CRREL REPORT 90-13

Wheels and Tracks in Snow

Second Validation Study of the CRREL Shallow Snow Mobility Model

Paul W. Richmond, George L. Blaisdell
and Charles E. Green

December 1990

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, *published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

Cover: Small Unit Support Vehicle and Heavy Expanded Mobility Tactical Truck in the snow.

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U.S. Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

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Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

PREFACE

This report was prepared by Paul W. Richmond, Mechanical Engineer, George L. Blaisdell, Research Civil Engineer, both of the Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory, and Charles E. Green, Research Civil Engineer, Mobility Investigations Group, Mobility Systems Division, U.S. Army Waterways Experiment Station (WES). The report documents some of the efforts expended in a joint study conducted by CRREL and WES. The Keweenaw Research Center (KRC) of Michigan Technological University was contracted with to provide services and expertise for this project as well. Funding for this report was provided by DA Project 4A762784AT42, *Cold Regions Engineering Technology*; Work Unit CS/040, *Wheels vs Tracks in Winter*.

Technical review of this report was graciously provided by Sally A. Shoop (CRREL) and Russell Alger (KRC).

The authors express their appreciation to the personnel at CRREL, WES and KRC who worked on this project. Particular thanks go to Stephen Decato and Andrew Sunderlund of CRREL and to Russell Alger of KRC.

to contents

CONTENTS

ILLUSTRATIONS

TABLES

NOMENCLATURE

Symbols

a	length of tire or track in contact with undeformed snow
b	width of tire or track
b_a	average width of the deformed snow under a wheel or track
d_t	apparent distance traveled by a tire or track
d_v	actual distance traveled by a vehicle
DBP	draw bar pull
DIV	differential interface velocity
h	initial snow depth
ℓ	track length
n	number of wheels or tracks
n'	number of driven wheels or tracks
N	normal stress acting under a tire or track
p	tire or track contact pressure
r	tire radius
R_h	hard surface motion resistance
R_s	external resistance attributable to snow compaction
R_t	total motion resistance
T_g	gross traction
TMR	towed motion resistance
T_n	net traction
W	vehicle weight
z	vehicle sinkage
z_{max}	maximum sinkage for a vehicle
ρ_f	theoretical final density
ρ_o	initial density

Abbreviations

CIV	CRREL Instrumented Vehicle
HEMTT	Heavy Expanded Mobility Tactical Truck
HMMWV	High-Mobility Multipurpose Wheeled Vehicle
KRC	Keweenaw Research Center
LAV	Light Armored Vehicle
NDCC	Non-Directional Cross Country (a type of tire)
SUSV	Small Unit Support Vehicle

to contents

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PAUL W. RICHMOND, GEORGE L. BLAISDELL
AND CHARLES E. GREEN

INTRODUCTION

During the winters of 1988 and 1989, a winter mobility study was jointly conducted by WES and CRREL. These studies, part of the larger U. S. Army *Wheels/Tracks* program, were to be used to compare predictions of the CRREL shallow snow mobility model with actual snow mobility data for a wide variety of vehicles. Some of the 1988 results are reported in Blaisdell et al. (1990) and Green and Blaisdell (in press). The winter phase of the *Wheels/Tracks* study encompassed two winter field seasons; this report presents the results of the second winter field season (1989).

The major accomplishment of the first (1988) field study was the development of a new traction algorithm, which was incorporated into the second version of the shallow snow mobility model (SSM2.0). This traction equation was based on shear failure of snow via the Mohr–Coulomb criterion and used test data to arrive at a best-fit failure curve. The curve was found to predict traction well for all snow densities because tractive effort in most cases occurs on similar snow conditions (compacted snow with a density of approximately 550 kg/m^3) regardless of the initial snow conditions. Additionally, the equation was developed using data from wheeled vehicles equipped with state-of-the-art tires and several tracked vehicles. Vehicle motion resistance, however, was not predicted well by the shallow snow model.

Based on the results and analysis of the 1988 data, we decided that the final winter field season in the *Wheels/Tracks* program would primarily address vehicle motion resistance. Limited attention would be given to the traction aspect of mobility and this would be oriented towards removing some of the known caveats in the SSM2.0 traction algorithm.

During the second field season, tests were conducted primarily during January 1989 with limited testing continuing in March and April 1989.

BACKGROUND

The primary goal of this study was to investigate vehicle motion resistance in snow to continue validation of the CRREL shallow snow mobility model. The model is based on theoretical relationships and empirical expressions developed in the past from a large, but scattered, data base.

Briefly, SSM2.0 uses the following expressions to calculate shallow snow mobility:

$$\text{Net traction: } T_n = T_g - R_s \tag{1}$$

where T_g is gross traction and R_s is the external motion resistance attributable to snow compaction. Gross traction (in kilopascals) can be estimated for a wide range of vehicles using

$$T_g = 0.851\, N^{0.823} \tag{2}$$

where N is the normal stress under a tire or track (in kilopascals). R_s is primarily determined by the amount a vehicle sinks in the snow; SSM2.0 uses the following equations to estimate sinkage (z)

$$\text{Maximum sinkage: } z_{max} = h\left(1 - \frac{\rho_o}{\rho_f}\right) \tag{3}$$

where h is the depth of undisturbed snow (in meters), ρ_f is the theoretical final density in the rut following vehicle passage (kilograms per cubic meter, see Table 1 for values) and ρ_f is the initial undisturbed snow density (kilograms per cubic meter).

Both SSM1.0 and SSM2.0 were described fully by Blaisdell et al. (1990); we repeat a detailed description of SSM2.0 in Appendix A for reference, and refer the reader to Appendix A for the equation describing R_s.

Table 1. Final snow densities used in SSM2.0.

Maximum ground pressure (kPa)	*Final density* (kg/m^3)
< 210	500
211–350	550
351–700	600
> 701	650

FIELD EXPERIMENTS

The field experiments described in this report were carried out at Keweenaw Research Center (KRC) located at the Houghton County Airpark, Michigan (KRC is located on the Keweenaw Peninsula of Lake Superior). Tests were conducted by personnel from WES, KRC and CRREL. Two types of mobility tests were conducted—traction tests in various snow conditions and resistance tests in undisturbed snow.

CRREL and KRC personnel conducted mobility tests using the CRREL Instrumented Vehicle (CIV). The CIV, which is fully described by Blaisdell (1983), is based on a 1977 Jeep Cherokee with modifications to its braking and driving components to accommodate typical mobility tests. In addition to its onboard computer-based data acquisition system, the vehicle contains a number of transducers for force and speed measurements. In previous tests the CIV has produced results (traction data) that agreed very well with data obtained from larger vehicles with similar ground contact pressures (Blaisdell et al., 1990) in side by side tests. For this reason the CIV was used again this field season to extend the winter mobility data base. The CIV was equipped with several different tires during this study to examine the effects of tire parameters on traction and resistance.

The standard or control tire was a Michelin XCH4 all-season mud and snow tire and was tested at inflation pressures of 179 and 103 kPa (26 and 15 lb/in.^{2}). During the traction tests two additional tires were used: an NDCC (Non-Directional Cross Country) tire, which is the old standard military tire, and another Michelin XCH4 that had its tread buffed off. The NDCC tire was to represent a tire that wasn't up to the latest standards in tire design, and the buffed Michelin was used to determine the effect of tire tread, as compared with the unmodified control tire.

For the resistance tests, the control tire and two other tires were used. These two additional tires were not used for traction tests and were chosen for resistance testing based solely on their width and availability. The Firestone T145/80 is a temporary spare tire with a maximum width of 0.156 m (6.1 in.) and the Goodyear Eagle P225/60R15 is a low profile "street-rod" tire with a maximum width of 0.274 m (10.8 in.). The tires used with the CIV and their characteristics are given in Table 2.

Table 2. CIV tire data.

Tire nomenclature	*Inflation pressure (kPa)*	*Contact area* (m^2)*	*Radius† (m)*	*Width** (m)*	*Contact length (m)*	*Tire code*
Michelin	179	0.0412	0.375	0.260	0.2512	A
LT235XCH4	103	0.0635	0.375	0.279	0.3825	A
Michelin (buffed)††	179	0.0443	0.37	0.260	0.253	a
LT235XCH4	103	0.0586	0.37	0.272	0.335	a
NDCC	234	0.0238	0.39	0.215	0.1993	B
700-16LW	138	0.029	0.39	0.217	0.2377	B
Firestone T145/80	414	0.0204	0.325	0.156	0.187	C
Goodyear Eagle P225/60R15	248	0.0319	0.35	0.274	0.1636	D
Goodyear Tiempo	179	0.028	0.356	0.254	0.2073	E
P225/75R15	103	0.034	0.349	0.267	0.2564	

* Hard surface contact area.
† Radius of undeformed part of tire.
** Maximum deformed width.
†† The tread was buffed off to below the wear bars.

to contents

Table 3. Tire and track data for selected vehicles.

Vehicle	*Tire nomenclature*	*Inflation pressure (kPa)*	*Contact area* (m²)*	*Radius† (m)*	*Width** (m)*	*Contact length (m)*
HMMWV	37.00 × 12.5 R16.5	138/152	0.074	0.429	0.33	0.247
	36.00 × 12.5 LT	138		0.425		
HEMTT	16.0 R20	241/276	0.149	0.617	0.475	0.429
		139/207	0.171	0.589	0.483	0.472
LAV25††	12.50/75 R 20XL	207	0.100	0.445	0.378	0.368
		103	0.141	0.414	0.343	0.518
	11.00 R 16XL	290	0.580	0.434	0.314	—
		165	0.102	0.417	0.332	—
SUSV	Track	—	1.18	32.5°	0.6096	3.7592
Bradley††	Track	—	2.09	25°	0.533	3.920
M113A1††	Track	—	1.02	21°	0.381	2.667
M601A1	Track	—	2.8	35°	0.66	4.248

* Per tire on track.
† Radius for wheeled vehicles, entrance angle (degrees) for tracked vehicles.
** Maximum deformed width.
†† From 1988 tests.

Personnel from WES conducted mobility tests using the following group of military vehicles:

1. M988—High-Mobility Multipurpose Wheeled Vehicle (HMMWV), 4×4, equipped with Michelin 37×12.5R16.5LT tires.
2. M977—Heavy Expanded Mobility Tactical truck (HEMTT), 8×8, equipped with Michelin 16.0R20 tires.
3. M973—Small Unit Support Vehicle (SUSV), articulated, tracked.
4. M60A1—Main battle tank, tracked.

These vehicles were chosen to span the full range of typical ground vehicle contact pressures and to represent a cross section of current military vehicles. The characteristics of these vehicles, as well as those used during the 1988 field season, are given in Table 3.

Test procedures

The test procedures followed typical mobility field studies, in that measurements of net traction T_n and total motion resistance R_t were made with each vehicle under varying snow conditions. Although we wanted to conduct tests using all the vehicles on each day, the shortness of the available field time and the lack of appropriate snow falls precluded this. All of the tests were done in areas that had a packed snow base, with the exception of some traction and resistance tests, which were done on a snow-covered area that was underlaid by ice (the KRC ice rink).

CIV

The CIV's resistance to motion is measured with its rear tires driving and its front wheels rolling free. Since the triaxial load cells are located just inside the front wheels, this test measures the total amount of resistance felt at the front tires only. Motion resistance is first established on a level, undeformable surface. Measurements of hard surface resistance R_h are obtained for each tire type and selected inflation pressure. By convention, motion resistance tests are conducted at a vehicle speed of 8 km/hr (5 mi/hr), and it is known that resistance values are independent of moderate variations (± 3.2 km/hr [± 2 mi/hr]) in vehicle speed. Variations in R_h values between tire types are the result of differences in the forces necessary for tire flexing and can be attributed to differences in their design.

The external vehicle motion resistance in a snow cover (R_s) is calculated by measuring the motion resistance (R_t) in the test area using the above procedure and subtracting the hard surface motion resistance (R_h).

Traction is measured by accelerating the front (driving) wheels while braking the rear wheels to hold the vehicle speed constant at 8 km/hr ± 1 km/hr (5 ± 1/2 mi/hr). In this manner the front tires are driven through a wide range of slip values, starting at zero slip. A plot of measured T_n vs differential interface velocity (*DIV*) is used to obtain tractive effort. The T_n value is taken as the average tractive force in a window centered around the

to contents

maximum tractive force reading. The window is chosen to represent a range of slip values that could reasonably be maintained by a vehicle operator. Gross traction T_g is then calculated from eq 1 for each pair of resistance and traction tests.

Military vehicles

The tractive performance of the military vehicles was determined by measuring drawbar pull (*DBP*) and towed motion resistance (*TMR*). These measurements are not exactly the same as the T_n and R_t obtained with the CIV, since these were standard military vehicles and not modified for research. Drawbar pull tests were conducted by measuring the force that a vehicle can exert on a cable that is being used to resist vehicle motion. Thus

$$T_n = \frac{DBP}{n'} \qquad (4)$$

where n' is the number of driven tires or tracks. T_n represents the average tractive force per driven wheel or track.

Motion resistance is determined by measuring the vehicle's resistance to towing. Here,

$$R_t = \frac{TMR}{n} \qquad (5)$$

where n is the number of tires or tracks and R_t is the total motion resistance on an average tire or track.

Our procedure for measuring *DBP* was as follows. A load vehicle of approximately the same size and performance as the test vehicle was selected to apply a resistance to the test vehicle. A steel cable 0.016 m in diameter (0.6 in.) and 15.3 m in length (50 ft) was connected from the front of the load vehicle to a load cell attached to the rear pintle hook of the test vehicle. A string payout system (fishing reel) for measurement of true ground distance was also mounted on the test vehicle. Tachometers were mounted on the drive wheels or sprockets of the test vehicle and used to measure wheel or track travel during a test.

During each test, the test vehicles were operated in their lowest gear and at optimum engine rpm, yielding vehicle speeds between 3.2 and 8 km/hr (2 and 5 mi/hr). The vehicle proceeded into the test lane with the load vehicle following, the cable between the two vehicles being slack and unloaded. The load vehicle driver gradually applied load to the test vehicle by braking. The test sequence proceeded from the test vehicle initially experiencing a no-load, no-slip condition and increased up to a high-load, high-slip condition or a power limited condition in which the test vehicle could not maintain the desired track or tire speed. Forward speed and wheel or track speed were maintained (very nearly) constant for several seconds of steady-state pull measurements. Vehicle slip was calculated from a magnetic tape record by using both vehicle travel distance and wheel travel distance. The vehicle slip, in percent, is equal to

$$\frac{d_t - d_v}{d_v} \times 100 \qquad (6)$$

where d_t = apparent distance traveled by the wheel or track

d_v = distance actually traveled by the vehicle.

Continuous measurements were made in this manner until a sufficient number of load and slip combinations were recorded to develop a curve of drawbar pull–slip data (usually two good test sequences in the same area). As with T_n in the CIV traction test, *DBP* is a function of slip or *DIV*. Generally, in low density snow (less than 500 kg/m^3) maximum *DBP* occurs at rates of slip greater than 20%. However, efficiency of operation is inversely proportional to slip; little useful work is being done at very high slip rates. A slip of 20% is generally used as the cut off for power efficiency. Thus, the maximum *DBP* that occurred in the vicinity of 20% slip was used for the calculation of T_n (eq 4). Equation 1, again, is engaged to determine gross traction. This procedure agrees with the CIV data analysis process, which averaged the upper 15% of the gross traction data.

The procedure used for obtaining the *TMR* of the test vehicle in each test area was to tow the vehicle (with its transmission in neutral) at a speed of approximately 3.2 km/hr (2 mi/hr). After each traction test, the vehicle was steered into an undisturbed area adjacent to the traction test area, usually in a position straddling the ruts of the associated traction test. The load vehicle then towed the test vehicle forward to determine the *TMR*. The test proceeded for a sufficient distance to permit the load cell readings to stabilize and to be recorded on magnetic tape. An average value during the stable portion of the record was taken as *TMR*, and R_t was then calculated from eq 5. Finally, external resistance from snow compaction R_s was found by subtracting R_h from R_t.

Measurements of snow characteristics (depth, density, temperature and sinkage) were obtained at each test area while tests were being conducted. The undisturbed densities ranged from 70 to 320 kg/m^3 (4.4 to 20 lb/ft^3), and depths ranged from 3 to 30 cm (1 to 12 in.). Generally, each test condition represented snow from one storm and the air temperatures were well below freezing.

RESULTS AND ANALYSIS

Traction

The objective of traction tests during this series of tests was to obtain traction data for snow and tire condi-

to contents

Table 4. CIV traction data.

