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MODELING, VALIDATION AND ANALYSIS OF HMMWV XM1124 HYBRID POWERTRAIN

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ABSTRACT

Vehicle electrification technology has demonstrated its effectiveness for passenger vehicles, mainly due to environmental performance needs to meet fuel economy and green-house-gas emissions standards. Military vehicles require, among other specific features, not only the ability to move undetected but to perform at the lowest combined fuel and energy consumption possible. An experimental prototype HMMWV XM1124 with a series hybrid powertrain, which provides the ability for electric mode only and hybrid operation for reducing fuel consumption, is being investigated. The aim of this paper is to create a model of XM1124, validate it and utilize it to analyze the effect of vehicle electric range and performance. Additionally, the validated model allows evaluation of various operating strategies and hardware configurations for reducing the fuel consumption and improving vehicle performance.

INTRODUCTION

Previous researches have proposed improvements in powertrain efficiency by limiting the engine operational region to the most efficient one by means of sliding mode controllers [1]. For series powertrains the operation of the ICE can be decoupled from the required tractive force to maneuver the vehicle. However, it is important to analyze the effect of certain key powertrain components on vehicle fuel economy and performance [2, 3]. In the present paper, a sensitivity analysis to quantify the effect of battery capacity and weight on vehicle electric range and performance is conducted. To achieve this, the XM1124 is modeled by means of AVL CRUISE.

The paper is organized as follows. Firstly, prototype XM1124 main features and powertrain layout are provided. Secondly, modeling in AVL Cruise is explained. Afterwards, validation and results of the developed model for several driving cycles and deep analysis are provided. Finally, conclusions are presented.

DESCRIPTION OF PROTOTYPE XM1124

The highly multipurpose wheeled vehicle (HMMWV or HUMVEE) XM1124 platform is based on M1113, with XM1124 having a series hybrid powertrain as shown in Figure 1. The XM1124 has a turbocharged diesel Peugeot internal combustion engine of 2.2 liters that provides a maximum power of 100 kW. In addition, it has a generator, a battery and two 100 kW permanent magnet motors [4], one for each axle. In this work the XM1124 hybrid electric powertrain has been modeled in AVL CRUISE. The vehicle component specifications provided by the manufacturer have been incorporated in the model.

The internal combustion engine (ICE) is responsible for charging the batteries when the battery management commands it. To convert the mechanical energy of the ICE into electric energy, in order to be stored in the battery, a generator, an inverter and a converter DC/DC are necessary. The function of the generator is to convert the mechanical energy from the ICE into electric one. The output stage of the generator includes a rectifier, which converts the alternate current (AC) into direct current (DC). Finally, the converter DC/DC adapts the voltage between the output of the generator and the battery itself. The DC/DC converter can either work as a step-down voltage converter (buck converter) or as a step-up (boost converter).

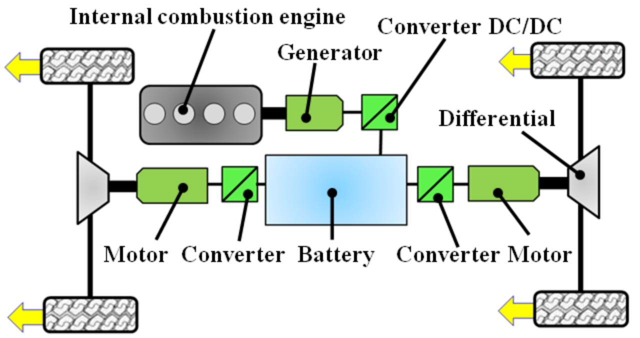

Figure 1: Powertrain layout of XM1124.

The battery is a lithium-ion battery pack of 7 modules connected in series between them and in parallel with another set of 7 modules. Each module has 12 cells connected in series. Therefore, the battery has 2 rows with 84 cells per row, providing 20 kWh. The energy stacked in the battery is used to power the motors that will provide movement to the wheels, via a differential. This vehicle does not have a gearbox. Additional reduction other than that provided by each differential can be achieved by means of hub gear ratio.

