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GPS-BASED MOBILITY POWER ANALYSIS OF MILITARY VEHICLES

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ABSTRACT

Determining the required power for the tractive elements of off-road vehicles has always been a critical aspect of the design process for military vehicles. In recent years, military vehicles have been equipped with hybrid, diesel-electric drives to improve stealth capabilities. The electric motors that power the wheel or tracks require an accurate estimation of the power and duty cycle for a vehicle during certain operating conditions. To meet this demand, a GPS-based mobility power model was developed to predict the duty cycle and energy requirements of off-road vehicles. The dynamic vehicle parameters needed to estimate the forces developed during locomotion are determined from the GPS data, and these forces include the following: the gravitational, acceleration, motion resistance, aerodynamic drag, and drawbar forces. Initial application of the mobility power concept began when three U.S. military's Stryker vehicles were equipped with GPS receivers while conducting a proofing mission at the Pohakuloa Training Area (PTA) in Hawaii on a soil with a known rating cone index (RCI). An analysis was conducted on the GPS data which allowed for the variation in the Stryker's mobility power to be estimated as the vehicle traversed the terrain. The subsequent power duty cycle and required energy for the vehicle was determined along with predicted specific energy consumption and production values. Initial validation of the mobility power model began by tracking a hybrid 2006 Toyota Highlander during acceleration tests and on-road maneuvers. The model had an R^2 *and average absolute percent error of 0.91 and 12.9% respectively during the acceleration tests. The predicted and measured mobility power duty cycles were similar during the on-road maneuvers while an* R^2 *and average absolute error of 0.44 and 7.1 kW was attained.*

INTRODUCTION

Determining the required power for the tractive elements of military vehicles has always been a critical aspect of the design process. In recent years, state-of-the-art military vehicles have been equipped with hybrid diesel-electric drives to improve stealth capabilities. The control systems for the complex drivetrains must efficiently and precisely supply, harvest, and manage the power required for locomotion. Such systems demand accurate estimates of the power requirements of the vehicle during all types of combat operations. Previous efforts to estimate the power requirements during certain vehicle operations utilized a virtual vehicle-terrain interface to develop the simulated, mission-specific power requirements. Currently, there is not an in-field method for quantifying a vehicle's "comprehensive combat vehicle usage profile, or 'duty cycle' " [1]. As a result, there is a need for a cost effective method for quantifying the power and duty cycle requirements for a vehicle at the given operating conditions. To meet this demand, a GPS-based, mobility power and duty cycle analysis is one approach that may accurately predict the mobility power requirements of military vehicles.

There are numerous forces that must be overcome in order for vehicle locomotion to occur while the gravitational force may aid or resist vehicle motion. The summation of these forces in the longitudinal direction results in the net tractive effort or thrust force required for the given operating conditions [2]. The following equation represents the longitudinal model:

$$F_{Thrust} = F_{MR} \pm F_{Gravity} + F_{Acceleration} + F_{Drag} + F_{Drawbar} \quad (1)$$

Eq. (1) provides the basis for estimating the energy and power of a vehicle in the mobility power/energy analysis. To determine the motion resistance of the tractive elements during operation, the vehicle terrain interface (VTI) approach developed by the U.S. Army Corps of Engineers at the Waterways Experiment Station (WES) facility in Vicksburg, MS is utilized in the analysis [3]. For wheeled vehicles, the dimensionless wheel numeric, N_c, is determined for the non-steered wheels of the vehicle while operating in a fine-grained soil, and the equation is given by the following:

$$N_c = \frac{CI \cdot bd}{W\left(1-\frac{\delta}{h}\right)^{3/2}\left(1+\frac{b}{d}\right)^{3/4}} \quad (2)$$

Where CI is the measured cone index of the 0 to 0.152 m layer of the soil determined for on-road and off-road conditions, b is the tire section width, d is the nominal wheel diameter, h is the tire section height, δ is the tire deflection, and W is the normal load per a tire. The steered-wheel numeric ($N_{c\alpha}$) for vehicles operating in fine-grained soils is determined from the following equation:

$$N_{c\alpha} = N_c\left(1 - 2.26\alpha^{3/2}\right) \quad (3)$$

Where α is the tire steering angle (radians) for each wheel determined from the GPS data [3]. The motion resistance force, R, generated as the vehicle traverses in a fine-grained soil is calculated by the following:

$$R = W\left(\frac{12}{{N_c}^2} + .007\right) \quad (4)$$

R for steered wheels utilizes the same equation; except, $N_{c\alpha}$ is substituted for N_c [3]. The steered and non-steered wheel numeric, N_s, for vehicles operating in a coarse-grained soil is represented by the following expression:

$$N_s = \frac{G \cdot (bd)^{3/2} \cdot \delta}{Wh} \quad (5)$$

Where G is the cone index slope gradient. The motion resistance force of the steered and non-steered wheels that occurs during locomotion is quantified from the following equation:

$$R = W\left(1.275\alpha^{1.23} + 0.83 - \frac{46}{N_s + 55.4}\right) \quad (6)$$

The WES model relies on the calculated Vehicle Cone Index (VCI) for a tracked vehicle and the remolded cone index (*RCI*) to estimate the motion resistance that occurs while operating in fine-grained soils [3]. *RCI* is the product of the original *CI* multiplied by the remolded index (*RI*) where *RI* is the ratio of the *CI* before and after remolding. The VCI for a vehicle represents the required *RCI* needed for the vehicle to make a single pass over the terrain. Excess soil strength (C_x) is determined by subtracting the calculated VCI of the tracked vehicle from the measured *RCI* [4]. If the excess soil strength is greater than or equal to zero, the motion resistance force for a tracked vehicle operating in a fine-grained soil is predicted by the following expression:

$$R = W\left(a + \frac{b}{C_x + c}\right) \tag{7}$$

Where *a*, *b*, and *c* are constants defined in Table 1 for the given USCS soil type and condition [3].

Table 1: Constants for estimating motion resistance of a tracked vehicle in a fine-grained soil

Condition	*a*	*b*	*c*
Normal	0.05	2.31	6.5
Slippery	0.06	2.31	6.5

For tracked vehicles operating in coarse-grained soils, the WES model assumes the motion resistance force is directly proportional to the normal load on the track. The motion resistance forces for vehicles with flexible and rigid tracks operating in a coarse-grained soil are estimated by Eq. 8 and 9 respectively [3].

$$R = 0.145W \tag{8}$$

$$R = 0.119W \tag{9}$$

To estimate the power that is required to overcome the motion resistance of the vehicle's tractive elements, the following equation determines the equivalent motion resistance power:

$$P_{MR} = \sum_{n=1}^{n}\left(V_{Vehicle} \cdot R_i\right) \tag{10}$$

Where P_{MR} is the motion resistance power, *n* is the number of wheels, $V_{Vehicle}$ is the travel speed, and R_i is the motion resistance force for the i^{th} wheel.

By determining the rate at which the elevation of the terrain changes as a function of time, the required power to displace the vehicle vertically is defined by the following:

$$P_{Elevation} = (mg) \cdot \frac{\partial_h}{\partial_t} \tag{11}$$

Where $P_{Elevation}$ is the elevation power, m is the mass of the vehicle, g is the acceleration due to gravity, and $\frac{\partial_h}{\partial_t}$ is the rate of elevation change acquired from the GPS data.

