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EFFECTS OF LOW GROUND PRESSURE VEHICLE TRAFFIC ON TUNDRA AT LONELY, ALASKA

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Traffic tests were conducted with two low-pressure-tire Rolligon-type vehicles and a small, tracked Nodwell for 1, 5, and 10 vehicle passes on tundra near Lonely, Alaska. The traffic impact was limited to compression of the vegetation and the organic mat and a maximum terrain surface depression of several centimeters, with virtually no shearing or disaggregation of the mat. After one year, the visibility of the traffic signatures had increased, surface depression remained the same, and the thaw depth below the multiple pass tracks had increased a few centimeters.

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PREFACE

This study was conducted and this report was prepared by Gunars Abele, Research Civil Engineer, Applied Research Branch, Experimental Engineering Division; Dr. Jerry Brown, Chief, Earth Sciences Branch, Research Division; David M. Atwood, Photographer, Engineering Services Branch, Technical Services Division - U.S. Army Cold Regions Research and Engineering Laboratory; Donald A. Walker, Institute of Arctic and Alpine Research, University of Colorado; and Dr. Max C. Brewer, U.S. Geological Survey, Anchorage, National Petroleum Reserve Alaska (NPRA).

This work was performed under DA Project 4A161102AT24, Research in Snow, Ice, and Frozen Ground; Task A2, Cold Regions Environmental Interactions; Work Unit 002, Cold Regions Environmental Factors. The work in 1977 was also funded under U.S. Dept. of Interior, Geological Survey Order No. 1220-255-7, August 1977, Petroleum Exploration Activities Study.

This report was technically reviewed by K.L. Carey of CRREL and by Dr. K.R. Everett of the Institute of Polar Studies and the Department of Agronomy, Ohio State University, Columbus, Ohio.

The field work was conducted on 3 August 1976 with the assistance of Phil Jeans, Camp Manager, Husky Oil, and on 1-2 August 1977.

The Naval Arctic Research Laboratory, Barrow, and the NPRA Base Camp at Lonely, Alaska, operated by Husky Oil, provided logistics support, including facilities, equipment and aircraft. The assistance of Lieutenant Commander A.E. Corcoran, formerly Officer in Charge, NPR-4, is greatly appreciated.

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NOMENCLATURE

C = CATCO (8-wheel vehicle)

H = Houston (6-wheel vehicle)

N = Nodwell (tracked vehicle)

n = Number of vehicle traffic passes

y_c = Depression of terrain surface under the center of tire (cm)

y_e = Depression of terrain surface under the edge of tire (cm)

h_C = Thaw depth, control area (cm)

h_T = Thaw depth, below track (cm)

Δh = Difference between track (center) and control thaw depth, $h_T - h_C$ (cm); "Increase in thaw depth"

$w_{p(C)}$ = Moisture content of peat, control area (%)

$w_{p(T)}$ = Moisture content of peat, below track (%)

$w_{m(C)}$ = Moisture content of mineral soil, control area (%)

$w_{m(T)}$ = Moisture content of mineral soil, below track (%)

$\rho_{p(C)}$ = Dry density of peat, control area (g/cm^3)

$\rho_{p(T)}$ = Dry density of peat, below track (g/cm^3)

$\rho_{m(C)}$ = Dry density of mineral soil, control area (g/cm^3)

$\rho_{m(T)}$ = Dry density of mineral soil, below track (g/cm^3)

Traffic Direction: ↓ towards observer (to South)

↑ away from observer (to North)

Visibility Index: Darkness of traffic signature relative to the adjacent undisturbed terrain surface (viewed from the South end of the test area), based on an arbitrary numerical scale;

Negative value: lighter than adjacent surface
0: same as adjacent surface
Positive value: darker than adjacent surface

Visibility Index (Mean): Mean of both traffic directions, after 1 year (for same vehicle and same n), viewed from South end of test area.

Impact Score: Relative damage caused by vehicle traffic in terms of:

Vegetation compression	Co
Displacement	Di
Breakage	Br
Deposition	De

based on an arbitrary numerical scale.

Impact Score (Total): Sum of the 4 individual scores (Co+Di+Br+De)

INTRODUCTION

The recent increase in the petroleum exploration activities on the Arctic Coastal Plain of Alaska has resulted in a corresponding increase in surface transportation requirements. Not all traffic can be confined to the winter months when the ecological impact of vehicle operations is minimal. Traffic across tundra during summer can result in effects that vary significantly in the degree of severity depending on the vehicle, traffic and terrain characteristics.

A number of studies have been conducted on the effects of off-road vehicular traffic on tundra, including wheeled, tracked, and air cushion vehicles (Abele, 1976; Abele and Brown, 1977; Burt, 1970a, 1970b; Gersper and Challinor, 1975; Kevan, 1971; Miller, et al., 1977; Radforth, 1970, 1972, 1973a, 1973b; Rickard and Brown, 1974; Sterrett, 1976; Walker, et al., 1977). As a follow-up to these studies, a series of traffic tests with three different vehicles was performed on tundra near Lonely, Alaska, in August 1976 to obtain additional environmental information which will provide added insight for decisions on operations of National Petroleum Reserve Alaska (formerly Naval Petroleum Reserve No. 4).

The test site was visited exactly 1 year later to obtain follow-up data, which included classification of the effects of traffic using an impact rating scheme developed by Walker et al., (1977) during similar tests at Prudhoe Bay, Alaska. (The study at Prudhoe Bay involved traffic impact with one type of Rolligon vehicle on various vegetation-landform combinations. The study at Lonely deals with the impact of three vehicles on relatively homogeneous terrain.)

DESCRIPTION OF STUDY

Test Site

Location of the test area, approximately 3 km south of Lonely, is shown in Figure 1. The immediate test site can be characterized as fairly homogeneous mesic coastal tundra, poorly drained with weakly developed polygonal ground patterns and a minimum of micro-scale terrain variability. The organic layer is approximately 12 cm thick with a mean water content of approximately 400%, and thaw depth generally in the 20 to 30 cm range (1976 data). The vegetation is very similar to that occurring on mesic sites at Barrow, Alaska, and corresponds to Type 6 on the Walker and Webber (1973) vegetation map of the International Biological Program (IBP) study area at Barrow.

Ten meter-square quadrats placed along a transect through the test lanes show the dominant vascular species are *Carex aquatilis, Eriophorum angustifolium, Salix planifolia* ssp., *pulchra, Salix rotundifolia,* and *Dupontia fisheri*. The composition of the moss layer is more variable, and appears to be sensitive to minor variations in soil moisture. In

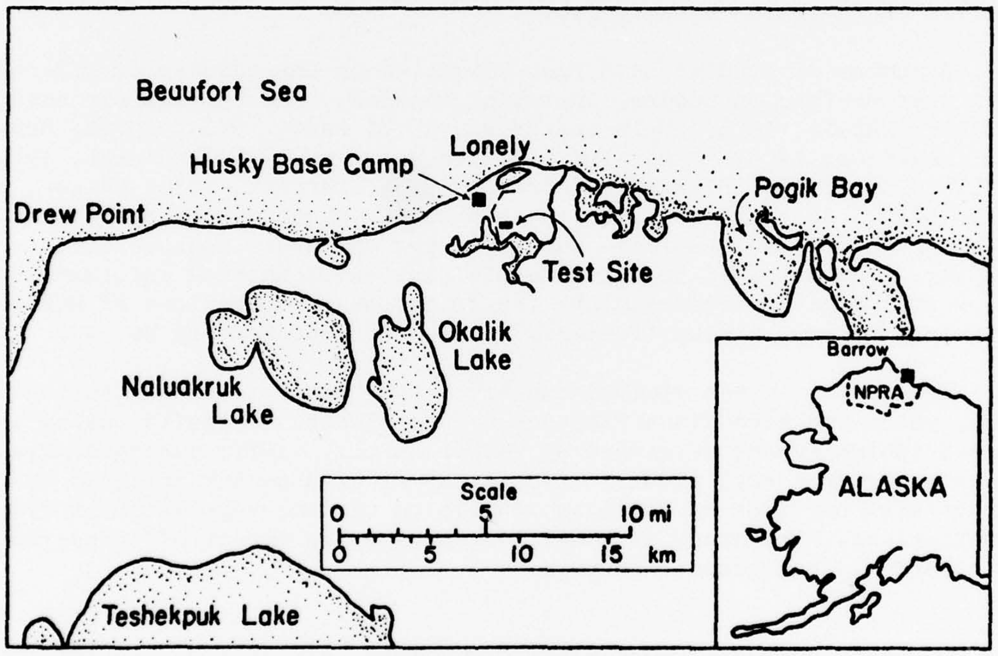


Figure 1. Location map

the slightly drier microsites the dominant mosses are usually *Dicranum elongatum, Tomenthypnum nitens,* and *Aulacomnium turgidum.* More moist sites have *Drepanocladus lycopodioides* var. *brevifolius* and *Calliergon* sp. Lichens are not an important component of the vegetation. *Eriophorum vaginatum* and *Sphagnum* spp., although occurring only at scattered locations in the test lanes, are noteworthy components of the vegetation because they are particularly susceptible to damage. For the complete vegetation characteristics at this test site, refer to Table A-1 in the Appendix.

To determine whether or not there was any significant difference in the thaw depth between the north and the south ends of the lanes, mean values were calculated for each end of the three traffic test loops for both years (Table 1).

At the time of the traffic tests (1976), the mean difference in the thaw depth between the north and south ends of the test area was 1.6 cm. This difference can be considered insignificant when compared with local variations in thaw depth. One year later (1977), the difference was 5.4 cm. The trend of increasing thaw depth towards east, across the test lanes, was noticeable, but small in relation to local variations.

More significant was the difference between the 1976 and 1977 mean thaw depth values in this area: 4.5 cm at the south end, 8.3 cm at the north end, 6.4 cm for the overall mean. (The measurements were taken at the same locations both years.)

Table 1. Comparison of 1976 and 1977 control area thaw depth.

Loop	Lane No.	South End		North End	
		1976	1977	1976	1977
1	1 - 6	22.9	17.5	21.1	13.6
2	7 - 12	25.0	21.8	22.9	13.3
3	13 - 18	26.6	21.7	25.5	17.7
	Mean	24.8	20.3	23.2	14.9

Overall mean 3 Aug 1976: 24.0 cm (mean of 138 measurements)
Overall mean 2 Aug 1977: 17.6 cm (mean of 108 measurements)

Test Vehicles

Three vehicles were used for the traffic tests:

1. CATCO Rolligon (11,700 kg or 26,000 lb, empty), an 8-wheel, low pressure, smooth, wide tire vehicle, inflation pressure 0.35 kg/cm^2 (5 psi), minimal load (Fig. 2)

2. Houston Rolligon (6,800 kg or 15,000 lb, empty), a 6-wheel, low pressure, ribbed, wide tire vehicle, inflation pressure 0.2 to 0.3 kg/cm^2 (3 to 4 psi), no load (Fig. 3)

3. Nodwell, FN-10 (2,250 kg or 5000 lb empty), low pressure (0.1 kg/cm^2 or 1.4 psi), tracked vehicle, no load (Fig. 4)

Figure 2. CATCO Rolligon

Figure 3. Houston Rolligon

Figure 4. Nodwell

Traffic Test Layout

The test lane layout is shown in Figure 5.

The test area consists of three traffic loops, one for each of the three traffic conditions: 1, 5, and 10 passes. Each loop consists of 6 parallel lanes, 2 for each test vehicle, for a total of 18 parallel test lanes, each approximately 100 m long. The direction of traffic on each lane is indicated in Figure 5.

The vehicle speed during the tests was approximately 8 km/hr. The traffic tests were completed within a period of a few hours.

Data Obtained

1976: Immediately after the traffic tests, color photographs were taken from the south end of each lane, looking toward north, to document the visual appearance of the traffic signatures (trails). A few aerial photographs of the area were also taken after takeoff from Lonely en route back to Barrow.

Surface depression and thaw depth measurements were obtained across both ends of each test lane, marked with wooden stakes.

Moisture content, dry density, peat and thaw depth measurements were obtained across the midpoint of some of the test lanes (refer to Fig. 5) and from the control areas between lanes. The dry density values were computed from the oven-dried (at 110°C) moisture samples, obtained in open-end cans and returned to the soils lab in Hanover, N.H., in sealed plastic bags.

The field data and samples were obtained within two hours after the traffic tests.

1977: During the visit to the test area one year later, aerial and ground photographs were again taken to compare the visual appearance of the traffic signatures after one year with their appearance immediately after the tests. Surface depression and thaw depth measurements were also obtained in the same locations as before.

The condition of vegetation in each test lane was evaluated by using an impact rating scheme (Walker et al., 1977) to compare the damage caused by each vehicle/traffic condition in terms of vegetation compression, displacement, breakage and deposition.

Barrow Tests: Observations and photographs, covering a period of 3 years after Rolligon traffic tests at Barrow, Alaska, are included for comparison purposes in Appendix B.

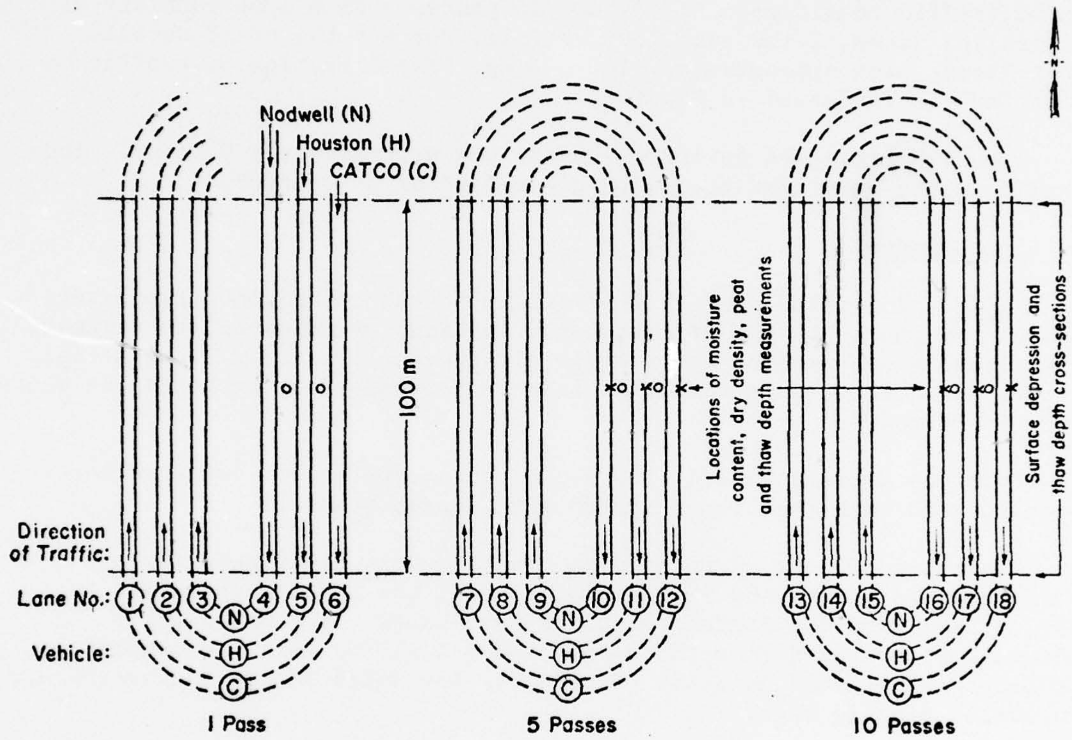


Figure 5. Traffic test lane layout

DISCUSSION OF RESULTS

Photographic Record

Figures 6 through 41 are photographs of the 18 test lanes, viewed toward the north. The photos at the top of each page (even Figure numbers) show the traffic signatures (trails) immediately after the tests; at the bottom of each page (odd Figure numbers) are the corresponding photos after 1 year. (The arrow in the caption denotes direction of traffic.)

Immediately after the tundra has been subjected to traffic in one direction only, the traffic signatures, when viewed against the direction of travel, appear darker than the surrounding terrain (Figs. 12,14,16, 24,26,28,36,38,40) and are more visible than when the traffic signatures are viewed in the direction of travel, in which case they appear slightly lighter than the adjacent terrain surface (Figs. 6, 8, 10, 18, 20,22, 30, 32, 34). It is, therefore, usually quite easy to determine the direction in which a vehicle has recently traveled by merely a quick glance, without close inspection of the vegetation (direction of bending).

One year after the traffic tests, 4 specific observations can be made regarding the visual appearance of the traffic signatures:

1) The trails which originally appeared lighter than the adjacent terrain surface are now darker (greener) than the undisturbed surface (typical examples: Fig. 8 vs Fig. 9, Fig. 22 vs. Fig 23).

2) Although all trails are now darker than the adjacent, undisturbed surface, the ones viewed against the direction of travel are darker than those viewed in the direction of travel (typical examples, same vehicle and same number of passes: Fig. 11 vs. Fig. 17, Fig. 23 vs. Fig. 29, Fig. 35 vs. Fig. 41).

3) Virtually all trails are more visible now than after the tests during the previous year (compare top row of photos with those in the bottom row on each page). The only exception is Lane 2 (Fig. 18 vs. Fig. 19), which is no longer visible from the ground.

4) The CATCO (4 tire passes per vehicle pass) has left a slightly more visual impact than the Houston (3 tire passes per vehicle pass) and the lower pressure, tracked Nodwell has left the least visual impact.

