USE OF FLEXIBLE VARIABLE STIFFNESS WHEELS FOR HIGH SPEED LUNAR AND PLANETARY EXPLORATION ROVERS AND THEIR POTENTIAL IMPACT ON THE COST OF TRANSPORT

Vassilios Papantoniou[1], Stylianos Skevakis[1], Anastasios Katelouzos[1], Ares Papantoniou[1], Konstantinos Kapellos[2], Evangelos Papadopoulos[3], and Michel van Winnendael[4]
[1]Hellenic Technology of Robotics (HTR), [2]TRASYS, [3]National Technical University of Athens, [4]ESA-ESTEC

1. Abstract

In the context of future Lunar and Martian exploration rover operations, "high speeds" (ranging from 300 m/h to several km/h) are going to be necessary for covering the required distances within the mission planning constraints [23]. Such speeds may require increased power for rovers. As the mass of rovers is also expected to increase, there may be questions of how to power these vehicles. In this context, investigating ways to optimize the efficiency of rover motion over various types of terrain (ranging from solid bedrock to loose sand), is becoming a relevant research topic.

Answering to this need, an innovative concept of an all-metal flexible wheel with variable stiffness is presented. The wheel can continuously and automatically adjust its radial stiffness according to soil conditions. Wheel breadboard models have been tested individually as well as by using a set of six of them, mounted on an ExoMars-like triple bogie full-scale rover model, on a dedicated testbed facility.

A number of authors have studied traction ([1, 3, 4, 5, 7, 17), with some addressing wheel operation in reduced gravity conditions, ([10, 11, 18, 20, 21]. Very few authors addressed energetics. Issues of energetics have been investigated for transport in general by [2, 22]. For all-terrain land vehicles, the subject has been addressed in [1], with focus on the morphology of the overall vehicle rather than wheel design.

In this paper, the Cost of Transport (CoT) has been derived as a function of wheel stiffness, rover load and soil conditions. The experiments were done at HTR's Laboratories (Lamia, Greece) and the results presented in this paper refer to test campaigns that took place both in the context of the ESA project Adaptable Wheels for Exploration (AWE) and after the end of the contract. The related work (ESA Contract number 4000112936/14/NL/SFE) has been performed by HTR SA Greece in collaboration with the Control Systems Laboratory (CSL) of the School of Mechanical Engineering of the National Technical University of Athens (NTUA), as well as with TRASYS International SA Belgium. The developed prototype wheel is patented and consists of metallic parts only. It is intended for use on Lunar or Martian rovers.

2. Introduction

The AWE (Adaptable Wheel for Exploration) wheel design consists of a fully metallic wheel, using leaf springs for flexibility. The springs are arranged in a way to provide non-linear, gradually increasing radial stiffness behavior upon loading, mimicking the behavior of wheels with pneumatic tires. Figure 1.1 shows such a wheel on the testbed.

Figure 1.1: AWE Prototype wheel.

Using a patented mechanism, the AWE wheel has the capability to modify its radial stiffness. This is done during normal wheel operation and does not require any type of external intervention on the wheel. The stiffness is controlled by a dedicated microcontroller mounted on the wheel. Figure 2.1 shows the leaf spring arrangement for the AWE wheel.

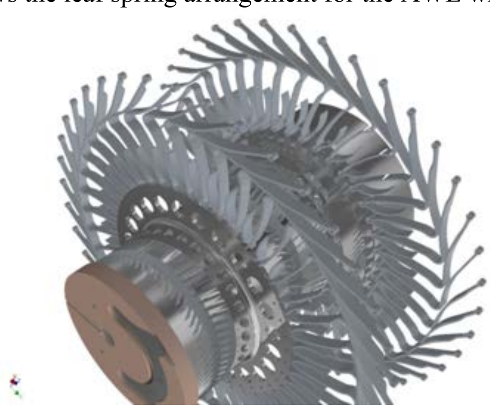

Figure 2.1: AWE wheel leaf spring arrangement.

Thanks to a specially designed mechanism, the springs are preloaded against each other, altering in that way the stiffness of the wheel rim consisting of hinging caterpillar track plates, much in a similar way a pneumatic tire can be inflated or deflated. As a result, the contact surface of the wheel periphery with the ground decreases at higher stiffness and increases with lower stiffness, for given axis load and soil conditions.