Date (1989)	Tire Code	Tire Pressure (kPa)	Normal load Left (N)	Normal load Right (N)	Normal stress Left (kPa)	Normal stress Right (kPa)	Resistance Left (N)	Resistance Right (N)	Net traction Left (N)	Net traction Right (N)	Gross traction Left (kPa)	Gross traction Right (kPa)	Average Traction (kPa)	Average Load (kPa)
17 Jan*	A	179	7408	6876	180	167	128	172	2323	2124	59	56	57.6	173.3
	A	179	7369	6913	179	168	128	172	1859	1696	48	45	46.8	173.3
	A	103	7514	6912	118	109	338	348	2076	1978	38	37	37.3	113.6
	A	103	7509	6905	118	109	338	348	1949	2010	36	37	36.6	113.5
	a	179	7488	6598	169	149	128	147	2679	2483	63	59	61.4	159.0
	a	179	7455	6486	168	146	128	147	2854	2705	67	64	65.8	157.4
	a	103	7336	6869	125	117	276	253	2977	2788	56	52	53.7	121.2
	a	103	7543	6747	129	115	276	253	2502	2297	47	44	45.5	121.9
	B	234	7631	7015	321	295	79	59	1441	1190	64	52	58.2	307.7
	B	234	7561	6886	318	289	79	59	1474	1337	65	59	62.0	303.5
	B	138	7554	6990	238	220	179	134	1486	1366	52	47	49.8	228.7
	B	138	7506	7029	236	221	179	134	1489	1566	52	53	52.9	228.5
1 Mar†	A	179	7312	6725	177	163	786	713	1645	1421	59	52	55.4	170.4
	A	179	7184	6559	174	159	786	713	1474	1470	55	53	53.9	166.8
	A	103	7251	6672	114	105	795	818	1693	1491	39	36	37.8	109.6
	A	103	7368	6647	118	106	795	818	1662	1465	39	37	37.9	112.1
	a	179	7483	6886	169	155	885	863	893	923	40	40	40.2	162.2
	a	179	7293	6617	165	149	885	863	1466	1107	53	44	48.8	157.0
	a	103	7171	6618	122	113	1055	876	1934	1770	51	45	48.1	117.7
	a	103	7188	6419	123	110	1055	876	1832	1697	49	44	46.6	116.1
	B	234	7404	6748	311	284	578	624	1697	1173	96	75	85.6	297.3
	B	234	7332	6708	308	282	578	624	1762	1544	98	91	94.7	295.0
	B	138	7332	6719	231	211	657	696	1616	1241	71	61	66.2	220.9
	B	138	7295	6710	229	211	657	696	1512	1147	68	58	63.1	220.2
6 Apr**	A	179	6477	6179	157	150	842	756	1978	1901	68	64	66.2	153.6
	A	179	6383	6257	155	152	842	756	2202	2256	74	73	73.3	153.4
	A	179	6278	6185	152	150	842	756	2222	2219	74	72	73.1	151.3
	A	179	6544	6212	159	151	149	163	2226	2249	57	58	57.8	154.8
	A	179	6549	6247	159	152	149	163	2273	2200	58	57	57.8	155.3

* On 17 January the tests were done on a packed and groomed snow road, the snow was approximately 6 cm deep and had an average density of 560 kg/m^3.
† On 1 March the tests were done on undisturbed dry snow, the initial snow density was 150 kg/m^3 and the depth ranged from 10 to 20 cm.
** On 6 April the snow was wet, the average density was 510 kg/m^3 and the depth was 2–7 cm, the last two tests on this date were done on packed wet snow.

tions distinctly different from those given in Blaisdell et al. (1990), which were used to develop eq 2. These new conditions were to be used to extend the usefulness of eq 2 from undisturbed snow with state-of-the-art tires to other tires and snow conditions; additionally, a feel for the general applicability (robustness) of the equation would be obtained. Using the CIV, we examined three additional initial snow conditions for traction—wet snow, wet packed snow and a groomed packed snow road. The military vehicles were tested for traction on the packed snow road and in undisturbed snow overlaying ice.

CIV traction

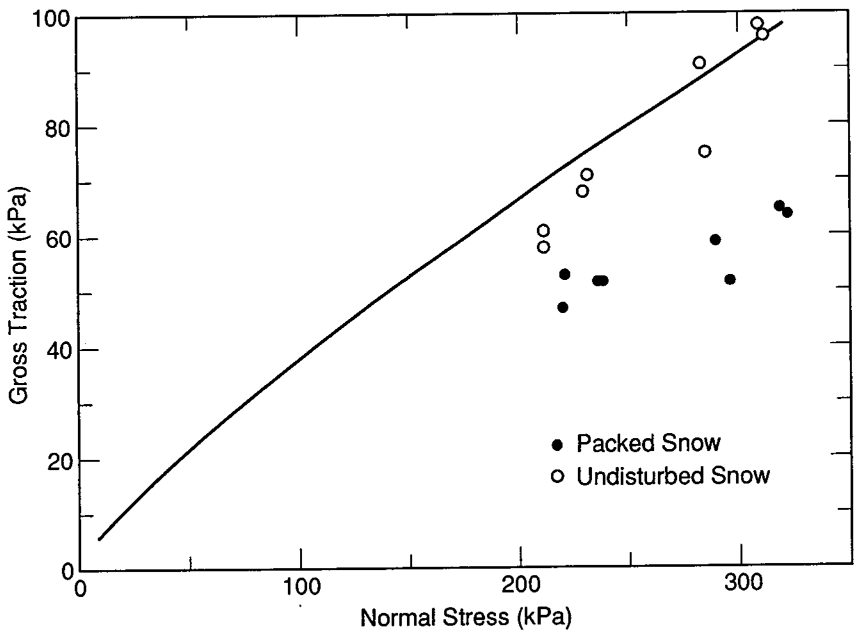
The traction data obtained using the CIV, sequentially equipped with three different tire types, and snow conditions are given in Table 4. The load values are those measured with the vehicle's load cells. The stress is obtained by dividing the load by the hard surface contact areas given in Table 2 for each tire and inflation pressure. These stress values are plotted in Figure 1; eq 2 (undisturbed snow, underlain by packed snow or frozen soil) is drawn on the plots for reference. There is good agreement between the traction equation and the data under all but two conditions. The performance of the NDCC tire on packed snow is over-predicted by eq 2, and the Michelin XCH4's performance is under-predicted on wet snow. The performance of the NDCC tire may be explained by considering tread geometry (deep, widely spaced lugs, see Appendix B) and the older style tire compound and carcass design. In undisturbed snow, the lugs of the NDCC tire were able to dig into the snow, developing the same magnitude of interfacial strength (traction) as the state-of-the-art tires. However, on packed snow the less-than-optimal tread design and tire compound could not engage the same amount of interfacial strength as observed with newer type of tires. In wet snow the Michelin XCH4 was able to develop more traction than expected. This may be ascribable to some uniqueness of the tire's compound, which provides greater stickiness between wet snow and the tire. We

to contents

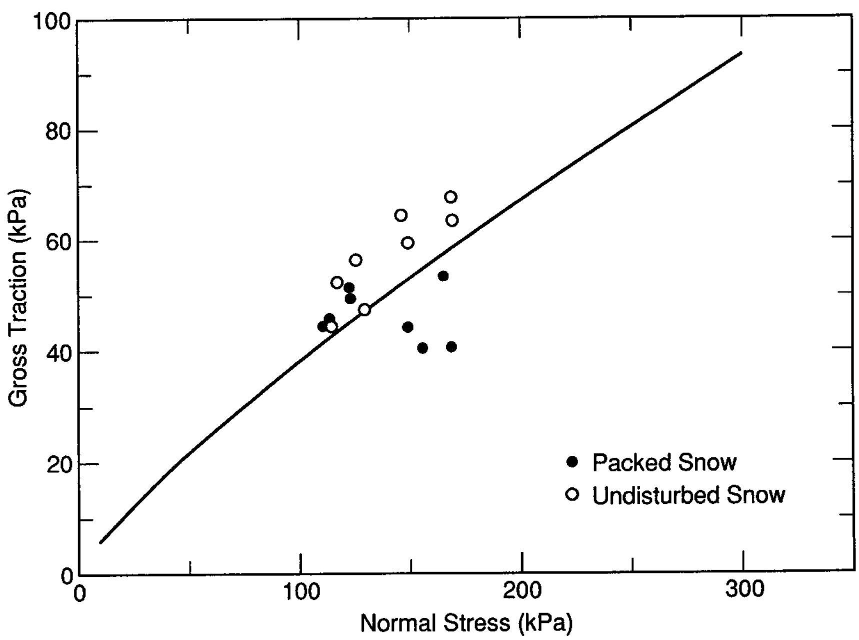
suspect the tire compound rather than the tread design because of the good performance of the buffed (treadless) Michelin in dry snow conditions (Fig. 1b).

Military vehicles

The data obtained from the military vehicles are given in Table 5 and plotted on Figure 2. Here again the vehicles were tested on several different types of snow conditions and eq 2 (undisturbed snow underlain by packed snow or soil) is drawn on the plot for reference. The range of traction values obtained with the CIV on ice (Blaisdell and Harrison 1981) with various tires is also shown in the figure. The following observations can be made from Figure 2: 1) there is a slight reduction in



a. NDCC tire.



b. Buffed Michelin XCH4.

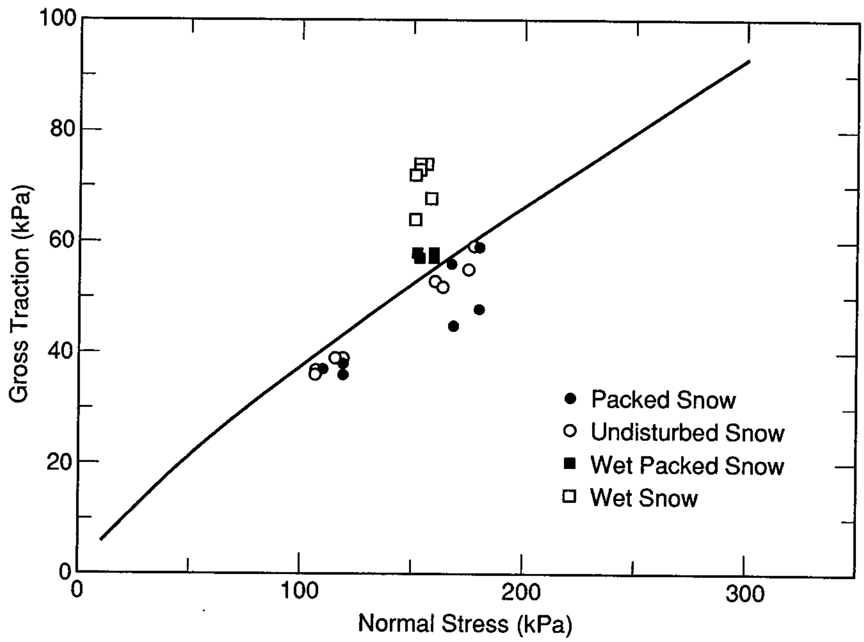
Figure 1. Traction data for the CIV equipped with three different tire types.

to contents

traction on hard-packed snow (approximately –21%) as compared to undisturbed snow, 2) the traction obtained when undisturbed snow overlays an ice cover is significantly reduced (approximately –51%), and is slightly higher than that observed on ice alone and 3) the values obtained under natural (undisturbed) snow conditions with the HMMWV and Bradley agree well with eq 2 (i.e., the data obtained in a prior field season). Least squares regression analysis yielded these two equations for the above conditions

$$\text{Hard-packed snow: } T_g = 0.321\, N^{0.97} \tag{7}$$

$$\text{Snow over ice: } T_g = 0.127\, N^{1.06}. \tag{8}$$



c. Michelin XCH4.

Figure 1 (cont'd).

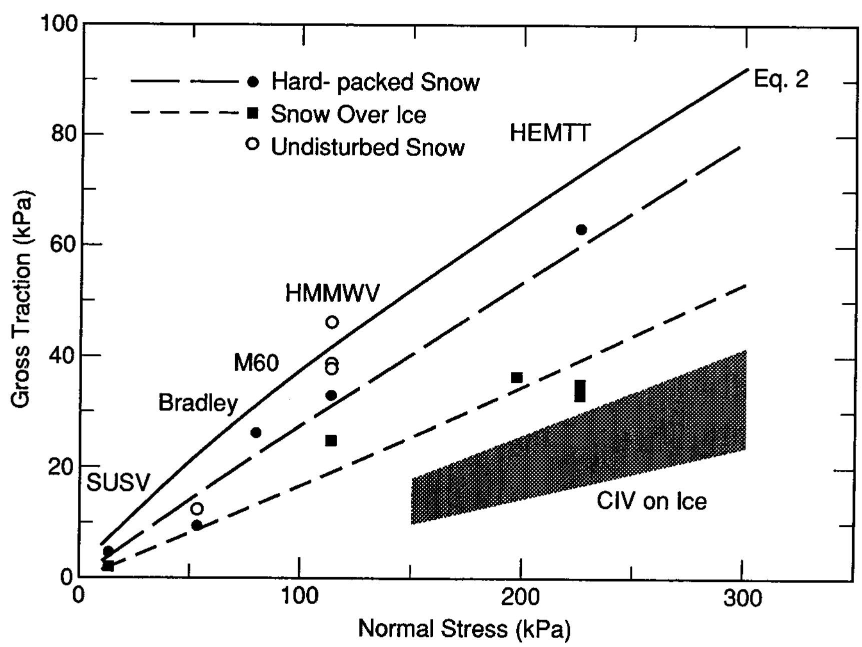


Figure 2. Traction data for the military vehicles.

Table 5. Military vehicles' traction data.

Date (1989)	Gross traction Coeff.	Gross traction Stress (kPa)	Normal stress (kPa)	Density (kg/m^3)	Snow description
a. HMMWV Weight: 33,450 N Contact area: 0.074 m^2					
17 Jan	0.335	37.9	113.0	180	undisturbed
	0.294	33.2	113.0	560	hard-packed
	0.222	25.1	113.0	120	undisturbed over ice
19 Jan	0.347	39.2	113.0	160	undisturbed
20 Jan	0.411	46.4	113.0	160	undisturbed
b. HEMTT Weight: 268,560 N Contact area (at 241/276 kPa): 0.149 m^2 Contact area (at 138/207 kPa): 0.171 m^2					
14 Jan	0.187	36.7	196.3	250	undisturbed over ice
	0.158	35.6	225.3	250	undisturbed over ice
18 Jan	0.282	63.5	225.3	560	hard-packed
	0.149	33.6	225.3	250	undisturbed over ice
c. SUSV Weight: 61,340 N Contact area: 1.18 m^2					
17 Jan	0.138	1.8	13.0	140	undisturbed over ice
	0.342	4.4	13.0	560	hard-packed
19 Jan	0.346	4.5	13.0	120	undisturbed
d. Bradley Weight: 223,299 N Contact area: 2.09 m^2					
14 Jan	0.182	9.7	53.4	560	hard-packed
17 Jan	0.238	12.7	53.4	230	undisturbed
e. M60A1 Weight: 444,820 N Area: 2.8 m^2					
17 Jan	0.332	26.4	79.4	560	hard-packed

At this point one might question the difference in results between the military vehicles and the CIV on hard-packed snow. The CIV (with the control Michelin tires) obtained only slightly less traction than predicted by eq 2, and compares well to data from the other vehicles, as seen in Figure 3. The buffed Michelin tires generated more traction than predicted by eq 2; this seems to indicate the effect of increased contact area (no voids on the tire's surface). The low traction values obtained with the NDCC tire (as discussed above) are seen to fall well below the other tires.

Resistance

The amount a vehicle sinks in the snow (sinkage) or the depth of the rut left by vehicle passage greatly affects the amount of motion resistance exerted by the snow. The shallow snow model calculates resistance based on the amount of sinkage. The maximum sinkage predicted by SSM2.0 is determined from eq 3. SSM2.0 uses Table 1 to obtain the theoretical final density (ρ_f) for the snow, using nominal vehicle contact pressure to enter the table. We know of no systematic study of actual rut density for wheeled vehicles, presumably because of the difficulty in measuring densities of this generally small layer of dense snow. Thus, it is customary to estimate or calculate a compacted density.

