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Cold Regions Research and Engineering Laboratory

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J.H. Lever,* J.C. Weale,* R.G. Alger,† and G.L. Blaisdell**

**Cold Regions Research and Engineering Laboratory*
U.S. Army Engineer Research and Development Center
72 Lyme Road
Hanover, New Hampshire 03755

† Institute of Snow Research
Michigan Technological University
Houghton, Michigan

***Office of Polar Programs*
National Science Foundation
Arlington, Virginia

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ABSTRACT

The U.S. Antarctic Program is conducting a proof-of-concept traverse to haul heavy cargo 1600 km from McMurdo Station to South Pole Station. During the 2003–04 season (year two), the tractor-trains experienced poor mobility over undisturbed snow on the Ross Ice Shelf. despite relatively low sled ski pressures and encouraging results of pre-departure tests conducted on the McMurdo Ice Shelf. To understand why, we conducted expedient mobility tests, snow-strength measurements, and snow-pit studies along 250-km of route as the traverse returned to McMurdo. The key phenomenon causing train immobility appears to be traction–slip–resistance feedback resulting from the sled skis riding in the ruts made by the towing tractors. We measured much lower towing resistance when the same sleds were towed over undisturbed snow outside of the tractor ruts. Large pitch and roll motions, and consequently large resistance peaks, also occurred when several sleds were towed in series. The role of snow strength was more difficult to assess. Hard sastrugi caused severe motions and sled breakdowns. Decreasing average strength towards the center of the Ross Ice Shelf agreed with qualitatively worsening mobility but quantitative results were inconclusive. Also, increased measured strength on the previously traveled trail was insufficient to account for improved mobility of the returning fleet. The year-two results formed the basis for recommendations to improve fleet mobility for year three: tow fuel sleds in 2 × 2 configurations, rather than four in-line; increase the gauge of the other sleds to place the skis outside of the tractor ruts; increase ski area and alter nose shape for the fuel sleds; and install instrumentation to monitor towing forces, sled sinkage, and snow strength along the entire route. The U.S. Antarctic Program adopted these recommendations.

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PREFACE

This report was prepared by Dr. James H. Lever, Mechanical Engineer, Applied and Military Engineering Branch, Jason. C. Weale, Research Civil Engineer, Applied and Military Engineering Branch, Cold Regions Research and Engineering Laboratory, U.S. Army Engineer Research and Development Center, Russell G. Alger, Director, Institute of Snow Research, Michigan Technological University, Houghton Michigan, and George L. Blaisdell, Operations Manager, Office of Polar Programs, National Science Foundation, Arlington, Virginia.

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1 INTRODUCTION

The United States Antarctic Program (USAP) operates a year-round research station at South Pole. It is supplied predominantly by ski-equipped LC-130 aircraft flown from McMurdo Station, with fuel delivery accounting for the majority of payload delivered. To reduce costs and open LC-130 flights to support field work elsewhere in Antarctica, the USAP is exploring use of tractor–sled trains to haul heavy cargo along a 1600-km over-snow route from McMurdo Station to South Pole Station (Blaisdell et al. 1997, Blaisdell 2000).

In 2002, the USAP initiated a proof-of-concept (POC) traverse project to develop a route that crosses the Ross Ice Shelf and uses the Leverett Glacier as a path through the Transantarctic Mountains to the Polar Plateau (Fig.1). Year-one efforts succeeded in preparing a safe route through a crevasse field in the shear zone connecting the McMurdo and Ross ice shelves. The objectives of year two (2003–04 season) were to operate a representative fleet of tractor–sled trains across the Ross Ice Shelf and to prepare the route up the Leverett Glacier. Unfortunately, as the POC fleet broke trail heading south, it encountered unexpectedly large towing resistances and sled motions; immobilized trains and broken equipment frequently resulted. These circumstances prevented the fleet from reaching the Leverett Glacier despite the determined efforts of the crew.

Mobility tests conducted on the McMurdo Ice Shelf at the start of the season indicated that towing resistances of the departing sled configurations were within the capabilities of the tractors. To understand the subsequent mobility problems, we conducted expedient mobility tests, snow-strength measurements, and snow-pit studies along a 250-km section of the route as the fleet returned to McMurdo. This report summarizes the results obtained, interprets the mobility problems and recommends sled improvements for year three.

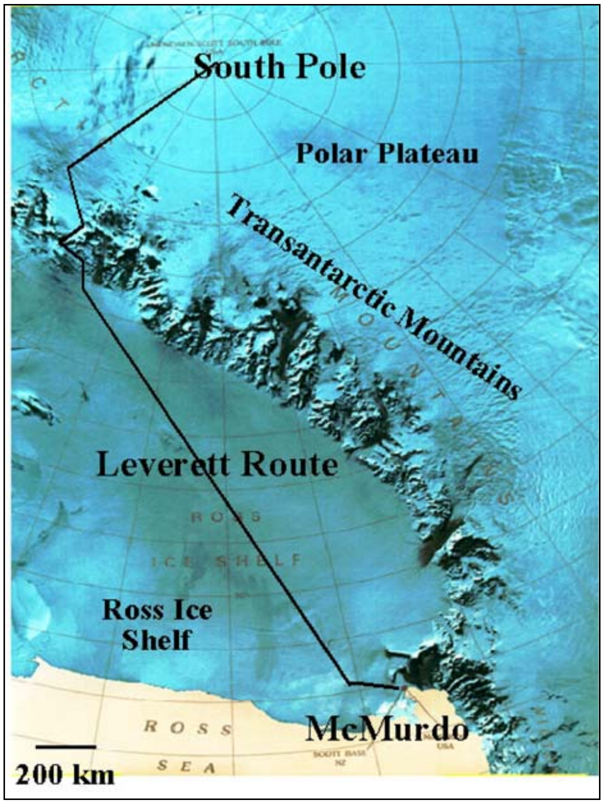


Figure 1. Traverse route from McMurdo Station across the McMurdo and Ross ice shelves, up the Leverett Glacier, and across the Polar Plateau to Amundsen-Scott South Pole Station.

2 PROOF-OF-CONCEPT TRAVERSE FLEET

The year-two POC traverse fleet consisted of four tractors (Fig. 2) and a variety of fuel, cargo and support sleds (Fig. 3). Table 1 lists the overall dimensions and weights of these vehicles.

a. Caterpillar LPG-D8R.

b. Caterpillar Challenger 95.

Figure 2. Tractors used during year two of POC traverse.

c. Kress Challenger with tracked trailer.

d. Case Quadtrac with two fuel sleds in tow.

Figure 2 (cont'd). Tractors used during year two of POC traverse.

The Caterpillar LPG-D8R has steel tracks and a large snowplowing blade (Fig. 2a). It is the heaviest and slowest tractor, with the greatest towing capacity. The Caterpillar Challenger 95 (C95, Fig. 2b) has rubber-belted tracks; it was equipped with a utility crane for the POC traverse. The Kress Challenger is a modified C95 tractor that has a six-person cabin and a fifth-wheel-style hitch to tow tracked trailers (Fig. 2c). The Case Quadtrac has two pairs of rubber-belted drive tracks and steers through an articulated body (Fig. 2d).

Two primary sled designs were used in year two. The housing and energy modules (HM/EM) and the three ISO sleds were of similar design (Fig. 3a, 3b). Each sled consisted of four skis mounted in pairs on front and rear bogies. The bogies were attached to the undersides of the modules, and cables transmitted forward towing forces between the bogies. Rubber bushings connected the skis to the bogies to permit ski-pitching motion. Each bogie could yaw through a turntable pin to follow tractor-turning actions. The turntables did not specifically allow for lateral rolling motions of the bogies, and this became a source of fatigue failures of the pins. The D8R normally towed the HM/EM modules in tandem, and either the Case or C95 normally towed the three ISO sleds in tandem.

Table 1. Weights and overall dimensions of year-two POC traverse vehicles.

Vehicle	Short ID	Weight loaded (kN)	Running gear dimensions: No. of tracks or skis	Width (m)	Length (m)	Contact area (m^2)	Track or ski gauge (m)	Nominal contact pressure (kPa)
Tractors								
Kress KT-95 Challenger	Kress	267	2	0.76	2.74	4.18	2.34	64
Case STX450 Quadtrac	Case	250	4	0.79	1.85	5.84	2.20	43
Caterpillar Challenger 95	C95	184	2	0.76	2.74	4.18	2.34	44
Caterpillar D8R LGP	D8R	383	2	0.97	3.20	6.18	2.34	62
Trailers/Sleds								
KTT-60 Trailer		267	2	0.90	2.92	5.27	2.54	51
KTD-40 Dolly		178	2	0.81	1.83	2.97	2.54	60
ISO Container Sled	ISO Sled	116	4	0.91	2.74	10.0	1.98	12
Living Module	LM	191	4	0.61	2.13	5.20	2.29	37
Energy Module	EM	203	4	0.61	2.13	5.20	2.29	39
Refrigeration Van Sled	Ref Sled	121	4	0.91	2.74	10.0	1.98	12
Fuel Sled		138	2	0.65	5.79	7.50	2.30	18

a. Housing and energy modules.

Figure 3. Sleds used during year two of POC traverse.

b. Three ISO sleds (flatbed, mil van, and refrigeration module).

c. Two fuel sleds towed behind the Case tractor.

d. Dual-pipe and pipe-chain drags trailing sled trains.

Figure 3 (cont'd). Sleds used during year two of POC traverse.

The eight fuel sleds each consisted of a 12,000-L tank, with internal baffles, mounted on a pair of skis. To accommodate ski pitch, front mounting bars pivoted transversely on rubber bushings, and the skis attached to the rear of the tanks through rubber bushings. This mounting arrangement did not yaw to follow tractor-turning action but nevertheless was quite durable and caused few problems. Cables running underneath the tanks between towing hitches transmitted forward towing forces along a train of tanks.

Note that the gauge or lateral separation of all sled skis ensured that the skis would ride within the ruts made by the towing tractors. Sheets of durable, ultra-high-molecular-weight polyethylene (UHMW) covered the bottoms of all skis to reduce sliding friction along the snow. Normally, each tractor-sled train terminated with a dual-pipe or pipe-chain drag to smooth the trail surface (Fig. 3d).

The year-two fleet also included two Kress KTT-60 tracked-trailers, coupled by a KTD-40 tracked Dolly. Each trailer carried an empty 20,000-L fuel tank intended for delivery to South Pole (Fig. 2c). The fleet also included a small supplemental sled and lightweight, dual-track vehicle (Kassbohrer PB 100) mounted with a ground-penetrating radar to detect crevasses. It normally led the tractor-trains and marked the trail heading south.

3 SEASON OVERVIEW

The year-two fleet was assembled at McMurdo Station in October 2003 and successfully completed a trial traverse across the snow-covered sea ice on McMurdo Sound to re-supply a helicopter fueling facility at Marble Point. Two of us (Weale and Blaisdell) then conducted mobility tests (tractor drawbar-pull and sled towing resistance) on the McMurdo Ice Shelf near the Williams Field skiway. The purpose of these tests was to determine allowable tractor-train combinations for the southerly trip across the Ross Ice Shelf. The results indicated that the four tractors could tow the HM/EM, three loaded ISO sleds, eight full fuel sleds, and two loaded tracked-trailers. The fleet departed for the Ross Ice Shelf on 18 November 2003.

