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CRREL

Estimated Snow Parameters for Vehicle Mobility Modeling in Korea, Germany and Interior Alaska

Timothy Horrigan and Roy E. Bates

September 1995

Abstract

Snow is a crucial factor affecting the U.S. Army's operations in cold regions. Values for snow depth and snow density are needed for vehicle mobility studies, but unfortunately the available historical records of these parameters tend to be relatively sparse. This report deals with the estimation of snow density and snow depth from readily available parameters such as air temperature and wind speed. As a basis for further study, the authors have summarized previous work in three areas of particular interest to the U.S. Army's vehicle mobility programs: Korea, Germany and Alaska. Empirical models are presented for estimating snow parameters in these regions.

For conversion of SI units to non-SI units of measurement consult *Standard Practice for Use of the International System of Units (SI)*, ASTM Standard E380-93, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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September 1995

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OFFICE OF THE CHIEF OF ENGINEERS

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PREFACE

This report was prepared by Timothy Horrigan, Physical Science Technician, Geological Sciences Division, Research and Engineering Directorate; and Roy E. Bates, Meteorologist, Remote Sensing / GIS Center, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire. Funding was provided by Office of the Chief of Engineers under Project 633734T08, *Combat Engineering Systems.* The authors thank Austin Hogan and Paul Richmond for their technical reviews. Others who have made valuable contributions to this study include Michael Bilello, Richard K. Haugen, Janet P. Hardy, Sally Shoop, Darryl Calkins and David Cate.

Estimated Snow Parameters for Vehicle Mobility Modeling in Korea, Germany and Interior Alaska

TIMOTHY HORRIGAN AND ROY E. BATES

INTRODUCTION

Snowfall and snow density are two important factors for mobility modeling and simulation. Knowledge of the regional distribution of these parameters would also contribute materially toward the solution of numerous other winter problems. This report is a result of a request to CRREL from the Waterways Experiment Station (WES) in Vicksburg, Mississippi, for realistic estimated values of the regional variation of snow cover. These values are needed for verifying and validating WES's mobility prediction models.

Three areas of the Northern Hemisphere were selected to test and validate current prediction algorithms residing within the mobility models: interior Alaska, central and southern Germany, and Korea north of the 38th parallel. The snow parameters needed are the average and worst-case monthly and winter snow density (g/cm^3) and the accumulated snow depth (cm). To accomplish this task, average and worst-case values were estimated by gleaning results from many earlier published reports. Much of the data was selected from a CD-ROM called *International Station Meteorological Climate Summary* (ISMCS) (U.S. Navy, U.S. Air Force, U.S. Dept. of Commerce 1992).

INTERIOR ALASKA

The results of a study completed at Fort Greely by Bilello et al. (1970) are a good starting point for estimating the snow conditions in interior Alaska. The terrain and climate at Fort Greely is typical of interior Alaska in general. This study dealt primarily with field tests conducted in the winter of 1966–67, which was unusually snowy. (The unusually high snowfall is useful from a mobility modeling standpoint, since one of the most important objectives of such modeling is to define a plausible worst-case scenario.)

Snow density was one of several properties of the snowpack investigated during the study. This was measured by means of density tubes inserted into various layers of the snowpack, and a weighted average of the density tube values was used to represent the overall density of the snowpack. These weighted-average snow density values do not take into account the densities of the ice crusts and ice lenses within the snowpack. However, the contribution of such ice inclusions to the overall density should presumably be minor.

The average snow density at the nine test sites at Fort Greely was 0.233 g/cm^3, which represents a medium snow density. The lightest snow tended to be found early in the season and at sites with vegetation cover. (Uncovered open areas had denser snow because of snow drifts from wind packing.) The lightest measured density of the entire snowpack came on November 28 at the forested site, when the average snow density was only 0.140 g/cm^3.

The top layer of the deep snowpack is the most important from a mobility modeling viewpoint (since vehicles travel over the top of the snow). The newer snow in the top layer is much lighter than the older snow in the lower layers. Most top-layer density values were on the order of 0.100 g/cm^3, but values as low as 0.038 g/cm^3 and as high as 0.424 g/cm^3 were observed.

The worst case for mobility modeling purposes is most likely to have average snow densities from approximately 0.350 to 0.500 g/cm^3 when traversing upslope. Above 0.500 g/cm^3 there would be little or no vehicle sinkage, and trafficability would be of little concern. On level ground, snow density has less effect; the depth of snow is the major concern in this case.

