XM1124, the engine operation is decoupled from the vehicle road load. In the XM1124, the battery system is charged by the Power Generation Unit (PGU) (engine-generator) and by regenerative braking. The PGU can potentially be operated at higher efficiency, producing more power than what is required at the wheels, since the battery pack can absorb the difference between PGU power and road load power, within the limits of its allowable state of charge.

Drive Cycles

Three drive cycles were analyzed for fuel economy comparisons between the conventional HMMWV M1113 and the series hybrid XM1124. These drive cycles are illustrated in Figures 1 to 3. All three drive cycles were tested using JP-8.

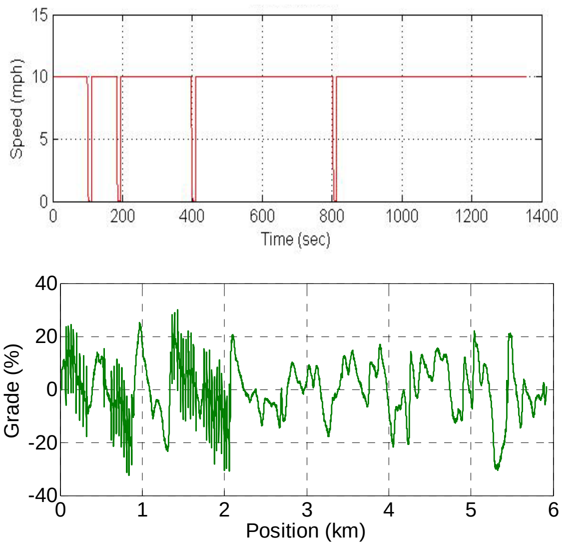

Figure 1: Churchville Drive Cycle

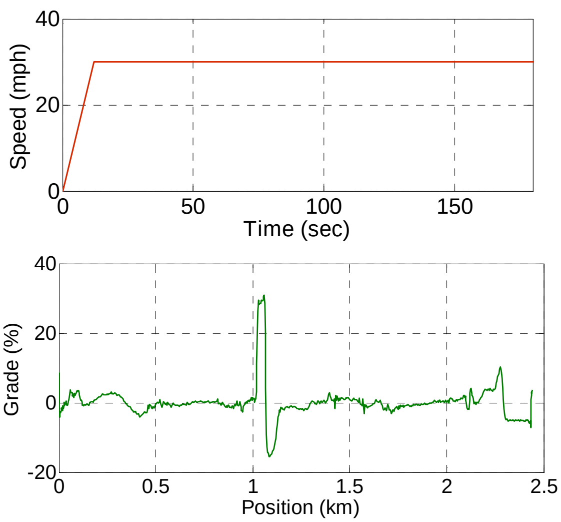

Figure 2: Munson Drive Cycle

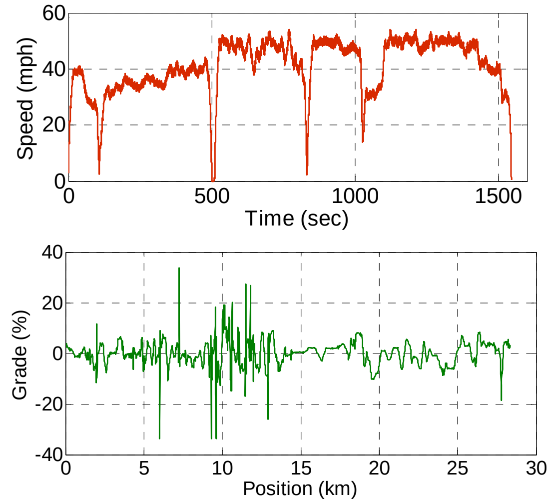

Figure 3: Harford Drive Cycle

HMMWV M1113 Vehicle

The HMMWV M1113 (See Figure 4) has been operational in the U.S. Army since around 1994. It is equipped with a 6.5 L V8 turbo-charged diesel engine from AM General, a four speed automatic transmission and has a gross weight of 5216 kg. Table 1 summarizes the vehicle parameters of the HMMWV M1113 that was analyzed in this paper.