Snow properties, rut depth and densities were measured for comparison with those calculated in the SSM2.0. Table 6 presents the measured snow and rut characteristics and the sinkage values obtained using eq 3 where

to contents

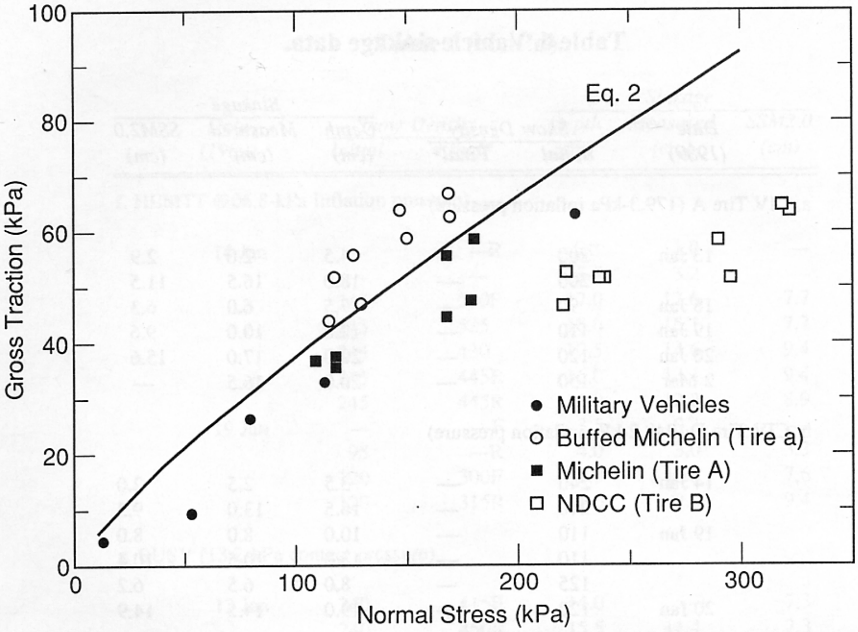


Figure 3. Vehicle traction on hard-packed snow.

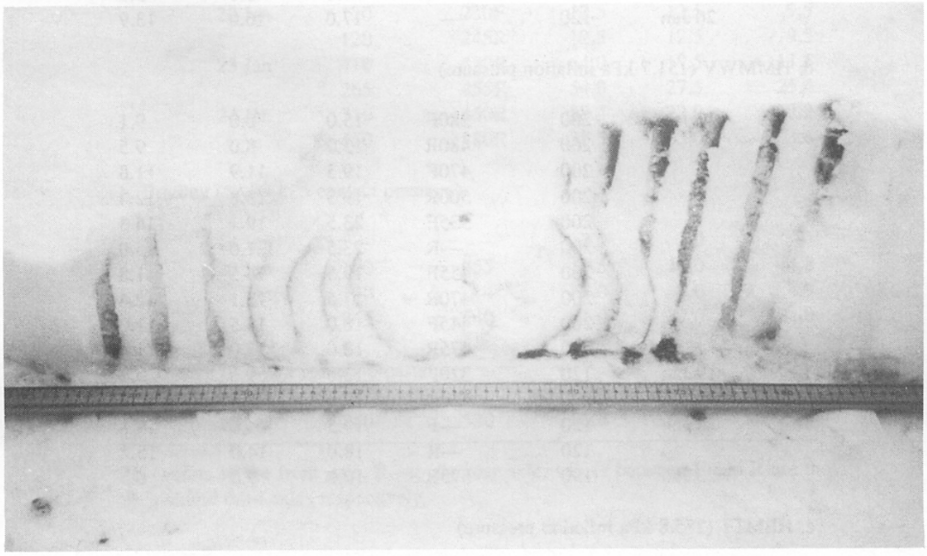


Figure 4. Chalk dust displacement around a tire rut.

final density is obtained from Table 1. In general, the measured rut density values do not agree very well with those used in SSM2.0; however, the values obtained for sinkage are very close.

Equation 3 was derived by assuming that the width of the deformed snow is a constant that is equal to the width of the tire or track and that the deformed snow is at a uniform density. In an effort to observe how the snow deforms, we marked the snow by filling 12.5-mm (0.5-in.) diameter vertical holes punched in the snow, perpendicular to the direction of wheel travel, with chalk dust. A vehicle was then driven into the marked area. Figure 4 shows the results of such an experiment and indicates that there is significant lateral snow displacement. To account for this lateral deformation, the deformed region under the tire rut (Fig. 4) can be assumed to have an average width b_a, while the tire (track) has a width of b. Using the same volumetric procedure used to develop eq 3, we obtained the following

to contents

Table 6. Vehicle sinkage data.

Date (1989)	Snow Density Initial	Snow Density Final*	Depth (cm)	Sinkage Measured (cm)	Sinkage SSM2.0 (cm)
a. CIV Tire A (179.3-kPa inflation pressure)					
13 Jan	200	—	4.5	2.0	2.9
	200	—	18.0	16.5	11.5
18 Jan	90	—	7.5	6.0	6.3
19 Jan	110	—	12.0	10.0	9.6
20 Jan	120	—	20.0	17.0	15.6
2 Mar	150	—	20.0	16.5	—
b. CIV Tire D (248.2-kPa inflation pressure)					
14 Jan	240	—	3.5	2.5	2.0
	240	—	16.5	13.0	9.3
19 Jan	110	—	10.0	8.0	8.0
	110	—	13.0	10.5	10.4
	125	—	8.0	6.5	6.2
20 Jan	120	—	19.0	14.5	14.9
c. CIV Tire C (413.7-kPa inflation pressure)					
19 Jan	110	—	12.0	11.0	10.0
19 Jan	95	—	6.0	5.0	5.1
20 Jan	120	—	17.0	16.0	13.9
d. HMMWV (151.7-kPa inflation pressure)					
13 Jan	200	380F	15.0	8.0	9.1
	200	480R	15.0	8.0	9.5
	200	470F	19.5	11.9	11.8
	200	500R	19.5	13.8	12.4
	200	535F	23.5	19.1	14.3
	200	—R	23.5	21.0	15.0
	200	455F	19.5	14.5	11.8
	200	470R	17.5	13.1	12.4
	200	445F	18.0	14.5	11.0
	200	475R	18.0	13.0	11.5
19 Jan	120	320F	13.0	9.0	9.7
	120	410R	12.0	8.5	10.2
20 Jan	120	—F	19.5	14.0	14.5
	120	—R	18.0	14.0	15.2
23 Jan	190	575R	10.0	9.0	6.5
e. HEMTT (275.8-kPa inflation pressure)					
14 Jan	250	490F	20.0	12.4	10.2
	250	440	21.0	16.9	10.2
	250	520	20.0	16.2	10.9
	250	460R	20.0	15.6	10.9
	250	490F	16.5	12.4	8.4
	250	490	18.0	13.2	8.4
	250	510	20.5	15.4	9.0
	250	510R	20.0	15.6	9.0
	245	—F	20.0	14.3	10.4
	245	460R	17.0	12.6	11.1
20 Jan	120	—F	13.0	10.0	9.5
	120	—R	13.0	—	10.2

to contents

Table 6 (cont'd).

Date (1989)	Snow Density Initial	Snow Density Final*	Depth (cm)	Sinkage Measured (cm)	Sinkage SSM2.0 (cm)
f. HEMTT (206.8-kPa inflation pressure)					
14 Jan	—	—R	6.0	1.0	—
	—	—	3.5	3.2	—
	245	510F	17.0	12.6	7.7
	245	525	18.0	15.1	7.7
	245	430	17.5	14.6	9.4
	245	445R	16.0	13.1	9.4
	245	445R	16.0	12.2	8.9
19 Jan	—	—F	3.5	0.3	—
	95	—R	4.0	3.0	3.3
	120	300F	12.0	10.5	7.6
	120	315R	11.0	9.0	9.4
g. SUSV (13.2-kPa contact pressure)					
13 Jan	240	415F	14.0	—	7.3
	240	450R	15.5	11.4	7.3
	250	460F	18.5	10.2	9.3
	250	450R	21.0	10.8	9.3
	250	440F	17.5	8.9	8.8
	250	430R	17.0	9.5	8.8
20 Jan	120	230F	12.5	12.5	9.5
	120	245R	12.5	12.5	9.5
23 Jan	410	430R	64.0	19.5	11.5
	265	455R	54.0	27.5	25.4
24 Jan	310	450R	58.4	22.9	22.2
	450	480R	35.5	5.0	3.6
h. Bradley (53.09-kPa contact pressure)					
14 Jan	—	—	3.0	2.0	—
20 Jan	100	355	18.5	16.0	14.8
23 Jan	190	—	8.0	7.0	4.9
	265	540	51.0	37.0	24.0
i. M60A1 (79.4-kPa contact pressure)					
16 Jan	340	520	56.0	32.0	17.9

*F—refers to the front axle, R—to the rear axle, values between F and R are the second and third axles respectively.

$$z = h\left(1 - \frac{b\rho}{b_a\,\rho_f}\right). \qquad (9)$$

Since (b/b_a) is less than 1, the effect of this term is to increase the sinkage. This explains why, even with the estimates of final theoretical density (ρ_f) being too high, eq 3 still yields good predictions of sinkage in SSM2.0.

The predicted sinkage values in Table 6 were determined following the SSM2.0 algorithm (eq 3) with the caveat that the snow depth used for the front tires was also used for all following tires, even though the measured snow depths (at the following wheels) may have been different. The use of this algorithm produces fairly good results.

The measured sinkage data from different vehicles are depicted in Figure 5. The y-axis variable ($\rho \times h$) and the x-axis variable (h–z) were obtained by rearranging eq 3 so that the slope on this plot would represent the final density (ρ_f). The data fall quite neatly on a straight line, which has a slope of 563 kg/m^3. Predictions of sinkage made using the least-squares regression equation (y=563.0x+7.11) are only slightly different (and no better on the average) from those obtained using the algorithm of SSM2.0.

Motion resistance data for the CIV are given in Table 7. Motion resistance tests were conducted using three different width tires to determine the effect of tire width

to contents

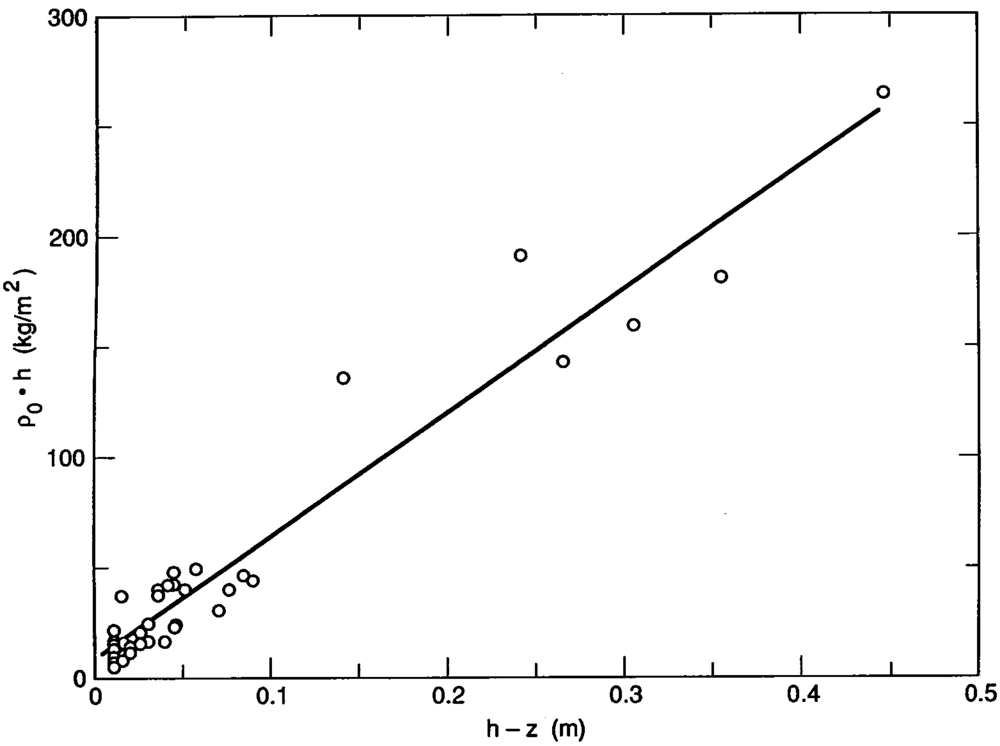


Figure 5. Vehicle sinkage analysis.

on resistance. Comparing the data for tests conducted sequentially in the same test area with similar snow conditions revealed no clear trend when tire width was the only changing parameter. We wanted a parameter that could be used to combine vehicle characteristics and varying snow conditions. After several iterations, the parameter ($\rho_o \times b \times a$) was tried, where a is the length of the tire or track in contact with undisturbed snow (Fig. A1), and is determined from the calculated sinkage and tire or track geometry. The CIV resistance attributable to snow deformation reported here and that from Blaisdell et al. (1990) are plotted in Figure 6a. The scattered data in Figure 6a tend toward 0 as the snow parameter approaches 0. A 0 intercept is expected since no snow yields no external resistance. An equation of the form $y=dx^e$ was fit to the data in Figure 6b.

Table 8 contains the resistance data obtained from the military vehicles during both field seasons (see Table 3); also included are calculations of the parameter ($\rho_o \times b \times a$) as defined above. The resistance value presented is per tire (track) and thus all vehicle data can be shown on the same graph. The SUSV was considered a two-track vehicle (as opposed to four), since it appears that the trailing track does not act like a trailing tire on a wheeled vehicle owing to its extremely low ground pressure.

The division of R_s by the number of wheels or tracks is a departure from traditional thoughts on vehicle resistance in snow. In the past, and in SSM2.0, it was believed that trailing tires with contact pressures lower than the preceding tires would have little or no external resistance. By dividing by the number of wheels, we are assuming here that following tires displace as much snow (on a mass basis) as preceding tires. This theory was not explicitly examined during these tests, and the sinkage measurements discussed above do not apply since sinkage was measured behind each axle after the vehicle came to a stop. To test this idea, the sinkage should be measured at the same location in the snow as each axle passes by.

The resistance per wheel (per track) are plotted in Figure 7 and are combined in Figure 8. The results of least-squares regression analysis based on an equation of the form $y=dx^e$ are shown on each plot. The equation obtained from using all the data

$$R_s = 68.083\ (\rho_o a w)^{0.9135}$$

$$\text{(correlation coefficient } r^2 = 0.39) \qquad (10)$$

is used to estimate resistance for the vehicles and is compared with both the measured values and the results from SSM2.0 in Tables 7 and 8.

Table 9 summarizes the percent errors shown in Tables 7 and 8. From this table it can be seen that eq 10 unfortunately does not offer any improvement over SSM2.0.

to contents

Table 7. Motion resistance for the CIV.

Date	Tire Width (m)	Tire Diameter (m)	Arc (a) (m)	Density (ρ) (kg/m^3)	Depth (b) (cm)	ρxbxa (kg/m)	Sinkage (cm)	Temp. (°C)	Net resist. (N)	Eq 10 Est. resist.	Eq 10 Diff.* (%)	SSM2.0 Est. resist.	SSM2.0 Diff.* (%)
1988													
23 Jan	0.254	0.712	0.28	75	12.5	5.38	10.6	–5	125	317	153	526	321
	0.267	0.698	0.28	75	12.5	5.60	10.6	–5	76	328	332	340	348
	0.254	0.712	0.25	70	10.0	4.49	8.6	–2	58	269	363	410	607
	0.267	0.698	0.25	70	10.0	4.67	8.6	–2	125	278	123	265	112
26 Jan	0.254	0.712	0.22	148	9.0	8.11	6.3	–5	305	461	51	442	45
	0.267	0.698	0.21	148	9.0	8.43	6.3	–5	247	477	93	286	16
10 Feb	0.254	0.712	0.35	190	25.0	16.68	15.5	–8	1021	890	–13	1213	19
	0.267	0.698	0.39	190	32.0	19.89	19.8	–8	1085	1045	–4	1004	–7
	0.254	0.712	0.32	190	22.0	15.57	13.6	–7	721	836	16	1067	48
	0.267	0.698	0.27	190	16.0	13.67	9.9	–7	696	742	7	502	–28
12 Feb	0.254	0.712	0.28	200	18.0	14.47	10.8	–16	716	782	9	864	21
	0.267	0.698	0.35	200	27.0	18.71	16.2	–16	894	989	11	838	–6
17 Feb	0.254	0.712	0.27	265	20.7	18.15	9.7	–4	1079	961	–11	876	–19
	0.267	0.698	0.27	265	20.7	18.87	9.7	–4	801	997	24	567	–29
1989													
18 Jan	0.260	0.75	0.22	90	7.5	5.10	6.2	–4	136	301	122	343	153
	0.156	0.65	0.18	95	6.0	2.72	5.1	–4	102	170	66	0	–100
	0.274	0.7	0.21	125	8.0	7.23	6.2	–4	158	415	163	0	–100
19 Jan	0.260	0.75	0.27	110	12.0	7.74	9.4	0	200	442	121	579	189
	0.156	0.65	0.26	110	12.0	4.45	9.8	0	89	266	199	0	–100
	0.274	0.7	0.26	110	11.5	7.83	9.2	0	245	446	82	0	–100
20 Jan	0.260	0.75	0.33	120	17.4	10.14	13.2	–11	274	565	107	854	212
	0.156	0.65	0.40	120	27.5	7.56	22.0	–11	509	432	–15	0	–100
	0.274	0.7	0.37	120	22.3	12.03	17.4	–11	432	660	53	0	–100
2 Mar	0.156	0.65	0.36	170	25.5	9.63	18.3	–7	1026	539	–47	0	–100
	0.156	0.65	0.38	120	25.0	7.15	20.0	–7	776	411	–47	0	–100
	0.274	0.7	0.33	170	20.7	15.29	14.3	–7	905	822	–9	0	–100
	0.274	0.7	0.32	120	17.0	10.38	13.3	–7	430	577	34	0	–100
	0.260	0.75	0.32	170	19.8	14.27	13.1	–7	747	772	3	996	33
	0.260	0.75	0.34	120	19.0	10.63	14.4	–7	601	590	–2	933	55
	0.260	0.75	0.35	120	20.0	10.93	15.2	–7	767	605	–21	982	28
	0.260	0.75	0.35	120	20.0	10.93	15.2	–7	724	605	–16	982	36
	0.260	0.75	0.35	120	20.0	10.93	15.2	–7	918	605	–34	982	7
									Average:		60		36
									Standard deviation:		98		
											156		

* Percent difference from the measured net resistance.

to contents

Table 8. Motion resistance data for military vehicles.

a. Tracked vehicles.