Aerial views of the test area are shown in Figures 42 through 45. It is interesting to compare the appearance of the traffic signatures in Figure 42 (immediately after the tests) and in Figure 43 (1 year later). Both sets of photos were taken late in the afternoon, looking towards north, so that the sun angles in both are similar.

After the tests (Fig. 42), the trails with traffic direction towards north, away from the viewer, particularly Rolligon lanes 1 and 2, 7 and 8, 13 and 14, are easily visible. The trails with traffic direction towards the viewer are barely perceptible from the air and, in some cases, not visible at all, contrary to their very prominent appearance on the ground (refer to Figs. 14 and 16, 26 and 28, for example).

After one year (Fig. 43), the visual appearance of the trails from the air corresponds to the observations on the ground, discussed previously. The difference in appearance due to traffic direction is obvious (compare Fig. 43 with Fig. 45, a view of the test area from the opposite direction). And, as in the ground observations, the CATCO trails are slightly more prominent than the Houston trails, the Nodwell trails being the least prominent, and the degree of visibility (traffic signature darkness) increasing with the number of traffic passes for all vehicles. The lower visibility of the Nodwell signature, when viewed from the air, is also due to the narrower track, in comparison with the wider Rolligon tire.

A numerical scheme, developed to compare the relative visibility of the various vehicle signatures, is discussed later.

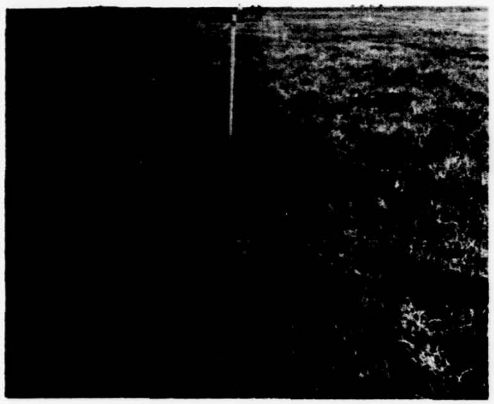


Figure 6. Lane 1, CATCO, 1 pass

Figure 8. Lane 7, CATCO, 5 passes

Figure 10. Lane 13, CATCO, 10 passes

Figure 7. Lane 1, after 1 year

Figure 9. Lane 7, after 1 year

Figure 11. Lane 13, after 1 year

Figure 12. Lane 6, CATCO, 1 pass

Figure 14. Lane 12, CATCO, 5 passes

Figure 16. Lane 18, CATCO, 10 passes

Figure 13. Lane 6, after 1 year

Figure 15. Lane 12, after 1 year

Figure 17. Lane 18, after 1 year


Figure 18. Lane 2, Houston, 1 pass


Figure 20. Lane 8, Houston, 5 passes


Figure 22. Lane 14, Houston, 10 passes

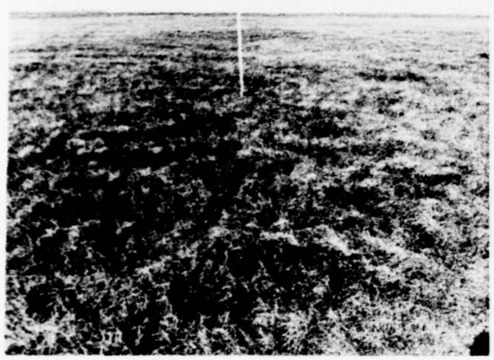


Figure 19. Lane 2, after 1 year


Figure 21. Lane 8, after 1 year


Figure 23. Lane 14, after 1 year

Figure 24. Lane 5, Houston, 1 pass

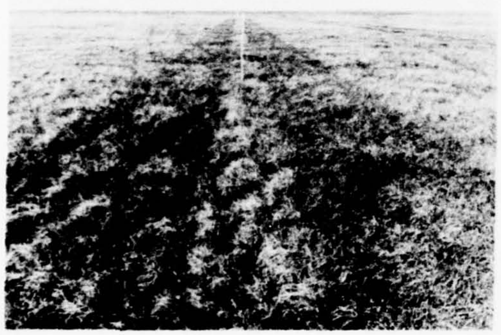


Figure 25. Lane 5, after 1 year

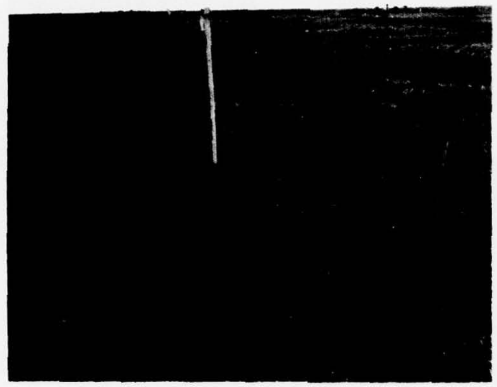


Figure 26. Lane 11, Houston, 5 passes

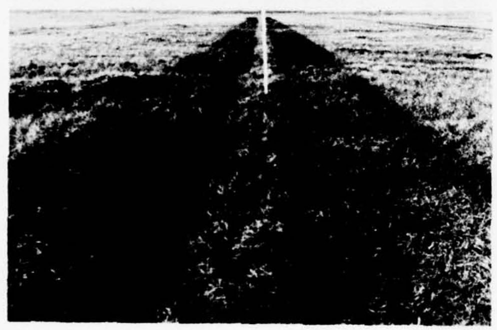


Figure 27. Lane 11, after 1 year

Figure 28. Lane 17, Houston, 10 passes

Figure 29. Lane 17, after 1 year

Figure 30. Lane 3, Nodwell, 1 pass

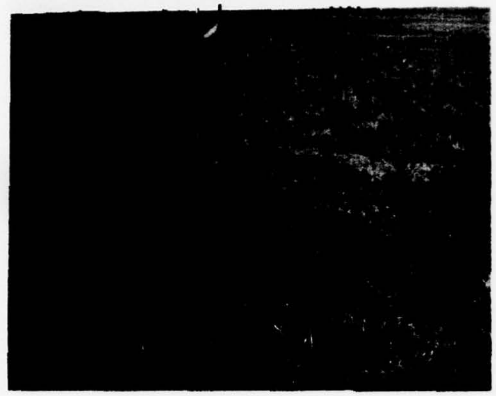


Figure 32. Lane 9, Nodwell, 5 passes

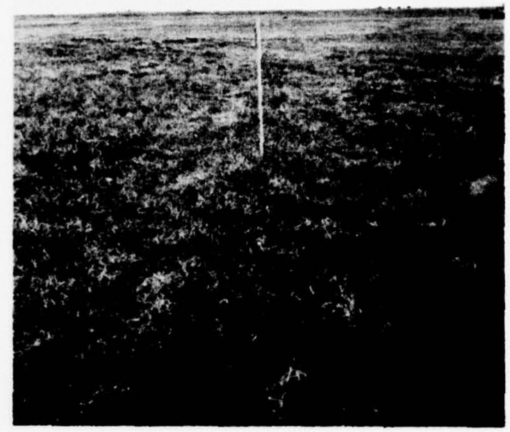


Figure 34. Lane 15, Nodwell, 10 passes

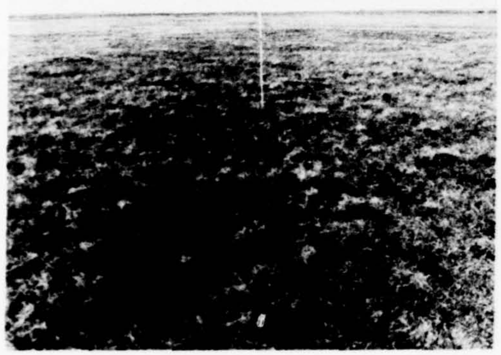


Figure 31. Lane 3, after 1 year

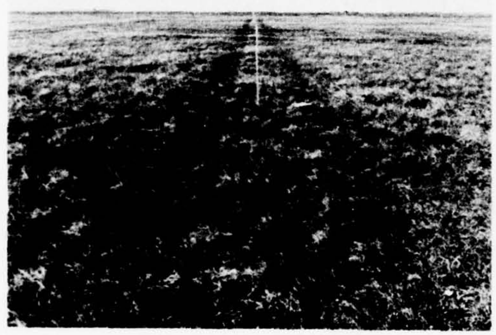


Figure 33. Lane 9, after 1 year

Figure 35. Lane 15, after 1 year

Figure 36. Lane 4, Nodwell, 1 pass

Figure 38. Lane 10, Nodwell, 5 passes

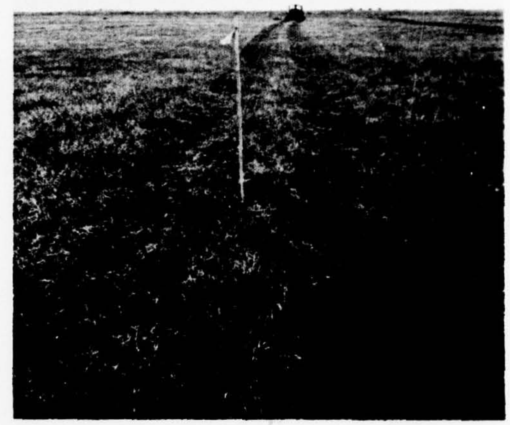


Figure 40. Lane 16, Nodwell, 10 passes

Figure 37. Lane 4, after 1 year

Figure 39. Lane 10, after 1 year

Figure 41. Lane 16, after 1 year

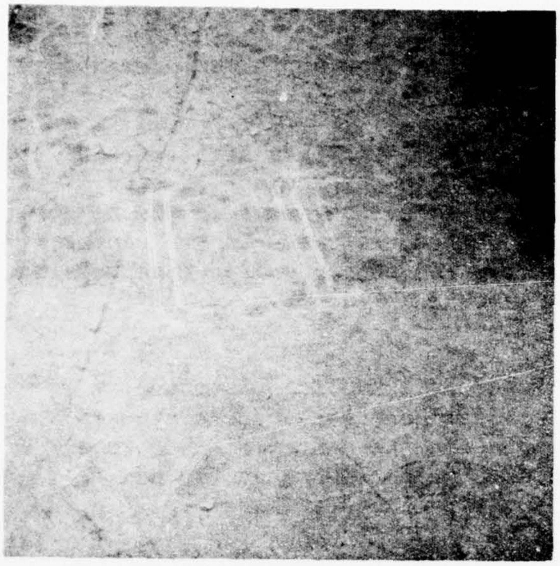


Figure 42. Aerial view of test site, after test, viewed toward north

Figure 43. Aerial view of test site, after 1 year, viewed toward north

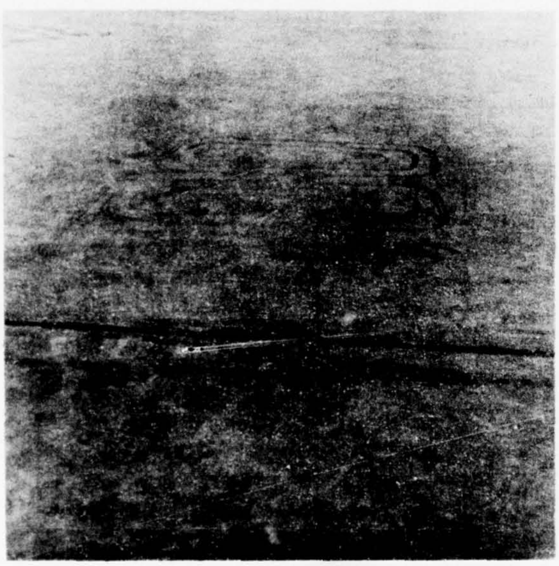


Figure 44. Aerial view of test site, after 1 year, viewed toward east

Figure 45. Aerial view of test site, after 1 year, viewed toward south

Terrain Surface Depression

The locations of the surface depression and thaw depth measurements across each lane are illustrated in Figure 46.

The depression left by a soft, wide, rubber tire in a soft terrain is not uniform in cross section; penetration below the center of tire can be considerably less than that below the edges, as shown in Figure 46. The surface depression measurements were, therefore, taken in the center as well as in both edges of the tire track. The center and edge depression data were treated separately, since the average would not be a very meaningful value.

In the wheeled vehicle (CATCO and Houston) test lanes, surface depression measurements were taken as follows: one measurement at each edge of each wheel track and one measurement in the center of each wheel track at both ends of the lane, a total of 8 measurements at the edge (y_e) and 4 measurements at the center (y_c) for each test lane.

In the tracked vehicle (Nodwell) test lanes, two surface depression measurements ($y_c = y_e$) were taken in each track at both ends of the lane, for a total of 8 measurements for each test lane (refer to Fig. 46).

Table A-2 (Appendix) contains the thaw depth and surface depression data after the traffic tests and after 1 year for both ends of the test lanes separately. (Note that the "thaw depth in track," h_T, measurements were obtained after the traffic tests, as shown in Figure 46; therefore, the y_c value has to be added to the h_T to obtain the original, 1976 before-traffic thaw depth in those locations.)

The surface depression data are summarized in Table 2. The mean depression values for each test condition are plotted as cross sections in Figure 47 (vertical scale exaggerated approximately 10 times that of horizontal). The immediate impression is that the smooth-tire CATCO caused the most sinkage and the tracked Nodwell the least. This is also evident in Figure 48a, where the surface depression (at edge of track) is plotted vs the number of traffic passes. It should be noted, however, that the CATCO had the highest ground pressure, that the Nodwell had the lowest, and that one vehicle pass with the CATCO represents 4 wheel passes, compared with 3 for the Houston.

One year after the tests, there were no significant changes in the surface depression (dashed lines in Fig. 47). (Refer also to Fig. A-1 in the Appendix for complete data plots of 1-year vs. after-test depression values.) In most cases, the apparent change (either rebound or increase in depression) was less than the measurement accuracy (0.5 cm). Consequently, in a surface depression vs. traffic passes plot (Fig. 48), the after-test and 1-year data can be represented by a common curve for each vehicle. The surface depression data are also plotted in a cross-sectional format in Figure 50.