The fleet made good progress along the trail generated during year one across the McMurdo Ice Shelf and through the shear-zone. However, soon after heading south across the Ross Ice Shelf, the tracked-trailers and sled trains encountered manifestly higher resistances and larger-amplitude motions than experienced on the McMurdo Ice Shelf. This resulted in two major time-consuming problems: 1) frequent train immobilization because of insufficient traction, and 2) frequent breakage of sled turntable pins and bogie-module attachment hardware. The first required halting the fleet and disconnecting a tractor from its train to assist towing the immobilized tractor-train from its stuck location. The second resulted in "train wrecks" that often required repairing the broken part and remounting a container or module on a sled bogie (Fig. 4). The crew (J. Wright, R. Magsig, J. McCabe, J. Penney, and R. Vaitonis) became quite adept at rescuing stuck trains and repairing broken ones. They also cached one tracked-trailer and began shuttling fuel tanks almost immediately upon heading onto the Ross Ice Shelf.

The cumulative effect of stoppages and shuttling caused the southerly advance rate to average less than 20 km per day. When the fleet had consumed half of its available fuel, the project manager (J. Wright) decided to turn the fleet around. This occurred on 30 December 2003 at route marker RIS-1, about 640 km onto the Ross Ice Shelf and 300 km short of the Leverett Glacier (Fig. 5).

Figure 4. Large sled motions caused numerous failures of ISO sled attachment hardware, leading to "train wrecks."

To assess whether snow conditions could account for the poor fleet mobility, a radar operator (N. Yankielun) and mountaineer (S. Metcalf) conducted snow-pit measurements along the route. Two of us (Lever and Alger) and another mountaineer (M. Szundy) were already scheduled to replace these two individuals and to assist with route assessment up the Leverett Glacier. With the approval of project manager, we decided to conduct expedient sled-resistance tests and Rammsonde snow-strength measurements for more direct assessment of the causes of the poor fleet mobility. We joined the fleet at location South+32 (approximately 210 km onto the Ross Ice Shelf) on 7 January 2004 and remained with them until 21 January 2004, after they arrived back at the shear zone (GAW, Fig. 5). Note that location designations (e.g., South+32) refer to approximate distance in miles from major route markers, following the convention used by the traverse crew.

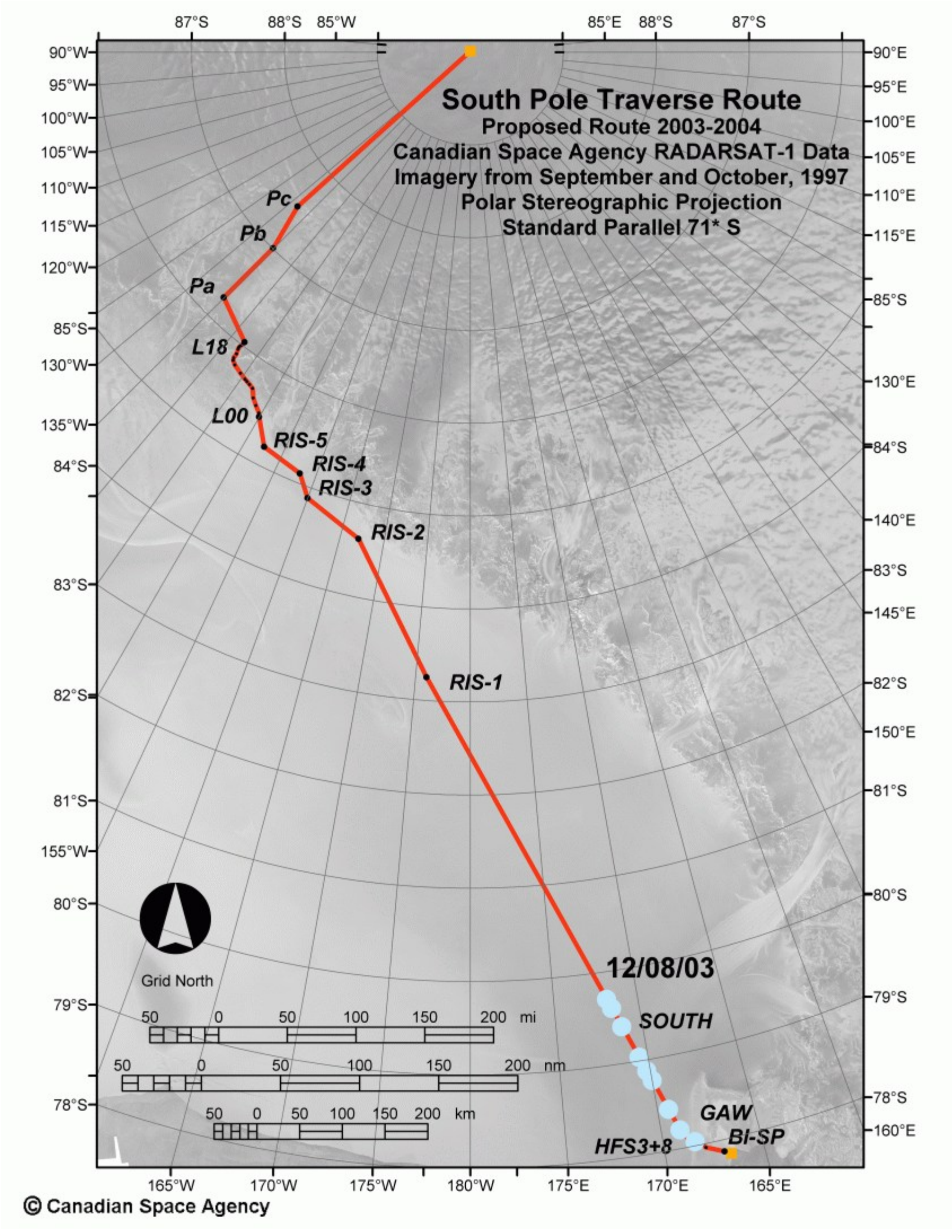


Figure 5. South Pole traverse route showing key waypoints. Year-two fleet turned around on 30 December 2003 at RIS-1, about 640 km onto the Ross Ice Shelf and 300 km short of the Leverett Glacier (L00). The shear zone between the McMurdo and Ross ice shelves lies between GAW and HFS3+8. Williams Field is near BI-SP.

4 METHODS

The pre-departure mobility tests on the McMurdo Ice Shelf measured drawbar-pull of the C95, Kress and Case tractors and the towing resistance of the tracked trailers and individual sleds (empty and fully loaded). These measurements used a 44-kN load cell with a 1-second-update digital display. We manually estimated and recorded the average load for each test and repeated most tests several times.

Drawbar measurements were obtained with a given tractor connected to the D8R via the load cell on a pulley system for a 2:1 multiplier (Fig. 6). Both vehicles would begin in motion at about 8 km/hr. The D8R operator would maintain this speed as the test tractor attempted to accelerate away. We recorded the maximum average force value at this constant speed as the drawbar-pull and normalized it by vehicle weight to compute the traction coefficient. We conducted four traction tests on the Kress, Case, and C95 tractors. Note that we measured drawbar-pull of the Kress tractor towing through its drawbar or low-hitch not its fifth-wheel hitch (Fig. 6). The D8R drawbar-pull could exceed the capacity of the load-cell system, and consequently we did not attempt to measure it.

Figure 6. Dynamic drawbar measurement of Kress tractor conducted at 8 km/hr using D8R as load vehicle. Note that the Kress tractor towed through its drawbar (low hitch) not its fifth-wheel hitch.

We also measured the capability of each tractor to maneuver sleds by 1) conducting drawbar tests on a 30-m-radius circle and 2) with the tractor towing the Kress dolly and trailer (through their towing hitches) on a decreasing-radius spiral. For the latter test, we recorded the radius at which the tractor lost steering control or otherwise could not tighten the circle.

The pre-deployment tests also measured towing resistance of individual sleds, and the tandem tracked trailers, by connecting them directly through the load cell to the Case tractor and towing at a constant speed of about 8 km/h. To measure the resistance of a single tracked trailer, we connected it to the Case via the tracked Kress Dolly and subtracted the resistance of the Dolly towed separately.

Mobility tests conducted during the return across the Ross Ice Shelf relied on expedient methods to measure the towing resistance of sled trains towed within and outside of the ruts made by the towing tractors (Fig. 7). We used the same load cell, connected to a looped cargo strap, to obtain a 2:1 multiplier, and supported it on a small cargo sled to prevent it from plowing through the snow. It was clear that variations in the towing force, in addition to the average value, were important. Thus, we manually recorded the load-cell readings at approximately 1-second intervals and conducted tests lasting 30–60 seconds. After each test, we measured rut depths at several locations along the test track; for later tests, we measured rut-depth profiles along the test direction for both left and right ruts.

To document the snow strength along the route and at locations of resistance tests, we conducted numerous profiles using a Rammsonde, falling-weight cone-penetrometer (Abele 1990). These measurements consisted of successively recording the penetration depth of a 60° × 4-cm-dia. cone after 1–5 drops of a 1-kg mass from a height of 50 cm. Usually, we conducted three separate profiles, to depths of 1 m, within about 5 m of each other. We also dug snow pits to record density and temperature profiles and to observe snow characteristics within the top 1 m. On one occasion, the D8R dug for us a 3-m-deep snow pit.

a. Three ISO sleds towed in the ruts of the C95 tractor.

Figure 7. Sled towing-resistance tests on Ross Ice Shelf.

b. Four fuel sleds towed in Y-configurations between the C95 and Kress tractors so that the sleds rode on undisturbed snow outside of the tractor ruts.

Figure 7 (cont'd). Sled towing-resistance tests conducted on Ross Ice Shelf.

5 RESULTS

Mobility Tests and Observations

Table 2 summarizes the traction measurements obtained for the Kress, Case, and C95 tractors on the McMurdo Ice Shelf. The average traction coefficient for each tractor was consistent with the overall average for all tractors within one standard deviation (0.359 ± 0.007). This suggests that the tracks for each design are able to mobilize fully the shear resistance of the snow and that snow strength limits available traction. The slightly lower average coefficient for the Case relative to the Kress and C95 (the latter two share a common track design) could reflect the closer spacing and slightly shallower depth of grousers on the Case track. However, the effect is small. Assuming that the D8R track also fully engages the snow, we may estimate its drawbar-pull as the average coefficient times tractor weight (0.359 ± 0.007) × 383 kN = 138 ± 3 kN. Note that the measured drawbar-pull of the Kress exceeded that of the C95, consistent with its higher weight.

Table 3 summarizes results of the maneuvering tests for the Kress, Case and C95 tractors on the McMurdo Ice Shelf. Note that each tractor was able to maintain essentially its full drawbar-pull while turning on a 30-m radius circle. Also, loss of steering control limited the turning radii of the two skid-steer tractors (Kress and C95). By comparison, the Case articulated steering could maintain control at much smaller radii, essentially until the minimum radius where the Kress trailer simply pivoted on its tracks. This result was consistent with the performance of the Case later observed on the Ross Ice Shelf: it was less likely than the Kress and C95 to become immobilized as it attempted steering corrections in difficult towing conditions.

Table 4 summarizes results of the towing-resistance tests conducted on the McMurdo Ice Shelf. Repeated trials yielded fairly consistent resistance values, with the tracked trailers and the ISO sleds having the lowest resistance coefficients and the fuel sleds having the highest. An interesting exception was the very low resistance obtained for the single fuel-sled test conducted at high speed ($R/W = 0.07$ at 16–19 km/h versus $R/W = 0.124 \pm 0.005$ at 8 km/h).