MODELING OF XM1124 POWERTRAIN

Powertrain modeling of XM1124 has been developed in AVL CRUISE. The model is depicted in Figure 2. The top six modules represent energy management, regenerative braking, anti-slip control and constant parameters. All of these functionalities have been programmed in C code. From top to down the front axle (wheels, brakes and front differential), front motor, DC/DC converter for front and rear axle, rear motor and rear axle are represented. On the right hand side the generator set is shown. It includes the internal combustion engine, a generator and a DC/DC converter. A specific module for the battery is also included. In addition, vehicle control via a driver module and vehicle parameters are also part of the model (left hand side of Figure 2).

In each of the modules specific data and/or curves to describe its performance is provided. However, some modules need information from others. For example, the brakes need information of the applied brake pressure, which is provided by the driver. By means of a virtual bus connection the user is able to specify these links of information between modules.

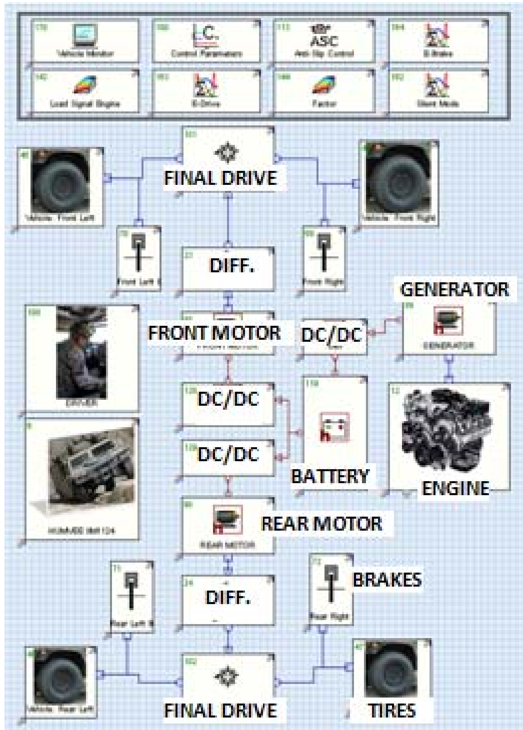

Figure 2: Powertrain modeled in AVL CRUISE.

The developed model also allows the user to specify certain constant parameters from a constant parameter module without having to change the desired values in each of the modules. The following subsections describe the main parameters of the modules.

Modeling of the vehicle

The vehicle is modeled attending to parameters such as weight, height of the center of gravity, wheelbase and gas tank volume. The vehicle module also requires information regarding frontal area and drag coefficient. Longitudinal dynamics is modeled applying Newton's second law. The vehicle has a mass of 5216 kg.

Modeling of the engine

The engine is a 2.2 l diesel turbocharged engine with maximum power of 100 kW (134 hp) at 4500 rpm. Power and torque curves are shown in Figure 3. Maximum torque is 314 N·m at 2000 rpm. In addition, fuel map has been created from engine brake specific fuel consumption data as a function of brake mean effective pressure (BMEP), provided by the manufacturer.

$$T(N\cdot m) = \frac{BMEP\ (\mathrm{Pa})\cdot 10^{5}\cdot 0{,}002179}{2\cdot\pi\cdot 2} \qquad (1)$$

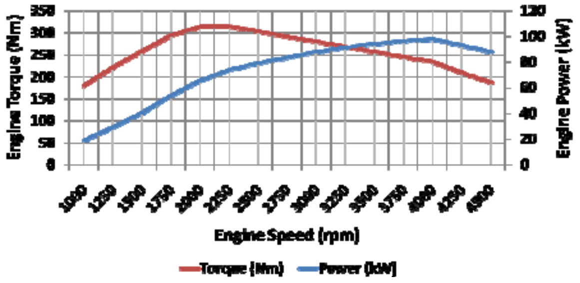

Figure 3: Engine power and torque curves.

It is worth noting that the engine is controlled by means of the desired engine speed, specified by the user in the control parameter module, and by the load signal, which is a linear function of the driver accelerator. To control the engine speed, specific C programming code has been developed in the module.

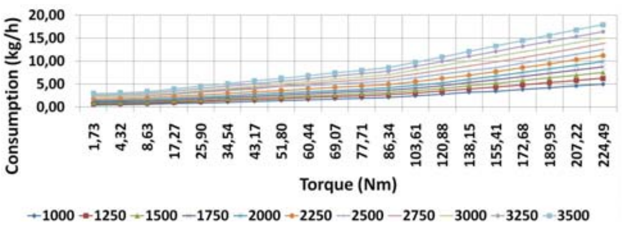

Figure 4: Engine fuel consumption map.