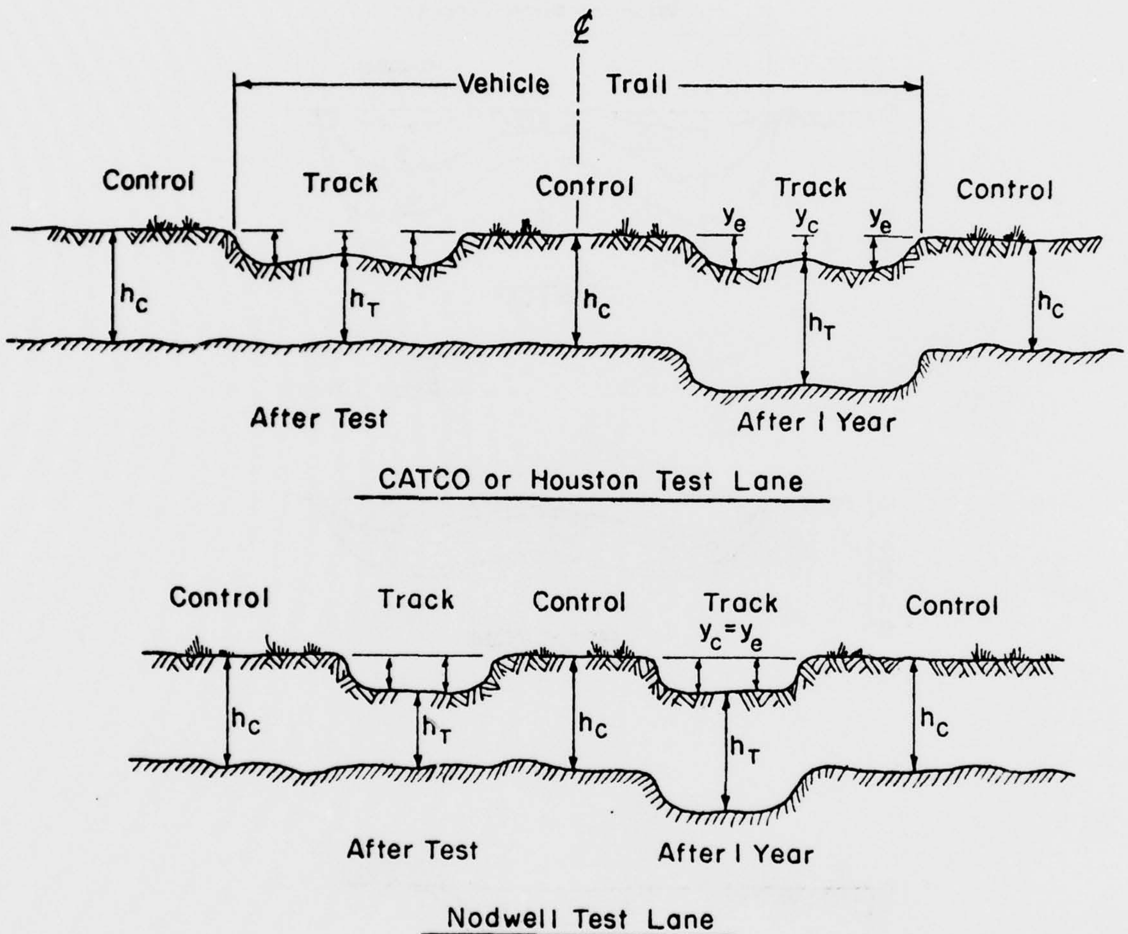


Figure 46. Location of thaw depth and surface depression measurements

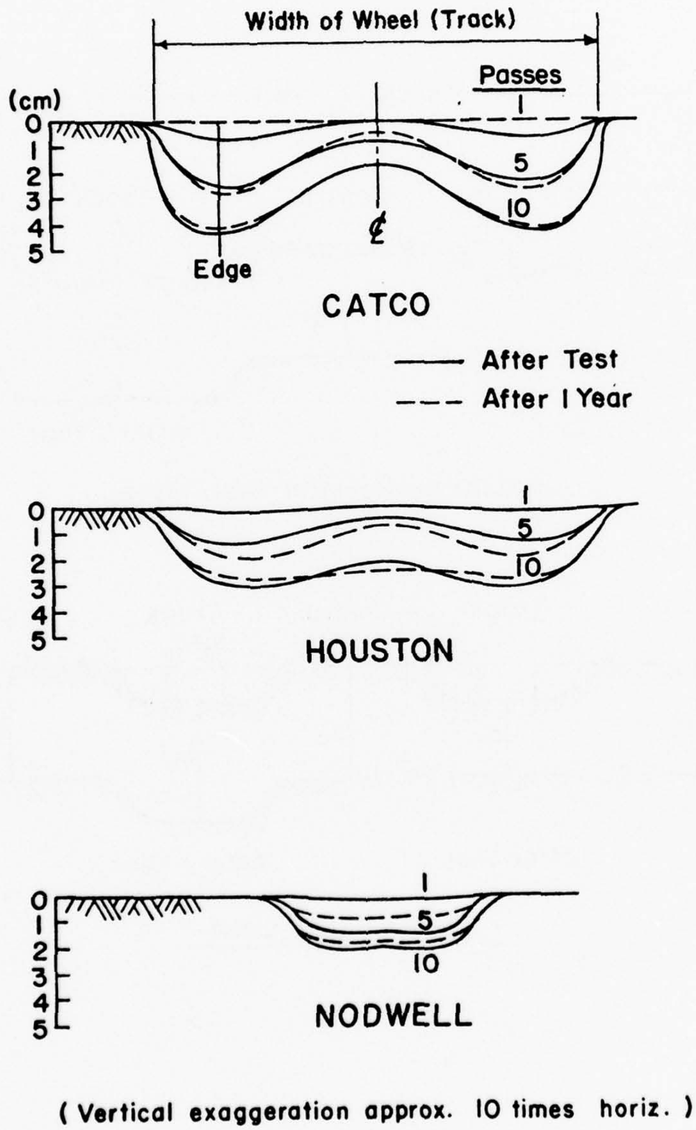


Figure 47. Surface depression caused by traffic

If the surface depression (at edge of track) is plotted vs. the number of wheel (instead of vehicle) passes, the difference between the CATCO and the Houston is not as significant (Fig. 49a). There is no realistic way to present the Nodwell traffic in terms of equivalent wheel passes (although this was done later in some graphs by considering one track pass equal to one wheel pass).

The surface depressions at the center of the track vs. the number of traffic and wheel passes are shown in Figures 48b and 49b, respectively. Here the sinkage of the Houston tire is slightly more than that of the CATCO tire; at the edges, the Houston penetration was less, implying that the Houston tire is less flexible than the CATCO tire for the air pressures used.

The terrain surface depression appears to increase at a nearly constant rate with increasing traffic, at least up to 10 vehicle (30 to 40 wheel) passes. Thereafter, the sinkage-traffic curve may start to level off slightly if no shearing or disaggregation of the organic mat occurs, or it may begin to curve upward rapidly, if the durability of the organic mat is exceeded, resulting in complete mat failure and sinkage down to the frost line, as was the case at Barrow (see Appendix B).

Table 2. Summary of mean surface depression and thaw depth values

Vehicle	No. of Passes n	Surface Depression (Mean) After Test Center y_c(cm)	Surface Depression (Mean) After Test Edge y_e(cm)	Surface Depression (Mean) After 1 Year Center y_c(cm)	Surface Depression (Mean) After 1 Year Edge y_e(cm)	Thaw Depth (Mean) After 1 Year Control h_C(cm)	Thaw Depth (Mean) After 1 Year Center of Track h_T(cm)	Thaw Depth (Mean) After 1 Year Difference $(h_T - h_C)$ Δh(cm)
CATCO	1	0.1	0.7	0	0	17.7	19.3	1.6
Houston	1	0	0	0	0	15.9	17.3	1.4
Nodwell	1	0		0		13.9	14.3	0.4
CATCO	5	0.8	2.4	0.4	2.6	19.4	23.0	3.6
Houston	5	0.5	1.4	0.9	2.0	19.8	20.9	1.1
Nodwell	5	1.4		0.9		15.9	18.6	2.7
CATCO	10	1.8	4.3	1.7	4.1	20.1	24.5	4.4
Houston	10	2.2	3.0	2.3	2.8	19.0	22.1	3.1
Nodwell	10	2.1		1.6		20.9	21.8	0.9

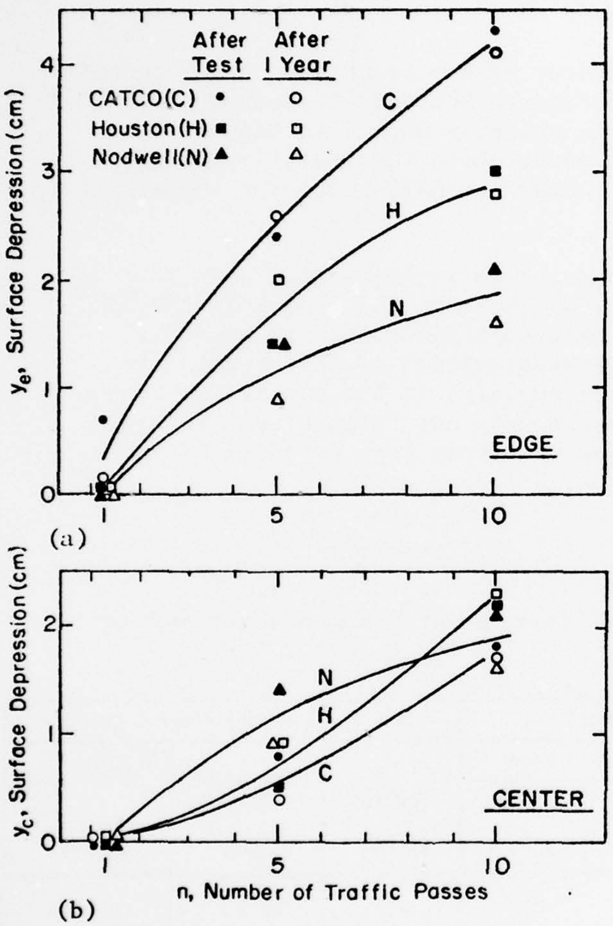


Figure 48. Surface depression vs number of traffic passes

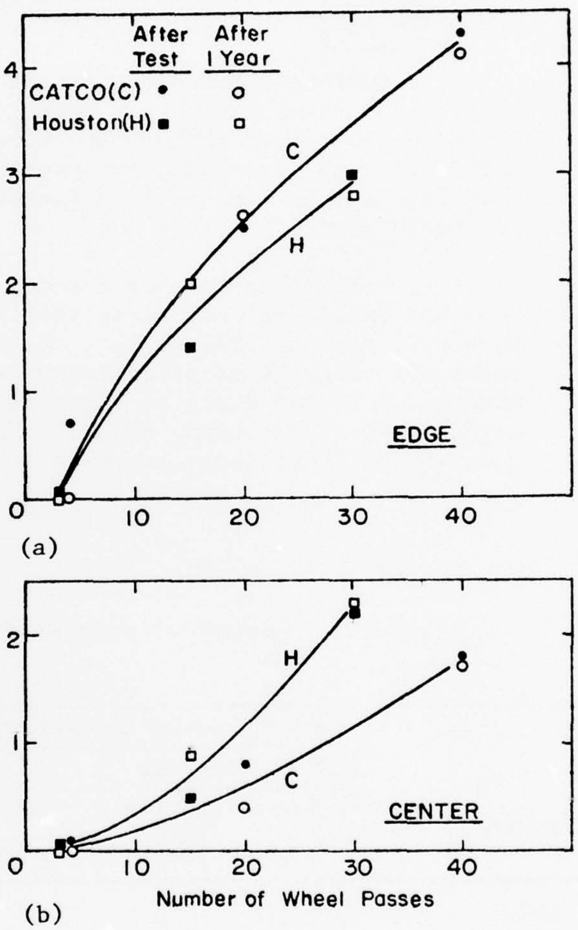


Figure 49. Surface depression vs number of wheel passes

Effect on Thaw Depth

Figure 50 shows in a cross-sectional format all the surface depression and thaw depth data obtained in this test area after the tests and after 1 year. The surface depression data, center and edge for both tracks of each lane, are shown graphically at an exaggerated vertical scale, with the thaw depth profiles plotted below. The thaw depth in the center of each track (h_T) after 1 year is identified with open circles. The heavy vertical line from the control thaw depth profile (solid line) to the track thaw depth indicates the apparent increase in thaw depth due to traffic (Δh) after 1 year. Note that in several cases, especially at the south end, the track thaw depth is the same as or even less than the control. (Refer also to Figure A-2 in the Appendix for complete data plots of the 1-year track vs. control thaw depth values.)

The local variations in the thaw depth across both ends of the test lanes are quite severe (range: 15 to 36 cm for 1976; 9 to 40 cm for 1977). It is also obvious that during 1977 the thaw depth at Lonely was considerably less than during 1976 (Table 1).

Because of the great variations in the natural thaw depth in this area, any attempt to determine the effect of traffic on the thaw depth below the vehicle trail may not be very reliable, unless a very great number of data are obtained.

The general 1-year trends of thaw depth increase vs. number of traffic passes for the three vehicles are shown in Figure 51. The thaw depth data are listed in Table A-2 and are plotted in Figure A-2 in the Appendix. The 1-year mean values for h_C, h_T, and Δh are shown in Table 2.

Effect on Soil Properties

The moisture content and dry density data, obtained during the traffic tests, are listed in Table 3, and plotted according to location in Figure A-3 in the Appendix (refer to Fig. 5 for the locations of these measurements). The peat thickness and thaw depth data at these measurement sites are also shown in Table 3.

Since only a limited amount of data were obtained, it is not really possible to determine the impact of traffic on the moisture content and density conclusively. However, to investigate whether there was any apparent effect from the traffic, the data from below the vehicle tracks were plotted vs. the closest adjacent control data. No data were obtained in the 1-pass tracks.

Figure 52 shows the moisture content of peat below the track, $w_{p(T)}$, vs. the adjacent control area, $w_{p(C)}$. No conclusions can be drawn from this graph. However, the effect on the moisture content in the mineral soil is more evident (Fig. 53). There appears to be some decrease in the moisture content of the mineral soil below the vehicle tracks. This

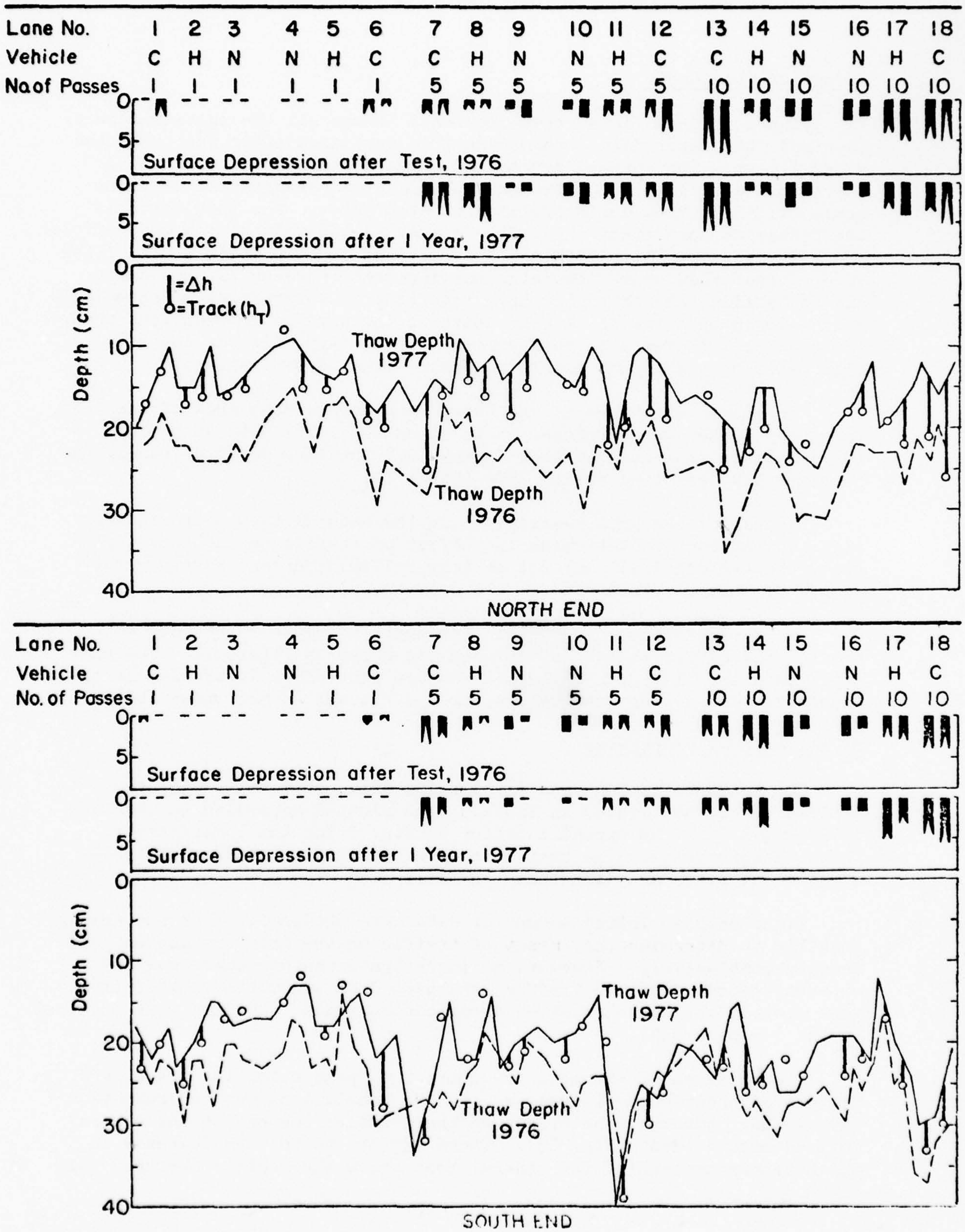


Figure 50. Surface depression and thaw depth profiles across test area

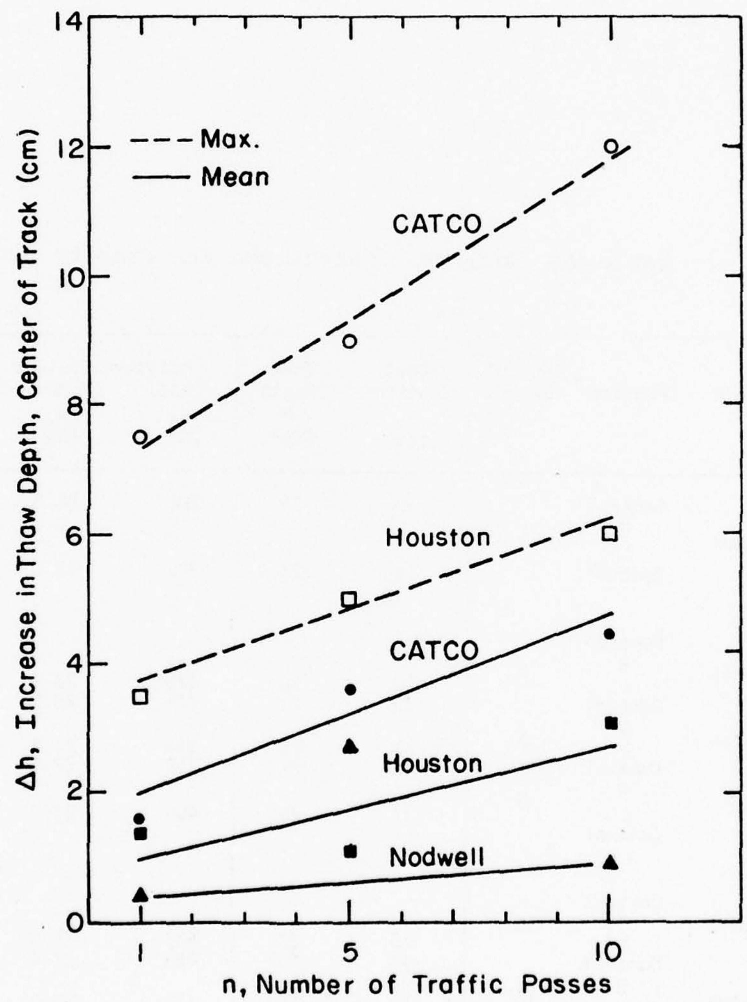


Figure 51. Increase in thaw depth below track vs number of traffic passes, after 1 year

observation, combined with the evidence that there may have been some increase in the dry density of the mineral soil (Fig. 55), implies that the mineral soil has been subjected to some degree of compaction due to traffic. Any comparable influence on the dry density of peat is not conclusive from the available data (Fig. 54). Soil data were not obtained 1 year after the tests.