The acceleration power necessary to increase or decrease the vehicle's speed along the path traversed is calculated by the following equation:

$$P_{Acceleration} = F_{Acceleration} \cdot V_{Vehicle} = (m \cdot A) \cdot V_{Vehicle} \tag{12}$$

Where $P_{Acceleration}$ is the acceleration power, $F_{Acceleration}$ is the force required to accelerate the vehicle, and A is the acceleration of the vehicle.

As the viscous fluid (air) flows over the vehicle surface during locomotion, a drag force that resists forward motion is exerted on the vehicle [5]. The drag force exerted on a body is given by the following equation:

$$F_{Drag} = \frac{\rho}{2} C_D A_f V_r^2 \tag{13}$$

Where F_{Drag} is the drag force exerted on the vehicle that opposed forward movement, ρ is the density of the air, C_D is the drag coefficient of the vehicle, A_f is the frontal area of the vehicle, and V_r is the speed of the air, relative to the vehicle [5]. The density of air, ρ, is given by the following expression:

$$\rho = 1.225\left(\frac{P_r}{101.325}\right)\left(\frac{288.16}{273.16+T_r}\right) \qquad (14)$$

Where P_r is average atmospheric pressure (kPa) at the given elevation and T_r is the mean air temperature (ºC) [5]. The drag power is determined from the following equation:

$$P_{Drag} = F_{Drag} \cdot V_{Vehicle} = \left(\frac{\rho}{2} C_D A_f V_r^2\right) \cdot V_{Vehicle} \qquad (15)$$

Where P_{Drag} is the drag power. If V_r is assumed to be equal to the vehicle speed because the relative air speed is not measured, the drag power reduces to the following expression:

$$P_{Drag} = \left(\frac{\rho}{2} C_D A_f\right) \cdot V_{Vehicle}^3 \qquad (16)$$

A towed implement or trailer exerts a force upon the hitch of a vehicle which opposes the forward motion of the vehicle during locomotion. This force is termed the drawbar load on a vehicle, and the subsequent power required to tow the implement is given by the following equation:

$$P_{Drawbar} = \left(F_{Drawbar} \bullet Cos(\Theta)\right) \cdot V_{Vehicle} \qquad (17)$$

Where $P_{Drawbar}$ is the drawbar power and $F_{Drawbar}$ is the drawbar load applied at the hitchpoint.

The power required to overcome the forces in Eq. (1) represents the mobility power. Mobility power is the power dissipated by the wheels of the vehicle in order to develop the tractive or thrust force along the vehicle's path. The total mobility power, $P_{Mobility}$, required for the vehicle to maneuver across the terrain at the measured velocity, turning radius, and loading conditions, while taking into account the vehicle's tire characteristics, is determined from the following equation:

$$P_{Mobility} = P_{MR} + P_{Elevation} + P_{Acceleration} + P_{Drag} + P_{Drawbar} + P_{Inertial} \qquad (18)$$

The calculated mobility power could be equated with the required engine power for the vehicle by completing a drivetrain analysis that calculates the overall drivetrain efficiency losses between the engine and the tractive elements. The mobility power is determined for each second of operation of the vehicle using Eq. (18), and integration of the mobility power function yields the energy required during a given time span. The net energy required for mobility power in a given time period is defined by the following equation:

$$E = \int_{t_1}^{t_2} \left(P_{Mobility} \cdot dt\right) \qquad (19)$$

Where E is the net energy required, and the difference between t_2 and t_1 is the timespan.

OBJECTIVES

The principle objective of this study was to develop and validate a model that utilizes GPS tracking data to conduct a mobility power and energy analysis. Mounting Stryker vehicles with Vehicle Tracking Systems (VTS) while the vehicles operated in the on-road and off-road environment at the Pohakuloa Training Area (PTA) in Hawaii allowed for critical vehicle operating parameters to be estimated. Strykers from the 2nd Brigade of the 25th Infantry Division were tracked in 2009 while conducting an on/off-road proofing mission.

Differences between the on-road and off-road mobility power and duty cycle requirements for the Stryker maneuvers were identified along with the specific energy consumption and the daily specific energy consumption. Tracking data from a hybrid 2006 Toyota Highlander was utilized for initial validation of the model. Acceleration and on-road tracking of the Toyota Highlander provided for an accuracy assessment of the model.

VEHICLE AND SOIL PARAMETERS

The vehicle analyzed was the Stryker Infantry Carrier Vehicle (ICV), and it is an 8-wheeled, 17,237 kg vehicle that is powered by a 261 kW V-8 diesel engine. General dimensions of the vehicle are shown in Figure 1.

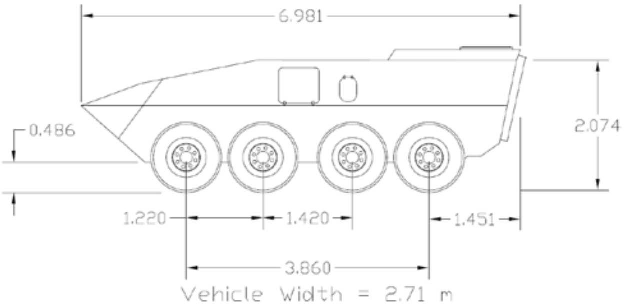


Figure 1: Stryker vehicle geometry (units: meters)

The maximum travel speed of the vehicle is 27 m/s. The vehicle is either 4 or 8-wheel drive; during maneuvers, the vehicle was operated in the 4-wheel drive mode. The vehicle is equipped with a Central Tire Inflation System (CTIS) that allows the operator to vary the inflation pressure of all tires simultaneously according to the terrain conditions [6]. All wheels were equipped with Michelin X tires. The inflation pressure of the tires remained a constant 483 kPa during the 2009 Stryker maneuvers. The tire parameters necessary for applying Eq. (2) and (5) are given in Figure 2 while the tire deflection represents in Figure 2 was at a 483 kPa inflation pressure.

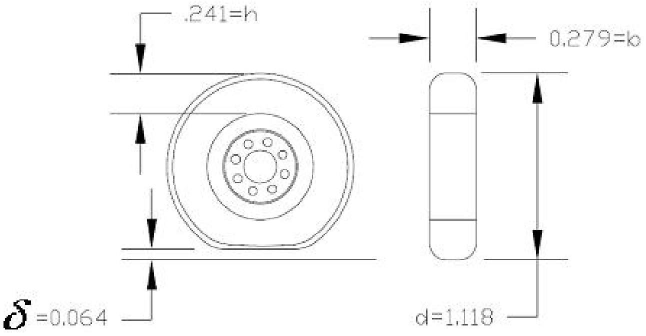


Figure 2: Michelin X tire geometry at during Stryker maneuvers at PTA (units: meters)

The frontal area, A_f, was determined to be approximately 4.5 m^2 based on the geometry of the Stryker. C_D was assigned a value of 1.0 for the Stryker vehicle because large military vehicles typically have a C_D value approximately equal to 1.0 [4].

