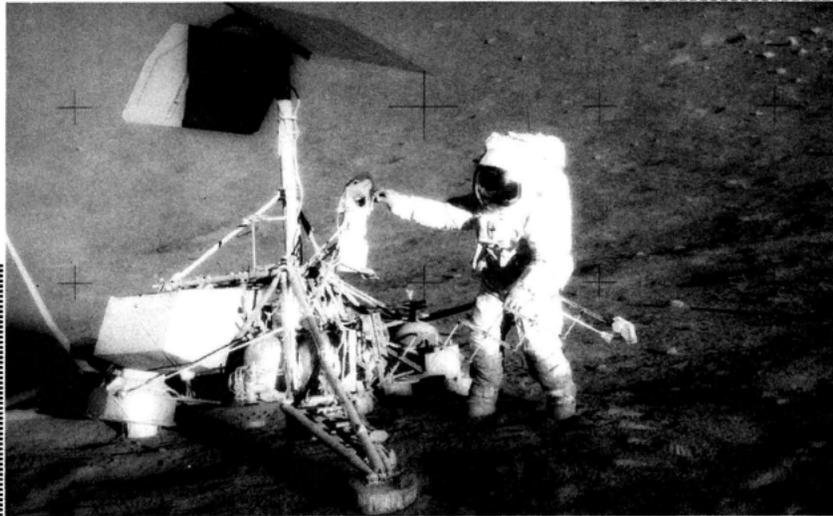


Lunar Geotechnical Institute

LGI TR94-02



**TRAFFICABILITY OF
LUNAR MICROROVERS
(Part 1)**

by

W. David Carrier, III

1994

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TRAFFICABILITY OF LUNAR MICROROVERS

(Part 1)

This report analyzes the behavior of a flexible, elastic wheel resting on a rigid surface. It is the first in a series of reports whose goal is to accurately predict the trafficability performance of various proposed lunar microrovers.

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April 1994

TRAFFICABILITY OF LUNAR MICROROVERS

(Part 1)

by

W. David Carrier, III^a

Introduction

The trafficability performance of "standard-sized" wheels on the lunar surface is well established and documented. In particular, the Russian Lunokhods and American Lunar Roving Vehicles (LRVs) operated successfully over traverses totaling nearly 140 km [Baldwin, 1973; Kemurdzhian et al., 1976, p. 135; Kemurdzhian, 1990; Carrier, 1991, 1992a].

The Lunokhod wheels were rigid, whereas the LRV wheels were flexible. The respective wheel diameters were 510 mm and 820 mm and the load carried by each wheel in lunar gravity was 154 N and 289 N [Alexandrov et al., 1972; Costes et al., 1972; Carrier, 1991 and 1992a]. By comparison, various lunar microrovers have been proposed with wheel diameters varying from 100 to 200 mm and wheel loads of 4 to 10 N.

The effect of the in situ lunar soil on the energy consumption and slope-climbing ability of the Apollo LRVs was originally analyzed on the basis of empirical equations developed by Bekker (1969):

Wheel sinkage (cm), $z = (W/Ak)^{1/n}$

Soil compaction resistance per wheel (N), $R_c = [bk/(n + 1)]z^{n+1}$

Gross pull per wheel (N), $H = (Ac_b + W \tan \phi_b) [1 - (1 - e^{-sL/K})K/sL]$

Maximum trafficable slope = $\tan^{-1} [(H - R_c)/W]$

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where W = wheel load (N); A = wheel footprint area (cm^2); L = wheel chord length of ground contact (cm); b = wheel width of ground contact (cm); $k = (k_c/b) + k_\phi$; k_c = cohesive modulus of soil deformation (N/cm^{n+1}); k_ϕ = frictional modulus of soil deformation (N/cm^{n+2}); n = exponent of soil deformation; c_b = coefficient of soil/wheel cohesion (N/cm^2); ϕ_b = soil/wheel friction angle (deg); K = coefficient of soil slip (cm); s = wheel slip (dimensionless).

Based on Surveyor and Apollo data, the following design trafficability parameters were selected for the LRV: $k_c = 0.14 \text{ N}/\text{cm}^2$; $k_\phi = 0.82 \text{ N}/\text{cm}^2$; $n = 1$; $c_b = 0.017 \text{ N}/\text{cm}^2$; $\phi_b = 35^\circ$; and $K = 1.8 \text{ cm}$ [Costes et al., 1972; Carrier, 1991 and 1992a]. The actual trafficability performance of the LRV compared very well with the predicted performance. Hence, it is generally agreed that the trafficability performance of any future "standard-sized" (i.e., manned) lunar rovers can be accurately predicted with the available tools. In order to facilitate the analysis of future LRV-type wheels, Carrier (1992b) wrote the computer program ROVER, and distributed it to interested members of the lunar community. A copy of the latest version of ROVER is included on the computer disk in Appendix 1.