Table 3. Moisture content and dry density data

Lane No.	Vehicle	Location*	No. of Passes n	Peat Thickness (cm)	Thaw Depth h (cm)	Moisture Content (Peat) w_p (%)	Moisture Content (Mineral) w_m (%)	Dry Density (Peat) ρ_p (g/cm^3)	Dry Density (Mineral) ρ_m (g/cm^3)
		Control		12	25	394	36.8	0.16	1.14
5	Houston	R	1						
		L							
		Control		14	21	375	55.0	0.19	0.86
		Control							
10	Nodwell	R	5						
		L		13	28	429	25.8	0.16	1.27
		Control		12	27	425	28.5	0.17	1.26
11	Houston	R	5						
		L		9	25	314	21.7	0.17	1.50
		Control		12	24	318	23.4	0.22	1.40
12	CATCO	R	5						
		L		11	25	406	20.7	0.16	1.34
		Control							
		Control							
16	Nodwell	R	10						
		L		15	22	523	15.8	0.13	1.58
		Control		13	27	452	22.4	0.15	1.34
17	Houston	R	10						
		L		10	16	370	23.4	0.19	1.36
		Control		14	25	455	30.6	0.12	1.33
18	CATCO	R	10						
		L		14	35	428	22.4	0.16	1.45
		Control							

* R or L denotes right or left track of test lane; note that measurements were taken in the left track.

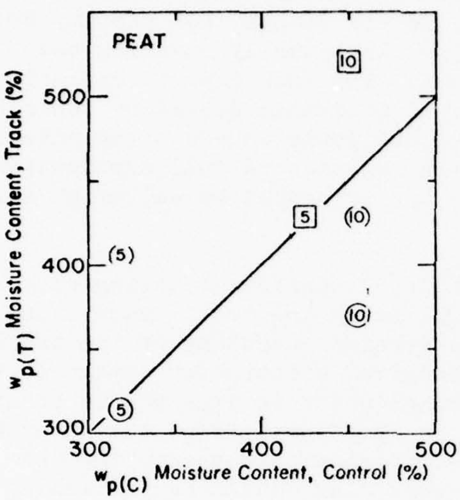


Figure 52. Moisture content of peat, track vs control

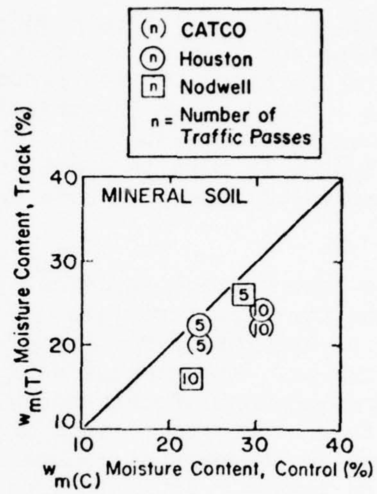


Figure 53. Moisture content of mineral soil, track vs control

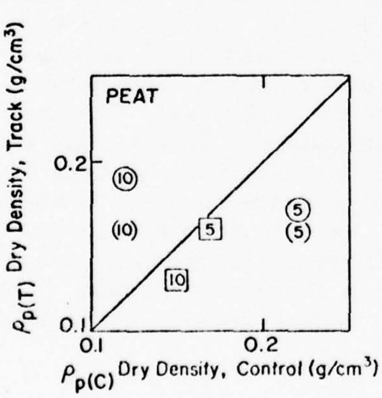


Figure 54. Dry density of peat, track vs control

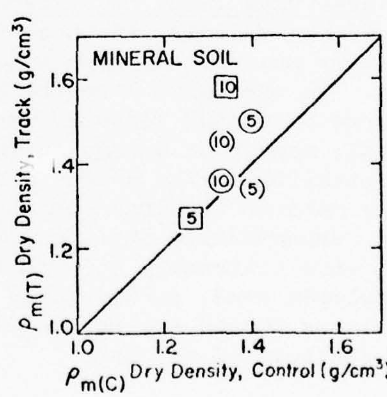


Figure 55. Dry density of mineral soil, track vs control

(The straight lines represent track data = control data, i.e., y=x)

Impact On Vegetation

The impact on the vegetation was rated according to the system shown in Table 4. The major advantage of the system is that it allows various aspects of damage to be compared separately. For example, two vehicles may both create moderately severe damage, but one may be compressing the vegetation while the other is actually shearing and displacing portions of the vegetation mat. The four impact categories shown in Table 4 cover the principal types of damage caused by vehicles to coastal tundra vegetation. It may be desirable to add other categories if the system is used in other vegetation regions. A full explanation and examples of impact in each category are presented by Walker et al., (1977).

The observations reported here (Table 5) consist of rating each test lane for impact visible one year following the test. Each lane was scored separately for impact in the straight sections of the track and in the curves. Each impact category was given a score for damage at time of observation and another score for damage which is expected to be apparent in another year. This is shown in fractional form, the numerator representing the current damage and the denominator representing the predicted damage. Total impact scores were also determined by adding the scores of the four restricted impact categories. Although this method weighs all aspects of the damage equally, it does give a rough method for comparing total damage. Total values equal to or less than 4 can be considered slight impact, values from 5 to 8 are moderate impact, and values greater than 8 represent severe impact.

Single pass lanes (Nos. 1-6). There was very little damage caused by any of the vehicles in these lanes. In fact, the Houston and Nodwell tracks were practically undetectable except in certain lighting conditions. In the CATCO lane the microrelief was slightly flattened. *Eriophorum vaginatum* tussocks were also slightly flattened. The most noticeable aspect of damage in the CATCO track was the slight compression and orientation of the sedges and grasses in the direction of travel. Slightly more moist sites (determined by the presence of certain mosses, such as *Drepanocladus* spp., *Calliergon* spp. and *Campylium stellatum*) did not show noticeably different impact. There was increased damage on a few polygon rims, particularly in areas with abundant *Sphagnum*. None of the lanes showed any marked difference in impact between straight and curved sections of the lane.

Five pass lanes (Nos. 7-12). In the straight sections of the lanes, the CATCO Rolligon created significantly more impact than the other two vehicles. The microrelief was nearly totally flattened, and the graminoid species were strongly oriented in the direction of travel. The compression of the vegetation carpet was enough to cause a slightly more moist microenvironment in the tracks, which could lead to changes in relative abundance of certain species, particularly the mosses. *Eriophorum vaginatum* tussocks were disturbed, dislodged and flattened on one side but not overturned. A few polygon rims in the CATCO lane had deep im-

Table 4. Rating scheme for evaluating vehicle traffic impact on vegetation.

Impact Categories and Scores

Compression to tundra surface - refers to the bending and compressing of live and standing dead vegetation to the tundra surface so that it becomes flattened and oriented to the direction of travel.

0 - no observable compression vegetation to tundra surface.

1 - slight compression of vegetation (1-10% of plants affected).

2 - moderate compression of vegetation (11-50% of plants affected).

3 - severe compression of vegetation (>50% of plants affected).

Displacement - refers to several categories of disturbance, including tussocks of moss or cottongrass moved or overturned, displacement of wet mosses by splashing action, and exposure of bare soil by removal of vegetation mat.

0 - no displacement of vegetation.

1 - some displacement of vegetation (1-10% of plants affected).

2 - moderate displacement of vegetation (11-50% of plants affected).

3 - severe displacement of vegetation (>50% of plants affected).

Breakage - refers to breakage of plant stems or flowering stalks.

0 - no breakage observed.

1 - some breakage observed (1-10% of plants affected).

2 - moderate breakage observed (11-50% of plants affected).

3 - severe breakage observed (>50% of plants affected).

Deposition - refers to accumulation of mud and moss to sides of track.

0 - no mud or moss accumulation at sides of track.

1 - few shallow patches of mud or moss.

2 - many shallow patches of mud or moss.

3 - continuous thick deposit of mud or moss.

Table 5. Impact scores one year after traffic (Numerator represents current observed impact; denominator represents predicted impact 1 year later, 2 years after traffic)

No. of Passes	Portion of Track	Vehicle	Compression to Tundra Surface	Displacement	Breakage	Deposition of Moss or Mud	Total
1	straight	CATCO	1/1	1/0	0/0	0/0	2/1
1	straight	Houston	1/0	0/0	0/0	0/0	1/0
1	straight	Nodwell	0/0	0/0	0/0	0/0	0/0
1	curve	CATCO	1/1	0/0	0/0	0/0	1/1
1	curve	Houston	1/1	0/0	0/0	0/0	1/1
1	curve	Nodwell	0/0	0/0	0/0	0/0	0/0
5	straight	CATCO	2/2	1/1	1/0	1/1	5/4
5	straight	Houston	1/1	1/1	1/0	0/0	3/2
5	straight	Nodwell	1/1	1/0	1/0	0/0	3/1
5	curve	CATCO	2/2	1/1	1/0	1/1	5/4
5	curve	Houston	2/1	1/1	1/0	0/0	4/2
5	curve	Nodwell	1/1	2/1	1/0	1/1	5/3
10	straight	CATCO	3/2	1/1	1/0	1/1	6/4
10	straight	Houston	2/2	1/1	1/0	1/1	5/4
10	straight	Nodwell	2/2	1/1	1/1	1/0	5/3
10	curve	CATCO	3/2	2/2	1/0	2/2	8/6
10	curve	Houston	3/2	2/2	1/1	1/1	7/6
10	curve	Nodwell	2/2	2/2	2/1	2/2	8/7

pressions, whereas this did not occur in the other vehicle lanes. In the curved sections of the lanes, the Nodwell tracks tore the vegetation mat in several places. Both Rolligons also created this type of damage but to a much less extent. In the CATCO and Nodwell lanes there was some minor deposition of peat to the sides of the tracks.

Ten pass lanes (Nos. 13-18). Again the CATCO created the most severe impact in straight portions of the lanes. This was particularly true at a few frost boils and polygon rims. The rims which were most severely affected, had thick (> 10 cm) moss carpets, consisting mainly of *Sphagnum* and *Dicranum.* There was also noticeable deposition of peat along both sides of the tire tracks. In the curved sections, the Nodwell tracks tended to abrade the vegetation more than in the straight sections. This was evident from damaged *Eriophorum vaginatum* tussocks, broken *Salix planifolia* ssp. *pulchra* branches, and displaced sedges and mosses. There was some tearing of the vegetation carpet with the Houston and CATCO, but not as severe as with the Nodwell. Typical results of the 10-pass traffic in the curved sections are shown in Figures 56 through 59.

To enable a more convenient comparison of the impact (after 1 year) caused by the three vehicles, the impact scores listed in Table 5 are shown in a graphical format in Figure 60.

It should be noted that the values shown in Table 5 or Figure 60 represent observed damage without regard for variations in vehicle weight, payload, tire characteristics, or number of tire passes. On this basis alone, the CATCO Rolligon created more damage than either of the other two vehicles, particularly along the straight portions of the tracks (Fig. 61a). This was due mostly to the deeper, more uniform compression of the vegetation in the smooth tire CATCO track. The ribbed tires of the Houston and the Nodwell tracks tended to abrade the vegetation in the curves of the 5 and 10-pass lanes, and although the total damage in the curves was similar for all three vehicles (Fig. 61b), the causes of the damage were different.

When the total impact scores for the two Rolligons are replotted (from Fig. 61) as a function of the number of wheel passes, instead of vehicle passes, the difference in impact between the CATCO and the Houston is less significant in the straight sections (Fig. 62a) and the same in the curved sections (Fig. 62b).

Noticeably more damage to the terrain surface occurs when a vehicle is turning, because of the lateral shear forces caused by a tire and particularly by the hard edge of a track. The degree of damage increases with the vehicle's speed, with the amount of tire sinkage, and with a decrease in the turning radius.

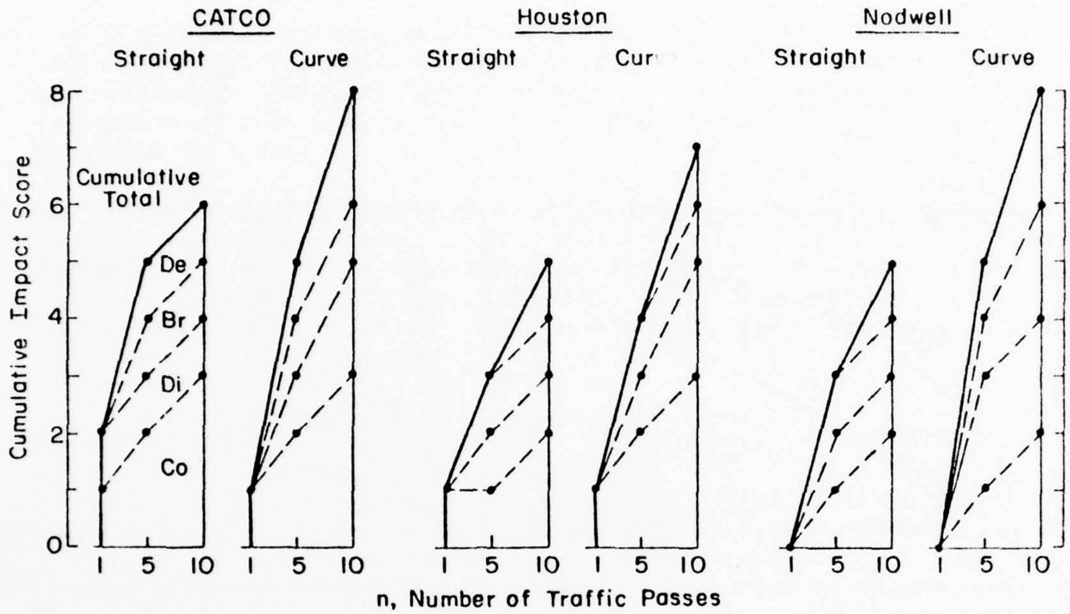
The relative total impact of each of the three vehicles, based on both the observed current impact (1977 score) and the predicted next year's impact score (refer to Table 5) is shown in Table 6 by listing the vehicles in order of increasing impact.

Figure 56. 10 passes CATCO, curve (south end)

Figure 57. 10 passes CATCO, curve (north end)

Figure 58. 10 passes Houston, curve

Figure 59. 10 passes Nodwell, curve



Co = Compression of Vegetation to Tundra Surface
Di = Displacement of Vegetation
Br = Breakage of Plant Stems or Stalks
De = Deposition of Moss or Mud to Sides of Track

Figure 60. Comparison of impact scores for each vehicle (1 year after traffic)

Table 6. Relative total impact of various traffic conditions

Impact	1 Pass		5 Passes		10 Passes	
	Straight	Curve	Straight	Curve	Straight	Curve
Least	Nodwell (0/0)	Nodwell (0/0)	Nodwell (3/1)	Houston (4/2)	Nodwell (5/3)	Houston (7/6)
	Houston (1/0)	Houston (1/1)	Houston (3/2)	Nodwell (5/3)	Houston (5/4)	CATCO (8/6)
Most	CATCO (2/1)	CATCO (1/1)	CATCO (5/4)	CATCO (5/4)	CATCO (6/4)	Nodwell (8/7)

(Total impact score in parenthesis; Current, 1977/Predicted, 1978)

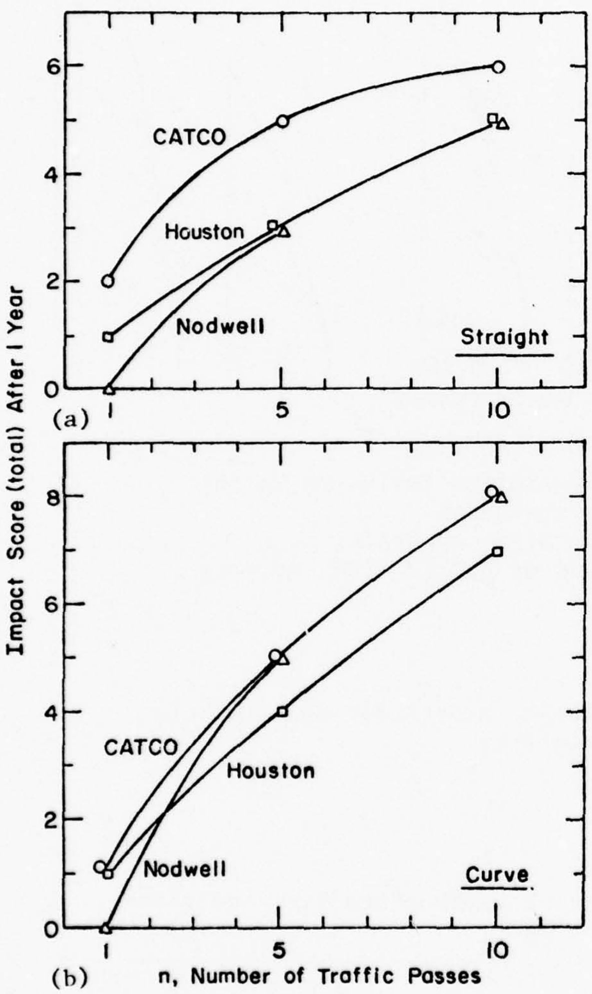


Figure 61. Impact score vs number of traffic passes

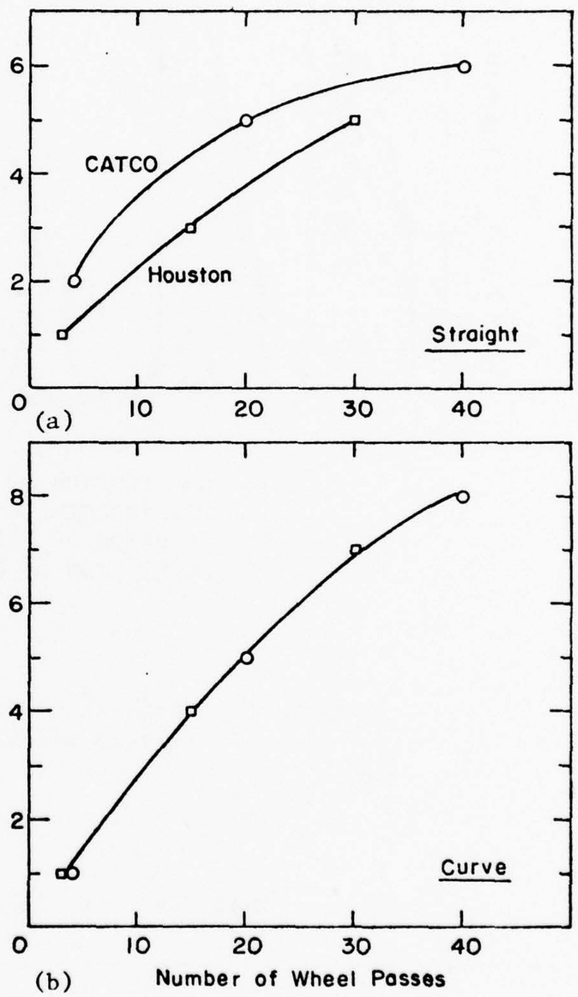


Figure 62. Impact score vs number of wheel passes

Visibility of Traffic Signatures

The general appearance of the various traffic trails after tests and after 1 year has been discussed earlier under "Photographic Record" in qualitative terms. It would be helpful if a comparison of the visual appearance of the 18 test lanes could be made using some type of a quantitative scheme.