The Toyota Highlander used during validation testing had a hybrid-electric drivetrain with a 3.3 L V-6 gasoline engine capable of supplying electric and mechanical power to the wheels. The weight of the vehicle during testing was 20.8 kN which included the operator and passengers along with the testing equipment. The vehicle had a continuously variable transmission (CVT) which eliminated the loss of the vehicle's kinetic energy that typically occurs in a standard manual or automatic transmission. The vehicle is equipped with a power meter that displays the power produced (kW) by the hybrid powertrain, and it is thought that this value is analogous to an engine's rated brake power. The measured value from this display allowed for the initial validation of the mobility power model. The Toyota Highlander's A_f was calculated to be 2.85 m^2 while C_D was estimated to be approximately 0.4. All four tires of the vehicle were of similar geometry, and the *b*, *h*¸ *d*, and δ values were 0.225, 0.146, 0.724, and 0.022 m respectively.

The steering angles of wheels on the steered axles were determined from the calculated turning radius of the vehicle by assuming the slip angle of each tire was negligible. The turning radius was calculated from the vehicle's GPS data. For the steered angle calculations, it was assumed the vehicle's center of gravity was at the geometric center of the vehicle, and the vehicle turned about this point. The normal loads on each tire were assumed to be equal and constant during maneuvers with minimal effects due to weight transfer. The vehicles analyzed did not have a drawbar load so Eq. (17) was not used in the analysis.

The vehicle's calculated acceleration and change in elevation values determined from the GPS position, elevation, and time data were filtered to smooth the predicted acceleration and elevation of the vehicle. For the Stryker mobility power analysis, the filter consisted of applying a 5 s running average to the acceleration and elevation values. A 3 s running average was applied only to the calculated acceleration values for the Toyota Highlander data. This was necessary to remove some of the extraneous variability of the position and elevation values obtained from the GPS data.

The soils at PTA are characterized as poorly developed soils with minimal vegetation while some areas have a barren lava surface. The altitude and minimal precipitation drastically reduces the weathering of the soil while excessive wind, steep grades, and sparse vegetative cover tend to increase runoff and soil erosion [6]. The cone index (CI) from Eq. (2) and the cone index slope gradient (G) from Eq. (5) must be determined for the vehicles. In 2009, the CI values for the two off-road maneuvers areas at the Keamuku parcel were measured. A cone penetrometer was used to measure CI value at each location in the top 0.152 m of the soil. The measured CI values for the two off-road terrains were 1536 and 1970 kPa. The CI value of the on-road surfaces could not be measured with a cone penetrometer.

The asphalt and concrete surfaces were assigned a CI value of 4137 kPa because this value is typically assigned to such surfaces when applying the Waterways Experiment Station (WES) model [7]. The CI value was assumed be 4137 kPa for the 2009 on-road Stryker maneuvers because the hard-packed gravel surface of the roads were similar to a firm pavement. A CI of 4137 kPa was also used in Eq. (2) for the initial validation with the Toyota Highlander since it operated on hard concrete or asphalt surfaces.

FIELD TESTING METHOD

The VTS units used for tracking of the Stryker and Toyota Highlander vehicles had a Garmin 18 WAAS differential Global Positioning System (DGPS) that was configured to output data at a rate of 1 Hz. The data was stored via Acumen's Serial Data Recorder (SDR). The SDR stored the data to compact data storage cards. The GPS and SDR were supplied 12 V DC power from a battery, and the components were self-contained in a watertight plastic case, except for the magnetic GPS receiver that was mounted to the exterior of the case or vehicle [8].

In 2009, three Stryker vehicles from a reconnaissance platoon from the 2nd Brigade of the 25th Infantry Division conducted a single day proofing mission on November 9, 2009. During the proofing mission, off-road maneuvers were conducted at the Keamuku parcel of PTA. The objective of the proofing mission was to assess the trafficability of the region while identifying optimum access points and hazardous areas of the terrain. On-road maneuvers were conducted only on roads consisting of compacted gravel surface [8].

Validation of the mobility power model occurred on June 20, 2011 while maneuvers were conducted with a Toyota Highlander in an urban environment in Knoxville, Tennessee. Acceleration tests were performed on a flat concrete surface with a length of

150 m. 14 different acceleration tests were executed at approximately constant levels of power input for each test. On-road maneuvers in an urban environment were also tracked which provided for further initial validation of the mobility power model. These on-road maneuvers occurred on asphalt and concrete surfaces with varying grades. A DVD video recorder was used to measure fluctuations in the power meter of the Highlander during maneuvers.

MODEL RESULTS

From the mobility power analysis of the 2009 Stryker data, the operating characteristics and mobility power/energy requirements were identified along with the mission-specific power duty cycle requirements. Table 2 summarizes the vehicle data obtained from the GPS data for the 2009 Stryker maneuvers.

Table 2: 2009 Stryker data at PTA for the 1-day proofing mission

VTS No.	Terrain	Maneuver Time [hours]	Dist. Traveled [km]	Daily Travel [km/day]	Average dh / dt [m/s]	Average Speed [m/s]
08	On-road	3.27	59.94	59.94	0.22	5.09
08	Off-road	0.47	5.42	5.42	0.16	3.21
17	On-road	5.38	106.10	106.10	0.23	5.41
17	Off-road	1.10	11.96	11.96	0.20	3.03
19	On-road	5.62	107.53	107.53	0.24	5.32
19	Off-road	0.72	9.65	9.65	0.20	3.74
Total	On-road	14.26	273.57			
Total	Off-road	2.28	27.03			

The estimated mobility power value was determined for each GPS point using Eq. (18). With the aid of ArcGIS 9.3, the mobility power and GPS data from the Stryker maneuvers at PTA were spatially mapped. Figure 3 shows the spatial mobility power map for a Stryker during the off-road proofing mission at the Keamuku parcel of PTA in 2009.