Snow depths are difficult to characterize, since they vary greatly according to the microclimate, microgeography, aspect and vegetation cover (open or forested). Open sites tend to have lower snow depths, because the higher winds in open areas tends to compact the snow more. The snow in the forested areas is also colder than the snow in open areas, which means that there is less melting of the outer surfaces of the ice crystals in the snowpack, slowing down the compaction and settling process.

The greatest snow depth measured in a forested site at Fort Greely was 116 cm, and the greatest snow depth at the open site was 50 cm. The Fort Greely study did not address the issue of drifting, and the snow depths are determined by taking the average of snow courses set out over a relatively wide area. A worst-case value for the maximum seasonal snow depths at Fort Greely would be approximately 125 cm. A slightly higher figure should be used for higher-precipitation areas in interior Alaska.

The Fort Greely study cites an earlier study by Bates and Bilello (1966) where an empirical relation between air temperature, wind speed and snow density was derived:

$$R = 0.152 - 0.0031T + 0.019W \tag{1}$$

where R = average seasonal snow cover density (g/cm^3)
T = average seasonal air temperature (°C)
W = average wind speed (m/s).

This equation was taken from measurements for Alaska, the northern contiguous United States and Canada. It presumably should be limited to these relatively cold areas.

We next apply this equation to a few stations in Alaska. We will assume that the snow season runs from the beginning of November through the end of April. The average temperatures at these sites over the period of record (1948–1990) are shown in Table 1.

The average wind speeds over the same period are shown in Table 2. Using these data and eq 1 results in the estimates of average snow density over the whole season shown in Table 3. Equation 1 can also be used for estimating the average densities for each of the months of the snow season by estimating the snow density for the entire period from November through the month in question and then using a weighted-average technique to remove the previous month's estimated value (Table 4).

A somewhat less complicated approach to estimating monthly snow densities is found in a

Table 1. Average temperature (°C) at various Alaska sites (1948–1990). The data are derived from the *International Station Meteorological Climate Summary* (U.S. Navy, U.S. Air Force, Dept. of Commerce 1992).

	Nov	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*
Anchorage	–5.6	–8.9	–9.4	–7.8	–3.9	2.2
Barrow	–17.8	–23.3	–24.4	–26.7	–25.0	–17.8
Bethel	–5.0	–10.0	–10.6	–10.6	–6.1	0.0
Big Delta	–13.9	–19.4	–20.0	–16.7	–10.6	–1.1
Fairbanks	–15.6	–21.1	–22.8	–19.4	–11.7	–0.6
Kotzebue	–12.8	–17.8	–17.8	–19.4	–17.2	–11.1

Table 2. Average wind speed (m/s) at various Alaska sites (1948–1990). The data are derived from the *International Station Meteorological Climate Summary* (U.S. Navy, U.S. Air Force, Dept. of Commerce 1992).

	Nov	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*
Anchorage	2.78	2.68	2.83	3.04	3.04	3.19
Barrow	5.92	5.25	5.35	5.09	5.09	5.20
Bethel	5.35	5.76	5.97	6.28	5.81	5.35
Big Delta	4.37	5.40	5.61	4.73	4.22	3.40
Fairbanks	1.59	1.34	1.39	1.75	2.32	2.83
Kotzebue	6.28	6.02	6.28	5.92	5.30	5.35

Table 3. Average seasonal snow density (g/cm^3) at various Alaska sites calculated using eq 1.

Location	*Density*
Anchorage	0.225
Barrow	0.323
Bethel	0.283
Big Delta	0.282
Fairbanks	0.235
Kotzebue	0.313

Table 4. Cumulative snow density (g/cm^3) at various Alaska sites calculated using eq 1 and a weighted-average technique.

