LUNAR SOIL SIMULATION

and

TRAFFICABILITY PARAMETERS

by

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1.0 RECOMMENDED LUNAR SOIL TRAFFICABILITY PARAMETERS

Table 9.14 in the *Lunar Sourcebook* (Carrier et al. 1991, p. 529) lists the current recommended lunar soil trafficability parameters:

$$c_b = 0.017 \text{ N/cm}^2$$

$$\phi_b = 35°$$

$$K = 1.78 \text{ cm}$$

$$n = 1$$

$$k_c = 0.14 \text{ N/cm}^2$$

$$k_\phi = 0.82 \text{ N/cm}^3$$

$\mathbf{c_b}$ and $\boldsymbol{\phi_b}$ define the maximum shear strength of the soil available to drive the wheel. $\mathbf{c_b}$ is the coefficient of soil/wheel cohesion and its units are N/cm^2; and $\boldsymbol{\phi_b}$ is the soil/wheel friction angle.

K defines the fraction of the maximum soil shear strength that is actually mobilized due to wheel slippage: **K** is the coefficient of soil slip and its unit is cm.

n, $\mathbf{k_c}$, and $\mathbf{k_\phi}$ define the pressure-sinkage characteristics of the soil under a wheel load. **n** is the exponent of soil deformation and is dimensionless; $\mathbf{k_c}$ is the cohesive modulus of soil deformation and its units are N/cm^{n+1}; $\mathbf{k_\phi}$ is the frictional modulus of soil deformation and its units are N/cm^{n+2}.

[How these parameters are measured and how they are utilized to predict wheel sinkage, gross pull per wheel, soil compaction resistance, and slope-climbing are beyond the scope of this report. Suffice it to say that the design approach was developed by Bekker (1956, 1969) and it is highly empirical: The subscript "b" in $\mathbf{c_b}$ and $\boldsymbol{\phi_b}$ refers to soil properties measured with a special shear device called the bevameter, which stands for BEkker VAlue METER.]

2.0 ORIGIN OF RECOMMENDED PARAMETERS

The NASA Request for Proposals for the Lunar Roving Vehicle (LRV), used on Apollos 15, 16, and 17, was issued just after the Apollo 11 mission. Consequently, the lunar soil properties in the design specifications were primarily based on Surveyor measurements and observations. A range of values were specified (Costes et al. 1972):

$$c_b = 0 \text{ to } 0.035 \text{ N/cm}^2$$

$$\phi_b = 35° \pm 4°$$

$$K = 1.78 \pm 0.76 \text{ cm}$$

$$n = 1$$

$$k_c = 0 \text{ to } 0.28 \text{ N/cm}^2$$

$$k_\phi = 0.82 \text{ N/cm}^3$$

The prime contractor for the LRV, The Boeing Company, subsequently defined five sets of parameters:

	Soil Type				
Parameters	A	A_1	B	C	C_1
c_b (N/cm^2)	0	0	0.017	0.035	0.035
ϕ_b (deg)	31	31	35	39	39
K (cm)	1.02	2.54	1.78	2.54	1.02
n	1	1	1	1	1
k_c (N/cm^2)	0	0	0.14	0.28	0.28
k_ϕ (N/cm^3)	0.82	0.82	0.82	0.82	0.82

n and $\mathbf{k_\phi}$ are the same for all five soil types. Soil Type A corresponds to the *minimum* design values in the specified ranges. Soil Type A_1 is the same as Soil Type A, except that **K** has the *maximum* specified value of 1.78 + 0.76 = 2.54 cm.

Soil Type C corresponds to the *maximum* design values in the specified ranges. Soil Type C_1 is the same as Soil Type C, except that **K** has the *minimum* specified value of 1.78 − 0.76 = 1.02 cm.

Soil Type B corresponds to the *median* design values in the specified ranges. [And note that the values for Soil Type B are the same as the recommended lunar soil trafficability parameters listed in Section 1.0 above and in Table 9.14 of the *Lunar Sourcebook*.]

3.0 SIMULANT TESTING

In fact, there were no actual soils with the same parameters as Soil Types A, A_1, B, C, and C_1. And so, an extensive program of wheel/soil testing was undertaken at the Land Locomotion Laboratory at the Waterways Experiment Station of the US Army Corps of Engineers (see Figures 1 and 2). These tests were run on a crushed basalt lunar simulant and on Yuma Sand, each compacted to different densities, in an attempt to "bracket" the performance of the LRV wheel. In addition, archival soil values that had been measured in other trafficability studies were compared analytically. Altogether, Costes et al. reported the results of 38 numerical analyses.

After the Apollo 15 mission, the performance of the LRV was evaluated in detail and compared to the simulation results. Costes et al. and Mitchell et al. (1973, 1974) concluded that Soil Type B was the best match.

However, it was also observed that all 38 soil types yielded reasonable design estimates, in spite of the wide range of properties. This was because the low ground pressure of the LRV made its performance essentially independent of the soil type. This was an astonishing conclusion, given the effort that had gone into the testing, including the development of a lunar soil simulant. This is what led me to write in the *Lunar Sourcebook*: "From the experience of the Apollo and Lunokhod missions, we now know that almost any vehicle with round wheels will perform satisfactorily on the lunar surface, provided the ground contact pressure is no greater than about 7 - 10 kPa." (p. 522)

4.0 COMPARISON OF PARAMETERS FROM LRV STUDY

4.1 Coefficient of Soil/Wheel Cohesion: $\mathbf{c_b}$

A bar chart of the $\mathbf{c_b}$ values from the LRV study is shown in Figure 3. Soil Number 1 indicates the value for Soil Type B (or the recommended design value): 0.017 N/cm^2.

