Can. Aeronaut. Space J., Vol. 57, No. 1, pp. 65–74, 2011

A Parametric study and experimental testing of lunar-wheel suspension on dynamic terrainability

M. Faragalli, D. Pasini, and P. Radziszewski

Abstract. The development of a flexible metallic wheel proved to be one of the most challenging and time-consuming aspects of the Lunar Roving Vehicle of the Apollo missions (V. Asnani, D. Delap, and C. Creager. 2009. *Journal of Terramechanics*, 46: 89 103). The design was realized through an iterative trial and error design process, driven primarily by manufacturability and physical testing. Although the wire-mesh-compliant wheel design was identified as the best choice for the Lunar Roving Vehicle, mission scenarios have evolved and future lunar vehicles are bound to have to meet different functional requirements and more severe life and operational constraints. For example, these vehicles will have to travel farther on the lunar surface, explore permanently shadowed craters, and perform a variety of tasks such as transporting sensitive payloads and excavatiing regolith, and allow for both unmanned and manned operation. This work focuses on optimizing the suspension design parameters of a flexible, compliant wheel for maximizing the dynamic terrainability performance of a lunar rover. The suspension design parameters are identified, independently of the explicit wheel configuration. The terrainability of the rover is defined here as the rover's ability to negotiate terrain irregularities. Terrainability is quantified by the objective functions describing road holding and rider comfort. These objective functions ensure that the rover payload is isolated from vehicle terrain-induced vibrations, and that the wheels maintain ground contact during higher speed traversals. A simplified vehicle model is used for the dynamics analysis of the terrain vehicle system with the terrain modeled as a random stationary ergodic process characterized by a power spectral density function. A sensitivity analysis is performed to identify conflicting objectives, and a recommendation on optimal wheel suspension design variables is made. Finally, experimental testing of reduced-scale wheels with different suspension properties is conducted on three irregular terrain types and results confirm the theoretical predictions. Ultimately, the results of this research will be used in a system-level analysis of the wheel design parameters on vehicle performance to guide the structural optimization of the compliant wheel for lunar surface exploration vehicles.

Résumé. Le développement d'une roue en métal flexible s'est avéré l'un des aspects les plus problématiques et onéreux en termes de temps lors du développement du Lunar Roving Vehicle pour les missions d'Apollo (V. Asnani, D. Delap, and C. Creager. 2009. *Journal of Terramechanics*, 46: 89 103). Le concept a été réalisé au moyen d'une procédure itérative de conception basée sur des essais et des erreurs développée principalement à partir de tests de fabricabilité et physiques. Bien que le concept de roue souple fabriquée d'un treillis métallique ait été identifié comme étant le meilleur choix pour le « Lunar Roving Vehicle », les scénarios des missions ont évolué et les véhicules lunaires futurs devraient vraisemblablement remplir des besoins fonctionnels différents et affronter des contraintes de vie et opérationnelles plus sévères. Par exemple, ces véhicules devront se déplacer sur de plus grandes distances à la surface de la Lune, explorer des cratères ombragés de façon permanente et accomplir une diversité de tâches comme le transport de charges sensibles, l'excavation du régolite et permettre la réalisation de maneuvres avec ou sans pilote. Ce travail vise à optimiser les paramètres de la suspension d'une roue souple flexible dans le but d'optimiser la performance dynamique de la capacité d'un astromobile (rover) lunaire à surmonter les obstacles. Les paramètres de la suspension sont identifiés indépendamment de la configuration explicite de la roue. La capacité à surmonter les obstacles de l'astromobile est définie ici en termes de sa capacité à négocier les irrégularités du terrain, celle-ci étant quantifiée par l'intermédiaire de fonctions objectives reliées à la tenue de route et au confort du passager. Ces fonctions objectives s'assurent que la charge utile de l'astromobile est isolée des vibrations induites par le véhicule et le terrain et que les roues gardent contact avec le sol durant les trajets à plus grande vitesse. Un modèle simplifié du véhicule est utilisé pour l'analyse dynamique du système véhicule-terrain, le terrain étant modélisé comme une procédure ergodique aléatoire stationnaire caractérisée par une fonction de densité spectrale de puissance. Une analyse de sensibilité est réalisée pour identifier les objectifs conflictuels et on fait une recommandation quant aux variables optimales du concept de système de suspension des roues. Enfin, des essais expérimentaux de roues à échelle réduite présentant différentes caractéristiques au niveau de la suspension sont menés sur trois types de terrain irrégulier et les résultats confirment les prédictions théoriques. Ultimement, les résultats de cette recherche seront utilisés dans le contexte d'une analyse au niveau du système des

Received 4 January 2011. Accepted 23 March 2011. Published on the Web at http://pubs.casi.ca/journal/casj on 18 November 2011.

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paramètres du concept de la roue sur la performance du véhicule afin d'orienter l'optimisation structurelle de la roue souple pour les véhicules d'exploration de la surface lunaire.
[Traduit par la Rédaction]

Introduction

Manned and robotic surface vehicles will facilitate scientific, exploratory, and even economic development of the Moon by scouting for resources, performing geological surveying, transporting astronauts, and mining the Moon for resource production and utilization (Eckart, 1999). Unlike the Lunar Roving Vehicle and Lunakhod, which operated for short periods in the harsh lunar environment (Asnani et al., 2009), future lunar vehicles will be required to perform a wide variety of tasks over the course of lunar-infrastructure development. As lunar development extends towards a permanent human presence, vehicles must be adaptable, robust, and reliable. The vehicles will be required to dig, push, and carry regolith, climb steep craters and hills, negotiate irregular and unknown terrains, and drive through soft, unconsolidated soil for long distances. To design an appropriate mobility system for completing a number of mission scenarios, the performance requirements of the vehicles must be known.