Table 2. Tractor drawbar pull measurements on McMurdo Ice Shelf near Williams Field. Note that the drawbar estimate for the D8R equals the tractor weight time average traction coefficient from the other three tractors.

Tractor	Weight (kN)	Drawbar pull (kN)	Traction coefficient	Average coefficient	Standard deviation
Kress					
Test 1	229	80	0.35	0.360	0.018
Test 2	229	78	0.34		
Test 3	229	87	0.38		
Test 4	229	85	0.37		
Est. for Loaded Weight	*267*	*96 ± 5*	*0.360 ± 0.018*		
Case					
Test 1	250	85	0.34	0.352	0.009
Test 2	250	89	0.36		
Test 3	250	89	0.36		
Test 4	250	89	0.36		
C95					
Test 1	184	67	0.36	0.365	0.006
Test 2	184	69	0.37		
Test 3	184	67	0.36		
Test 4	184	67	0.36		
D8R					
Est.	*383*	*138 ± 3*	*0.359 ± 0.007*	0.359	0.007

Table 3. Tractor maneuverability measurements on McMurdo Ice Shelf near Williams Field. Drawbar-pull tests used the D8R as the load vehicle, while decreasing-radius-spiral tests used the Kress dolly and trailer. All tractors towed through their low hitches.

Tractor	Drawbar pull on 30-m circle (kN)	Spiral minimum radius (m)	Comments
Kress	85	13	Full drawbar pull in circle but lost steering control; spiral limited by loss of steering
Case	89	< 7.6	Full drawbar pull in circle with complete steering control; spiral limited by trailer turning on itself
C95	66	12	Full drawbar pull in circle but lost steering control; spiral limited by loss of steering

Table 4. Trailer and sled towing-resistance measurements on McMurdo Ice Shelf near Williams Field based. Each resistance measurement is the visual average of the hand-held display readings for that test. All tests were conducted at steady 8 km/h except for one test of a 95%-full fuel tank at 16–19 km/h.

Trailer/sled	Weight (kN)	Resistance (kN)	Resistance coefficient	Average coefficient	Standard deviation
Kress trailer					
Single—Test 1	94	11	0.12	0.108	0.007
Single—Test 2	94	10	0.11		
Double—Test 1	190	20	0.11		
Double—Test 2	190	19	0.10		
Kress dolly					
Test 1	42	5.8	0.14	0.132	0.007
Test 2	42	5.3	0.13		
Fuel sled (12,000 L)					
Empty—Test 1	47	5.6	0.12	0.139	0.015
Empty—Test 2	47	6.9	0.15		
Empty—Test 3	47	6.4	0.14		
Empty—Test 4	47	7.1	0.15		
95% Full—Test 1	133	16	0.12	0.124	0.005
95% Full—Test 2	133	17	0.13		
95% Full @ 16–19 km/h	133	10	0.07	0.07	
Est. for 100% Full	*138*	*17 ± 1*	*0.124 ± 0.005*		
ISO sled					
Test 1	65	7.1	0.11	0.109	0.005
Test 2	65	6.7	0.10		
Test 3	93	10	0.11		
Test 4	93	11	0.11		

Table 5 lists the test sites and conditions for towing-resistance tests conducted during year two. The pre-departure tests on the McMurdo Ice Shelf are listed for completeness, but all other tests were part of the expedient program conducted as the fleet returned along the Ross Ice Shelf and back through the shear zone. Table 6 summarizes the results of the expedient tests in terms of the averages and standard deviations of the sled resistances and rut depths.

Table 5. Locations, conditions and supporting measurements for towing-resistance tests conducted during year two.*

Date	Site	Towing Resistance			Rut Depths	Rammsonde Profiles	Snow Pit
		Trailers/Sleds	Conditions	Loads			
Oct-Nov 03	Williams Field	single & double trailers, all sleds individually	undisturbed snow, in tracks of Case or Kress	y		(on 21 Jan 04)	y
7 Jan 04	South+47					2 undisturbed, 2 in Case tracks	
	South+32					2 undisturbed, 2 in Case tracks	
						undisturbed, surface only	
8 Jan 04	South+32					undisturbed, next to pit	y
8 Jan 04	South+16	1 fuel sled, full	undisturbed snow, in tracks of D8R	y	max/min	1 undisturbed	
			undisturbed snow, outside tracks		ave/std		
			on trail, outside tracks		max/min	1 trail, 1 undisturbed	
			on trail, in tracks of D8R		ave/std		
9 Jan 04	South+16					1 undisturbed next to pit, 1 trail	3-m undisturbed
10 Jan 04	South-17	2 fuel sleds, full-empty	undisturbed snow, in tracks of D8R	y	between sleds	1 undisturbed, 3 between sleds	1 undisturbed, 1 rut
			undisturbed snow, outside tracks		ave/std	1 undisturbed	
11 Jan 04	South-17	4 fuel sled, full-empty-full-empty	on trail, in tracks of Case	n			
			undisturbed snow, in tracks of Case		max	3 undisturbed (deep/shallow ruts)	
			undisturbed snow, outside tracks		max		
			undisturbed snow, circle outside tracks		max/min		
13 Jan 04	South-29	4 fuel sleds, full-empty-full-empty	undisturbed snow, outside tracks	y	profile	3 undisturbed	
			undisturbed snow, in tracks of C95		max		
17 Jan 04	HFS+4.6	pipe/chain drag	on trail, behind C95	y			y
			undisturbed snow, behind C95				
		4 fuel sleds full-empty-full-empty	undisturbed snow, outside tracks		profile	2 undisturbed (deep/shallow ruts)	
		2 fuel sleds full-empty	undisturbed snow, outside tracks		profile	2 undisturbed (deep/shallow ruts)	
			undisturbed snow, in tracks of C95		profile	2 undisturbed (~ uniform ruts)	
20 Jan 04	GAW	refrig-flatbed-milvan	undisturbed snow, in tracks of C95	y	profile	3 undisturbed	y
			undisturbed snow, outside tracks		profile		
		Kress tractor on UHMW sleds	undisturbed snow, in tracks of C95		ave		
			on trail, in tracks of C95		ave	1 in trail	
21 Jan 04	Williams Field	(on Oct-Nov 03)	near Oct-Nov 03 tests			3 undisturbed	

* Tests on the McMurdo Ice Shelf were conducted at Williams Field and GAW; all other tests were conducted along the Ross Ice Shelf portion of South Pole Traverse route. Site designations (e.g., South+47) refer to approximate distance in miles from major route markers, following the convention used by the traverse crew. Additional snow pit and Rammsonde profiles, not associated with resistance tests, were also obtained along the route.

Table 6. Summary of towing-test results conducted on the Ross Ice Shelf and on the McMurdo side of the shear zone crossing (GAW).

Location	Tractor	Sleds	Condition	Total towed weight, W (kN)	Average resistance, R (kN)	Std. dev. resistance, σ_R (kN)	R/W	$3\sigma_R/R$	Average rut depth, z (cm)	Std. dev rut depth, σ_z (cm)
South+16	D8R	1 fuel sled (full)	Undisturbed snow, In tracks	136	13.4	5.2	0.098	1.17	32.0	6.1
			Undisturbed snow, Outside tracks	136	6.4	1.5	0.047	0.68	9.2	1.6
			On trail, Outside tracks	136	5.9	3.0	0.043	1.52	8.3	5.8
			On trail, In tracks	136	11.0	5.5	0.081	1.49	29.3	10.6
S-17	D8R	2 fuel sleds (full-empty)	Undisturbed snow, In tracks	183	13.4	3.2	0.073	0.72	30.0	5.0
			Undisturbed snow, Outside tracks	183	15.3	2.4	0.084	0.48	11.2	4.0
S-29	Kress & C95	4 fuel sleds (full-empty-full-empty)	Undisturbed snow, Outside tracks	366	34.3	4.8	0.094	0.42	17.0	6.9
	C95		Undisturbed snow, In tracks	366	58.8	10.5	0.161	0.53	44.2	9.7
HFS+4.6	C95	Pipe-chain drag	On trail	8.9	8.3	0.7	0.932	0.24		
			Undisturbed snow	8.9	6.0	0.7	0.674	0.33		
	Kress & C95	4 fuel sleds (full-empty-full-empty)	Undisturbed snow, Outside tracks	366	39.6	6.5	0.108	0.49	17.3	6.7
		2 fuel sleds (full-empty)	Undisturbed snow, Outside tracks	183	19.5	4.6	0.107	0.71	16.2	4.7
	C95	2 fuel sleds (full-empty)	Undisturbed snow, In tracks	183	23.6	4.3	0.129	0.54	24.8	5.6
GAW	C95	3 ISO sleds (refrig-flatbed-milvan)	Undisturbed snow, In tracks	349	37.6	6.0	0.108	0.48	15.9	16.1
	Kress & C95	3 ISO sleds (refrig-flatbed-milvan)	Undisturbed snow, Outside tracks	349	35.1	4.2	0.101	0.36	10.1	15.1
	C95	Kress on UHMW sleds	Undisturbed snow, In tracks	229	36.7	5.5	0.160	0.45	44.8	3.0
		Kress on UHMW sleds	On trail, In tracks	229	11.5	2.9	0.050	0.75	3.0	2.0

Manual recording of measured towing forces at about 1-second intervals allowed us to obtain approximate time series and to compute averages and standard deviations of the towing forces. Figure 8 shows a typical plot for a test where the C95 attempted to tow four fuel tanks in its tracks over undisturbed snow. The test started with the C95 towing the tanks on the established trail along a straight path angled onto undisturbed snow. The tractor succeeded in pulling the tanks completely onto undisturbed snow but broke traction within about 30 m of doing so. Several points regarding this test should be noted. The four tanks were alternately full-empty-full-empty and weighed 366 kN or the equivalent of only 2.7 full fuel tanks. When towing them it its tracks, the C95 broke traction at 62 kN, close to the dynamic drawbar-pull of 67 kN measured on the McMurdo Ice Shelf. Because the tractor broke traction, the maximum towing force is a minimum estimate of the peak resistance of the four sleds in this configuration. As with all sled tests, the sled train did not include a trailing drag.

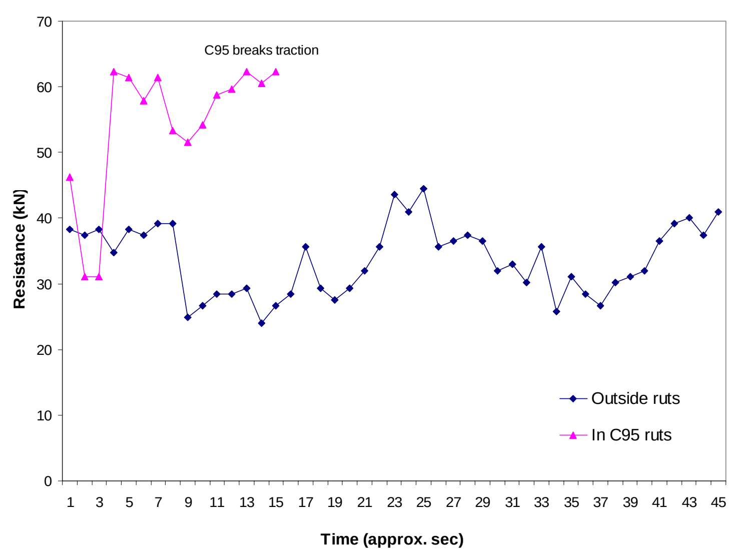


Figure 8. Measured towing resistance of four fuel sleds (empty-full-empty-full) over undisturbed snow when towed outside of and within C95 ruts. Note that C95 broke traction at 62 kN when towing the four fuel sleds within its ruts. This value is very close to its drawbar pull of 67 kN measured on the McMurdo Ice Shelf

Separate towing tests for a pipe-chain drag yielded resistance values of 8.3 ± 0.7 kN when towed along the established trail and 6.0 ± 0.7 kN when towed over undisturbed snow. These values are about 10% of the drawbar-pull of the C95, and can therefore be significant additional loads when the sled trains experience high resistance.

