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Cover Page Footnote

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Vehicle Multi-pass Rut Volume and Mobility Power

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This paper presents the relationship between applied power by a wheeled vehicle to soil and the rutting effects. Specifically, a strong positive relationship was found between cumulative applied power and total rut volume across multiple passes by the vehicle over the same tracks. Field-testing was conducted using a high-mobility multi-purpose wheeled vehicle (HMMWV) and two distinct soil types. Sensors on the vehicle measured torque and angular velocity of each of the four wheels, from which applied power was calculated. A rut profile meter was used to document the shape of the rut after set numbers of passes and this profile was used to calculate rut volume. These results are useful for determining vehicle mobility power requirements based on soil rutting during multi-pass operation.

Introduction

In concordance with literature, multiple passes by a vehicle over the same course produce larger ruts. The effects of multiple passes in the form of width and depth are quantifiable; a project by Saarilahti and colleagues modeled rut depth for a range of soil conditions and load parameters (1). Led by Mechanical Simulation International, Incorporated, the University of Tennessee, and the University of Wisconsin-Madison, this project aimed to develop a vehicle/terrain interaction model to support power and energy analysis. This model will be used for real-time simulation of the tire, track, and soil effects and the accurate calculation of power and energy requirements for vehicle mobility. Multiple studies have analyzed the effects of military vehicles on rut formation and the associated vehicle-terrain interactions, but the effects that these ruts have on vehicle power requirements have not been quantified (2)(3)(4).

With the facilities of the Tank Automotive Research Development Engineering Center (TARDEC) Ground Vehicle Simulation Laboratory (GVSL), an instrumented, high-mobility multi-purpose wheeled vehicle (HMMWV) ran a series of maneuvers under varying soil conditions to provide field validation for the model. Testing was performed near Vicksburg, Mississippi, from August 8th to August 10th, 2012. The coarse grain soil testing was conducted at a site on the bank of the Mississippi River, and the fine grain soil testing was performed a few miles inland. Soil parameters were taken at various points on the testing field, soil disturbances were documented for each test, and vehicle sensor data was recorded. Vehicle metrics were also recorded for the HMMWV as a reference point for the model validation. One of the tests was the straight-line multi-pass test; the HMMWV made eight passes at a set velocity through the same tracks, and rut depth, width, and profile were documented after the first, second, fourth, and eighth passes. Meanwhile, computers onboard the instrumented HMMWV recorded data from an array of sensors, including wheel torque, wheel angular velocity, vehicle velocity, accelerometry, gyro position, and GPS position provide field validation for the model. Testing was performed near Vicksburg, Mississippi, from August 8th to August 10th, 2012. The coarse grain soil testing was conducted at a site on the bank of the Mississippi River, and the fine grain soil testing was performed a few miles inland. Soil parameters were taken at various points on the testing field, soil disturbances were documented for each test, and vehicle sensor data was recorded. Vehicle metrics were also recorded for the HMMWV as a reference point for the model validation. One of the tests was the straight-line multi-pass test; the HMMWV made eight passes at a set velocity through the same tracks, and rut depth, width, and profile were documented after the first, second, fourth, and eighth passes. Meanwhile, computers onboard the instrumented HMMWV recorded data from an array of sensors, including wheel torque, wheel angular velocity, vehicle velocity, accelerometry, gyro position, and GPS position.

Due to the multitude of soil types, test maneuvers, and test parameters, a nomenclature system was used to label each test (Table 1). Data was taken from two test conditions: coarse grain, multi-pass, fast speed, low pressure (C M# F L D/P) and fine grain, multi-pass, fast speed, high pressure (F M# F H D/P).

Soil Type	Test Type	Speed	Tire Pressure	Vehicle Side
F (fine grain)	L (lane change)	F (fast, 10 mph)	H (high, 20% deflection)	P (passenger)
C (coarse grain)	T150, T100, T50 (turning radius, ft.)	S (slow, 5 mph)	L (low, 30% deflection)	D (driver)
	M1, M2, M4, M8 (multi-pass #)			

Table 1: Test nomenclature

Methods

The traditional method of calculating rut volume uses width and depth and assumes a rectangular or triangular rut. A transverse rut profile is a more precise assessment of rut volume due to its measurement of the imperfect shape (5). This method is based on the principles of rectangular approximations of curves in a two-dimensional coordinate system. An array of pins with depth markings rests on the surface of the soil across the profile of the rut (Figure 1). The depth reading of each pin was taken, and a graph of the profile was made (Figure 2). In the graph, the maximum height of the displaced soil on either side of the rut constitutes the rut boundaries; the depth readings (h) that fall outside the rut boundary were averaged to approximate the ground height (GH) for each individual profile. Depth readings (D) inside the rut boundaries that fell below the ground height were multiplied by the horizontal distance between pins (1 cm); this yielded partial volume values (V_i), the sum of which constituted the total volume (V) for the rut profile.