Modeling of the motor/generator

Each motor is a permanent synchronous machine which delivers a power of 100 kW and a maximum torque of 550 N·m. Maximum rotating motor speed is 4500 rpm. The motor is modeled in two quadrants in order to be able to work either as a motor or as a generator. In addition, this module has an inverter for AC/DC, or *viceversa*, conversion. The voltage level at the motor is higher than the battery one, therefore, a converter DC/DC is placed between the motor/generator and the battery. The DC/DC converter has been programmed with a voltage controller.

Modeling of the battery

The battery is a lithium-ion battery pack with 84 cells in series and two rows. The total battery capacity is 66 Ah, with a nominal open circuit voltage of 3.6 V and 20 kWh. Additional parameters for the thermal model of the battery are specified in the model.

Modeling of the DC/DC converter

A DC/DC converter is needed in order to step-up (boost) or step-down (buck) voltage between the battery and the motor/generator. A buck converter is placed between the generator and the battery and two boost converters are situated between the battery and both axle motors. These converters are voltage controlled, being the specified desired voltage the one corresponding to the motor side with a value of 310 V.

Modeling of the differential

For both axle differentials a reduction gear ratio of 5.4 is used. Additional reduction may be included by multiplying by the hub ratio.

Energy management

A special module has been created in order to perform energy management. This module has been programmed in C code and its aim is to switch on and off the generation set (engine and generator) attending to the battery state of charge (SOC). When the battery SOC is below the targeted limit the engine and generator are switched on in order to recharge the battery. For SOC levels above a targeted threshold value the engine is shut down. Figure 5 depicts a charge/discharge dynamic cycle when a New European driving cycle (NEDC) is used. It can be seen how the SOC increases when the engine is switched on and how the battery depletes when turned off. As expected significant increase of battery current (in red) and voltage (in blue) are registered during battery charging.

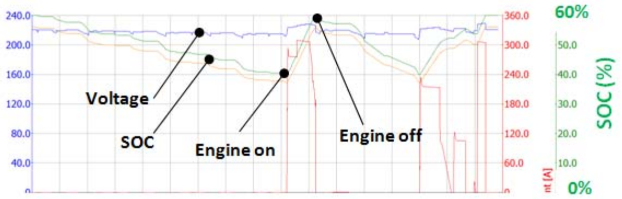

Figure 5: Energy management.

VALIDATION OF THE MODEL

In order to validate the developed model, performance results obtained by means of the created model were compared with test results published in [5], used as reference for validation. In Figure 6, results of XM1124 performance obtained by means of the developed Cruise model (labeled as “Simulation data (Gauchia et al.)”) show that it slightly overlaps with reference simulation and testing (Brudnak et al.) [5]. The developed model overlaps with [5], especially at speeds below 50 km/h. Top velocity discrepancies are due to dispersion in differential gear and wheel hub ratio values between reference and developed model.

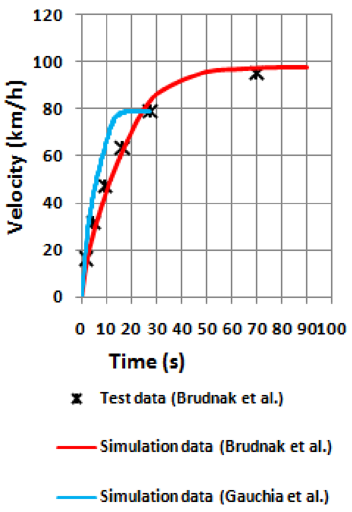

Figure 6: Validation of developed model

Therefore, it can be concluded that the XM1124 developed model is validated.

SENSITIVITY ANALYSIS

One of the major concerns when designing a hybrid electric vehicle is evaluation of performance and electric range, because the selection of some components may come at a certain tradeoff. For example, an increase in battery capacity may yield extended range at the cost of a heavier vehicle with more battery modules. In order to quantify this effect, a sensitivity analysis is conducted.