The above-mentioned mechanism can effectively modify the AWE wheel stiffness by a factor of 4. The minimum stiffness achieved for the given wheel design is 2.5 kN/m, while the maximum stiffness obtained is 10.0 kN/m. The experimental wheels have a diameter of 340 mm, a mass of around 3.5 kg and a nominal load capacity of 300 N. The motorization applied allows torques up to 30 Nm and speeds up to 1 km/h. The wheel is designed for a maximum speed of 10 km/h. Wheel breadboard models have been tested individually as well as by using a set of six of them, mounted on an ExoMars-like triple bogie full-scale rover locomotion subsystem model, on a dedicated HTR-designed testbed facility, see Fig. 2.2.

Figure 2.2: Full scale ExoMars type rover integrated by HTR for AWE tests, also equipped with solar panels for outdoor tests.

Energetics have been measured as a function of wheel stiffness, wheel load, drawbar pull and soil conditions, and demonstrate significant impact from the use of variable stiffness wheels in varying soil conditions. Rover tests studying the soil-wheel interaction, focused on the power used by the rover for a range of speeds, as a function of wheel stiffness. The rover has a mass of 96 kg plus a 10 to 50 kg payload and has been moving over lunar simulant crushed basalt soil of 20%, 40% and 60% relative density.

3. Test setup and measuring process

3.1 Testbed

A specially designed facility has been integrated at HTR for the purpose of AWE wheel testing. The facility consists of a double-corridor testbed where soil conditions, slope, axis load and imposed draw bar pull can be modified at will, see Fig. 3.1.

Figure 3.1: Testbed setup for rover tests.

Figure 3.2 shows the setup for single wheel tests. For single wheel tests, the wheel is kept on track by a passive chariot. The sole motorization applied is the wheel motor on the wheel axis. There is no imposed motion on the chariot. For drawbar pull tests, there is an imposed force on the chariot in the form of dead weight, dragging the wheel against its direction of motion (Figure 3.2). Adequate small balancing weights compensate friction of the guiding chariot. Additional sensors measure the real time value of drawbar pull force developed by the wheel.

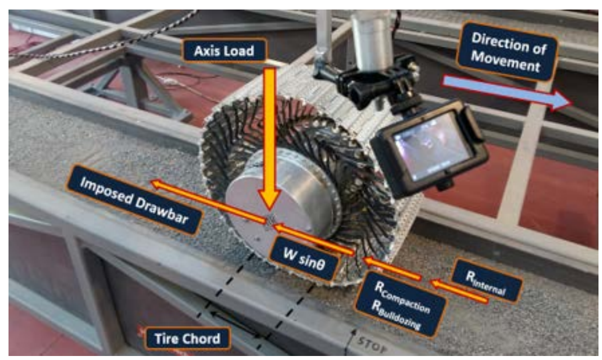

Figure 3.2: Test setup for single wheel tests.

For CoT tests, the imposed drawbar pull is zero; however, the wheel / soil interaction induces motion resistances that the wheel actuator has to overcome.

When tests for energetics are performed at single wheel level, the power is directly connected to the wheel actuator (not through power electronics) and voltage and current are measured at motor level.

All motion parameters and developed forces are monitored and logged.

For rover tests, the rover has been mounted on the testbed, as shown in Fig. 3.3.

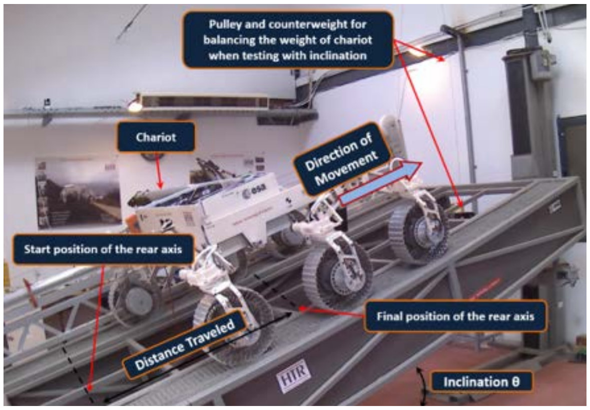

Figure 3.3: Test setup for the entire rover.

For tests with the entire rover, the on-board controller of the rover was used for wheel motion control. The reported power needs at the rover level was around 18W of power used by the on-board controller, as well as for the losses of the power electronics of each of the 6 motors of the rover.

3.2 Lunar soil simulant used

Crushed basalt has been used as lunar soil simulant, [6], imported from Sicily, South Italy. Fig. 3.4 shows an X-Ray diffraction graph for the composition of our soil sample as obtained by the Laboratory of Soil Mechanics at NTUA.