Figure 1: Example picture of rut profile and meter, from which pin readings were taken. Test indicated is CM8FLD, which corresponds to coarse grain, multi-pass number eight, fast speed, low pressure, driver side.

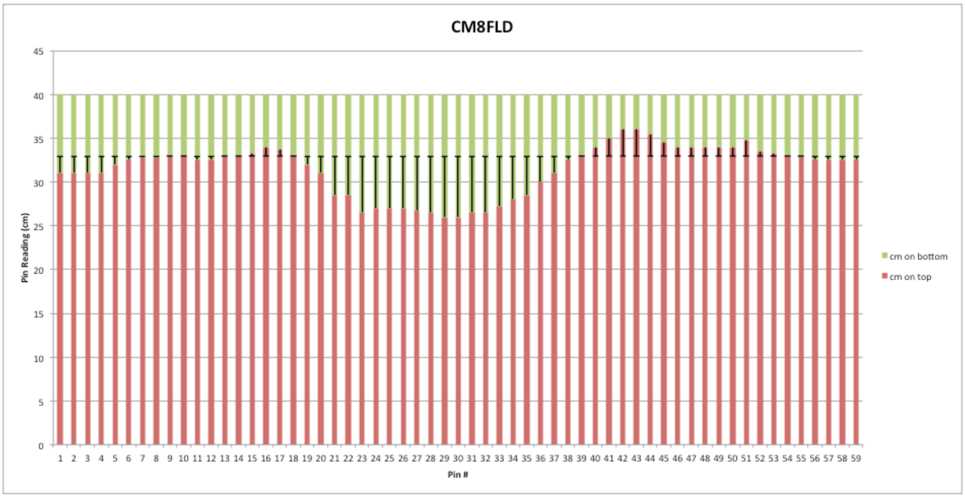

Figure 2: Example rut profile compiled from individual pin readings. Approximated ground height is shown as a horizontal line by error bars on each pin.

Torque and angular velocity data from each wheel across the duration of each test was averaged. Multiplying these values and using a conversion factor yielded average applied axle power values for each wheel, average total axle power for the HMMWV, and cumulative applied power through the eight passes for driver and passenger sides. This data was joined with rut volume data for passes one, two, four, and eight; the passenger and driver side data were consolidated.

Results

By standardizing ground heights across each measured pass and the passenger/driver side of the vehicle, a compounded profile was created for both coarse and fine grain soil (Figure 3, Figure 4).

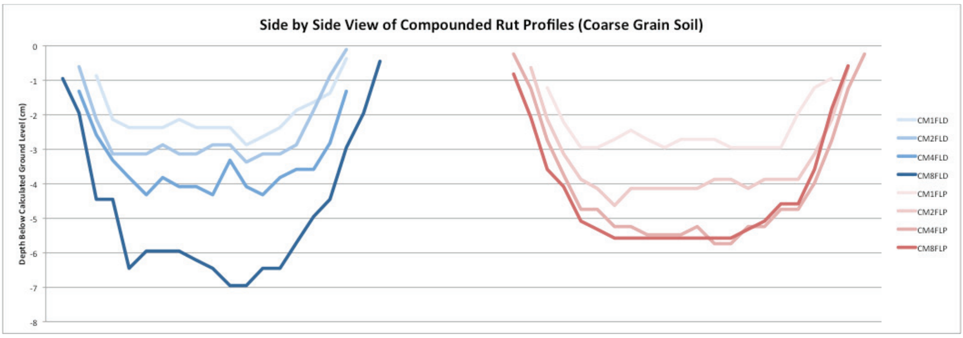

Figure 3: Compounded profiles for driver (blue) and passenger (red) sides at pass one, two, four, and eight on coarse grain soil. Profiles are shown in identical scale.

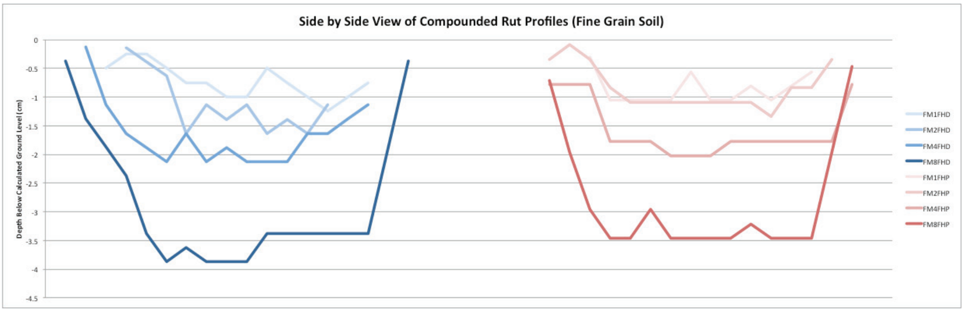

Figure 4: Compounded profiles for driver (blue) and passenger (red) sides at pass one, two, four, and eight on fine grain soil. Profiles are shown in identical scale.