During a similar previous study at Barrow, the visibility of Air Cushion Vehicle and Weasel (light, tracked vehicle) traffic trails was compared by classifying the signatures into groups according to their apparent darkness (Abele and Brown, 1977). This scheme permitted a convenient assessment of the relative aesthetic impact of vehicle traffic on tundra.

A similar scheme, based on a numerical scale, was developed for the traffic impact study at Lonely. The following procedure was used:

1) The 36 photographs (Figs. 6-41), one of each of the 18 lanes taken after the traffic tests and again after 1 year, were arranged in order of increasing darkness of the traffic signatures. This was done several times by two observers, using both the color photographs and black-and-white Xerox reproductions of the photos. The final order, identified by Figure numbers and traffic characteristics, is shown in Table 7.

2) Those signatures which were not visible in the photos (same apparent color or darkness as the adjacent natural terrain surface) were assigned a "visibility index" value of 0. Those signatures which appeared darker than the natural surface were given positive "visibility index" values, and those that appeared lighter were given negative values.

3) The numerical scale for the "visibility indices" was chosen according to geometric progression (....1,2,4,8....); that is, doubling of a previous value indicates doubling of the apparent darkness of the signature. The judging of the relative darkness was based on a tonal variation chart (the frequency of dark lines or dots on a light area increased in a geometric progression). For example, a traffic signature with a value of 2 appears twice as dark as that with a value of 1, one with a value of 4 appears twice as dark as that with a value of 2, etc. A similar procedure was used for the lighter-than-natural-surface signatures, the corresponding numerical values being negative.

Table 7 lists the visibility index values for each photo of the traffic trails in order of increasing signature darkness. The same data, arranged according to the test vehicles and traffic characteristics, are shown in Table 8, and plotted in Figure A-4 in the Appendix.

During the field observations at the test site in 1977, it was obvious that, with a few exceptions, the traffic trails were more visible after 1 year than they were after the tests. The visibility index

Table 7. Visibility indices of traffic signatures in order of increasing darkness

Fig. No.	Vehicle	Passes	Direction	Years	Visibility Index
22	H	-10	↑	0	-2½
10	C	-10	↑	0	-2½
20	H	-5	↑	0	-2
18	H	-1	↑	0	-2
8	C	-5	↑	0	-1½
6	C	-1	↑	0	-1
34	N	-10	↑	0	- ½
32	N	-5	↑	0	- ¼
30	N	-1	↑	0	0
19	H	-1	↑	1	0
31	N	-1	↑	1	½
7	C	-1	↑	1	½
36	N	-1	↓	0	1
24	H	-1	↓	0	2
37	N	-1	↓	1	2
33	N	-5	↑	1	3
40	N	-10	↓	0	3
35	N	-10	↑	1	3
21	H	-5	↑	1	3
38	N	-5	↓	0	3
26	H	-5	↓	0	3½
12	C	-1	↓	0	4
25	H	-1	↓	1	4
9	C	-5	↑	1	4
23	H	-10	↑	1	4
11	C	-10	↑	1	4½
13	C	-1	↓	1	4½
28	H	-10	↓	0	4½
14	C	-5	↓	0	4½
39	N	-5	↓	1	4½
41	N	-10	↓	1	5
27	H	-5	↓	1	6
15	C	-5	↓	1	6
16	C	-10	↓	0	6
29	H	-10	↓	1	7
17	C	-10	↓	1	7½

Table 8. Visibility indices of traffic signatures

Vehicle	No. of Passes	Traffic Direction *	Visibility Index: After Test (Fig.No.)		Visibility Index: After 1 Year (Fig.No.)	
CATCO	1	↑	(6)	-1	(7)	½
	5	↑	(8)	-1½	(9)	4
	10	↑	(10)	-2½	(11)	4½
	1	↓	(12)	4	(13)	4½
	5	↓	(14)	4½	(15)	6
	10	↓	(16)	6	(17)	7½
Houston	1	↑	(18)	-2	(19)	0
	5	↑	(20)	-2	(21)	3
	10	↑	(22)	-2½	(23)	4
	1	↓	(24)	2	(25)	4
	5	↓	(26)	3½	(27)	6
	10	↓	(28)	4½	(29)	7
Nodwell	1	↑	(30)	0	(31)	½
	5	↑	(32)	-¼	(33)	3
	10	↑	(34)	-½	(35)	3
	1	↓	(36)	1	(37)	2
	5	↓	(38)	3	(39)	4½
	10	↓	(40)	3	(41)	5

* Traffic Direction: ↑ away from viewer

↓ towards viewer

exercise with the photographs confirms the initial visual impressions in the field. This is illustrated in Figures 63, 64 and 66. The data can be represented by a common curve if the visibility index is plotted vs. the number of wheel passes (Fig. 64) instead of vs. the traffic passes (Fig. 63). Figure 65 shows the increase in the relative visibility of the traffic signatures when the 1 year data are plotted vs. the after-test data. (Note that the data from those test lanes where the direction of traffic was away from the viewer, cannot be plotted in Figures 63-65, because those traffic signatures, being lighter than the control surface, resulted in negative index values after the tests.)

After 1 year, all the visible signatures appeared darker than the control surface; therefore, a mean visibility index value of both traffic directions (Table 9) can be used to evaluate the relative aesthetic effect of the various vehicles as a function of passes 1 year after the tests (Figs. 66 and 67).

The increased visibility of the traffic signatures after 1 year can be attributed primarily to the "green belt" effect. Vehicular traffic alters the natural color scheme of the tundra. The light colored standing dead vegetation and litter, which have been depressed into the wet organic mat by the tires or tracks during the previous year, remain in that position and, being wet and partly decomposed, appear much darker than before. The new growth, consisting primarily of grasses, is green and darker in comparison with the natural tundra surface. Also, the very dark organic soil is more exposed than before, resulting in even more darkening of the traffic signature. This phenomenon usually occurs when the tundra has been subjected to moderate traffic impact, in this case 5 or 10 vehicle passes. However, in the case of light traffic, such as some of the 1-pass lanes, or where very little disturbance of the vegetation has occurred, the signature visibility after 1 year may be less than that immediately after the traffic.

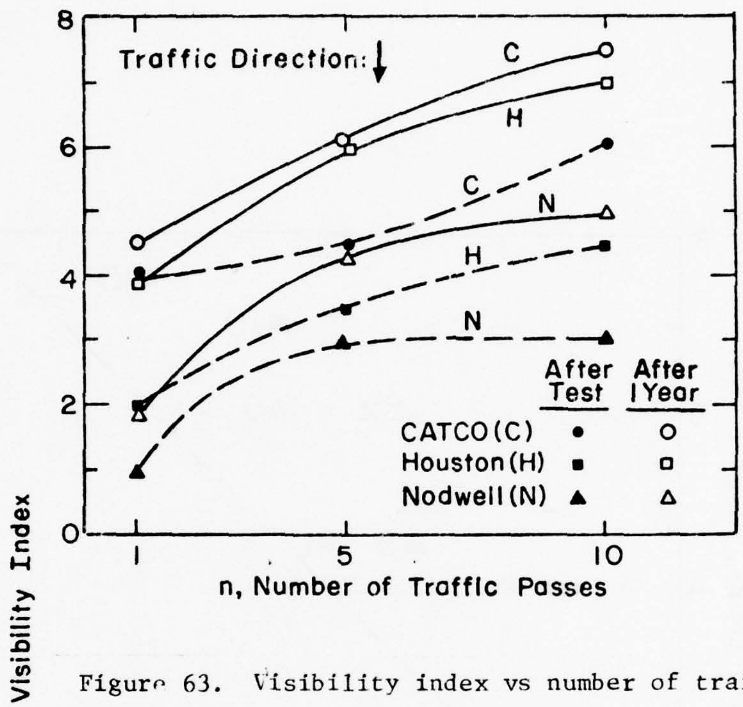


Figure 63. Visibility index vs number of traffic passes

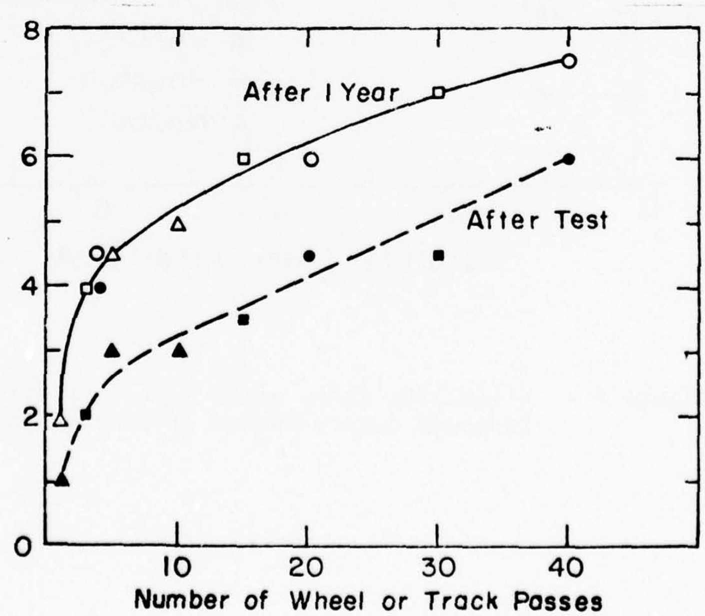


Figure 64. Visibility index vs number of wheel or track passes

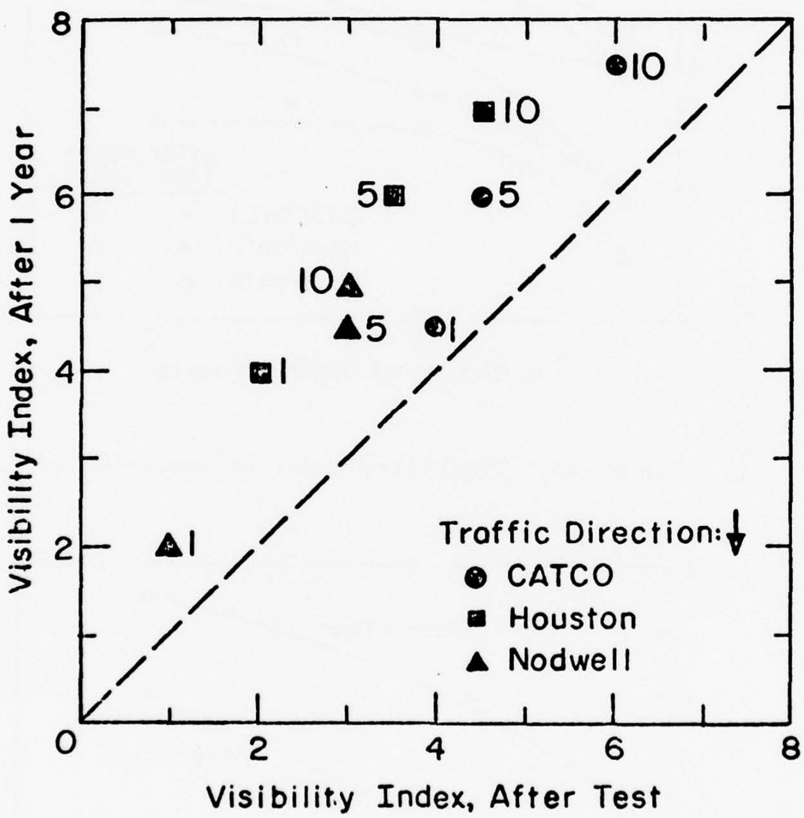


Figure 65. Visibility index after 1 year vs after test (numbers denote number of traffic passes)

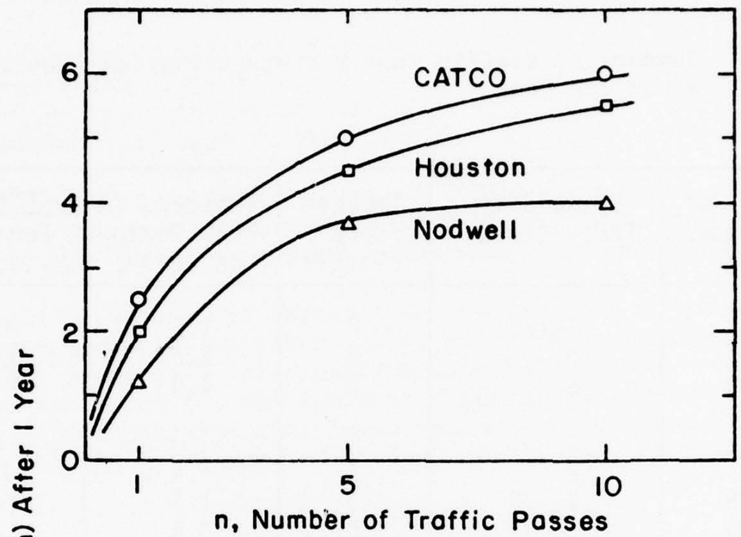


Figure 66. Mean visibility index after 1 year vs number of traffic passes

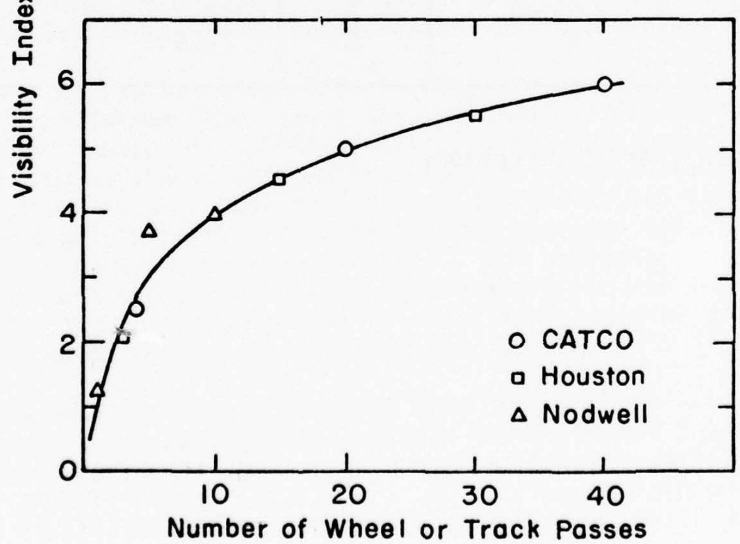


Figure 67. Mean visibility index after 1 year vs. number of wheel or track passes

Table 9. Summary of traffic impact characteristics (descriptors) after one year

Vehicle	No. of Passes n	Visibility Index (Mean)*	Impact Score (Total)	Increase in Thaw Depth Δh (cm)	Surface Depression	
					Center y_c (cm)	Edge y_e (cm)
CATCO	1	2-1/2	2	1.6	0	0
	5	5	5	3.6	0.4	2.6
	10	6	6	4.4	1.7	4.1
Houston	1	2	1	1.4	0	0
	5	4-1/2	3	1.1	0.9	2.0
	10	5-1/2	5	3.1	2.3	2.8
Nodwell	1	1-1/4	0	0.4	0	
	5	3-3/4	3	2.7	0.9	
	10	4	5	0.9	1.6	

* Mean of both traffic directions

Relationships Between Impact Descriptors

The results in this study have been described here in terms of four of the more easily observable impact characteristics or, more appropriately, "descriptors" (Table 9);

1) Aesthetic (Visibility Index)
2) Vegetation (Impact Score)
3) Relief (surface depression)
4) Thermal (increase in thaw depth)

The first two represent subjective evaluations based on numerical schemes which had been developed specifically for this type of a study. The last two are based on physical measurements in the field.

It would be natural to expect some relationship to exist between these 4 characteristics or descriptors; if not a correlation, at least a trend. The 6 possible interrelationships between the 4 variables, illustrated in Figure 68, are shown in Figures 69a - 69f. For the sake of simplicity, the summarized data (mean values, after 1 year) from Table 9, instead of all the available individual points, were plotted in these graphs.

In the first four graphs (Figs. 69a-69d), where the measured values (y and Δh) are plotted vs. the subjective descriptors, no correlation is apparent. However, the data scatter is such that an envelope (dashed line) can be used to represent the upper range of the y and Δh values for any particular impact score or visibility index value.