Figure 9 shows histograms of the towing forces from the expedient program, with the average resistance, R, and three standard deviations, $3\sigma_R$, stacked together for each test. This approach recognizes that tractors must provide sufficient traction to overcome resistance peaks, rather than just the average resistance, to avoid frequent immobilization. For tests on undisturbed snow, $3\sigma_R \approx 70\%\ R$ for sleds towed in tractor tracks compared with $50\%\ R$ for sleds towed outside tractor tracks. The histograms do not include the pre-deployment measurements on the McMurdo Ice Shelf because only average resistance was recorded for those tests.

Sleds towed in the tracks or ruts of the towing tractor have significantly higher towing resistance. Peak resistance, characterized by $R+3\sigma_R$, of four fuel sleds (full-empty-full-empty) exceeds the drawbar-pull of the C95, Kress, and Case tractors; towing resistance of three ISO sleds approaches the drawbar-pull of the C95. Again, these measurements do not include the resistance of a pipe-chain drag that normally terminated each sled train during fleet movement. It is, therefore, not surprising that the C95, Kress, and Case were unable to pull four full tanks and a drag along undisturbed snow when breaking trail southward across the Ross Ice Shelf.

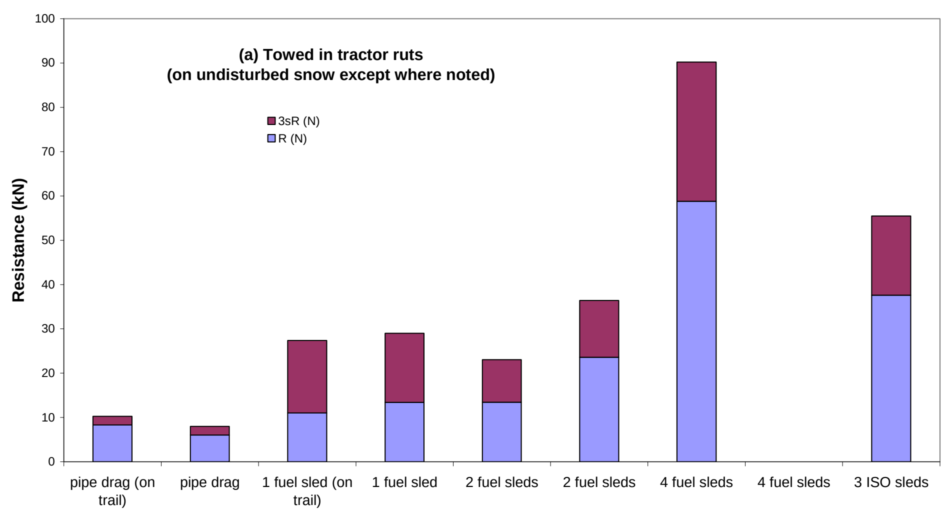


Figure 9. Measured towing resistance of sleds (average and three standard deviations) from expedient tests on Ross Ice Shelf and McMurdo side of shear zone.

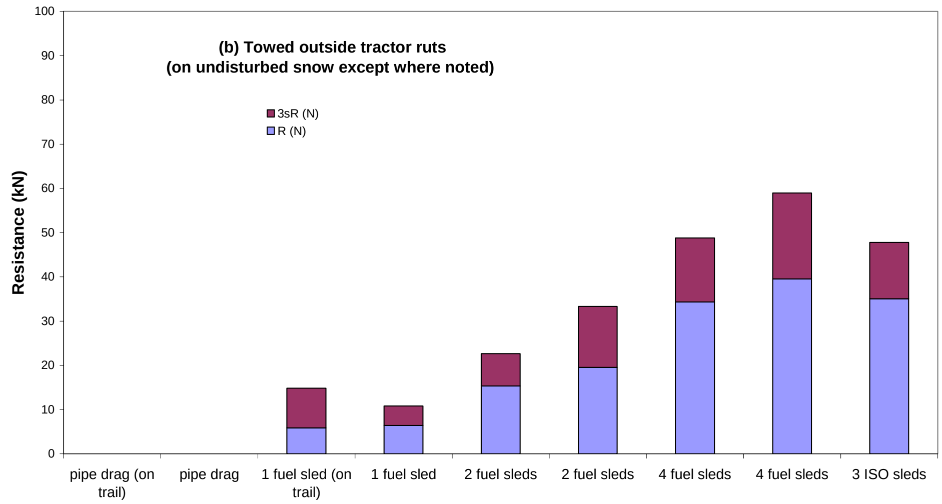


Figure 9 (cont'd). Measured towing resistance of sleds (average and three standard deviations) from expedient tests on Ross Ice Shelf and McMurdo side of shear zone.

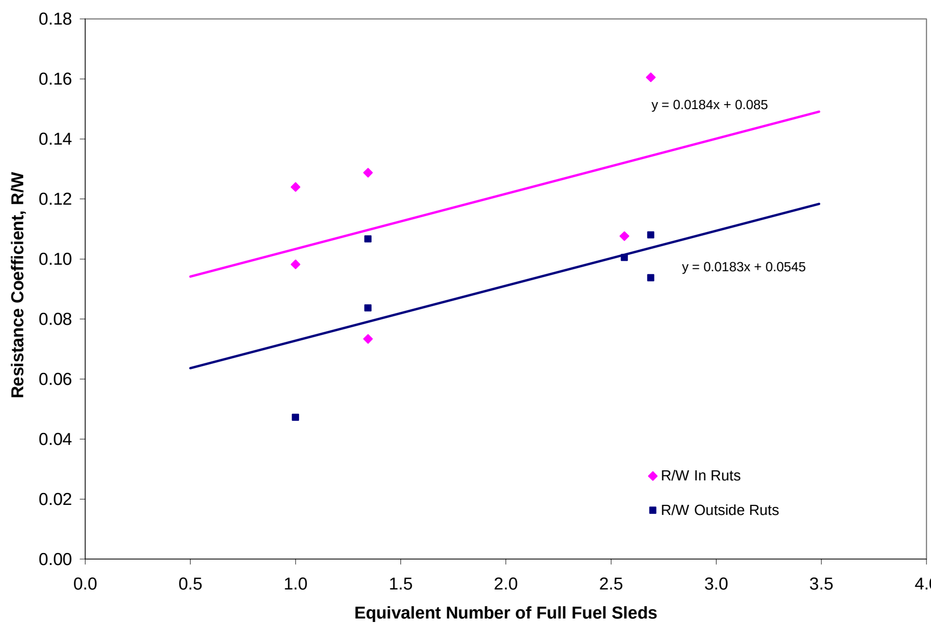


Figure 10. Increase in measured resistance coefficient with number of full fuel sleds in train. Data are from expedient tests on Ross Ice Shelf and resistance tests at Williams Field (McMurdo Ice Shelf).

Figure 10 presents the average resistance coefficients, R/W, measured for all fuel-sled tests versus the equivalent number of full fuel sleds in the train (train weight normalized by weight of one full tank sled). The in-track and outside-track results show similar increases with number of sleds, with the in-track values higher by $R/W \approx 0.03$.

On 20 January 2004, we conducted one set of towing tests to quantify the performance of the small UHMW tractor-recovery sleds. These sleds consisted of ~ 1-cm-thick sheets of ultra-high molecular weight polyethylene and measured about 1-m-wide × 3-m-long. They were intended to permit towing of a disabled tractor by acting as a low-friction surface beneath the tractor's tracks. We secured the Kress tractor onto the UHMW sleds and towed it behind the C95 over undisturbed snow and along the well-traveled trail that connects the shear zone at GAW to McMurdo (Fig.11). Over undisturbed snow, the Kress/UHMW sank deeply (45 ± 3 cm) and plowed snow at the front of its tracks. Its towing resistance was about 55% of the C95's drawbar-pull (Table 6). Nevertheless, the C95 did not dig itself deeply into the snow from slip-sinkage and was able to pull the load steadily about 200 m without breaking traction. On the trail, the C95 easily pulled the Kress/UHMW with little sinkage of either vehicle, providing an estimate of the friction coefficient of the UHMW sleds as $R/W = 0.050 \pm 0.013$. Similar UHMW material covers undersides of all sled skis used in year two; thus, all skis should display similar friction coefficients.

a. On undisturbed snow. Note the shallow rut left by the C95 when towing on undisturbed snow.

Figure 11. Kress on UHMW tractor-recovery sleds towed behind C95 at GAW.

b. On well-traveled trail from GAW to McMurdo.

Figure 11 (cont'd).

Several important qualitative towing-resistance observations supplement the resistance measurements made during the expedient program. On 11 January 2004, we prepared for a test with the Case pulling four fuel sleds (full-empty-full-empty) only to discover that the load cell was not working (we later dried it out and checked its calibration). Nevertheless, we continued with the tests for their qualitative value. The Case easily pulled the four sleds in its tracks along the trail to prepare for the tests, but it became immobilized within about 50 m of pulling the sleds onto undisturbed snow along side of the trail (Fig. 12). We used a second tractor in a Y configuration to pull the sleds onto the undisturbed snow and then attached the sleds to the Case only via a long tether. In this way, the Case was able to pull the sleds in a large-radius circle (~ 100 m) on top of the undisturbed snow such that the sleds always stayed to the inside of its ruts. The Case completed a full circle at ~ 11 km/h without becoming stuck; it then pulled the tanks onto the trail and back to camp. Even though the slowly turning tank sleds experienced additional plowing resistance, compared with straight-line travel, the towing resistance was clearly less than the drawbar-pull of the Case.

On another occasion, the C95 pulled four tanks (full-empty-full-empty) 21 km along the trail at 14 km/h without getting stuck. The Case nearly duplicated this feat, pulling the same four tanks 20 km and extricating itself without help on the single occasion that it got stuck. On both occasions, the operators reported that driving at higher speed (14 km/h versus the normal fleet speed of 8 km/h) helped them to ride through soft-snow patches, without causing discomfort from excessive motions of the cab. Note that the trail here was simply the path that had been traversed once by the fleet heading south 20–30 days earlier. Neither tractor could successfully pull these tanks over undisturbed snow when the tanks rode in the tractor's ruts. These observations also reflect the pre-deployment measurement that towing resistance dropped significantly when a fuel sled was towed at high speed (Table 4).

a. Case pulling four tanks (full-empty-full-empty) along trail to test site.

b. Case breaks traction within ~50 m of pulling tanks off-trail in its tracks.