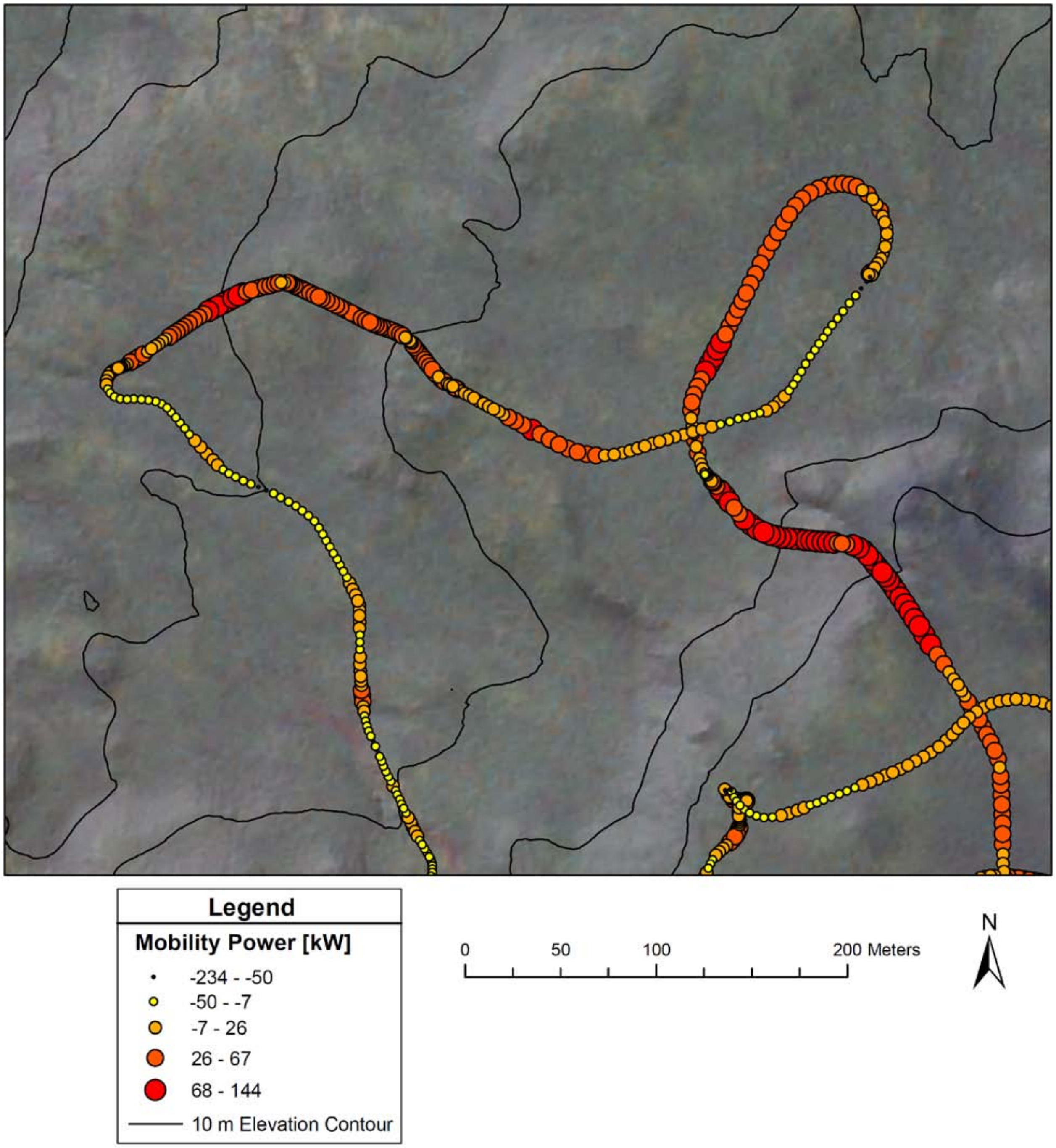


Figure 3: A mobility power map for a Stryker (VTS No. 08) operating at the Keamuku parcel of PTA in 2009

The map indicates that the Stryker's mobility power was less than zero while traversing a negative grade, and a positive mobility power was required when increasing in elevation. This trend was observed in Figure 3 for the parallel GPS tracks taken by the vehicle during the off-road proofing mission. The mobility power values of the parallel paths signify that a positive and negative grade was traversed by the vehicle. Figure 4 shows how the motion resistance, elevation, acceleration, drag, and mobility power vary over a 30 s time period while traversing the terrain at varying speed.

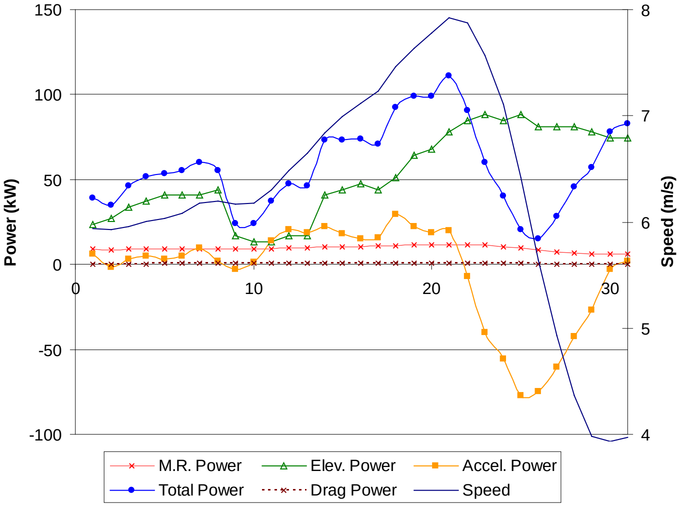


Figure 4: Stryker mobility power and speed data during 30 s of off-road operation at PTA in 2009

Due to the vehicle's increase in elevation as time increased, the elevation power was the main factor that contributed to the positive mobility power requirement. Increasing travel speed increased the motion resistance power, but it did not significantly impact the net mobility power. The aerodynamic drag power had minimal effects on net mobility power. However, the decrease in speed between a time of 21 and 30 s produced a significant negative acceleration which resulted in the overall mobility power value decreasing substantially.

The mobility power value for each GPS point was an indicator of the load on the vehicle's engine. A negative net mobility power value indicated minimal engine power was required, and the vehicle's brakes may have been applied by the operator. If the negative mobility power increased in magnitude, this was an indication that heavier braking may have occurred by the operator. A high positive mobility power indicated that significant power was required by the vehicle's engine to maintain the operating conditions indicated by the GPS data. It is important to note that data was not acquired on the vehicle's fuel consumption rate and braking while tracking at PTA. The power duty cycles of the Stryker vehicles were estimated only for the periods when the vehicle was moving. The Stryker mobility power duty cycles for a given power range are given by Figure 5.