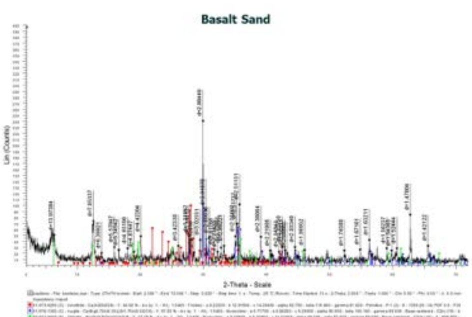

Figure 3.4: X-Ray diffraction graph for the composition of our crushed basalt soil sample.

3.3 Determination of soil relative density.

A methodic process has been followed in order to guarantee the homogeneity of the relative density of the soil in the testbed. The testbed has been filled with soil using a special canister. The canister used is of cylindrical shape, 17 cm height and 16 cm diameter, see Fig. 3.5.

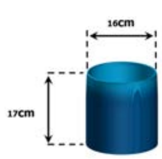

Figure 3.5: Soil canister dimensions.

The canister weights 300 g; when filled with soil (crushed basalt) it weighs 5200 g. So, the amount of the soil that it contains weighs 4900g. The soil in the canister is uncompressed.

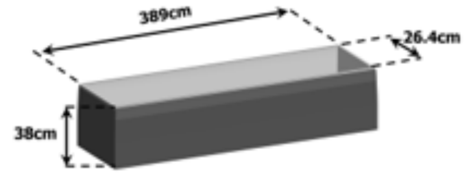

Figure 3.6: HTR testbed bin dimensions.

To fill one of the bins of the testbed with soil, 112 canisters are needed. Knowing all the dimensions, we are able to calculate the volume and the mass of the soil. The volume in a bin is equal to 0.3697 m^3, and the soil mass in the bin is measured as explained above. Using the equation for the relative density we can easily find the relative density of each bin. In this way, we can achieve a relative density ranging from 20% to 60 %, by compacting the layers of soil filled in the bin during the process. In our tests, we used 3 relative densities for the crushed basalt, 20% ReD (114 canisters of soil needed), 40% ReD (121 canisters of soil needed) and 60% ReD (129 canisters of soil needed).

3.4 Cost of Transport

A large number of tests have been conducted in HTR's facilities to determine the impact on energetics that can be achieved from the stiffness modification of the wheels. As a metric for efficiency, the CoT has been used. The term has been introduced by Gabrielli and Von Karman [2, 22] and relates to:

$$\varepsilon = \frac{Power}{Weight \cdot Speed} \quad \left[\frac{W\cdot s}{N\cdot m} = \frac{J}{N\cdot m}\right] \qquad (1)$$

Where Power is the power provided to the vehicle, Speed is the average speed of the motion in m/s and Weight is the weight of the vehicle in N. For a given vehicle, operating on a specific type of soil, the CoT represents a metric of its efficiency. The CoT applies to all transport means, i.e. land vehicles, trains, ships, airplanes, etc. In the context of AWE, we investigated if it was possible to optimize the CoT for the given wheel and actuator design, by modifying the wheel stiffness for given axis load, soil conditions and speed.

4. Test results

The CoT tests are conducted on flat terrain, with zero drawbar pull. Direct measurements of the power provided to the wheel motor (without the use of the power control electronics) have been used, in order to guarantee that the power measured was only used by the wheel motor and not by other passive components.

Tests comprised individual wheel tests as well as tests at rover level. The tests focus on the power used by the wheel for operation on soils of various relative densities, as a function of wheel stiffness, axial load and wheel speed, affecting the resulting CoT of the vehicle. Representative results can be seen in the following sections, related to Single Wheel Tests and Rover Tests.

(a) Single Wheel Tests

Multiple tests are represented in each graph, showing the evolution of power needs as a function of speed. The CoT is calculated in each case and presented in the graph. The wheel during tests is shown in Fig. 4.1.

Figure 4.1 : Single wheel during tests.

In the first graph shown in Fig. 4.2, the wheel moves on a 40% ReD crushed basalt soil, with an axis load of 180 N (yellow line) and an axis load of 220 N (blue line). Wheel stiffness is 7 kN/m.

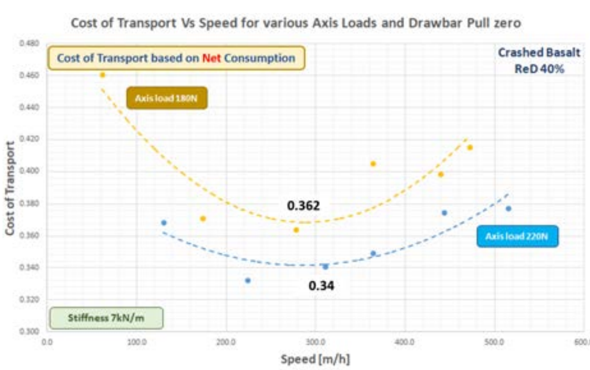

Figure 4.2: Cost of transport for wheel stiffness 7 kN/m for axis loads 180 N and 220 N based on total consumption and zero inclination.