Figure 12. Qualitative tests on 11 January 2004.

c. Case and C95 in Y-configuration pull tanks onto undisturbed snow.

d. Case successfully pulls tanks on long tether in large-radius circle with tanks riding on undisturbed snow inside the radius of tractor ruts.

Figure 12 (cont'd).

Another important qualitative observation was the poor towing performance of the Kress tractor on the Ross Ice Shelf. The traverse crew initially responded by caching one tracked-trailer almost immediately upon heading southward. The downward force of the trailer and the high fifth-wheel location caused the Kress to tow its trailer with a significant positive trim (Fig. 13). Yet even when towing from its drawbar (low hitch, equivalent to the C95 hitch), the Kress was only able to tow two fuel tanks without risk of frequent immobilization. This poor performance relative to the similar C95 tractor was particularly unexpected, given that its drawbar-pull measured on the McMurdo Ice Shelf exceeded that of the C95 (Table 2) and the measurements were made from the same locations on the tractors (i.e., the drawbars) that were used to tow sleds..

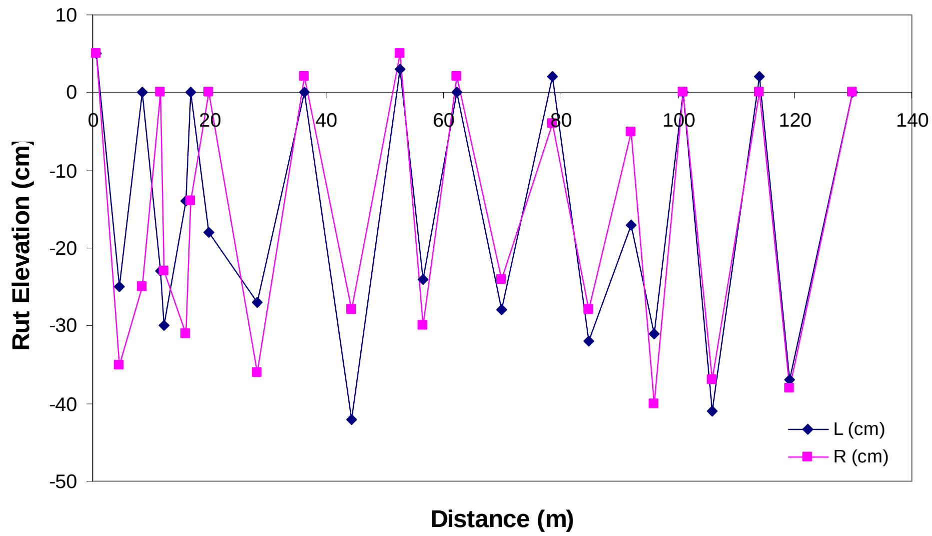
Figure 13. Kress tractor pulling tracked-trailer over undisturbed snow.

Figure 14. Tracked-trailer's insufficient lateral support of track by idler and bogie wheels.

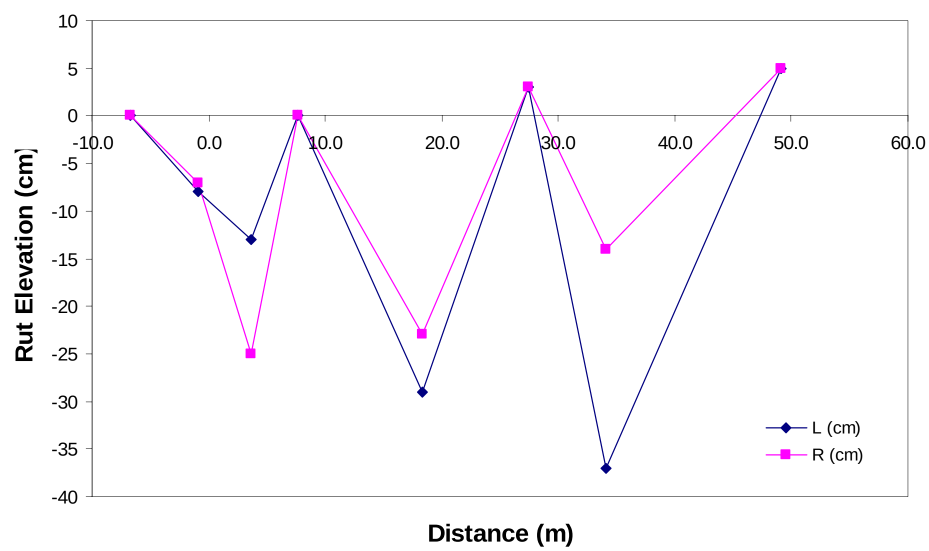
The Kress tracked-trailer experienced its own problems on the Ross Ice Shelf. The idler and bogie wheels provided insufficient lateral support to distribute weight evenly across the tracks, causing them to curl up along their outer edges (Fig. 14). This effectively reduced the stance (gauge) of the trailer, which combined with the high center-of-gravity of the cargo to permit large-amplitude roll motion of the trailer (Fig. 15). It is likely that roll motions caused dynamic increases in track pressure and sinkage that, in turn, increased roll amplitude.

Figure 15. Large-amplitude roll motion of tracked trailer along trail northward.

Rut-depth measurements complemented measurements of towing resistance and reflected similar fluctuations from average values. Figure 16 shows rut-depth profiles obtained after towing tests of three ISO sleds at GAW (McMurdo Ice Sheet side of shear zone). Figure 17 shows the corresponding towing-resistance time series. The spacing between maximum rut depths was 15–20 m, which correlates well with the occurrence of peak towing forces at intervals of 8–10 seconds for the estimated tractor speed of 2 m/s (7 km/h).



a. In ruts of C95.



b. Outside ruts of C95.

Figure 16. Rut-depth profiles (L = left rut, R = right rut) after passage of three ISO sleds towed over undisturbed snow. Elevation is relative to local snow surface. The profiles capture sled porpoising (pitching) motions when left and right ruts are in-phase and roll motions when ruts are out-of-phase. Note that the bottoms of the ruts were often higher than the surrounding snow surface because of plowing.

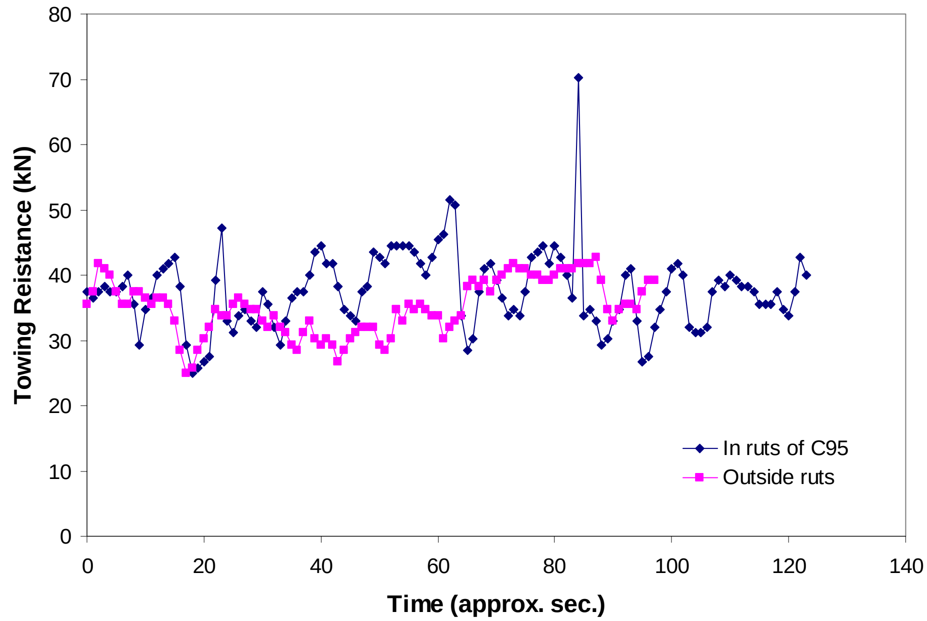


Figure 17. Resistance measured for three ISO sleds towed over undisturbed snow by the C95. Peak forces occurred at about 8–10 second intervals, which correlates well with 15–20 m spacing of peak rut depths for a tractor speed of 2 m/s.

Motions of the sleds were preserved in the ruts: peak rut depths approached three times average depths, minimum ruts were often above the elevation of the surrounding snow surface, and left and right rut profiles could be out-of-phase. Large amplitude pitch (termed “porpoising”) and roll motions of the sleds resulted. For fuel sleds, plowing by the rear support saddle occurred for ruts deeper than about 25 cm. Deposition of the plowed snow could form a center ridge between the ruts that was higher than the undisturbed snow surface (Fig. 18).

Large sled motions produced numerous breakdowns. Common failures included the sled turntable pins (that permit yaw motion of the skis with respect to the container) and container–bogie attachment pins (called pineapples). After all spares were used up, the crew fixed both problems using chains to secure the bogie components yet allow for some relative motion (Fig. 19).

Figure 18. Deep ruts made after passage of four fuel sleds (full-empty-full-empty) towed in ruts of C95 over undisturbed snow. Dragging of tank saddle produced the sculpted center ridge, which can be higher than the undisturbed snow surface.

a. Pitch of ISO sleds.

Figure 19. Large sled motions caused numerous equipment breakdowns and delays for repairs.

b. Roll of housing and energy modules.

c. Holding bogies and containers together with chains.

Figure 19 (cont'd).

d. Placing container back on sled bogie.

Figure 19 (cont'd). Large sled motions caused numerous equipment breakdowns and delays for repairs.

Snow Characterization

We converted Rammsonde-hardness readings to unconfined compressive strength using the correlation by Abele (1990):

$$\sigma = 0.37\ R^{0.55} \quad (1)$$

where

σ = unconfined compressive strength (kg/cm^2)

R = Rammsonde hardness (kg) obtained at each depth.

This provides an index of snow strength that can assist with mobility analyses.

Figure 20 shows three strength profiles in undisturbed snow at South-17, adjacent to the ruts from a towing test (four fuel tanks towed in circle outside ruts by Case). As with most locations, they did not show a strong trend of snow strength with depth, although strong and weak layers were apparent. Interestingly, the average strength in the top 63 cm did not correlate with rut depths left by the tanks. This was also true for tests at HFS+4.6 (our only other attempt to correlate snow strength and rut depth).

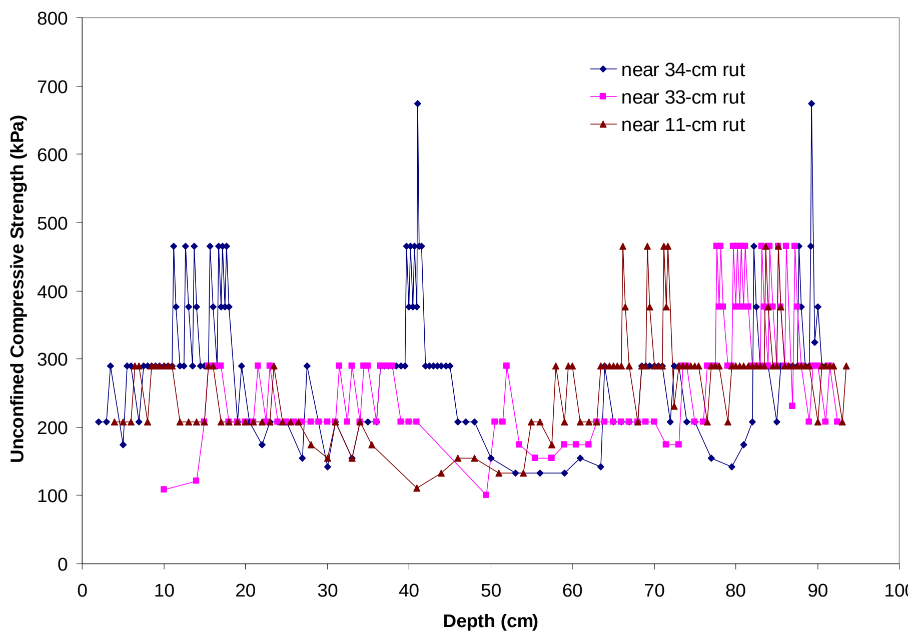


Figure 20. Three Rammsonde strength profiles taken in undisturbed snow adjacent to towing-resistance tests at South-17. In the top 63 cm, the profile averages ranged 180–220 kPa and showed no clear correlation to rut depths made by the four fuel sleds (towed outside the ruts of the Case).

