

SIMULATION-BASED ROVER PERFORMANCE EVALUATION AND EFFECTS OF TERRAIN MODELLING

A. Azimi (a), M. Hirschhorn (a), B. Ghotbi (a),
J. Kövecses (a*), J. Angeles (a), P. Radziszewski (a),
M. Teichmann (b), M. Courchesne (b), Y. Gonthier (c)

(a) Department of Mechanical Engineering and Centre for Intelligent Machines, McGill University, 817 Sherbrooke St. West, Montreal, Quebec, Canada H3A 2K6

(b) CMLabs Simulations, Inc., 420 Notre Dame St. West, Suite 505, Montreal, Quebec, Canada H2Y 1V3

(c) Canadian Space Agency, 6767, route de l'Aéroport, Saint-Hubert, Quebec, Canada J3Y 8Y9

(*) corresponding author, E-mail: jozsef.kovecses@mcgill.ca

Abstract

In this work we investigate the effect of terrain modelling on the performance of planetary rovers, for the evaluation of design concepts under typical rover operation tasks. These tasks include: (1) straight line motion on a flat terrain or climbing a given slope; (2) climbing over a rock with one wheel-set while the other wheels move on flat or inclined terrain. The primary characterization and comparison will be based on performance measures that characterize the vehicle-terrain interaction such as energy expenditure and efficiency. We will use three rover concepts that are either already space-qualified or in the development phase. The analysis is based on implementations in CMLabs' Vortex, a dynamics simulation environment for complex mechanical and mechatronic systems. Vortex can be used to model the contact of wheels under various terrain conditions. We will particularly focus on motion on soft terrain and investigate the physical phenomena exhibited by such terrain and the possibilities to model these with the primary purpose of representing the effects of the terrain on the rover behaviour. We look at the effects of various terrain modelling approaches on the performance of rover concepts, and their applicability and validity for different operating conditions.

1. Introduction

Mobile robotic systems represent key elements for future planetary exploration. Envisioned applications cover many different situations, ranging from small rovers assisting astronauts to large pressurized vehicles transporting humans and cargo. Such mobile robots have to operate on various different types of unstructured terrain. In this study we investigate the dynamics and performance of three existing rover concepts. These are the Dune rover developed at Tohoku University in Japan [1], the Juno rover from Canada [2], and the Rocky rover developed by NASA [3]. The analysis is carried out using CMLabs' Vortex [4], a dynamics simulation environment for complex mechanical and mechatronic systems. Vortex can be used to model the contact of wheels under various terrain conditions, which can have a significant influence on rover performance. In this paper, two semi-empirical terramechanics models developed by Bekker [5, 6] and Wong and Reece [7] are used; their results are then compared. In this paper, Wong's model refers to the model developed by Wong and Reece [7]. These two models have a very broad range of application in characterizing vehicles on soft terrain. Both models have significant application in mobile robotics, as well. For example, in the AESCO Soft Soil Tyre Model (AS²TM), developed by AESCO [8], the Bekker model is used to predict rolling resistance and sinkage. Furthermore, Shibly et al. [9] and Ishigami et al. [1] used the Wong model in their rigid wheel-soil interaction studies. In addition, Wong and Asnani [10] compared the performance of several lunar vehicle wheels by means of the NWVPM software package [6], which uses the Wong model.

2. Description of the Rovers

The Dune rover [1] is a four-wheeled robot with separate drive and active steering for each wheel. Its overall dimensions are 0.68 m in length, 0.44 m in width, and 0.32 m in height, with a total mass of

approximately 35 kg. On each side, the two wheels of the rover are connected to the main body via a rocker suspension. Each rocker is pinned to the main body while the pitch angle of the body is related to the relative position of the rockers via a differential mechanism.