	Nov	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*
Anchorage	0.222	0.230	0.235	0.234	0.222	0.206
Barrow	0.320	0.324	0.329	0.331	0.326	0.306
Bethel	0.269	0.292	0.298	0.304	0.281	0.254
Big Delta	0.278	0.315	0.321	0.294	0.265	0.220
Fairbanks	0.231	0.243	0.249	0.246	0.232	0.207
Kotzebue	0.311	0.321	0.326	0.325	0.306	0.288

1957 report by Bilello. The equations, which do not account for wind speed and which are applicable only to locations north of 62°00′N at elevations less than 1500 ft (or approximately 450 m), are as follows:

$$\begin{aligned}\text{Nov: } & R\,(\text{Nov}) = -0.0098 T_{avg}\,(\text{Nov}) + 0.090 \\ \text{Dec–Feb: } & R\,(\text{month}) = -0.010 T_{avg}\,(\text{month}) + 0.016 \quad (2) \\ \text{March: } & R(\text{Mar}) = -0.0048 T_{avg}\,(\text{Mar}) + 0.197\end{aligned}$$

where R (month) is the average monthly snow density (g / cm^3), and T_{avg} (month) is the average monthly air temperature (°C). These equations yield the monthly estimated snow density values shown in Table 5.

Table 5. Estimated snow density (g/cm^3) at various Alaska sites calculated using the equations of Billelo (1957).

	Nov	*Dec*	*Jan*	*Feb*	*Mar*
Anchorage	0.144	0.105	0.110	0.094	0.216
Barrow	0.264	0.249	0.260	0.283	0.317
Bethel	0.139	0.116	0.122	0.122	0.226
Big Delta	0.226	0.210	0.216	0.183	0.248
Fairbanks	0.242	0.227	0.244	0.210	0.253
Kotzebue	0.215	0.194	0.194	0.210	0.280

A later study by Bilello (1984) examined snow cover properties in the former Soviet Union by analyzing published data from 41 locations where both snow density and wind speed were measured. The Soviet data proved to be consistent with the North American data in Bilello's earlier studies, once an adjustment was made for the Soviet densitometers, which systematically gave readings about 25% lower than those obtained by the equivalent measurement instruments used in the U.S.

A recent study by Sturm et al. (in press) proposed a scheme for classifying snow cover into seven categories. Data collected in the field in Alaska showed that snow density was the most powerful statistical criterion for distinguishing between various types of snow. The goal of Sturm's work is to develop techniques for distinguishing between these classes of snow without an extensive field measurement program, using readily available information such as satellite imagery and climatic data. Five of these classes (excluding ephemeral snow, which is found in areas with intermittent snow cover, and mountain snow, which is found in mountainous areas and other cold areas with highly variable snow cover) are defined by a binary scheme whereby temperature, wind speed and precipitation are characterized as high or low.

CENTRAL GERMANY

The snowfall data for Germany are relatively sparse in the most readily available data sources (at least for those commonly used by U.S.-based researchers); for example, only 10 stations in the Airfield Weather Summary database have complete snow data (U.S. Navy, U.S. Air Force, Dept. of Commerce 1992). However, there are numerous stations where air temperature data are available but no snow data. Bates and Bilello (1988) compensated for this shortage of data by matching data for the northeastern United States with that for Germany. Snow and temperature conditions are quite comparable in these two areas, if the analysis is limited to those areas with a mean January temperature ≥–8°C and an elevation <600 m.

A linear regression of 45 U.S. stations and 10 German stations (Bates and Bilello 1988) yields the following relationship between average January temperature and annual total snowfall:

$$S(\text{Total}) = 54.0 - 17.6\ T(\text{Jan}) \qquad (3)$$

where S(Total) is the total annual snowfall (cm), and T(Jan) is the average January temperature (°C).

Snow depth data were available only for the U.S. cities (Bates and Bilello 1988). When the values for the average maximum snow depth (during an average winter) were regressed against the January temperature, the following relationship was derived:

$$D(\text{max}) = 14.1 + 5.34\ \text{T(Jan)} \qquad (4)$$

where D(max) is the average maximum snow depth (cm).

Bates and Bilello's (1988) work was applied to the Hunfelds quadrangle, which is a roughly 22- ×22-km area just west of the border between the former East Germany and West Germany. The Hunfelds area has been intensively studied by WES and other Corps of Engineers laboratories to determine the environmental factors that affect Army materiel. The estimated January temperatures and other climatic parameters were determined for every grid square within the quadrangle (at 30-m resolution), and these estimated parameters were used to estimate the snowfall and snow depth (Fig. 1).