Mobility performance of a surface-exploration vehicle

In the existing literature, the performance requirements of lunar surface vehicles are not clearly outlined. Although a classification of performance indices is provided in Apostolopoulos (2001), the focus is on robotic vehicles for which vehicle terrain dynamics is omitted. An extension of the work in Apostolopoulos (2001) to include the dynamic effects of the off-road vehicle terrain interaction encountered on the Moon is necessary. A preliminary revised classification of the performance indices introduced in Apostolopoulos (2001) is provided here.

- *Trafficability*: The ability to traverse soft soils or hard ground without loss of traction, as well as the ability to perform work (such as pulling, pushing, or excavating)
- *Manoeuvrability*: The ability to navigate efficiently through an environment
- *Terrainability* (static and dynamic): The ability to negotiate terrain irregularities while maintaining stability and isolating the vehicle chassis and payload from the vehicle terrain dynamics
- *Reliability*: The ability to perform and maintain the vehicle's required functions in routine and unexpected circumstances for a specified life cycle

As the wheel provides the vehicle terrain interface, the wheel interacts with the lunar regolith, therefore the effect of wheel design variables on the above performance metrics is of particular interest in this parametric study. To use the existing multidiscplinary models (Ben Amar et al., 1997; Apostolopoulos, 2001) to quantify the effect of wheel designs on vehicle performance, a set of system-level wheel design variables is identified. These system variables describe the flexible wheels independently of the explicit structural configuration. Component-level design variables are used to describe explicit wheel structural elements such as the thickness or contour of tire carcasses in pneumatic tires or the number or thickness of spokes in bicycle wheels. The differentiation between design-variable classes will be of importance when formulating the wheel-design problem using structural multiobjective optimization (MOO) theory. Formulating the component optimization of explicit wheel configurations as a structural MOO will allow the designer to meet the required vehicle performance from the system-level analysis. Further investigation of the effects of system-design variables on trafficability and maneuverability of the vehicle is described here (Faragalli et al., 2010), but the reliability aspects of wheel performance will be addressed in future work as they cannot be quantified independently of wheel configurations. The focus of the work presented here is to quantify the performance effect of the wheel suspension design parameters on the dynamic terrainability of a lunar vehicle.

In this work, a simplified quarter-car model is used to simulate the response of the vehicle suspension system to excitation from forward velocity over irregular terrain. The terrain is assumed to follow a random stationary ergodic process, and is modeled by a power spectral density function as the input to the vehicle model. A sensitivity analysis of the wheel design parameters on dynamic terrainability is performed, and recommendations concerning parameters for optimal lunar wheel suspension design are provided. Finally, reduced-scale wheels with different suspension properties were tested on three irregular terrain types and the results confirm the theoretical predictions. The results presented here will contribute to future research on multiobjective design optimization of compliant lunar wheels.

Simplified vehicle dynamics models

Vehicle suspension systems and their role in off-road performance have been studied in considerable detail (Ben Amar et al., 1997; Wong, 2008), together with the optimization of the suspension system design parameters for improved rider comfort and road handling (Gobbi and Mastinu, 2001; Verros et al., 2005; Uys et al., 2006). Furthermore, the relationship between vehicle performance and pneumatic-tire and wheel designs has been studied extensively for road mobility and some work has been conducted in determining the relationship between tire and vehicle suspension design parameters and off-road mobility performance (Raper et al., 1995; Li and Sandu, 2007). In the literature, however, nothing has been found on optimizing non-pneumatic, non-rubber compliant wheels for extraterrestrial or off-road mobility.

To satisfy the terrainability requirements of the compliant wheel, a dynamics model of the terrain vehicle interaction is necessary. This model will couple the performance indices of dynamic terrainability with the wheel and vehicle suspension design parameters and terrain model. A simplified model of the vehicle and wheel is used here to analyze the response of the vehicle when traveling at a constant speed over irregular terrain. This model is named the quarter-car model and its use is reported extensively in the literature (Gobbi and Mastinu 2001; Verros et al., 2005; Li and Sandu, 2007) for analyzing vehicle response and optimizing the suspension-system parameters. Models of higher fidelity, such as full three-dimensional car models (Uys et al., 2006), are not employed at this stage of wheel optimization, owing to the added complexity of terrain modeling and lack of detailed design of the vehicle and wheel. High fidelity dynamics models will be utilized when vehicles and wheels can be modeled accurately and when precise performance predictions are preferred over an analytical approach to determining optimal wheel suspension design parameters.