Soil Numbers 2 to 5 indicate Soil Types A, A_1, C, and C_1, respectively.

Soil Numbers 6 to 8 indicate representative values for loose, air-dry crushed basalt; and Number 9 is the average value for all tests on this simulant.

Soil Number 10 indicates a representative value for loose, moist crushed basalt; and

Number 11 is the average value for all tests on this simulant.

Soil Numbers 12 and 13 indicate representative values for intermediate density, air-dry crushed basalt; and Number 14 is the average value for all tests on this simulant.

Soil Numbers 15 to 17 indicate representative values for dense, air-dry crushed basalt; and Number 18 is the average value for all tests on this simulant.

Soil Numbers 19 to 22 indicate values for Yuma Sand, increasing in density. Numbers 23 to 26 indicate the same Yuma Sand, but in which **K** was arbitrarily increased from 2.54 cm to 4.32 cm as part of a sensitivity analysis.

Finally, Soil Numbers 27 to 38 are archival values of $\mathbf{c_b}$ from other trafficability studies.

[Note that the Soil Numbers do not correspond to the Soil Types listed in Costes et al. The latter have been re-arranged herein for greater clarity.]

The value of $\mathbf{c_b}$ used in the LRV analyses ranged from a minimum of 0 to a maximum of 0.417 N/cm^2.

4.2 Soil/Wheel Friction Angle: ϕ_b

A bar chart of the ϕ_b values is shown in Figure 4. Soil Number 1 is the recommended design value: 35°. The other Soil Numbers are in the same order as for $\mathbf{c_b}$.

The value of ϕ_b used in the LRV analyses ranged from a minimum of 13.8° to a maximum of 50.0°.

4.3 Coefficient of Soil Slip: **K**

A bar chart of the **K** values is shown in Figure 5. Soil Number 1 is the recommended design value: 1.78 cm. The other Soil Numbers are in the same order as for $\mathbf{c_b}$.

The value of **K** used in the LRV analyses ranged from a minimum of 1.02 cm to a maximum of 4.32 cm.

4.4 Exponent of Soil Deformation: **n**

A bar chart of the **n** values is shown in Figure 6. Soil Number 1 is the recommended design value: 1. The other Soil Numbers are in the same order as for $\mathbf{c_b}$.

The value of **n** used in the LRV analyses ranged from a minimum of 0.52 to a maximum of 4.24.

4.5 Cohesive Modulus of Soil Deformation: $\mathbf{k_c}$

The units for $\mathbf{k_c}$ are unusual, in that they are dependent on the value of **n**: N/cm^{n+1}. Thus, before the $\mathbf{k_c}$ values for the 38 soil types can be compared, they must be "rationalized" in terms of the width of the soil/wheel contact, **b**. The rationalized cohesive modulus of soil modulus, $\mathbf{k_c}'$ is given by:

$$k_c' = b^{n-1} k_c$$

The unit of **b** is cm; and the units of $\mathbf{k_c}'$ are N/cm^2.

Thus, a bar chart of the $\mathbf{k_c}'$ values is shown in Figure 7, based on the approximate average width of the LRV soil/wheel contact in the tests: **b** = 18 cm (the overall width of the LRV wheel is 23 cm). Soil Number 1 is the recommended design value: 0.14 N/cm^2 (corresponding to $\mathbf{k_c}$ = 0.14 N/cm^2).

The value of $\mathbf{k_c}'$ used in the LRV analyses ranged from a minimum of −2.81 N/cm^2 (corresponding to $\mathbf{k_c}$ = −0.70 $N/cm^{2.48}$) to a maximum of 1.74 N/cm^2 (corresponding to $\mathbf{k_c}$ = 1.03 $N/cm^{2.18}$). [The values for Soil Numbers 27 to 38 are all 0.]

4.6 Frictional Modulus of Soil Deformation: $\mathbf{k_\phi}$

The units for $\mathbf{k_\phi}$ are also dependent on the value of **n**: N/cm^{n+2}. Again, the $\mathbf{k_\phi}$ values must be rationalized:

$$k_\phi' = b^n k_\phi$$

The units of $\mathbf{k_\phi}'$ are N/cm^2.

A bar chart of the $\mathbf{k_\phi}'$ values is shown in Figure 8, also based on the width of the LRV soil/wheel contact. Soil Number 1 is the recommended design value: 14.8 N/cm^2 (corresponding to $\mathbf{k_\phi}$ = 0.82 N/cm^3).

The value of $\mathbf{k_\phi}'$ used in the LRV analyses ranged from a minimum of 7.1 N/cm^2 (corresponding to $\mathbf{k_\phi}$ = 0.87 $N/cm^{2.73}$) to a maximum of 42,000 N/cm^2 (corresponding to $\mathbf{k_\phi}$ = 0.20 $N/cm^{6.24}$).

4.7 Penetration Resistance Gradient: **G**

The US Army Corps of Engineers has developed an alternate trafficability method to the Bekker method, which it uses to predict and assess the performance of vehicles such as heavy trucks and tanks. This method utilizes a standardized cone penetrometer to measure penetration resistance of the soil vs. depth. The slope of this curve is called the penetration resistance gradient, or **G**. The units are stress ÷ depth = MN/m^3 (= N/cm^3).

