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McMurdo Snow Roads and Transportation

Final Program Summary

Sally A. Shoop, Wendy L. Wieder, and Terry D. Melendy

August 2022



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Final Program Summary

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Final Report

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Prepared for National Science Foundation, Office of Polar Programs
2415 Eisenhower Avenue
Arlington, VA 22314

Under Engineering for Polar Operations, Logistics, and Research (EPOLAR)
EP-ANT-13-03, "Snow Roads and Transportation Monitoring and Guidance"

Abstract

The snow roads at McMurdo Station, Antarctica, are the primary transportation corridors for moving personnel and material to and from the airfields servicing intra- and intercontinental air traffic. The majority of the road system is made of snow overlying a snow, firn, and icy subsurface and is particularly susceptible to deterioration during the warmest parts of the austral summer when above-freezing temperatures can occur for several days at a time. Poor snow-road conditions can seriously limit payloads for all types of ground vehicles. The US Army Cold Regions Research and Engineering Laboratory (CRREL) studied the McMurdo snow roads for the National Science Foundation Office of Polar Programs as part of the Snow Roads and Transportation (SRT) program. The goals of the SRT program was to improve construction, maintenance, and use of the McMurdo's snow roads, with particular attention on minimizing warm-season deterioration. This is the final report of the SRT program, summarizing the program's activities and findings and emphasizing those parts of the program not previously documented in CRREL Reports, conference papers, or journal articles.

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Preface

This study was conducted for National Science Foundation (NSF), Office of Polar Programs (OPP), US Antarctic Program (USAP), under Engineering for Polar Operations, Logistics, and Research (EPOLAR) EP-ANT-13-03, “Snow Roads and Transportation Monitoring and Guidance.” The technical monitors were Ms. Margaret Knuth and Mr. George Blaisdell, chief program managers, NSF-OPP, USAP.

This report was prepared by the Force Projection and Sustainment Branch of the Research and Engineering Division, US Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Wade Lein was acting branch chief, and Dr. Caitlin A. Callaghan was division chief. Mr. Bryan E. Baker was acting deputy director of ERDC-CRREL, and Dr. Joseph L. Corriveau was the director.

We worked closely with personnel at NSF, Raytheon Polar Service Company (RPSC), and Antarctic Support Contract on all aspects of this project and would specifically like to thank Ms. Margaret Knuth of NSF for her insight, tireless fieldwork, and review. Additional thanks go to Ms. Renee Melendy and Dr. Rosa Affleck of CRREL; Mr. George Blaisdell (CRREL, formerly NSF); Martin Reed, Bill Ames, Kent Colby, and Mr. Gary Cardullo, RPSC managers; Ms. Julia Uberuaga, Mr. Christopher Tomac, Mr. Alan Shaw, Mr. John Hills, Mr. William Sundee, and Mr. Brett Allen, RPSC Fleet Operations ice-shelf crew and Shuttle Transportation crew; and Mr. Russ Alger and Mr. Joel Kunnari of the Keweenaw Research Center. Ms. Amy Burzynski, Ms. Nicole Buck, and Mr. Matthew Bigl of CRREL assisted with the imagery.

Technical review comments were provided by Dr. Rosa Affleck and Dr. Zoe Courville of CRREL. Ms. Emily Moynihan provided excellent editorial and publishing support.

Portions of this report have been modified and reprinted from S. Shoop, J. Hill, and J. Uberuaga, *Maintenance and Drainage Guidance for the Scott Base Transition, Antarctica*, ERDC/CRREL TR-14-25 (Hanover, NH: US

Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory, 2014), <http://hdl.handle.net/11681/5505>.

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Portions of this report have been modified and reprinted from S. A. Shoop, G. Phetteplace, and W. Wieder, *Snow Roads at McMurdo Station, Antarctica*, ERDC/CRREL TR-10-5 (Hanover, NH: US Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory, 2010), <http://hdl.handle.net/11681/5524>.

Portions of this report have been modified and reprinted from T. D. Melendy, *Maintenance Costs of Equipment Owned by the National Science Foundation*, ERDC/CRREL LR-14-6 (Hanover, NH: US Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory, 2014).

Portions of this report have been modified and reprinted from S. Shoop, M. Knuth, and W. Wieder, “Measuring Vehicle Impacts on Snow Roads,” *Journal of Terramechanics* 50, no. 1 (February 2013): 63–71, <https://doi.org/10.1016/j.jterra.2013.01.004>.

This report was revised 29 August 2022 for minor corrections. While it supersedes the previous version, the changes do not impact the reliability of the scholarly content.

COL Teresa A. Schlosser was commander of ERDC, and Dr. David W. Pittman was the director.

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1 Introduction

1.1 Background

The snow roads at McMurdo Station, Antarctica, are the primary transportation corridors for moving personnel and material to and from the airfields servicing intra- and intercontinental air traffic. However, with the majority of the system constructed solely of snow overlaying a snow and ice subsurface, these roads are particularly susceptible to deterioration during the warmest parts of the austral summer when above-freezing temperatures can occur for several days at a time. Poor snow conditions can seriously limit payloads for all types of ground vehicles. The US Army Engineer Research and Development Center's Cold Regions Research and Engineering Laboratory (ERDC-CRREL) studied the construction and maintenance of the snow roads for several years to develop best practices to optimize road construction, maintenance and use.

1.2 Objective

Beginning in 2002, the National Science Foundation (NSF), Office of Polar Programs, US Antarctic Program (USAP), under the Antarctic Infrastructure and Logistic and CRREL agreement, funded the series of studies for the McMurdo Station Snow Roads and Transportation (SRT) program. The SRT program grew to include investigations of multiple aspects of the snow-road system supporting McMurdo Station. As part of that effort, this report aims to compile an account of the work performed under the mantle of the SRT program from 2009 through 2013 and specifically to document portions of the project not reported elsewhere. The information in this report reflects changes that have occurred between 2013 and 2021 where applicable.

1.3 Approach

Conference papers, journal articles, and other CRREL, technical reports have already documented specific projects under the SRT program. This report cites those in the appropriate sections. Further, this report presents previously unpublished work in more detail to complete the documentation of the efforts. Some of these tasks were later explored in subsequent projects while others were purely exploratory, but this report includes them here for completeness. Appendix C presents a full list of publications associated with the SRT program.

2 Primary Research Areas

CRREL worked to understand, document, and improve the snow roads at McMurdo Station under the NSF SRT program for several years between 2002 and 2013. As the program continued to evolve, several primary focus areas emerged. This chapter mentions only briefly those major studies fully documented elsewhere while additional efforts not formally documented in other reports warrant individual chapters: “Road Maintenance Reporting,” “Vehicle Tracking for Snow-Road Use,” “Experiments to Quantify Traffic Impacts on the Snow Roads,” “Road-Load Estimates,” and “Snow-Road Preservation.”

2.1 Historical and recent Antarctic snow-road practices

A review of the literature, significantly US Navy technical documents, provided insight into how the snow-road system at McMurdo Station evolved and some of the standard techniques developed for the maintenance of the system. Shoop, Phetteplace, and Wieder (2010) documented the literature review along with observations during a 2002–2003 deployment to study the road operations. This report provided information used to formulate focus areas for further evaluation of optimizing road maintenance tasking and equipment usage, among other topics.

To facilitate meaningful discussion on road maintenance and practices between the program investigators and the various McMurdo staff members, the SRT team assigned standardized names to Pegasus Road and the intersections of other roads with Pegasus Road. Figure 1 shows the 2012–2013 McMurdo road-system map, the last year of the SRT Program. Appendix A provides the annual maps generated through the course of the SRT work, as well as the 2021 map.

During the SRT program, the portion of Pegasus Road near the Scott Base Transition was specifically constructed with four lanes designated A, B, C, and Track as shown in Figure 2. In 2021, Pegasus Road operated with a single lane except for at the Scott Base Transition, which is more typical of the current, more limited operations. In all cases, however, the Scott Base Transition is heavily used and suffers from warmer temperatures. It therefore has multiple lanes to allow alternate lane use while other lanes are being reworked or allowed to “rest” or harden for future use. A tracked lane

also operates between the Scott Base Transition and the South Pole Traverse staging area (see current and previous road maps in Appendix A).

Mile Post (MP) markers indicate distance in miles along Pegasus Road starting from where the road enters the ice shelf at the Scott Base Transition. The markers are a useful designation both in terms of denoting locations along the road as well as allowing specific sections to be easily referenced.

Figure 1. The 2012–2013 McMurdo road-system map.

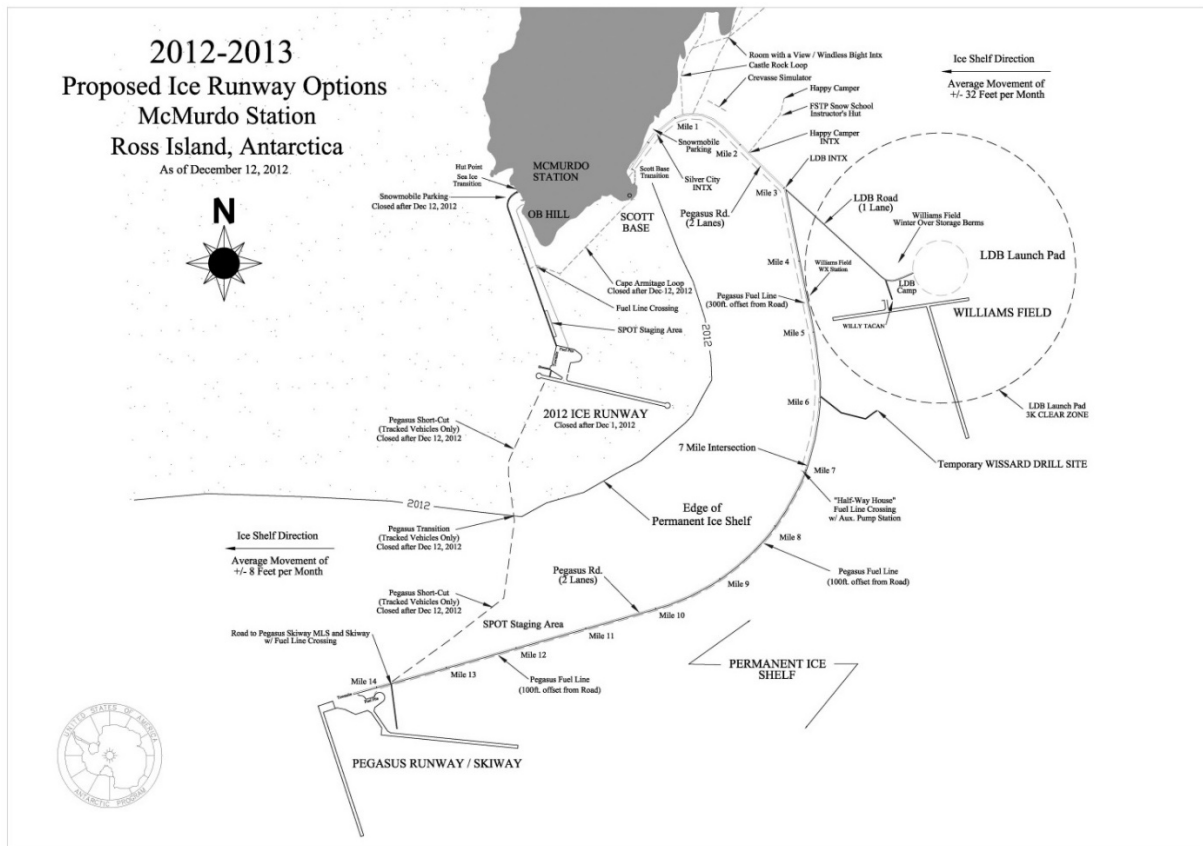
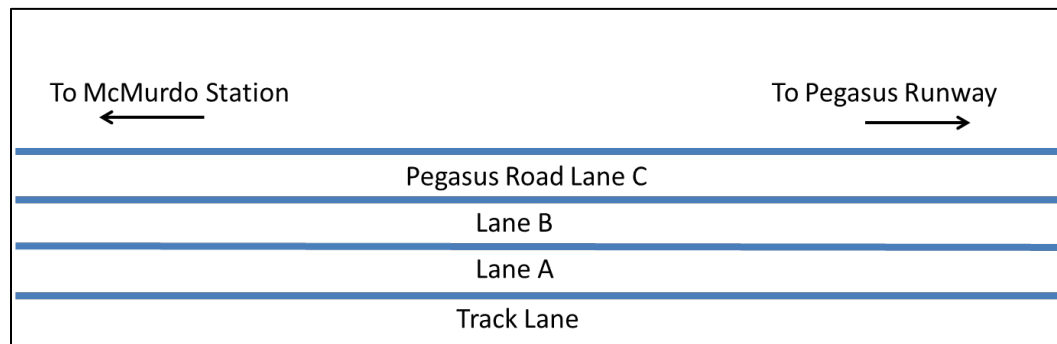


Figure 2. Pegasus Road multilane designations during the Snow Roads and Transportation (SRT) program.



2.2 Vehicle and equipment fleet identification and maintenance

2.2.1 Cargo and passenger vehicles

The vehicle fleet at McMurdo consists of many different vehicles and vehicle types and changes frequently. The SRT program used predominantly six vehicle types, typical of the fleet: Ford F350 trucks (with wheels and Mattracks), Ford E350 vans, Foremost Deltas, a Foremost Terra Bus (“Ivan”), and Challenger tractors (Figure 3 through Figure 7). These vehicles were used in the testing because they spend a good deal of time on the snow roads and because they also represent a wide array of vehicle types and uses. Apart from the tractors, which are used for road construction and maintenance, all other vehicles are used for passenger or cargo transfer to the airfield. The usage of passenger and cargo vehicles was studied in both the vehicle tracking and road-load estimate efforts, discussed in detail in Chapter 4 and Chapter 6, respectively.

Figure 3. Ford F2350 truck with pneumatic tires.



Figure 4. Ford F350 truck with Mattracks.



Figure 5. Ford E350 van.



Figure 6. Foremost Delta II.



Figure 7. Foremost Terra Bus.



2.2.2 Road construction and maintenance vehicles and equipment

The SRT program cataloged the equipment used to construct and maintain snow roads and runways at McMurdo Station during the study. The following paragraphs briefly describe the more heavily used, and in one case experimental, equipment in use from 2003 to 2013. The testing and analysis performed during the SRT program used this vehicle fleet.

The following bullets describe the vehicle fleet of tractors and pieces of tow-behind equipment used to construct and maintain the road system during the SRT program:

- The Caterpillar Challenger 95E (Figure 8, *left*) is a dual-tracked agricultural tractor modified to operate in harsh Antarctic weather conditions. These tractors are designed to pull construction equipment, trailers, and sleds. Prior to introduction of the AGCO MT-865s and Case Quadtracs, these were the backbone of the McMurdo heavy-construction fleet. Since the SRT program, the number of these tractors has decreased from five to two on station.
- The Caterpillar low ground pressure (LGP) “stretch” D8 bulldozer (Figure 8, *right*) was originally designed and used as a traverse vehicle in Greenland. It is a longer, lower-ground-pressure version of the LGP D8s currently used by USAP. The blades are modified for use in deep snow. These stretch D8 tractors were used to haul equipment, personnel, and supplies to the Camp Century construction site approximately 120 miles* east of Thule, Greenland. USAP has 3 LGP stretch D8s operating in McMurdo that were brought to Antarctica from Greenland. During SRT, the Greenland tractors were used to haul the Long Duration Balloon buildings into position at the balloon launch site, and modern Caterpillar LGP D8s were used as needed for snow-road and runway construction. The LGP D8s were gradually replaced by Case Quadtrac agricultural pulling tractors (see photo in Appendix B, Figure B-1) and subsequently AGCO MT-865 tractors.

* For a full list of the spelled-out forms of the units of measure used in this document and their conversions, please refer to *U.S. Government Publishing Office Style Manual*, 31st ed. (Washington, DC: U.S. Government Publishing Office, 2016), 245–252, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

- The Goose is a modified land plane used to remove long-wavelength undulations on snow and ice roads (Figure 9). It is designed to remove snow from the peaks of bumps or ridges and deposit it in the valleys between. The Goose can also be used to scrape snow and move it laterally from one side of a road to the other.
- A drag is used to smooth the surface of the snow roads (Figure 10). The drag is most commonly the final piece of construction equipment used during road construction. It is also used to redistribute snow evenly over the road surface following a snowstorm or wind event.
- The pneumatic tire load cart, also called a light ox cart, is used for deep compaction of snow lifts during layered construction activities (Figure 11). It is also used as a “proof” cart to test the bearing support of roads and skiways prior to opening them for heavy-vehicle and airplane traffic. The load cart was replaced by a bulldozer track compaction technique during some layered snow construction activities (Jason Weale, CRREL, pers. comm., 2009).
- A smooth-tired Delta is used to compact the top wearing surface of snow roads (Figure 12) and for transport of equipment and supplies
- A sheepsfoot roller (Figure 13) weighs approximately 15,000 lb and includes two steel drums with 6 in. tines or feet that can be weighted. The sheepsfoot is used for deep precompacting and reconditioning of the snow in soft snow conditions before using the pneumatic-tire load cart.
- An experimental implement, the SnowPaver, designed by Michigan Tech University, was deployed in November 2010. The SnowPaver was designed to be capable of smoothing, grading, milling, and compacting the snow surface with a single pass of the equipment. It would otherwise take three passes to complete the same tasks. During initial testing, the power available was not sufficient to operate all of the equipment at once, so only plate vibratory compacting the surface and grading were used. An on-board power pack was designed, implemented, and attached to the SnowPaver in 2012 to make it fully functional (Figure 14; Shoop, Alger, et al. 2014). The SnowPaver was returned to Michigan Tech after the SRT program ended.

- Other pieces of equipment, such as the Caterpillar 966G fat-tire loader and 955L LGP track loader, were used on the apron or yard areas near Williams Field. These pieces of equipment are more typically used for airfield support. Only the equipment actively involved in the road construction and maintenance operations during the SRT program were considered here. Further discussion of equipment use is in Chapter 3, “Road Maintenance Reporting.”

Figure 8. Caterpillar Challenger 95E (*left*) and Caterpillar low ground pressure (LGP) “stretch” D8 (*right*).



Figure 9. Goose.



Figure 10. Drag.



Figure 11. The 34,400–67,400 lb capacity pneumatic-tire load cart.



Figure 12. Smooth-tired Canadian Foremost Delta III loaded for compaction.



Figure 13. Sheepsfoot roller.



Figure 14. SnowPaver with power-pack upgrade attached, 2012.



2.2.3 Vehicle maintenance cost analysis

With the aging of the vehicles and equipment in the McMurdo fleet and the harsh conditions under which they operate, maintenance costs and the associated labor time is of significant concern.

Figure 15 plots maintenance data by annualizing the total 3-year cost (2011–2013) of the labor and materials applied to each type of equipment located at McMurdo Station (Melendy 2014). McMurdo data were separated from the South Pole and Palmer Station data because over 95% of the fleet is located in McMurdo.

The total McMurdo annual equipment maintenance cost is \$2.1 million for the time frame studied. Half of this expenditure is for three types of vehicles: bulldozers, pickup trucks, and loaders. Each one of these types of

equipment costs over \$200,000 to maintain annually, with USAP spending approximately \$486,000 annually during the 2011–2013 study period to maintain its fleet of 40 loaders. Melendy (2014) discusses the particular cases of the three most expensive vehicles (loaders, pickup trucks, and bulldozers), as well as snow blowers, which have the highest per-hour rate to maintain of all the McMurdo equipment.

Melendy (2014) studied the maintenance on the five Challenger 95 tractors used to maintain the snow roads and runways on the ice shelf from 2001 through January 2012. Two of the tractors were purchased in 2001 and the other three in 2002. Figure 16 shows the total number of hours these five Challengers were inoperable or “down” for maintenance for each year. The hours “down” vary according to the regular maintenance cycle (i.e., every 3 years, more extensive scheduled maintenance is performed, and “breakdown” maintenance subsequently decreases). The red line provides the linear trend of the data.

During the 11 years studied, the hours that the fleet of five Challengers was “down” for maintenance increased by 312.5 hours per year (Figure 16). As a result, the team expects each season to see an average annual increase in fleet maintenance labor requirements of 90 hours per year, with the potential to increase up to 200 hours per year (Figure 17). This is for only the Challenger tractors and does not include the maintenance of other vehicles and equipment in the fleet.