As the name suggests, the quarter-car model represents one-quarter of a four-wheeled vehicle. The model is illustrated in **Figure 1**, where m_1 represents the unsprung mass, typically the wheel and wheel assembly, and m_2 represents one-quarter of the sprung mass or the mass of the vehicle, k_1 and C represent the suspension system spring stiffness and damping coefficients, respectively, and k_2 represents wheel stiffness. In road vehicles, pneumatic tires have minimal damping, primarily caused by the hysteresis in the rubber in comparison with the vehicle's shock absorbers, thus they are typically neglected in ground vehicle analysis (Wong, 2008). However, owing to the large temperature fluctuations and possible dust infiltration, fluid-based shock absorbers for lunar vehicles are ineffective. Thus,

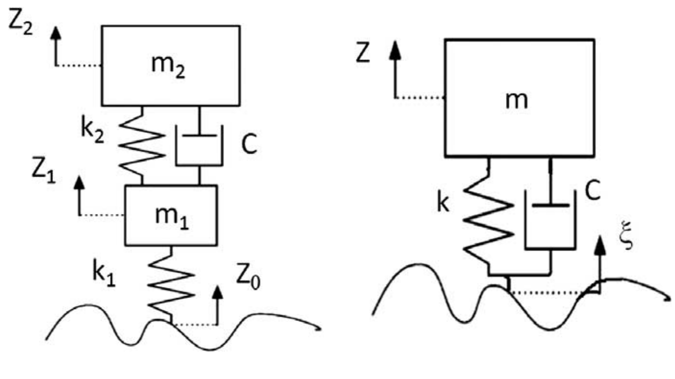

Figure 1. (*a*) Quarter-car model with explicit suspension system. (*b*) Quarter-car model without explicit suspension system.

the damping characteristics of the compliant wheels will be significant in the vehicle's suspension performance. Additionally, traditional coil springs for the suspension system may prove inefficient for use in the low-gravity environment, where the mass of the rover will likely fluctuate significantly between missions. Therefore, the case for a lunar vehicle with no explicit sprung suspension is illustrated in **Figure 1b**, where the spring and damper k_1 and C can be ignored and the quarter of the vehicle mass, m_2, can be combined with the wheel-assembly mass, m_1.

The single degree of freedom (DoF) spring mass damper system shown in **Figure 1b** is used to model the behavior of compliant lunar wheels mounted directly onto the vehicle chassis. The excitation of the system is caused by the constant forward velocity (v) of the vehicle and the surface elevation profile (ξ). The equation of motion for the single DoF system is shown in Equation 1.

$$m\ddot{Z} + C\dot{Z} + k(Z - \xi) = 0 \tag{1}$$

Vehicle-suspension performance is typically described by rider comfort, road handling, and suspension travel (Gobbi and Mastinu, 2001; Wong, 2008). These performance indices are described, in the quarter-car model, by the vehicle's vertical acceleration ($\ddot{Z}$) and the normal force acting on the ground (F_Z). In the case of a vehicle without an explicit sprung suspension system, suspension travel is restricted to the wheel deflection. The wheel deflection can be derived from the normal force acting on the ground with known linear spring stiffness.

According to Gobbi and Mastinu (2001) and Gobbi et al. (2006), both ride comfort and road-holding performance are computed by finding the standard deviation of the vertical acceleration of the wheel ($\ddot{Z}$) and the wheel's radial force (F_Z). For ride comfort, the higher the standard deviation, the greater the discomfort. Similarly, for road holding, a higher standard deviation of the wheel's radial force will lead to poor handling ability because of loss of contact with the ground. Therefore, both standard deviations must be minimized to improve performance.

From Equation 1, the transfer function of the imposed displacement from the ground ($\xi(j\omega)$) to the vertical acceleration of the wheel is found in Equation 2.

$$H_1(j\omega) = \frac{\ddot{Z}(j\omega)}{\xi(j\omega)} = \frac{-\omega^2 k}{m(j\omega)^2 + C(j\omega) + k} \tag{2}$$

Similarly, the transfer function of the imposed displacement from the ground ($\xi(j\omega)$) to the wheel's radial force is found in Equation 3.

$$H_2(j\omega) = \frac{Fz}{\xi(j\omega)} = \frac{-m\omega^2 k + (j\omega)k}{m(j\omega)^2 + C(j\omega) + k} \tag{3}$$