Date	Track: Width (m)	Track: Arc (a) (m)	Density (ρ) (kg/m^3)	Depth (b) (cm)	ρ×b×a (kg/m)	Sinkage (cm)	Motion resistance: Coeff.	Motion resistance: Gross (N)	Motion resistance: Net (N)	Eq 10: Est. resist.	Eq 10: Diff.* (%)	SSM2.0: Est. resist.	SSM2.0: Diff.* (%)
1. SUSV													
<u>1988</u>													
21 Jan	0.6096	0.06	60	3.5	2.10	3.1	0.130	7974	1840	134	–93	48	–97
26 Jan	0.6096	0.12	148	9.0	10.64	6.3	0.160	9815	2760	590	–79	157	–94
28 Jan	0.6096	0.14	150	11.0	13.10	7.7	0.170	10428	3067	714	–77	192	–94
10 Feb	0.6096	0.32	220	31.0	43.33	17.4	0.170	10428	3067	2129	–31	514	–83
10 Feb	0.6096	0.20	250	22.0	31.20	11.0	0.170	10428	3067	1577	–49	344	–89
13 Feb	0.6096	0.23	290	30.0	41.46	12.6	0.150	9201	2454	2045	–17	418	–83
13 Feb	0.6096	0.21	250	23.0	32.62	11.5	0.160	9815	2760	1643	–40	359	–87
<u>1989</u>													
17 Jan	0.6096	0.05	140	4.0	4.57	2.9	0.072	4417	61	273	345	69	13
17 Jan	0.6096	0.00	560	6.0	0.00	0.0	0.083	5091	399	0	–100	0	–100
19 Jan	0.6096	0.07	120	5.0	5.17	3.8	0.085	5214	460	306	34	85	–82
19 Jan	0.6096	0.19	160	15.0	18.52	10.2	0.152	9324	2515	979	–61	262	–90
19 Jan	0.6096	0.14	160	11.0	13.58	7.5	0.112	6870	1288	738	–43	192	–85
23 Jan	0.6096	0.43	320	64.0	83.65	23.0	0.218	13372	4539	3883	–14	794	–82
23 Jan	0.6096	0.09	190	8.0	10.69	5.0	0.071	4355	31	593	1832	138	349
23 Jan	0.6096	0.16	190	14.0	18.71	8.7	0.108	6625	1165	989	–15	241	–79
									Average		102		–52
									Standard deviation:		909		110
2. M113.													
<u>1988</u>													
22 Jan	0.381	0.13	160	7.0	8.10	4.8	0.060	6245	572	460	–20	295	–48
23 Jan	0.381	0.28	75	12.0	8.13	10.2	0.050	5204	52	462	788	431	728
28 Jan	0.381	0.26	80	11.0	7.86	9.2	0.080	8327	1613	448	–72	404	–75
10 Feb	0.381	0.48	220	31.0	40.60	17.4	0.130	13531	4216	2007	–52	1242	–71
10 Feb	0.381	0.31	250	22.0	29.24	11.0	0.090	9368	2134	1486	–30	830	–61
13 Feb	0.381	0.32	250	23.0	30.57	11.5	0.130	13531	4216	1548	–63	868	–79
									Average:		92		66
									Standard deviation:		311		296

to contents

Table 8 (cont'd).

a. Tracked vehicles (cont'd).

Date	Track Width (m)	Track Arc (a) (m)	Density (ρ) (kg/m³)	Depth (b) (cm)	ρ×b×a (kg/m)	Sinkage (cm)	Motion resistance Coeff.	Motion resistance Gross (N)	Motion resistance Net (N)	Eq 10 Est. resist.	Eq 10 Diff.* (%)	SSM2.0 Est. resist.	SSM2.0 Diff.* (%)
3. Bradley													
21 Jan	0.5334	0.07	60	3.5	2.33	3.1	0.060	13398	1563	148	–91	167	–89
23 Jan	0.5334	0.20	75	10.0	8.05	8.5	0.060	13398	1563	457	–71	523	–67
28 Jan	0.5334	0.22	80	11.0	9.33	9.2	0.080	17864	3796	524	–86	589	–84
12 Feb	0.5334	0.28	230	22.0	34.49	11.9	0.180	40194	14961	1728	–88	1264	–92
12 Feb	0.5334	0.18	260	16.0	25.20	7.7	0.110	24563	7146	1298	–82	860	–88
1989													
14 Jan	0.5334	0.05	240	4.0	6.30	2.1	0.049	10942	335	366	9	225	–33
17 Jan	0.5334	0.00	560	6.0	0.00	0.0	0.062	13845	1786	0	–100	0	–100
18 Jan	0.5334	0.00	560	6.0	0.00	0.0	0.063	14068	1898	0	–100	0	–100
20 Jan	0.5334	0.26	230	20.0	31.35	10.8	0.083	18534	4131	1584	–62	1149	–72
										Average:	–74		–81
										Standard deviation:	32		20

b. Wheeled vehicles.

Date	Wheel Width (m)	Wheel Diameter (m)	Arc (a) (m)	Density (ρ) (kg/m³)	Depth (b) (cm)	ρ×b×a (kg/m)	Sinkage (cm)	Motion resistance Coeff.	Motion resistance Gross (N)	Motion resistance Net (N)	Eq 10 Est. resist.	Eq 10 Diff.* (%)	SSM2.0 Est. resist.	SSM2.0 Diff.* (%)
1. HMMWV														
1988														
19 Jan	0.33	0.858	0.00	550	5.0	0.00	0.0	0.050	1673	226	0	–100	0	–100
21 Jan	0.33	0.858	0.16	60	3.5	3.24	3.1	0.050	1673	226	199	–12	163	–28
23 Jan	0.33	0.858	0.30	75	12.0	7.48	10.2	0.070	2342	393	428	9	583	48
26 Jan	0.33	0.858	0.24	148	9.0	11.53	6.3	0.090	3011	560	635	13	465	–17
28 Jan	0.33	0.858	0.29	80	11.0	7.57	9.2	0.050	1673	226	433	92	541	139
10 Feb	0.33	0.858	0.40	220	31.0	29.06	17.4	0.140	4683	978	1478	51	1469	50
10 Feb	0.33	0.858	0.31	250	22.0	25.92	11.0	0.100	3345	644	1332	107	974	51
13 Feb	0.33	0.858	0.34	290	30.0	32.29	12.6	0.130	4349	895	1628	82	1174	31
26 Jan	0.33	0.858	0.34	148	18.0	16.53	12.7	0.070	2342	393	883	125	930	136
15 Feb	0.33	0.858	0.28	240	17.0	22.21	8.8	0.120	4014	811	1156	43	772	–5
1989														
13 Jan	0.33	0.858	0.25	220	12.7	18.19	7.1	0.106	3546	694	964	39	593	–15
13 Jan	0.33	0.858	0.23	240	11.4	18.07	5.9	0.069	2308	385	958	149	517	35

to contents

Table 8 (cont'd). Motion resistance data for military vehicles.

b. Wheeled vehicles (cont'd).

Date	Wheel Width (m)	Wheel Diameter (m)	Arc (a) (m)	Density (ρ) (kg/m³)	Depth (b) (cm)	ρ×b×a (kg/m)	Sinkage (cm)	Motion resistance Coeff.	Motion resistance Gross (N)	Motion resistance Net (N)	Eq 10 Est. resist.	Eq 10 Diff.* (%)	SSM2.0 Est. resist.	SSM2.0 Diff.* (%)
1. HMMWV (cont'd)														
13 Jan	0.33	0.858	0.33	250	23.5	26.83	11.8	0.140	4683	978	1374	40	1040	6
13 Jan	0.33	0.858	0.30	250	20.3	24.85	10.2	0.071	2375	401	1281	219	899	124
13 Jan	0.33	0.858	0.30	250	20.6	25.04	10.3	0.086	2877	527	1290	145	912	73
16 Jan	0.33	0.858	0.00	560	6.0	0.00	0.0	0.035	1171	100	0	−100	0	−100
17 Jan	0.33	0.858	0.26	180	12.0	15.49	7.7	0.090	3011	560	832	48	605	8
17 Jan	0.33	0.858	0.00	560	6.0	0.00	0.0	0.046	1539	192	0	−100	0	−100
17 Jan	0.33	0.858	0.16	120	4.0	6.43	3.0	0.060	2007	309	373	21	206	−33
19 Jan	0.33	0.858	0.30	160	15.0	15.95	10.2	0.073	2442	418	854	104	770	84
20 Jan	0.33	0.858	0.33	160	18.0	17.55	12.2	0.110	3680	728	932	28	924	27
23 Jan	0.33	0.858	0.29	190	15.0	18.05	9.3	0.077	2576	452	957	112	747	65
									Average:			51		22
									Standard deviation:			80		68
2. HEMTT														
1988														
21 Jan	0.429	1.234	0.20	60	3.5	5.06	3.1	0.04	10742	604	300	−50	217	−64
21 Jan	0.483	1.178	0.19	60	3.5	5.58	3.1	0.04	10742	604	327	−46	178	−71
23 Jan	0.429	1.234	0.33	75	10.0	10.64	8.6	0.03	8057	269	590	120	643	139
23 Jan	0.483	1.178	0.32	75	10.0	11.70	8.6	0.05	13428	940	644	−31	514	−45
28 Jan	0.429	1.234	0.35	80	11.0	11.85	9.4	0.05	13428	940	652	−31	714	−24
28 Jan	0.483	1.178	0.34	80	11.0	13.04	9.4	0.06	16114	1276	711	−44	566	−56
11 Feb	0.429	1.234	0.44	220	25.0	41.52	15.0	0.05	13428	940	2048	118	1593	70
11 Feb	0.483	1.178	0.43	220	25.0	45.67	15.0	0.08	21485	1947	2234	15	1068	−45
11 Feb	0.429	1.234	0.38	200	18.0	32.81	11.5	0.05	13428	940	1652	76	1179	25
11 Feb	0.483	1.178	0.37	200	18.0	36.09	11.5	0.08	21485	1947	1802	−7	806	−59
1989														
14 Jan	0.483	1.178	0.36	250	20.0	43.98	10.9	0.08	21485	1947	2159	11	1209	−38
14 Jan	0.429	1.234	0.38	250	21.0	41.01	11.5	0.08	21485	1947	2025	4	824	−58
18 Jan	0.429	1.234	0.00	560	6.0	0.00	0.0	0.08	21485	1947	0	−100	0	−100
18 Jan	0.429	1.234	0.19	230	5.0	18.79	2.9	0.08	21485	1947	992	−49	1314	−33
16 Jan	0.429	1.234	0.00	560	6.0	0.00	0.0	0.08	21485	1947	0	−100	0	−100
16 Jan	0.483	1.178	0.00	560	6.0	0.00	0.0	0.08	21485	1947	0	−100	0	−100
19 Jan	0.429	1.234	0.12	220	2.0	11.51	1.2	0.08	21485	1947	635	−67	128	−93
23 Jan	0.429	1.234	0.26	190	8.0	20.89	5.2	0.08	21485	1947	1093	−44	530	−73
23 Jan	0.429	1.234	0.32	210	13.0	28.71	8.0	0.08	21485	1947	1462	−25	841	−57
									Average:			−19		−41
									Standard deviation:			63		59

to contents

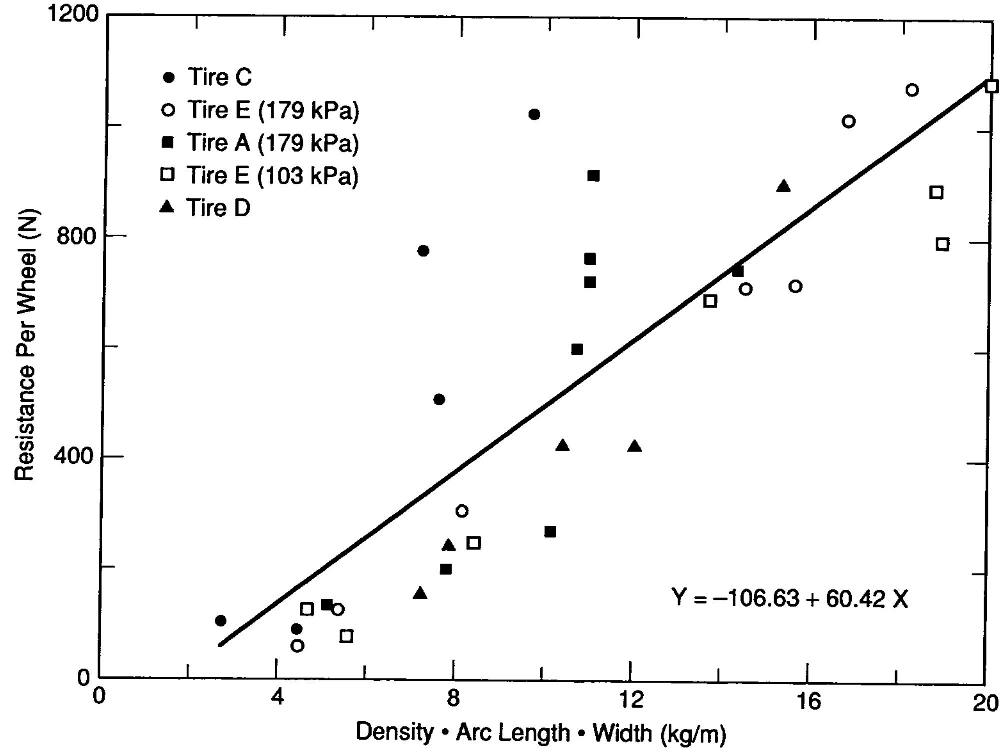
Table 8 (cont'd).

b. Wheeled vehicles (cont'd).