Although the Corps method was not used to design the LRV, values for **G** were reported by Costes et al. for eight of the test soils, and these are presented in Figure 9. The value of **G** ranged from a minimum of 0.20 MN/m^3 to a maximum of 3.17 MN/m^3, or a factor of about 16. This is another measure of the wide range of soil properties used to design the LRV wheel.

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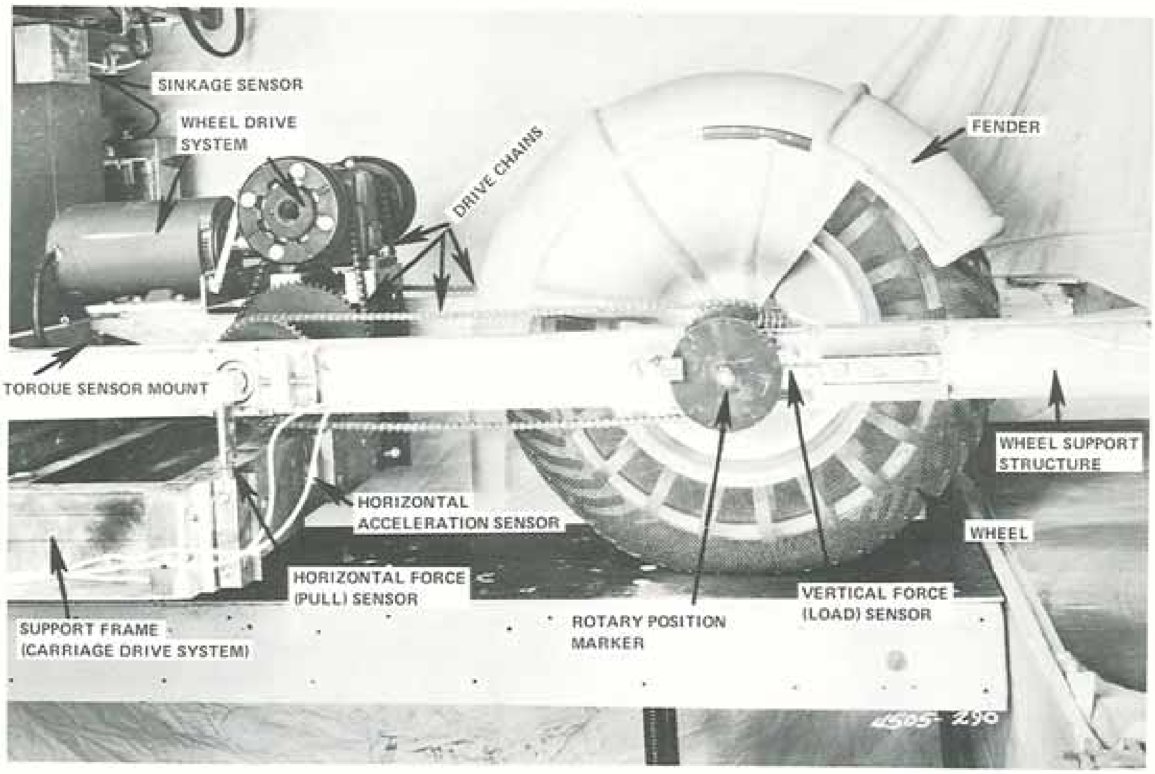
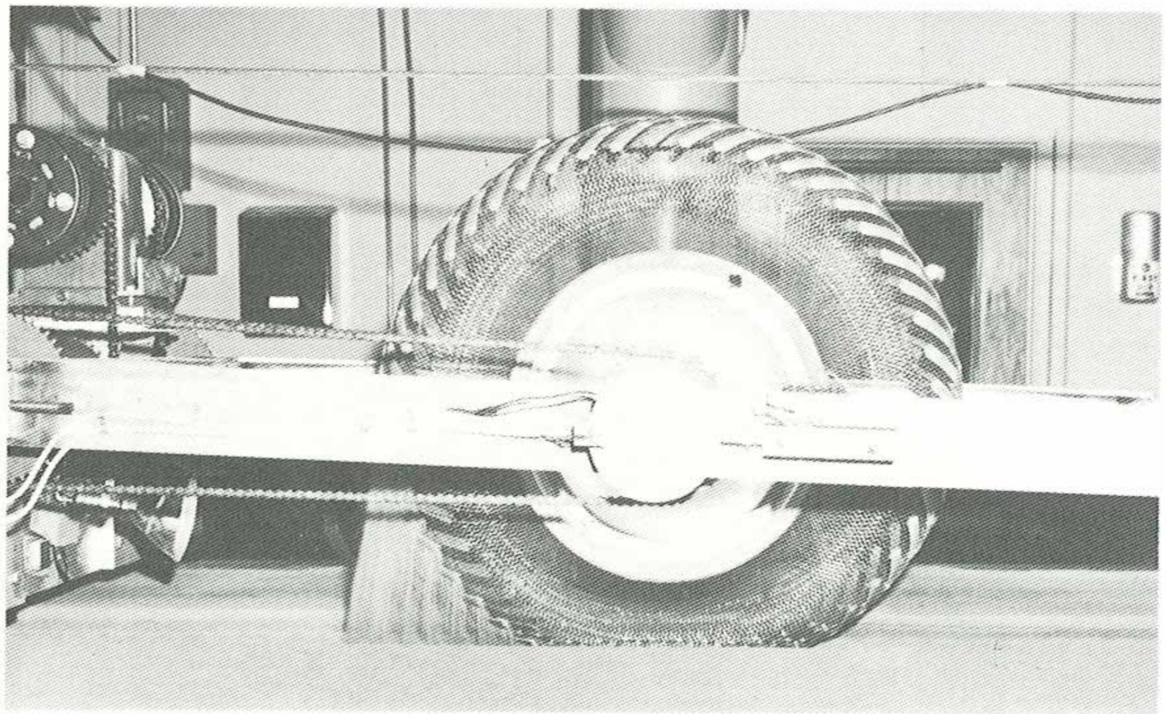


Figure 6. Apparatus for LRV wheel-soil interaction tests performed at the WES, Vicksburg, Mississippi.