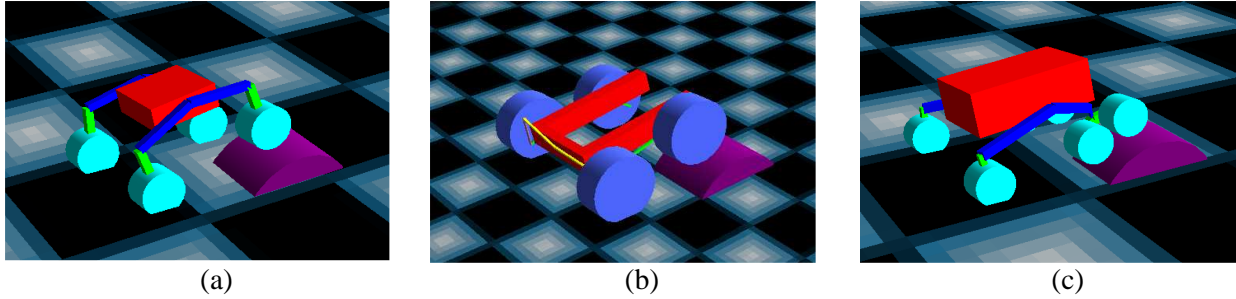


Fig. 1. The three rover models: (a) Dune; (b) Juno; and (c) Rocky

Juno is a four-wheeled rover with a linked walking beam suspension system. It is being developed by Neptec and Ontario Drive Gear (ODG) for the Canadian Space Agency. Juno has two walking beams, which are connected to form the suspension system. This suspension makes the rover capable of adjusting the orientation of its main body while traveling over obstacles. On each side of the rover, two wheels are connected to a walking beam; the wheels are driven using a single DC motor. In addition, Juno uses skid steering. Its overall approximate dimensions are 1.4 m in length, 1.5 m in width, and 0.6 m in height, with a total mass of approximately 190 kg. It is noteworthy that Juno's center of mass is considerably lower than that of the other two rovers.

Rocky 7 was developed by the Jet Propulsion Laboratory as a testbed for Mars rovers [3]. It is the modified version of a space-qualified rover called Sojourner with improved ability of autonomous navigation. Rocky 7 is a six-wheeled rover with a rocker-bogie suspension that has only steering capability at the rear wheels, which gives six actively controlled degrees of freedom for providing system mobility. The overall dimensions of the rover are 0.61 m in length, 0.49 m in width, and 0.31 m in height with total mass of 11.5 kg.

The models in Vortex were generated based on the reference articles and specifications available for the rovers. They were not validated against actual outputs of the physical rover prototypes. Our objective in this study is to compare the design concepts based on multibody models and particularly assess the effects of terrain models. This can provide the designer with reference information and can serve as one element of the overall design and development process of rovers. However, it cannot fully eliminate the need for experimental testing and validation.

3. Application of Terramechanics in Rover Simulation

The relations developed by Bekker [5] or by Wong and Reece [7] can be used with some modifications, to be described presently, when the wheel is moving on a straight line. Ishigami et al. [1] used the semi-empirical relations developed by Wong and Reece [7], by defining the slip ratio as:

$$i_s = \begin{cases} (r\omega - v)/(r\omega) & \text{if } |r\omega| \geq |v| \\ (r\omega - v)/v & \text{if } |r\omega| < |v| \end{cases} \quad (1)$$

where ω is the wheel angular velocity, v is the velocity of the wheel centre, and r is the wheel radius. Therefore, one set of equations can be used for different wheel motion conditions, i.e., accelerating or braking. This simplification is also used in the results included herein. Using Bekker's or Wong's models, normal and shear stress distribution in the wheel-soil contact area can be calculated based on the wheel sinkage and the slip ratio. Then, the soil reactions including motion resistance R_c , traction force F_t , resisting moment T_r , and vertical load F_z can be obtained as:

$$R_c = rb \int_{\theta_2}^{\theta_1} \sigma(\theta) \sin \theta d\theta, \quad F_t = rb \int_{\theta_2}^{\theta_1} \tau(\theta) \cos \theta d\theta \quad (2)$$

$$T_r = r^2 b \int_{\theta_2}^{\theta_1} \tau(\theta) d\theta, \quad F_z = rb \int_{\theta_2}^{\theta_1} [\tau(\theta) \sin \theta + \sigma(\theta) \cos \theta] d\theta - c_z \dot{z} \quad (3)$$

where the meaning of θ , θ_1 , and θ_2 are shown in Fig. 2, and b is the wheel width. By knowing the slip ratio and wheel sinkage, Eqs. (2–3) can be used to define soil reactions. However, F_z in Eq. (3) is modified from its original form by adding a damping term, in which c_z is a damping coefficient and \dot{z} represents the velocity of the wheel normal to the contact plane.