Curiously, the two subjective descriptors show the best (actually, the only) correlation (Fig. 69e); the two measured descriptors (y, Δh) show no relationship (Fig. 69f). But, this may not be so surprising: the impact scores and visibility indices were obtained by evaluating the entire test lanes, while the surface depression and thaw depth measurements were done at a relatively few, discrete locations and are influenced by natural, local variations. The increase in thaw depth is also a function of other parameters, besides surface depression. (Note that since the Δh data were obtained in the center of each track, only the y_c data, not y_e, are appropriate for Fig. 69f.)

It has been frequently observed that just because a vehicle trail is visible does not necessarily indicate damage to the tundra surface. In this case, no vegetation impact could be observed until the visibility index was greater than 1 (Fig. 69e). No surface depression had occurred until the visibility index was greater than 3 (Fig. 69c) and the total impact score greater than 2 (Fig. 69a).

Inspection of the interrelationships of the four impact descriptors after 1 year allows comparison of the relative sensitivity of each descriptor to vehicular traffic and listing them in order of decreasing sensitivity:

1) Aesthetic - most sensitive, occurs first and can occur without the other three. A vehicle can leave a temporarily visible signature (bending of the vegetation, for example) without causing any other noticeable damage or impact.

2) Thermal - can occur after the aesthetic impact has been present for a period of time (at least a number of weeks). Thaw depth, if shallow relative to the width of the traffic signature, can be influenced by a change in color of the signature (change in albedo) without the presence of any measurable vegetation impact or surface depression.

3) Vegetation - can occur without any measurable terrain surface depression, but the traffic signature is obviously visible and quite likely subject to thermal changes below.

4) Relief - when a measurable surface depression occurs, the other three impacts are also apparent.

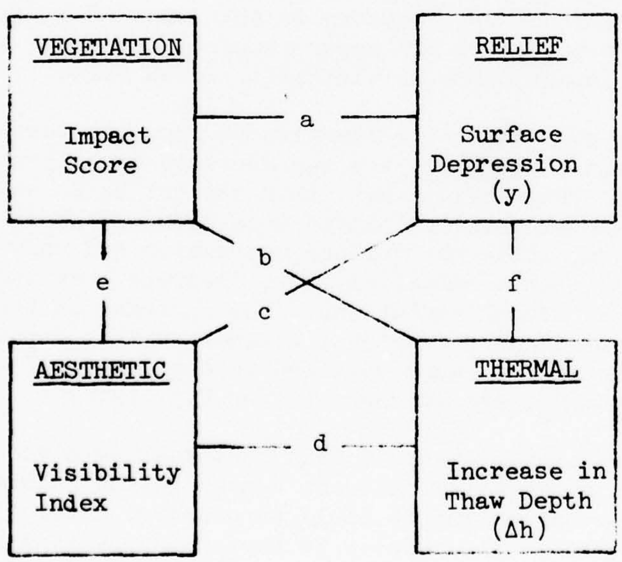


Figure 68. Principal impact descriptors (letters identify **relationships plotted in Fig. 69**).

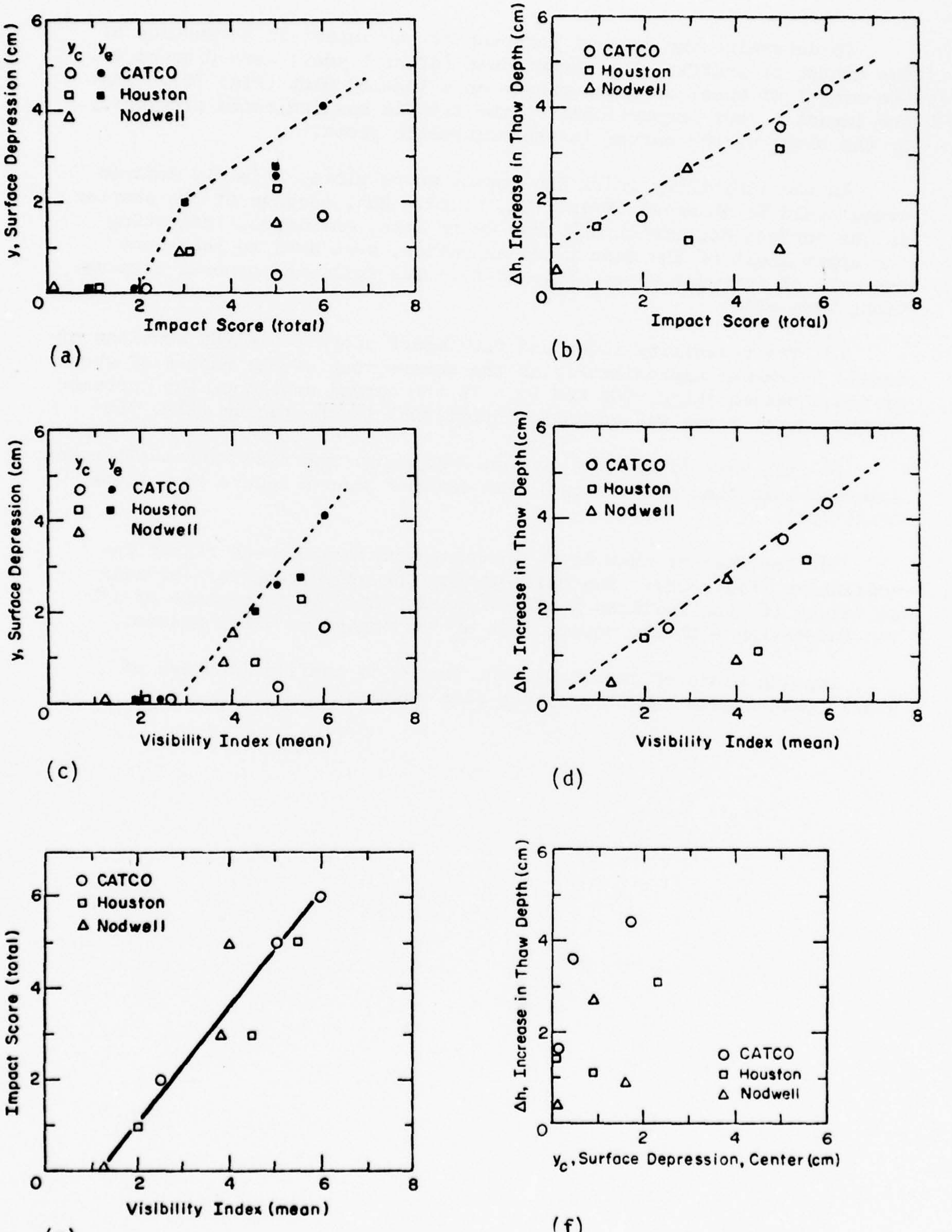


Figure 69. Interrelationships between the four impact descriptors after 1 year (Dashed lines are envelopes)

To determine the rate of increase of the impact as a function of the amount of traffic, the impact data (after 1 year) were plotted vs. the number of wheel or track passes on a log-log plot (Fig. 70). That the impact is not proportional to the traffic was indicated previously by the shape of the curves in the arithmetic plots.

In the visibility index and impact score plots, a fairly defined trend could be observed (Figs. 70a, b, c). But, because of the scatter in the surface depression and thaw depth data, envelopes, indicating the upper limit of the mean y and Δh values, were used to represent the rate of increase (Figs. 70d and e). The following general observations were made:

1) The visibility index and the impact score (straight sections of trail) increased approximately as the square root of the number of wheel or track passes (Figs. 70a and b). In the curved sections, the increase of the impact score was roughly proportional to the passes (Fig. 70c).

2) The rate of maximum surface depression increase with traffic was somewhat less than proportional, but steeper than a square root slope (Fig. 70d).

3) The rate of thaw depth increase with traffic was rather inconclusive (Fig. 70e). The envelope for the upper range of the mean Δh values for the Rolligon traffic (dashed line) is at a slope of 1/2 (Δh increasing with the square root of the number of wheel passes).

Log-log plots of impact vs. the number of traffic (instead of wheel) passes give essentially the same results.

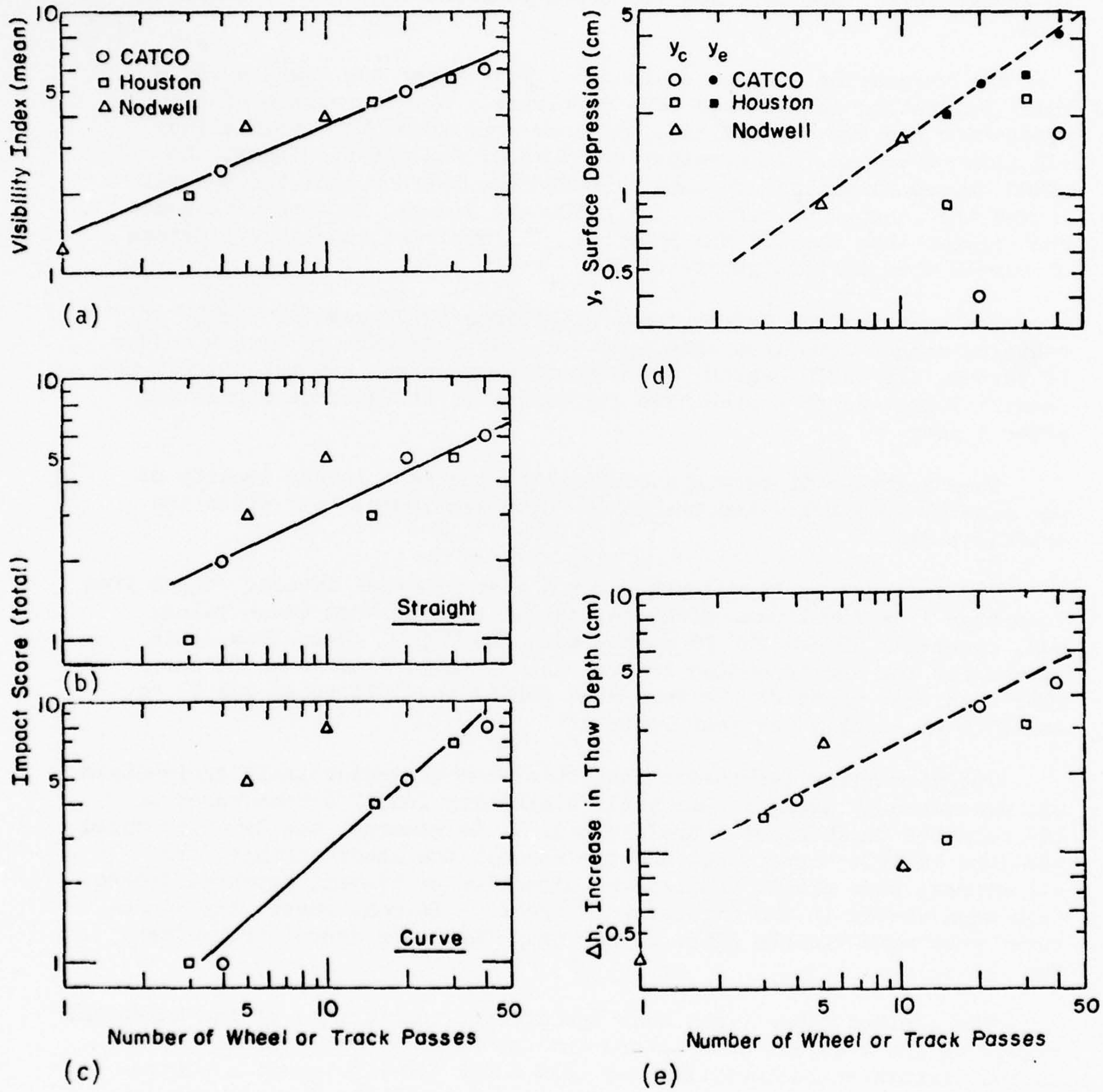


Figure 70. Impact descriptors vs number of wheel or track passes after 1 year (Dashed lines are envelopes)

SUMMARY AND CONCLUSIONS

Traffic tests on tundra with two low pressure tire Rolligon-type vehicles (CATCO and Houston) and a light, tracked Nodwell, for 1, 5 and 10 passes with minimum or no load, were conducted near Lonely, Alaska in August 1976. The site was visited 1 year later to obtain follow-up data.

The vegetation impact, evaluated 1 year after the tests using a numerical rating scheme, was caused primarily by compression of the vegetation and the organic mat, and some displacement of vegetation and plant breakage. In straight sections of the traffic lanes, the CATCO caused slightly more total impact than the Houston; the Nodwell caused the least. On curves, the CATCO and Nodwell impacts were somewhat higher than that of the Houston. All vehicles caused more damage on curves than on straight sections.

The mean surface depression (relief impact) values for the 3 vehicles ranged from less than 1 cm for 1 vehicle pass to 2 to 4 cm for 10 passes, the CATCO causing the deepest depression, and the Nodwell the least. There was no appreciable difference in the surface depression after 1 year.

Some decrease in moisture content and increase in dry density of the mineral soil below the tracks was observed immediately after the traffic tests.

The increase in thaw depth after 1 year (thermal impact) ranged from less than 1 cm for 1 pass with the Nodwell to over 4 cm (mean value; max. observed: 12 cm) for 10 passes with the CATCO. Mean thaw depth values for the corresponding control areas ranged from 14 to 21 cm. (The mean thaw depth of the test area during the 1976 tests was 24 cm, and 17.6 cm exactly one year later.)

The visibility (aesthetic impact) of the vehicular traffic signatures was described by using a numerical "visibility index" scheme based on the relative darkness of a traffic trail. In general, the CATCO produced the most visible signatures, and the Nodwell the least visible; the signatures, when viewed against the direction of travel, appeared darker than when viewed in the direction of travel. In most cases, the signatures were more visible after 1 year than they were immediately after the tests.

The limited range (less than one order of magnitude) of the numerical values of the 4 impact descriptors and the natural local variations in the terrain characteristics and thaw depth did not permit a comprehensive analysis of the interrelationships between the 4 principal impact descriptors used in this study. Only the two subjective descriptors (vegetation and aesthetic) showed an apparent correlation for the available range of values. It was quite clear, however, that the most sensitive descriptor is the aesthetic impact; it can occur without causing any other measurable effect. The relief impact (surface depression) is the most acute since it also implies the presence of the other types of impact.

In virtually all cases, the 8-wheel CATCO produced more impact than the 6-wheel Houston, if the impact was expressed in terms of vehicle traffic passes. If, however, the impact was plotted vs. the number of wheel passes, the degree of impact or damage caused by both vehicles was approximately the same.

As a result of the above observation, it was not clear how to compare the tracked Nodwell traffic with the wheeled Rolligon traffic. If the number of track (or vehicle) passes was compared with the number of Rolligon vehicle passes, the Nodwell impact was less than that of the Rolligons; if the number of track passes was compared with the number of wheel passes, the Nodwell impact was usually slightly more.

The rate of increase of the impact on the tundra surface was generally less than proportional to the amount of traffic; in most cases the rate of increase was closer to the square root of the number of wheel or track passes.

Since there was no significant shearing or disaggregation of the organic mat, it is expected that all of the traffic lanes will recover, the surface depression and the disturbance of the vegetation and the active layer being short term impacts (a few years), the visibility of the vehicle tracks ("green belt" effect) lasting somewhat longer. It has been observed (Abele, 1976) that a depressed, but unsheared, organic mat displays considerable ability to rebound during a period of a few summers.