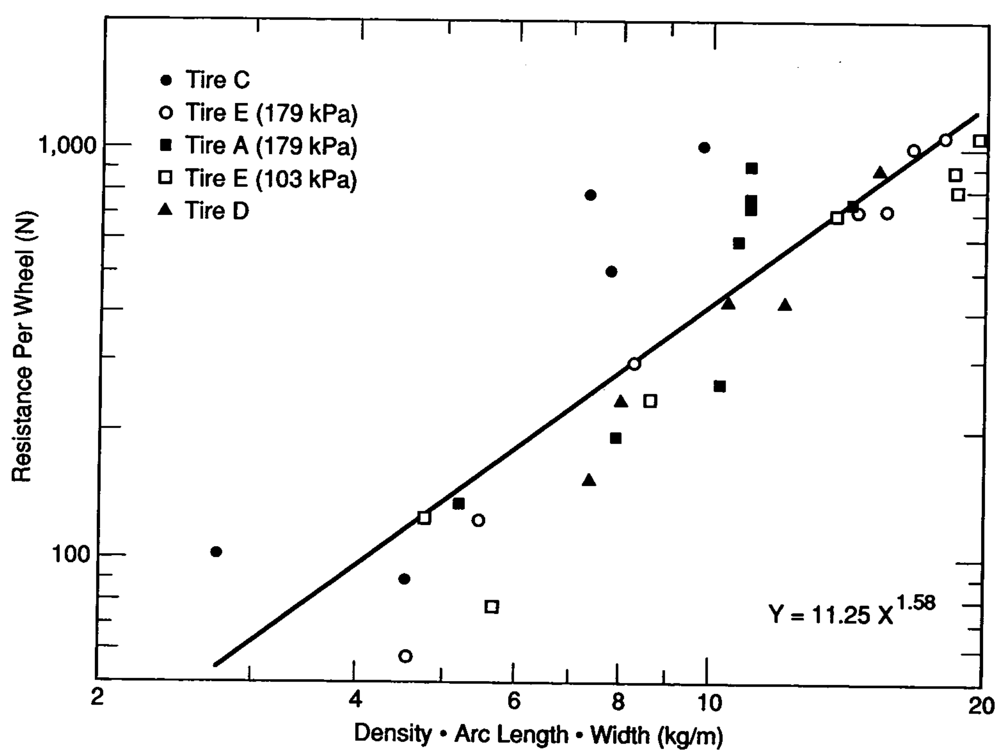
Date	Wheel Width (m)	Wheel Diameter (m)	Arc (a) (m)	Density (ρ) (kg/m³)	Depth (b) (cm)	ρ×b×a (kg/m)	Sinkage (cm)	Motion resistance Coeff.	Motion resistance Gross (N)	Motion resistance Net (N)	Eq 10 Est. resist.	Eq 10 Diff.* (%)	SSM2.0 Est. resist.	SSM2.0 Diff.* (%)
3. LAV														
<u>1988</u>														
19 Jan	0.353	0.89	0.00	550	5.0	0.00	0.0	0.05	6274	173	0	–100	0	–100
19 Jan	0.378	0.83	0.00	550	5.0	0.00	0.0	0.06	7529	329	0	–100	0	–100
21 Jan	0.353	0.89	0.17	60	3.5	3.55	3.1	0.06	7529	329	217	44	116	–65
21 Jan	0.378	0.83	0.16	60	3.5	3.64	3.1	0.06	7529	329	222	46	48	–85
23 Jan	0.353	0.89	0.31	75	12.0	8.21	10.4	0.06	7529	329	466	108	433	32
23 Jan	0.378	0.83	0.30	75	12.0	8.42	10.2	0.06	7529	329	477	110	180	–45
28 Jan	0.353	0.89	0.29	80	11.0	8.32	9.4	0.07	8784	486	472	41	406	–16
28 Jan	0.378	0.83	0.28	80	11.0	8.53	9.2	0.09	11294	800	482	–13	169	–79
28 Jan	0.353	0.89	0.29	80	11.0	8.32	9.4	0.07	8784	486	472	41	406	–16
28 Jan	0.378	0.83	0.28	80	11.0	8.53	9.2	0.09	11294	800	482	–13	169	–79
29 Jan	0.353	0.89	0.27	150	11.0	14.35	8.0	0.07	8784	486	776	79	464	–5
29 Jan	0.378	0.83	0.26	150	11.0	14.55	7.7	0.11	13803	1114	786	–21	193	–83
13 Feb	0.353	0.89	0.37	290	30.0	37.41	14.2	0.14	17568	1584	1862	–16	1010	–36
13 Feb	0.378	0.83	0.33	290	30.0	36.37	12.6	0.09	11294	800	1815	63	419	–48
13 Feb	0.353	0.89	0.34	250	23.0	30.23	12.5	0.12	15058	1271	1532	–5	868	–32
13 Feb	0.378	0.83	0.32	250	23.0	29.88	11.5	0.12	15058	1271	1516	–6	361	–72
										Average:		–3		–52
										Standard deviation:		56		36

* Percent difference from the measured net resistance.

to contents



a. Linear scale.



b. Log-log scale.

Figure 6. CIV resistance data.

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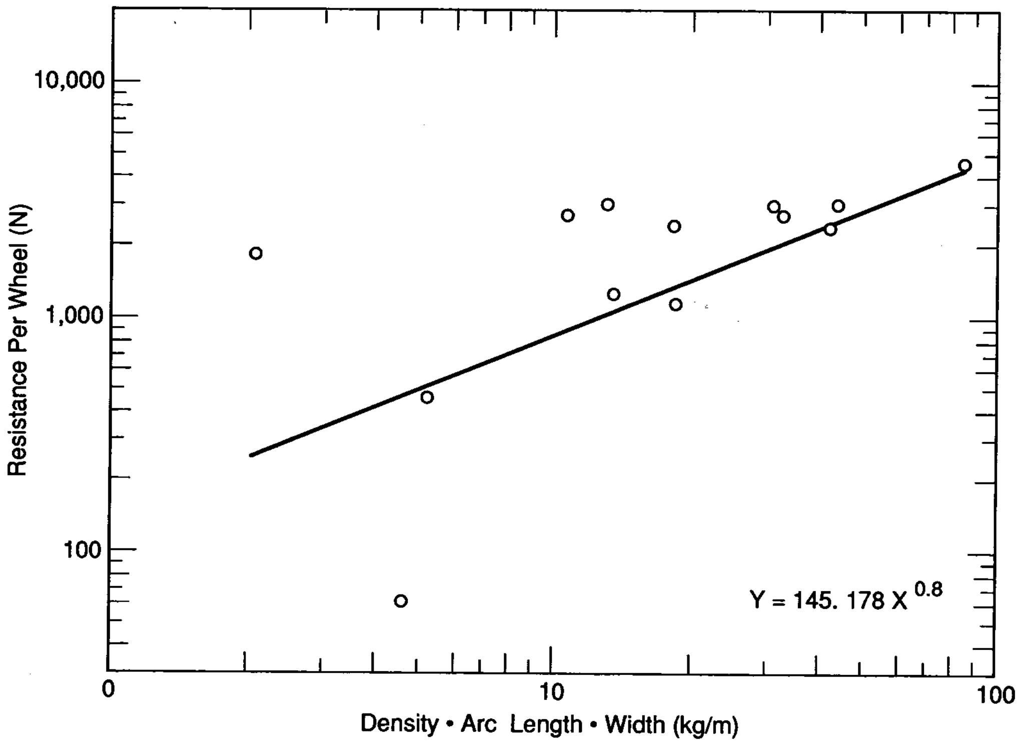
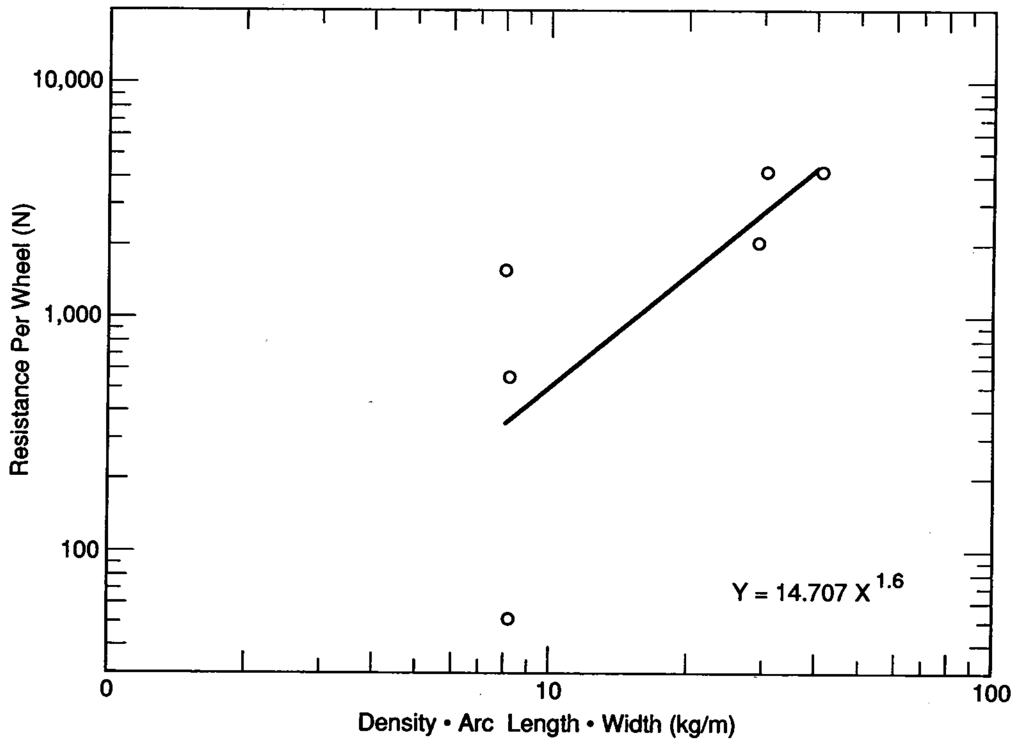


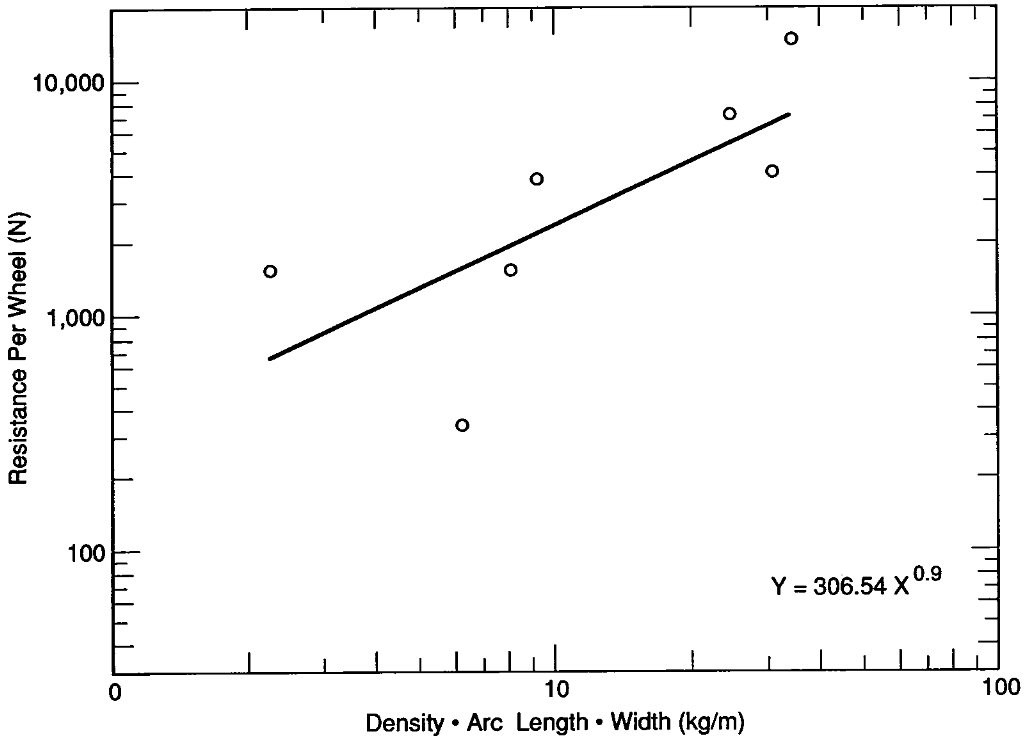
a. SUSV.



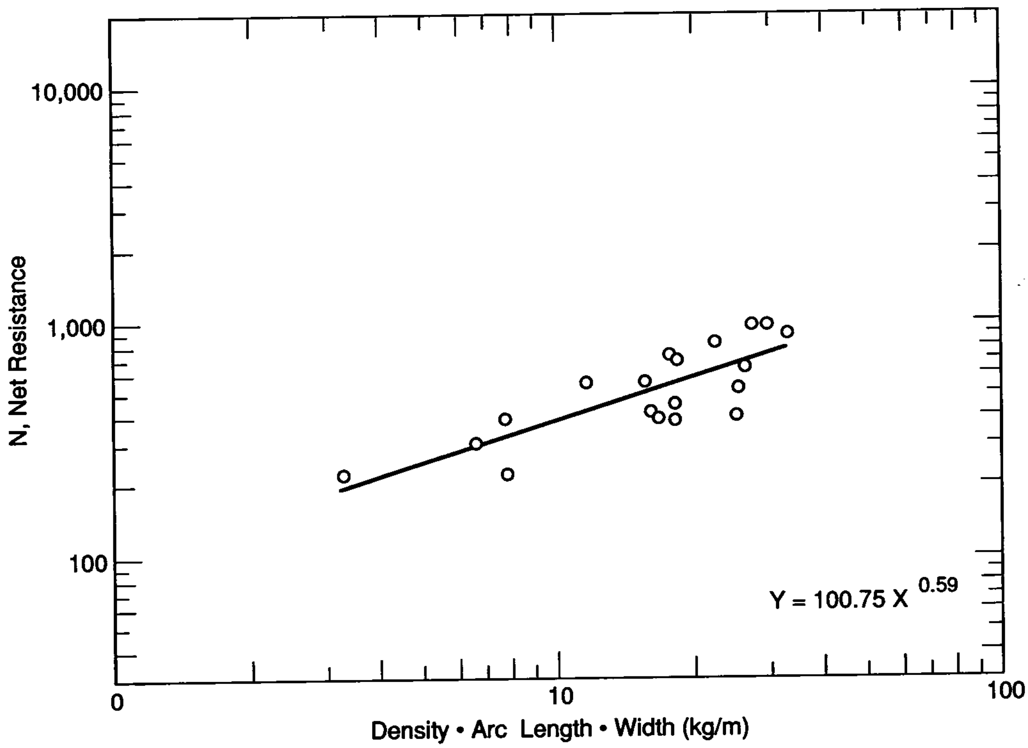
b. M113.

Figure 7. Resistance data for military vehicles.

to contents

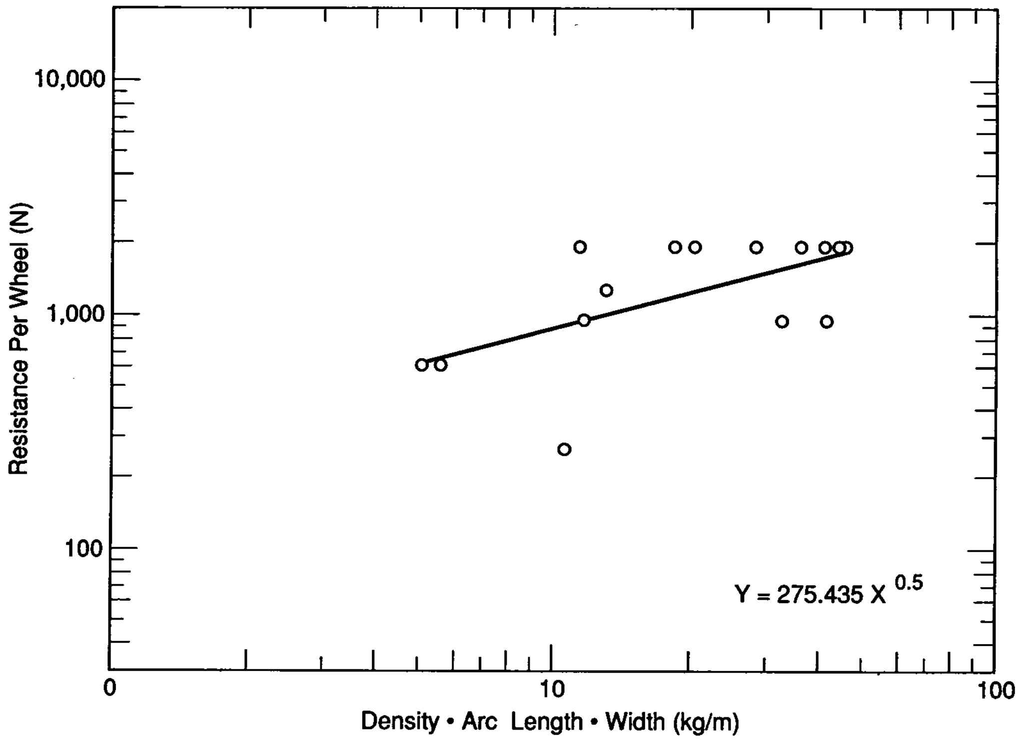


c. Bradley.