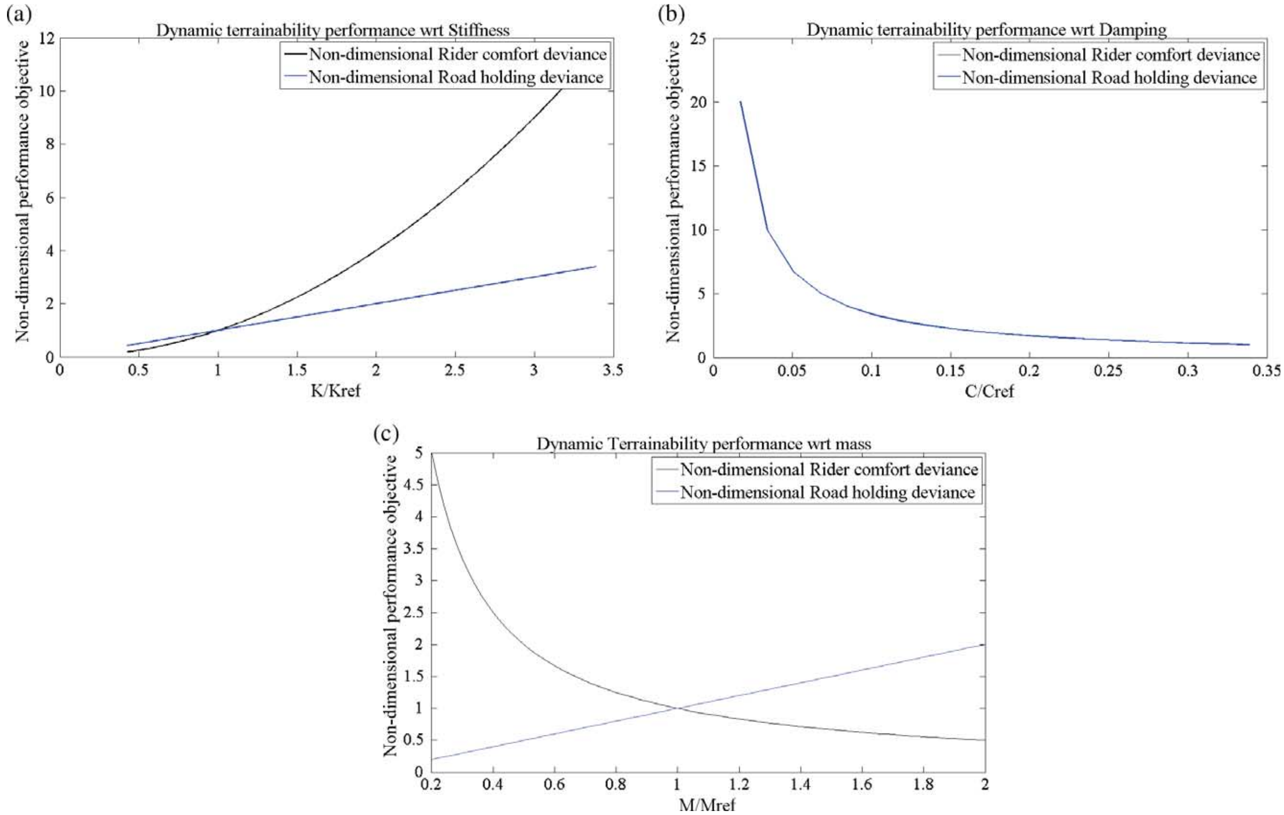

Figure 2. Effect of wheel parameters on ride comfort and road-holding performance with respect to (a) stiffness, (b) damping, and (c) mass.

Terrain model

The imposed displacement, or road irregularity, can be represented by a random variable defined by a stationary and ergodic stochastic process with zero mean value (Wong, 2008; Yong and Eiyo, 1990). The formulation of the power spectral density (PSD) of the process is represented in Equation 4. The values used in the PSD function are based on experimental measurements, where G_0 is the roughness constant (m^2/(cycles/m)), v is vehicle velocity (m/s), N is the slope constant, and ω is the circular frequency (rad/s). More complex representations of the PSD provide a better correlation with measured spectra from road surfaces, but can only provide analytical solutions.

$$S_{\xi} = \frac{G_o}{v^{N-1}\omega^N} \tag{4}$$

Although a PSD model of the lunar terrain in the form shown in Equation (4) has not been found in the literature, the assumption is that the terrain is considered "very poor" (road Class E) according to the ISO classification of road surfaces (Wong, 2008). The values used in Equation 4 are found in **Table 1**. It should be noted that the terrain is modeled as non-deformable, which is not the case for lunar soil. More complex terrain modeling would be required to accurately model the regolith particle interaction and terrain deformation.

Analysis of design-parameter sensitivity

Response model

The PSD (S_l) of the output of an asymptotically stable system can be computed as in Equation 5.

$$S_i(\omega) = |H_i(j\omega)|^2 S_{\xi}(\omega) \quad \text{with } l = 1, 2 \tag{5}$$

Note that for $l = 1$, S_1 represents the PSD output of the vertical acceleration, and for $l = 2$, S_2 represents the PSD output of the wheel's radial force. By definition, the variance

Table 1. Design variables for analysis.

Design parameter	Reference value	Lower upper bound
Wheel stiffness	5 kN/m	1–20 kN/m
Wheel-damping coefficient	1 kN.s/m	0.5–2 kN.s/m
Quarter-vehicle mass	50 kg	25–100 kg
Vehicle speed	5 km/h	N/A
Surface-roughness constant	7×10^{5} m^2/(cycles/m)	N/A

of a random variable described by a stationary ergodic process is found in Equation 6.

$$\sigma_l^2 = \frac{1}{2\pi}\int_{-\infty}^{+\infty} S_l(\omega)\,\mathrm{d}\omega = \frac{1}{2\pi}\int_{-\infty}^{+\infty} |H_l(j\omega)|^2 S_\xi(\omega)\,\mathrm{d}\omega \qquad (6)$$

For the case where $l = 1$ and $N = 2$, Equation 6 becomes Equation 7.

$$\sigma_1^2 = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \left|\frac{-\omega^2 k}{m(j\omega)^2 + C(j\omega) + k}\right|^2 \left(\frac{G_0}{\omega^2 \nu}\right)\mathrm{d}\omega \qquad (7)$$

Similarly, when $l = 2$ and $N = 2$, Equation 6 becomes Equation 8.

$$\sigma_2^2 = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \left|\frac{m\omega^2 k - (j\omega)C + k - k^2}{-m(j\omega)^3 - C\omega^2 + k(j\omega)}\right|^2 \left(\frac{G_0}{\omega^2 \nu}\right)\mathrm{d}\omega \qquad (8)$$

As shown in Pierce and Foster (1956), analytical solutions to the integral are possible if it is in the form of Equation 9.