Table 1: HMMWV M1113 Parameters

Component	Parameter
Engine	6.5 L V8 turbo-charged, 142 kW
Transmission	4 speed automatic (2.48, 1.48, 1.0, 0.75)
Final drive ratio	2.73
Wheel hub ratio	1.92
Gross Vehicle Weight	5216 kg


Figure 4: The HMMWV M1113 Vehicle

HMMWV XM1124 Vehicle

The XM1124 is a series-hybrid version of the M1113 with a PGU consisting of a 4 cylinder, 100 kW Peugeot diesel engine, coupled to a 100 kW PM brushless generator from UQM. The electric traction is provided by two 100 kW PM brushless motors from UQM. The XM1124 utilizes a 100 kW Li-Ion battery pack developed by Saft. Table 2 summarizes the vehicle parameters for the XM1124.

Table 2: HMMWV XM1124 Parameters

Component	Parameter
Engine	4 cylinder turbo-charged, 100 kW
Generator	100 kW peak/85 kW continuous
Electric Motor	100 kW peak/50 kW continuous
Battery Pack	Li-Ion 141 kW/18.6 kWh, 288 volt nominal.
Gross Vehicle Weight	5216 kg

Figure 5 shows the schematic of the series hybrid XM1124.

Figure 5: The XM1124 Schematic

Fuel Economy Comparison of the HMMWV M1113 versus the XM1124

The fuel economy comparisons, presented in this Section, are based on HEVEA (Hybrid Electric Vehicle Experimentation and Assessment) data collected at APG (Aberdeen Proving Grounds) by TARDEC for both the XM1124 and the M1113 vehicles over the three drive cycles of Figures 1 to 3. In addition, only HEVEA data was analyzed that resulted in SOC (State of Charge) equalization, i.e. the battery SOC is equal at the beginning and end of the test cycle. The HEVEA data collected comprised of time versus vehicle speed, front and rear motor current, generator current, battery current, battery pack voltage, battery pack SOC, fuel rate, and engine speed. The fuel economy was calculated from the fuel rate and vehicle speed. During the HEVEA data collection program, both vehicles (XM1124 and M1113) were tested on the Churchville driving cycle at speeds from 10 mph to 25 mph in increments of 5mph. The Munson tests were conducted from 10 mph to 30 mph in increments of 5 mph. The Harford tests were conducted over multiple laps with two different drivers.

Figure 6 summarizes the fuel economy improvement of the XM1124 versus the M1113 over various speeds of the Churchville and Munson drive cycles. The data shown in Figure 6 is from the HEVEA data set.

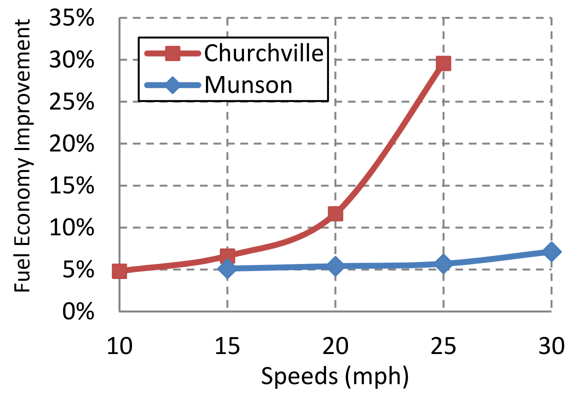

Figure 6: Fuel economy improvements for the Churchville and Munson drive cycles

Table 3 summarizes the fuel economy improvement of the XM1124 over the M1113 for the Harford drive cycle.

Table 3: Fuel economy improvement for the Harford drive cycle

M1113 (mpg)	XM1124 (mpg)	Fuel Economy Improvement (%)
9.4	10.65	12%

Fuel Economy Improvement Analysis

In this Sub-section, the fuel economy improvements of the HMMWV XM1124 over the M1113, summarized in Figure 6 and Table 3, are analyzed in terms of the benefit due to efficient engine operation and regenerative braking. For the purpose of this paper, engine operation is defined as the locus of all engine torque and speed points for a test run.

Fuel Economy Improvement Due to Efficient Engine Operation

The engine operation efficiency was analyzed by superimposing the engine operating speed-torque points over the engine efficiency map (which shows the speed-torque characteristics at different efficiencies of the engine). Figures 7 and 8 show the M1113 and XM1124 engine efficiency maps, respectively. JP-8 was used to generate the fuel maps of Figure 7 and 8. Both fuel maps were furnished from TARDEC [5].