Figure 1

Wheel/soil testing apparatus at the Land Locomotion Laboratory at the Waterways Experiment Station, US Army Corps of Engineers (from Costes et al. 1972)



b. "OPEN" WIRE-MESH WHEEL WITH 50-PERCENT CHEVRON TREAD COVER DESIGNS

Figure 2

Testing one of the designs of the wheel for the Lunar Roving Vehicle; the direction of motion is to the right. Note the soil pouring back out of the open weave of the wheel. (from Costes et al. 1972)

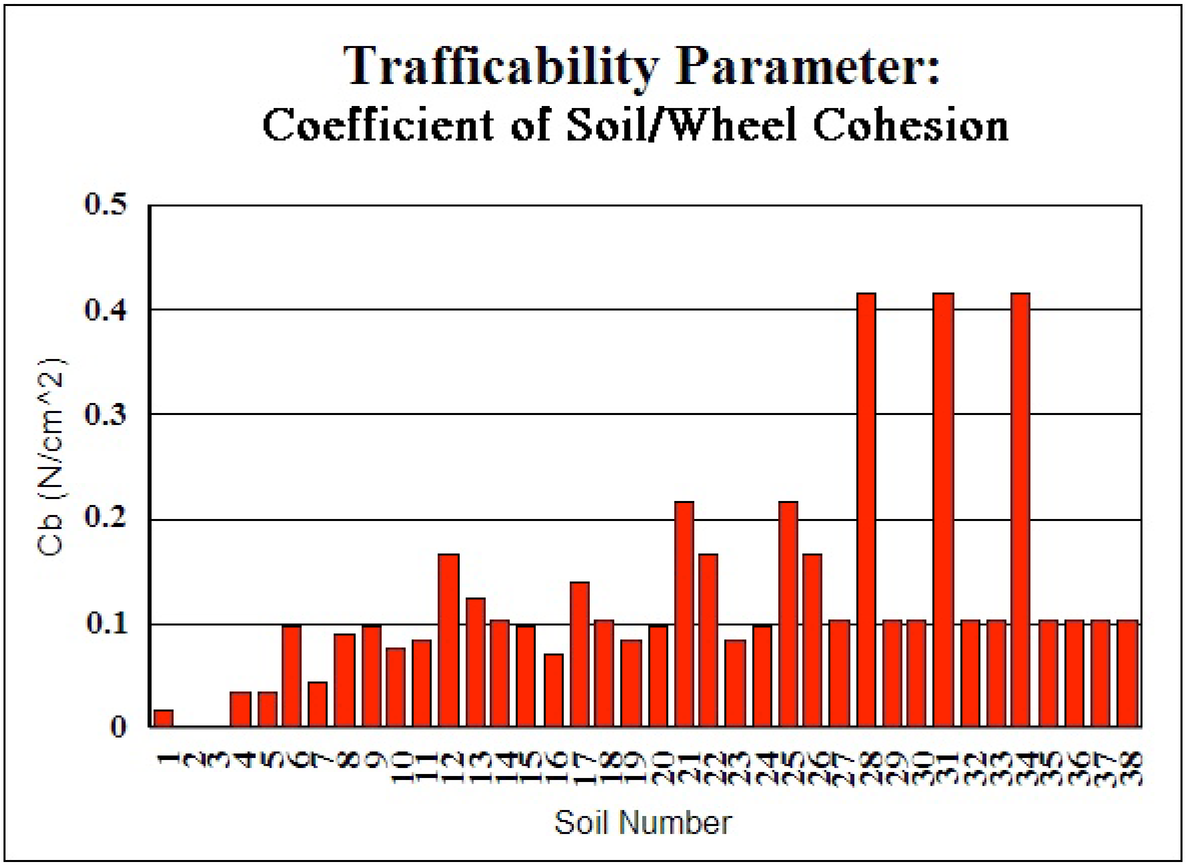


Figure 3

Soil Number	Description
1	**Soil Type B: recommended design value**
2 to 5	**Soil Types A, A_1, C, and C_1, respectively**
6 to 8	**Loose, air-dry crushed basalt: representative values**
9	**Loose, air-dry crushed basalt: average**
10	**Loose, moist crushed basalt: representative value**
11	**Loose, moist crushed basalt: average**
12 and 13	**Intermediate density, air-dry crushed basalt: representative values**
14	**Intermediate density, air-dry crushed basalt: average**
15 to 17	**Dense, air-dry crushed basalt: representative values**
18	**Dense, air-dry crushed basalt: average**
19 to 22	**Yuma Sand, increasing in density**
23 to 26	**Yuma Sand, increasing in density with K increased**
27 to 38	**Archival values from other trafficability studies**