The average annual cost of parts to keep the Challengers operational is \$10,000. However, a single engine replacement would cost \$40,000, plus the additional cost due to waiting time for any parts that need to be shipped to McMurdo. Figure 18 conveys the total yearly cost to operate the fleet of five Challengers.

Figure 15. Yearly cost to maintain various equipment fleets at McMurdo Station.

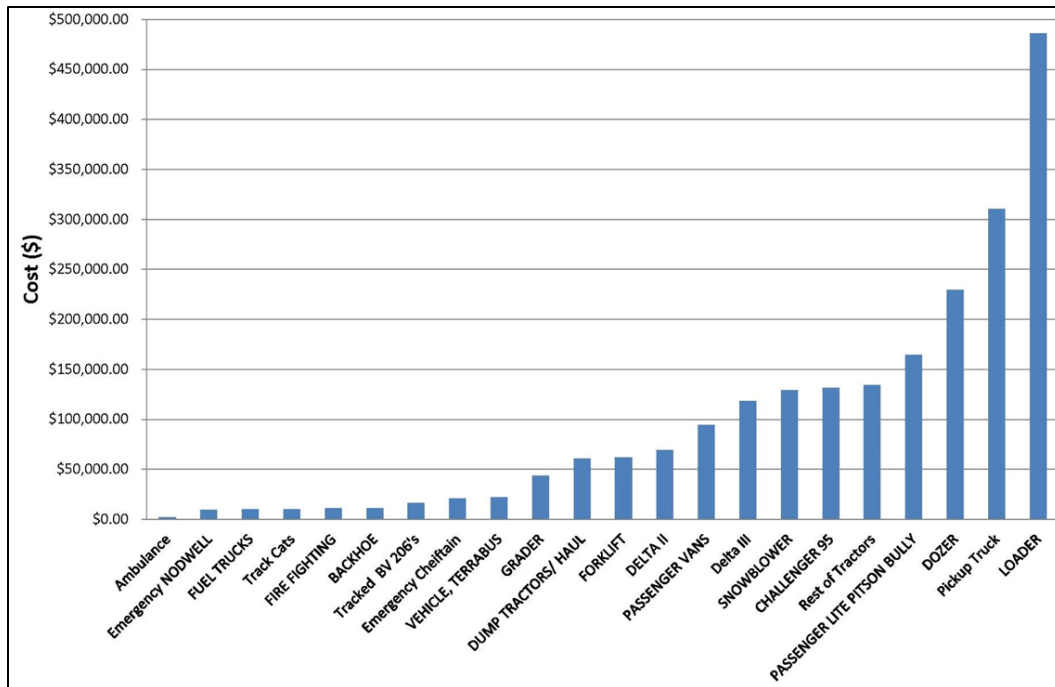


Figure 16. Annual hours of "down" time for the five Challenger 95 tractors.

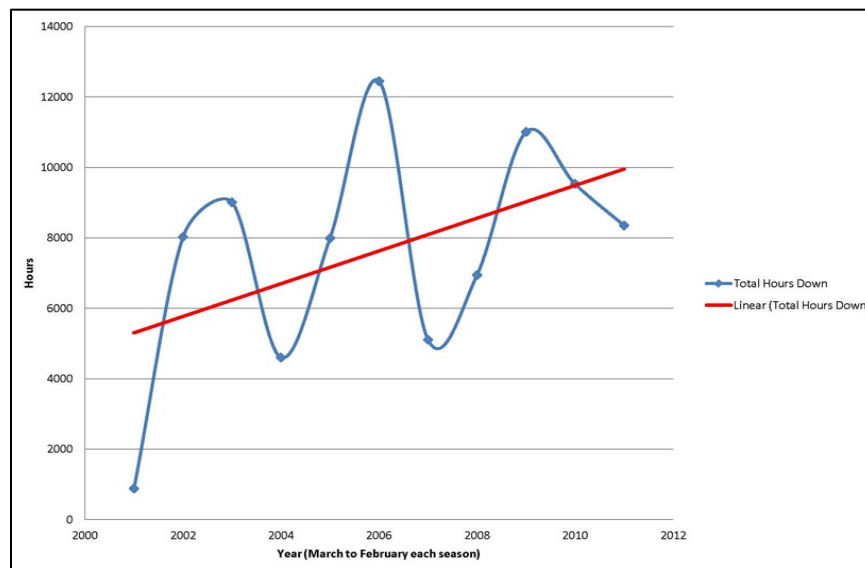


Figure 17. Annual labor hours for Challenger 95 tractor maintenance.

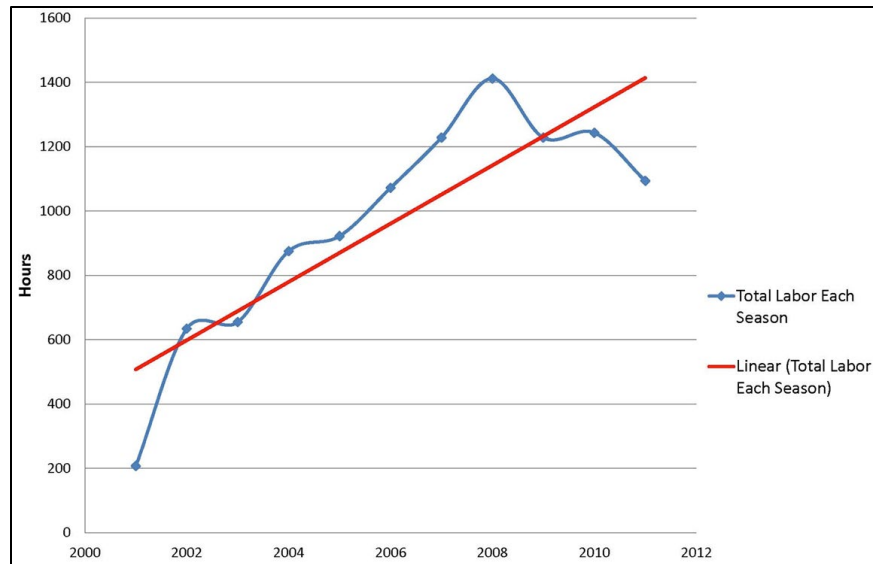
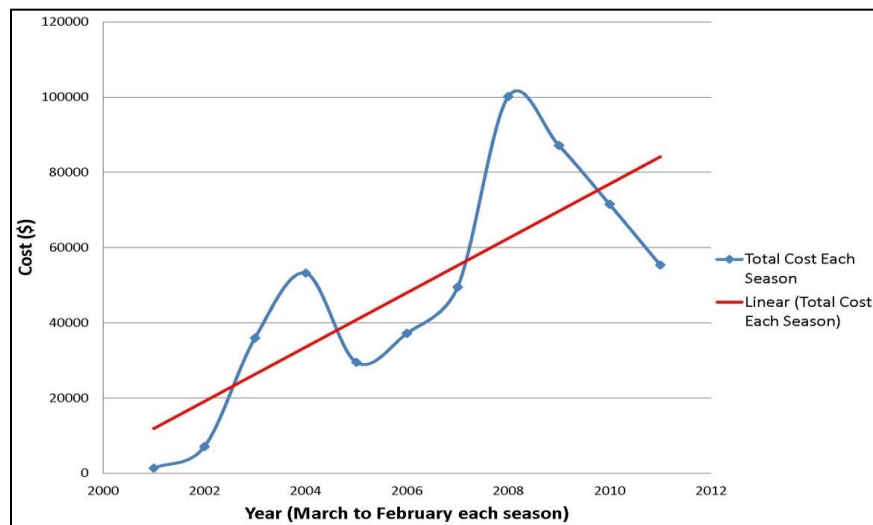


Figure 18. Challenger 95 fleet yearly maintenance cost.



2.2.4 Tires

Improvements and innovations within the tire industry have been significant in the last several decades. The SRT program investigated the benefits of improved tire technology while new tires were being purchased and tested on the McMurdo passenger vans and trucks operating on the snow roads. Tire and vehicle characteristics measured and compared between the new and old tires included snow imprint and rutting at various loadings and tire pressures, vehicle response during straight-line and turning maneuvers, vehicle handling, associated road damage, and footprint area based on vehicle load and tire pressure (Shoop et al. 2014). Thus, tires also

played a role in the vehicle tracking portion of the snow roads work as discussed in Chapter 4.

2.2.5 Current 2021 equipment

Changes to the snow-road construction and maintenance equipment were at least partially influenced by the results of these studies and are documented in the 2021 equipment list presented in Table 1. The table identifies the piece of equipment, its purpose, and the frequency of use.

Appendix B provides photos of the equipment currently used, several of which were either new or not included in SRT-specific studies.

Table 1. Equipment used in 2021 at McMurdo Station for snow-road and runway maintenance and construction (Jessica Palen, USAP contractor, pers. comm., September 2021).

Name	Type	Quantity	Frequency of Use	Purpose
Caterpillar Challenger	95E	2	Daily	Tow implements, assist in recovery, and transport
Case Quadtrac	STX530 and STX535	1 and 3	Daily	Tow implements, assist in recovery, and transport
Delta (smooth tire)	Foremost type III	1	Occasionally	Wheel-pack snow roads, transport cargo and water
Land planes	Art's Way, Eversman, Goose, and drag	1 each but 2 Gooses	Often	Clear drifts, smooth road undulations
Caterpillar dozer	D6D and D6H	2 and 1	Rarely	Transport, recovery, and clear drifts
Caterpillar heavy dozers	D7E and D8R	2 each	Rarely	Transport, recovery, and clear drifts
Land scrapers	Conway, Reynolds, and Bronco	1 each	Occasionally	Clear drifts, smooth road undulations
Sheepsfoot compactors	15,800 lb; 2,400 lb; and 14,200 lb	1 each	Occasionally	Compact surfaces and remove air pockets
Ox cart compactors	34,400 lb and 43,200 lb (minimum capacity)	1 each	Occasionally	Compact surfaces
Drags	Serrated and smooth	>5	Daily	Smooth surfaces
Kress trucks	730	2	Rarely	Compact roads (must be driven slowly)

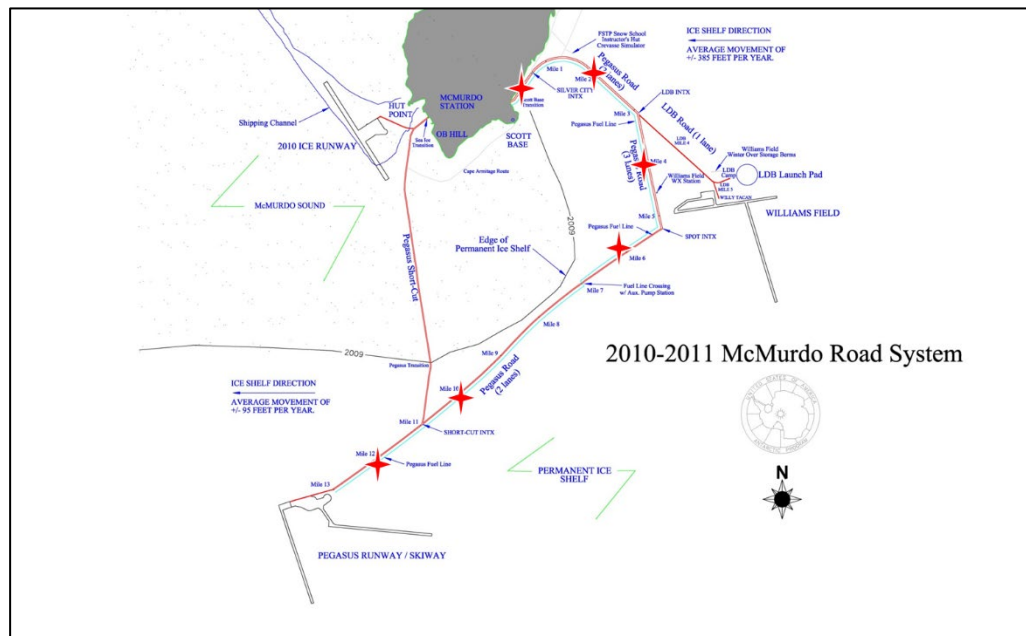
2.3 Snow-road-condition monitoring

Monitoring of the Pegasus Road began in fiscal year (FY) 2010 to collect data on the temperature and strength parameters of the road system under various weather, maintenance, and vehicle-use conditions. Table 2 lists the types, locations, and frequency of the data collected. Figure 19 shows the locations of the monitoring on the road system.

Table 2. Road-condition-monitoring variables and locations.

Data Collected
• Temperatures • Strength • Road condition
Monitoring Locations and Times
• Pegasus Road at MP 0.5, 2, 4, 6, 10, and 12 • Lane A and the Track lane • 2 to 3 times per week

Figure 19. Map of McMurdo Station road and airfield test-site locations for the 2010–2011 season.



2.3.1 Temperature profiles

At each monitoring location, a CRREL-manufactured probe measured both the air temperature and the snow temperature at specific depths. A total of four measurements were taken at each location: (1) in the air at

3 in. above the snow, (2) at the snow surface, (3) at 3 in. below the surface, and (4) at 6 in. below the surface. Typically, the air temperature was highest, and temperatures below the surface at 3 and 6 in. depths were lower since measurements were made during the warming part of the day (morning). At all of the monitoring locations, temperatures rose from October to December, leveled off during January, and started to drop in late January. Figure 20 shows an example.

Snow-road temperatures were also measured using an infrared probe mounted to a vehicle, as shown in Figure 21. This instrumentation measures the road surface temperature only but gives more of a snapshot in time along the road. Figure 22 shows the temperatures on 12 January 2012 clearly above freezing at the Scott Base Transition plus along the cliff edge and out through the transition zone to approximately 1 mile, while the rest of the snow road is at below-freezing temperatures.

Figure 20. Pegasus Road at Mile Post (MP) 0.5 temperatures for air, snow surface, and 3 and 6 in. depths, October 2011 through February 2012.

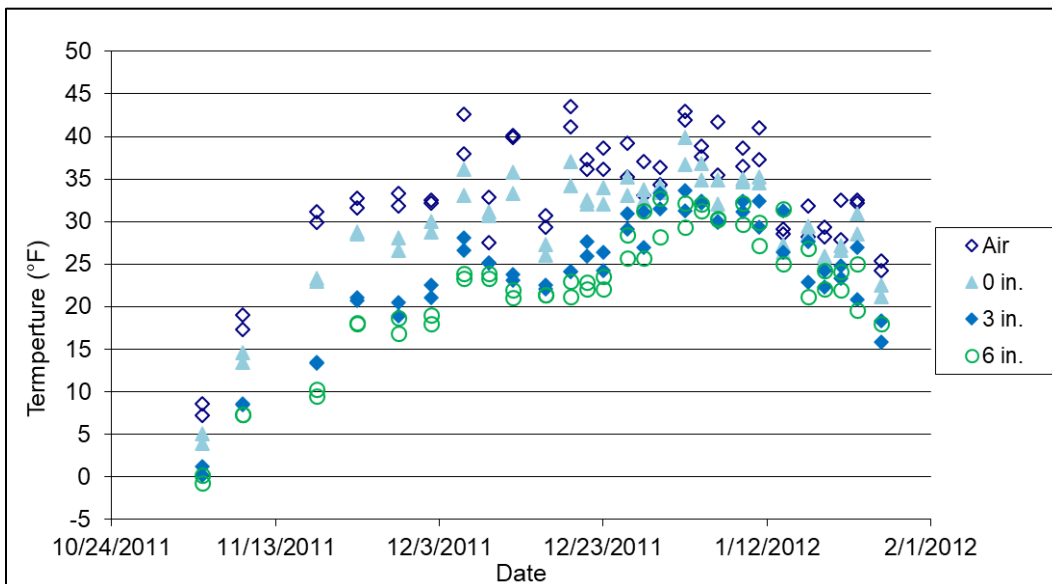
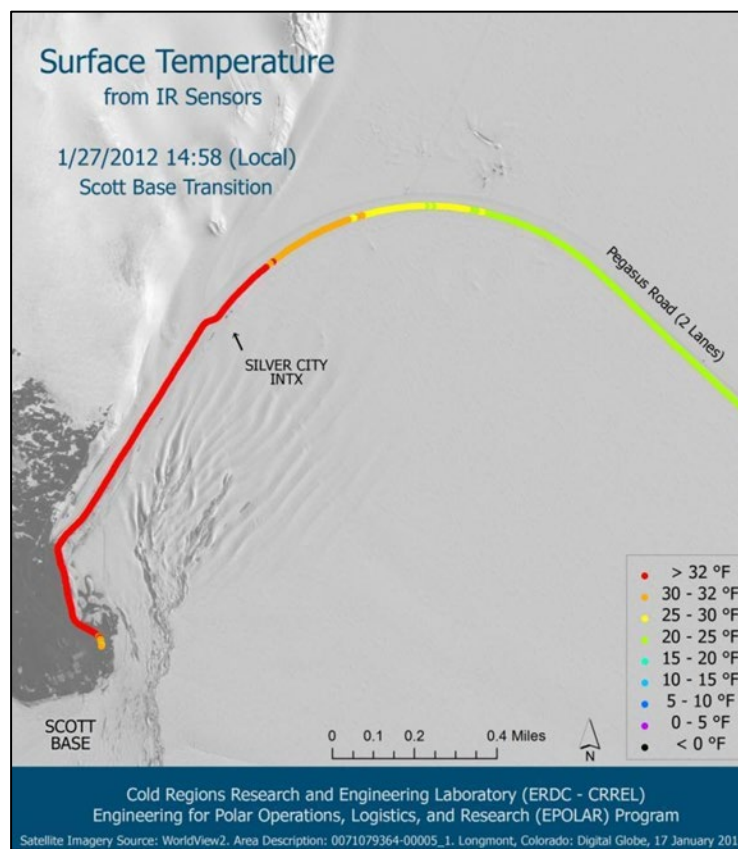


Figure 21. Temperature measurements using a thermocouple probe at each monitoring location along the roads (*left*) and an infrared sensor mounted on a vehicle and driven along the snow roads (*right*).



Figure 22. Road surface temperatures taken with an infrared probe.

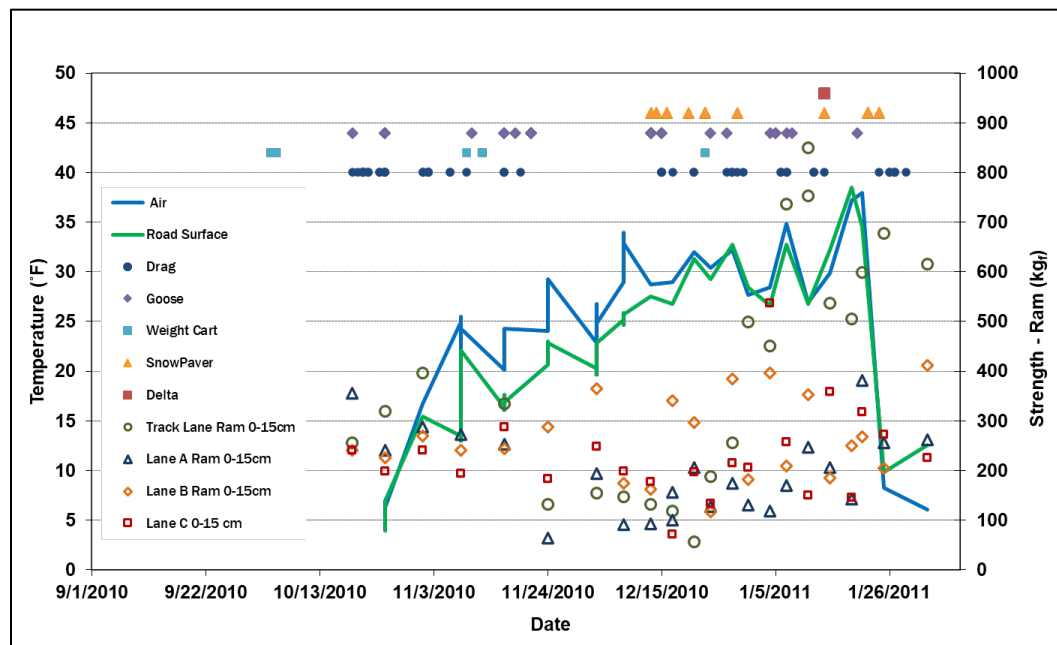


2.3.2 Strength

Historically, snow strength at McMurdo was measured using a Rammsonde snow penetrometer, which measures the resistance to penetration as the instrument is pounded deeper into the snow.