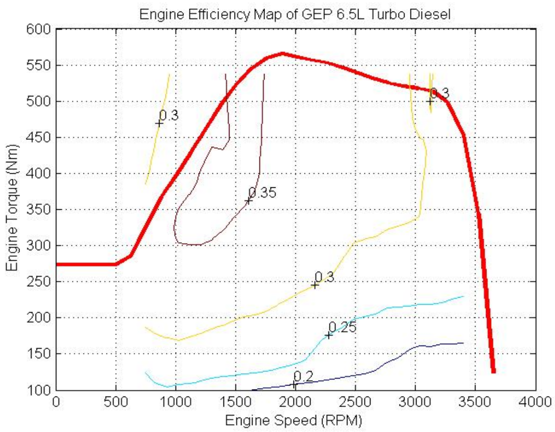

Figure 7: HMMWV M1113 Engine Efficiency Map

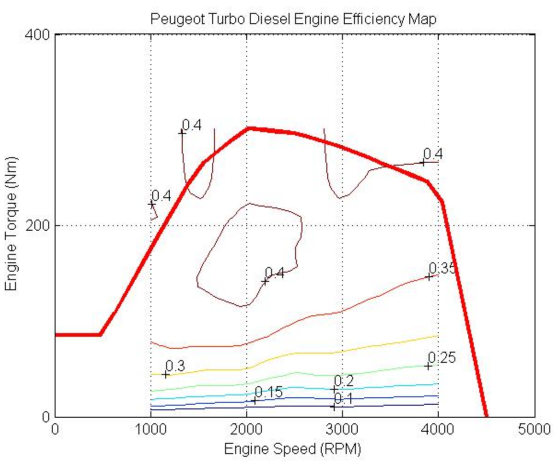

Figure 8: HMMWV XM1124 Engine Efficiency Map

A comparison of Figure 8 with Figure 7 shows that the XM1124 engine is more efficient than the older M1113 engine.

The engine torque was not directly measured during the HEVEA tests, since this was not available on the CAN (Controller Area Network) data bus for either the XM1124 or the M1113. As a result, the engine torque was derived from the other available data. In the case of the XM1124, generator electrical current, engine speed, and battery voltage were recorded. The following equations were used to compute the engine torque for the XM1124:

$$P_{gen} = I_{gen} V_{battery} \quad (1)$$

$$\tau_{gen} = \frac{P_{gen}}{N_{eng}} \quad (2)$$

$$\tau_{eng} = \tau_{gen} \quad (3)$$

where:

P_{gen} = *Generator electrical power*

I_{gen} = *Generator current*

$V_{battery}$ = *Battery voltage*

τ_{gen} = *Torque absorbed by generator*

τ_{eng} = *Torque available from the engine*

N_{eng} = *Engine speed*

In the case of the M1113, the engine torque was calculated using an inverse table lookup of the known fuel map (engine speed and torque vs. fuel rate) and measured instantaneous fuel rate.

Figure 9 shows a comparison of the engine operating points for both the XM1124 and the M1113 over the Churchville drive cycle at 25 mph.

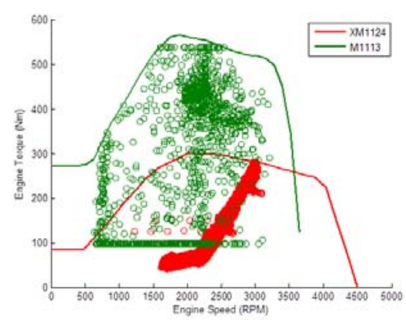

Figure 9: Engine Operating Points for the XM1124 and the M1113 over a 25-mph Churchville Drive Cycle

Figure 9 shows the main advantage of the series hybrid topology (XM1124) over the conventional powertrain (M1113). The engine speed of the XM1124 is constrained over a narrow speed range, whereas the conventional M1113 engine speed is coupled to the vehicle speed. Figure 10 shows a histogram plot of the engine efficiency of both the XM1124 and the M1113.