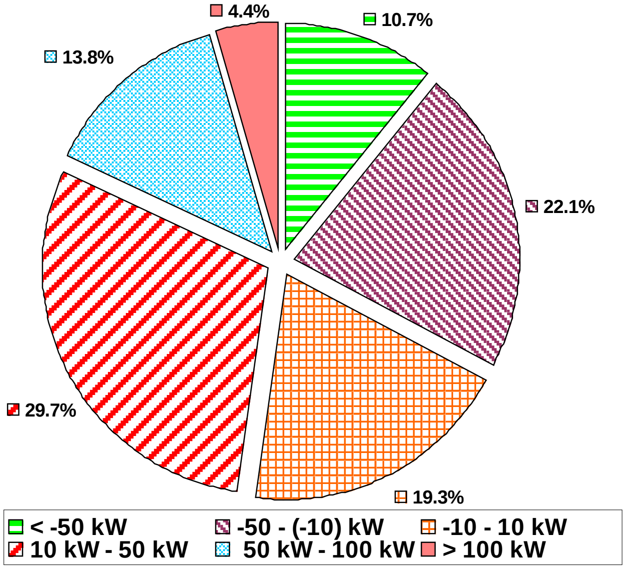
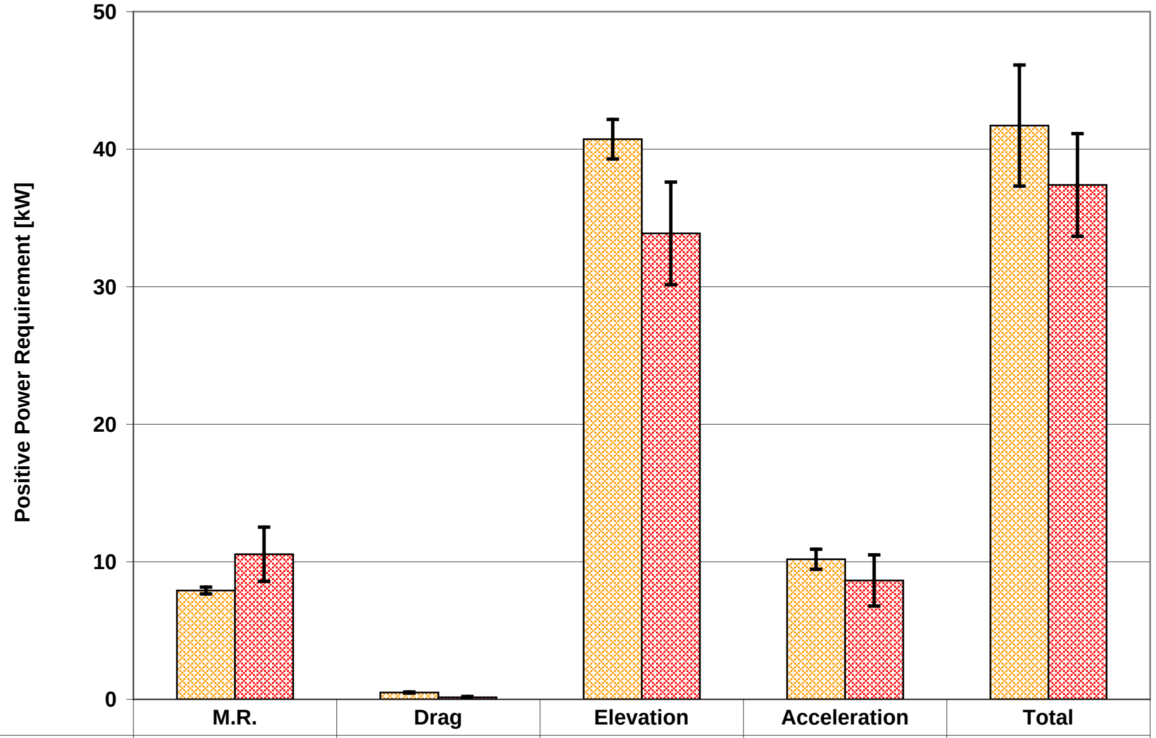


Figure 5: Mobility power duty cycles for the combined on-road and off-road 2009 Stryker maneuvers

The 10 – 50 kW mobility power range had the largest duty cycle while the mobility power ranges greater than 100 kW and less than -50 kW had the lowest duty cycles. The mobility power range that was less than -10 kW and greater than -50 kW had the 2nd largest duty cycle due to the Stryker's negative elevation and/or acceleration power. A negative mobility power indicated that the vehicle was decreasing in travel speed and/or the vehicle was decreasing in altitude at that time while braking by the operator may have been required. The elevation change of some Stryker vehicles during the maneuvers exceeded 700 m which resulted in significant negative mobility power duty cycle values. The -10 – 10 kW duty cycle was 19.3% which indicated that minimal power was required (braking and/or drivetrain frictional losses occurred) for approximately a fifth of the time the vehicle was maneuvering. The mobility power demand exceeding 100 kW for the vehicle occurred 4.4% of the time when the vehicle was moving. When the vehicle was in this mobility power duty cycle range, the required power by the vehicle's engine was the greatest.

The 2009 Stryker maneuvers at PTA were further analyzed to compare and contrast the mobility power and duty cycle requirements for the vehicle in the on-road and off-road terrain. The average individual and total positive mobility power values are given in Figure 6 for the on-road and off-road 2009 Stryker data.



	M.R.	Drag	Elevation	Acceleration	Total
▨ On-road Data	7.9	0.5	40.7	10.2	41.7
▨ Off-road Data	10.5	0.1	33.9	8.6	37.4

Figure 6: Individual and total positive, average mobility power values for the on-road and off-road 2009 Stryker data at PTA with one standard deviation bars for three vehicles

The results indicated total positive mobility power requirement by the vehicles was 4.3 kW greater (11.6%) when operating on-road. The on-road power requirement was greater because the vehicle's average speed was 2.0 m/s greater while maneuvering on-road, despite the average motion resistance power being 2.6 kW greater (33.2%) in the off-road terrain. Positive elevation and acceleration values, along with the drag power, were also greater for the on-road maneuvers because of the increased travel speed. The variability of the mobility power data was similar for the on-road and off-road maneuvers. However, greater mobility power variability was observed for the off-road maneuvers because the GPS tracks of the vehicles differed. The vehicles were conducting a proofing mission where each vehicle traverses a different area of off-road terrain. As a result, different travel speeds were maintained according to the given terrain conditions. This was the principle source of the increased variability for the off-road data. The on-road and off-road mobility power duty cycles for the 2009 Stryker maneuvers are characterized in Figure 7.