To better understand how these reaction forces and moments are included in Vortex, consider a rigid wheel in contact with soft soil in 2D under the effect of gravity (Fig. 3). W and F_x are external forces applied on the wheel by the vehicle and gravity, and T is the applied external moment on the wheel. The free-body diagram is illustrated in Fig. 3.

When $i_s \neq 0$, F_t and T_r , calculated from Eqs. (2) and (3), respectively, are used in simulation. However, when the wheel is in a rolling condition, i.e. $i_s = 0$, the calculated F_t and T_r are the *maximum* values; the actual values depending on the applied torque on the wheel, due to the nature of this contact, i.e., dry friction.

A simple model of a rigid wheel in contact with soil considers a one-contact point with dry friction, the contact point being the bottom-dead-centre of the wheel (point A in Fig. 3). In addition, R_c should be applied as an external load acting on the wheel centre. In spite of the simplicity of this model, all the effects of wheel-soil contact, calculated by either Bekker's or Wong's models, can be included, except that the resistant torque T_r is approximated by $F_t r$, which means $\cos(\theta)$ is approximated by unity in Eq. (2). In the case of a shallow sinkage, this assumption is reasonable but for higher sinkages, especially when Wong's relations are used, it can cause considerable inaccuracy. For example, for the rigid wheel and soil condition used by Ishigami et al. [1], the error in the T_r calculation for a sinkage of $r/3$ would be 7.5% and 5.0% for Wong's and Bekker's models, respectively. This error is expected to be higher for Wong's model, because the maximum shear stress does not occur when $\theta = 0$, as opposed to the case of Bekker's model.

The above error can be avoided by applying a correction torque in the contact model. When $i_s \neq 0$, T_r is known from Eq. (3), and the correction torque can be readily applied; however, if $i_s = 0$, T_r should be approximated first. When $i_s = 0$, the actual shear stress distribution is not known, and only the maximum shear stress distribution is known from Janosi and Hanamoto equation [6]. Here, it is assumed that the shear stress distribution is scaled linearly in the rolling regime. Therefore, the actual resistant torque T_r' can be calculated from the actual applied traction F_t' :

$$T_r' = \frac{F_t'}{F_t} T_r \quad (4)$$

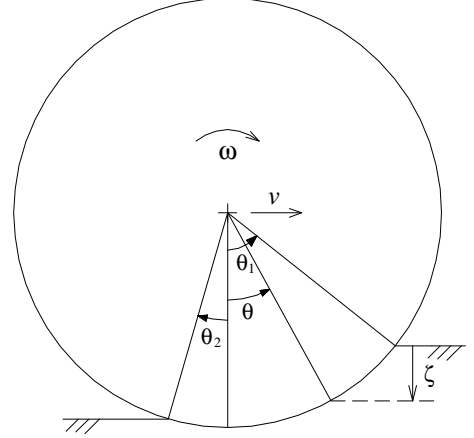


Fig. 2. Schematic of rigid wheel-soil contact

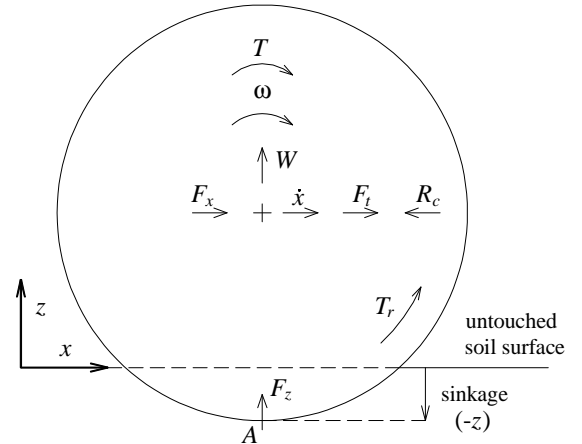


Fig. 3. Free-body diagram of the rigid wheel in contact with soil

The rigid wheel and soil condition used in [1] is simulated in Vortex. The wheel is placed on the soil with zero initial velocity and a vertical applied load of 100 N. Then, a torque is applied to the wheel with a trapezoidal profile with: ramp to 7 Nm over 1 s, hold for one second, and ramp down to 0 Nm over 1 s. For this case, the total distance travelled by the wheel, with and without applying correction to the resistant torque, is 8.2 m and 11.2 m, respectively.