In many profiles, distinct hard and soft layers existed, typically 10–20 cm thick with average strengths ranging from ~140 to >700 kPa. The depth of these layers, relative to the snow surface, could vary by 10–30 cm between locations only 5 m apart. Snow densities did not always reflect strength differences, but snow crystal structure did. Strong layers appeared to be wind slabs with well-bonded sub-millimeter equiangular grains. Weak layers, typically located immediately below strong ones, were usually composed of 1–2-mm of poorly bonded depth-hoar crystals.

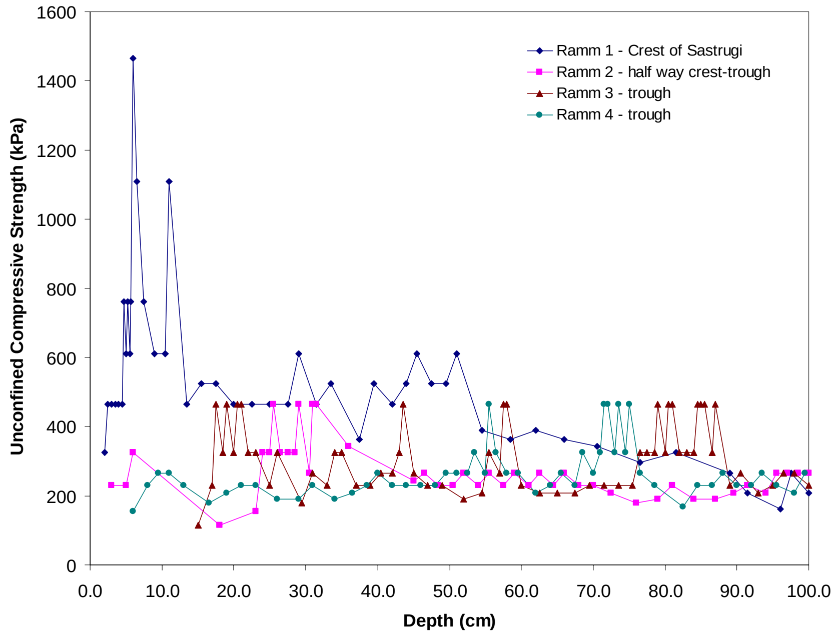


Figure 21. Snow strength profiles at South-82 in undisturbed snow with sastrugi. Sastrugi crest-to-trough heights were ~60–90 cm and crest-to-crest distances ~20 m. The crest snow averaged 500 kPa through the top 63 cm, while the other three profiles averaged only 230 kPa.

Wind-sculpted sastrugi (rounded crests aligned parallel to the wind) were noticeable at many locations, with crest-to-trough heights ranging 20–90 cm and crest-to-crest spacing of 10–30 m. Passage of the tractors and sleds barely dented some of the sastrugi. Older, buried sastrugi probably account for the strong buried snow layers. Unfortunately, the sastrugi were visually difficult to detect under commonly occurring flat-light conditions, and buried strength variations usually had no surface expression. Passage of the tractor-trains through such terrain caused violent, unexpected pitch and roll motions of the sleds and numerous breakdowns. The crew named these hard features “dorniks” after a farming term for a buried rock that could break a plow. Figure 21 shows four snow-strength profiles taken in a sastrugi area. The strength of the crest to a depth of 63 cm averaged 500 kPa and peak values exceeded 1000 kPa. This is considerably higher than the three profiles taken away from the crest, which averaged 230 ± 4 kPa over the same depth. This sastrugi extended across the trail and showed little indentation by the tractor-trains.

Compilation of average snow strength (excluding sastrugi) along the route reveals a decreasing trend onto the Ross Ice Shelf (Fig. 22). Average snow density snows no such trend. Note that the traverse crew felt that fleet mobility worsened towards the center of the Ross Ice Shelf, despite average strengths that were much greater than ski pressures (Table 2).

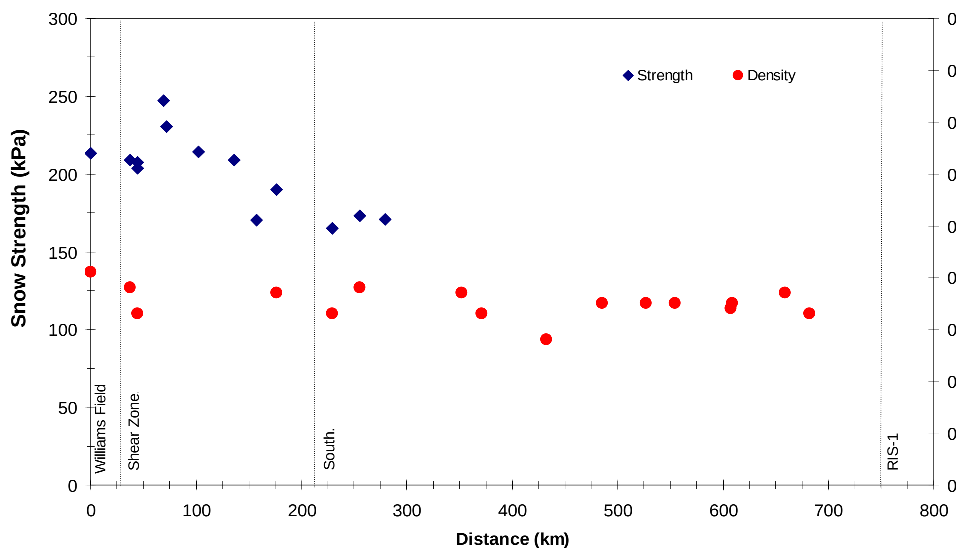


Figure 22. Average undisturbed snow strength (unconfined compressive strength) and density in top 0.63 m along traverse route. Density measurements beyond 300 km were obtained by N. Yankielun and S. Metcalf. Data do not include crests of sastrugi.

An important qualitative observation regarding snow strength was the lack of strength in the bottom of tractor ruts immediately after the passage of a tractor. When a tractor towed several sleds past a location, even along the established trail, very loose, cohesionless snow lined the bottom of the ruts. This loose snow was typically 20–30 cm deep and supported almost no shear stress. Many of us stepped into tractor ruts and could not walk along the weak snow. This was particularly annoying in flat light, an embarrassingly simple way to end up flat on one's back. A tractor traveling on its own would also chew-up the snow surface, but the ruts and the depths of mealy snow were much smaller than when towing sleds.

We were unable to measure reliably the low strength of recently chewed-up snow using the 60° × 4-cm-diameter Rammsonde probe. Interestingly, snow immediately adjacent to tractor ruts appeared to retain most of its strength. Sleds towed along the edge of a rut did not cave in the rut wall unless they overlapped the rut by a few centimeters.

The only occasion when snow chewed-up by tractor passage was immediately cohesive was 10 January 2004. The air temperature was about –6°C and the air was noticeably moist with some fog. Apparently, the moisture facilitated rapid re-bonding of the loose snow. That day also produced the only test where tanks towed outside the tractor's ruts had higher towing resistance than the same tanks towed in the ruts (Table 6). We attribute this to increased ski–snow friction owing to high humidity and local adhesion as the skis press moist surface snow into colder snow underneath. A similar effect occurs with cross-country skis in humid air over cold snow.

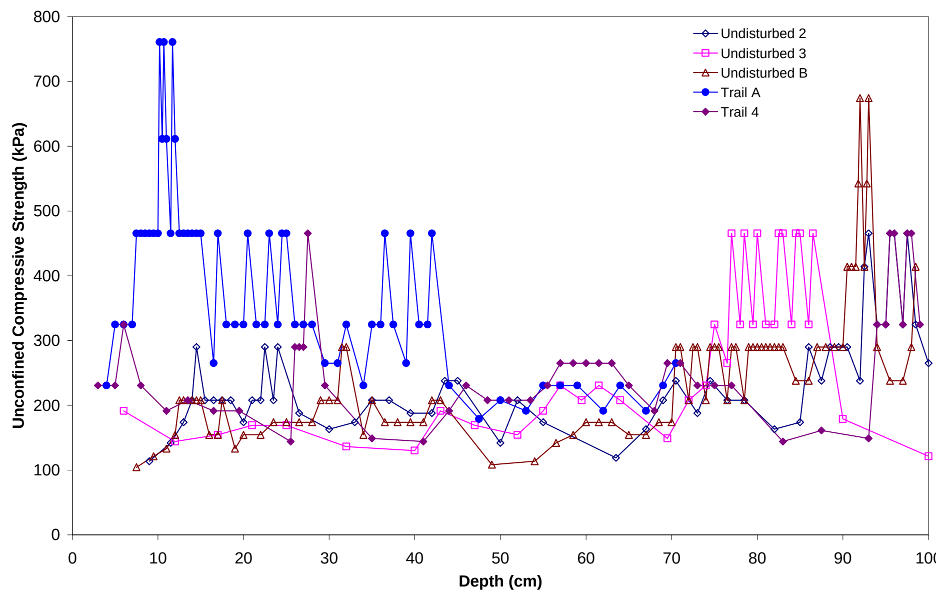


Figure 23. Snow-strength profiles at South+16. The three profiles in undisturbed snow were similar and averaged 165 ± 8 kPa over the upper 63 cm. The Trail 4 profile was taken in the trail section used for the fuel-tank resistance test and averaged 204 kPa over the same depth. The fleet passed this section six times, three times shuttling southbound and three times shuttling northbound 5 weeks later. The Trail A profile was taken in a section of trail that was back-bladed 15 hours earlier by the D8R; it averaged 304 kPa over the upper 63 cm.

Rammsonde penetrometer profiles along the trail indicated that fleet passage and grooming with drags produced a modest increase in snow strength compared with undisturbed snow. Figure 23 shows snow-strength profiles taken in undisturbed snow and along the trail at South+16 adjacent to the location of fuel-sled resistance tests. The three profiles in undisturbed snow were similar and averaged 165 ± 8 kPa over the upper 63 cm. The fleet passed this trail section six times, three times shuttling southbound and three times shuttling northbound 5 weeks later, and increased the average snow strength to 204 kPa. By comparison, single-pass back-blading by the D8R increased the trail strength to 304 kPa over the upper 63 cm.