Similar tests are done with wheel stiffness of 4 kN/m and shown in Figure 4.3.

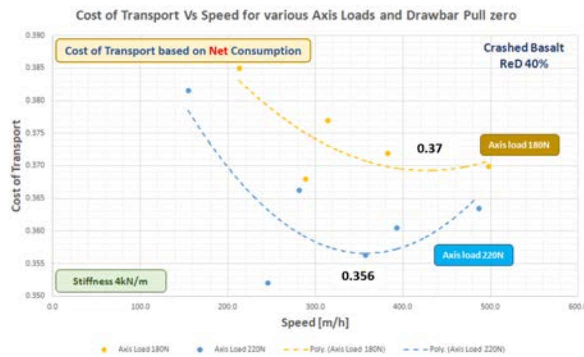

Figure 4.3: Cost of transport for wheel stiffness 4kN/m for axis loads 180N and 220N, based on total consumption and zero inclination.

Finally, the same tests have been repeated with a fully rigidified wheel. This has been achieved by blocking all spring action on the wheel. The results are shown in Fig. 4.4.

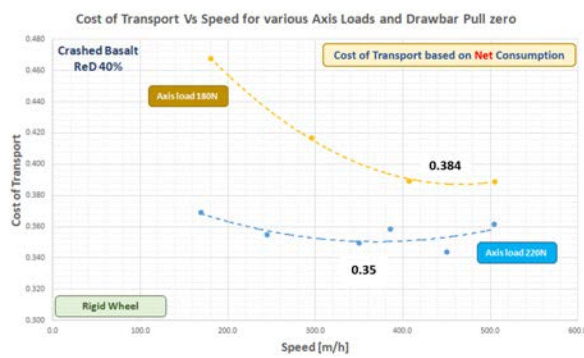

Figure 4.4: Cost of transport for rigid wheel for axis loads 180 N and 220 N based on total consumption and zero inclination.

In the above graphs, the CoT for the wheel in operation at a speed from 200 m/h to 500 m/h, is shown on the same soil conditions (crushed basalt, 40% ReD) with two different axis loads, 180N and 220N. The wheel, with zero drawbar pull and 7 kN/m rigidity, has an average CoT of 0.34 with axis load of 220 N, and an average CoT of 0.362 with an axis load of 180 N, for speed of around 300 m/h. It is noticeable that in both axis load cases, the curves present minima.

A similar situation is observed for a rigid wheel on Figure 4.3 with a CoT value around 0.35 for 220 N load and a CoT value of 0.384 for 180N load.

For the wheel with stiffness at 4 kN/m, see Figure 4.2, a clearer minimum appears, with a CoT value of 0.356 for 220N and 0.37 for 180N.

The tests show that the best performing wheel for the range of 180N to 220N axis load appears to be the one with 7 kN/m stiffness. This situation changes drastically when the axis load is modified, as it can be seen from the figures below.

The graphs show again the results from multiple single wheel experiments. A comparison for 90 N and 130 N axis load and 4 kN/m stiffness is shown in Fig. 4.5. In this case a minimum CoT of 0.44 is observed at 380 m/h.

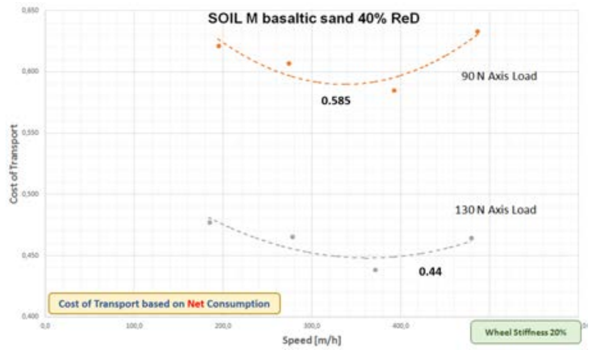

Figure 4.5: Cost of transport for 4kN/m elastic wheel with axis load 90N and 130 N and speed from 200 to 500m/h.

If we increase the wheel stiffness to 7 kN/m (60% of the full range) operating on 40% relative density crushed basalt, we obtain for axis load 130N the results shown in Figure 4.66. The test presents a minimum CoT of 0.52 at a speed of 240 m/h up to 460 m/h .