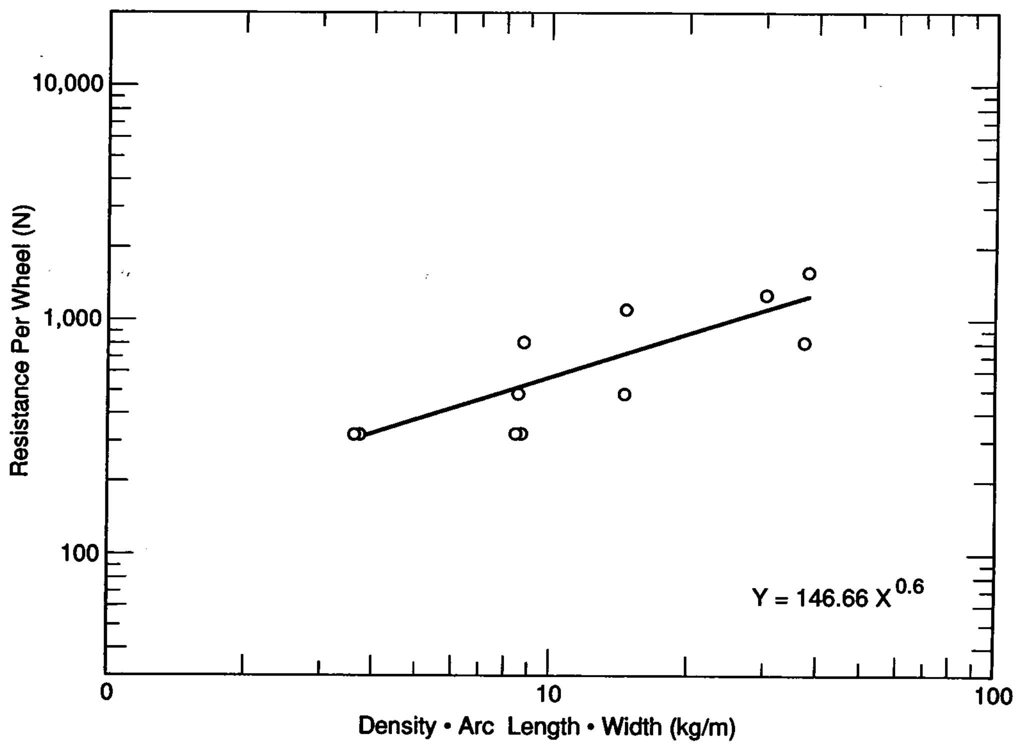


d. HMMWV.

Figure 7 (cont'd). Resistance data for military vehicles.



e. HEMTT.



f. LAV.

Figure 7 (cont'd).

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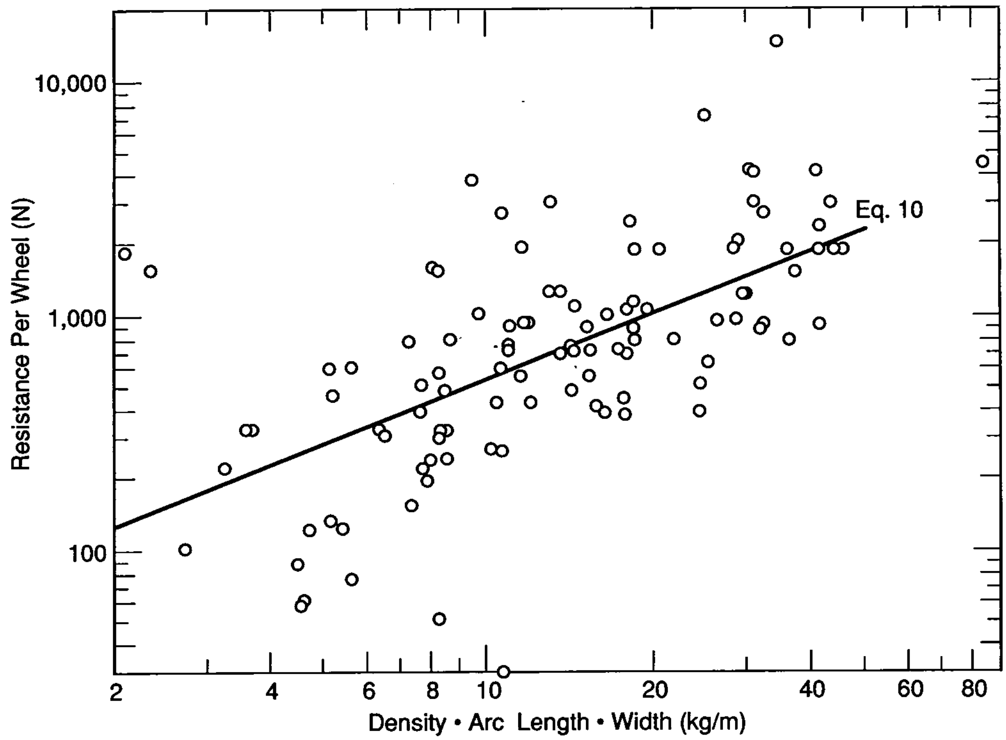

Figure 8. Resistance data for all vehicles.

Table 9. Summary of percent differences between resistance calculations.

	SSM2.0		Eq 10	
	Average	Standard deviation	Average	Standard deviation
SUSV	–52	–110	102	909
CIV	36	156	60	98
M113	66	296	92	312
Bradley	–81	20	–74	32
HMMWV	22	68	51	80
LAV	–52	36	–3	56
HEMTT	–41	59	–19	63
Avg.	–15	75	30	221
Min.	–81	–110	–3	32
Max.	66	296	102	909
Average of absolute values:	50		57	

CONCLUSIONS AND RECOMMENDATIONS

In this study we have developed some empirical equations that further define gross vehicle traction, specifically for conditions of hard-packed snow and for snow over ice.

The sinkage equation used in the SSM2.0 was shown to produce good results and no improvement was obtained by modifying the equation based on field observations of snow compaction.

The data base of resistance measurements for vehicles in snow has been increased and a parameter developed that appears to describe the wheel–or track–snow interaction well. Vehicle-specific empirical analysis produced promising results; however, when all the vehicle data are combined, an adequate predictive relationship is still not obtained. Vehicle motion resistance using SSM2.0 is only predicted to within 50% on average.

The primary problem with resistance analysis seems to be with trailing tires and how their resistance should be handled. The assumption used here that trailing tires produce as much resistance as leading tires needs to be confirmed experimentally. Future shallow snow mobility work should concentrate in this area.

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to contents

APPENDIX A: SHALLOW SNOW MOBILITY MODEL (SSM2.0)

Description

The two principal quantities governing mobility are gross traction T_g and external motion resistance R_s. This model produces estimates of both T_g and R_s and calculates net traction T_n from their difference

$$T_n = T_g - R_s \,. \tag{A1}$$

If the net traction is greater than 0 the vehicle is mobile, otherwise it is immobilized.

Motion resistance (R_s) is the resistance generated by terrain deformation, in our case by snow compaction. Compaction is partially the result of vertical forces (vehicle weight) applied to the snow surface by the tire; however, it takes place along a curved path and, therefore, horizontal forces are also applied. When compaction occurs, it can be witnessed by the presence of a rut in the snow following vehicle passage.

Motion resistance R_s is a function of many parameters. A partial list includes the load, contact pressure, snow strength and depth, and width of the tire or track. During the past 30 years, several resistance models have been proposed in the literature for deformable materials. With the goal of keeping SSM2.0 simple (i.e., a model that has a short list of input parameters that are easily obtained) and allowing it to address a broad range of vehicle and snow conditions, these resistance expressions were scrutinized. The vehicle data required by each of these expressions are similar from model to model, and are readily accessible. The snow data required to process any of these expressions, however, vary considerably. The only model that requires snow data that can be quickly and routinely obtained in the field is that of Liston (1974).

Liston assumes that a hyperbolic relationship exists between compacting pressure and volume. Applying energetics, he then integrates between the initial and final volumes of snow to obtain the work of snow compaction. If no volume change occurs (no sinkage z), no work is done. Finally, the work of compaction is equated to external motion resistance R_s times the horizontal distance traveled.

If we assume that lateral flow of the snow during compaction is insignificant (i.e., compaction is confined to the width of the tire or track), volume change in the snow can be expressed in terms of the sinkage z. Further, if the total mass of the snow does not change during compaction, then initial and final volumes of snow can be related to the initial and final densities of snow. We can then write

$$R_s = pbh\rho_o \left\{ \left[1/(\rho_f - \rho_o) \right] \ln \left(\rho_f/\rho_o \right) - \left(1/\rho_f \right) \right\} . \qquad \rho_o < \rho_f \; (z > 0) \tag{A2}$$

$$R_s = 0 \qquad \rho_o = \rho_f \; (z = 0)$$

where p = tire inflation pressure
b = maximum tire or track width
h = snow depth
ρ = snow density after passage of a given tire
ρ_o = initial snow density (prior to tire or track passage)
ρ_f = maximum (final) snow density (after vehicle passage)
z = sinkage.

Equation A2 is used in SSM2.0 for the calculation of motion resistance attributable to snow compaction.

Driving traction is also a sum of the interaction of many snow and vehicle parameters. Those that were mentioned above for resistance still apply, along with more detailed features of the tire or track (e.g., tread pattern, tire or track "rubber" compound, grouser spacing and height, grouser or tread geometry). The number of traction models proposed in the literature is fewer than is the case for motion resistance. These models seem to fall into two categories, either they are very simplistic, lumping many parameters together into a few constants, or they are exceedingly detailed.

The SSM2.0 uses the Mohr–Coulomb failure criteria relationship obtained by Blaisdell et al. (1990) to determine gross traction

$$T_g = 0.851\ N^{0.823} \tag{A3}$$

where N is the normal stress under a tire (track) in kilopascals. This equation is based on data from a wide range of vehicles, but was limited to initially undisturbed snow conditions and for tracked vehicles or wheeled vehicles equipped with tires.

The mobility expressions given by eq A1–A3 should be thought of for a single tire or traction element. For a mobility model to be flexible, neither the specific nor general configuration of a vehicle should be limited by the model. Being per tire or per track, the relationships for traction and resistance given here are used on the vehicle's tires or tracks one at a time in SSM2.0 until all of the traction elements have been accounted for. In this way, tires or tracks with different loads, inflation pressures, sizes, configurations (dual or single, driven or free-wheeling), degree of tracking and position on the vehicle are all accommodated for with one set of equations. Placed in a loop in SSM2.0, these expressions are used for each station, and a running sum for the whole vehicle is accumulated to produce a measure of the net performance of the vehicle. A station is defined here as a transverse section of the vehicle including a single axle (single or dual tires) or track loop (i.e., both sides of the vehicle are assumed to be similar).

To apply the traction and resistance equations above to even a single tire or track, it is necessary that we calculate or measure several parameters. The determination of T_g requires only the hard

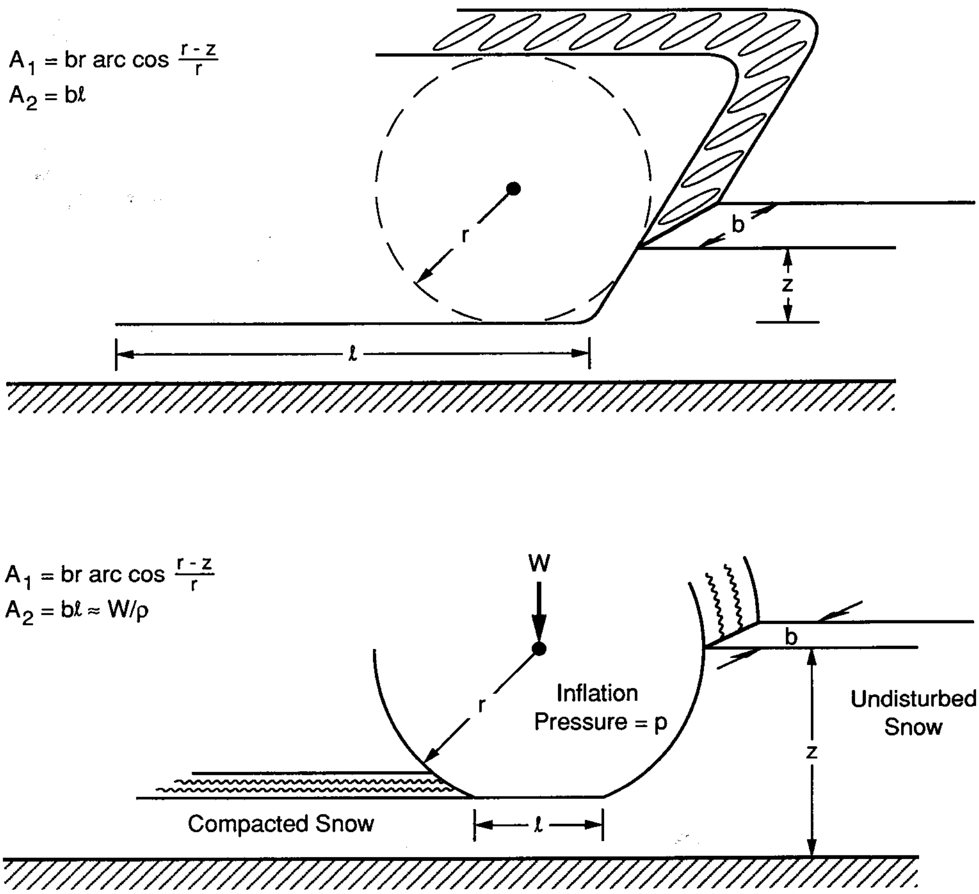

Figure A1. Tire and track dimensions.

to contents

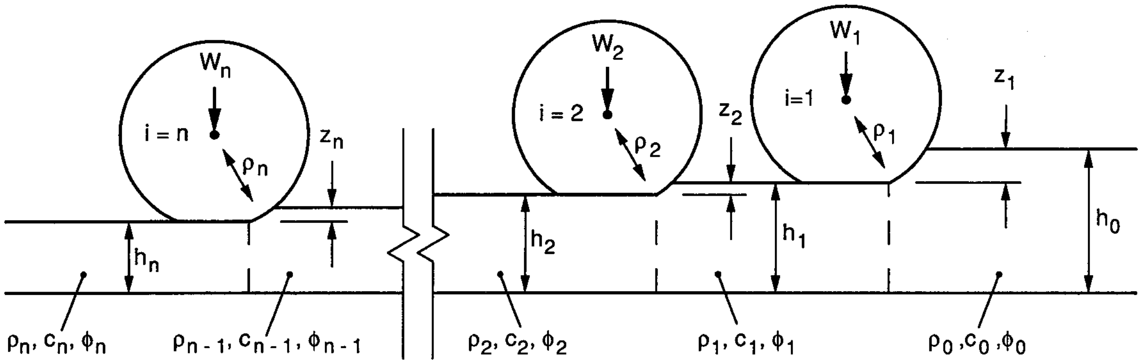

Figure A2. Depiction of progressive change in snow parameters with tire or track passage.

contact area of the tire or track and the vehicle weight. To calculate R_s, initial and final densities associated with the passage of a tire or track are necessary. In the following paragraphs, we first describe how these densities are determined and then proceed to show how the mobility equations are adapted for application to a whole vehicle in SSM2.0.

At each station, the vehicle parameters p, W (for wheeled vehicles only), ℓ (for tracked vehicles only), b and r of the tire or track are required (see Fig A1).

For the snow, it is required that we know the sinkage of each wheel (track). To determine the sinkage, it is assumed that compaction (within the realm of loads that are most common for vehicles) only occurs in the vertical dimension. First, we assume that the maximum sinkage (z_{max}) that occurs as the result of vehicle passage can be calculated from

$$z_{max} = h_o \left(1 - \frac{\rho_o}{\rho_f}\right) \qquad \text{(A4)}$$

where h_o = depth of the undisturbed snow

ρ_f = maximum or final density (Yong and Fukue 1977) in any rut following vehicle passage.

It is reasonable to believe that z_{max} and thus ρ_f will occur under the tire or track applying the largest ground pressure. ρ_f is thus determined in the SSM2.0 based on the highest pressure (p_{max}) exerted by any tire or track on the vehicle. The four major categories are based on experience and are defined in Table 1.