4. Effects of the Terramechanics Models in Rover Simulation

The rovers are simulated in Vortex, with both the Bekker and the Wong models, for soil properties similar to those reported in [1]. The rovers were commanded for straight-line motion in velocity-control mode, where the angular speeds of the driving wheels are directly controlled. The velocity command has a trapezoidal profile with: ramp to 0.5 m/s over 4 s, hold for 10 s, and ramp down to 0m/s over 2 s. The computed velocity profiles for the Dune over using Bekker's and Wong's models are displayed in Fig. 4, along with the command velocity profile, which represents the no-slip condition. In addition, the slip ratio of the right front wheel of the Dune rover is displayed in Fig. 5. As can be seen from Figs. 4 and 5, the simulation results using these two models are very different; Bekker's model predicts considerably lower slip ratio than Wong's model. In addition, the total distance that the rover could travel using Wong's and Bekker's models is 3.94 m and 5.39 m, respectively, on horizontal, flat ground. However, in a 5° slope, the rover could move only about 1.87 m, when Wong's model was used, but with Bekker's model, it could travel about 4.42 m on the slope.

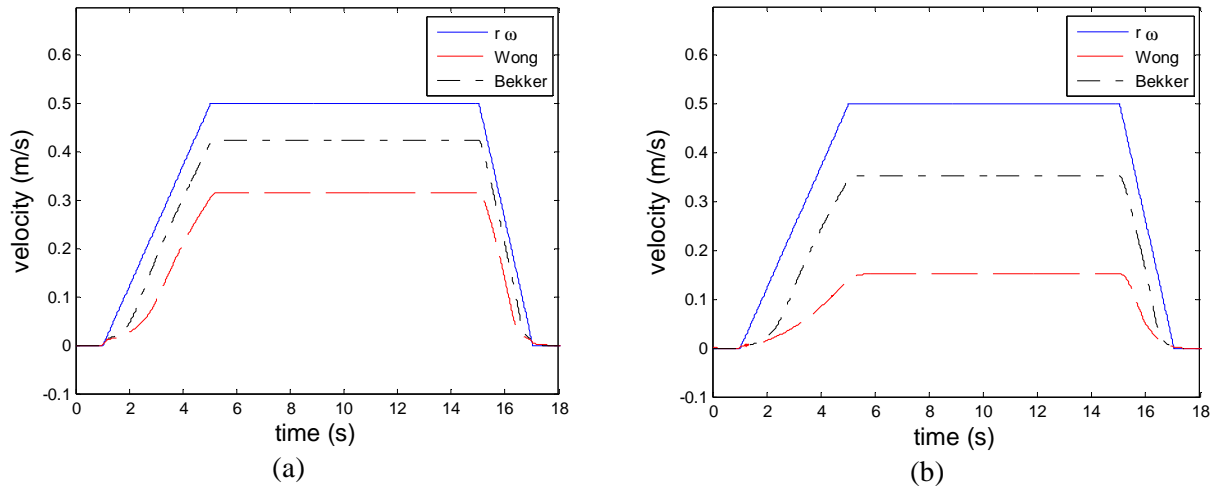


Fig. 4. Commanded velocity profile “ $r\omega$ ” and the actual velocities for the Dune rover computed using Wong’s and Bekker’s soft soil models on (a) horizontal terrain; and (b) a 5° slope

Furthermore, a typical task for rovers consists in climbing over an obstacle with one wheel-set while the wheels on other side of the rover move on flat terrain or up an incline. This arrangement is shown in Fig. 1. In addition, the energy usage for rovers when moving on flat terrain or moving up a slope, is an important factor in off-road rover design. As described above, the dimensions and mass of the three rovers are quite different. Therefore, in order to find means of comparison between these rovers, the obstacle is scaled based on the length of the rovers. In addition, energy usage is scaled based on the total rover weight and travelled distance, which provides a kind of efficiency factor of the rover in performing that particular task. In this context, a so-called *energy coefficient* is defined as the total energy required for a particular manoeuvre per rover weight per total travelled distance.