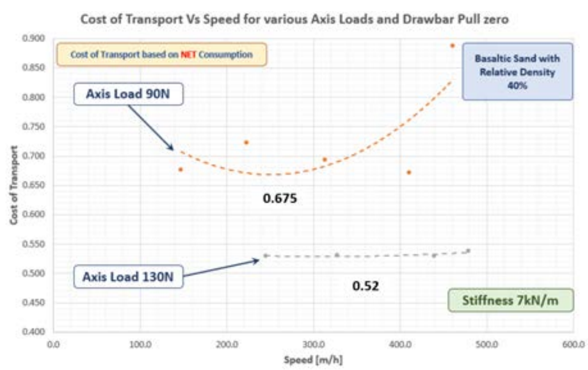

Figure 4.6: Cost of transport for a 7kN/m elastic wheel with speed from 150 to 500m/h.

The above results show the different impact that variable compliance can have on CoT, as a function of the axis load. In the case of 220N axis load, the impact of variable compliance on CoT was negligible, slightly favoring the wheel at 7 kN/m stiffness. However, for axis load of 90 to 130N, the wheel at 4 kN/m stiffness is obviously performing better, with a CoT ranging from 0.585 to 0.44 versus the performance of the 7 kN/m wheel, with a CoT ranging from 0.675 to 0.52. The difference in CoT reaches an average of a 20% gain in favor of the wheel with the lower stiffness, for axis loads 90 to 130N.

It seems therefore that there can be a significant impact from stiffness on the energetics of the wheel during motion with varying axis loads. Of course, if the soil conditions change, this performance can be modified (for instance, on a very soft soil, the power drain of a stiffer wheel can be expected to become a lot higher than the drain of a more flexible wheel). Obviously, the results also largely depend on the actuator used. The actuator in use here has been optimized for operation at a speed around 400 m/h. However, it appears that the optimization process should also take into account the stiffness of the wheel for each case.

(b) Rover tests

Regarding tests with the rover, see Fig. 4.7, the following figures present a number of consolidated test results. Tests with the rover involved measurement of the power used by the rover at battery level, therefore comprising the overhead of processors and power cards (overhead estimated in total around 18 W).

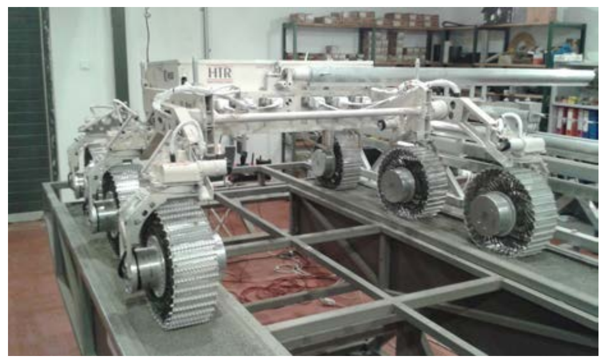

Figure 4.7: Rover during tests.

Fig. 4.8 displays results for a wheel of stiffness 4 kN/m. The rover has 100 N additional load and a total weight of 1060 N.

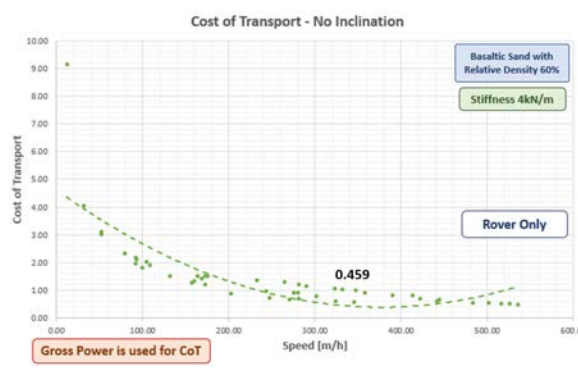

Figure 4.8: Cost of transport for rover with average stiffness 4kN/m and soil relative density 40%. Average axis load per wheel: 177N.

The optimal CoT of 0.459 occurs around 400 m/h. If we change the wheel stiffness to 8.5 kN/m and run the tests again, the results in Fig. 4.9 are obtained.

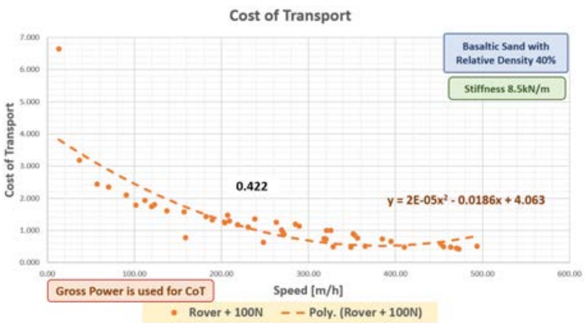

Figure 4.9: Test with total weight 1060N, stiffness 8.5 kN/m.