$$H(j\omega) = \frac{j\omega B_1 + B_0}{-\omega^2 A_2 + j\omega A_1 + A_0}$$
$$\int_{-\infty}^{+\infty} |H(j\omega)|^2 \mathrm{d}\omega = \pi\left[\frac{(B_0^2/A_0)A_2 + B_1^2}{A_1 A_2}\right] \qquad (9)$$

Manipulating Equations 7 and 8 to resemble the format of Equation 9, the variance of both ride comfort and road holding are found analytically in Equations 10 and 11.

$$\sigma_1^2 = \frac{G_0 K^2}{2mCv} \qquad (10)$$

$$\sigma_2^2 = \frac{G_0(C^2 + 3mk - 2mk^2)}{Ckv} \qquad (11)$$

Parameter sensitivity analysis

A sensitivity analysis was completed to verify whether any parameters conflict in minimizing the variance of rider comfort and road handling. **Table 1** shows the reference values and ranges for each design parameter. The reference values were selected as being relevant to an existing lunar-rover prototype developed by the Neptec Design Group and called *Juno* (Jones et al., 2010). *Juno* has a total mass of roughly 200 kg without payload, and uses 24 in. diameter (1 in. = 2.54 cm) rubber all-terrain vehicle wheels. Under static load, the deflection of the wheel was measured as approximately 1 in. with a nominal tire inflation pressure of 5 psi (1 psi = ca. 6.895 kPa), which yields an estimate of static stiffness of 19.3 kN/m. Note that the appropriate wheel stiffness used in the analysis is the dynamic rolling stiffness and can be up to 26% lower than the static wheel stiffness (Wong, 2008). The dynamic rolling stiffness of *Juno*'s tires is unknown. The damping-coefficient range used was of the order of magnitude of the road vehicle wheels found in Wong (2008), as the damping coefficient of *Juno*'s rubber tires is unknown. Ultimately, the non-rubber, non-pneumatic compliant wheel will replace the current rubber wheels, therefore it is assumed that the rubber wheel suspension parameters are of an appropriate order of magnitude to conduct this analysis.

Each parameter was varied to verify the change in response of the system with respect to the reference value. The non-dimensional performance σ_l^2/σ_R^2, where subscript l is defined as in Equation 5, is plotted against the non-dimensional stiffness (k/k_R), the non-dimensional damping coefficient (C/C_R), and the non-dimensional mass (m/m_R) in **Figure 2a, 2b, and 2c**, respectively.

From **Figure 2**, it can be seen that

- decreasing stiffness improves both rider comfort and road handling
- increasing damping improves both rider comfort and road handling
- increasing mass improves rider comfort, and
- decreasing mass improves road handling

Furthermore, speed and surface roughness cancel out in the computation of the non-dimensional performance value. This signifies that although speed and surface roughness do affect the response of the system, their magnitude does not change the direction of the wheel design parameter's improvement of dynamic terrainability performance.

Optimal design parameters

For both wheel stiffness and damping, there are no conflicts in improving rider comfort and road handling. Hence, minimizing dynamic rolling stiffness and maximizing damping will allow improved dynamic terrainability performance.

Theoretically, there are no constraints on wheel-damping coefficients in the dynamics analysis. In practice, however, a wheel with large damping will lead to low rolling and turning efficiency, as in an under-inflated tire (Wong, 2008). In a multidisciplinary analysis of vehicle performance, a wheel with high damping is not optimal when the power requirements of the vehicle are considered (Yong and Eiyo, 1990). Nonetheless, only dynamic terrainability objectives are considered here, so the maximum damping achievable by a compliant wheel design is desired. Further investigation of the effect of wheel-design variables on multidisciplinary mobility performance objectives is reported here (Faragalli et al., 2010).

Wheel stiffness is also constrained physically; under the applied load, wheel deflection cannot exceed the allowable wheel deformation, which is the distance between the outer wheel surface and the outer rigid portion of the hub. Statically, the constraint on stiffness results in Equation 12, derived from Hooke's law, where W is 1/4 of the vehicle weight, FS is a safety factor to allow variable static loading on the wheel, R_w is the wheel radius, and R_h is the wheel-hub radius.

$$k_{static} > \frac{(W/4)}{R_w - R_h} FS \tag{12}$$

The dynamic rolling stiffness is typically 10%–15% lower than the static stiffness in passenger road vehicles and up to 26% lower in tractor tires (Wong, 2008). This relationship between static and dynamic rolling stiffness greatly depends on wheel design and must be addressed at the component level. To ensure that dynamic loading does not cause the wheel to lift off, or the wheel to deform to the hub, the normal load on the wheel must be greater than zero. Equation 13 describes the upper and lower bounds on wheel deformation:

$$R_h < (Z - \xi) < (R_w + R_h) \tag{13}$$

To satisfy Equation 12 for the *Juno* rover with a baseline mass of 200 kg, safety factor of 2, wheel diameter of 24 in, and hub diameter of 11 in., the static stiffness of the wheels must be greater than 0.98 kN/m for the Moon and 5.9 kN/m for the Earth. The lowest allowable dynamic rolling stiffness used in **Table 1** is estimated here as 5.9 kN/m, to achieve optimal dynamic terrainability performance. Like high damping coefficients, however, low stiffness will also result in poor rolling efficiency and lateral deformation during maneuvers. Therefore, the multidisciplinary performance of wheel stiffness must be verified in future work.