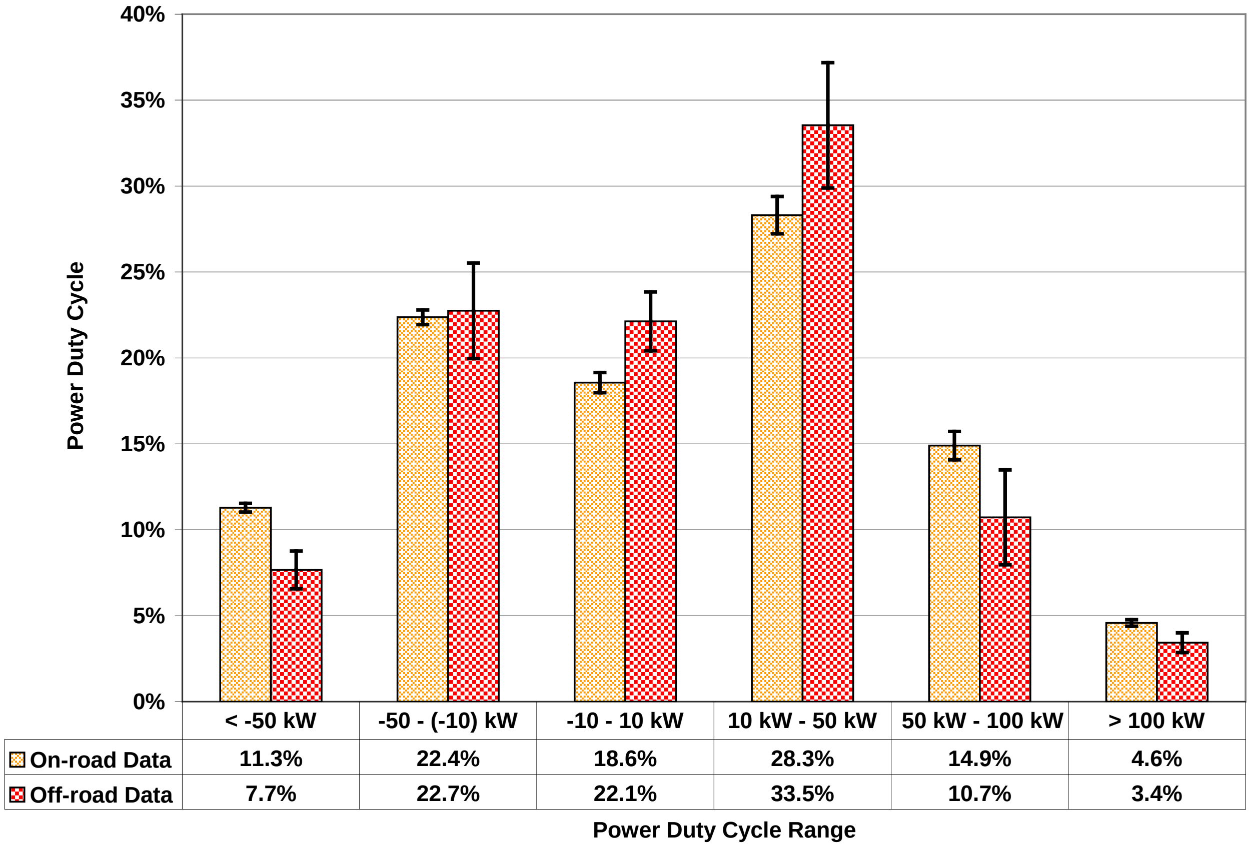


Figure 7: Power duty cycles for the on-road and off-road 2009 Stryker data at PTA with one standard deviation bars for three vehicles

Since the on-road maneuvers had a higher travel speed, the on-road data had greater power duty cycle requirements for the mobility power ranges that were greater in magnitude. The off-road -10 – 10 and 10 – 50 kW power duty cycle ranges had 5.2 and 3.6 % respectively greater duty cycles than the on-road maneuvers.

The amount of energy consumed by the power plant of the vehicle is a critical concern when designing off-road vehicles. Furthermore, the potential regenerative energy available for harvesting by a hybrid drivetrain is of principle interest. Equation (19) was used to estimate the energy consumption and production by the vehicle during maneuvers. One approach to characterize the mission-specific energy requirements of a vehicle is to estimate the specific energy consumption/production (MJ/km) and the daily specific energy consumption/production (MJ/day). The specific energy consumption and production values were calculated by summing the positive or negative energy values associated with the entire GPS track and dividing by the total distance traveled or the number of days the vehicle maneuvered. Table 3 details the specific energy requirements for the Stryker data.

Table 3: Specific energy consumption and production for the 2009 Stryker maneuvers conducted at PTA

Year	Mission Type	Specific Energy Consumption [MJ/km]	Daily Specific Energy Consumption [MJ/day]	Potential Specific Energy Production [MJ/km]	Daily Potential Specific Energy Production [MJ/day]
2009	Proofing	4.9	516.8	3.1	307.2

The energy consumption values in Table 3 are an indicator of the energy consumption requirements by the Stryker vehicle during maneuvers. If the vehicle was equipped with a hybrid powertrain, the specific energy consumption values represent the mobility energy required by the electric power source during stealth operations. The potential specific energy production by the vehicle provided an estimate of the theoretical energy available for harvesting via regenerative braking from a hybrid powertrain. Estimating the specific energy consumption and potential specific energy production may allow for the duration that a hybrid military vehicle can operate in 'stealth' mode (electric power only) to be predicted for the given terrain conditions.

MODEL VALIDATION

The on-road tests performed with the Toyota Highlander provided for an initial validation of the mobility power model. The 14 acceleration tests performed at various levels of constant power were compared to the predicted average power from the model. GPS data during the 14 acceleration tests was collected for 0.08 hours. The measured and predicted power values during each test were averaged over the duration of the test, and the results are shown in Figure 8.

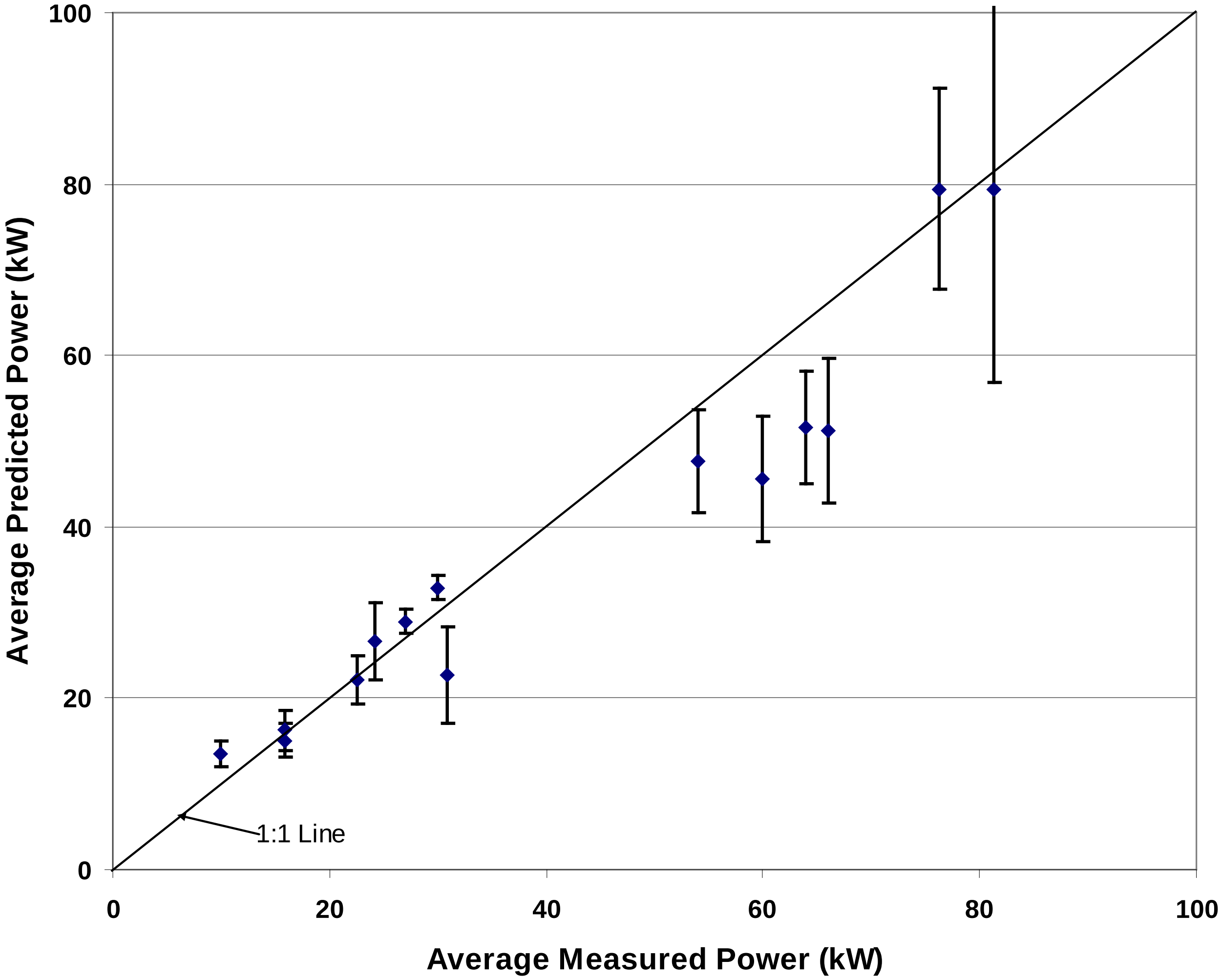


Figure 8: The average measured and predicted power requirements for the Toyota Highlander during the 14 acceleration tests in Knoxville, TN

The results from the initial model validation indicated that the model's predicted average power was similar to the measured power from the vehicles power plant. The model explained 91% of the variability ($R^2 = 0.91$) in the measured average power during the acceleration tests. The average absolute error and percent error were 5.2 kW and 12.9 % respectively. It can be concluded from the accuracy assessment that the mobility power model sufficiently explains the average power requirement of the vehicle during the acceleration tests. However, further field validation across varying terrain and vehicle conditions is necessary in the future.