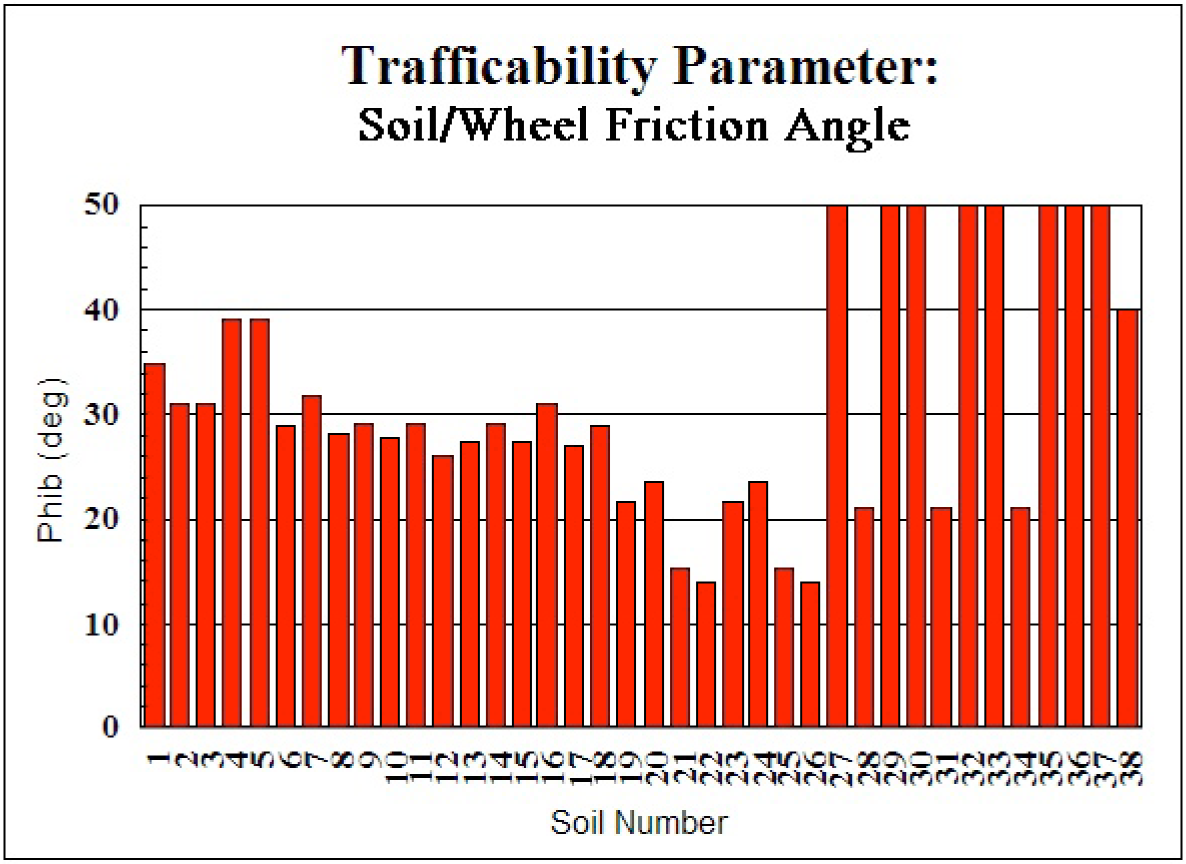


Figure 4

Soil Number	Description
1	Soil Type B: recommended design value
2 to 5	Soil Types A, A_1, C, and C_1, respectively
6 to 8	Loose, air-dry crushed basalt: representative values
9	Loose, air-dry crushed basalt: average
10	Loose, moist crushed basalt: representative value
11	Loose, moist crushed basalt: average
12 and 13	Intermediate density, air-dry crushed basalt: representative values
14	Intermediate density, air-dry crushed basalt: average
15 to 17	Dense, air-dry crushed basalt: representative values
18	Dense, air-dry crushed basalt: average
19 to 22	Yuma Sand, increasing in density
23 to 26	Yuma Sand, increasing in density with K increased
27 to 38	Archival values from other trafficability studies