The quarter-vehicle mass, unlike stiffness and damping, has the opposite effect on rider comfort and road holding. **Figure 3** illustrates the relationship between the two non-dimensional dynamic terrainability objectives, with stiffness and damping at their optimal values.

From **Figure 3** it is evident that there exists no optimal mass to minimize both objective functions. Prioritization of rider comfort and road handling is required to find a trade-off solution for the mass of the system. In this case, a weighting function combining the two objective functions is used to solve the optimization problem.

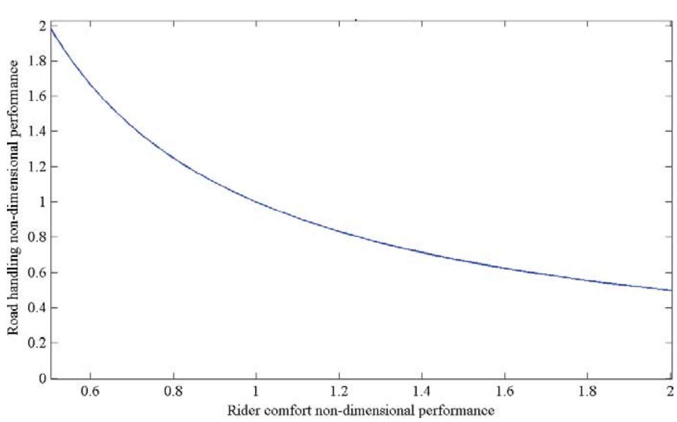

Figure 3. Relationship between rider comfort and road-handling performance with respect to varying mass.

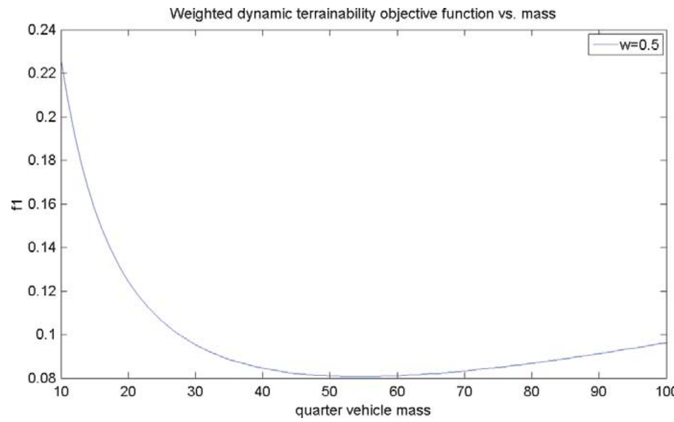

Figure 4. Weighted dynamic terrainability objective function response to variation in mass.

$$\min f(m) = w\sigma_1^2 + (1 - w)\sigma_2^2 \tag{14}$$

For the case where the two objectives are of equal importance ($w = 0.5$) and optimal stiffness and damping values are used, a mass of 54 kg yields the best trade-off between rider comfort and road handling for the parameters given in **Table 1**, as can be seen in **Figure 4**.

Physical testing

To confirm the predictions made in the previous section, wheels of different suspension properties were manufactured. Although the explicit configuration designs of the wheels are significantly different, only the suspension-design parameters of the wheel are considered in the comparative analysis. **Figure 5** illustrates the two separate wheel designs: iRings wheels and rubber wheels.

A set of four 8 in. diameter particulate-filler chain-mail tires, dubbed iRings wheels, were built to fit a remotely controlled all-terrain vehicle. The iRings wheel, developed at McGill University, is a novel type of compliant wheel that deforms plastically. This deformation mechanism allows

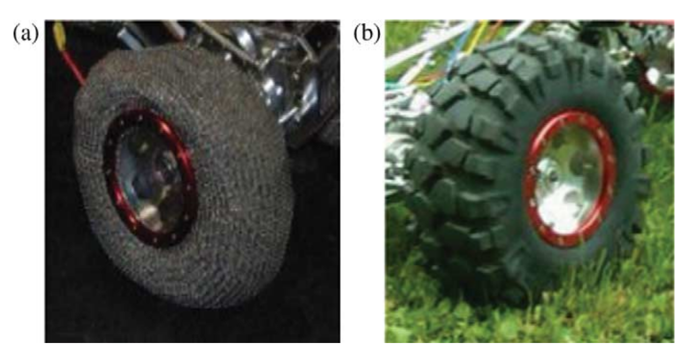

Figure 5. Reduced-scale wheel prototypes. (a) The iRings wheel. (b) The rubber wheel.

Table 2. Design variables for analysis.

Wheel type	Stiffness (N/m)	Damping coefficient (kN s/m)	Mass (kg)
iRings	5710	194.5	3.62
Rubber	1540	15.8	0.91

the wheel to conform easily to surface irregularities and provide some shock-absorption characteristics to the wheel. The downside to this design includes higher rolling resistance and increased wheel mass. A more detailed description of this wheel design is available in Radziszewski et al. (2010).

The suspension properties of the iRings and benchmark rubber wheels were characterized by means of a standard drop test (Wong, 2008) for which the properties are shown in **Table 2**. Although iRings wheels deform primarily through plastic deformation, some elasticity was seen in the drop test.

It was found that although the iRings wheels are qualitatively extremely flexible, the tire does have a low elastic deformation once the particles have rearranged themselves under the applied load. Thus, the iRings wheels are stiffer than the benchmark rubber wheels, yet have a higher damping coefficient by an order of magnitude.