Here, the detailed log from each individual run is given below:

LOG ; CoT for 8.5kN/m, 100N

Speed [m/h]	365	384	395	410	451	455	463	470	473
CoT []	0.51	0.73	0.66	0.47	0.58	0.49	0.48	0.45	0.42

continue…

Speed [m/h]	493
CoT []	0.50

with an optimal value of 0.422 at 472m/h. The results confirm the single wheel tests. As in the case of a single wheel, the axis load of 177 N seems to favor a higher stiffness in order to achieve a lower CoT.

A comparative test for the same soil, with the rover with a load of 200N and an axis load for each wheel at 193 N, with wheels at 4 kN/m is shown below.

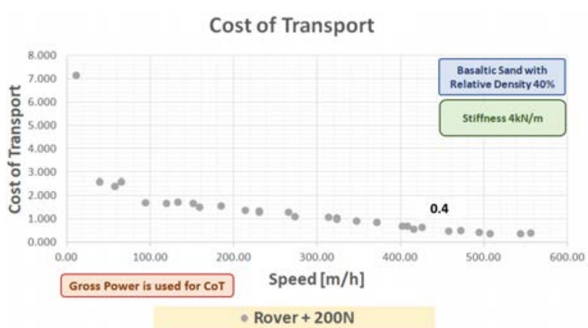

Figure 4.10: Test with rover of 200N load, 4 kN/m stiffness.

The following table gives the log during the test:

LOG: CoT for 4kN/m, 200N Load

Speed [m/h]	407	415	425	458	472	494	506	543	556
CoT []	0.69	0.57	0.64	0.48	0.51	0.42	0.38	0.38	0.39

with an optimal around 0.4 at 500 m/h.

Keeping the rover load to 200 N, we obtain the results in Fig. 4.11, for stiffness of 8.5 kN/m. The detailed log from each individual run is given next:

LOG: CoT for 8.5 kN/m, 200 N load

Speed [m/h]	400	403	416	424	427	453	456	483	519
CoT []	0.58	0.58	0.50	0.40	0.43	0.48	0.38	0.47	0.31

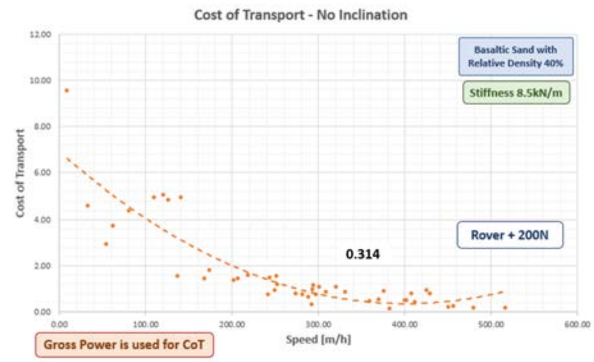

Figure 4.11: Cost of transport for rover with total weight of 1160N with average stiffness 8.5kN/m and soil relative density 40%.

Giving a CoT of 0.314 for 520 m/h. Again, the higher the axis load, the best results are obtained from higher stiffness wheels for the specific soil.

(c) Comparative Graphs for rover tests

Figure 4.12 shows a comparative graph for stiffness 4 kN/m and 8.5 kN/m for the same soil at 40% ReD, for the rover of total weight of 1160N.

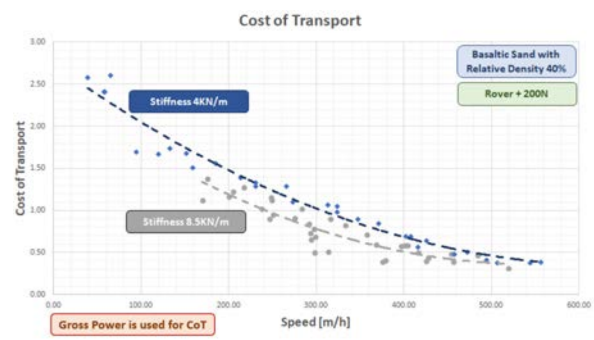

Figure 4.12: Cost of transport comparison for 40% ReD soil cases for rover of 1160N total weight and two different wheel stiffness used.