Figure 23 shows an example of the Rammsonde data for the surface layer taken at MP 0.5 near the Scott Base Transition for the 2010–2011 season. This figure also plots air and snow surface temperatures, as well as the individual maintenance events that occurred. In general, the road strength decreases as temperatures warm and increases as the temperatures drop. However, the Track lane consistently has higher strengths throughout the season (discussed in the following pages). Melendy and Shoop (2017) includes the full data set and details the relationship to maintenance and weather events.

Figure 23. Example of seasonal trends in Rammsonde snow-road strength at Pegasus Road at MP 0.5 (*hollow symbols*) along with temperature (*solid lines*) and individual maintenance events using the drag, Goose, weight cart, SnowPaver, and Delta (*solid symbols at top of graph*).



While the strength of the entire snow profile is important, it is primarily the top layer (approximately 12 in.) that changes from day to day with different maintenance practices and road use. The Rammsonde provides a good measure of the strength profile with depth but does not characterize the near surface well. The Clegg Impact Hammer is an instrument developed to

assess the bearing capacity of soils, as measured at the surface, and is now used for snow-road assessment. The Clegg provides a quick and easy method to measure the surface condition of the snow roads and quantify the effectiveness of maintenance procedures and impacts of vehicle traffic.

The Clegg Impact Hammer provides a strength index in response to a mass free-falling from a specific height, displaying the deceleration upon impact. During the austral summer of 2009–2010, Shoop, Knuth, and Crandell (2012) assessed the Clegg Hammer’s usefulness and best practice for using it on the snow, using Clegg Hammers in three different masses on the snow roads at McMurdo Station. That study performed tests on a uniform snow surface and on the operational snow road for comparison. Because snow is more compressible than soils, they analyzed several methods to analyze the Clegg data, including averaging the impact values for several drops versus the use of a single representative drop value. Figure 24 provides an example of the Clegg Hammer measurements for the 2011–2012 austral summer along with the air and snow surface temperatures and major snowfall and windstorm events, as those directly impact the snow-road surface.

Both the Rammsonde and the Clegg strength data show the changes in snow strength generally decreasing with higher temperature (especially at near- or above-freezing temperatures) and increasing as the temperatures drop, even though these trends are also affected by maintenance and weather events (Melendy and Shoop 2017). Both strength measurements also show the Track lane generally has a higher surface strength. Presumably this is because of the more dispersed surface loading of the wide-tired Deltas, tracked vehicles, and sleds, which use the Track lane during the warmer months. The compacted and sometimes icy layer in the Track lane did not occur at depth, however, so could fail if the snow below this strong layer is weak.

Finally, the team also evaluated an equation used to convert Clegg measurements into California Bearing Ratio (CBR), a common pavement-strength measurement:

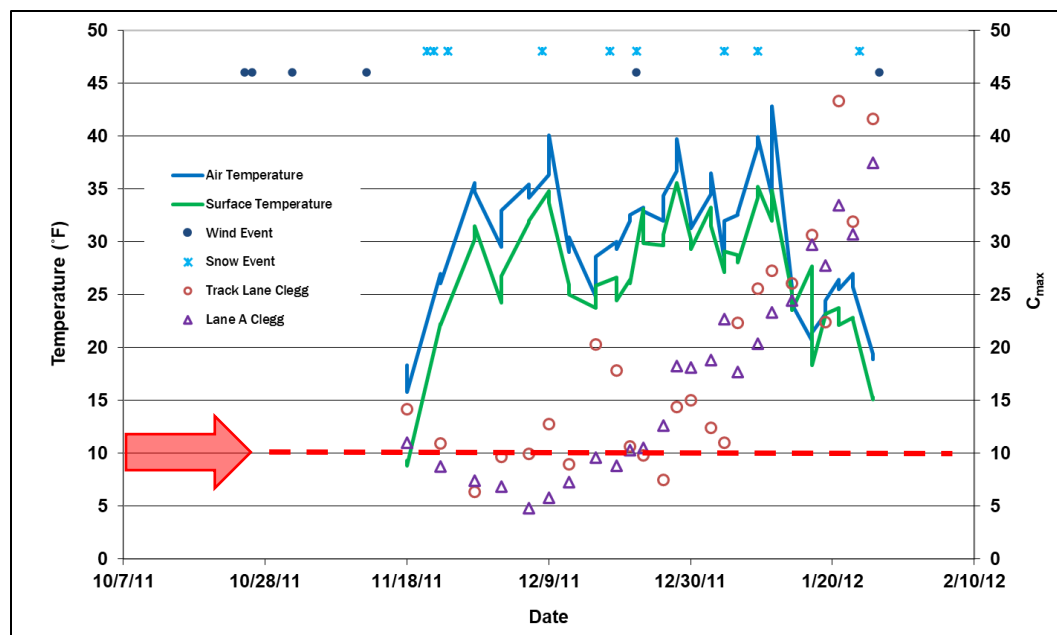
$$\text{CBR} = e^{[(10x - 14.936)/79.523]}, \quad (1)$$

where x is the peak deceleration in $C_{\max}$ (Clegg units) for the third drop of the medium Clegg Hammer (5 lb [2.25 kg]) from a height of 1.5 ft. The

equation was developed for clay soils (MVMBNI JV 2016) but showed good correlation for snow strength, resulting in an r^2 value of 0.932 (Shoop, Knuth, and Crandell 2012).

Observing experiential data for Clegg road strength versus when vehicles become stuck on McMurdo snow roads, the team determined that a threshold value of approximately a $C_{\max}$ of 10 yields sufficient snow-road strength for vehicle operations. Using Equation (1), a $C_{\max}$ of 10 is equivalent to a CBR value of 3. A CBR value of 3, though very low for a gravel road, is sufficient for specialized low-tire-pressure vehicles driving at low speeds (less than 25 mph) and will support the careful operations of the McMurdo shuttle and cargo hauling to and from the airfields. Figure 24 shows this operation threshold against the Pegasus Road strength and temperature data from the 2001–2012 season.

Figure 24. Example of Clegg snow strength on Pegasus Road at MP 10 (*hollow symbols*) along with temperature (*solid lines*) and weather events (*solid circles* and *crosses*). The value of CBR = 3 ($C_{\max} = 10$) indicates the threshold of sufficient road strength shown by the *red dashed line*.



2.3.3 Visual road-condition monitoring

The SRT program developed a quick and easy methodology to document the state of the roads for planning and scheduling road repair and maintenance by using a system similar to that used for rating the condition of unsurfaced roads (Eaton, Gerard, and Cate 1987). The technique is to visually assess the different types of distresses on the roads and to color code the

need for repairs based on the severity of the distress: red needs immediate attention, yellow indicates to watch the area and repair when convenient, and green indicates no repair is needed.

The distresses identified for categorizing surface conditions of specific importance to snow roads were rutting, potholes, drifting, melt pockets, dirt on roadway, albedo, washboarding, and rooster tails (caused by spinning tires piling up snow behind the tires, which later refreezes into a mound). These were later reduced to just the major distress types and each assigned limits for levels severity based on the need for maintenance. Table 3 shows the major distress severity levels and also the color bar used to assess the snow brightness (related to albedo) on a scale of 1 to 10.

Table 3. The severity levels for the major snow-road distresses (*top*), and the gray-scale color bar used to assess the snow brightness (related to albedo) on a scale of 1 to 10 (*bottom*).

Severity Rating	Whiteness Value Using Color Bar below	Rutting Depth (in.)	% of Lane Impassible	Snow Depth—Drifting or Fresh (in.)	Pothole Depth (ft)
Green = Good	0–2	0–2	0–24	0–2	0–1
Amber = Caution	3–5	0–10	25–49	3–5	2–3
Red = Needs Attention	6–10	10+	>50	6+	3+



Based on the severity of the disturbance, each distress type is given a rating, and then the information is color coded (as shown in Table 4) to inform maintenance decisions. Green-shaded areas indicate good snow-road conditions. Yellow areas indicate snow-road conditions are beginning to deteriorate and that the area should be watched for worsening conditions. Red shading indicates the distress is at a level requiring road maintenance. The threshold levels for these ratings are based on knowledge of the distress levels when passenger transport vehicles are likely to get stuck. The conditions can also be mapped with time and location for specific road condition issues as shown in Table 5 for rutting.

Table 4. Guidelines for maintenance action based on visual distress identification. Green = Good. Yellow = Caution advised, track this area for future maintenance needs. Red = Immediate maintenance required.

Location	MP12	MP10	MP6	MP4	MP2	MP0.5
Date	1/15/2011	1/15/2011	1/15/2011	1/15/2011	1/15/2011	1/15/2011
Open Lane	Track	Track	B	B	B	B
Surface color (0 = white, 10 = black)	3	1	0	0	0	0
Rutting (<2 in., <6 in., 6–10 in., or >10 in.)						
Dirt on Road or Dirt Craters (diameter or size)						
Snow Drifting (max depth)	None	0–4 cm	7–22 cm			
Fresh Snowfall (depth)	None			3–10 cm	8 cm	8 cm
Soft Spots						
Potholes (<3 ft) or Blowouts (>4 ft)						
Tiger Traps				One near MP 3.5		
Melt Pockets, Lensing or Greenhouse Effect under Smooth, Shiny Snow in Warm Temperatures (<1 ft, >2 ft)						
Washboarding or Corrugation (linear feet, wavelength, amplitude)			Occasional dips in Track lane			
Balls/Chunks on Surface (max diameter)						
Notes					Delta was tire packing lane B	

Table 5. Example of tracking maintenance needs “at a glance” using rut depth observations (in inches) by Mile Post and observation date.

Date	MP 12	MP 10	MP 6	MP 4	MP 2	MP 0.5
Saturday, November 12, 2011	1	4	1	0	0	0
Wednesday, November 16, 2011	3	3	2	0	0	0
Wednesday, November 23, 2011	3	3	1	1	0	0
Monday, November 28, 2011	0	0	0	1	0	0
Friday, December 2, 2011	0	2	1	3	2	0
Tuesday, December 6, 2011	4	6	2	2	0	4
Wednesday, December 7, 2011	10	8	6	4	0	4
Friday, December 9, 2011	1	4	3	0	0	5
Tuesday, December 13, 2011	2	4	2	0	0	0
Tuesday, December 20, 2011	0	0	2	0	0	0
Wednesday, December 21, 2011	2	1	4	3	2	4
Friday, December 23, 2011	2	3	1	0.5	0.5	2
Monday, December 26, 2011	0	4	0	0	0	2
Wednesday, December 28, 2011	0	0	0	1	0	2
Friday, December 30, 2011	2	2	4	4	3	0
Monday, January 2, 2012	0.5	0.5	0.5	0.5	0.5	2
Friday, January 6, 2012	0	0	0	0	0	2
Monday, January 9, 2012	0	0	2	0	0	0
Wednesday, January 11, 2012	1	1	0	0	0	0
Saturday, January 14, 2012	2	2	1	3	4	2
Tuesday, January 17, 2012	2	2	2	0	0	2
Friday, January 20, 2012	0	1	4	1	1	0
Thursday, January 26, 2012	0	0	0	0	0	0

2.4 Vehicle impact testing

During the austral summer of 2009–2010, Shoop, Knuth et al. (2014) conducted a study to determine the impact of various vehicle and tire types on the condition of the McMurdo snow roads. Appendix C summarizes this study, which was extensive enough to warrant a separate ERDC-CRREL technical report.

2.5 Equipment deployment

In 2010, a promising new piece of equipment developed by the Keweenaw Research Center of Michigan Technological University was shipped to McMurdo Station. The SnowPaver (Figure 14) was intended to perform multiple functions required for snow-road construction and maintenance

with a single piece of equipment (Shoop, Alger, et al. 2014). Appendix C summarizes the results of several seasons of work with this equipment.

3 Road Maintenance Reporting

3.1 Data entry and spreadsheets

For any road management system, it is important to know what maintenance activities are happening and their impact on the road condition to decide how to best use the maintenance budget. Therefore, the SRT team standardized across the road maintenance staff recording the maintenance activities on the McMurdo snow-road system. This gave management a tool to help with maintenance decisions, to develop something similar to a pavement management system, and to determine the most effective maintenance routine.

Starting in FY 2010 a computerized maintenance form was instituted to document snow-road maintenance activities. The intent was a single sheet that would be quick and easy for a vehicle operator to fill in and submit. In the beginning, crew members filled out paper copies of the sheet that were then entered into the computerized version of the form. By 2013, the spreadsheet entry system had evolved to automatically update a master spreadsheet and was subsequently maintained by Antarctic Support Contract (ASC) personnel. Figure 25 show the resulting maintenance-activity data-entry form and the maintenance records collated into a spreadsheet to track the type and location of road and airfield maintenance.

Figure 25. Maintenance data spreadsheet.

	A	B	C	D	E	F	G	H	I	J	K
1	Name	Date	Shift	Purpose	Primary Vehicle	Towed	Added Weight	Road Name	Lanes	Start	Stop
717	Fairchild	1/23/2011	Night	General Maintenance	Challenger	Drag		Pegasus Road	A		
718	Fairchild	1/23/2011	Night	General Maintenance	Challenger	Drag		Pegasus Skiway	A		
719	Lorenson	1/22/2011	Night	General Maintenance	Challenger	PEG Weight Cart (144,000#)	144000	White Ice Runway	A		
720	Fogg	1/21/2011	Day	General Maintenance	Challenger	PEG Weight Cart (144,000#)	144000	White Ice Runway			
721	Fogg	1/21/2011	Day	General Maintenance	Challenger	PEG Weight Cart (144,000#)	144000	White Ice Runway			
722	Fairchild	1/21/2011	Night	General Maintenance	Challenger	Drag		Fuel pits, taxiway A (diagonally)			
723	Wenger	1/21/2011	Night	General Maintenance	Challenger	Drag		Ramp 1 and 3			
724	Fairchild	1/21/2011	Night	General Maintenance	Challenger	Drag		Pegasus Road	Track		
725	Wenger	1/20/2011	Night	General Maintenance	Challenger	PEG Weight Cart (144,000#)	144000	White Ice Runway			
726	Fairchild	1/20/2011	Night	General Maintenance	Challenger	Drag		PEG Town-site			
727	Fairchild	1/20/2011	Night	General Maintenance	Challenger	Drag		Pegasus Road	Track		
728	Fairchild	1/20/2011	Night	General Maintenance	Challenger	Drag		Pegasus Road	B		
729	Stev Wenger	2/1/2011	Night	General Maintenance	Challenger	Drag		Pegasus Skiway			
730	Jim Fairchild	2/1/2011	Night	General Maintenance	Challenger	Drag					
731	Jim Fairchild	1/31/2011	Night	General Maintenance	Challenger	Drag		PEG Town-site			
732	Jim Fairchild	1/30/2011	Night	General Maintenance	Challenger	Drag		PEG Town-site			
733	Jim Fairchild	1/30/2011	Night	General Maintenance	Challenger	Drag		Pegasus Skiway			
734	Jeff Fogg	2/1/2011	Day	General Maintenance	Challenger	Drag		Pegasus Skiway			
735	Jeff Fogg	1/29/2011	Day	General Maintenance	Challenger	Drag		White Ice Runway			
736	Carney	2/1/2011	Day	General Maintenance	Challenger	Drag		Pegasus Road	B	SBT/MP 0	Silver City Intersection
737	Carney	2/1/2011	Day	General Maintenance	Challenger	Drag		Pegasus Road	B	LDB Intersection	SPoT Intersection
738	Carney	1/29/2011	Day	General Maintenance	Challenger	Drag		Pegasus Road	Track	LDB Intersection	SBT/MP 0
739	Carney	1/29/2011	Day	General Maintenance	Challenger	Drag		LDB Road	Track	LDB Town	LDB Intersection
740	Carney	1/31/2011	Day	General Maintenance	Challenger	Drag		Willy Field			
741	Jeff Fogg	2/2/2011	Day	General Maintenance	Challenger	Drag		Pegasus Road			

3.2 Use of maintenance tracking results

CRREL analyzed the data from the maintenance-activity reporting program for FY 2011 through FY 2013. Figure 26 is a bar chart showing the number of road maintenance events performed by each type of equipment during the 2012–2013 season. The road section maintained is indicated by MP location. This figure shows that many pieces of equipment, such as the drag and the SnowPaver, were used on all sections of the road. But some pieces, like the Goose and dozer, were used farther out on the road, closer to Pegasus Field, while others were used closer to Scott Base (the Delta and Kress) for this particular year. However, specific pieces of equipment used and the type of maintenance needed can change from year to year, as discussed below. Figure 27 further explores the maintenance events by looking at the maintenance for each lane of the snow road. While Lane A clearly gets the most maintenance, this chart also shows the maintenance needed for Lane B past MP 4 (out to MP 12) and the additional maintenance needed for the multilane systems near the Scott Base Transition (MP 0.5). Furthermore, the chart shows the additional Track lane maintenance needed at MP 2, presumably because the reduced number of wheeled-vehicle lanes available caused additional wear by wheeled vehicles using the Track lane. Note that MP 2 lies within the warmer and most heavily used part of the road system, which includes traffic for the Snow School and Williams Field in addition to the Pegasus Airfield traffic.

Figure 28 shows the number of maintenance events by year and lane for the three austral summer seasons studied. This is further broken down into the type of maintenance equipment used and the MP covered, showing MP 2 and MP 10 in Figure 29. Again, while some pieces of equipment are used more on one section of the road than another, this changes significantly by year, depending on weather events, snow conditions, road use needs, and equipment available. Like Figure 27, Figure 28 shows more maintenance in austral summer FY13 in general.

Figure 30 further parses equipment use per month for each year, thus illustrating the power of collecting this data for tracking what equipment is being used where and to what effect. Two important examples of this track the compaction events for the 2013 season (Figure 31), showing the compaction sequence from sheepsfoot roller to lightweight compaction cart to the heavyweight compaction cart for September through November and then the SnowPaver and high molecular weight (HMW) plastic sheet sleds for the warm season compactions during December and January. Con-

versely, Figure 32 shows the winter season maintenance using the drag and Goose, which peaks during the austral winter in June.

Figure 26. Maintenance event tracking for equipment use at specific MP marker locations on Pegasus Road (October 2012 through February 2013).

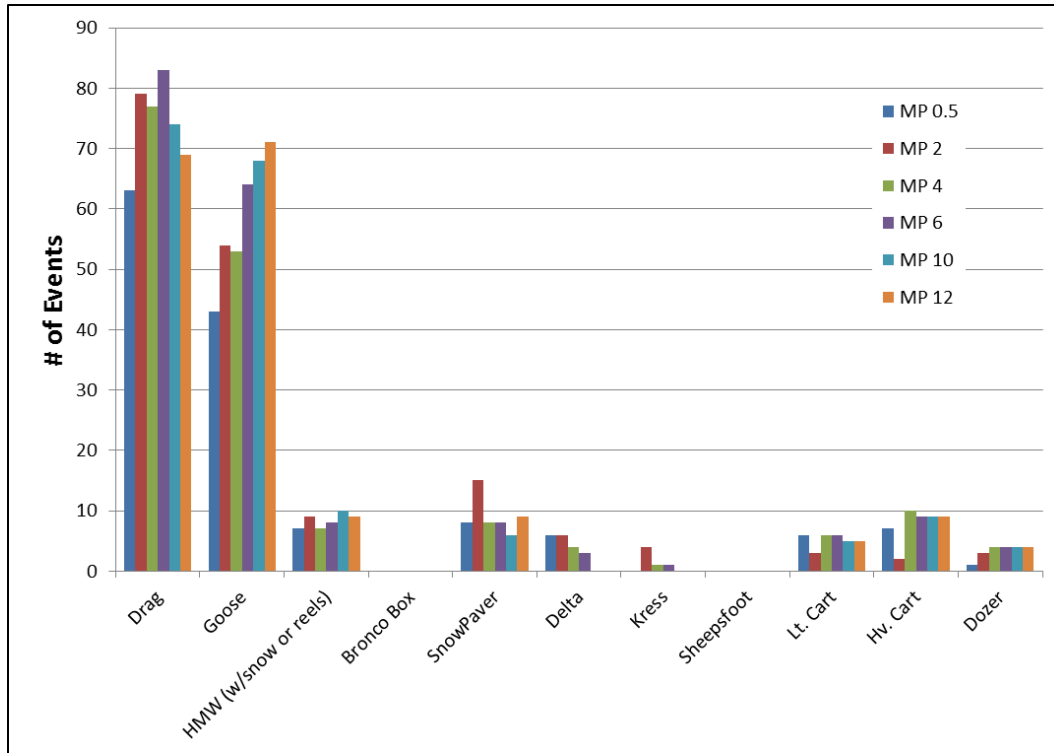


Figure 27. Fiscal Year 2013 austral summer seasonal maintenance events by MP and lane (Pegasus Road).