The wheels were tested repeatedly over three terrain types: grass, soft sand, and hard sand/gravel (**Figure 6**).

An accelerometer was mounted vertically on the axel between the two rear wheels to measure the vertical acceleration of the unsprung mass. This allowed evaluation of the rider-comfort metric for the various wheels in different terrain and speed conditions. Road-holding ability was not measured, as it required a more complex system that was unavailable at the time of testing. This will be investigated in future work.

Terrain 1 results

The vehicle was driven over a 10 m distance four times using both sets of wheels. A summary of the results for terrain 1 is shown in **Table 3**. It should be noted that the speed was controlled by the user through a joystick and so it varied throughout the test. The speeds tabulated represent the average velocity over the 10 m distance.

Although the average speed varied among the tests, the iRings wheels demonstrated a reduction in the standard deviation of vertical acceleration, which is the rider-comfort metric. This is clear from a comparison of tests 3 and 8, where the rider-comfort value is improved by 12% for iRings wheels. Furthermore, the shock acceleration seen is also reduced significantly, by up to 30%, as can be seen from the peak acceleration results. **Figure 7** illustrates the improvement in rider comfort, with the results plotted against the average rover speed. An increase in speed causes an increase in vertical acceleration. This dictates that at higher speeds, higher wheel damping is useful for reducing the transmission of vibrations to the rover chassis. The variation in performance between the wheel types is difficult to see clearly in **Figure 7**, as speed was difficult to control accurately. Furthermore, as will be shown in later sections, higher damping will further improve rider comfort in more irregular terrain.

Terrain 2 results

Terrain 2 is a much softer terrain than terrain 1. This terrain slows the rover, so speeds are lower than in terrain 1. Therefore, the peak and standard deviation of vertical acceleration in soft sand is lower than for grass, as can be seen in **Table 4**.

Figure 8 illustrates the rider-comfort metric. In this test, the average speed was more consistent among tests, allowing a better comparison between the two wheels. Although previously the iRings wheels did quantitatively better, the difference in rider comfort is smaller than for terrain 1: a 7%–8% improvement between tests 1 and 5 and between 4 and 8. Also, repeatability between tests is low: tests carried out at similar speeds (tests 7 and 8) show an increase of approximately 7% in rider comfort. The lower difference in vertical acceleration between the two wheels is due to two main factors:

- at reduced speed, the vertical acceleration will be lower
- on a soft soil, like terrain 2, a significant amount of damping is provided by terrain deformation, thus reducing the impact load on the wheel.

Figure 6. Terrain sites for vehicle testing. (a) Terrain 1: grass. (b) Terrain 2: soft sand. (c) Terrain 3: hard sand/gravel.

Table 3. Results for terrain 1.

Test No.	Wheel type	Avg. speed (m/s)	SD of vertical acceleration (*g*)	Positive peak acceleration (*g*)	Negative peak acceleration (*g*)
1	Rubber	0.84	0.22	0.91	−0.6
2	Rubber	0.74	0.16	0.59	−0.48
3	Rubber	0.94	0.24	0.82	−0.61
4	Rubber	1.24	0.36	0.97	−1.04
5	iRings	0.56	0.13	0.42	−0.57
6	iRings	0.48	0.09	0.25	−0.29
7	iRings	0.64	0.13	0.41	−0.44
8	iRings	0.94	0.21	0.62	−0.74

Table 4. Results for terrain 2.

Test No.	Wheel type	Avg. speed (m/s)	SD of vertical acceleration (*g*)	Positive peak acceleration (*g*)	Negative peak acceleration (*g*)
1	Rubber	0.56	0.14	0.85	−0.46
2	Rubber	0.63	0.2	0.77	−0.71
3	Rubber	0.64	0.19	1.10	−0.73
4	Rubber	0.74	0.23	1.18	−0.85
5	iRings	0.54	0.13	0.52	−0.41
6	iRings	0.58	0.13	0.32	−1.03
7	iRings	0.74	0.19	0.45	−0.75
8	iRings	0.73	0.21	0.45	−0.64

Unfortunately, only terrain elevation as a function of frequency is considered in the power spectral density for irregular terrains in Equation 4. Thus, for a full characterization of the dynamic performance of wheel-suspension properties, a more detailed consideration of soil types is necessary.

Terrain 3 results

Terrain 3 demonstrated a clear improvement in rider comfort with the higher damped iRings wheels. As this terrain is much more compact and irregular than terrains 1 and 2, and although this is visible in **Figure 6**, it is clear from the results shown in **Table 5** that the rover sees much higher vertical acceleration.

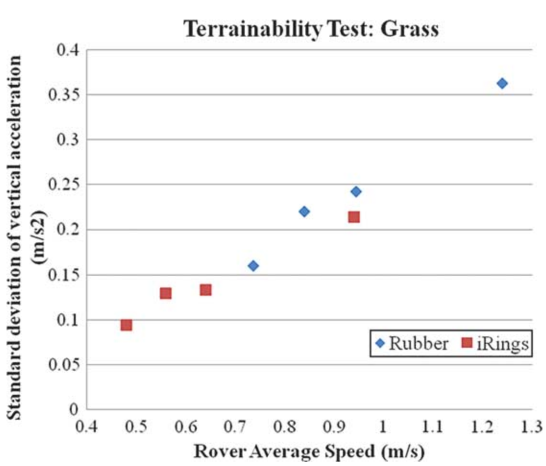

Figure 7. Test results for terrain 1.