Table 1 shows the total energy needed for the three prototypes to perform the manoeuvre for ground slopes of 0° and 5°, with and without an obstacle. It is also worth noting that Table 1 shows net energy values, under the assumption that the rovers recover energy on the backside of the obstacle. It can be

concluded from Table 1 that Juno has the least energy coefficient and is expected to perform better than the other rovers based on both Bekker's and Wong's models.

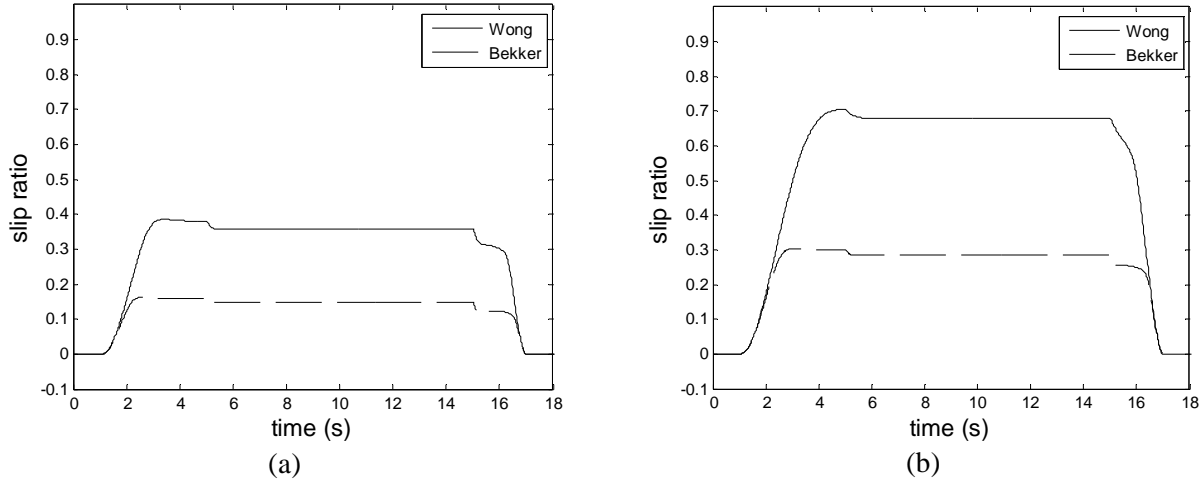


Fig. 5. Slip ratio of the right front wheel of the Dune rover calculated using Wong's and Bekker's soft soil models on (a) horizontal terrain; and (b) a 5° slope

Table 1. Energy expenditure per rover weight per total travelled distance (energy coefficient) using both Wong's and Bekker's models

Rovers	Bekker Horizontal no obstacle	Bekker Horizontal with obstacle	Bekker 5° Slope no obstacle	Bekker 5° Slope with obstacle	Wong Horizontal no obstacle	Wong Horizontal with obstacle	Wong 5° Slope no obstacle	Wong 5° Slope with obstacle
Dune	0.292	0.302	0.478	0.478	0.588	0.571	1.529	1.342
Juno	0.155	0.156	0.259	0.259	0.232	0.229	0.350	0.341
Rocky 7	0.275	0.278	0.525	0.514	0.628	0.597	2.082	1.644

The total distances that the rovers could travel in different cases are reported in Table 2. As expected, Juno has the maximum travelled distance, which means it has less slippage. In addition, in climbing the slope, the difference compared to the other two rovers is even higher, because Juno's centre of mass is considerably lower than that of the other two rovers.

Table 2. Total travelled distances for different cases using both Wong's and Bekker's models

Rovers	Bekker Horizontal no obstacle	Bekker Horizontal with obstacle	Bekker 5° Slope no obstacle	Bekker 5° Slope with obstacle	Wong Horizontal no obstacle	Wong Horizontal with obstacle	Wong 5° Slope no obstacle	Wong 5° Slope with obstacle
Dune	5.39 m	5.33 m	4.42 m	4.43 m	3.94 m	4.02 m	1.87 m	2.10 m
Juno	6.29 m	6.19 m	5.90 m	5.84 m	6.08 m	6.00 m	5.59 m	5.59 m
Rocky 7	4.74 m	4.76 m	3.49 m	3.59 m	3.16 m	3.31 m	1.22 m	1.54 m

Another set of tests was conducted to determine the maximum incline the rovers can handle for the given task. The results are shown in Table 3. As expected, Juno performed the best.