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APPENDIX A: SUPPLEMENTARY TABLES AND GRAPHS

Table A-1. Vegetation characteristics at the Lonely test site, 1 August, 1977

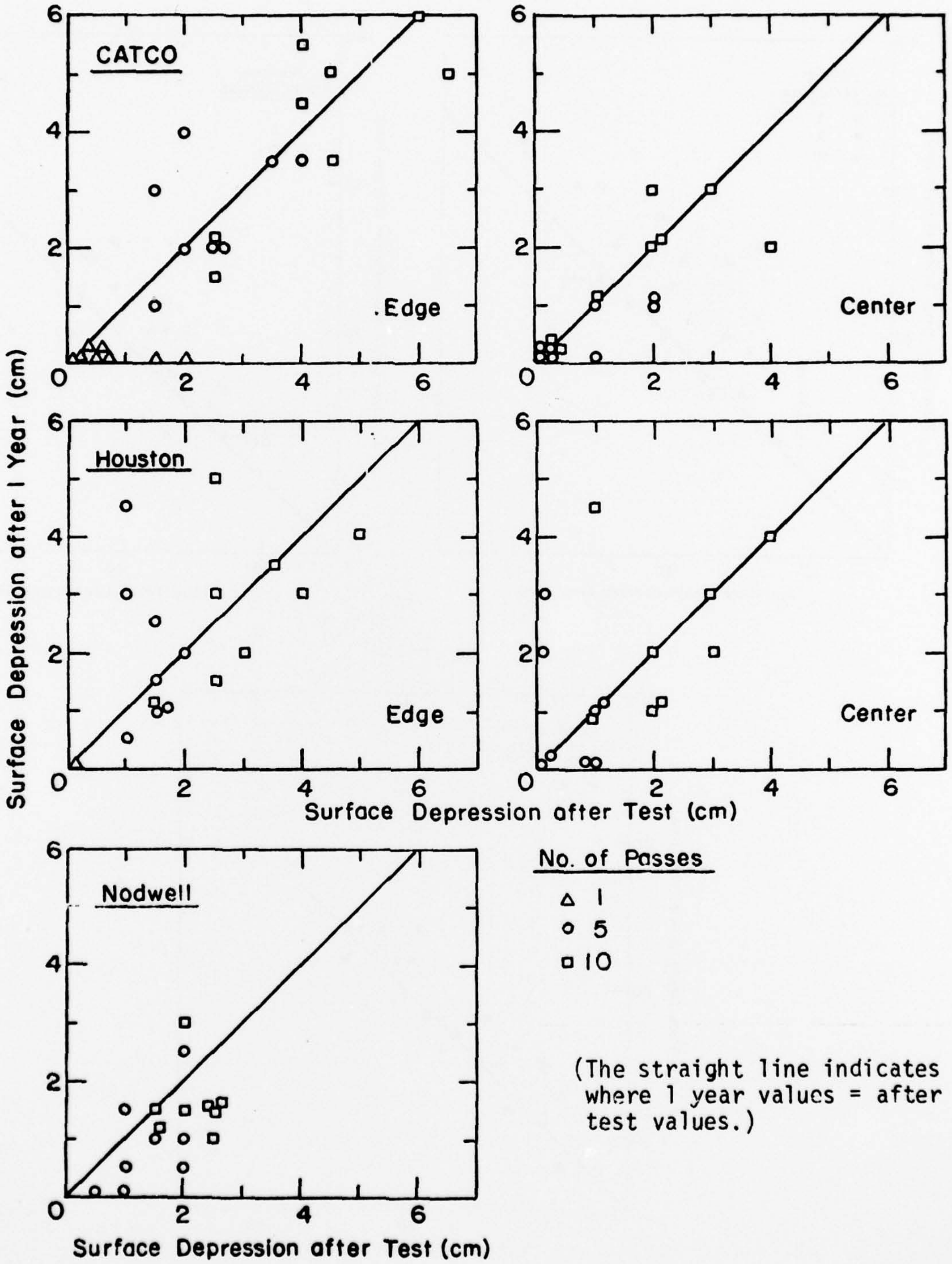
	Quadrat Number (each quadrat = 1 m^2)											
Quadrat sequence west to east:	1	2	3	4	5	6	7	8	9	10		
Site Factors:												
Moisture, Scale: 1 (dry) to 5 (emergent)	3	3	3+	3	3+	3+	3+	3+	3-	3		
Microrelief variation (cm)	5	10	10	10	5	5	<5	<5	<5	10		
Percentage erect dead vegetation	35	40	35	45	35	35	20	40	35	20		
Percentage prostrate dead & litter	20	30	25	35	20	25	25	40	20	35		
Depth of moss (cm)	5-10	5-10	3-7	5-10	3-9	3	3-5	3-7	7-10	5-10		
Species:	Percentage Cover										**F**	$\bar{C}$
Prostrate shrubs:												
Salix planifolia Pursh ssp. *pulchra* (Cham.) Argus	35	25	25		40		25	5	15	50	.8	22.0
S. reticulata L.							+				.1	+
S. rotundifolia Trauvt.	10	25	+	45	+	+	+	2	15	+	1.0	9.7
Dryas integrifolia M. Vahl.									+		.1	+
Caespitose monocotyledons:												
Eriophorum vaginatum L.	+	+	+								.3	+
Single monocotyledons:												
Carex aquatilis Wg.	35	35	30	30	20	20	20	20	20	10	1.0	24.0
Dupontia fisheri R.Br.	+	+	2	2	5	2	2	10	+	+	1.0	2.3
Eriophorum angustifolium Honck.	5	5	10	5	5	10	10	5	5	10	1.0	7.0
Poa arctica R.Br.	+										1.0	+
Dicotyledons:												
Cerastium jenisejense Hult.						I	+				.2	.1
Nardosmia frigida (L.) Hook.	+	+		+	+	+		+	+		.7	+
Bistorta vivipara (L.) S.F. Gray								+		+	.8	+
Saxifraga cernua L.			+	+	1	+	+	+	+	+	.8	+
S. foliolosa R. Br. var. *foliolosa*			+		+	1				+	.4	.1
S. hirculus L.		+	+	+	+	5	+	2		+	.8	.7
Stellaria laeta Richards								+	+		.2	+
Bryophytes:												
Aulacomnium palustre (Hedw.) Schwaegr.	5	5		+							.3	1.0
A. turgidum (Wahlenb.) Schwaegr.	5	10	+						15	+	.5	3.0
Brachythecium sp.	1	+	5	+	2	+	+	2	+	10	1.0	2.0
Calliergon sarmentosum (Wahlenb.) Kindb.			15								.1	
Calliergon sp.	+			+	15	10	15	+		+	.7	4.0
Campylium stellatum (Hedw.) C. Jens.	+		10	5	5	5	10	15		25	.8	7.5
Dicranum elongatum Schleich. ex Schwaegr.	60	5	10	10					20	5	.6	11.0
Distichium spp.		+	70	+	+		5	10	5	+	.8	3.0
Drepanocladus lycopodioides (Brid.) Warnst. var. *brevifolius* (Lindb.) Moenk.			25	5	25	40	40	20		5	.7	16.0
D. uncinatus (Hedw.) Warnst.	+	5		5	2			+		10	.6	2.2
Hylocomium splendens (Hedw.) B.S.G.		+	+	2				+			.4	.2
Oncophorus wahlenbergii Brid.	+	+									.2	+
Polytrichum juniperinum Hedw.	+	+		+	+			+	+	+	.7	+
Sphagnum spp.	+	1	+	+	5	+		15			.7	2.1
Tomenthypnum nitens (Hedw.) Loeske	5	2	+	25			+	+	40	5	.8	7.7
Leafy liverworts	+	+	+	+	10	2	+	+	+	+	.10	1.2
Lichens:												
Cetraria islandica (L.) Ach.	+										.1	+
Cladonia gracilis (L.) Willd.									+		.1	+
Dactylina arctica (Hook.) Nyl.									1		.1	.1
Peltigera canina (L.) Willd.		+	+	+							.3	+
Thamnolia subuliformis (Ehrh.) W. Culb.									+		.1	+

Nomenclature: Löve and Löve (1975) for vascular plants
Crum, Steere and Anderson (1973) for mosses
Hale and Culberson (1970) for lichens

F = Frequency
(1 = vegeation observed in every quadrat)
$\bar{C}$ = Mean % cover

Table A-2. Thaw depth and surface depression data (1977 data in parenthesis)

Lane No.	Vehicle	No. of Passes n	Track (Left or Right)	South End of Lane: Thaw Depth (Control) h_C(cm) '76('77)	South End of Lane: Thaw Depth (Track) h_T(cm) '76('77)	South End of Lane: Surface Depression (Center) y_c(cm) '76('77)	South End of Lane: Surface Depression (Edge) y_e(cm) '76('77)	North End of Lane: Thaw Depth (Control) h_C(cm) '76('77)	North End of Lane: Thaw Depth (Track) h_T(cm) '76('77)	North End of Lane: Surface Depression (Center) y_c(cm) '76('77)	North End of Lane: Surface Depression (Edge) y_e(cm) '76('77)
				(18)				(20)			
1	C	1	L	25 (22)	22 (23)	0 (0)	0.5 (0)	21 (15)	22 (17)	0 (0)	0 (0)
			R		22 (20)	0 (0)	0 (0)		18 (13)	0 (0)	2 (0)
				23 (18)(23)				22 (10)(15)			
2	H	1	L	22 (20)	30 (25)	0 (0)	0 (0)	24 (15)	22 (17)	0 (0)	0 (0)
			R		22 (20)	0 (0)	0 (0)		24 (16)	0 (0)	0 (0)
				28 (15)(15)				24 (10)(16)			
3	H	1	L	20 (18)	20 (17)	0 (0)		22 (15)	24 (16)	0 (0)	
			R		22 (16)	0 (0)			24 (15)	0 (0)	
				23 (17)(17)				19 (12)(10)			
4	H	1	R	17 (13)	21 (15)	0 (0)		15 (9)	16 (8)	0 (0)	
			L		18 (12)	0 (0)			18 (15)	0 (0)	
				23 (13)(18)				23 (12)(13)			
5	H	1	R	24 (18)	22 (19)	0 (0)	0 (0)	17 (14)	17 (15)	0 (0)	0 (0)
			L		14 (13)	0 (0)	0 (0)		16 (13)	0 (0)	0 (0)
				26 (15)(14)				19 (11)(16)			
6	C	1	R	30 (22)	22 (14)	1 (0)	0.5 (0)	29 (18)	25 (19)	0 (0)	1.5 (0)
			L		29 (28)	0 (0)	0.5 (0)		24 (20)	0 (0)	0.5 (0)
				- (19)(34)				- (14)(18)			
7	C	5	L	28 (25)	27 (32)	0 (0)	3.5 (3.5)	25 (14)	27 (25)	1 (1)	1.5 (3)
			R		24 (17)	2 (1)	2.5 (2)		17 (16)	0 (0)	2 (4)
				28 (15)(22)				20 (16)(9)			
8	H	5	L	23 (22)	23 (22)	1 (0)	1.5 (1)	24 (13)	18 (14)	0 (2)	1 (3)
			R		19 (14)	0 (0)	1 (0.5)		23 (16)	0 (3)	1 (4.5)
				21 (14)(23)				24 (12)(14)			
9	H	5	L	25 (20)	22 (23)	1.5 (1)		21 (12)	21 (19)	1 (0.5)	
			R		19 (21)	0.5 (0)			21 (15)	2 (1)	
				22 (18)(20)				26 (9)(13)			
10	H	5	R	28 (19)	24 (22)	2 (0.5)		26 (15)	22 (15)	1 (1.5)	
			L		24 (18)	1 (0)			28 (16)	2 (2.5)	
				24 (16)(14)				22 (10)(12)			
11	H	5	R	- (40)	23 (20)	1 (0)	1.5 (1.5)	25 (22)	22 (22)	1 (1)	2 (2)
			L		36 (39)	0 (0)	1.5 (1)		17 (20)	1 (1)	1.5 (2.5)
				27 (28)(25)				22 (11)(10)			
12	C	5	R	23 (27)	27 (30)	0 (0)	1.5 (1)	22 (12)	19 (18)	0 (0)	2 (2)
			L		23 (26)	1 (0)	2.5 (2)		24 (19)	2 (1)	4 (3.5)
				- (20)(21)				- (17)(16)			
13	C	10	L	24 (24)	17 (22)	1 (1)	2.5 (2)	25 (18)	22 (16)	2 (2)	6 (6)
			R		20 (23)	0 (0)	2.5 (1.5)		31 (25)	4 (2)	6.5 (5)
				26 (16)(15)				32 (20)(25)			
14	H	10	L	27 (25)	27 (26)	2 (1)	3 (2)	25 (15)	27 (23)	1 (1)	1.5 (1)
			R		26 (25)	3 (3)	3.5 (3.5)		21 (20)	2 (1)	2.5 (1.5)
				31 (22)(26)				24 (15)(20)			
15	H	10	L	27 (26)	25 (22)	2.5 (1.5)		31 (23)	25 (24)	2 (3)	
			R		26 (24)	1.5 (1)			28 (22)	2.5 (1.5)	
				25 (20)(19)				31 (25)(20)			
16	H	10	R	23 (19)	27 (24)	2.5 (1.5)		22 (17)	22 (18)	2.5 (1)	
			L		25 (22)	1.5 (1.5)			20 (18)	2 (1.5)	
				22 (22)(12)				23 (12)(20)			
17	H	10	R	25 (20)	15 (17)	1 (4.5)	2.5 (5)	23 (18)	20 (19)	3 (2)	4 (3)
			L		21 (25)	2 (2)	2.5 (3)		23 (22)	4 (4)	5 (4)
				36 (24)(30)				21 (15)(12)			
18	C	10	R	32 (20)	35 (33)	2 (2)	4 (4.5)	19 (16)	21 (21)	3 (3)	4.5 (3.5)
			L		28 (33)	[illegible] (3)	4 (5.5)		23 (26)	0 (0)	4.5 (5)
				(20)				(12)			



(The straight line indicates where 1 year values = after test values.)

Figure A-1. Surface depression after 1 year vs. surface depression after test

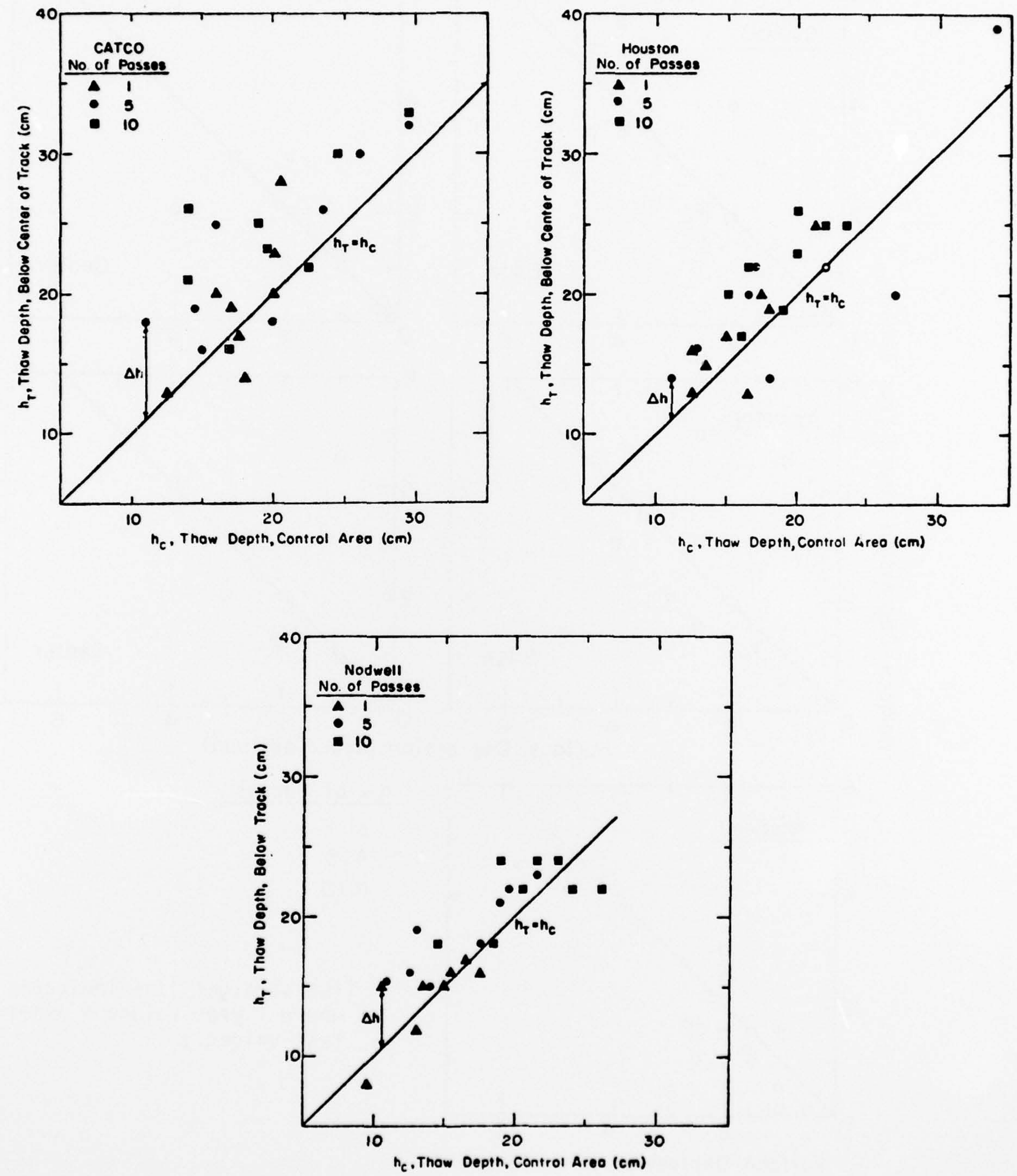


Figure A-2. Thaw depth below track vs thaw depth in control area, after 1 year

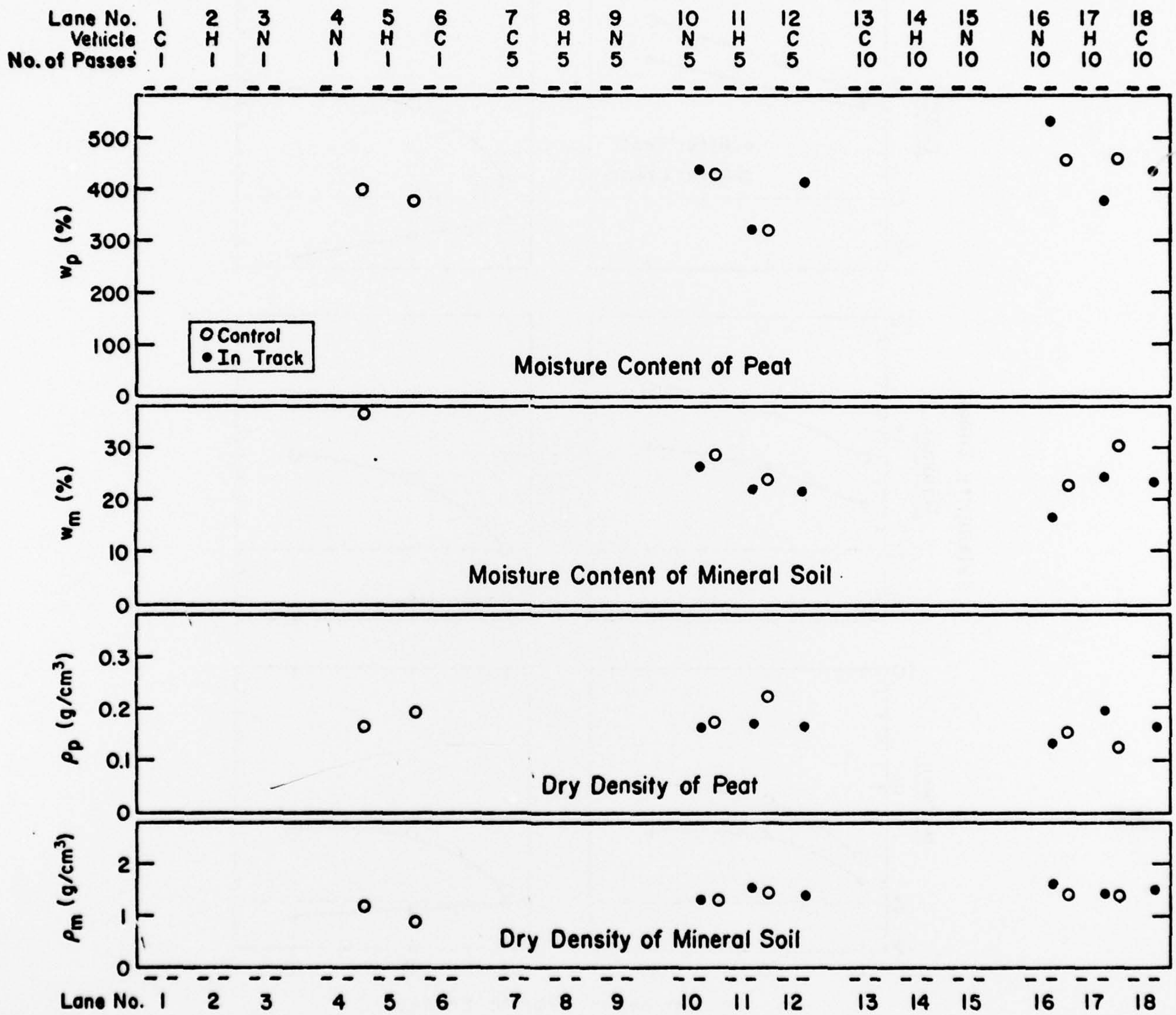


Figure A-3. Moisture content and dry density data plotted according to location, after tests