Tests 7 and 8, using iRings wheels, show an average reduction of 57% from tests 3 and 4 using rubber wheels at the same speed. Furthermore, peak acceleration is reduced by over 70% in some cases. **Figure 9** illustrates the rider-comfort metric as a function of rover speed, where the improvement in rider comfort with the iRings wheels rather than the rubber wheels is evident.

Conclusion

A sensitivity analysis was conducted to identify variable conflicts in the dynamic terrainability performance of wheel designs for the *Juno* rover. Both a decrease in dynamic rolling stiffness and an increase in damping were beneficial

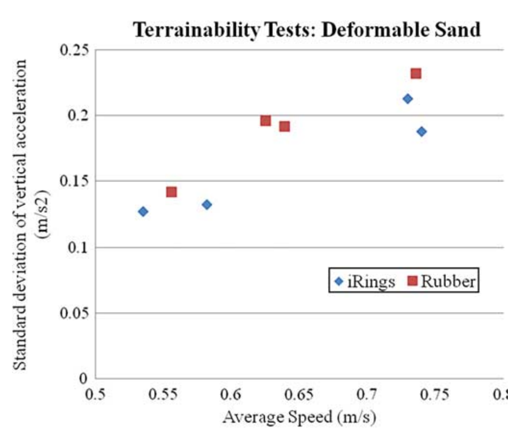

Figure 8. Test results for terrain 2.

Table 5. Results for terrain 3.

Test No.	Wheel type	Avg. speed (m/s)	SD of vertical acceleration (*g*)	Positive peak acceleration (*g*)	Negative peak acceleration (*g*)
1	Rubber	0.73	0.44	2.16	−1.14
2	Rubber	0.80	0.41	1.16	−1.12
3	Rubber	0.82	0.42	1.53	−0.99
4	Rubber	0.82	0.42	1.77	−1.15
5	Rubber	1.3	0.6	2.82	−1.19
6	iRings	0.66	0.17	0.49	−0.48
7	iRings	0.84	0.18	0.62	−0.52
8	iRings	0.86	0.18	0.49	−0.57
9	iRings	0.91	0.19	0.43	−0.68
10	iRings	0.96	0.21	0.51	−0.70

to rider comfort and road holding, while increasing the mass improved rider comfort and worsened road holding. Although both stiffness and damping do not conflict with performance objectives, physical constraints exist that limit their value, and a multidisciplinary analysis of the wheels should be undertaken to verify the effect on other wheel-performance indices such as trafficability and maneuverability. A weighted objective function was used to determine the optimal quarter-vehicle mass for the terrain and vehicle parameters described.

The physical test results further demonstrate that wheel damping is important in improving the rider-comfort metric. Two separate wheel configurations with different suspension properties were compared on three terrain types. Results show that depending on the terrain, iRings wheels can improve rider comfort by up to 57% while reducing shock loads by up to 70%. Thus, it appears that with respect to rider comfort, an increase in wheel damping has more benefit than a reduction in wheel stiffness in rough terrain. Although the number of tests performed was limited and repeatability between test results was low, it is still shown that a general trend towards improvement on rider comfort is seen using the iRings wheels. Additionally, it is observed that soil properties play an important role, in addition to the surface elevation profile. This signifies that describing the terrain simply by using a power spectral density function provides incomplete information for the dynamics model. It may be useful, then, to create more complex terrain models that account for soil types to further investigate the effects of wheel-suspension parameters on dynamic terrainability.

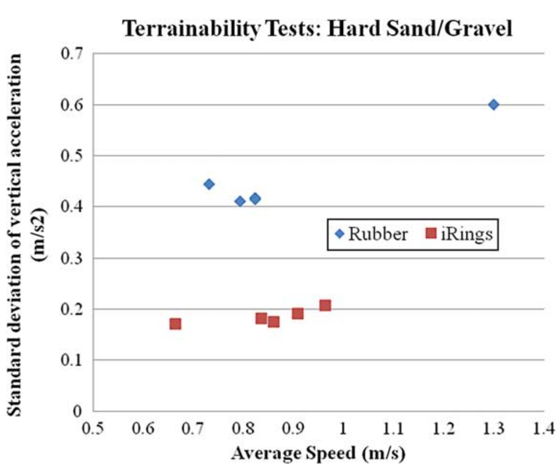

Figure 9. Test results for terrain 3.

Future work

It should be noted, however, that no explicit sprung suspension system was used in this dynamics analysis to reflect the design of the *Juno* rover, where all the dynamic suspension is due to wheel compliance. According to Verros et al. (2005), who used a sprung suspension on the vehicle, additional conflicts concerning suspension design variables will be identified. Although vehicle design parameters are outside the scope of the current work, their effect is important in optimizing a wheel for the *Juno* rover and other potential lunar vehicles. Furthermore, more complex terrain modeling, including soil properties, and varying vehicle speed can also have an effect on design-variable sensitivity.

The results reported here will be used as system design variables in a multilevel, multidisciplinary optimization of a compliant wheel design. These system-level design variables, which are independent of the specific wheel topology, will become design targets for multiobjective structural optimization at the wheel-component level.

Acknowledgements

This research is made possible through the generous support of the following organizations: Fonds Québécois de Recherche sur la Nature et les Technologies, The Canadian Space Agency, Neptec Design Group, and McGill University.

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