Figure 24 shows another comparison between strength profiles in undisturbed snow and on the trail at GAW (the McMurdo side of the shear zone). This trail section had experienced numerous vehicle passes during year-one and year-two traverse work. The three profiles in undisturbed snow were quite similar, with an average strength of 210 ± 20 kPa to 63 cm depth. By comparison, the trail profile had an average strength of 390 kPa to the same depth, although strength varied widely. The very strong snow (~ 1000 kPa) below 60 cm was probably the trail surface from year one.

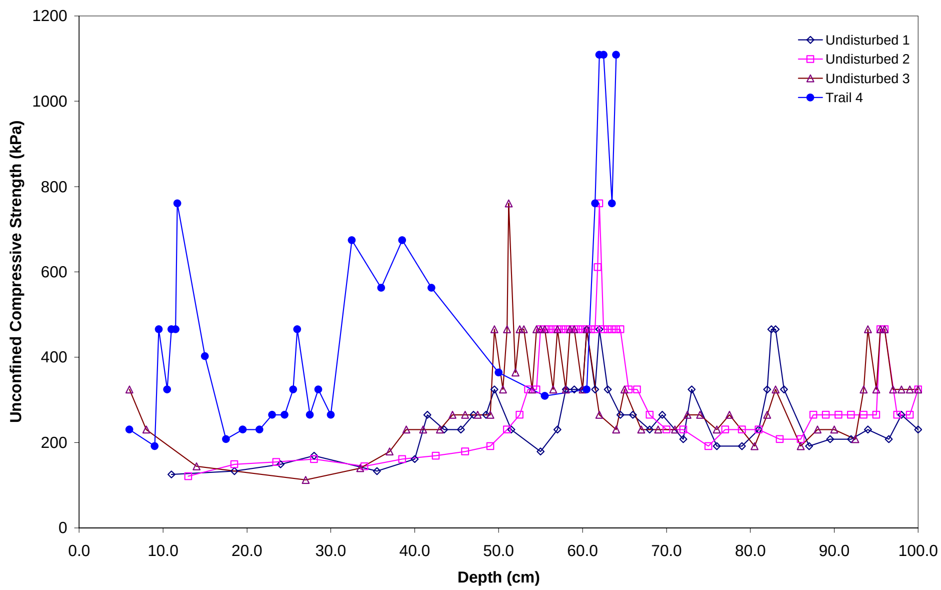


Figure 24. Snow-strength profiles at GAW. The three profiles in undisturbed snow were quite similar, with an average strength of 210 kPa to 63 cm depth. By comparison, the trail profile had an average strength of 390 kPa to the same depth, although strength varied widely.

6 DISCUSSION

Our main objective was to understand the causes of poor fleet mobility on the Ross Ice Shelf, particularly in light of encouraging pre-departure test results on the McMurdo Ice Shelf. The dramatic improvement in tractor-train mobility, quantitatively and qualitatively, with sleds towed outside of the tractor ruts offers critical insight. Evidence suggests positive feedback occurs between traction, track slip and sled resistance when skis ride in the ruts made by a towing tractor. The role of undisturbed-snow strength is less clear.

At constant speed, tractor net traction equals towing resistance of the sled train (Fig. 25). Resistance, in turn, consists of contributions from ski–snow friction, snow compaction, and snow plowing. To develop traction, some track slip occurs, which fractures inter-granular bonds in the otherwise cohesive snow surface. Moderate to large amounts of track slip significantly disaggregate the snow to produce a mealy, loose material in the tractor's ruts. Slip also increases tractor sinkage or rut depth. Skis traveling in the ruts encounter the loose snow and compact it, thereby increasing compaction resistance. Deeper ruts also cause plowing resistance of sled components, especially tank saddles, to increase. Increased sled resistance requires the tractor to develop more traction, which comes at the price of increased slip and sinkage. When the average sled resistance is high relative to tractor drawbar-pull, a momentary demand for increased traction can cause slip to increase beyond the value for peak traction, and the tractor can dig itself into the snow as slip reaches 100% (no forward speed, track still churning up the snow). This traction–slip–resistance feedback can occur quickly, within a few seconds, and abrupt immobilization can result. Tractor operators experience this process by realizing that they have very little margin for steering corrections or traction increases at low speed under heavy load. At high speeds, momentum can carry the tractor-train through spikes in resistance without the onset of catastrophic traction–slip–resistance feedback.

We did not conduct sufficient tests to quantify the feedback process, but tests results on 11 January (Case tractor) and 13 January (C95 tractor) provide convincing evidence of its importance. Neither tractor could tow in its ruts the equivalent of 2.7 full fuel tanks over undisturbed snow. But the Case handily towed them in a large circle outside its ruts, and the C95 could have towed them outside its ruts based on their measured resistance ($R + 3\sigma_R$). To support this last point, note that the C95 easily towed the Kress tractor on UHMW sleds at an average resistance of 55% of its drawbar-pull, slightly higher than the average sled resistance measured on 13 January. Note also that on 11 January maximum rut depths around the circle were similar to those when the Case pulled the tanks in its tracks and broke traction. Towing outside of the tractor ruts disrupts traction–slip–resistance feedback, reduces peak towing forces, and allows a tractor to tow sleds closer to its maximum drawbar-pull without risk of immobilization.

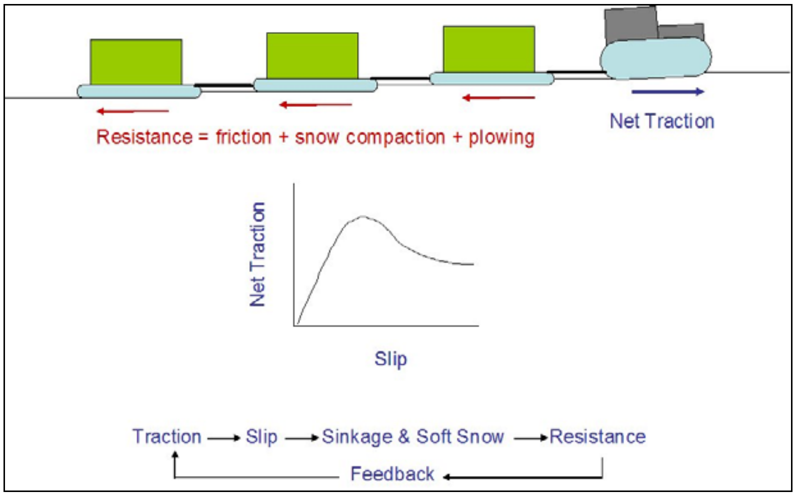


Figure 25. Schematic of traction–slip–resistance feedback process for tractor–sled trains. At constant speed, tractor net traction equals towing resistance. To develop traction, some track slip occurs, which disaggregates the snow surface to produce mealy, loose snow in the tractor's ruts. Skis traveling in the ruts encounter increased resistance, which requires more traction to overcome. When average sled resistance is near maximum net traction (tractor drawbar-pull), traction–slip–resistance feedback can cause towing resistance momentarily to exceed peak traction and abrupt immobilization results. The traction–slip curve for snow may display a clear maximum, as shown, or asymptotically approach maximum net traction (Wong 1989, Richmond et al. 1995).

Runaway traction–slip–resistance feedback apparently requires the tractor to operate at higher than 55% of its maximum drawbar-pull, again based on the C95-Kress/UHMW test. During this test, the C95 produced relatively shallow ruts, suggesting relatively low slip, compared with the ruts made when it broke traction. Longer tests would be more convincing, but the tractor–sled trains were immobilized within much shorter distances than the successful 200-m C95-Kress/UHMW test. Tractors traveling by themselves also produced very shallow ruts compared with when they were towing sleds. That is, tractor sinkage is small except at high slip (traction) where slip–sinkage becomes important.

For fuel sleds, deep tractor ruts also increase the likelihood of plowing by the saddle. This plowing force is 0 for sinkage less than about 25 cm and probably increases rapidly beyond that depth. When towed within tractor ruts, tank saddles plowed snow even if the train consisted of only one or two tanks.

Conceptually, we may describe sled resistance as the sum of forces from sliding friction, snow compaction, and plowing:

$$R = \mu W + f_1(z) + f_2(z - c) \qquad (2)$$

where

μ = sliding-friction coefficient

f_1 = snow-compaction resistance

f_2 = plowing resistance (non-zero for $z > c$)

z = ski sinkage

c = sled clearance to the snow surface.

Dividing by sled-train weight, W, produces an expression for towing resistance coefficient:

$$R/W = \mu + f_1(z)/W + f_2(z - c)/W \qquad (3)$$

Friction coefficient is approximately independent of weight or contact pressure. Classic mobility theory for tracked vehicles on soft terrain (Bekker 1956, Wong 1989) suggests that compaction resistance varies linearly with sinkage. That is, a plot of R/W versus z should yield a straight line with intercept μ, until sinkage exceeds sled clearance. Figure 26 suggests that this may be a reasonable relationship for the traverse sleds tested. Except for the ISO sleds, the slopes are similar and the intercepts average $\mu = 0.045 \pm 0.016$. This value is consistent with the resistance coefficient obtained for the Kress/UHMW test on the GAW-McMurdo trail section, where sinkage was small. UHMW also lined the bottom of the sled skis.

Figure 10 quantified the reduction in average towing resistance for fuel sleds towed in tractor ruts versus outside the ruts. The difference was $R/W \approx 0.03$. The same data revealed another important finding: resistance coefficient, R/W, increased with the number of fuel sleds, n, for both in-rut and outside-rut towing (Fig.10). More tests would help reduce uncertainty, but these results are consistent with observed tractor-train behavior.

In shallow snow, where passing vehicles compact snow against a hard substrate, R/W decreases with the number of passes because snow in the rut increases in density and strength (Richmond et al. 1995). On the deep snow of the Ross Ice Shelf, possible reasons for increasing R/W with n include incrementally greater sinkage, increased plowing by tank saddles, steady-state traction–slip–resistance feedback, or plowing associated with increased pitch motions (porpoising).

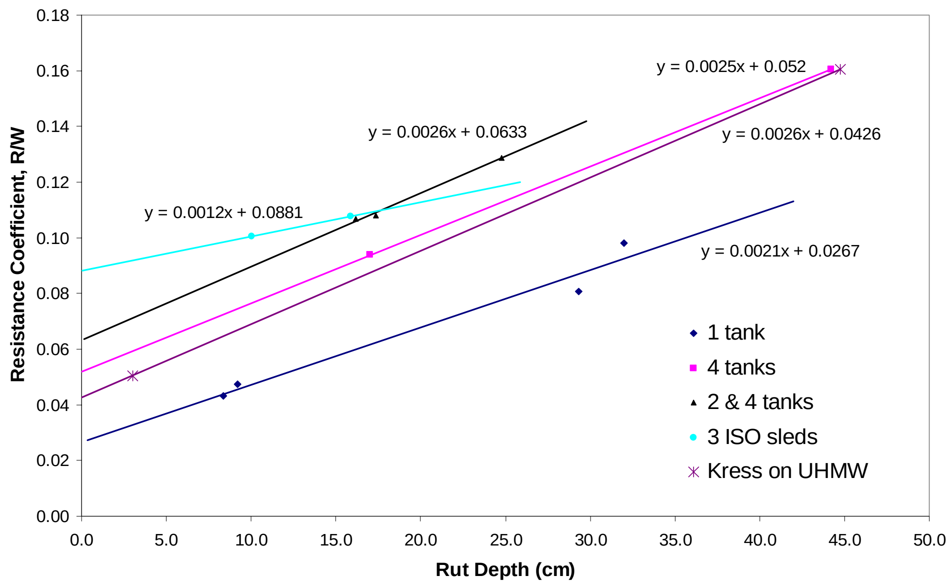


Figure 26. Resistance coefficient versus rut depth for all tests, grouped according to test location.