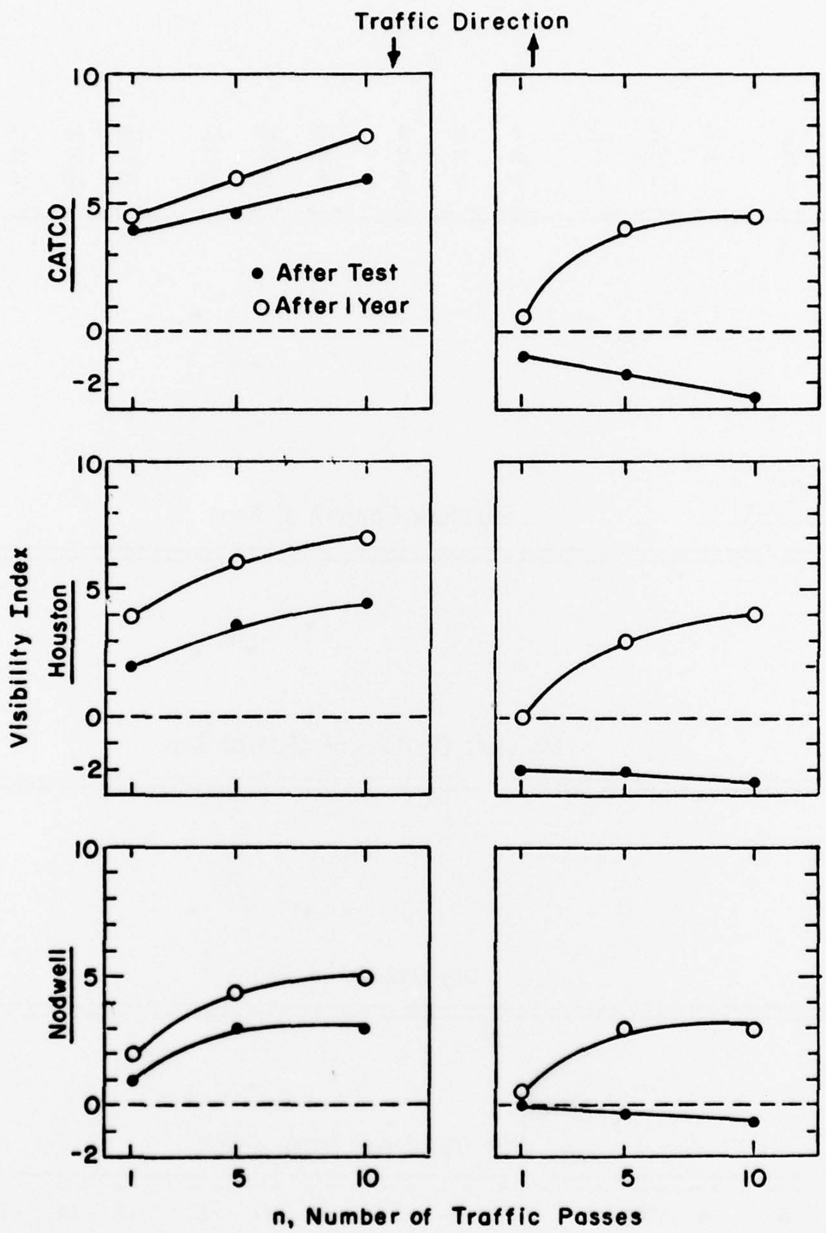


Figure A-4. Visibility index vs.
number of traffic passes,
after test and after 1 year

APPENDIX B: ROLLIGON TESTS, BARROW, 1974

On 7 August 1974, three test lanes, 1, 5 and 15 traffic passes, were made with a 4-wheel Rolligon Vehicle (Fig. B-1) at a site approx. 4 miles southeast of Barrow, near the Ikpik Slough, where Air Cushion Vehicle (ACV or SEV) and Weasel traffic tests had been conducted during the summer of 1971 (Abele, 1976). The test area is on a level, drained lake bottom, with a relatively uniform and homogeneous saturated active layer and vegetation, the organic mat having a moisture content of approx. 1000% and thaw depth in the 20-30 cm range.

The Rolligon tests were not planned; they were done on the spur-of-the-moment during inspection of the 3-year old ACV and Weasel test lanes. During subsequent monitoring of the ACV and Weasel lanes in 1975, 1976, and 1977, photographs of the Rolligon lanes were also taken.

The test vehicle had ribbed (cleated) tires with an inflation pressure between 0.2 and 0.3 kg/cm^2 (approx. 3 to 4 psi) and carried no load. In one section of the 15-pass lane, initially intended for 25 passes, the Rolligon tires had penetrated through the active layer almost down to the permafrost after 10 passes; traffic was therefore stopped after 15 passes.

Figure B-2 shows the cross-sections of the Rolligon test lanes. For the 15-pass lane, two cross-sections are shown, one for the area where complete failure of the thawed layer occurred (south end of lane) and the other where the terrain was slightly elevated, drier and had a higher frost line (north end of lane) and thus only partial failure had occurred.

During traffic on the 15-pass lane, a visual observation was made on the apparent failure mechanism of the organic mat, i.e., how the mat is gradually weakened to the point of failure with repeated traffic. This is shown and explained in Figure B-3.

Figures B-4 through B-15 show the Rolligon test lanes immediately after traffic, and after 1, 2 and 3 years.

Figure B-1. Rolligon vehicle used for traffic tests. Ribbed (cleated) rubber tires; tire inflation pressure (and approximate ground contact pressure) between 0.2 and 0.3 kg/cm^2 (3 to 4 psi); no load, except for 2 men and fuel.

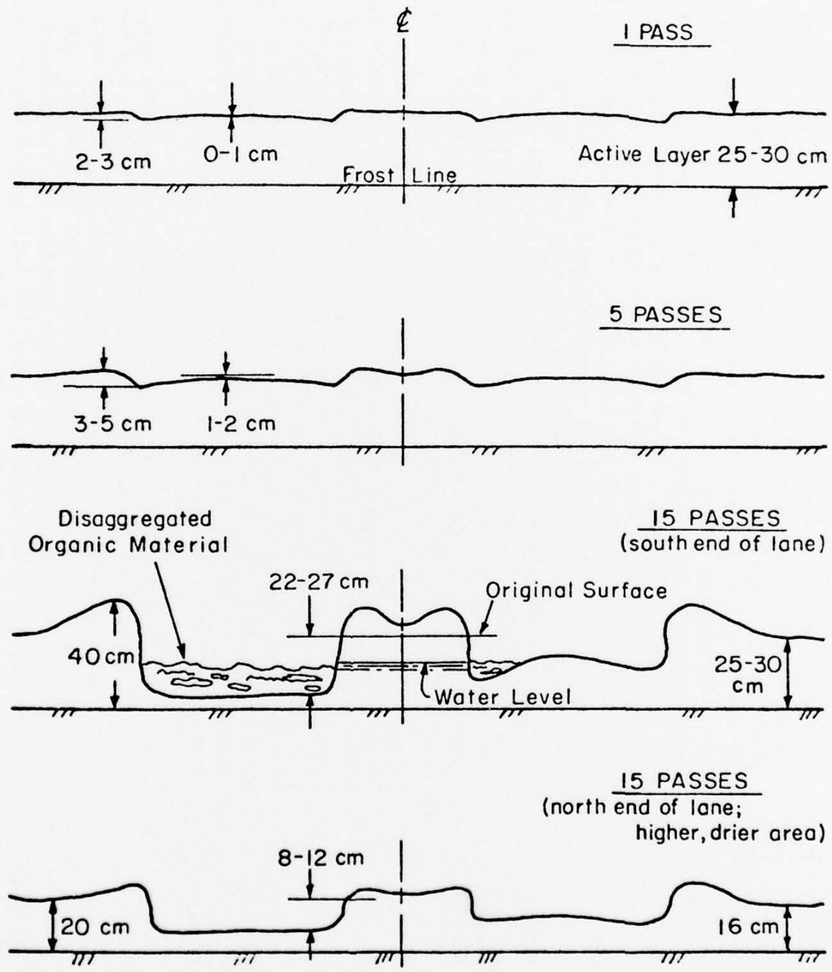
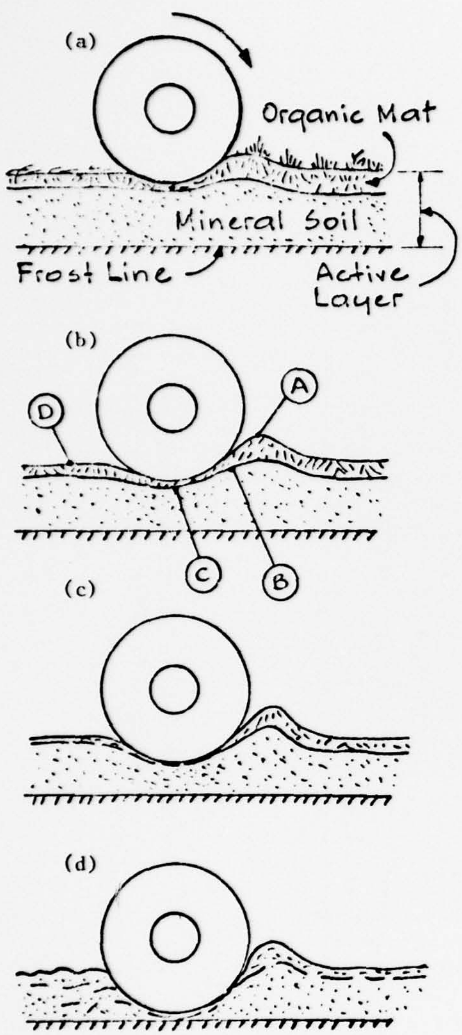


Figure B-2. Cross sections of Rolligon traffic lanes after test



(a) During travel over saturated tundra, a wave is formed in front of the tire; the organic mat is subjected to some flexing and longitudinal (in the direction of travel) stressing in front of the tire, lateral (perpendicular to the direction of travel) tension when tire sinkage occurs, compaction below the tire, and friction between the tire and the mat surface.

(b) During repeated traffic passes, the wave being pushed ahead of the tire becomes more prominent (increased amplitude); the organic mat is subjected to repeated horizontal and vertical stresses. Immediately in front of the tire and through the crest of the wave, the surface of the organic mat (A) is pushed up and ahead further than the bottom of the mat (B), causing longitudinal shear and thus tearing of the root system between (A) and (B). At (B) there is also some weakening of the bond between the organic mat and the mineral soil because of lifting of the mat. Below the tire (C), the mat is not only under vertical compression, but is also subjected to longitudinal and lateral tension because of depression (and thus stretching) due to the non-rigid mineral soil layer below. Since there is very likely some slippage of the tire, the vegetation and mat surface is subjected to frictional abrasion over the tire-terrain contact area. There is obviously some disturbance of the mineral soil in front of the tire below the wave (longitudinal shear) and below the tire (compression, resulting in water being *squeezed out laterally*), *causing some weakening of the water-soil* matrix. There is some rebound of the organic mat, and perhaps the mineral soil, at (D); but this is a very slow process.

(c) This is the critical phase in the supporting capacity of the active layer. The continuous stretching of the organic mat, due to repeated traffic, has caused a systematic breakdown (tearing) of the organic fibers, particularly the root system (which is the principal source of strength of the mat). And, the cyclic tension and compression have degraded whatever structural integrity the saturated mineral soil may have had. If, at this point (that is, before the tire shears through the organic mat) the trail is not subjected to any more traffic, recovery is quite likely.

(d) Once the fatigue point of the organic mat has been reached, additional traffic passes will cause complete failure of the mat and penetration of the tire through the mineral soil layer, since the latter has little strength of its own. When this happens, recovery of the traffic trail will, most likely, not occur; in fact, degradation may continue and increase with time. It should be noted that, depending on the soil properties and vehicle (or tire) characteristics, the failure point of the active layer can be reached or exceeded during the first pass of a vehicle.

Figure B-3. Failure mechanism of tundra under traffic

Figure B-4. After test

Figure B-5. After 1 year

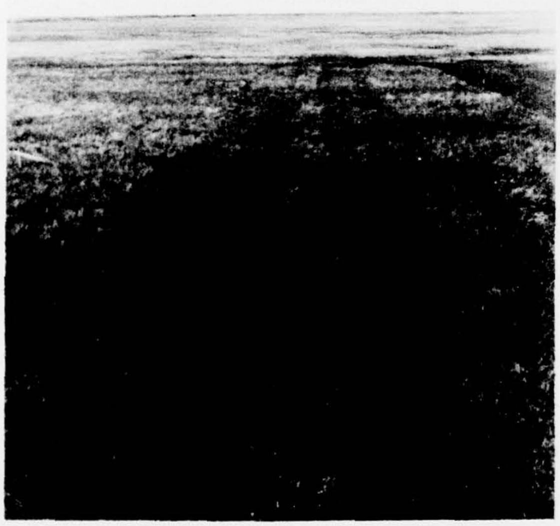


Figure B-6. After 2 years

Figure B-7. After 3 years

Rolligon - 1 traffic pass

Figure B-8. After test

Figure B-9. After 1 year

Figure B-10. After 2 years

Figure B-11. After 3 years

Rolligon - 5 traffic passes

Figure B-12. After test

Figure B-13. After 1 year

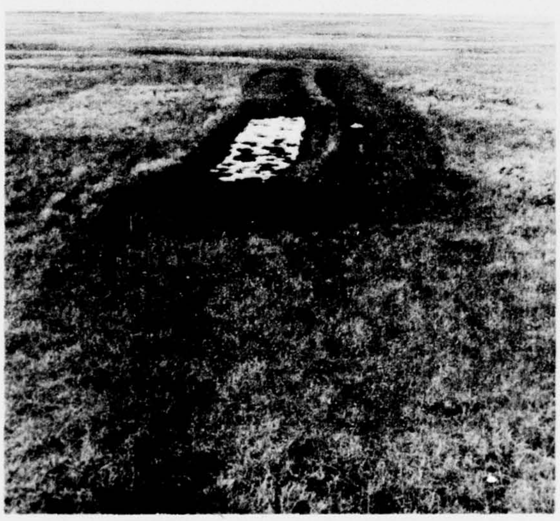


Figure B-14. After 2 years

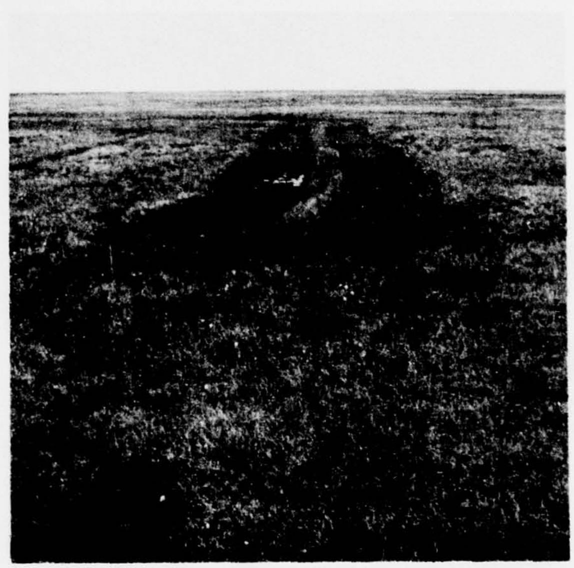


Figure B-15. After 3 years

Rolligon - 15 traffic passes