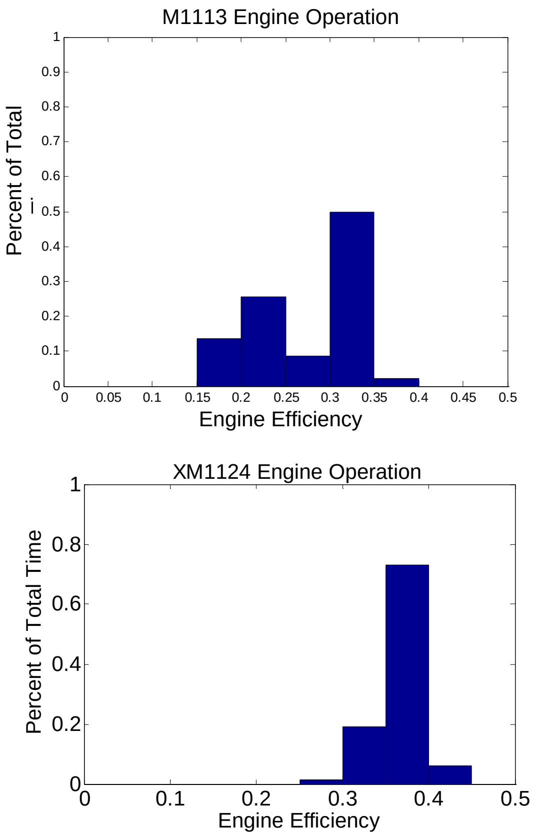

Figure 10: Histogram plot of the Engine Efficiency for the XM1124 and the M1113

Fuel Economy Improvement Due to Regenerative Braking

The contribution of regenerative braking on overall fuel economy was determined from analyzing the braking events of the HEVEA test data for the XM1124. Once the braking events were identified, the total regenerative braking energy was computed as follows:

$$E_{regen} = \int_{BrakingEvents} I_{motor} V_{bus} dt \qquad (4)$$

The computed E_{regen} is the additional energy that the engine would have to produce when regenerative braking is turned off. The total regenerative braking energy was converted to an equivalent fuel consumption using the minimum brake specific fuel consumption (BSFC) of the engine (220 g/kWh). This equivalent fuel consumption was added to the recorded fuel consumption for the cycle, and a new fuel economy was calculated. This new fuel economy represents the estimated fuel economy of the vehicle if regenerative braking was disabled. Table 4 summarizes the effect that regenerative braking has on fuel economy for the Churchville and Harford driving cycles.

Table 4: Effect of Regenerative Braking on Fuel Economy

Drive Cycle	Regenerative Braking On (HEVEA Test Data)	Regenerative Braking Off (Calculated)	Improvement due to Regenerative Braking
Churchville 25 mph	**6.554 mpg**	**6.534 mpg**	**0.31%**
Churchville 20 mph	**6.356 mpg**	**6.352 mpg**	**0.06%**
Harford	**5.117 mpg**	**5.114 mpg**	**0.06%**

Table 4 highlights a drawback in the braking control strategy of the XM1124. The regenerative braking plays a very small role in the fuel economy improvements of the XM1124 over the M1113. The main reason for this is that the regenerative braking of the XM1124 is restricted to 10% of its full potential. As a result, most of the available braking energy is lost in the friction brakes of the XM1124. It can therefore be concluded that the fuel economy benefits of the XM1124 over the M1113 are due to more efficient engine operation of the series hybrid powertrain over the conventional powertrain.

The HEVEA data was also analyzed for regenerative braking efficiency as a function of braking duration and braking deceleration. For the purpose of this paper, regenerative braking efficiency is defined as:

$$\eta_{regen} = \frac{\int P_{Battery} dt - \int P_{Gen} dt}{KE - E_{roll} - E_{Aero}} \qquad (5)$$

where:

$P_{Battery}$ = *Battery Power*

P_{Gen} = *Generator Power*

KE = *Vehicle Kinetic Energy*

E_{roll} = *Energy lost due to Rolling Resistance*

E_{Aero} = *Energy lost due to Aerodynamic Drag*

η_{regen} = *Regenerative Braking Efficiency*

Figures 11 and 12 show the regenerative braking efficiency as a function of braking duration and braking deceleration. The criteria used to quantify the regenerative efficiency in Figures 11 and 12 are: (a) the initial vehicle speed is greater than 18 mph and the final vehicle speed is less than 9mph for a braking event; (b) the elevation difference between the onset and completion of a braking event does not exceed 1 m; (c) the energy balance is maintained between the generator, motor, and battery during the braking event; and (d) the delta SOC during a braking event is greater than 0.