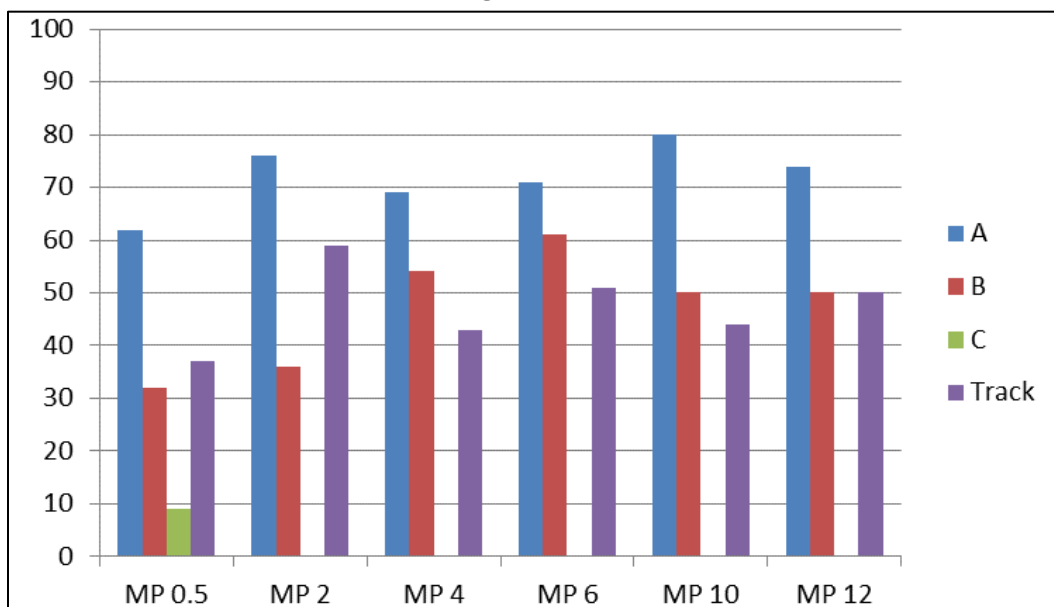


Figure 28. Comparison of maintenance events by lane along Pegasus Road for the three austral summer seasons studied.

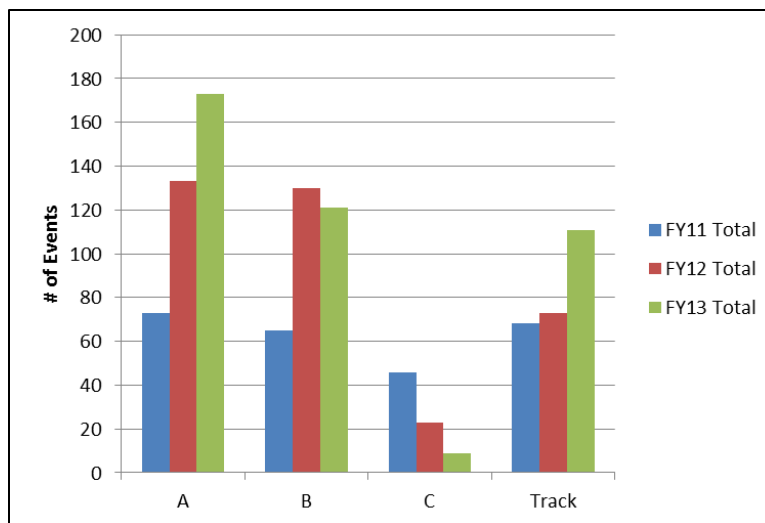


Figure 29. Comparison of maintenance equipment used at MP2 (*top*) and MP 10 (*bottom*) for the three austral summer seasons studied

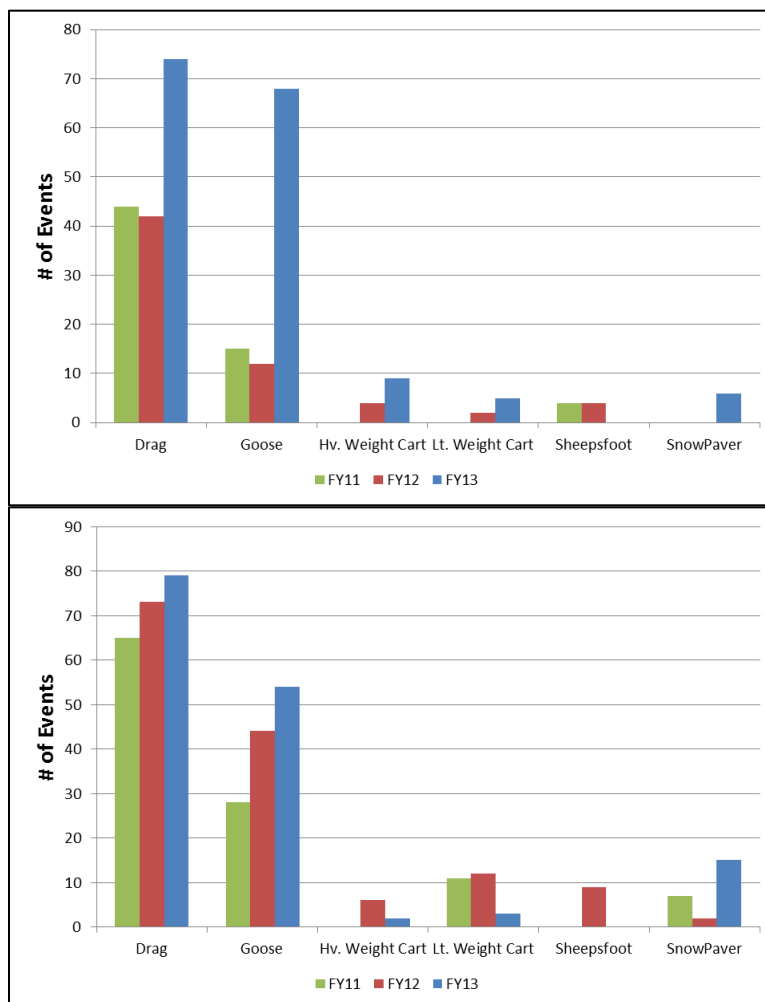
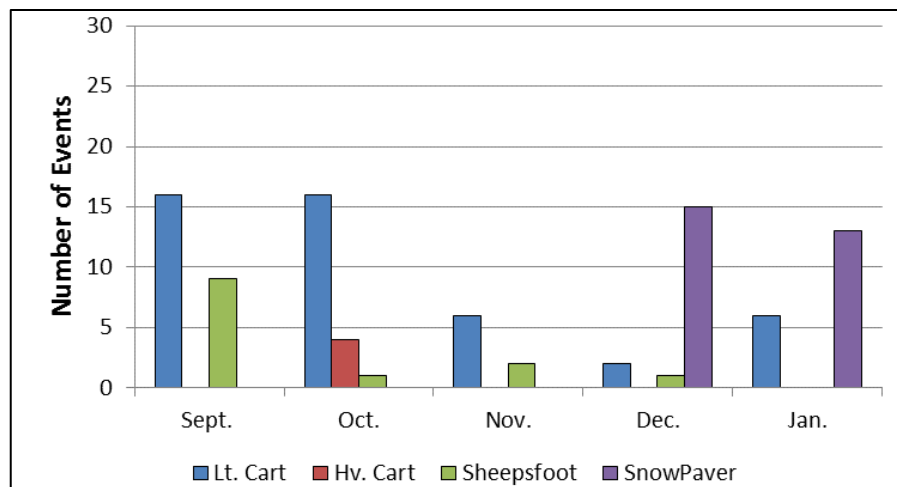
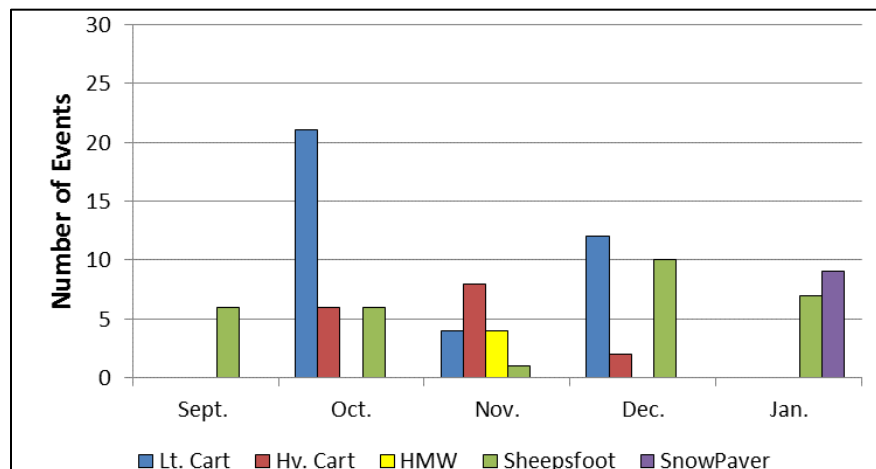


Figure 30. Number of compaction events by equipment type and month for each of the three austral summer seasons monitored.

FY 2011



FY 2012



FY 2013

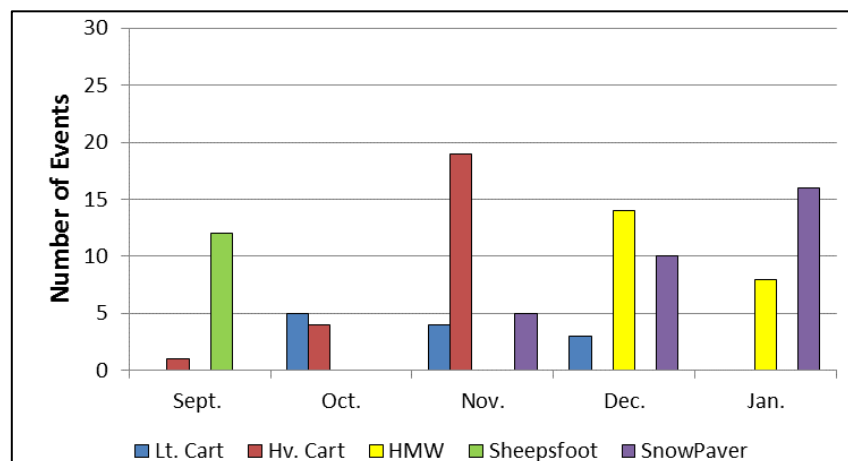


Figure 31. Compaction events on Pegasus Road during austral summer season 2012–2013.

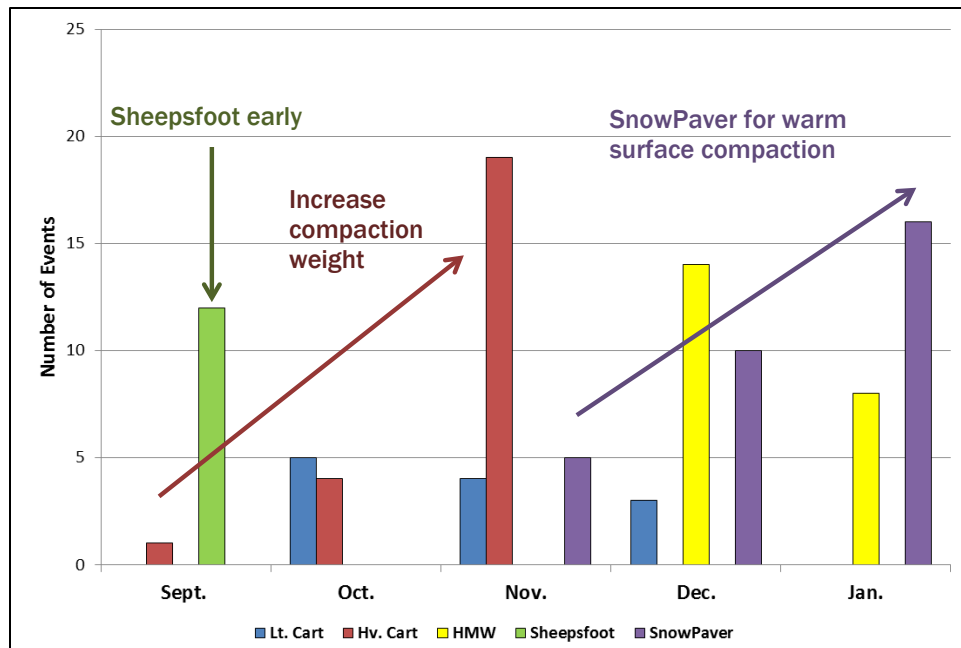
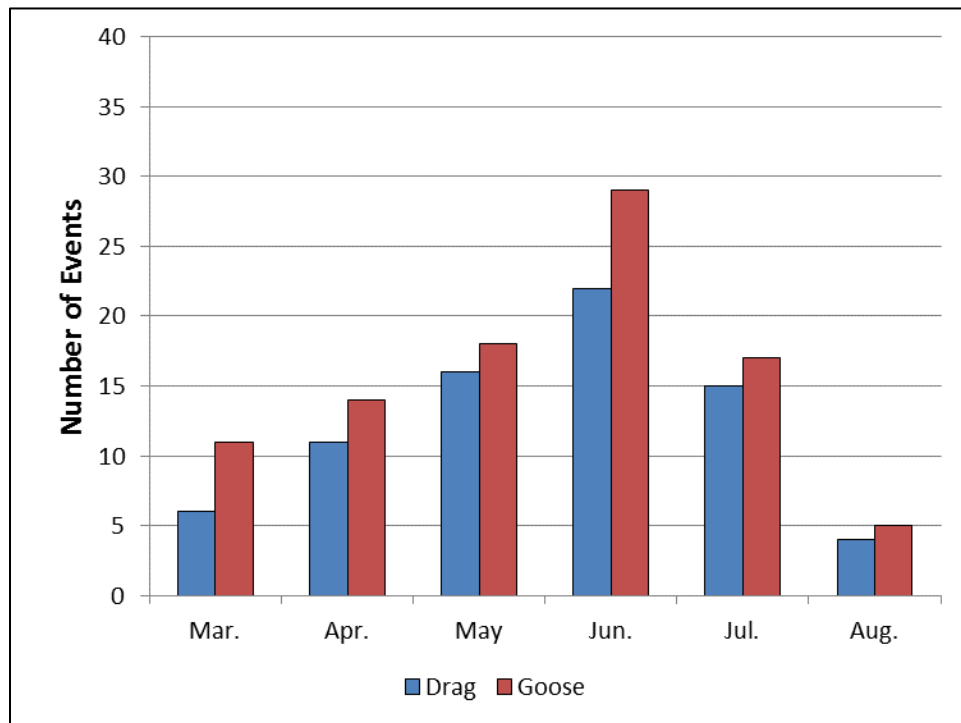


Figure 32. Calendar year 2012 austral winter season drag and Goose maintenance events by month.



4 Vehicle Tracking for Snow-Road Use

To optimize road construction and maintenance, it is necessary know what type of traffic the roads need to support. Similarly, it is also important to understand how the vehicle operations impact road conditions. Thus, from October 2009 through January 2010, CRREL monitored select passenger and cargo transportation vehicles to assess how the snow roads were being used by different vehicles and departments. Vehicle tracking was determined to be a simple yet powerful tool to provide information on vehicle use over a range of time and in a variety of vehicles.

4.1 Data collection equipment

After an extensive industry search, the CRREL team chose Super Tracksticks for their size, ease of use, and low cost. These GPS receiving devices measure $4.5 \times 1.25 \times 0.75$ in., require two AAA batteries for power, have 4 MB memory, and are easily downloadable via a USB 2.0 connection (Figure 33). The team expected from the product literature that the lithium batteries would provide 1–2 weeks of battery life (6–8 weeks using the “power save” mode) at the low temperatures anticipated; however, even in “power save” mode, the batteries lasted only 2–3 days, making this effort more labor intensive than anticipated.

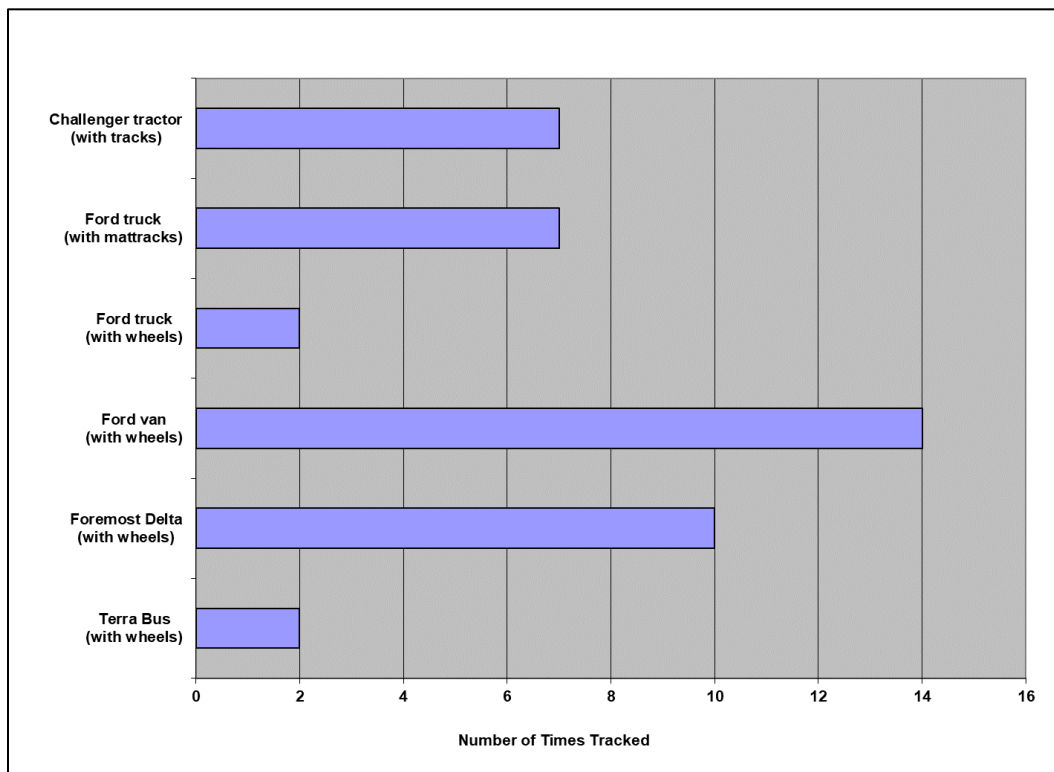
Figure 33. Super Trackstick shown with mounting clip and magnet attachment accessories.



4.2 Vehicles tracked

A total of 12 Tracksticks were purchased. They were installed in vehicles as often as possible from 1 December 2009 to 12 January 2010. They were mounted in the dash of vehicles by using the provided clip, magnet, or Velcro as necessary. Placement was dictated by the ability to have a clear-sky view for optimum satellite coverage. The ease of installation made it simple to quickly switch the Tracksticks between vehicles to accommodate changes in vehicle availability, scheduling, and maintenance. Six vehicle types were tracked over the test period: Ford E350 vans, Ford F350 trucks (with wheels and Mattracks), Foremost Deltas, a Foremost Terra Bus, and Challenger tractors. These vehicles represent a wide array of vehicle types and different purposes for using the snow roads. Apart from the tractors, which were used for road construction and maintenance, all other vehicles were used for passenger or cargo transfer to and from the airfields. The Tracksticks recorded a total of 42 tracking events (Figure 34)

Figure 34. Vehicle type and frequency tracked.



4.3 Data processing

After the data were collected, the Tracksticks were removed from the vehicle and data were downloaded and analyzed using the Trackstick Manager

software. The data collected include record number, date, time, latitude, longitude, altitude, temperature, status, course, GPS fix, and signal strength. The program allows filtering for specific date ranges, speeds, stop times, record number, or temperature range. Once any filtering is completed, there are many options for exporting the data. While .kmz files were the common export format, used for mapping in Google Earth, other options include .html (webpage) and .gpx (GPS exchange format). Our analysis included mapping the vehicle routes; monitoring travel time and vehicle speeds; and locating areas where vehicles slowed down on the road, which could indicate obstacles or poor road conditions.

