VELOCITY OF A ROVER AS A FUNCTION OF SLOPE OF LUNAR TERRAIN.

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Introduction: A robotic mission to the moon is limited in duration by the period of solar illumination (~14 earth days). Thus in the early stages of planning a robotic mission to the moon, it is important to understand how far a lunar rover is capable of traveling in a given amount of time. A significant factor in how fast a rover can traverse is the slope of the ground over which it is traveling; therefore, by understanding the relationship between speed and slope and by gathering slope data for a predetermined route, one may determine the time it would take a rover to traverse the given route, assuming constant motion.

To determine an equation for velocity as a function of slope, vehicle specifications must be taken into account. Without a specific vehicle in mind, generic parameters were assumed for the rover. The model uses rover parameters that resemble the Lunokhod 1 and 2 plus the LRV, all rovers that have traversed the lunar surface. The parameters used are: a total mass of 600 kg (where the center of mass is midway between the front and real wheels and 0.5 m above the ground), a constant power supply to the wheels of 200 W, and a four-wheel configuration in which each wheel has a radius of 0.3 m and a width of 0.25 m, and a wheelbase length of 2.2 m. The mechanical properties of the lunar soil are based on the recommended lunar soil trafficability parameters found in Carrier et al. [1].

Methodology: For a wheel moving at a constant velocity, the equilibrium equation for the moments on the wheel is given by:

$$T = DPl + Ne$$

where T is torque provided by the motor, DP is drawbar pull – the ground strength that can be utilized by engine torque (soil thrust minus soil resistance), N is the normal reaction from the soil, and e and l refer to the lever arms of drawbar pull and normal force, respectively. T is equal to the power provided to the wheel, P, divided by the angular velocity of the wheel, ω, and since slip is assumed to be zero, ω is equal to the tangential velocity of the wheel, v, divided by the wheel radius, r. Thus, the velocity of the wheel is given by

$$v = \frac{P * r}{DP * l + N * e}$$

Drawbar pull is equal to soil thrust minus resistance, or

$$DP = H - R$$

where H and R are given by:

$$H = Ac + W tan\varphi$$

$$R = \frac{bkz^{n+1}}{n+1}$$

A is the contact area between the wheel and the ground and z is the wheel sink depth, which for a rigid wheel is given by

$$z = \left(\frac{3W}{(3-n)(kk_c + bk_\varphi)\sqrt{D}}\right)^{2/(2n+1)}$$

In order to determine l and e, the lever arms for drawbar pull and normal force, respectively, θ_l, the entrance angle of the wheel, and θ_m, the angle of maximum stress, must first be defined. θ_l is defined by:

$$\theta_1 = \arccos(1 - z/r)$$

and θ_m is defined by the following linear relationship with θ_1:

$$\theta_m = c\theta_1$$

where c is a coefficient with a value between 0 and 1. With entrance angle and angle of maximum stress defined, the lever arms of normal force and drawbar pull can be defined by:

$$e = rsin(\theta_1 - \theta_m)$$

$$l = rcos(\theta_1 - \theta_m)$$

The above equations were combined to solve for velocity as a function of slope angle.

Results: The results of the model are shown in Figures 1-4. The rover's maximum velocity is shown to decrease with greater slope, with increasing gradient over the plotted range (Figure 1). One can see that, as the gradient increases, the maximum velocity of the rover decreases at a declining rate. The results indicate that a rover with the specifications described above can travel across flat ground at a speed of approximately 1.7 km/hr.

In addition to testing this generic parameter set, several parameters were varied within the model in order to test their effect on the maximum velocity. The wheel radius was varied between 0.2 m to 0.4 m, from which it was found that increasing the wheel radius increased the velocity of the rover (Figure 2). The mass was varied between 500 kg and 750 kg, showing that mass has a greater effect on velocity than wheel radius (Figure 3). Power input, was found to have the greatest impact on velocity (Figure 4); power was varied between 150 W and 300 W, increasing the maximum velocity on flat ground from 1.25 km/hr to 2.50 km/hr, illustrating a direct proportionality between the two, as can be seen in equation 1. Furthermore, by increasing power or radius, the slope of the line also increases. The opposite effect occurs when decreasing the parameters. However, varying mass only changes the initial velocity, but the slope of the line stays the same for all tested masses.

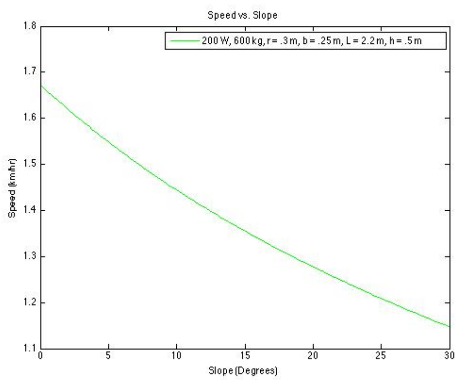

Figure 1: Speed vs. Slope

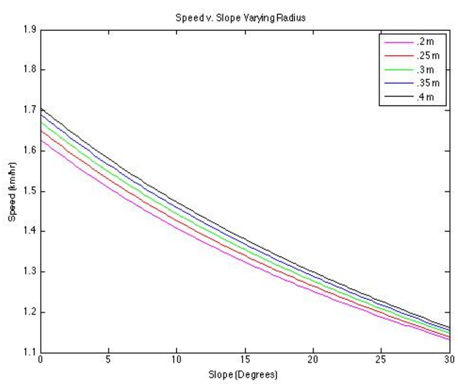

Figure 2: Speed vs. Slope varying wheel radius

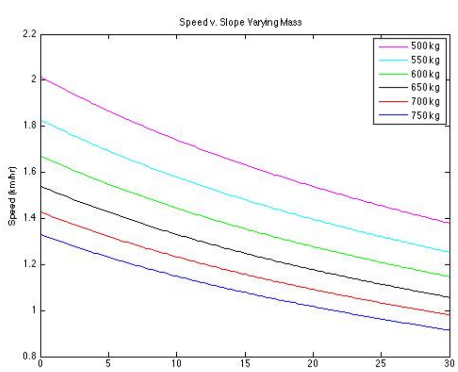

Figure 3: Speed vs. slope varying rover mass

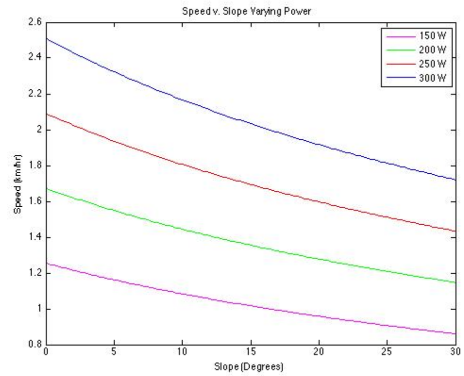

Figure 4: Speed vs. slope varying power

Conclusion: A mathematical model to determine the relationship between the speed of a rover and slope of lunar terrain was determined, thereby allowing the planning of rover missions on the lunar surface to be more accurate. This model was used to calculate traverse times in a mission proposal presented by the 2013 Lunar Exploration Summer Intern Program last summer.

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References: [1] Carrier, D. W., "Lunar Soil Simulation and Trafficability Parameters", Lunar Geological Institute, Jan. 2006 [2] Ding, L., et al., "Experimental study and analysis on driving wheels' performance for planetary exploration rovers moving in deformable soil", *Journal of Terramechanics*, 11 Aug. 2010 [3] Bekker, M.G., *Introduction to Terrain-Vehicle Systems*, The University of Michigan Press, 1969