It should be noted that the soft soil parameters used in this study are based on what is reported in [1], and the actual parameters might be different for the wheels used in Juno and Rocky 7, because their wheels have different dimensions from those of the wheels used in the Dune rover. In addition, as mentioned in the AS²TM manual [8], the rolling resistant force predicted by Bekker's model should be

increased, especially when used for sand, for which a factor of 1.68 is proposed therein. Furthermore, the multi-pass effect is not included in the simulation, yet. However, these models provide estimates of a typical rover performance and a means for comparison of different rovers.

Table 3. Maximum possible incline

Rovers	max. incline without obstacle (Bekker)	max. incline with obstacle (Bekker)	max. incline without obstacle (Wong)	max. incline with obstacle (Wong)
Dune	16°	13°	8°	7°
Juno	25°	16°	21°	15°
Rocky 7	13°	12°	7°	7°

5. Conclusions

In this work, we described elements of dynamics performance evaluation and comparison of mechanical designs of planetary rovers. Two widely used terramechanics models were implemented in a multibody dynamics simulator environment, Vortex. Three rover concepts were investigated based on these models for operations on dry sand. The two terramechanics models gave very different results. This clearly emphasizes the need for further validation of these models and the necessity of developing more accurate representations. In terms of performance, Juno gave the best results on dry sand, mainly because of its larger wheels. However, overall it is difficult to draw any conclusion about the superiority of one design over the other. This depends on the particular intended application, which can lead to special emphasis on a specific performance criterion. Our results can serve as one element to support design decisions. It is recommended to perform the analyses using both typical terramechanics models due to the large deviations observed in the results produced by the two models. Further validation and improvement of the terramechanics models are necessary.

References

- [1] G. Ishigami, A. Miwa, K. Nagatani, K. Yoshida: Terramechanics-Based Model for Steering Maneuver of Planetary Exploration Rovers on Loose Soil, *J. Field Robotics*, Vol. 24, No. 3, pp. 233–250, 2007.
- [2] B. Jones, P. Visscher, D. Boucher, P. Radziszewski, M. Faragalli, S. Spenser, and D. Apostolopoulos: The Juno Rover: An Extraction Vehicle for In-Situ Resource Utilization, Submitted to *15th CASI Astronautics Conference ASTRO 2010*, Toronto, ON, May 4–6, 2010.
- [3] R. Volpe, J. Balam, T. Ohm. R. Ivlev: The Rocky 7 Mars Rover Prototype, *1996 IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, pp. 1558–1564, Osaka, Japan, Nov. 4–8, 1996.
- [4] http://www.vxsim.com/en/software/vortex_core/index.php
- [5] M.G. Bekker: *Introduction to Terrain-Vehicle Systems*, Ann Arbor, The University of Michigan Press, 1969.
- [6] J.Y. Wong: *Terramechanics and Off-Road Vehicle Engineering: Terrain Behaviour, Off-Road Vehicle Performance and Design*, second edn, Elsevier, 2010.
- [7] J.Y. Wong and A.R. Reece: Prediction of Rigid Wheel Performance Based on the Analysis of Soil-wheel Stresses Part I. Performance of Driven Rigid Wheels, *J. Terramechanics*, Vol. 4, No. 1, 81–98, 1967.
- [8] AESCO: Matlab/Simulink Module AS²TM User’s Guide, 2005.
- [9] H. Shibly, K. Iagnemma, S. Dubowsky: An Equivalent Soil Mechanics Formulation for Rigid Wheels in Deformable Terrain With Application to Planetary Exploration Rovers, *J. Terramechanics*, Vol. 42, pp. 1–13, 2005.
- [10] J.Y. Wong and V. Asnani: Study of the Correlation Between the Performances of Lunar Vehicle Wheels Predicted by the Nepean Wheeled Vehicle Performance Model and Test Data, *Proceedings of the Institution of Mechanical Engineers, Part D (J. Automobile Engineering)*, Vol. 222(D11), pp. 1939–54, 2008.