4.4 Results

During the early part of the austral summer season (2009–2010) vehicles were able to travel to Pegasus Runway using the Pegasus Short-Cut Road that crossed the seasonal ice (Figure 35). This was a considerable time savings but was not feasible once the sea ice started to warm. Otherwise, vehicles transited the entire 15-mile route along the permanent ice shelf.

Figure 35. Trackstick output for the two routes from McMurdo Station to Pegasus Runway.



4.4.1 Travel Time

The location of Pegasus Runway was based on a variety of local environmental and climatological considerations. However, the 15-mile transit

made for a long commute for airfield support staff, flight crews, and air traffic controllers. The road condition changes with the weather, and the speed limit is seasonally capped at 25 mph to reduce wear and damage to the snow road. This is of particular concern for flight crews and air traffic controllers, who have strictly regulated work hours and rest times. Their transit to the airfield is included as work hours; and depending on the road conditions, their travel times can be up to one hour each way. This commute can sometimes reduce available flight hours by one or two flights per day for a crew; therefore, travel time to the airfield is critical.

As the primary people movers, Deltas (approximately 20 max passengers) and the van fleet (10 max passengers) were the focus for commute time tracking. The van data collection was further complicated when a new type of tire was introduced for use on the vans during the 2009–2010 season to help reduce wear and tear on the roads. Until then, all of the vans had been equipped with 38–40 in. tires filled to 20 psi (i.e., Dick Cepek Fun Country 40x16.5R17LT). The new tires were 38 in. with a bead lock to hold the tire to the rim so they could be run at lower inflation pressures (i.e., Interco TRXUS 38.5x14.5R17LT). On the graphs, these tires are described as the “old” and “new” tires respectively. For perspective, the Deltas use high floatation “Terra Tires” (i.e., tubeless nylon 66 x 44.00 25NHS).

Figure 36 shows a plot of the snow-road travel times between McMurdo Station and the Pegasus Runway using Pegasus Road. The average travel time for the Deltas was 62 minutes and for the vans was 37 minutes. As the figure shows, there was a period from approximately 11 December through 3 January without data for the Deltas because they were using the cut-off road over the sea ice at that time. Usually, warm weather during the austral summer causes serious road deterioration and increases the transit times during warm weather; however, that did not happen during the 2009–2010 season. In addition, in the van data, the “old” versus “new” tires had almost identical average transit times, thus the new tires appeared to have no effect on reducing transit time.

While analyzing the transit time, the team also looked briefly at vehicle speeds. As stated above, the speed limit on the snow roads is 25 mph. The Foremost Deltas were unable to reach speeds much greater than this; however, if the road and visibility conditions were good, the vans were driven at higher speeds (Figure 37). These graphs showed that the Delta was most often traveling at speeds between 11 and 20 mph. The vans were

mostly driven at speeds in the 26 to 30 mph range, but other speeds were not uncommon. All drivers were trained extensively at the beginning of the season and had a firm understanding of the roads and the need for the speed limit. However, to meet a demanding shuttle timetable and also to satisfy the passenger, a shorter transit time was desirable as a competing factor, which sometimes resulted in higher driving speeds.

Figure 36. Average travel time between McMurdo Station and the Pegasus Runway using the snow roads for the Delta (*top*) and vans (*bottom*).

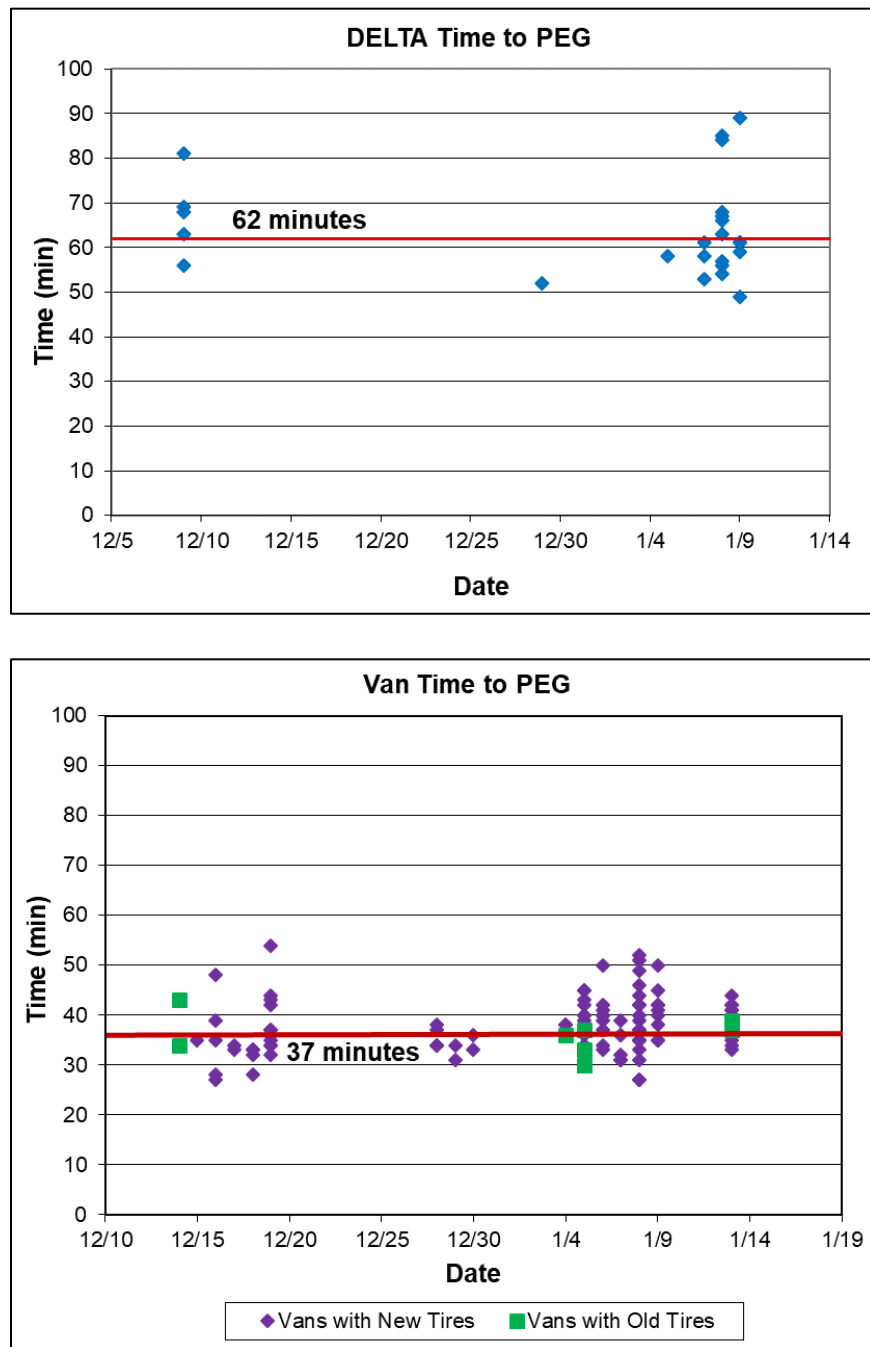
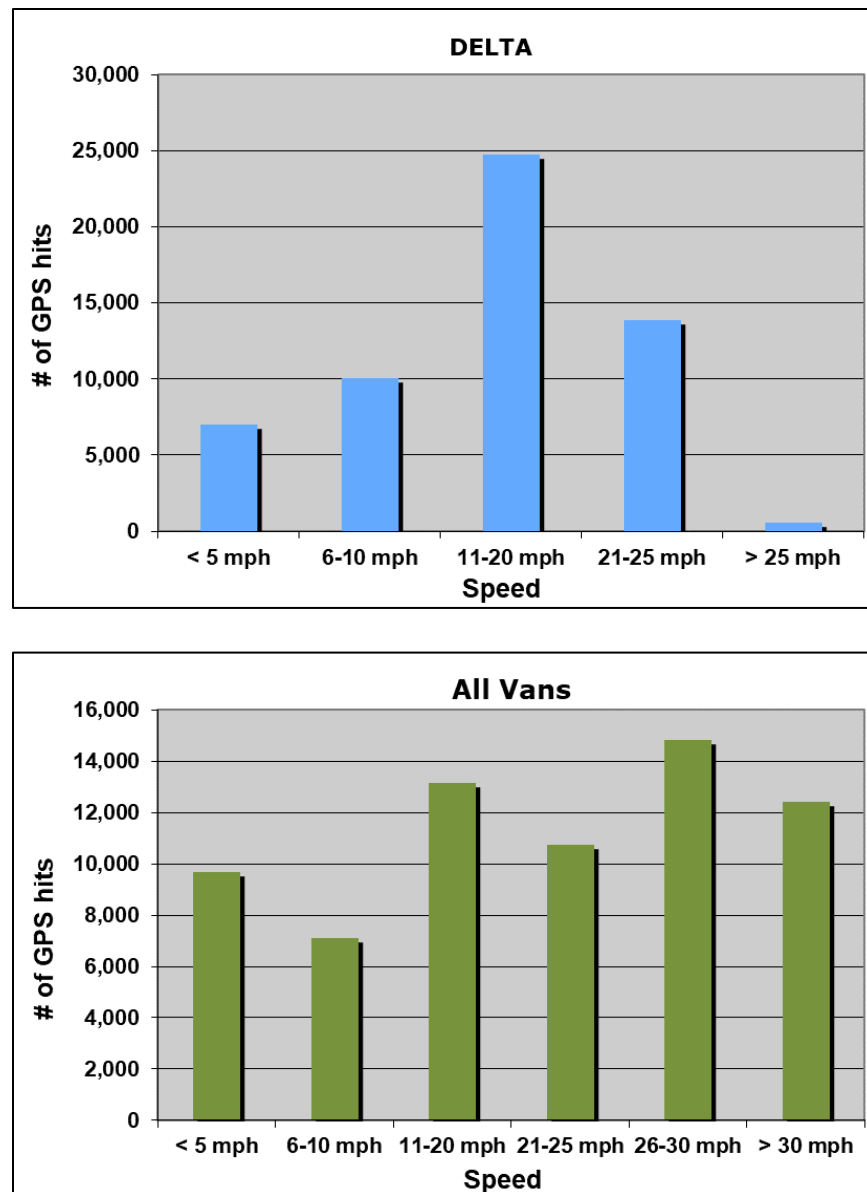


Figure 37. Range of van and Delta speeds during the tracking period.



4.4.2 Stops and slow spots

CRREL also analyzed the Trackstick data to determine if it could provide information on the location of obstacles or poor road conditions. The data were filtered for locations where vehicles were consistently traveling slowly or where they were stopped (e.g., stuck) for extended periods. Unfortunately, two issues made the postprocessing of this more difficult than anticipated. While the Super Trackstick was able to follow 12 satellites, depending on the location in McMurdo, the receivers consistently obtained low numbers of available satellites (Figure 38). Approximately 85% of the time, the Deltas and vans saw four or more satellites. Four is enough to get

a reading, but the greater the number of satellites, the more accurate the location. In this case, that leaves 15% of the time where there were bad or inaccurate locations. These can be filtered manually, but not with the software provided by the manufacturer. The other issue was due to the vehicles used. In “power save” mode, when the Trackstick receiver senses a vibration, it assumes the vehicle is in motion and starts collecting data. While this was less of a problem for the vans, the Deltas are very large, old vehicles that produce quite a bit of vibration when the engine is on, even if the vehicle is not moving. Because of this vibration, there were many times when the Delta was actually stopped and idling but, combined with the GPS location inaccuracies due to low satellite coverage, it appears that the Delta was still moving at 1 or 2 mph (Figure 39).

Despite these complications, patterns were still apparent in the data. While the data did not capture any specific times when vehicles were stuck due to road conditions, they did show where the vehicles were slowing or stopping to observe a group of emperor penguins that were vacationing by the side of the road on the way to Pegasus Runway between 7–14 January 2010 (Figure 40).

Figure 38. Number of satellites in view during data collection.

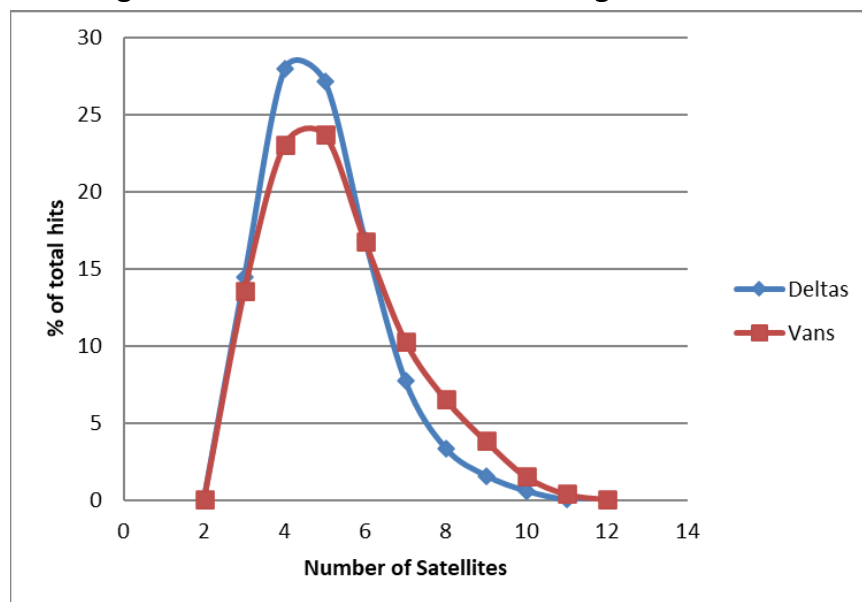


Figure 39. Image with pins marking Delta location tracking on 7 December 2009. The red pins indicate the vehicle is stopped while the yellow pins are for motion of 1–2 mph. The radius of the circle shown is 46 ft, and the total time passed in this plot is only 5 minutes, indicating erroneous locations and therefore vehicle speed recorded while the Delta was stopped with the engine idling.

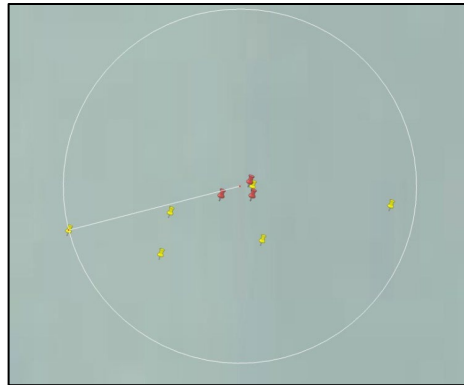
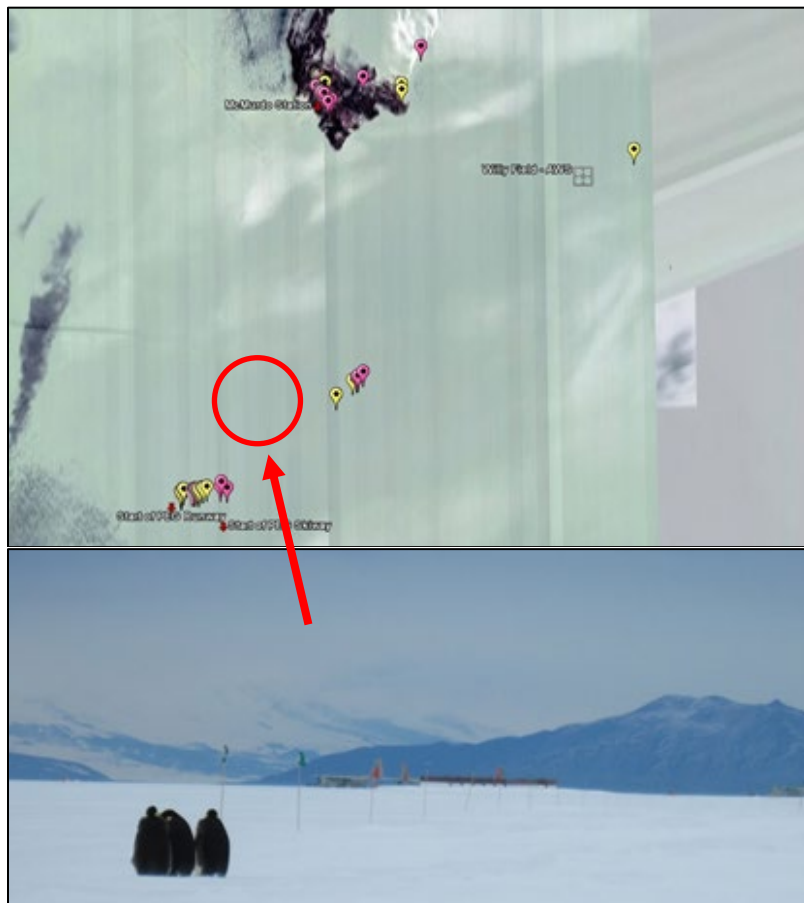
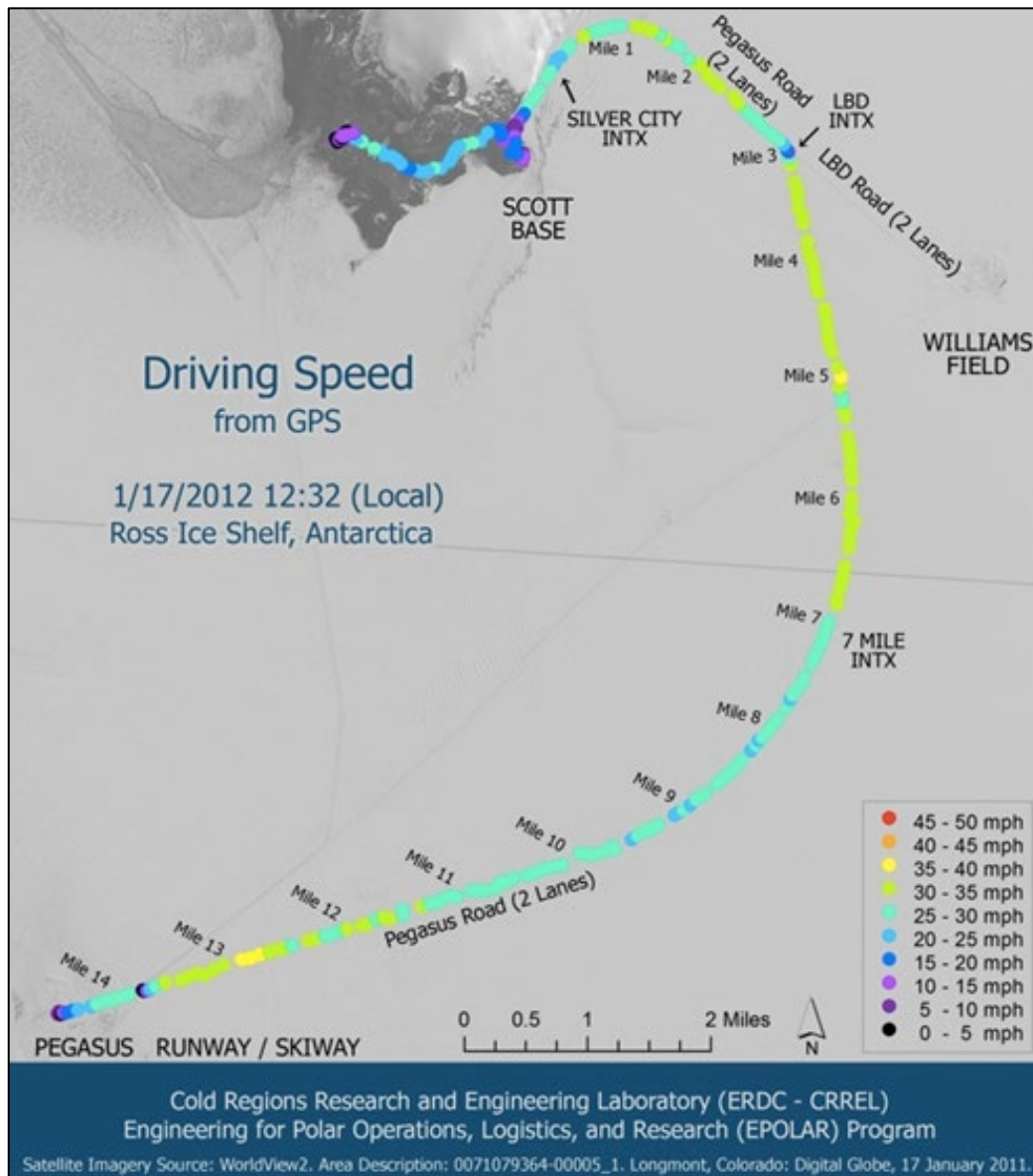


Figure 40. Pinpoints in the *top* image show instances where vehicles slowed or stopped. The multiple vehicles that stopped or slowed along the snow road were viewing the molting emperor penguins from a safe distance (*bottom*) from 7 to 14 January 2010.