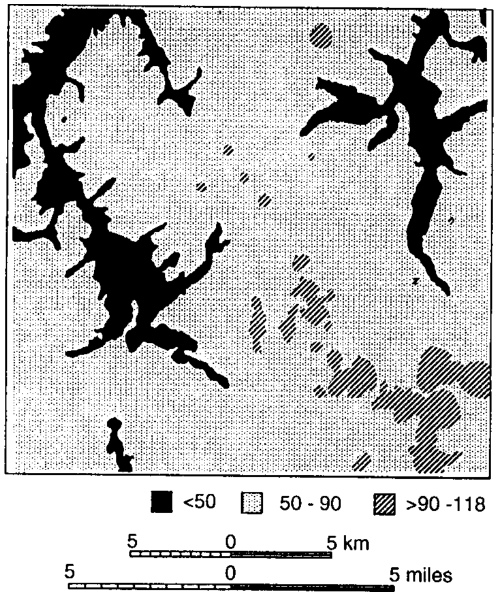

Figure 1. Average annual snowfall (cm), Hunfeld Quadrangle area. (After Causey and West 1990.)

The most obvious limitation of Bates and Bilello's approach is that Germany is not the U.S. However, the German snowfall data do appear to be similar to the U.S. data, and it seems safe to assume (in the absence of better data) that snow values are comparable in the two regions.

An equally important, though slightly less obvious, limitation is that the climatic data in the study were collected at open, urban locations. The microclimatic conditions on the battlefield would not, of course, necessarily be similar to those found at the places where the recordings are being made. Luckily, there are also a number of rural areas in the northeastern U.S. where field data have been collected. As at Fort Greely, this study has the additional limitation of not addressing the issue of drifting, which is crucial to vehicle mobility.

Average midwinter average snow depths for central Germany are 20–30 cm, with midwinter average snow densities of 0.25–0.30 g/cm^3. A good set of worst-case numbers for central Germany are a minimum snow density of 0.04 g/cm^3 and a maximum snow depth of 60 cm. [The minimum snow density value is slightly lower than the lowest value obtained in the field mobility tests at CRREL, reported by Richmond (1993).]

One of the relatively few locations where snowfall and snow depth data are readily available is Fulda (U.S. Navy, U.S. Air Force, Dept. of Commerce 1992). The average January temperature at Fulda was approximately 0.3°C over the period of record (1960–1990). This implies an estimated average maximum snow depth of 15.6 cm. The average of the recorded yearly snow depth maxima over the same period of record was 12.3 cm, which means that the algorithm is somewhat inaccurate in this case, but still close enough to be useful for initial mobility analysis purposes, in the absence of further information. Two important parameters have been left out of this simple algorithm: elevation and wind speed. Fulda's elevation (301 m) is relatively high for central Germany (though obviously much lower than the more alpine locations to the south), as is its average wind speed (5 knots, or 2.6 m/s).

A long-term frequency distribution for snow depth at Fulda for 1960–1990 is shown in Table 6. Even during the three snowiest months of the winter (December through February) there is usually no measurable snow on the ground at Fulda: for example, even in the snowiest month, January, there was no measurable snow on the ground 59% of the time. The median snow cover when there is a measurable snow cover is approximately 2–3 in. (5–8 cm), but the snow depth can get much greater on occasion. The deepest snow recorded between 1960 and 1990 at Fulda was 46 cm, in both January and February 1963.

Table 6. Frequency distribution for daily snow depth at Fulda AAF, Germany (50°33′N, 009°39′E, 301 m elev). The data are derived from the *Internation Station Meteorological Climate Summary* (U.S. Navy, U.S. Air Force, Dept. of Commerce 1992).

Amount (cm)	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Total*
None	44.2	53.2	81.6	98.3	100	100	100	100	100	99.7	84.9	65.3	85.0
Trace	15.1	15.7	11.4	1.6						0.3	8.1	11.5	5.5
0–3	9.0	10.0	2.3								3.5	8.1	2.8
3–5	7.3	7.6	1.7	0.1							1.4	5.1	2.0
6–10	7.2	2.9	1.1								1.5	4.1	1.5
10–15	10.2	6.2	1.1								0.6	4.9	2.0
16–30	6.3	0.8	0.9									0.9	0.8
31–60	0.7	3.6											0.4
Meas. amt.	40.7	31.1	7.0	0.1							7.0	23.2	9.5
No. of obs.	764	713	754	688	687	685	685	700	666	701	714	738	8495

KOREA

The situation regarding snow data for Korea is similar to that for Germany, i.e., snowfall and snow depth data are mostly unavailable in the standard climatic data sources. The ISMCS CD-ROM, for example, has only three stations in Korea with snowfall data, and two of those stations have short periods of record.