Deviations between the predicted and measured average power values can be attributed to numerous factors. The tests were conducted on a relatively flat concrete surface, but slight grade changes in some areas made it difficult to maintain a constant level of measured power. The abrupt grade changes placed an increased load on the vehicle's suspension which reduced the kinetic energy of the vehicle while making it difficult to maintain a constant level of input power. Another source of variability was that the measured average power was analogous to an engine's rated brake power while the predicted mobility power was the net power required by the driven wheels of the vehicle. The difference between the measured power from the power meter and the predicted mobility power value may be an indicator of the drivetrain efficiency losses of the vehicle. By applying a least-squares linear regression to the measured and predicted power values, the theoretical mechanical efficiency from the vehicle's power sources (electric and gasoline motors) to the wheels was estimated from the slope of the linear regression line. A linear regression of the data resulted in a slope of 0.91, and this value represents the theoretical mechanical efficiency between the vehicle's power sources and the driven wheels.

Preliminary validation of the model was also conducted when the Toyota Highlander was operated in an urban environment in Knoxville, Tennessee for 0.51 hours. Outliers caused by GPS drift and poor signal quality were identified and removed during the analysis. Poor signal quality was primarily a result of the GPS signal being blocked by tall trees and buildings. Figure 9 provides for a comparison of the predicted and measured power requirement for the Toyota Highlander during the maneuvers.

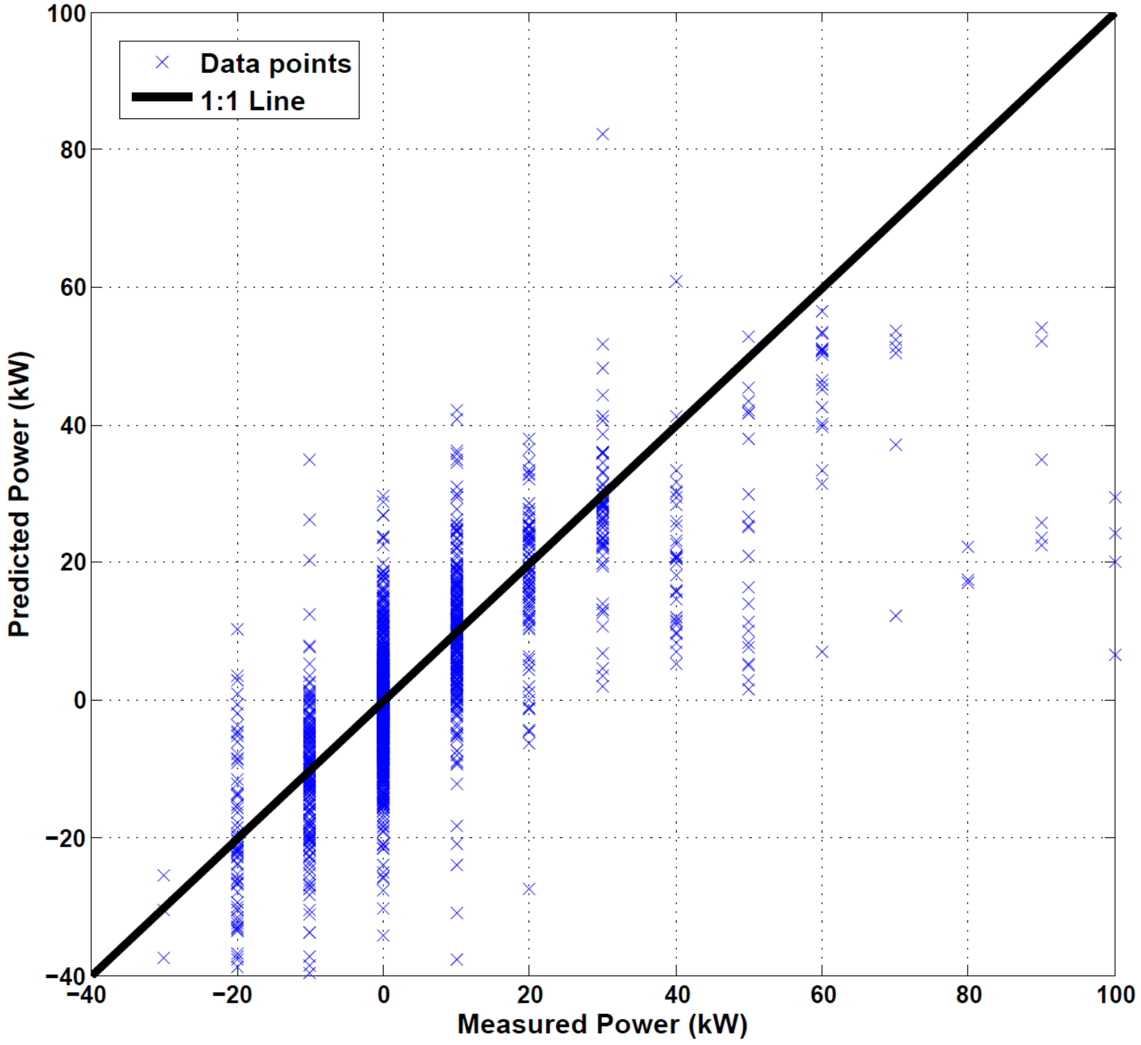
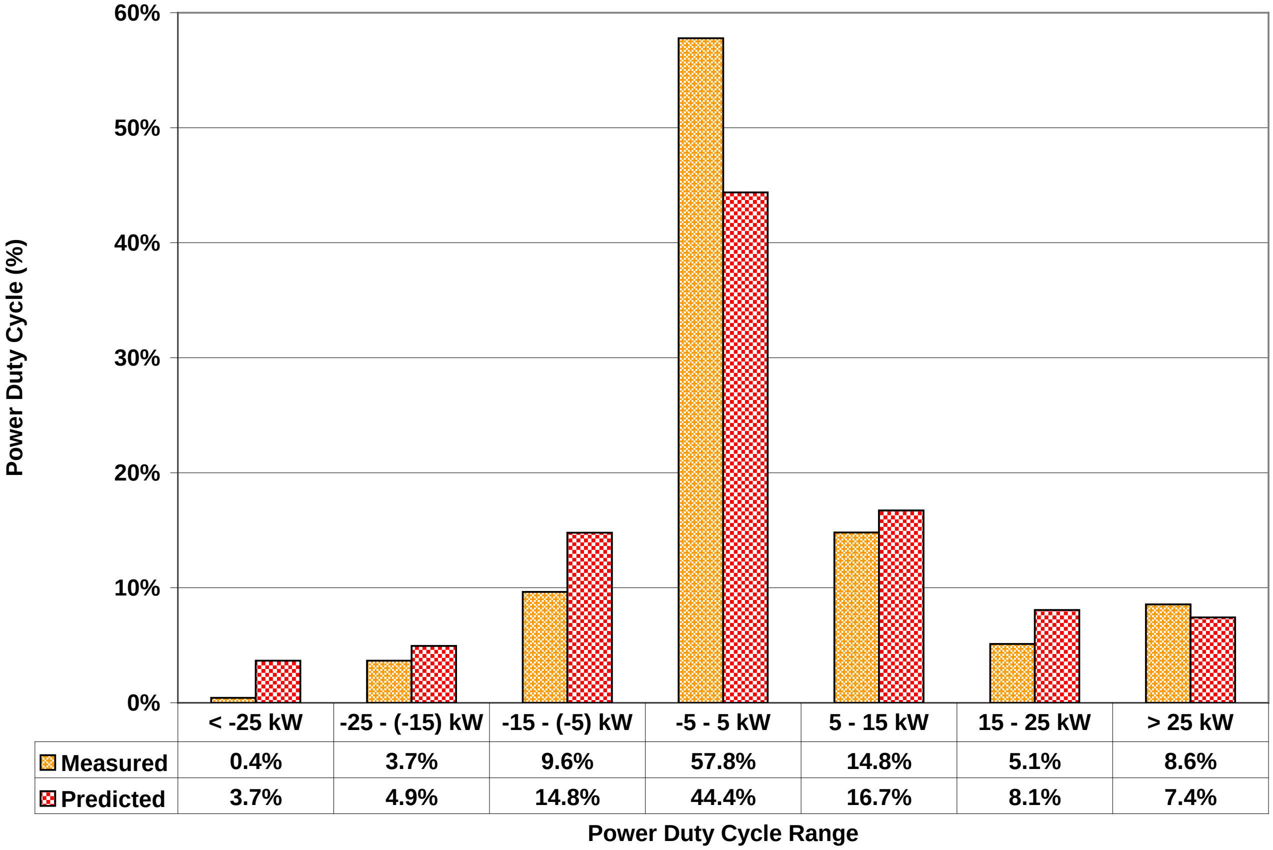