Additional vehicle tracking during the FY 2012 season also evaluated the vehicle speed along the road to look for other areas where vehicles typically slowed or stopped. Figure 41 provides an example of this, showing the slowest areas at the start and stop of trips and at the Scott Base transition. Other slow areas include at the road and trail intersections; along curved sections; and for the last mile of Pegasus Road, an area of known snow deterioration.

Figure 41. Vehicle tracking 17 January 2012.



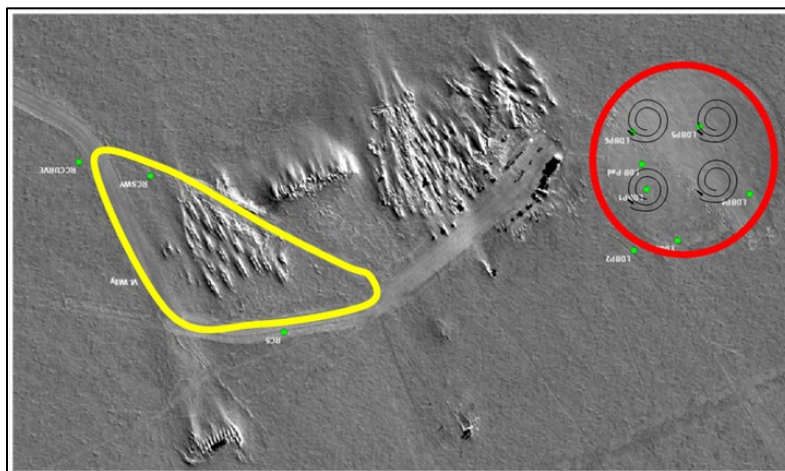
5 Experiments to Quantify Traffic Impacts on the Snow Roads

Shoop, Knuth, et al. (2014) conducted experiments from 16 to 20 December 2009 for the vehicle impacts study. The objective of the study was, again, to look at which vehicles had the biggest impact on the snow road. The test program to accomplish this included vehicles driving at varying speeds and performing various maneuvers. The study performed three basic types of tests with four vehicles: spiral or circle test patterns to investigate the effect of turning; straight-line constant-speed, acceleration, and deceleration tests; and road course tests, which allowed both turns and speed variation.

5.1 Spiral, circle, and straight-line tests

The spiral, circle, and straight-line tests were performed on a flat, smooth area of prepared snow previously used as the Long Distance Balloon launch pad. Two of the larger transport vehicles, a Delta and the Terra Bus, made multiple passes on a designated test course. The test course used existing snow roads with a variety of curves and surface roughness characteristic of the actual road conditions. Initial strength measurements characterized the test sites. After the vehicle trafficking tests, measurements included snow surface strength both in and between tire tracks, tire-track rut depth and width, and the height and width of the resulting snow piles adjacent to the tire tracks. Figure 42 shows a satellite image of the locations of the spiral tests and the road test course.

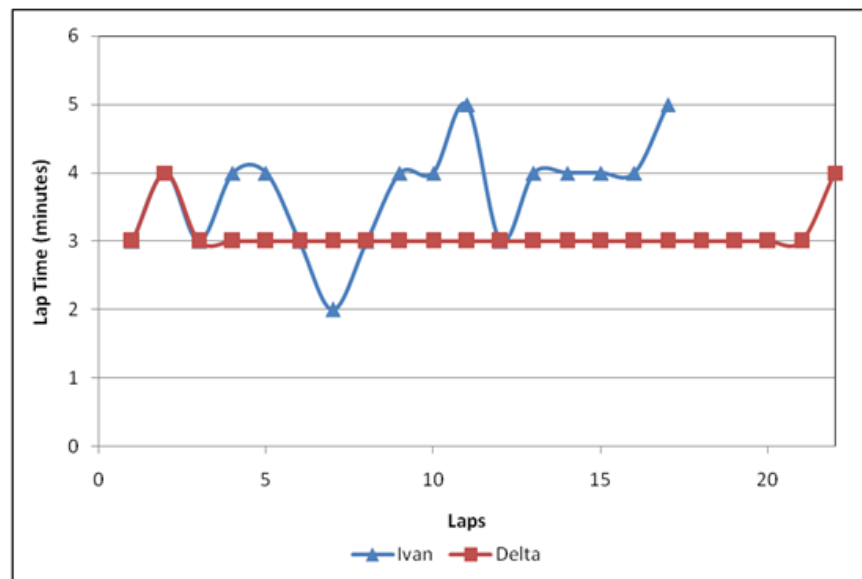
Figure 42. Satellite image showing the location of the spiral tests (within the *red circle*) and road test course (*yellow triangular shape*).



5.2 Road course vehicle tests

During the road course testing it became obvious that the Terra Bus had the greatest impact on the course, causing large amounts of rutting and generally tearing up the road surface much more than the Delta. This resulted in the test driver having to reduce the speed of the Terra Bus in many of these areas, causing slower lap times as the test proceeded. The test was finally aborted after 17 laps. In comparison, the Delta caused such minor damage to the road surface that after 20 laps the vehicle was still able to hold a consistent speed (Figure 43).

Figure 43. Road course lap times for Ivan the Terra Bus and a Delta.



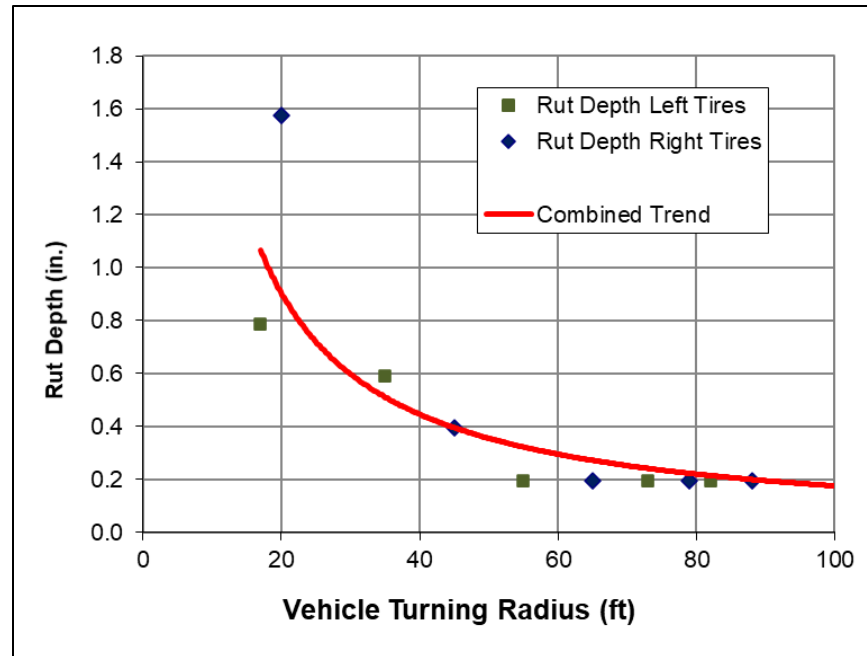
The road course study determined what specific maneuvers and measurements were helpful in distinguishing between vehicles. Measurements of the snow disturbance in terms of rutting and piles formed helped to determine how speed, turning radius, and tire type affected the surface. The road course provided a more operationally relevant test with compounded factors (turns, bumps, strength variations, etc.) and very clearly distinguished which vehicle maneuvers caused the greatest impacts.

5.3 Rut width and depth with turning-radius tests

The vehicle impact studies performed with the F350 Ford truck determined that sharper vehicle turns had more impact, resulting in deeper ruts in the road surface (Figure 44). The practical implementation of this result

is that smoother turns with a larger turning radius will minimize damage (Shoop, Knuth, et al. 2014).

Figure 44. Rut depth at various turning radii from vehicle impact studies.



5.4 Speed tests

Vehicle speed plays an important part in road disturbance and degradation. Vehicles that hit irregularities in the road surface tend to start “bouncing,” which in turn creates more irregularities in the surface and eventually, with refreeze, a rough washboard area. Figures 45–47 illustrate this point.

Figure 45. Speeds of 20 mph leave only a tire imprint.



Figure 46. Speeds of 25 mph leave “rooster tails.”



Figure 47. Refrozen road with a washboard surface.



5.5 Lane-change-maneuver tests

Lastly, a higher-speed, dynamic vehicle event was tested called a “lane-change maneuver” (Figure 48). This type of maneuver is more common for rapid events, like avoiding an accident from a sudden change or obstruction. In the test, the vehicle moves from one lane to the next within the cones placed for the test and repeats this at a range of speeds. This allows the observers to monitor the vehicle response to the maneuver and also to monitor the impact of the vehicle maneuver on the roadway surface.

These tests along with the speed tests show how increased speed, acceleration and deceleration, and decreased turning radius (i.e., tighter turns) all increase road disturbance. Shoop, Knuth, and Wieder (2013) and Shoop, Knuth, et al. (2014) document the full data set and analysis.

Figure 48. The van and trailer perform a lane-change maneuver to study the vehicle and trailer dynamics, and control, and their impact on the snow-road surface.



6 Road-Load Estimates

The additional knowledge needed to optimize road maintenance is how much traffic the road must support. For the 2010–2011 and 2011–2012 seasons, CRREL estimated the average daily traffic for Pegasus Road by using aircraft use records from the Pegasus Runway and the vehicle loading practices for both the passenger shuttles and cargo vehicles.

6.1 Data sources

The following end-of-season summary reports generated by ASC provided data for this analysis:

- Intercontinental Airlift (2010–2011 and 2011–2012)
- South Pole Airlift (2010–2011 and 2011–2012)
- Inland Camps Airlift (2010–2011 and 2011–2012)
- McMurdo Shuttle Ops (2010–2011 and 2011–2012)

Figures 49 and 50 present two examples of the data available for inbound and outbound intercontinental flights landing on the Pegasus Runway. Intracontinental flights to other Antarctic stations were accounted for in the other data files listed. From this data, CRREL determined the daily number of passengers and the pounds of cargo off- and on-loaded onto aircraft.

Figure 49. Inbound aircraft to Pegasus Runway, December 2010–January 2011.

INTERCONTINENTAL FLIGHT RECORD 2010 - 2011: SOUTHBOUND (CHC-MCM)

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MISSION	TYPE	TAIL #	DATE	ARFLD	PASSENGERS					SURV. BAG		ACL										REMARKS
					CIV	MIL	TTL	PAX WT	BAG WT	QTY	WT	US MAIL	FRESHIES	TDE	OTHR	CARGO	USED	OFFER	DIFF			
Week Ending: 25-Dec-10					17	13	30	6,838	2,179	4	180	1,004	1,541	8,265	365	103,307	123,679	129,000	-5,321			
AZM035	C-17	88196	27-Dec-10	NPG	37	3	40	8,548	2,592	0	0	3,200	12,545	5,325	-423	55,233	87,020	100,000	-12,980	C-130 ENGINE		
AZM036	C-17	88196	29-Dec-10	NPG	13	0	13	2,946	782	0	0	0	0	6,875	-1,211	88,031	97,423	100,000	-2,577			
Week Ending: 01-Jan-11					50	3	53	11,494	3,374	0	0	3,200	12,545	12,200	-1,634	143,264	184,443	200,000	-15,557			
GZM014	LC-130	SK094	02-Jan-11	NPG	5	17	22	5,362	1,519	8	360	280	0	355	-58	725	8,543	8,500	43	CREW ROTATION		
GZM015	LC-130	SK096	02-Jan-11	NPG	0	22	22	4,731	1,040	8	360	211	0	380	43	717	7,482	8,500	-1,018	CREW ROTATION		
AZM037	C-17	88196	04-Jan-11	NPG	66	0	66	14,748	5,449	0	0	0	8,263	3,725	52	34,723	66,960	70,000	-3,040	C-130 ENGINE, NOSE & WING JACK		
AZM038	C-17	88196	05-Jan-11	NPG	41	4	45	10,320	2,817	0	0	0	0	5,865	-3	48,010	67,009	70,000	-2,991	NPB CARGO		
AZM039	C-17	88196	07-Jan-11	NPG	26	3	29	6,499	1,894	0	0	3,083	1,090	5,110	-327	80,731	98,080	100,000	-1,920	C-130 PROP		
Week Ending: 08-Jan-11					138	46	184	41,660	12,719	16	720	3,574	9,353	15,435	-293	164,906	248,074	257,000	-8,926			
GZM016	LC-130	SK094	09-Jan-11	NPG	3	0	3	640	152	2	90	9	0	360	-26	3,798	5,023	5,900	-877			
GZM017	LC-130	SK301	09-Jan-11	NPG	0	0	0	0	0	0	0	0	0	720	-16	4,276	4,980	0	4,980			
AZM040	C-17	21105	11-Jan-11	NPG	30	1	31	7,134	2,131	0	0	3,166	8,286	5,480	-842	56,956	82,311	100,000	-17,689	T-3 20' ISO LABORATORY CONTAINER		
AZM041	C-17	21105	13-Jan-11	NPG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	MISSION CNX - WEATHER		
AZM041	C-17	21105	14-Jan-11	NPG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	MISSION ABORT - WEATHER		
GZM018	LC-130	SK300	14-Jan-11	NPG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	MISSION CNX - WEATHER		
AZM041	C-17	21105	15-Jan-11	NPG	62	32	94	21,009	7,714	0	0	821	4,694	3,470	571	21,884	60,163	100,000	-39,837	FRESHIES-ODEN/NBP/SP / T-3 INCINERATOR		
GZM018	LC-130	SK300	15-Jan-11	NPG	0	0	0	0	0	0	0	0	0	721	69	4,830	5,620	5,940	-320			
Week Ending: 15-Jan-11					95	33	128	28,783	9,997	2	90	3,996	12,980	10,751	-244	91,744	158,097	211,840	-53,743			
AZM042	C-17	21105	18-Jan-11	NPG	55	13	68	15,068	4,546	0	0	209	0	3,225	-93	41,591	64,546	100,000	-35,454	PISTON BULLY VEHICLE		
AZM043	C-17	21105	20-Jan-11	NPG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	MISSION CNX - WEATHER		
AZM043	C-17	21105	21-Jan-11	NPG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	MISSION CNX- WEATHER		
AZM043	C-17	21105	22-Jan-11	NPG	23	19	42	9,550	1,795	0	0	3,234	9,540	4,785	204	45,378	74,486	100,000	-25,514			
Week Ending: 22-Jan-11					78	32	110	24,618	6,341	0	0	3,443	9,540	8,010	111	86,969	139,032	200,000	-60,968			
AZM044	C-17	21105	23-Jan-11	NPG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	MISSION ABORT - WEATHER		
GZM019	LC-130	SK096	23-Jan-11	NPG	0	9	9	2,128	726	3	135	0	0	490	89	2,023	5,591	5,100	491	CREW ROTATION		
AZM044	C-17	21105	24-Jan-11	NPG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	MISSION CNX - WEATHER		

Figure 50. Outbound aircraft from Pegasus Runway, December 2010–January 2011.

INTERCONTINENTAL FLIGHT RECORD 2010 - 2011: NORTHBOUND (MCM-CHC)

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					PASSENGERS					SURV. BAG							ACL			
MISSION	TYPE	TAIL #	DATE	ARFLD	CIV	MIL	TTL	PAX WT	BAG WT	QTY	WT	US MAIL	TDE	OTHR	CARGO	USED	OFFER	DIFF	REMARKS	
Week Ending: 01-Jan-11					100	18	118	26,214	7,193	9	405	1,346	5,545	-237	37,231	77,697	212,400	-134,703		
ACH037	C-17	88196	04-Jan-11	NPG	21	0	21	4,410	963	0	0	1,432	1,545	344	6,218	14,912	100,000	-85,088		
ACH038	C-17	88196	05-Jan-11	NPG	23	0	23	4,900	1,394	0	0	207	1,260	151	8,046	15,958	100,000	-84,042		
ACH039	C-17	88196	07-Jan-11	NPG	49	5	54	11,923	3,481	0	0	0	1,140	-47	1,027	17,524	100,000	-82,476		
GCH011	LC-130	SK094	08-Jan-11	NPG	1	5	6	1,469	820	2	90	67	670	-115	2,059	5,060	9,000	-3,940	CREW ROTATION	
Week Ending: 08-Jan-11					94	10	104	22,702	6,658	2	90	1,706	4,615	333	17,350	53,454	309,000	-255,546		
ACH040	C-17	21105	11-Jan-11	NPG	57	0	57	13,024	3,469	0	0	3,857	5,382	-264	41,618	67,086	100,000	-32,914	MEDEVAC - LITTER	
GCH012	LC-130	SK096	12-Jan-11	NPG	3	3	6	1,930	675	2	90	66	335	0	0	3,096	7,900	-4,804		
ACH041	C-17	21105	15-Jan-11	NPG	80	27	107	24,734	6,157	0	0	6,095	2,745	166	3,495	43,392	100,000	-56,608		
Week Ending: 15-Jan-11					140	30	170	39,688	10,301	2	90	10,018	8,462	-98	45,113	113,574	207,900	-94,326		
ACH042	C-17	21105	18-Jan-11	NPG	110	4	114	24,353	6,369	0	0	50	2,070	-1,353	9,227	40,716	100,000	-59,284		
ACH043	C-17	21105	22-Jan-11	NPG	104	0	104	22,619	6,136	0	0	175	2,760	32	8,635	40,357	100,000	-59,643		
GCH013	LC-130	SK094	22-Jan-11	NPG	0	14	14	3,500	1,285	5	225	0	1,385	-40	3,680	10,035	10,200	-165		
Week Ending: 22-Jan-11					214	18	232	50,472	13,790	5	225	225	6,215	-1,361	21,542	91,108	210,200	-119,092		
ACH044	C-17	21105	26-Jan-11	NPG	74	1	75	16,836	4,616	0	0	70	4,500	321	50,337	76,680	100,000	-23,320	T-3 EMPTY LHE DEWAR, 2ea	
ACH045	C-17	21105	27-Jan-11	NPG	50	1	51	11,008	2,626	0	0	120	4,654	-461	40,315	58,262	100,000	-41,738	LOX CART	
ACH046	C-17	21105	28-Jan-11	NPG	5	1	6	1,853	0	0	0	41	3,792	-47	26,117	31,756	100,000	-68,244		
ACH047	C-17	21105	29-Jan-11	NPG	55	39	94	22,099	6,530	0	0	25	1,790	193	5,322	35,959	100,000	-64,041		
GCH014	LC-130	SK491	29-Jan-11	NPG	0	1	1	310	212	1	45	0	0	0	0	567	9,300	-8,733		
Week Ending: 29-Jan-11					184	43	227	52,106	13,984	1	45	256	14,736	6	122,091	203,224	409,300	-206,076		
ACH048	C-17	21105	31-Jan-11	NPG	28	0	28	6,217	1,819	0	0	26	1,460	110	14,425	24,057	100,000	-75,943	AntNZ HELICOPTER EC130	
ACH049	C-17	21105	02-Feb-11	NPG	73	0	73	15,830	4,840	0	0	166	1,685	138	7,915	30,574	100,000	-69,426	LOX DEWAR	
ACH050	C-17	21105	04-Feb-11	NPG	57	8	65	15,319	3,889	0	0	552	3,490	-18	19,912	43,144	100,000	-56,856		
Week Ending: 05-Feb-11					158	8	166	37,366	10,548	0	0	744	6,635	230	42,252	97,775	300,000	-202,225		
ACH051	C-17	88203	07-Feb-11	NPG	72	1	73	15,505	5,344	0	0	18	1,970	-70	8,530	31,297	100,000	-68,703	C-130 PROP	
ACH052	C-17	88203	09-Feb-11	NPG	62	2	64	14,062	4,645	0	0	297	2,820	476	11,888	34,188	100,000	-65,812	MEDEVAC - LITTER & AMBULATORY	
GCH015	LC-130	SK300	11-Feb-11	NPG	8	3	11	3,394	263	4	180	0	0	0	0	3,837	5,700	-1,863		
SCH008	A-319	AIRBUS	11-Feb-11	NPG	36	2	38	8,727	2,571	0	0	19	0	0	7	11,324	15,000	-3,676		

6.2 Assumptions

Antarctic Terminal Office (ATO) staff provided information on common practices for moving cargo and passengers (Pete Cruiser and Sharona Thompson, ASC, pers. comm., 2011–2012). From these interviews, along with others from ATO staff, the CRREL team made the following assumptions.