An excellent basic resource for studying the Korean climate is a very old but still useful study published by the Environmental Protection Section of the Department of the Army in 1950. This study points out that "outdoor conditions in Korea are in most respects like those which would be encountered in the corresponding places in the United States." In general, western Korea is climatically similar to the Mississippi Valley, and the Korean Pacific coast is similar to the mid-Atlantic and New England regions (Fig. 2).

A snowpack forms nearly every winter for at least 30 days in Korea north of 35°N latitude and at higher elevations south of this latitude. Good worst-case numbers for vehicle mobility analysis are similar to those used for Germany or the northeastern United States, i.e., a maximum snow depth of 60 cm, a maximum snow density of 0.4 g/cm^3 and a minimum snow density of 0.04 g/cm^3.

The three Korean stations in the ISMCS database that have records of snowfall are all in South Korea. Two of these—Camp Stanley (37°34′N, 127°06′E) and Camp Humphries (36°57′N and 127°02′E)—had periods of records that were less than ten years long, with a considerable amount of missing data. Suwon AFB (37°15′N, 127°00′E) had a long (1951–1988) and relatively complete record, however. Suwon is located at an elevation of 25 m on the east coast of South Korea, roughly 50 km south of Seoul. The areas of most interest are well to the north of Suwon and at much higher elevations.

The average annual snowfall over the period of record at Suwon was 36 cm, with an estimated depth on the ground of 15–20 cm. The average January temperature was –3.9°C, with an average daily maximum of +1.1°C and an average daily minimum of –8.9°C. In an average January–February period, the minimum temperatures fell below freezing 56 days out of the total 58. Winter conditions are presumably less severe here than in most other northern parts of Korea, including the areas of military interest near the border between South and North Korea.

The single greatest daily snow depth ever recorded at Suwon during the period of record was 38 cm, on 31 January 1969 (occurring shortly after the record daily snowfall of 26 cm on 28 January 1969.) In an average year the maximum snow depth was only 8.4 cm.

The median values for the beginning and end of the snow season over the period of record at Suwon were as follows:

First snowfall:	Nov 25
First measurable snowfall:	Dec 6
First measurable snow depth:	Dec 22
Last measurable snow depth:	Feb 12
Last measurable snowfall:	Mar 9
Last snowfall:	Mar 24.

The earliest date for the initial formation of the

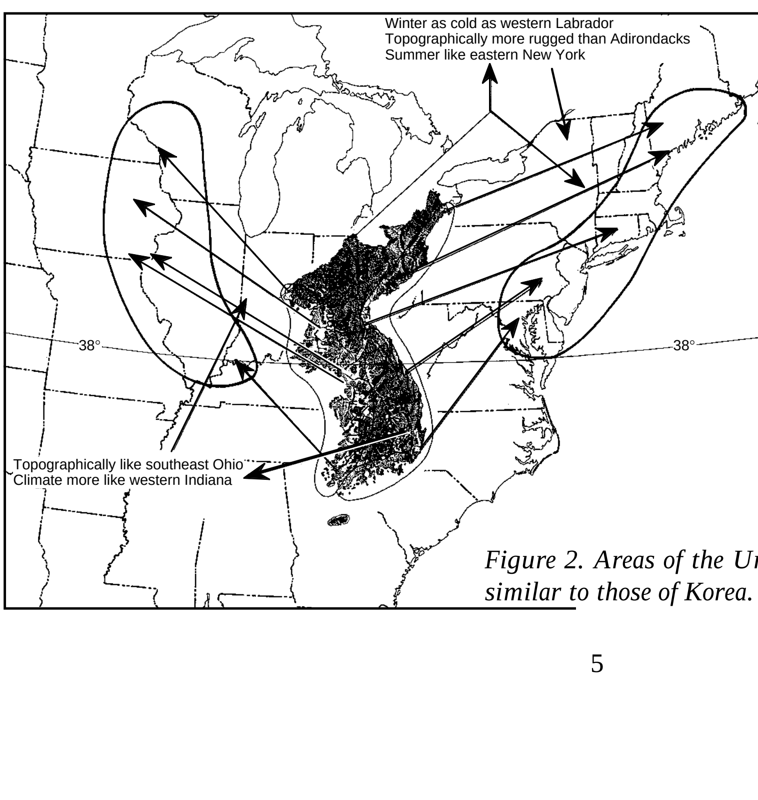

Figure 2. Areas of the United States with climates and topography similar to those of Korea. (After U.S. Army 1950.)

snowpack at Suwon was in 1985, when the first measurable snow depth occurred on 11 November. The latest date for the final disappearance of the snowpack was in 1976, when the last measurable snow depth occurred on March 22.