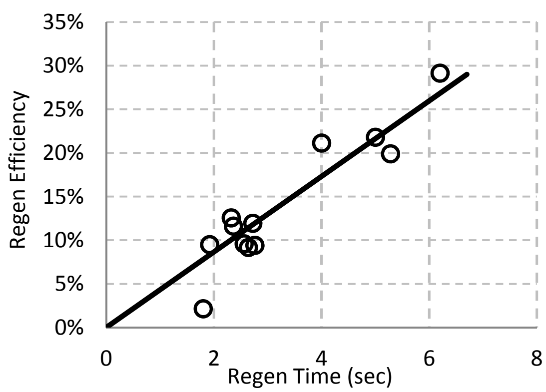

Figure 11: Regenerative braking efficiency as a function of braking duration

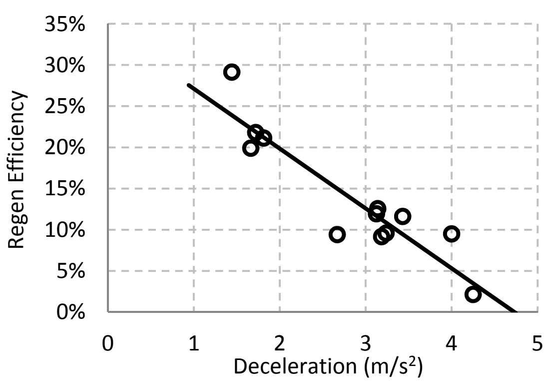

Figure 12: Regenerative braking efficiency as a function of braking deceleration

Figures 11 and 12 confirm previous literature on the subject of regenerative braking that the actual kinetic energy that is absorbed into the battery is a function of braking duration and deceleration. The higher decelerations or smaller braking durations result in a higher power that cannot be absorbed by battery chemistries, presently represented in the automotive market. This finding supports the fact that the batteries respond too slowly to accommodate the fast transient current flows produced by large decelerations and short braking durations.

Factors that affect the fuel economy of the HMMWV XM1124

The analysis of the HEVEA data (Figure 6) revealed that the hybrid HMMWV XM1124 does not always produce better fuel economy than the conventional HMMWV M1113. The following factors were found to adversely affect fuel economy of the XM1124:

- Low vehicle speeds (< 10 mph), resulted in the engine operating at lower efficiency
- Wet and cold road conditions affected the fuel economy of the XM1124
- Excessive charging of the battery using the PGU resulted in an overall lower efficiency from fuel tank to wheel.

Figures 13 and 14 illustrate that excessive charging of the battery pack by the PGU yields an unfavorable fuel economy, although the engine may be operating at best efficiency. In Figure 13, test results of two separate tests over the same drive cycle are shown (each test had the same initial and final SOC). One test resulted in a fuel economy of 8.95 mpg, while the other identical test resulted in a fuel economy of 12.13 mpg. In Figure 14, one test resulted in a fuel economy of 10.19 mpg, while the other identical test resulted in a fuel economy of 11.26 mpg. The higher generator power, shown in Figures 13 and 14, results in lower fuel economy.

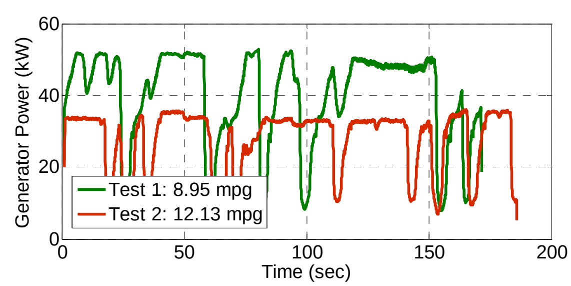

Figure 13: Generator Power for 30mph Munson

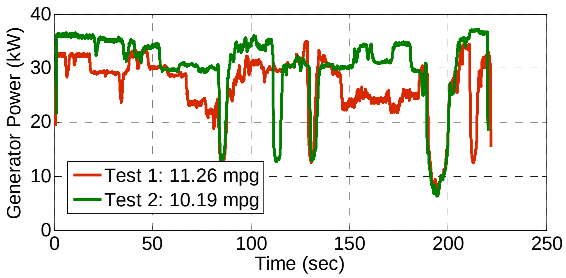

Figure 14: Generator Power for 25mph Munson

It should be noted that the vehicle power management control algorithm was not optimized for fuel economy to the maximum extent in this initial proof-of-concept XM1124. In principle it is possible to take into account the efficiency map of each of the constituent entities in this vehicle and create a mathematical cost function for optimization [6]. These entities are engine, battery, generator, and the electric motor. There are several factors to be considered during the optimization. These factors include: fuel economy, battery life, and engine emissions. While optimizing, sometimes these items may create conflicting situations, e.g. if battery life is given more emphasis in the cost function, it can lead to lesser fuel economy, and similarly for emission.