However, studies done by Carrier (1992c) and others have shown that when the Bekker equations and the Surveyor/Apollo trafficability parameters are used to analyze the performance of proposed *microrovers*, the predicted slope-climbing ability is impractically low: typically just 5° to 8° . These numerical results are contrary to empirical evidence obtained in the 1960s: At that time, a small rover was successfully operated on a 20° -soil slope under $1/6$ -th g conditions aboard an airplane flying Keplerian trajectories [Scott, 1992].

As a result of this inconsistency, efforts have been initiated at various NASA-affiliated organizations aimed at measuring Bekker parameters for small wheels under both $1 g$ and $1/6$ -th g conditions. The LGI has participated directly or indirectly in most of these efforts.

In addition, the LGI has herewith begun a study of soil-wheel interaction in an attempt to develop a more fundamental design procedure, as well as to utilize other lunar soil properties that have been measured in situ and on returned samples. The first, small step in the LGI study is to numerically analyze the behavior of a flexible, elastic wheel resting on a rigid surface, which is the subject of this report. The next step will be to analyze a flexible wheel resting on a flexible soil. Then a flexible wheel rolling on a flexible surface. And so on, until the slope-climbing ability of a lunar microrover can be predicted with confidence.

This study is very much a "work in progress" and input from interested parties is solicited.

Elastic Wheel on a Rigid Surface

If an elastic wheel contacted the ground surface at a single point on its circumference, the deflection of the wheel would be linearly proportional to the vertical force and could be simply calculated, given the Young's modulus of elasticity and the dimensions of the wheel. This is the basis of "proving rings", which have been used in laboratories for decades to measure forces.

However, in actuality, a wheel contacts the ground surface at multiple points. And as the force on the wheel increases, the number of contact points also increases, such that the force-deflection relationship is non-linear.

For purposes of this numerical analysis, we have considered the elastic wheel to consist of a series of independent springs: As the wheel deflects, more and more springs come into contact with the ground. This algorithm assumes that as the bottom of the wheel flattens against the rigid surface, the portion of the wheel not in contact with the ground remains perfectly round. Furthermore, it is assumed that the radius of curvature of the undeflected wheel does not change: Hence, the perimeter of the wheel is not conserved. None of these simplifying assumptions appears to be significant provided the deflection of the wheel is less than about 10% of the diameter. At 10% deflection, in fact, 60% of the wheel diameter is in contact with a rigid surface. Consequently, for practical applications, it is desirable to limit the wheel deflection to less than 10%, otherwise the wheel is too flat and too much energy is consumed in internal hysteretic flexure, independent of the nature of the ground surface.

Each of the individual springs that make up the wheel are assumed to deflect according to the following relationship:

$$F_i = (k_w/N) (d_i/D)^m$$

where

F_i	= force on the i-th spring
k_w	= spring constant for each spring
N	= number of springs that make up the wheel
d_i	= deflection of the i-th spring
D	= diameter of the undeflected wheel
m	= spring exponent

The total force exerted on the wheel is then given by

$$W = \Sigma F_i$$

The number of springs in the wheel has been left as a variable in order for the user to test the sensitivity and accuracy of a given analysis. This value must be an odd integer so that the initial contact between the wheel and the ground is through just one spring. Typical values of N are 11, 101, or 1001.

The exponent, m , has been introduced to account for any nonlinearities that may occur at large deflections (approaching 10%).

WHEEL-E

The WHEEL-E program is written in True BASIC™, Version 2.0, and operates in a PC/DOS environment. To run the program, type **WHEEL-E** {Enter}. The program begins by asking the user if he/she wants graphic output on the computer monitor; if so, then various resolution options are presented. The program then proceeds to request the following information:

1. The diameter, D , of the undeflected wheel (in millimetres); e.g., 100
2. The maximum deflection, d , of the wheel (in millimetres); e.g., 10
3. The constant, k_w , for the wheel 'springs' (in newtons); e.g., 1
4. The exponent, m , for the wheel 'springs' (dimensionless); e.g., 1
5. The number of 'springs', N , that make up the wheel (dimensionless; odd integer); e.g., 101
6. The name for the **OUTPUT** file; e.g., output

The program automatically divides the user-specified maximum deflection, d , into ten increments and calculates the corresponding forces, etc. If the graphics option is selected, the wheel will be seen to deflect like a shaky, animated cartoon. At full deflection, the computer monitor will appear as shown in the example in Fig. 1:

Note 2: True BASIC is a trademark of True BASIC, Inc.

1. In the upper left hand corner, the input data is repeated.
2. Along the mid-left hand side, the calculated wheel chord length, L , in contact with the ground surface and the total force, W , required to produce the input maximum deflection are shown.
3. In the central portion, the distribution of the deflection of the wheel is shown, at the same scale as the diameter of the wheel. Also shown is the distribution of contact stress between the wheel and the rigid ground, using an arbitrary scale.