The aim of this sensitivity analysis is to evaluate the influence of battery capacity in vehicle performance and range. Each of these variables is analyzed in detail.

Performance sensitivity analysis

The aim of this section is to describe how the battery capacity influences vehicle performance. Two vehicle configurations are analyzed:

- Original vehicle: Battery capacity is 66 Ah and mass 5216 kg.
- Modified vehicle: Battery capacity is 132 Ah and vehicle mass is 5416 kg.

The additional mass accounts for the additional modules and electronics to control these modules.

Vehicle performance sensitivity (S_{perf}) of battery capacity is computed attending to the following equation:

$$S_{perf} = \lim_{\delta C \to 0} \frac{\frac{A(C+\delta C)-A(C)}{A(C)}}{\frac{\delta C}{C}} = \frac{\Delta A}{\Delta C} \qquad (2)$$

where A represents the vehicle acceleration (or other parameter of interest), C represents battery capacity, δ the increment of the parameter of interest, and Δ the relative increase or decrease of the parameter.

For the original vehicle configuration a maximum acceleration of 3.1 m/s^2 was found. The vehicle accelerated from 0-50 km/h in 6 s. Performance results provided by the developed model is depicted in Figure 7.

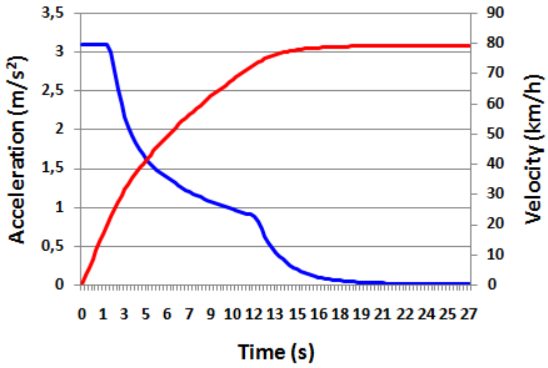

Figure 7: Performance results of original vehicle.

In the modified vehicle, battery charge is doubled from 66 Ah to 132 Ah at a cost of increasing mass by 3.8% in order to include the new modules, which would allow such increase in battery capacity, and electronics. The results, shown in Figure 8, reveal that the vehicle increases its acceleration time to 6.3 s. The effect of weight, due to battery increase, is heavier than the increase of battery charge. As observed, the vehicle performance is predominately influenced by base mass and motor features, rather than change in battery size and weight. However as expected, the battery capacity is important for the range sensitivity analysis, described in the following section.

In addition, vehicle longitudinal acceleration has decreased to 2.9 m/s^2.

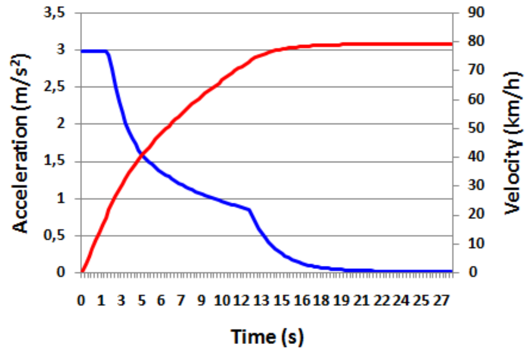

Figure 8: Performance results of modified vehicle.

For clarity, the following table summarizes the results for the case with battery size / charge doubled.

Table 1: Performance and sensitivity results.

Parameter	Original	Modified	Δ
Batt. capacity	66 Ah	132 Ah	100 %
Vehicle mass	5216 kg	5416 kg	3.8 %
0-50 km/h	6 s	6.3 s	5 %
Max. accele.	3.1 m/s^2	2.9 m/s^2	-6.5 %
Max. velocity	80 km/h	80 km/h	0 %
$S_{0\text{-}62}$	-	-	0.05
S_{acc}	-	-	-0.065
S_{vmax}	-	-	

The sensitivity parameters to evaluate the effect of increased battery capacity in acceleration time from 0 o 50 km/h ($S_{0\text{-}62}$), in acceleration (S_{acc}) and in maximum vehicle velocity (S_{vmax}) are shown in Table 1. A negative sign for the acceleration sensitivity implies a decrease in acceleration performance when battery capacity is increased. As expected, battery capacity does not influence maximum achievable vehicle velocity (S_{vmax}=0).