If fuel economy is the sole criteria for optimization, then the cost function can be formulated accordingly. A fuel economy maximizing cost function would provide the ideal fuel efficiency, but it can lead to a lower battery life expectance and/or higher emissions. Therefore, during the development of the power management algorithm, a judgment has to be made regarding the primary objective. In summary, the fuel efficiency of the hybrid vehicle can be improved over its conventional counterpart, by customizing the control algorithm.

Recommendations to Improve the Fuel Economy of the HMMWV M1113 and the XM1124

In this Section, recommendations are presented to improve the fuel economy of the M1113 and XM1124 based on analysis of the HEVEA test data set.

A repower option of the HMMWV M1113 engine (6.5 L V8 turbo-charged) from AM General with a Cummins ISB 6.7 L turbo-charged engine was analyzed by developing a validated model of the M1113 using the TARDEC vehicle modeling and simulation software package, VPSET (Vehicle Powertrain Systems Evaluation Toolbox) [7]. The Cummins ISB 6.7 L engine was benchmarked at SwRI and the complete speed-torque, fuel, and emissions maps were measured. These maps were used in the simulation model to quantify the fuel economy benefits of an engine repower option for the M1113. Table 5 summarizes the results of the computer simulations using both the current and recommended repower option, using an average JP-8 fuel density of 0.79 kg/L. The fuel economy improvements reported in Table 5 do not account for the additional cooling requirements for the Cummins ISB 6.7 L engine, as compared to the current AM General engine of the HMMWV. Therefore, the actual fuel economy improvement will probably be 5% less than what is predicted in Table 5. Further, it should also be noted that the packaging, cooling requirements of the Cummins 6.7 L ISB engine within the existing HMMWV platform would pose challenges since the repower engine is significantly more powerful and larger than the current engine. Finally, the current 4L80 transmission will not handle the higher torques of the 6.7 L ISB engine.

Table 5: Fuel economy benefits of an engine repower option for the HMMWV M1113

Drive Cycle	M1113 with Current Engine Option (mpg)	M1113 with Repower Option (mpg)	Fuel Economy Improvement (%)
Harford	7.39	8.51	15
Churchville-5 mph	4.36	4.68	7
Churchville-15 mph	5.53	6.74	18
Churchville-25 mph	5.02	6.45	19
Munson – 5 mph	7.41	9.00	18
Munson -15 mph	11.71	15.9	26
Munson -25 mph	10.47	12.45	19

The HEVEA test data shows that XM1124 uses a charge sustaining strategy, in which the engine speed is not at optimum efficiency for a given electrical power demand. In addition, the current XM1124 control strategy does not turn off the engine when the road load can be met by the battery pack. Figure 15 shows the engine speed vs. power curve, currently employed in the XM1124 control strategy, versus the optimum engine speed-power profile.

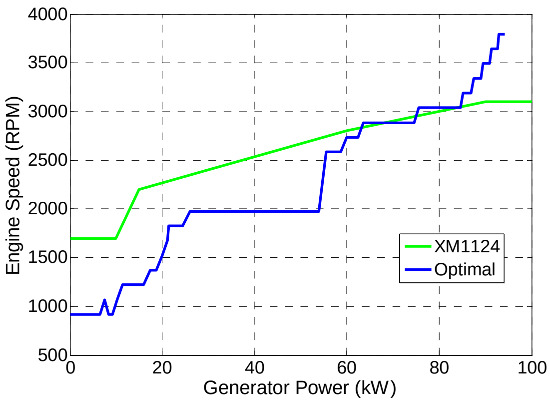

Figure 15: Engine speed-power profile for the XM1124 PGU

Employing an engine on-off strategy with the engine speed tracking the optimum engine speed-power curve shown in Figure 15 shows a 4.5% fuel economy improvement for the Harford drive cycle.

Acknowledgments

The work described in this paper was supported through funding from the US Army RDECOM-TARDEC. The authors gratefully acknowledge the valuable comments made by Dr. Peter Schihl, Senior Tech Expert, GVPM Dept., and Mr. Ghassan Khalil, Team Leader, Advanced Propulsion, GVPM Dept., US Army RDECOM-TARDEC.

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