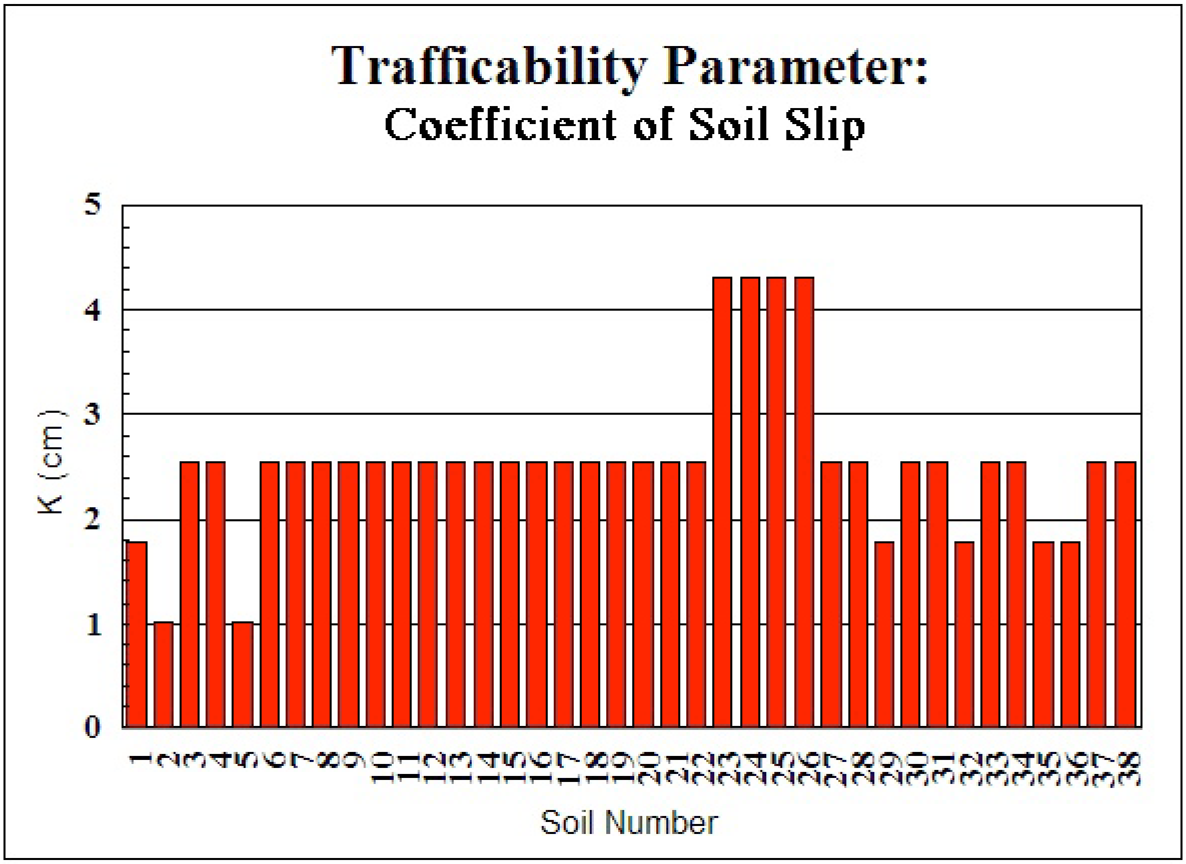


Figure 5

Soil Number	Description
1	**Soil Type B: recommended design value**
2 to 5	**Soil Types A, A_1, C, and C_1, respectively**
6 to 8	**Loose, air-dry crushed basalt: representative values**
9	**Loose, air-dry crushed basalt: average**
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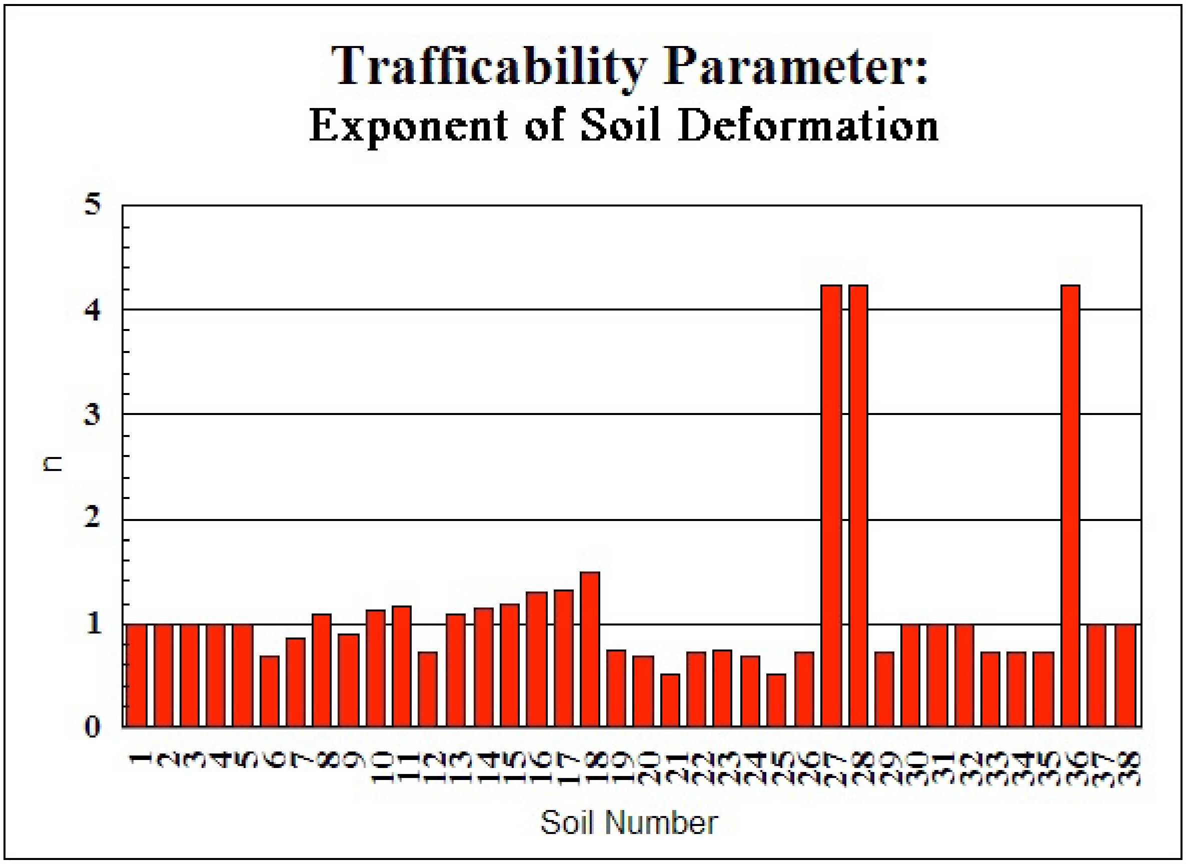