These experiments show that an average CoT difference of the order of 20% exists for the speed range of 100 m/h to 500 m/h, for the two selected values of wheel stiffness, favoring the wheels with higher stiffness. This difference can be expected to further increase, when the speed increases to one or several km/h. The overall impact on CoT can therefore be important. It is clear that the CoT heavily depends on the selected wheel actuators, the power control of these actuators, the mechanical transmission used, etc. However, the presented test campaign has kept all other significant parameters exactly the same, in order to evaluate the role of wheel stiffness in the process.

5. Results used as indications for a high-speed lunar rover application

Tests with the HTR rover at Earth gravity conditions have shown that the 96 kg rover with a 20 kg (200 N) payload is able to operate at a speed of 500m/h on soft ground at a CoT of 0.38. This represents a power cost of

$$P(W) = 1160 \text{ N} \times 0.139 \text{ (m/s)} \times 0.38 = 62 \text{ W}$$

including the 18 W power needed by its processors. This means that during the rover operation, the 6-wheel actuators need a total of 44 W only. According to the above, considering a lunar rover of similar configuration, it appears that 500 m/h could be achieved with this type of rover / wheels on the lunar surface at a similar cost of around 44 W, if the wheels operate at similar loads. Taking into account gravity factors, *we can observe that the 45 W anticipated power for the wheel drive motors of the rover could be sufficient for a total rover mass of 720 kg*, (with 1160N weight at lunar gravity conditions), and a similar *speed of 500 m/h* on soft basaltic soil. Although these extrapolations need to be verified in further terrestrial tests, these figures are promising for the future of high-speed exploration rovers. The use of variable compliance wheels appears to be promising towards the optimization of the operation of such rovers.

6. Proposed Wheel Stiffness optimization process

The test campaign has produced an amount of experimental results that help answer the questions related to wheel stiffness optimization for long traverses. It appears that optimal stiffness for given soil conditions and axis load on a wheel, may significantly modify its cost of transport for a specific speed range. The optimization process becomes more critical when the mass of the system increases. If wheels with fixed stiffness are to be selected for a mission, the stiffness to be applied should be validated through extended testing. AWE wheels could facilitate the selection of optimal wheel stiffness to be used. During the experimental campaign, the projected wheel load and speed should be tested with varying wheel stiffness in order to observe the impact of stiffness parameters on wheel performance and CoT. The AWE wheels would facilitate such test campaign, since their stiffness can be modified easily during tests. If the average axis load, actuator to be used and rover speed are a priori known for a certain mission, as well as the average type of soil to be encountered, the AWE wheel could be used for a test campaign aiming to define the optimal wheel stiffness to be applied. The AWE wheel could then be used for the tests and their stiffness altered until the optimal stiffness is selected through an optimization process based on important factors such as traction and energetics. The selected optimal stiffness could then be applied for the final wheel design.

7. Conclusion

This paper presents the results of AWE (ESA Contract Number 4000112936/14/NL/SFE) project, dealing with adaptable wheels for lunar and planetary exploration rovers. The wheels provide the opportunity to perform many experiments, relating wheel stiffness with traction and energetics on various soil conditions. The test results indicate that it is possible to optimize the wheel parameters (such as stiffness) for optimal performance (energy spent), on various soil conditions and wheel loads. Taking also into account the wheel actuator, the tests appear to offer a possibility to predict the wheel behavior (and the behavior of a rover utilizing these wheels), including the power and energy needed for given soil conditions.

A significant impact on the CoT from the use of variable stiffness wheels on varying soil conditions has been observed. The effect of wheel stiffness appears to achieve up to 20% economy on the *net power* needed by a wheel of a 4 kN/m stiffness over soft 40% ReD basaltic sand soils, when compared to the power needed for a wheel with a 7 kN/m stiffness over the same soils, when both wheels bear an axis load of 90 to 130N. Therefore, for the range of 90 to 130N, the wheel stiffness of 4 kN appears to be more efficient. On the other hand, there appears to be a 20% difference on the CoT from the use of a 8.5 kN/m stiffness of the wheel versus the use of a “sub-optimal” stiffness of 4 kN/m, when the wheel has an axis load of 180 to 200 N. Tests with the rover moving on the exact same soil conditions confirm this fact, under the same speed and the same payload values. These experiments show that adapting the wheel stiffness as a function of soil and axis load conditions may generate some significant economy on the CoT.

The overall results show that we can obtain a significant economy by altering the wheel stiffness on the energetics of the wheel, which can be in the order of 20% in terms of energy spent during locomotion. Also, it appears that the CoT varies with load and speed. Optimal results may vary with load, meaning that a wheel stiffness that appears optimal for certain load conditions may not be optimal when the load conditions are modified. Although the CoT measurements presented largely depend on the actuator used, the fact that for the same actuator, a number of optimal operating points can be defined, shows that the correct combination of stiffness and actuation can provide minimal cost of transport for a given wheel and vehicle configuration.