Although the Suwon data cover only point information, they do tell us a few simple but useful things. First, they show that there is a significant amount of snow in those parts of Korea north of 35°00′N latitude. Second, we can see that the snowpack is likely to be relatively dense, since most of the country experiences a large number of freeze–thaw cycles. Snow depth is in general highly elevation dependent, and of course the snow depths in most parts of Korea, especially North Korea, will be much higher than those at Suwon's relatively low elevation.

ESTIMATED AVERAGE AND WORST-CASE VALUES

Table 7 shows our recommendations for the estimated average and worst-case values for snow depth and density. The worst-case snow depth represents what one might find at the height of an unusually severe snow season, and the density is simply the density that one might find at the worst point of the same season. These values correspond to flat, open ground; in the field, one will of course typically have to deal with sloping ground with a variety of cover types.

Table 7. Recommendations for average and worst-case snow density and depth values for interior Alaska, central Germany and Korea.

	Density (g/cm^3)	*Depth (cm)*
Alaska		
Average	0.230	50
Worst-Case	0.425	125
Central Germany		
Average	0.275	25
Worst-Case	0.400	60
Korea		
Average	0.275	18
Worst-Case	0.400	38

Malcolm Mellor's 1964 monograph continues to be one of the best introductions to the properties of snow. One of Mellor's general comments about snow is of particular relevance:

> During its fall to earth, a snow crystal may undergo considerable change. Variation of temperature and humidity with altitude leads to changes in growth rate and form, and there may even be evaporation or melting of the crystal. Particles may be "recycled" through some layers by turbulence in the air and, during windy conditions at the surface, fragmentation of the more delicate crystal types often occurs.
>
> The character of the surface deposit after a snowfall depends on the form of the crystals and on the weather conditions during deposition. When there is no appreciable wind, dry stellar crystals (which commonly aggregate into large snowflakes) settle as a soft, fluffy mass whose density is generally less than 0.1 g/cm^3. Very small crystals of simple prismatic form, on the other hand, settle to relatively high initial densities (say 0. 2 g/cm^3) for obvious geometrical reasons. Snow deposited in wind-free weather has a smooth surface. When a snowfall is accompanied by strong winds, crystals are broken into fragments favorable for close packing, and the surface of the deposited snow is mechanically agitated by wind shear and by the impact of bounding particles. This produces high initial density, commonly greater than 0.3 g/cm^3, and also leads to the formation of snow dunes and sastrugi on the surface.
>
> After deposition, snow may be dissipated by melting and evaporation or it may persist for long periods. If it persists, it will undergo metamorphism, changing its grain texture and structure and eventually turning into hard, impermeable ice if it is part of a perennial snow deposit.

Attempts to estimate snow depth and snow density in the absence of direct data need to take three general classes of phenomena into account. Firstly, it is useful to know the upper air conditions (temperature, water content, etc.) that determine how much snow is produced in the cloud layer and what type of snow crystals fall. Second, one needs to know the temperature regime at the surface, which determines how fast the snow melts. Third, one needs to know about the wind regime at the surface, which regulates wind-packing, drifting, etc. Only the second and third classes of phenomena have been directly addressed in the work by Bilello, Bates and others that have been summarized above.

The most difficult snow conditions for vehicle mobility occur when snow densities are in the range around 0.3–0.4 g/cm^3. Newly fallen snow reaches these densities only when there is a significant amount of wind. This is not much consolation for a vehicle mobility modeler, however, since virtually all areas of the earth, including Korea, Alaska and Germany, do commonly experience significant winds.

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13. ABSTRACT (*Maximum 200 words*)

Snow is a crucial factor affecting the U.S. Army's operations in cold regions. Values for snow depth and snow density are needed for vehicle mobility studies, but unfortunately the available historical records of these parameters tend to be relatively sparse. This report deals with the estimation of snow density and snow depth from readily available parameters such as air temperature and wind speed. As a basis for further study, the authors have summarized previous work in three areas of particular interest to the U.S. Army's vehicle mobility programs: Korea, Germany and Alaska. Empirical models are presented for estimating snow parameters in these regions.

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