Figure 6

Soil Number	Description
1	Soil Type B: recommended design value
2 to 5	Soil Types A, A_1, C, and C_1, respectively
6 to 8	Loose, air-dry crushed basalt: representative values
9	Loose, air-dry crushed basalt: average
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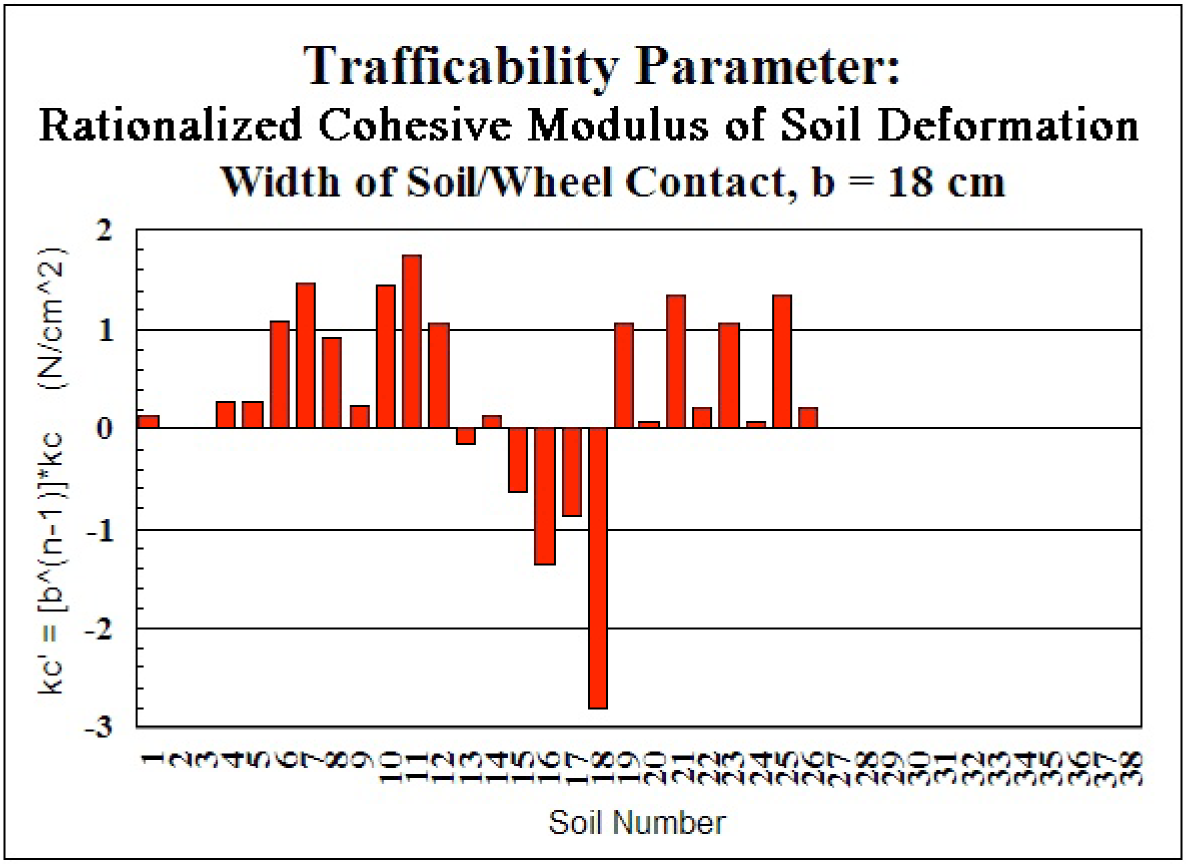

Figure 7

Soil Number	Description
1	Soil Type B: recommended design value
2 to 5	Soil Types A, A_1, C, and C_1, respectively
6 to 8	Loose, air-dry crushed basalt: representative values
9	Loose, air-dry crushed basalt: average
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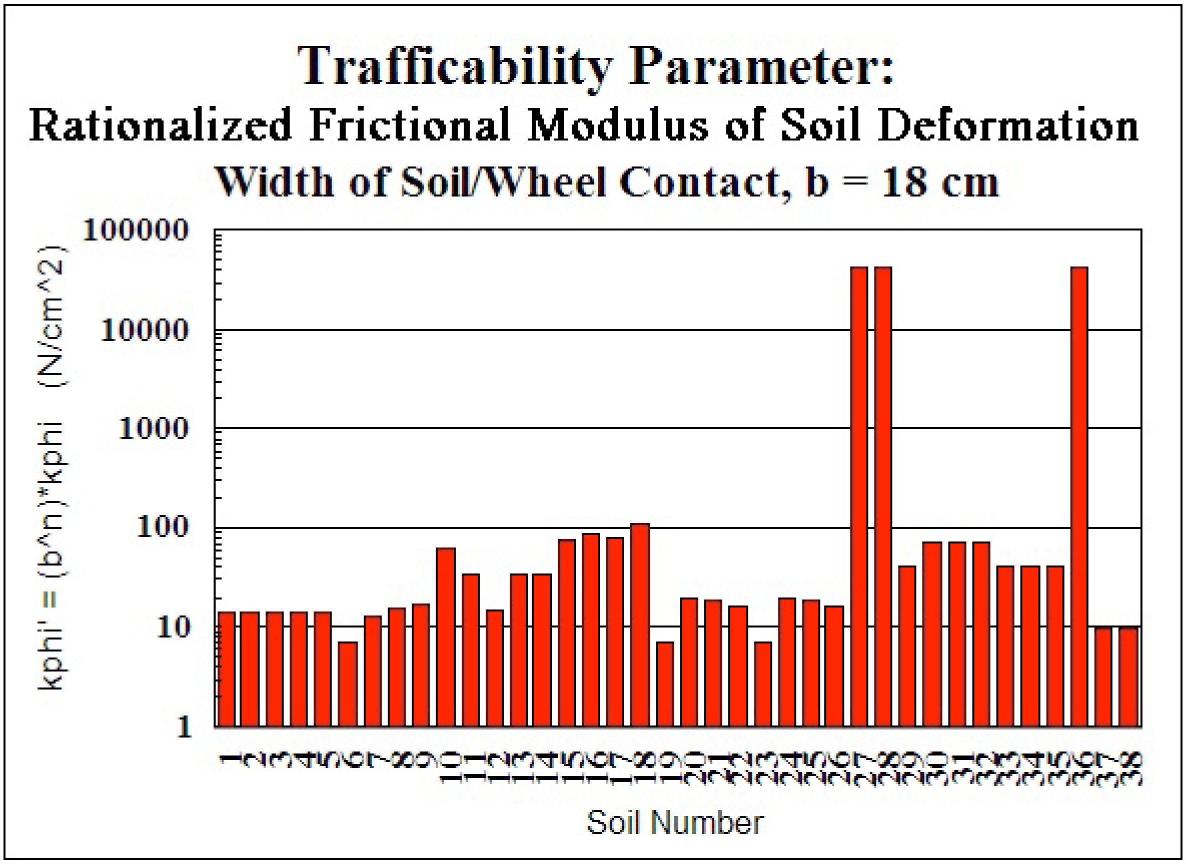