Total rut volume was compared to the number of passes imparted on the soil, and under both soil conditions a positive and direct correlation was noted; that is, rut volume increased predictably as the vehicle passed through the track (see Figure 5). This total rut volume was compared to the cumulative power applied by the vehicle over the corresponding amount of passes; again, rut volume was shown to increase predictably as the cumulative amount of power applied by the HMMWV to the ground increased (see Figure 6).

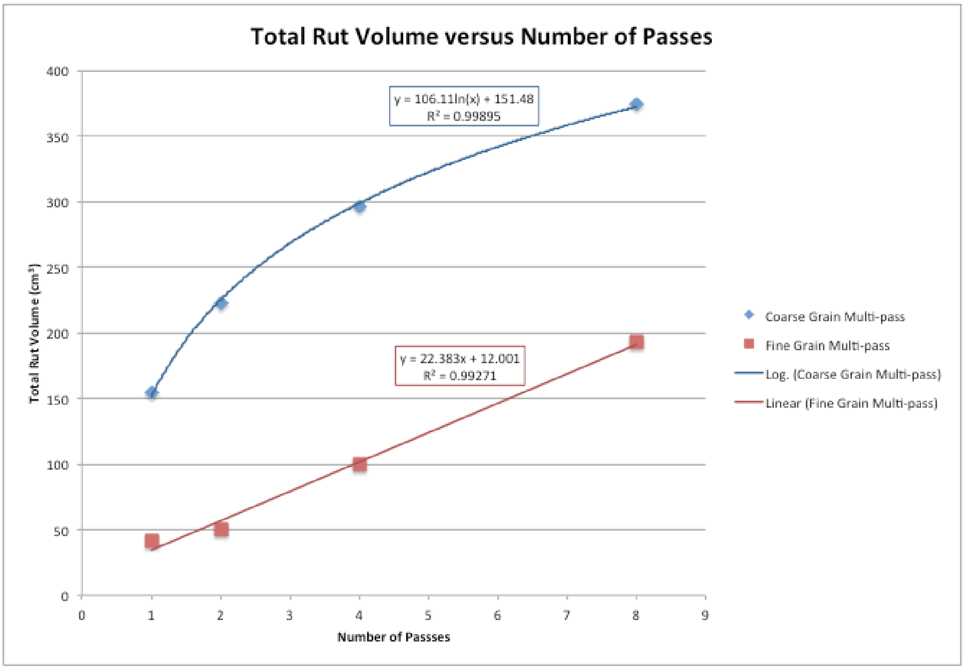

Figure 5: Rut volume increasing predictably over a number of passes for both coarse and fine grain soils. Note R^2 values of 0.99895 and 0.99271, respectively.

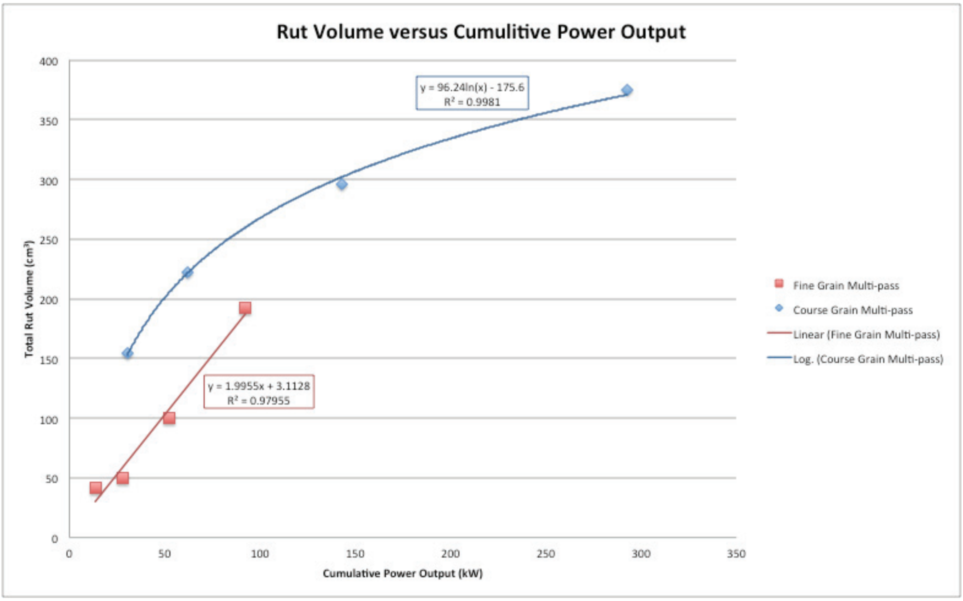

Figure 6: Rut volume increasing predictably as a function of applied power by the vehicle in both coarse and fine grain soils. Note R^2 values of 0.9981 and 0.97955, respectively.