Evidence does not support the first three explanations. We did not observe incrementally greater sinkage (increasing Δz) for successive tank sleds. For in-rut towing, the saddles of the third and fourth fuel sleds plowed more snow than those of the first two sleds. Visually, this plowing was very dramatic and could account for increasing R/W. However, for sleds towed outside ruts in straight paths (i.e., all quantitative tests), tank saddles did not drag, and this explanation fails. For sleds towed in ruts, increasing R/W with n could be linked to greater steady state traction–slip–sinkage interaction (higher traction requires higher slip, which produces higher R/W). Again, this interaction does not explain the similar increase in R/W for sleds towed outside ruts.

Sled pitch motions may offer a consistent explanation. Visually, sled porpoising noticeably increased with the number of sleds in a train for both in-rut and outside-rut towing. Rut profiles and force time series both reflect these cyclic motions. As a ski enters a trough, it plows downward and forward momentarily before rising to the next crest. The ski then deposits its plowed snow just after the crest, and the next ski in the train repeats the cycle with increased amplitude. Compared with nearly level motion of a one-sled train, multiple-sled trains expend extra energy on this cyclic plowing, and the average towing force increases.

We are unable to identify snow strength as the cause of poor fleet mobility overall. Clearly, “dorniks” or sastrugi caused unexpected, severe sled motions that led to breakdowns, and downtime for repairs significantly reduced fleet average speed. However, immobility of tractor-trains did not require such dramatic motions. Also, all fleet movements occurred with sleds riding in tractor ruts, so the sleds did not interact with intact undisturbed snow.

We measured snow-strength variations on wavelengths of 10–30 m, and this scale coincided with porpoising wavelengths. However, it also appeared that porpoising could occur in fairly uniform snow conditions, and strength variations did not correlate with rut depths. Porpoising probably results from dynamic interaction between sled skis and the snow they plow; ski longitudinal pitch and bogie dynamics may also play roles. Presumably, these dynamics cause porpoising at some characteristic wavelength and amplitude. Significant strength variations, from, say, sastrugi, may play secondary roles to trigger large motions or lock them into specific wavelength and amplitude.

The measured decrease in average strength of undisturbed snow (Fig. 22) could account for the crew’s qualitative assessment of worsening fleet mobility as they progressed southward towards the center of the Ross Ice Shelf. However, the fleet displayed poor mobility almost immediately upon entering the Ross Ice Shelf. Also, ski pressures were significantly lower than the lowest average strength: about four times lower for the housing/energy modules and about 10 times lower for ISO and fuel sleds. Note also that the Rammsonde-based strength measure, unconfined compressive strength, should underestimate pressure required to collapse the snow confined under a ski. Because all sleds rode in tractor ruts, failure of weak layers beneath the ruts would need to be the cause of poor mobility if undisturbed-snow strength is the culprit. Traction–slip–resistance feedback seems a more likely explanation. The sleds ride on the weak, disaggregated snow produced behind a tractor at high slip rather than the much stronger adjacent undisturbed snow.

The improved mobility of the returning fleet suggests a benefit from previous fleet passes (compaction and grooming). However, we measured only modest strength increase (from 165 ± 8 kPa for undisturbed snow to 204 kPa on the trail) for the top 63 cm resulting from fleet passes at South+16 on the Ross Ice Shelf. The top 30 cm of the trail surface was relatively stronger (250 kPa versus 180 ±

20 kPa for undisturbed snow). Nevertheless, undisturbed snow near the start of the Ross Ice Shelf was as strong. At South+16, the trail did not yield a quantitative reduction in towing force or rut depth, for either in-rut towing or outside-rut towing of one tank, compared with the same towing condition on undisturbed snow. Also, any trail benefit existed for only one tractor-train, and following trains needed to stagger their lanes to avoid immobilization.

It is difficult to reconcile these results with the significantly higher average speeds of the returning fleet. Also, the Case and C95 both successfully towed on the trail, at high speed, the same four fuel tanks that they were unable to tow on undisturbed snow. The minimally prepared trail must have produced a benefit. It is possible that even modest strength gain in the top 10–30 cm helps to preserve snow strength after tractor passage, thereby lessening the effects of traction–slip–resistance feedback. We apparently conducted too few tests, or the effect was too subtle, for us to quantify it.

A case can be made for formal trail-building to improve fleet mobility. The frequently traveled trail at GAW was much stronger than undisturbed snow (390 kPa), held up well to multiple train passes, and offered a huge reduction in towing force as seen by the Kress/UHMW test. Thus, an average strength of about 400 kPa in the top 60 cm would be a good target for trail strength. Clearly, the length and width of trail required demands very efficient trail-building procedures. Also, trail-building would need to precede the fleet by several days, depending on the density of the compacted snow, air temperature, and solar radiation, to allow time for sintering (Abele 1990). More tests to quantify the resistance reduction for multiple-sled trains and the time and cost per kilometer of trail are needed to assess the merits of this approach.

In retrospect, the causes of poor fleet mobility on the Ross Ice Shelf were difficult to anticipate. Pre-departure towing tests on single sleds could not reveal the existence of catastrophic traction–slip–resistance feedback or increasing R/W with number of sleds. The former is most noticeable at high loads and the latter noticeable only with multiple sleds.

Also, before year two, we had expected superior performance of tracked trailers relative to sleds as traverse cargo carriers. For similar contact pressures, the snow-compaction resistance should be the same for tracks and skis. Provided the internal resistance of the track system is less than sliding friction of skis over snow, tracked trailers should have lower R/W. However, uniform pressure distribution is much more difficult to achieve with tracks than skis, and the KTT-60 trailer tracks lacked adequate lateral support. Also, the trailers applied a downward force on the fifth-wheel hitch of the Kress tractor and exerted the towing force at a location fairly high above the snow surface. These effects caused significant upward trim angle when towing in the softer snow on the Ross Ice Shelf. Wagon-style tracked trailers, having a horizontal-load-transfer hitch, may perform better.

However, the Kress tractor also performed poorly as a towing tractor of fuel sleds using its low hitch. This result was particularly surprising given that its measured drawbar-pull on the McMurdo Ice Shelf exceeded that of the C95. We do not know the reasons for this poor performance. It is likely that the Kress weight distribution is forward-biased without some downward force at the fifth-wheel hitch. This could cause deeper sinkage and make it more susceptible to traction–slip–resistance feedback compared with the C95.

7 RECOMMENDATIONS

Based on the year-two tests and analysis, we made the following recommendations to improve mobility of the South Pole traverse proof-of-concept fleet for year-three:

If possible, tow four fuel sleds in a 2 × 2 configuration rather than four in line (Fig. 27). The train resistance coefficient should drop from ~0.16 to ~0.09 for four full fuel sleds, assuming that each tank pair acts as two tanks in line (Fig. 10). This will break the traction-slip-resistance feedback and reduce porpoising.

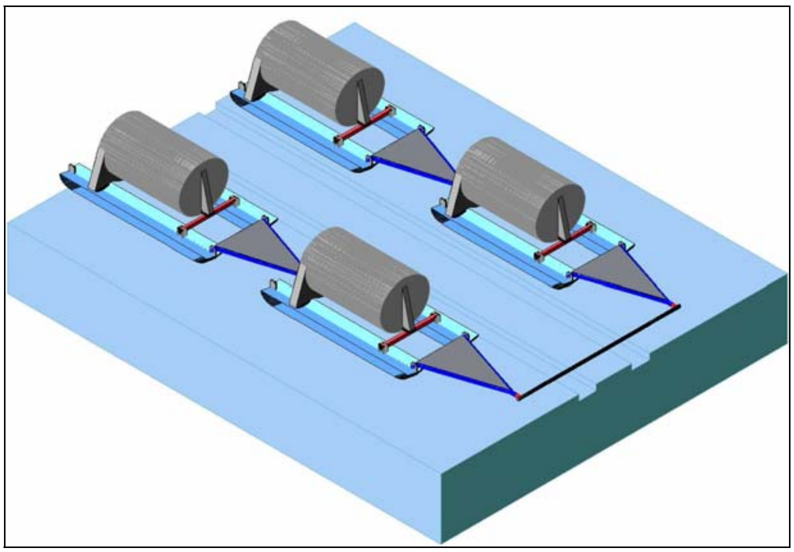


Figure 27. Drawing of fuel sleds towed by a spreader bar in 2 × 2 configuration. The left pair of tanks show the larger skis (0.91 m wide × 6.2 m long) recommended for four sleds for year three.

Provide some margin between expected train resistance and drawbar-pull of the tractor. As a guide, assemble each tractor-train to ensure that tractor drawbar-pull exceeds average plus three standard deviations of train resistance ($DB > R + 3\sigma_R$).

Obtain wider benches for the housing and energy modules and for the ISO sleds to place all skis outside of tractor ruts.

If possible, obtain wider skis for fuel sleds and HM/EM to reduce contact pressures and thus snow-compaction resistance.

Consider modifying the ski noses to reduce porpoising. One possibility is an elliptical nose that is more gently curved than the current quarter-round nose.

Explore the methods, cost, and time required for trail building and compare them with the mobility benefits gained.

Instrument the year-three tractor trains for routine recording of towing forces, sinkage, and porposing motions. Build an automated Rammsonde device for routine measurement of snow-strength profiles along the route. Thoroughly assess the resulting mobility improvements and their linkage to snow strength.

The U.S Antarctic Program adopted these recommendations at a workshop in April 2004 (USAP 2004).

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14. ABSTRACT
The U.S. Antarctic Program is conducting a proof-of-concept traverse to haul heavy cargo 1600 km from McMurdo Station to South Pole Station. During the 2003–04 season (year two), the tractor-trains experienced poor mobility over undisturbed snow on the Ross Ice Shelf. despite relatively low sled ski pressures and encouraging results of pre-departure tests conducted on the McMurdo Ice Shelf. To understand why, we conducted expedient mobility tests, snow-strength measurements, and snow-pit studies along 250-km of route as the traverse returned to McMurdo. The key phenomenon causing train immobility appears to be traction–slip–resistance feedback resulting from the sled skis riding in the ruts made by the towing tractors. We measured much lower towing resistance when the same sleds were towed over undisturbed snow outside of the tractor ruts. Large pitch and roll motions, and consequently large resistance peaks, also occurred when several sleds were towed in series. The role of snow strength was more difficult to assess. Hard sastrugi caused severe motions and sled breakdowns. Decreasing average strength towards the center of the Ross Ice Shelf agreed with qualitatively worsening mobility but quantitative results were inconclusive. Also, increased measured strength on the previously traveled trail was insufficient to account for improved mobility of the returning fleet. The year-two results formed the basis for recommendations to improve fleet mobility for year three: tow fuel sleds in 2 × 2 configurations, rather than four in-line; increase the gauge of the other sleds to place the skis outside of the tractor ruts; increase ski area and alter nose shape for the fuel sleds; and install instrumentation to monitor towing forces, sled sinkage, and snow strength along the entire route. The U.S. Antarctic Program adopted these recommendations.

15. SUBJECT TERMS

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