Figure 8

Soil Number	Description
1	Soil Type B: recommended design value
2 to 5	Soil Types A, A_1, C, and C_1, respectively
6 to 8	Loose, air-dry crushed basalt: representative values
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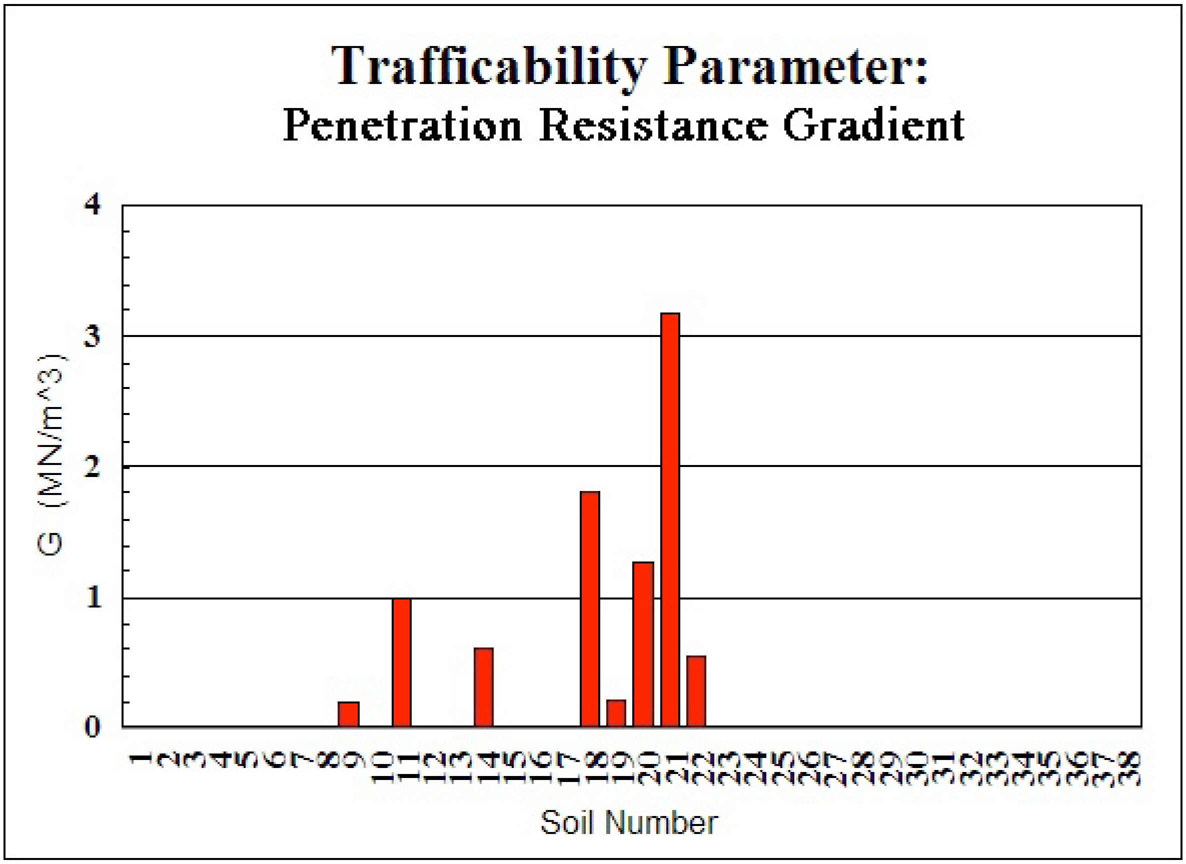

Figure 9

Soil Number	Description
9	Loose, air-dry crushed basalt: average
11	Loose, moist crushed basalt: average
14	Intermediate density, air-dry crushed basalt: average
18	Dense, air-dry crushed basalt: average
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