For cargo:

- Of the total flight cargo weight (including packaging and pallets), 95% is transported back to McMurdo Station from the airfield. The other 5% of the cargo is transferred onto intracontinental flights.
- Both inbound and outbound cargo numbers were used.
- The cargo per pallet was estimated at 6000 lb, and a Delta can carry three pallets per trip.
- *Runs* are defined as out and back.

For passengers (PAX):

- The runs-per-week data provided in the McMurdo Shuttle Operations End of Season Summary, specifically the data for Shuttle Movements to and from Pegasus Runway (designated NPG on the spreadsheets in Figures 49 and 50), was used to estimate the number and type of vehicle trips.
- The Ivan transport vehicle (56 passengers) was used for every C17 or Airbus aircraft arrival as these two types of aircraft typically carried larger passenger loads.
- The newer Kress vehicle (max capacity of 65 passengers) was used infrequently at end of the 2011–2012 season, so it was absorbed in the Ivan counts.
- Deltas (average 15 passengers) were used more in 2010–2011 than in 2011–2012.
- Vehicle calculations were based on the known number of vehicle runs per week (all trips). Then 40% (2010–2011) and 20% (2011–2012) of the runs were attributed to the Deltas after the passengers using the Ivan were accounted for.

Other data:

- A “single airfield” scenario was evaluated where all traffic would be to Pegasus Runway. This used data for the two airfield scenario (i.e., in-

cluding data for both the Sea Ice Runway and Pegasus Runway) and assumed that, in the future, all loads would have to traverse the entire Pegasus Road.

- Additional trafficking from the Vac Tank, Waste Bin Pickup, and Water Delivery was added as “miscellaneous Deltas” Traffic.
- Not included was traffic to the Long Duration Balloon Pad and any traffic with a “personal” vehicle (wheeled or tracked).

6.3 Results

Figure 51, Figure 52, and Table 6 present the results of the above analysis, showing the weekly road use for the transport vehicles for the 2010–2011 and the 2011–2012 seasons. As these show, the roads are used extensively from October to mid-February, which is the height of the austral summer and the science season in Antarctica, particularly for McMurdo Station. While the personnel vans do the most driving on the snow roads, the heavy vehicles carry more weight per trip.

Figure 51. Total vehicle runs per week to and from Pegasus Runway via Pegasus Road.

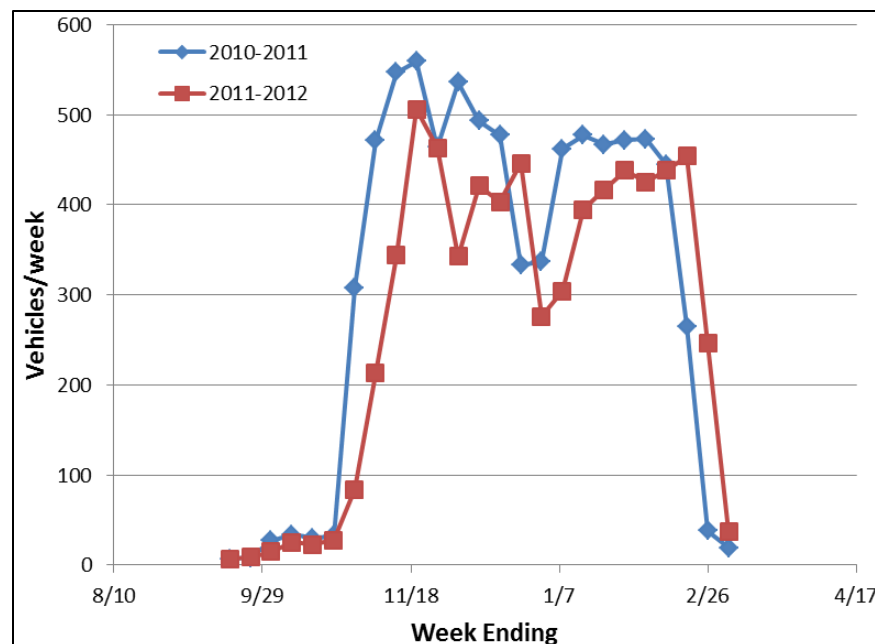


Figure 52. Vehicle runs by type per week to and from Pegasus Runway via Pegasus Road for the 2011–2012 season.

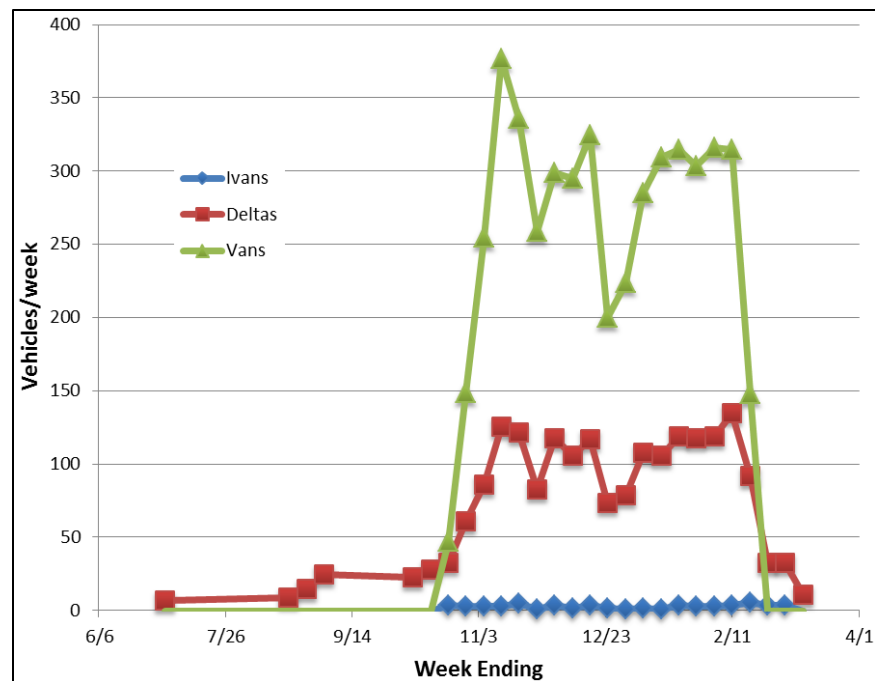


Table 6. Number of vehicle runs calculated for each of the austral summer seasons estimated.

Austral Summer Season	All Vehicles	Ivan	Delta	Van
Maximum number of runs per day				
2010–2011	93.2	1.0	42.5	50.7
2011–2012	84.3	1.0	22.5	62.8
Average number of runs per day				
2010–2011	51.9	0.5	21.3	30.2
2011–2012	42	0.5	12.3	29.4

7 Snow-Road Preservation

Operating vehicles on snow-surfaced roads is not only about learning to drive on slick surfaces but also learning to drive so that the vehicle has the least impact on the road surface, thus preserving the road and minimizing maintenance. Snow, and the sintered bonds between snow crystals, deform easily from vehicle loading, especially during warm or sunny days. The CRREL team used the results from the snow-road impact studies discussed in Chapter 5, along with information learned from monitoring the condition and maintenance of the snow roads, to develop guidance for vehicle use that would help preserve the snow roads throughout the warm part of the austral summer.

From the SRT program observations and results, a snow-road driver-training program was developed to inform drivers how driving on the McMurdo snow roads differs from driving on snow-covered conventional paved roads and that preserving the snow roads for use during the full season depends upon driving techniques. The resulting snow-road driver-training program provides a set of guidelines for the McMurdo road system and the reasoning behind those guidelines (also produced in Power-Point form in Shoop et al. 2016, Appendix E).

Basic vehicle operation guidelines include the following:

- Operate at low speed, generally less than 25 mph, especially during the warm season.
- Lower the tire pressures to 18 psi or less.
- Clean and wash vehicles to prevent transfer of dark, higher-albedo soil materials onto the snow-road surface.
- Limit the number of trips during warmer periods when snow roads are weakest.
- Limit traffic to low-ground-pressure vehicles during the warmest part of the season or if the roads begin to deteriorate.
- Use the entire lane width for driving to prevent channelized rutting and to help smooth ruts before they become deep and freeze up.

Road use is dependent on the weather and current road conditions. At the time of the SRT program, road-condition alerts were posted on the

McMurdo Station television system to keep drivers informed of road conditions and lane closures. Figure 53 provides a sample posting. Now road-condition information is available on the station internet page or by radioing or calling fleet operations.

Figure 53. Road-condition slide from McMurdo Station television.



8 Summary and Recommendations

The SRT program, led by CRREL and funded by NSF, studied the McMurdo Station snow-roads and transportation system. While much of the work was formally reported elsewhere, summarized briefly in Appendix C, some projects were previously documented in only presentations or memos so are documented in detail here.

The interim and final results of the SRT program served to inform many subsequent decisions on the following topics, among others:

1. Equipment use, maintenance costs, and needs
2. Optimizing road construction and maintenance activities
3. Traffic scheduling, adaptations, and driving methods to preserve road conditions
4. Potential for equipment specialized for creating snow-road and airfield surfaces
5. Documenting road maintenance procedures and techniques for delaying and controlling melting surfaces

At the end of the program, CRREL recommended additional studies of the ice shelf to help with future transportation issues and planning, some of which were subsequently funded and completed (e.g., Campbell, Lamie, and Schild 2018; Haehnel et al. 2019). The SRT program and these follow-on studies serve as critical contributions to the viable and sustainable future of logistics support to the US Antarctic science program.

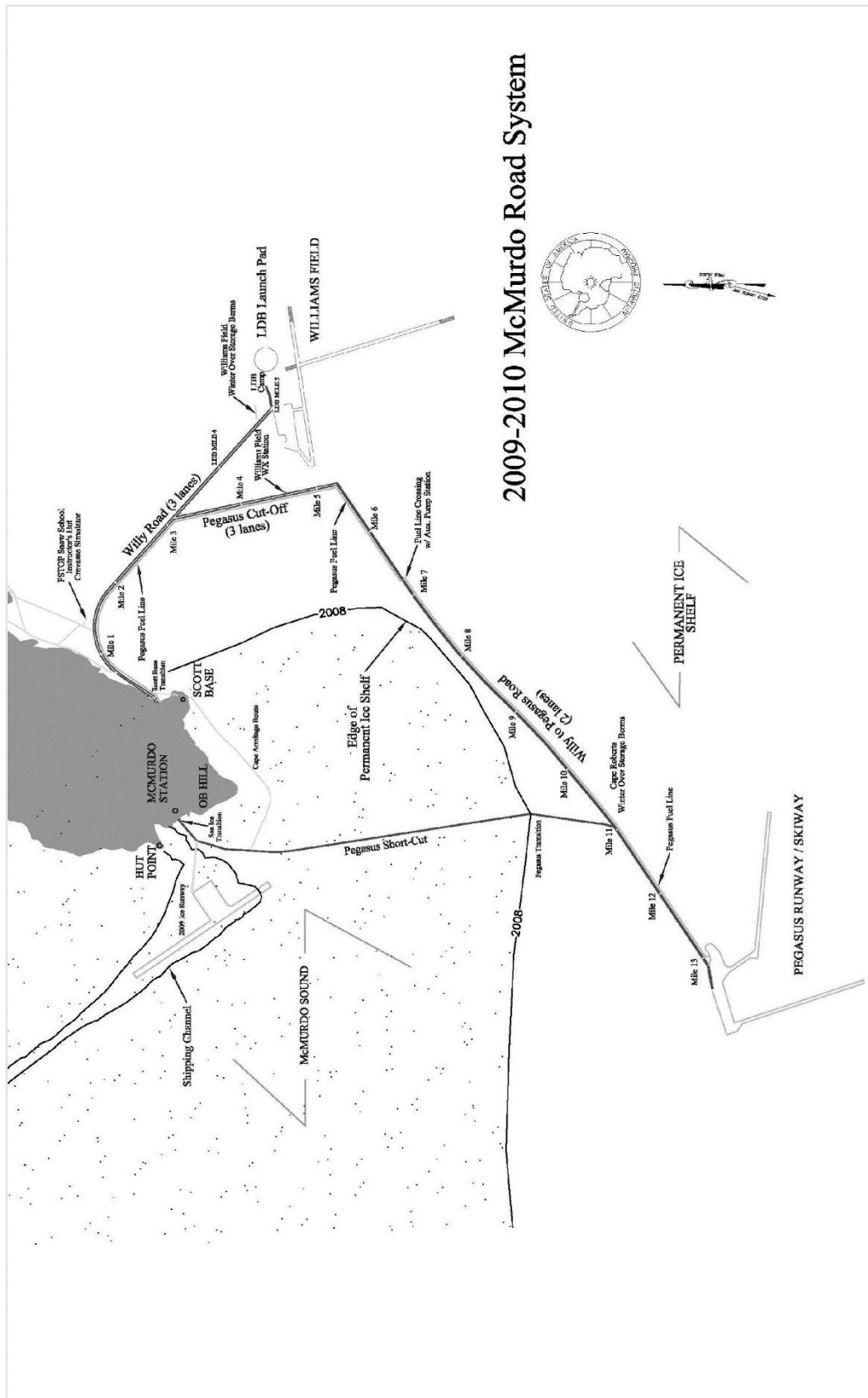
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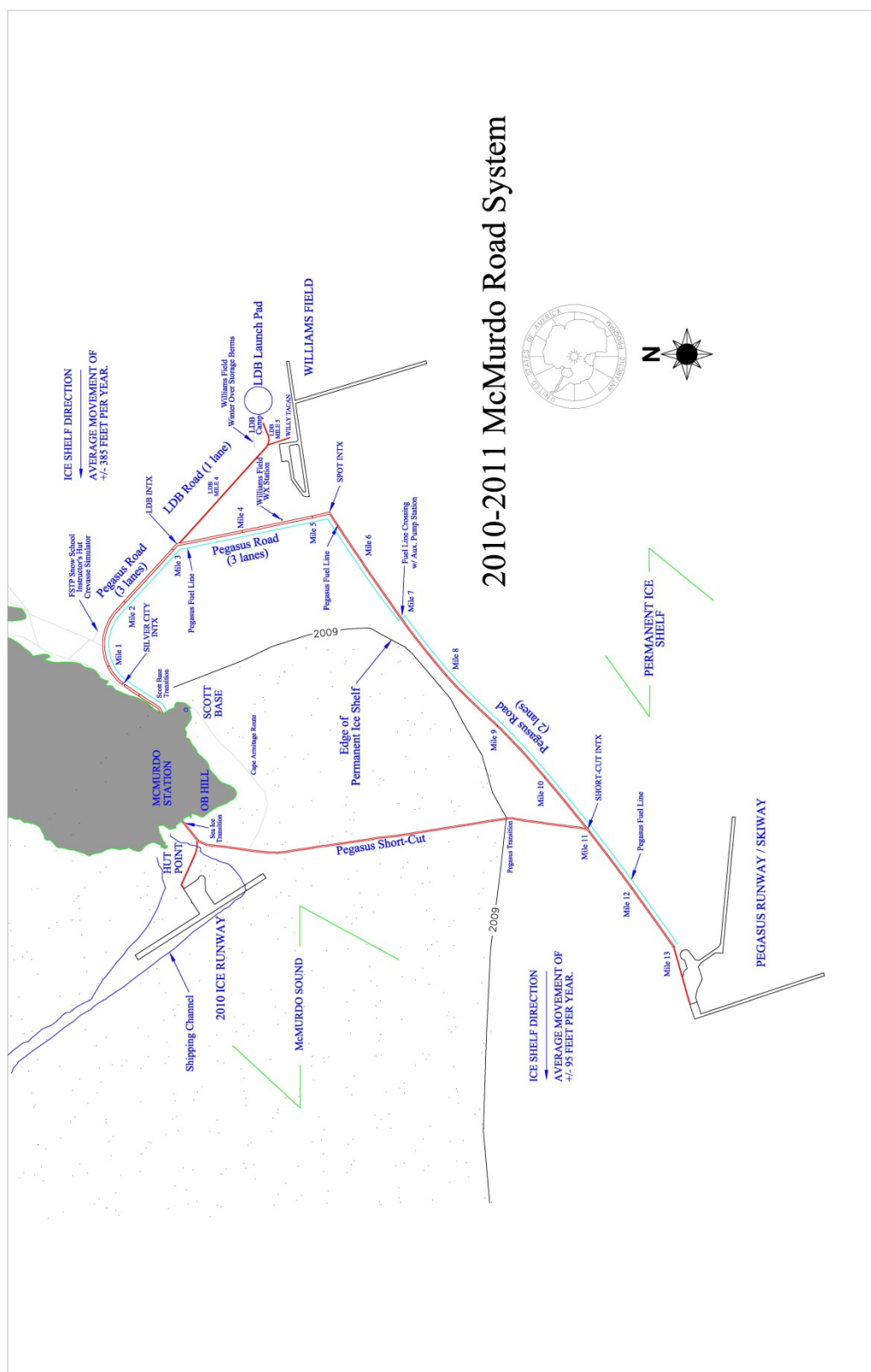
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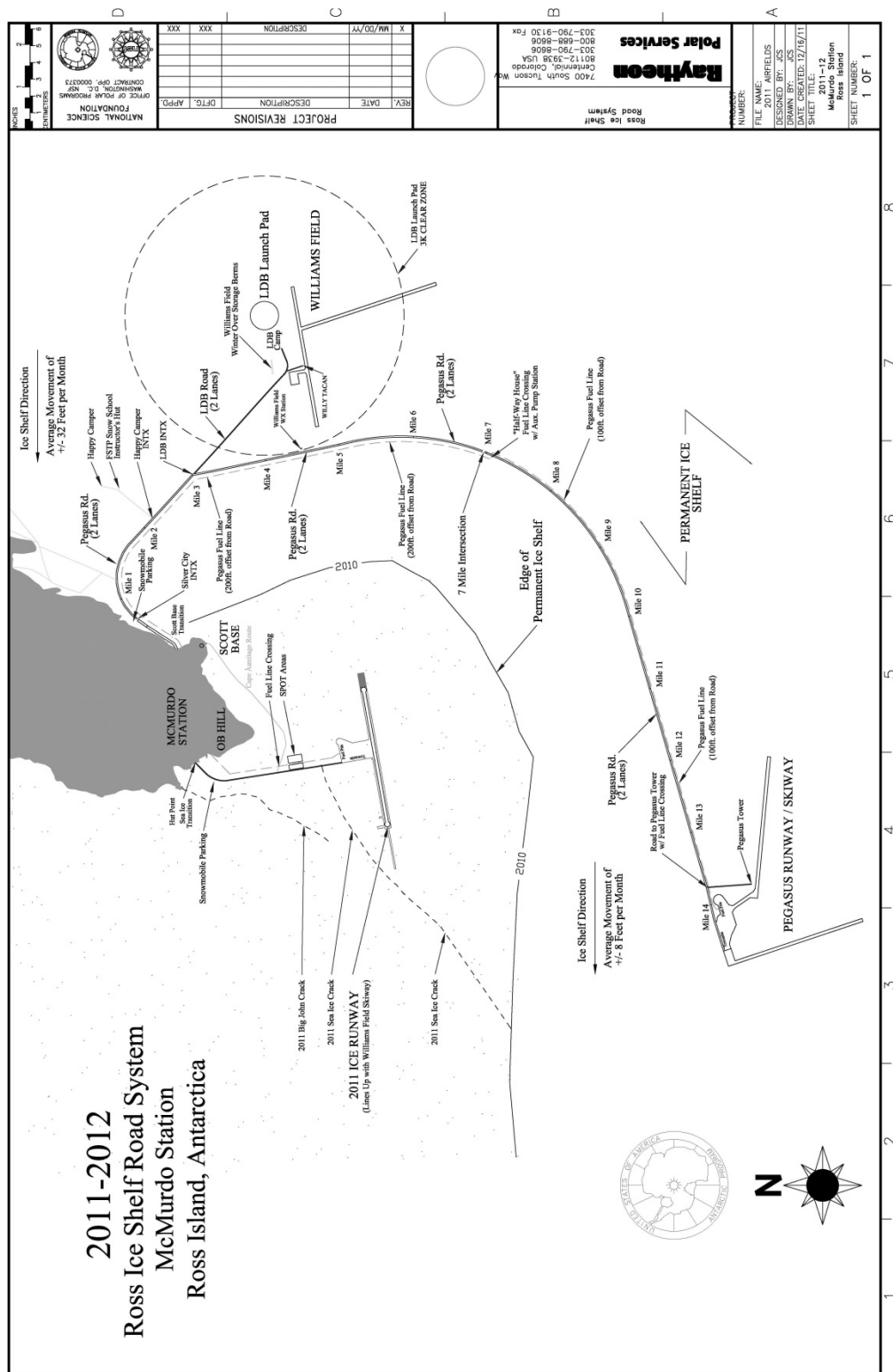
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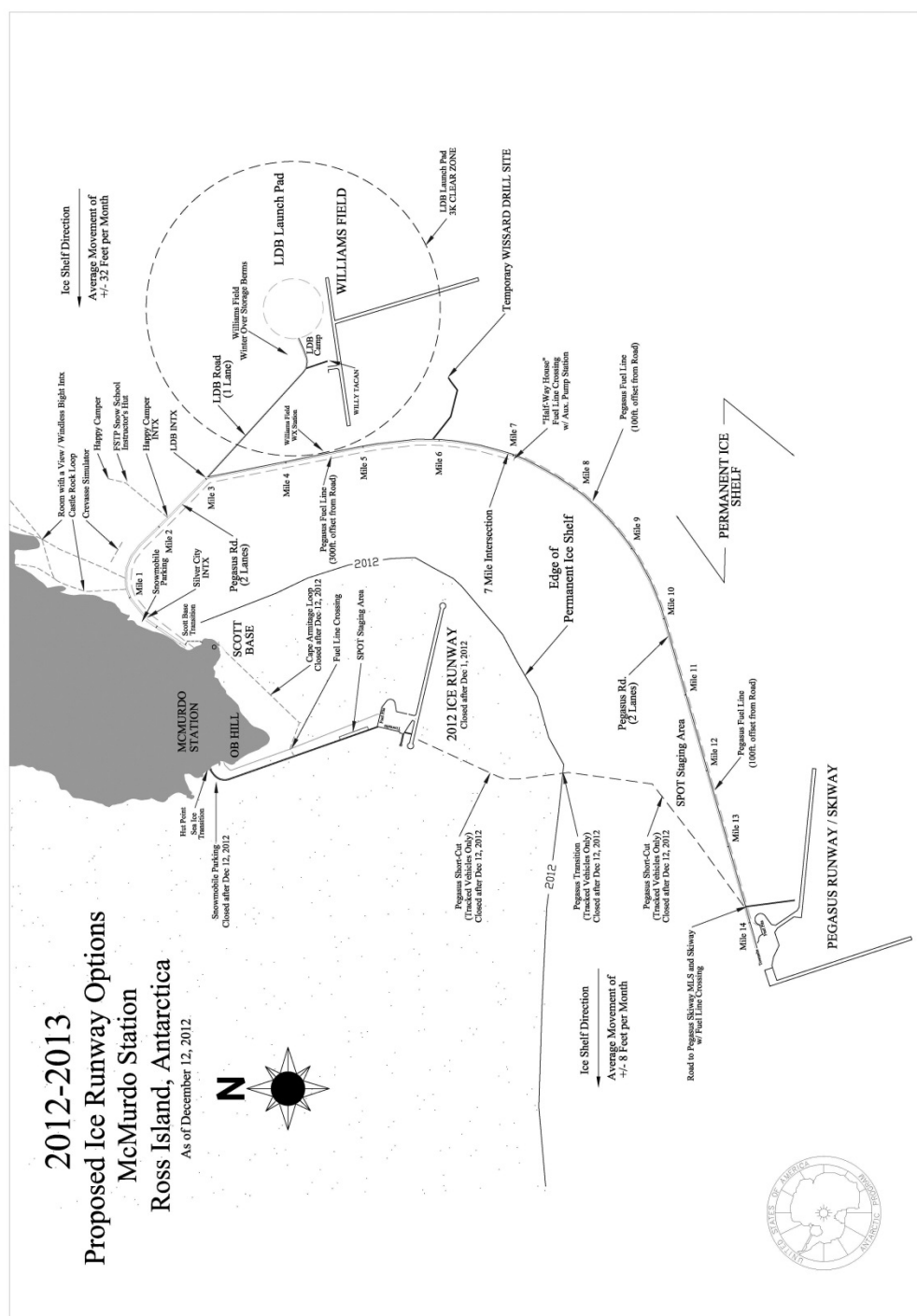
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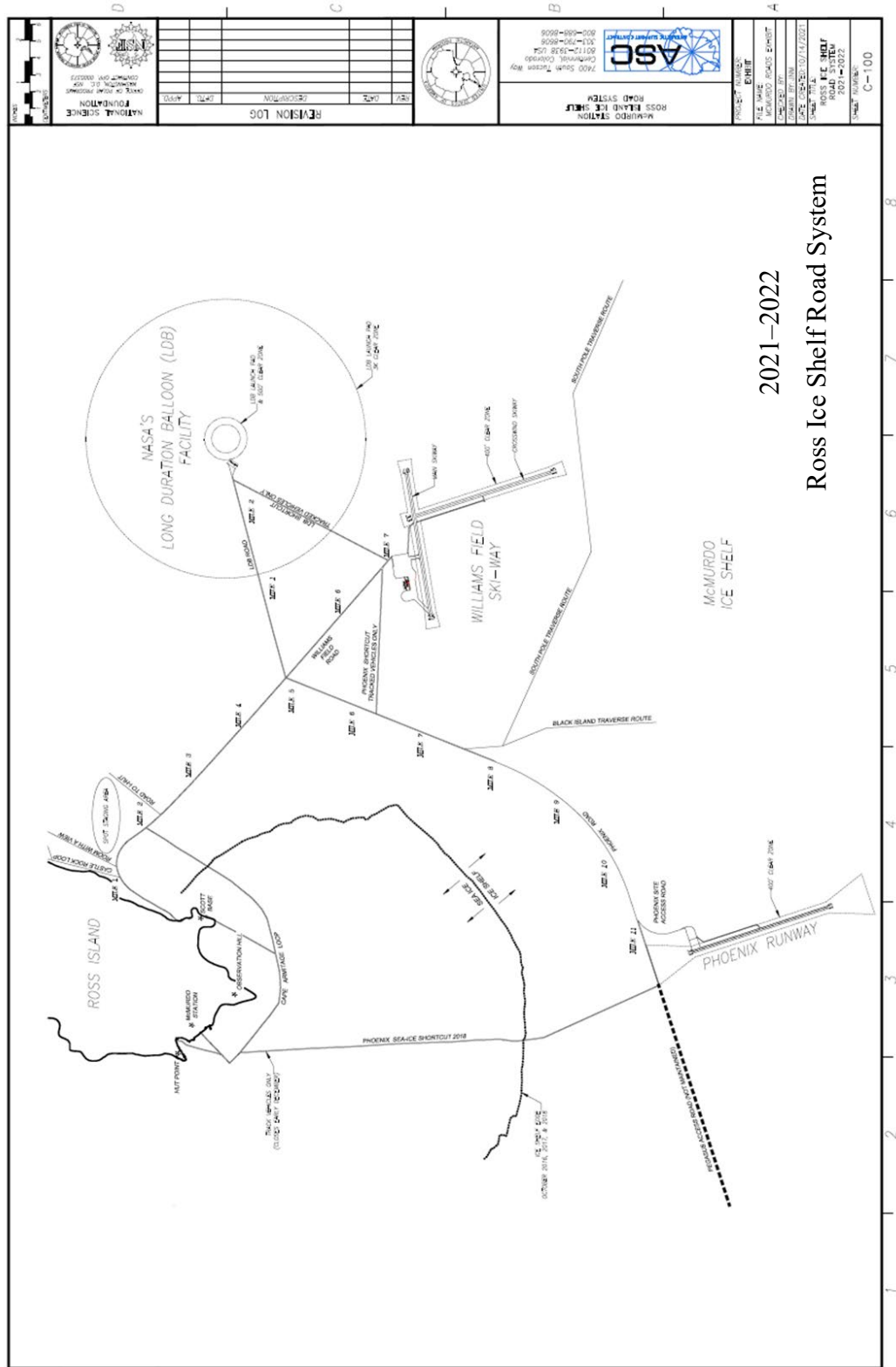
Appendix A: Annual McMurdo Road-System Maps