Electric range sensitivity analysis

The aim of this section is to analyze the effect of battery capacity on electric vehicle range. Battery operating SOC range is defined between 85% and 25%. Thus, initial SOC was set to 85%. Two scenarios were analyzed: battery capacity of original vehicle (66 Ah) and modified vehicle with 132 Ah. The effect of added weight (200 kg) due to the new modules and electronics has been considered. The aim is to find the distance the vehicle is able to travel in fully electric mode until it reaches a SOC target of 25%. Different driving cycles have been used to perform the current analysis.

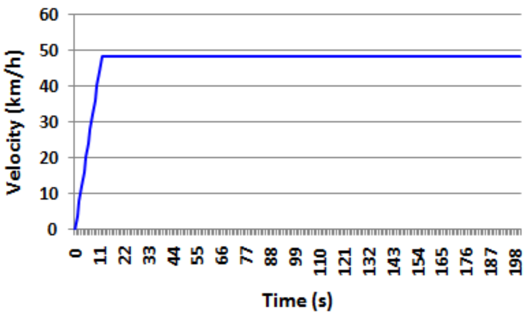

Figure 9: Munson Drive speed profile

The maximum travelling speed is 48 km/h (30 mph) and maximum grade 30%.

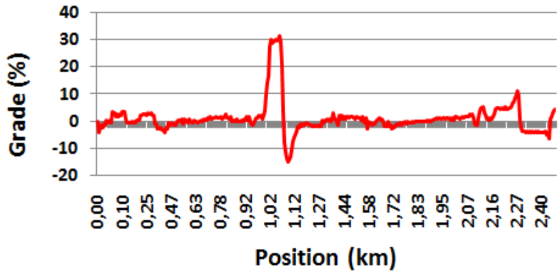

Figure 10: Munson Drive grade profile

Results are shown in Table 2.

Table 2: Electric range results.

Cycle	Original	Modified	λ
NEDC	39880.29 m	77963.57 m	1.95
FTP-75	29794.1 m	57760.45 m	1.94
Munson Drive	14217.95 m	26247.87 m	1.85
Urban Patrol DCE 5	21265.56 m	4013.18 m	1.91

Results show that modified battery (with 132 Ah) electric range is λ (1.85 – 1.95) times the range of the original vehicle with capacity of 66 Ah. It can be noted that doubling capacity almost doubles electric range and that the range multiplier λ is only weakly impacted by the drive cycle.

CONCLUSIONS

A powertrain model of the prototype HMMWV XM1124 was developed. The model has been validated, with slight differences at low travelling speeds. Performance and electric range were analyzed for two scenarios: vehicle with battery capacity of 66 Ah and vehicle with twice battery capacity. The vehicle model with 132 Ah included an additional 200 kg to account for the additional battery modules and electronics. Results show that doubling battery capacity almost doubles vehicle range with a tradeoff in vehicle acceleration decrease of 6.5%. Maximum traveling velocity is not significantly influenced by battery capacity, as the increase of weight to the additional battery modules only represents a 3.8% over the total vehicle mass.

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REFERENCES

[1] M. Gokasan, S. Bogosyan and D. J. Goering. "Sliding mode based powertrain control for efficiency improvement in series hybrid-electric vehicles", IEEE Transactions on Power Electronics, vol 21, no. 3, pages 779-790, May 2006.

[2] A. Nedungadi, R. Smith and A. Masrur, "Quantitative analysis of a hybrid electric HMMWV for fuel economy improvement", EVS26, Los Angeles, May 6-9, 2012.

[3] S. Fish, T. Savoie and H. Vanicek, "Modeling hybrid electric HMMWV power system performance", IEEE Transactions on Magnetics, vol 37, no. 1, pages 480-484, January 2001.

[4] J. Owen and M. Marcel, "Interior permanent magnet machine for use in the XM1124 hybrid electric HMMWV", Grounds Vehicle Systems Engineering and Technology Symposium (GVSETS), August 11, 2009.

[5] M. Brudnak, M. Pozolo, M. McGough, T. Mortsfield, A. Shvartsman, "Motion Base simulation of a Hybrid-Electric HMMWV for fuel economy measurement", SAE Paper, 2008-01-0775, 2008.

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