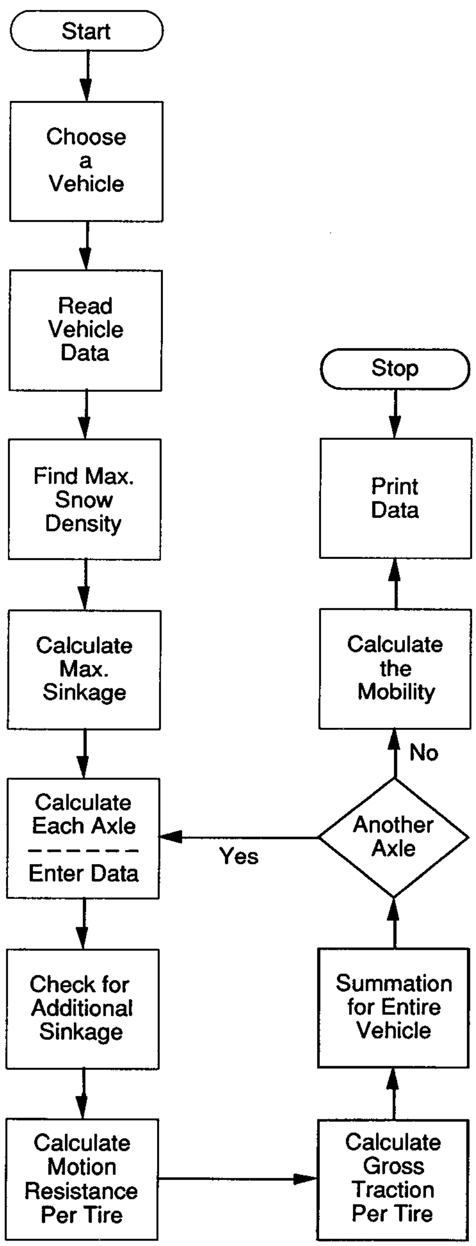

Figure A3. Flow chart for shallow snow mobility model.

to contents

Intermediate values of sinkage z for tires or tracks with contact pressures (p) less than p_{max} were determined by applying the ratio of (p/p_{max}) to z_{max}. Since the pressure–sinkage relationship is obviously not linear for compressible snow (less than 500 kg/m³) (Abele 1970), we assume that a power function relates ground pressure to sinkage. SSM2.0 calculates sinkage (referenced to the original snow depth h_o) for a given station from

$$z = z_{max}(p/p_{max})^{0.5} \tag{A5}$$

(see Mellor 1964, Fig. III-34).

The sinkage z, at a given station i on the vehicle, can then be calculated from

$$z_i = z_{max}\,(p/p_{max})^{0.5} - \sum_{j-1}^{i-1} z_j \qquad \rho_i > \rho_{i-1}, \rho_{i-2}, \cdots \rho_o \tag{A6}$$

$$z_i = 0 \qquad \rho_i \le = \rho_{i-1}, \rho_{i-2}, \cdots \rho_o .$$

To calculate motion resistance R_s we need to know the intermediate values of snow density as compaction progresses from initial density ρ_o to final density ρ_f. We have already stated that ρ_f is associated with maximum sinkage ($z = z_{max}$) and ρ_o corresponds to a sinkage of $z = 0$. Recalling eq A4, and the assumptions that it is based on, we can find the density beneath a particular station i from

$$\rho_i = \frac{\rho_{i-1}}{1-(z_i/h_{i-1})} \tag{A7}$$

where ρ_{i-1} and h_{i-1} are the snow density and depth prior to the passage of the tire or track at station i, and z_i (eq A7) is the sinkage produced at the current station (Fig. A2).

Lastly, we recognize that not all of the tires or tracks on a particular vehicle may be traveling in undisturbed snow. Some tires or tracks may follow exactly in the path of a preceding element, or may operate in undisturbed snow (e.g., a narrow or wide trailer behind a vehicle) or may encounter both compacted and uncompacted snow (e.g., dual tires following a single tire). We need then to account for the possibility of tires (tracks) having some percentage (α) of their width compacting new snow while the remainder is traveling in a previously created rut. The equations for R_s and T_g are therefore modified to become

$$R_{s_i} = \alpha\left[p_i\, b_i\, h_o\, \rho_o\left(\frac{1}{\rho_i-\rho_o}\ln\frac{\rho_i}{\rho_o}-\frac{1}{\rho_i}\right)\right] \tag{A8}$$

$$+\ (1-\alpha)\left[p b_i\, h_{i-1}\, \rho_{i-1}\left(\frac{1}{\rho_i-\rho_{i-1}}\ln\frac{\rho_i}{\rho_{i-1}}-\frac{1}{\rho_i}\right)\right] \qquad \text{for } \rho_i > \rho_{i-1}$$

$$R_{s_i} = \alpha\left[p_i\, b_i\, h_o\, \rho_o\left(\frac{1}{\rho_i-\rho_o}\ln\frac{\rho_i}{\rho_o}-\frac{1}{\rho_i}\right)\right] \qquad \text{for } \rho_i = \rho_{i-1}$$

$$R_{s_i} = 0 \qquad \text{for } \rho_i < \rho_{i-1}$$

$$T_g = 0.851\, N^{0.823}. \tag{A9}$$

Equations A8 and A9 provide the essence of the SSM2.0. These equations are executed for each station of the vehicle and a running sum for traction and resistance accumulated. The ultimate ability of the vehicle to move (total net traction T_n) is then determined from

to contents

$$T_n = \sum_{i=1}^{n} T_{gi} - R_{si} \quad \text{(A10)}$$

where n is the total number of stations on the vehicle. If T_n is positive, the vehicle is mobile and has the capacity to accelerate, climb hills or pull a payload in proportion with the magnitude of T_n. A value of 0 indicates impending immobilization, and a negative value of T_n predicts a definite no-go situation. A copy of the SSM2.0, in HP Basic computer code follows, along with the output from sample runs, and a flow chart is provided in Figure A3. Vehicle data for the SSM2.0 is in Table A1.

Table A1. Vehicle data for SSM2.0.

CIV, 179 kPa WHEELED
GVW = 24696.4 N
MAXIMUM GROUND (INFLATION) PRESSURE 179.30 kPa
AVERAGE HARD SURFACE CONTACT AREA 0.028 m²

STATION	RADIUS (cm)	WIDTH (cm)	WEIGHT PER WHEEL (N)	TIRE PRES. (kPa)	DRIVEN	DUALS	NEW SNOW PERCENT
1	35.6	25.4	6174.1	179.3	Y	N	100
2	35.6	25.4	6174.1	179.3	N	N	0

CIV, 103 kPa WHEELED
GVW = 24696.4 N
MAXIMUM GROUND (INFLATION) PRESSURE 110.30 kPa
AVERAGE HARD SURFACE CONTACT AREA 0.0345 m²

STATION	RADIUS (cm)	WIDTH (cm)	WEIGHT PER WHEEL (N)	TIRE PRES. (kPa)	DRIVEN	DUALS	NEW SNOW PERCENT
1	34.9	26.7	6174.1	110.3	Y	N	100
2	34.9	26.7	6174.1	110.3	N	N	0

HEMTT, 207/276 kPa WHEELED
GVW = 268560.1 N
MAXIMUM GROUND (INFLATION) PRESSURE 275.80 kPa
AVERAGE HARD SURFACE CONTACT AREA 0.149 m²

STATION	RADIUS (cm)	WIDTH (cm)	WEIGHT PER WHEEL (N)	TIRE PRES. (kPa)	DRIVEN	DUALS	NEW SNOW PERCENT
1	61.7	46.5	31004.0	241.3	Y	N	100
2	61.7	46.5	31459.9	241.3	Y	N	0
3	61.7	47.5	35785.8	275.8	Y	N	0
4	61.7	47.5	36030.4	275.8	Y	N	0

to contents

Table A1 (cont'd). Vehicle data for SSM2.0.

HEMTT, 138/207 kPa WHEELED
GVW = 268560.1 N
MAXIMUM GROUND (INFLATION) PRESSURE 206.80 kPa
AVERAGE HARD SURFACE CONTACT AREA 0.171 m²

STATION	RADIUS (cm)	WIDTH (cm)	WEIGHT PER WHEEL (N)	TIRE PRES. (kPa)	DRIVEN	DUALS	NEW SNOW PERCENT
1	58.9	48.9	31004.0	137.9	Y	N	100
2	58.9	48.9	31459.9	137.9	Y	N	0
3	58.9	48.3	35785.8	206.8	Y	N	0
4	58.9	48.3	36030.4	206.8	Y	N	0

HMMWV, 138/152 kPa WHEELED
GVW = 33450.5 N
MAXIMUM GROUND (INFLATION) PRESSURE 151.70 kPa
AVERAGE HARD SURFACE CONTACT AREA 0.074 m²

STATION	RADIUS (cm)	WIDTH (cm)	WEIGHT PER WHEEL (N)	TIRE PRES. (kPa)	DRIVEN	DUALS	NEW SNOW PERCENT
1	42.9	32.0	7228.3	137.9	Y	N	100
2	42.9	33.0	9496.9	151.7	Y	N	0

LAV,(12.5X20) 207 kPa WHEELED
GVW = 125483.7 N
MAXIMUM GROUND (INFLATION) PRESSURE 206.80 kPa
AVERAGE HARD SURFACE CONTACT AREA 0.100 m²

STATION	RADIUS (cm)	WIDTH (cm)	WEIGHT PER WHEEL (N)	TIRE PRES. (kPa)	DRIVEN	DUALS	NEW SNOW PERCENT
1	44.5	35.3	16102.5	206.8	Y	N	100
2	44.5	35.3	17281.3	206.8	Y	N	0
3	44.5	35.3	14501.1	206.8	Y	N	0
4	44.5	35.3	14857.0	206.8	Y	N	0

LAV,(12.5X20) 103 kPa WHEELED
GVW = 125483.7 N
MAXIMUM GROUND (INFLATION) PRESSURE 103.40 kPa
AVERAGE HARD SURFACE CONTACT AREA 0.141 m²

STATION	RADIUS (cm)	WIDTH (cm)	WEIGHT PER WHEEL (N)	TIRE PRES. (kPa)	DRIVEN	DUALS	NEW SNOW PERCENT
1	41.4	37.8	16102.5	103.4	Y	N	100
2	41.4	37.8	17281.3	103.4	Y	N	0
3	41.4	37.8	14501.1	103.4	Y	N	0
4	41.4	37.8	14857.0	103.4	Y	N	0

LAV,(11X16) 289 kPa WHEELED
GVW = 119634.3 N
MAXIMUM GROUND (INFLATION) PRESSURE 289.60 kPa
AVERAGE HARD SURFACE CONTACT AREA 0.058 m²

STATION	RADIUS (cm)	WIDTH (cm)	WEIGHT PER WHEEL (N)	TIRE PRES. (kPa)	DRIVEN	DUALS	NEW SNOW PERCENT
1	43.4	31.4	15346.3	289.6	Y	N	100
2	43.4	31.4	16480.6	289.6	Y	N	0
3	43.4	31.4	13822.8	289.6	Y	N	0
4	43.4	31.4	14167.5	289.6	Y	N	0

to contents

Table A1 (cont'd).

LAV, (11X16) 165 kPa WHEELED
GVW = 119634.3 N
MAXIMUM GROUND (INFLATION) PRESSURE 165.50 kPa
AVERAGE HARD SURFACE CONTACT AREA 0.102 m^2

STATION	RADIUS (cm)	WIDTH (cm)	WEIGHT PER WHEEL (N)	TIRE PRES. (kPa)	DRIVEN	DUALS	NEW SNOW PERCENT
1	41.7	33.2	15346.3	165.5	Y	N	100
2	41.7	33.2	16480.6	165.5	Y	N	0
3	41.7	33.2	13822.8	165.5	Y	N	0
4	41.7	33.2	14167.5	165.5	Y	N	0

SUSV TRACKED
GVW = 61340.7 N
MAXIMUM GROUND (INFLATION) PRESSURE 13.20 kPa
AVERAGE HARD SURFACE CONTACT AREA 1.180 m^2

STATION	RADIUS (cm)	WIDTH (cm)	WEIGHT PER TRACK (N)	TRACK LENGTH (cm)	NEW SNOW PERCENT
1	26.40	60.96	15390.80	190.50	100.00
2	26.40	60.96	15279.60	190.50	0.00

M113 TRACKED
GVW = 104087.9 N
MAXIMUM GROUND (INFLATION) PRESSURE 51.02 kPa
AVERAGE HARD SURFACE CONTACT AREA 1.020 m^2

STATION	RADIUS (cm)	WIDTH (cm)	WEIGHT PER TRACK (N)	TRACK LENGTH (cm)	NEW SNOW PERCENT
1	36.80	38.10	52043.50	266.70	100.00

BRADLEY TRACKED
GVW = 223299.6 N
MAXIMUM GROUND (INFLATION) PRESSURE 53.09 kPa
AVERAGE HARD SURFACE CONTACT AREA 2.090 m^2

STATION	RADIUS (cm)	WIDTH (cm)	WEIGHT PER TRACK (N)	TRACK LENGTH (cm)	NEW SNOW PERCENT
1	35.60	53.34	111649.75	391.20	100.00

5-TON, 207 kPa WHEELED
GVW = 105778.2 N
MAXIMUM GROUND (INFLATION) PRESSURE 206.80 kPa
AVERAGE HARD SURFACE CONTACT AREA 0.171 m^2

STATION	RADIUS (cm)	WIDTH (cm)	WEIGHT PER WHEEL (N)	TIRE PRES. (kPa)	DRIVEN	DUALS	NEW SNOW PERCENT
1	55.4	40.8	23842.4	206.8	Y	N	100
2	55.4	39.2	14523.4	206.8	Y	N	0
3	55.4	39.2	14523.4	206.8	Y	N	0

to contents

Computer code

```
10 !
20 !   SSM/2.01
30 !                  (trig tr sinkage and snow density function of cont. pr.)
40 !                  (manual input of all vehicle and snow data)
50 !                  (Liston's resis; best-fit power curve for traction)
60 !
70  net=0
80  RR=0
90 DB=0
100 go=0
110 pl=0
120 z=0
130 sumz=0
140  DISP "vehicle?"
150  INPUT Veh$
160  DISP "wheeled (w) or tracked (t)?"
170  INPUT type$
180  DISP "highest station ground pressure (kPa)="
190  INPUT pmax
200  pmax=pmax*0.1 ! convert from kPa to N/cm^2
210  !
220  !  **  establish final density based on largest footprint pressure  **
230  sigmaf=0.5
240  IF pmax>21 THEN sigmaf=0.55
250  IF pmax>35 THEN sigmaf=0.6
260  IF pmax>70 THEN sigmaf=0.65
270  !
280  DISP "snow depth (cm) ="
290  INPUT h0
300  DISP "snow density (g/cm^3) ="
310  INPUT sigma0
320  sigma1=sigma0
330  sigma2=sigma0
340  h1=h0
350  !
360  PRINT "Vehicle: ";Veh$
370  PRINT "  "
380  PRINT USING format1 ; "initial state:  snow depth =";h0;" cm"
390  PRINT USING format2 ; "                snow density =";sigma0;" g/cm^3"
400  !
410    zmax=h0*(1-sigma0/sigmaf) ! calculate maximum sinkage
420   IF zmax<0 THEN zmax=0
430  !
440  RAD ! compute in radians units for trig functions
450  !
460  !
470  ! **  enter vehicle data one tire station at a time  **
480  DISP "how many wheel or track stations on each side of the vehicle?"
490  INPUT N
500  !
510  FOR I=1 TO N
520  DISP ""
530  DISP "station ";I
540  DISP "wheel radius or approx radius of compacting portion of track cm) ="
550  INPUT rads
560  DISP "single tire or track width at this location (cm) ="
570  INPUT wid
580  DISP "single tire or track load (N) ="
590  INPUT loa
```