Appendix B: Maintenance Equipment and Vehicle Fleet as of 2021

Figures B-1 to B-11 show the vehicles and pieces of equipment in use as of 2021 in addition to or instead of the equipment and vehicles used during the SRT program.

Figure B-1. Case Quadtrac.



Figure B-2. Art's Way land plane.



Figure B-3. Eversman land plane towed behind a Challenger tractor.



Figure B-4. Royal land plane, also known as the purple Goose.



Figure B-5. Caterpillar D7E.



Figure B-6. Caterpillar D8R.



Figure B-7. Bronco land scraper.



Figure B-8. Sheepfoot compactors.



Figure B-9. Heavy ox cart with a 43,200 to 76,200 lb capacity.



Figure B-10. Kress Articulated Specialized Transport Truck (CAT730) used primarily with cargo or passenger trailers.



Figure B-11. PistenBully, primarily used for over-snow science personnel and equipment transport.



Appendix C: SRT Program Documentation

Several ERDC/CRREL technical reports and numerous journal articles and presentations have emerged from this work.

C.1 ERDC/CRREL Technical Reports

The ERDC/CRREL technical reports, listed in chronological order by publication date, are as follows:

Snow Roads at McMurdo Station, Antarctica, ERDC/CRREL TR-10-5 (Shoop, Phetteplace, and Wieder 2010)

Abstract: The McMurdo Station snow roads were observed during the 2002–2003 season to gain a better understanding of their behavior and to identify potential performance improvements that could be made. The objectives were; to explore ways to reduce the incidence of snow-road failures, to understand and document current construction and maintenance procedures, and to suggest processes to optimize labor and equipment use. This work monitored the snow conditions, compared strength measurements with processing techniques, monitored strength setup with time (sintering), monitored snow-road temperature profiles, observed any road failures, and collected fleet data (use, vehicles, tire pressures, speeds). Observations during the 2002 and 2003 austral summer are reported along with a substantial summary of historic snow-road observations and guidance including a literature review of the Navy technical guidance historically used to construct and maintain the McMurdo road system.

Airfield Passenger Transportation System at McMurdo Station, Antarctica, ERDC/CRREL TR-12-8 (Seman 2012)

Abstract: McMurdo Station is currently served by three airfields. Combined, these airfields are used for all passenger service and are a key element of the cargo supply system. The farthest of the sites, Pegasus Runway, lies approximately 16 miles from the main base on Ross Island, requiring travel across a glacial ice shelf. Travel time to Pegasus Runway currently takes one hour or more for passengers. The objective of this study was to explore the possibility of reducing this travel time by improving efficiencies in the McMurdo airfield passenger transportation system.

Requirements for the system were identified, defined, and quantitatively scored for use in evaluating future alternatives. Safety, reliability, and travel time were the highest priorities. A site visit in January 2008 to observe current practices and interview key staff concentrated on three facets of passenger transport: roads, vehicles, and passenger management. Current routes, vehicle needs, and data recording practices were assessed. Recommendations are provided for action and further study.

Vehicle Impact Testing of Snow Roads at McMurdo Station, Antarctica,
ERDC/CRREL TR-14-9 (Shoop, Knuth, et al. 2014)

Abstract: During the austral summer of 2009-2010, a study was conducted on the ice shelf near McMurdo Station, Antarctica to determine the impact of various vehicle and tire types on the condition of the snow roads. This study served to explore methodology that could quantify the impact of various vehicles, tires, driving speeds and maneuvers on the snow-road conditions. Basic maneuvers were used to isolate the impact of turning, acceleration, braking and speed using spirals, circles, and straight-line testing on flat, smooth snow pavements. In addition, a road course was set up to include corners and surface roughness using portions of the active snow-road system for more realistic conditions. Measurements included snow surface strength both in and between tire tracks, tire-track rut depth and width, and the height and width of the resulting snow piles adjacent to the tire tracks. Since this type of testing has not been previously conducted on snow roads or using these vehicle types, the experiments yielded valuable guidance regarding what types of maneuvers, test surfaces, and measurements could most easily differentiate performance. Results indicate the impacts of driving speed and vehicle type, including the importance of the tire and suspension components, on preserving satisfactory snow-road surfaces through the melt season.

Evaluation of a New SnowPaver at McMurdo Station, Antarctica,
ERDC/CRREL TR-14-16 (Shoop, Alger, et al. 2014)

Abstract: The Keweenaw Research Center (KRC) of Michigan Technological University, the Cold Regions Research and Engineering Laboratory (CRREL), and the National Science Foundation (NSF) have teamed to assess the feasibility of using new grooming and milling equipment to build snow pavements in Antarctica. The SnowPaver, a single unit consisting of leveling blades, a milling unit developed specifically for use on snow, and a

vibratory compactor, was built and shipped to McMurdo in November 2010. The SnowPaver was used to build several snow pavement sections that were monitored and subjected to controlled trafficking during the austral summer of 2010-2011. Measurements included snow strength and tire rut depths. Even though the miller portion of the paver was initially underpowered, the SnowPaver sections held up reasonably well. The paver was also found to be useful for reworking and compacting old and slushy snow during the height of the warm season. In November 2012 an upgrade the SnowPaver hydraulics and power was installed allowing full leveling, milling and compaction all with one pass of the implement.

Maintenance and Drainage Guidance for the Scott Base Transition, Antarctica, ERDC/CRREL TR-14-25 (Shoop, Hills, and Ueberuaga 2014)

Abstract: The snow roads at McMurdo Station, Antarctica, are the primary transportation corridors for moving personnel and material to and from the airfields servicing intra- and intercontinental air traffic. The majority of the road system is made of snow overlying a snow and ice subsurface. However, at the Scott Base Transition (SBT), the aggregate road leading from Scott Base transitions from the land mass of Ross Island on to the ice shelf and becomes a full depth snow road. Because of the transition between materials, the topography of the area, and extensive use during the austral summer, the SBT is prone to problems unique to that portion of the McMurdo road system and requires specific maintenance activities to remain passable during periods of higher temperatures. The SBT area is divided into two subsections: the Land Transition, a soil- or aggregate-surfaced road underlain by permafrost, and the Ice Transition, a snow-surfaced road underlain by snow and ice. The two sections of the SBT need entirely different construction and maintenance techniques to maintain road surface conditions that will support vehicle traffic. This document provides a baseline guide for construction, maintenance, and repairs of the two distinctly different segments of the SBT.

Snow-Road Construction and Maintenance Methods for McMurdo Station, Antarctica, ERDC/CRREL TR-16-16 (Shoop et al. 2016)

Abstract: The snow roads at McMurdo Station, Antarctica, are the primary transportation corridors for moving personnel and material to and from the airfields servicing intra- and intercontinental air traffic. These roads require specific construction and maintenance activities to allow passage

by the vehicles in the McMurdo fleet and to prevent significant deterioration during the warmer periods of the Antarctic summer. This document provides a guide for construction, maintenance, and repairs of the snow roads on the Ross Ice Shelf at McMurdo Station.

2010/11 McMurdo Station Snow-Road Strength and Maintenance,
ERDC/CRREL TR-17-3 (Melendy and Shoop 2017)

Abstract: During the 2010-2011 Antarctic field season a snow-roads and transportation study was carried out for a second year by the Cold Regions Research and Engineering Laboratory (CRREL) at McMurdo Station. Part of this season's study was to track road maintenance and temperature, and to test the snow-road strength at predetermined mile markers along the 13 miles of snow roads located on the permanent ice shelf that connects the Pegasus Runway to McMurdo Station. This data was recorded for each lane of road, at six locations, over a five month period. A Clegg Impact Hammer and a Rammsonde Cone Penetrometer were used to capture not only the surface strength but the strength of the road with regard to depth. The temperature data was collected using a handheld probe to measure temperature of the air, surface, approximately 7.6-cm and 15.2-cm deep.

Analysis of the data provides insight as to the direct effects of the various maintenance and environmental factors on the strength of the roads. Understanding the effects of these variables on the snow roads will ensure the roads are kept operational for as long as possible and increase the efficiency of McMurdo Station transportation infrastructure. This data will also contribute to the creation of standard operating procedures for maintaining the snow roads at McMurdo Station.

C.2 Conference and Journal Papers and Presentations

"Snow Roads at McMurdo Station Antarctica" (Shoop et al. 2009)

"Vehicle Tracking on Snow Roads, McMurdo Station, Antarctica" (Knuth and Shoop 2010)

"Development of Processed Snow Roads in Antarctica" (Alger et al. 2011)

"Impact of Snow Road Maintenance on Road Strength at McMurdo Station, Antarctica" (Melendy, Shoop, and Knuth 2011)

“Maintenance on Snow Roads in Antarctica” (Gervais et al. 2011)

“Measuring Vehicle Impacts on Snow Roads” (Shoop et al. 2011)

“Using a Clegg Impact Hammer to Measure Snow Strength” (Shoop, Knuth, and Crandell 2012)

“Evaluating a New Snow Miller/Paver for Snow Roads” (Shoop, Knuth, and Alger 2013)

“Measuring Vehicle Impacts on Snow Roads” (Shoop, Knuth, and Wieder 2013)

“Maintenance and Drainage Issues for Gravel and Snow Road Transitions: Case Study at the Scott Base Transition, Antarctica” (Shoop, Hills, and Uberuaga 2015)

C.3 Other Reports

Alger, R. G. 2004. *Development of Snow Roads, Runways, and Improved Trails*. Unpublished report for CRREL.

Alger, R.G. 2010. *SnowPaver Testing Notes*. KRC contract report for CRREL.

Arcone, S., and K. Bjella. 2009. *Ground Penetrating Radar (GPR) Study of the Transition Area Near Scott Base*. Unpublished report for NSF.

Abbreviations

ASC	Antarctic Support Contract
ATO	Antarctic Terminal Operations
CBR	California Bearing Ratio
CRREL	Cold Regions Research and Engineering Laboratory
ERDC	US Army Engineer Research and Development Center
FY	Fiscal Year
HMW	High Molecular Weight
KRC	Keweenaw Research Center
LGP	Low Ground Pressure
MP	Mile Post
NPG	Pegasus Runway Designator
NSF	National Science Foundation
PAX	Passenger
SBT	Scott Base Transition
SRT	Snow Roads and Transportation
USAP	US Antarctic Program

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1. REPORT DATE (DD-MM-YYYY) August 2022		2. REPORT TYPE Technical Report / Final		3. DATES COVERED (From - To) FY10–FY13	
4. TITLE AND SUBTITLE McMurdo Snow Roads and Transportation: Final Program Summary				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT	
6. AUTHOR(S) Sally A. Shoop, Wendy L. Wieder, and Terry D. Melendy				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army Engineer Research and Development Center (ERDC) Cold Regions Research and Engineering Laboratory (CRREL) 72 Lyme Road Hanover, NH 03755-1290				8. PERFORMING ORGANIZATION REPORT NUMBER ERDC/CRREL TR-22-11	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Science Foundation, Office of Polar Programs 2415 Eisenhower Avenue Arlington, VA 22314				10. SPONSOR/MONITOR'S ACRONYM(S) NSF	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES Funded under Engineering for Polar Operations, Logistics, and Research (EPOLAR) EP-ANT-13-03, "Snow Roads and Transportation Monitoring and Guidance."					
14. ABSTRACT The snow roads at McMurdo Station, Antarctica, are the primary transportation corridors for moving personnel and material to and from the airfields servicing intra- and intercontinental air traffic. The majority of the road system is made of snow overlying a snow, firn, and icy subsurface and is particularly susceptible to deterioration during the warmest parts of the austral summer when above-freezing temperatures can occur for several days at a time. Poor snow-road conditions can seriously limit payloads for all types of ground vehicles. The US Army Cold Regions Research and Engineering Laboratory (CRREL) studied the McMurdo snow roads for the National Science Foundation Office of Polar Programs as part of the Snow Roads and Transportation (SRT) program. The goals of the SRT program was to improve construction, maintenance, and use of the McMurdo's snow roads, with particular attention on minimizing warm-season deterioration. This is the final report of the SRT program, summarizing the program's activities and findings and emphasizing those parts of the program not previously documented in CRREL Reports, conference papers, or journal articles.					
15. SUBJECT TERMS Engineering--Cold weather conditions, EPOLAR, McMurdo Station (Antarctica), NSF, Roads--Antarctica--Design and construction, Snow mechanics					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code)