With or without graphics, the results of a computer run are stored in the user-specified **OUTPUT** file, as shown in the example in Table 1. The contents of the output file may be printed or viewed by means of the computer program BROWSE (see Appendix 1). Alternatively, the output data may be imported into a spreadsheet program for additional analyses, plots of force vs. deflection, etc.

Conclusions

A simple computer program, WHEEL-E, has been written which analyzes the behavior of a flexible, elastic wheel resting on a rigid surface. WHEEL-E may be used by the various lunar microrover investigators to evaluate the performance of their proposed wheels; in particular to back-calculate the spring constant, k_w , and exponent, m . It is requested that this data be obtained and transmitted to the LGI whenever convenient.

In anticipation of future developments, it is also requested that the microrover investigators measure the force required to roll their wheels on a rough, rigid surface under various load-deflection conditions. This data is needed in order to distinguish and compare with the rolling resistance due to soil compaction.

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TABLE 1

EXAMPLE OF THE OUTPUT FILE FROM A COMPUTER RUN

WHEEL-E

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Output File Name: OUTPUT

Mar 16, 1994 14:56

INPUT

Diameter of the undeflected wheel	D =	100	mm
Maximum deflection of the wheel	d =	10.0	mm
Constant for the wheel 'springs'	kw =	1.00e+2	N
Exponent for the wheel 'springs'	m =	1.0	
Number of 'springs'	N =	101	

OUTPUT

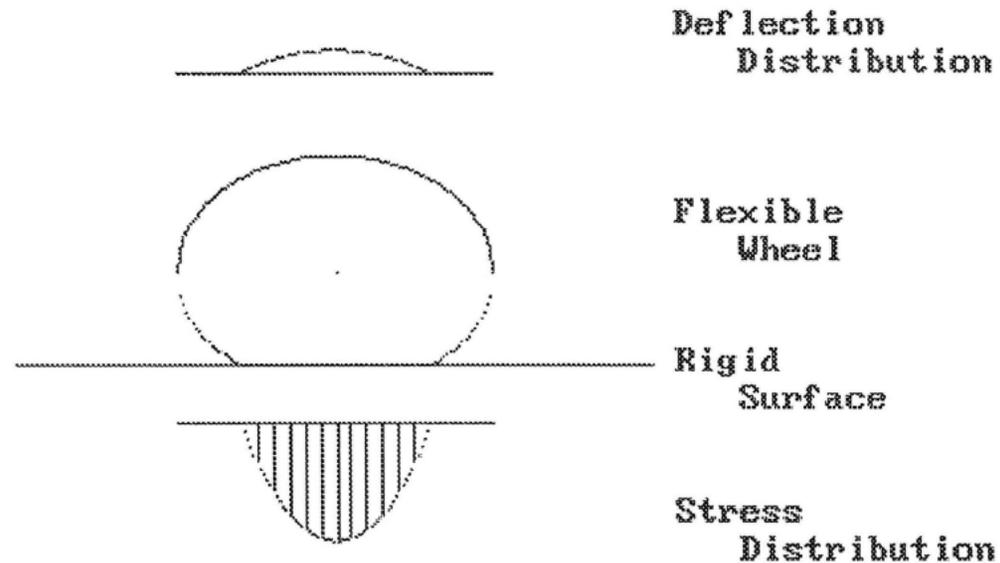
Deflection (mm)	Chord Length (mm)	Force Required (N)
.0	.0	0.00e+0
1.0	20.0	1.31e-1
2.0	28.0	3.71e-1
3.0	36.0	6.79e-1
4.0	40.0	1.04e+0
5.0	44.0	1.45e+0
6.0	48.0	1.90e+0
7.0	52.0	2.39e+0
8.0	56.0	2.91e+0
9.0	58.0	3.47e+0
10.0	60.0	4.05e+0

Maximum chord length	L =	60.0	mm
Maximum force required	W =	4.05e+0	N

Diameter of wheel = 100 mm
Maximum deflection = 10 mm
Wheel constant = 100 N
Wheel exponent = 1
Number of 'springs' = 101

WHEEL-E

Chord length = 60 mm
Force required = 4.05 N



Tap any key to erase plot

Copyright (c) 1994 LGI

Figure 1. Example of graphic display on computer monitor

Appendix 1

The following are PC/DOS programs:

ROVER.EXE	Type ROVER {Enter} Self-Explanatory
WHEEL-E.EXE	Type WHEEL-E {Enter} Self-Explanatory
BROWSE.COM	Type BROWSE filename [e.g., OUTPUT] {Enter} This is a public domain program for viewing an ASCII file without editing. To move around within a file, use the arrow keys and the {Page Up} and {Page Down} keys. To return to DOS, tap the {Esc} key.