to contents

```
600  DISP "contact area (m^2) ="
610  INPUT area
620  IF type$="t" THEN GOTO skip1
630  DISP "inflation pressure (kPa) ="
640  INPUT pres
650  pres=pres*0.1 ! convert from kPa to N/cm^2
660  GOTO skip2
670 skip1: pres=loa/area/10000 ! convert from N/m^2 to N/cm^2
680  !
690 skip2: DISP "driven?"
700  INPUT r$
710  IF type$="t" THEN GOTO skip3
720  DISP "duals ?"
730  INPUT R$
740  IF R$<>"y" AND R$<>"Y" THEN GOTO 780
750   wid=wid*2
760   loa=loa*2
770  !
780 skip3: DISP "percent of width compacting virgin snow (%) ="
790  INPUT prcnt
800  !
810  IF pres>pl AND sigma2<sigmaf AND h0>0 THEN GOTO 870 ! added sink. here?
820  z=0
830  tempres=0
840  IF prcnt>0 AND sigma2>sigma0 THEN GOTO 960
850  resis=0
860  GOTO 1010
870  z=(pres/pmax)^0.5*zmax-sumz ! calculate additional sinkage this station
880  !
890  ! **  set rut bottom values  **
900  h2=h1-z
910  sigma2=sigma1/(1-z/h1)
920  !
930  !   **  calculate resistance parameter  **
940  tempres=1/(sigma2-sigma1)*LOG(sigma2/sigma1)-1/sigma2 ! in rut
950  !
960  !  **  calculate motion resistance at this station  **
970  resis=prcnt/100*(pres*wid*h0*sigma0) ! in virgin snow
980  resis=resis*(1/(sigma2-sigma0)*LOG(sigma2/sigma0)-1/sigma2) !virgin snow
990  moreres=tempres*(1-prcnt/100)*(pres*wid*h1*sigma1) ! in rut
1000  resis=resis+moreres
1010  !
1020  !  **  calculate gross traction at this station  **
1030  trac=0.851*(loa/area/1000)^0.823 ! in kPa
1040  trac=trac*area*1000 ! in N
1050  !
1060  IF r$="n" OR r$="N" THEN trac=0 ! no traction if not driven
1070  !
1080  !  **  double to account for both sides of the vehicle  **
1090  arrea=2*area
1100  trac=2*trac
1110  resis=2*resis
1120  !
1130  !  **  print output for this station  **
1140  PRINT " "
1150  PRINT "station ";I
1160  PRINT USING format1 ; "  additional sinkage =";z;" cm"
1170  PRINT USING format1 ; "  total area=";arrea;" m^2"
1180  PRINT USING format1 ; "  snow resis =";resis;" N"
1190  PRINT USING format1 ; "  snow trac =";trac;" N"
```


to contents

```
1200  !
1210  !  **  running summation for whole vehicle  **
1220  RR=RR+resis ! sum for whole vehicle
1230  DB=DB+trac ! sum for whole vehicle
1240  net=trac-resis ! calculate net traction for individual station
1250  PRINT USING format1 ; " net snow traction for station = ";net;" N"
1260  PRINT USING format1 ; "     rut bottom:  depth=";h2;" cm"
1270  PRINT USING format2 ; "                        density=";sigma2;" g/cm^3"
1280  go=go+net ! sum net traction for vehicle
1290  !
1300  !  **  save last station values for next iteration  **
1310  IF pres>pl THEN pl=pres
1320  sigma1=sigma2
1330  h1=h2
1340  sumz=sumz+z
1350  !
1360  NEXT I
1370  !
1380  !  **  calculate mobility in English units for output  **
1390  eRR=RR/4.448222
1400  eDB=DB/4.448222
1410  ego=go/4.448222
1420  ez=sumz/2.54
1430  !
1440  !  **  print out whole vehicle results  **
1450  PRINT " "
1460  PRINT " "
1470  PRINT USING format1 ; " total sinkage for vehicle= ";sumz;" cm  (";ez;" in
)"
1480  PRINT USING format1 ; " total snown resistance = ";RR;" N  (";eRR;" lb)"
1490  PRINT USING format1 ; " total snow traction =";DB;" N  (";eDB;" lb)"
1500  PRINT " "
1510  PRINT USING format1 ; " net traction for vehicle = ";go;" N  (";ego;" lb)"
1520  PRINT " "
1530  PRINT " "
1540  PRINT " "
1550  !
1560 format1:  IMAGE 3(K,DDDDDD.DD)
1570 format2:  IMAGE 3(K,DZ.DDDD)
1580  !
1590  END
```

```
Vehicle: HMMWV

initial state:  snow depth =     5.00 cm
                snow density = 0.5500 g/cm^3

station  1
  additional sinkage =     0.00 cm
  total area= 0.1480 m^2
  snow resis =     0.00 N
  snow trac =  5467.65 N
 net snow traction for station =   5467.65 N
     rut bottom:  depth=     0.00 cm
                  density= 0.5500 g/cm^3

station  2
  additional sinkage =     0.00 cm
  total area= 0.1480 m^2
  snow resis =     0.00 N
  snow trac =  6844.84 N
 net snow traction for station =   6844.84 N
     rut bottom:  depth=     0.00 cm
                  density= 0.5500 g/cm^3


 total sinkage for vehicle=      0.00 cm  (     0.00 in)
 total snown resistance =      0.00 N  (     0.00 lb)
 total snow traction = 12312.49 N  (  2767.96 lb)

 net traction for vehicle =  12312.49 N  (  2767.96 lb)



Vehicle: HEMTT (241/276)

initial state:  snow depth =    25.00 cm
                snow density = 0.2200 g/cm^3

station  1
  additional sinkage =    14.03 cm
  total area= 0.2980 m^2
  snow resis = 11515.55 N
  snow trac = 20514.00 N
 net snow traction for station =   8998.45 N
     rut bottom:  depth=    10.97 cm
                  density= 0.5014 g/cm^3

station  2
  additional sinkage =     0.00 cm
  total area= 0.2980 m^2
  snow resis =     0.00 N
  snow trac = 20761.93 N
 net snow traction for station =  20761.93 N
     rut bottom:  depth=    10.97 cm
                  density= 0.5014 g/cm^3

station  3
  additional sinkage =      .97 cm
  total area= 0.2980 m^2
  snow resis =  1230.94 N
  snow trac = 23084.34 N
 net snow traction for station =  21853.40 N
     rut bottom:  depth=    10.00 cm
                  density= 0.5500 g/cm^3
```

```
Vehicle: HEMTT (241/276) (cont'd).

initial state:  snow depth =     25.00 cm
                snow density = 0.2200 g/cm^3

station  4
  additional sinkage =     0.00 cm
  total area= 0.2980 m^2
  snow resis =     0.00 N
  snow trac = 23214.12 N
 net snow traction for station =  23214.12 N
     rut bottom:  depth=     10.00 cm
                  density= 0.5500 g/cm^3


 total sinkage for vehicle=     15.00 cm  (     5.91 in)
 total snown resistance =  12746.49 N  (  2865.52 lb)
 total snow traction = 87574.39 N  ( 19687.50 lb)

 net traction for vehicle =  74827.90 N  ( 16821.98 lb)



Vehicle: SUSV

initial state:  snow depth =     9.00 cm
                snow density = 0.1480 g/cm^3

station  1
  additional sinkage =     6.30 cm
  total area=     2.36 m^2
  snow resis =   309.13 N
  snow trac = 16626.42 N
 net snow traction for station =  16317.29 N
     rut bottom:  depth=     2.70 cm
                  density= 0.4930 g/cm^3

station  2
  additional sinkage =     0.00 cm
  total area=     2.36 m^2
  snow resis =     0.00 N
  snow trac = 16527.49 N
 net snow traction for station =  16527.49 N
     rut bottom:  depth=     2.70 cm
                  density= 0.4930 g/cm^3


 total sinkage for vehicle=     6.30 cm  (     2.48 in)
 total snown resistance =   309.13 N  (    69.49 lb)
 total snow traction = 33153.90 N  (  7453.29 lb)

 net traction for vehicle =  32844.78 N  (  7383.80 lb)
```


to contents

APPENDIX B: TIRE TREAD FOOTPRINTS FOR TRACTION ANALYSIS

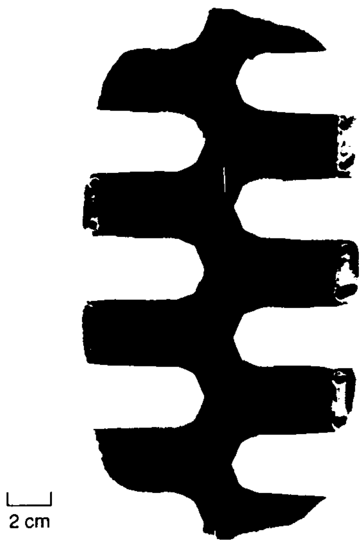

Figure B1. Tire B (NDCC 700-16LW; bias ply; 234-kPa inflation pressure; 0.0238-m^2 contact area).

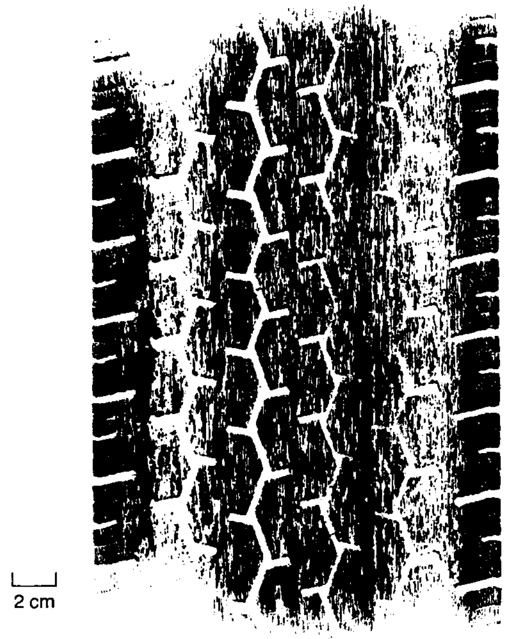

Figure B3. Tire a (buffed Michelin LT235XCH4; radial, all-season; 179-kPa inflation pressure; 0.0443-m^2 contact area).

Figure B2. Tire A (Michelin LT235XCH4; radial, all-season; 179-kPa inflation pressure; 0.0412-m^2 contact area).

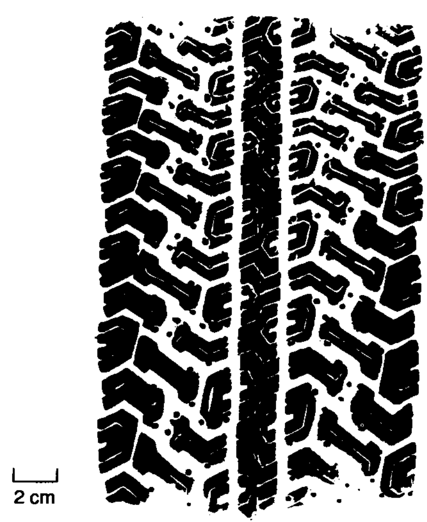

Figure B4. Tire E (Goodyear Tiempo P225/75R15; radial, all-season; 179-kPa inflation pressure; 0.028-m^2 contact area).

to contents

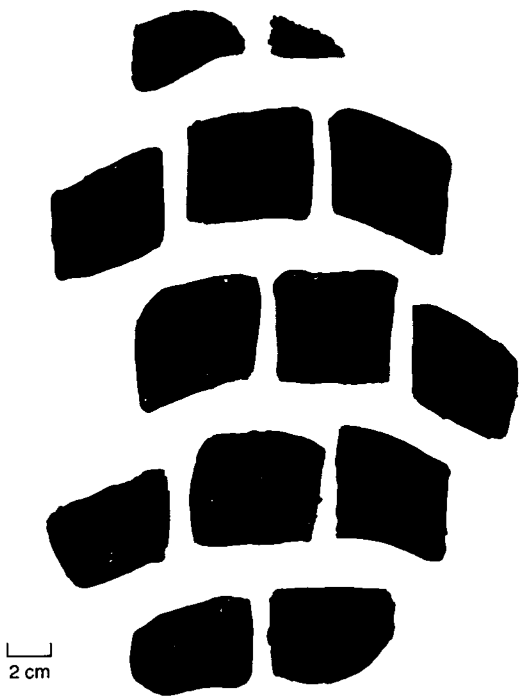

Figure B5. LAV-25 tire (Michelin 12.5/75 R20 XL; 207-kPa inflation pressure; 0.1-m^2 contact area).

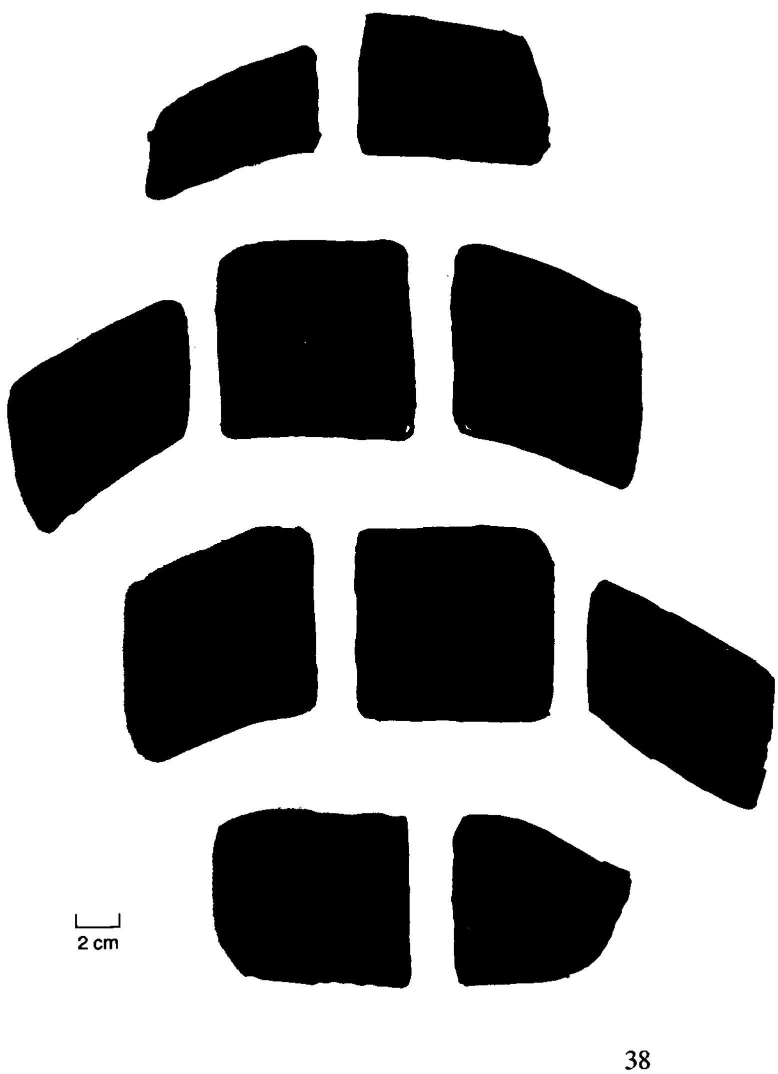

Figure B6. HEMTT tire (Michelin 16.0 R20; 276-kPa inflation pressure; 0.149-m^2 contact area).

to contents

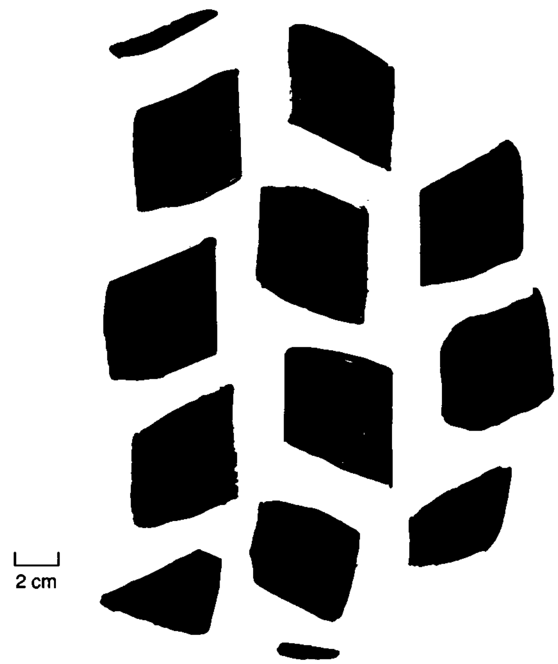

Figure B7. HMMWV tire (Michelin 37.00 X12.5 R 16.5L; 241-kPa inflation pressure; 0.149-m² contact area).

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13. ABSTRACT (*Maximum 200 words*)

This report presents and analyzes winter mobility data obtained during the winters of 1988 and 1989 at the Keweenaw Research Center, Houghton, Michigan. Traction data (1989) for the HMMWV, HEMTT, SUSV and M60 military vehicles, and the CRREL instrumented vehicle, are presented for hard-packed snow and for undisturbed snow overlaying ice. When these data are compared with an equation for undisturbed snow over soil or packed snow, slight reductions in traction are observed. Resistance data obtained in 1988 and in 1989 are evaluated based on a combined vehicle–snow parameter. An empirical equation based on this parameter and data from all the vehicles, including the CRREL instrumented vehicle using several different width tires, is developed. The resistance data and the empirical resistance equation are compared with the CRREL shallow snow mobility model (SSM2.0). The SSM2.0 predicted resistance is within 50% on average. The empirically derived resistance equation is slightly worse. The report recommends further research on vehicle motion resistance in snow.

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