Finally, it must be noted that the optimal cost has been measured on the single wheel tests as NET power provided to the wheel (excluding losses on electronics, processors etc.), while on the rover tests, all power consumptions related to the motion of the robot have been taken into account (electronics, processors etc.). This fact did not seem to have a significant impact on the CoT, due to the high mass of the rover.

8. References

[1] Bekker M.G. (1955). *Theory of Land Locomotion*. Ann Arbor. The University of Michigan Press.

[2] Gabrielli, G., von Karman, Th: What price speed? *Mech. Eng*. 72, 775–781 (1950)

[3] Bekker M.G. (1963). *Mechanics of Locomotion and Lunar Surface Vehicle Concepts*. Defense Research Laboratories, General Motors Corp.

[4] Wong J.Y. (2010). *Terramechanics and Off-Road Vehicle Engineering*. Elsevier.

[5] Wong, J.Y., et al. (1998). Optimization of the Tractive Performance of Four-Wheel-Drive Tractors: Theoretical Analysis and Experimental Substantiation, *Proc. Inst. Mech. Eng. D J. Automob. Eng*., v. 212, n. 4.

[6] Carrier, W.D.; Olhoeft, G.R.; and Mendell, W. (1991). *Physical Properties of the Lunar Surface. Lunar Sourcebook*, Grant H. Heiken, David T. Vaniman, and Bevan M. French, eds., Cambridge University Press, New York, NY.

[7] Gill, W.R., Vanden B., Glenn E. (1968). Soil Dynamics in Tillage and Traction. *U.S. Department of Agriculture*, Washington, DC.

[8] Macdonald M., Badescu V. (2014). *The International Handbook of Space Technology*, Springer.

[9] Siciliano B., Khatib O. (2008) *Springer Handbook of Robotics*, Springer.

[10] Kobayashi T., Fujiwara Y., Yamakawa J., Yasufuku N., Omine K. (2010). Mobility performance of a rigid wheel in low gravity environments. *Journal of Terramechanics*, 47 p.261-274.

[11] Wong J.Y. (2012). Predicting the performances of rigid rover wheels on extraterrestrial surfaces based on test results obtained on Earth. *Journal of Terramechanics*, 49 pp.49-61.

[12] Meirion-Griffith G., Nie C., Spenko M. (2014) Development and experiment validation of an improved pressure-sinkage model for small-wheeled vehicles on dilative, deformable terrain. *Journal of Terramechanics*, 51 p.19-29.

[13] Hambleton J.P., Drescher A.(2009). Modelling-induced rutting in soils: Rolling. *Journal of Terramechanics*, 46 p.35-47.

[14] Hambleton J.P., Drescher A. (2008). Modelling-induced rutting in soils: Indentation. *Journal of Terramechanics*, 45 p.201-211.

[15] Lyasko M. (2010). LSA model for sinkage predictions. *Journal of Terramechanics*, 47 p.1-19.

[16] Lyasko M. (2010). Slip sinkage effect in soil-vehicle mechanics. *Journal of Terramechanics*, 47 p.21-31.

[17] Laughery S., Gerhart G., Goetz R. (1990). Bekker's Terramechanics model for off-road vehicle research. *US Army TARDEC*, Warren, MI 48397-5000.

[18] Ishigami G., Miwa A., Nagatani K., Yoshida K. (2007). Terramechanics-based model for steering manoeuvre of planetary exploration rovers on loose soil. *Journal of Field Robotics,* v. 24, n. 3.

[19] Lee J.H., Gard K. (2014) Vehicle-soil interaction: Testing, modelling, calibration and validation. *Journal of Terramechanics*, 52 p.9-21.

[20] Asnani V., Delap D., Creager C. (2009) The development of wheels for the Lunar Roving Vehicle. *Journal of Terramechanics*, 46 p.89-103.

[21] Creager C. and Asnani V. – Drawbar Pull (DP) Procedures for Off-Road Vehicle Testing. (2017). *NASA/TP*-2017-219384.

[22] Transcossi M. – What price of speed? A critical revision through constructal optimization of transport modes, *Int. J. Energy Environ Eng*. 2015.

[23] Hosseini S., Rinnan T.B. (2018). HERACLES Surface Mission ConOps, Rev.2 30/10/2018, *ESA-E3P_HERA-TN-009*.