Figure 9: The measured and predicted power requirements for the Toyota Highlander during on-road maneuvers in Knoxville, TN

The average absolute error of the on-road maneuvers was 7.1 kW while Figure 9 indicated the variability of the model increased ($R^2 = 0.44$) when estimating the power requirement for each second of operation. The model can more accurately estimate the average power required compared to estimating the power needed for each second of vehicle maneuvers. The model tended to underestimate the required power by the vehicle when the measured power output by the vehicle's power plant exceeded 35 kW. Underestimating the high power requirements for the vehicle may be attributed to the filtering of the calculated acceleration and change in elevation values for each GPS point. The filtering smoothed peak power requirements over a longer duration of vehicle maneuvers. The measured and predicted power duty cycle values for a given power range are represented in Figure 10.



	< -25 kW	-25 - (-15) kW	-15 - (-5) kW	-5 - 5 kW	5 - 15 kW	15 - 25 kW	> 25 kW
▨ Measured	0.4%	3.7%	9.6%	57.8%	14.8%	5.1%	8.6%
▨ Predicted	3.7%	4.9%	14.8%	44.4%	16.7%	8.1%	7.4%

Figure 10: The measured and predicted power duty cycle requirements for the Toyota Highlander during on-road maneuvers in Knoxville, TN

The predicted power duty cycle values during the maneuvers in the urban environment were similar to the measured power duty cycle values for the Toyota Highlander. The measured -5 to 5 kW and greater than 25 kW mobility power duty cycles were 13.4 and 1.2 % greater respectively than the predicted power duty cycles. The predicted positive and negative 5 to 15 and 15 to 25 kW power duty cycles were greater in magnitude compared to the measured values. The predicted less than -25 kW power duty cycle range was significantly greater than (3.3 %) the measured duty cycle value. The difference in this power duty cycle range may be due the fact that the power meter display does not exceed -30 kW.

CONCLUSIONS

This paper provides a methodology for analyzing previously gathered GPS-based data for predicting the mission-specific mobility power duty cycle characteristics for military vehicles. GPS data from an on/off-road proofing mission performed by the Stryker vehicle while operating in 2009 at the Pohakuloa Training Area (PTA) in Hawaii was analyzed. The 10 to 50 kW and -10 to -50 kW ranges had the greatest mobility power duty cycles with values of 29.7 and 22.1 % respectively. The power requirements for the Stryker vehicle while operating in the on-road environment required 11.6 % positive mobility power due to the higher travel speed that was attained when maneuvering in the on-road environment. The power duty cycles that were greater in magnitude had significantly greater duty cycles when the Stryker operated in the on-road environment. The specific energy consumption and potential specific energy production for the Stryker vehicles was 4.9 and 3.1 MJ/km respectively.

Tracking data from a Toyota Highlander maneuvering in 2011 on concrete and asphalt surfaces was used for the initial validation of the mobility power model. During the acceleration tests, the average absolute percent error between the measured and predicted power values was 12.9 % while the model had an R^2 value of 0.91. The average absolute error and R^2 values during on-road maneuvers were 7.1 kW and 0.44 respectively. The model's predicted mobility power duty cycle values for the Toyota Highlander were similar to the measured values. The validation results indicated the potential accuracy that can be attained with the model, but further, in-depth validation is necessary to identify all sources of variability in the model. Future validation where power is measured at driven wheels or tracks of the vehicle while the vehicle operates in varying terrain conditions will provide for a more detailed analysis of the accuracy of the mobility power model.

REFERENCES

[1] M. Brudnak, M. Pozolo, A. Meldrum, T. Mortsfield, A. Shvartsman, W. Smith, J. Goodell, and D. Holtz, "Virtual Combat Vehicle Experimentation for Duty Cycle Measurement", SAE Conference, Detroit, 2008.

[2] J. Wong, "Theory of Ground Vehicles", 4th ed., NJ, Wiley, 2008.

[3] R. Jones, G. McKinley, P. Richmond, and D. Creighton. "A vehicle terrain interface", ISTVS Conference, Fairbanks, 2007.

[4] J. Wong, "Terramechanics and Off-road Vehicle Engineering" 2nd ed. New York, Elsevier, 2010.

[5] T. Gillsepie, "Fundamentals of Vehicle Dynamics" Warrendale, SAE, 1992.

[6] N. Potteti, "Quantifying Dust from Pre and Post Transformation at Pohakuloa Training Area", Master thesis, Knoxville, University of Tennessee, 2009.

[7] P. Richmond, S. Shoop, A. Reid, and G. Mason, "Terrain Surface Codes for an All-season, Off-road Ride Motion Simulator", MSIAC M&S journal, 2006.

[8] H. Howard, P. Ayers, D. Koch, A. Anderson, J. Kane, G. Bozdech, and N. Svendsen, "Predicting Soil Erosion Potential from Military Vehicle Tracking and Terrain Impacts", International symposium on erosion and landscape evolution. Anchorage, 2011.