Discussion

Analysis of the data for volume versus number of passes and volume versus cumulative output power shows that the two data sets appear almost identical in shape and correlation. The difference between them lies only in the scaling of each graph. Because the shape of the data in each case is similar, it can be concluded that the average vehicle power for each pass remained constant and did not vary as rut volume increased; that is, the quantitative differences can be expressed as a constant that depends on the magnitude of power applied. Moreover, this can be extrapolated to predict cumulative power output to be a linear function since the power for each pass will contribute equally to the cumulative value. The data supports this conclusion, as demonstrated by the strong linear correlation with R^2 values of greater than 0.99 (Figure 7).

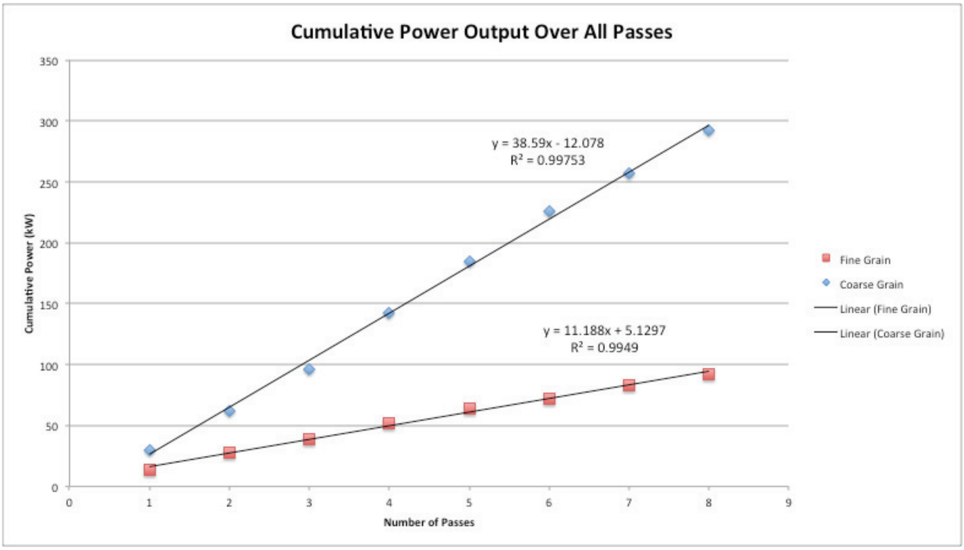

Figure 7: Cumulative power increases linearly over all passes, showing that average power over each pass held relatively constant. Note R^2 values of 0.99753 and 0.9949 for coarse and fine grain soils, respectively.

The realization that rut volume does not affect required vehicle power is critical for the model this research contributes. This is not to say that other factors, such as tire compression or soil compaction, do not contribute significantly to the vehicle mobility power. Rut volume remains important for other simulation purposes, such as terrain deformation. Strong correlation and adherence to trend lines of the rut volume data suggests that rut volume can be modeled predictably based on soil conditions; these findings are consistent with existing studies conducted on the subject (2)(3)(4)(6). In fine grain soil, rut volume increases linearly with respect to the number of passes made and the cumulative amount of power applied to the ground; as soil compaction progresses beyond the number of passes performed in this study, however, this may change. For a fine grain soil such as clay, this linear correlation makes sense; rutting is similar in shape to the profile of the tire because it involves both compaction and displacement of the soil, hence the increasing volume of the rut. In the case of coarse grain soil such as sand, a logarithmic correlation is also understandable. Compaction is very minimal, while displacement increases quickly but begins to reach a threshold because of the tendency of displaced soil to fill back into the rut (7).

Conclusions

Data collected associating rut volume with cumulative vehicle output power shows reliable correlation, with R^2 values of 0.9981 and 0.97955 for coarse and fine grain soils, and compares very closely with data associating rut volume with the number of passes imparted on the rut. The two independent variables, cumulative output power and number of passes, are related to each other by the average vehicle power applied across each pass; that is, compounding power applied on each pass by the total number of passes yields cumulative power output. This similarity between data sets shows that the differentiating factor, average vehicle power per pass, does not vary significantly. As the volume of the rut increases, the power required to traverse the rut does not increase accordingly. In application to the targeted model, a vehicle traversing the same path may create increasingly large ruts, but the required power to drive in the path will not change significantly. The fact that multiple passes creates increasingly large ruts has been well established (6), but this study shows that large rutting does not affect the power required to traverse the terrain on the same path. In relation to the military applications for which this model is under development, this study suggests that vehicle power will not be a limiting factor for high-traffic terrain, where heavy rutting occurs.

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