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# DEMONSTRATION OF A PORTABLE DEVICE FOR PREDICTING VEHICLE TRACTIVE PERFORMANCE IN SNOW

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**Summary.**—This workshop study program which was sponsored by the ISTVS Snow Mechanics Committee examined the problems of snow traction and methods of predicting vehicle mobility on snow. This study presents one aspect of the field prediction problem where a portable, hand-held instrument is used and prescribed by requirements for simplicity, portability and facility.

## INTRODUCTION

DURING A recent workshop on mobility and snow traction mechanics [1], a demonstration was conducted on a portable device for predicting vehicle performance in deep snow. The field portion of the workshop was located in a deeply snow covered portion of Little Cottonwood Canyon lying within a mountain chain neighbouring Salt Lake City, Utah. For this particular field study, the simple hand-held tool was chosen as the candidate device. One such tool available—in the developmental stage—is a hand-held penetrometer equipped with vanes. This had not yet been used in a field predictive system for vehicle drawbar pull and sinkage prior to this Workshop trial series. Of particular interest is the use of such a tool in support of track-laying vehicles operating in deep, soft, snow. It is useful to note at this stage that the snow-vane-cone device differs from the soft soil vane-cone in that the cone used is considerably wider—as shown in Fig. 1. The device, if successful in its use for field operations, would offer distinct advantages of lightness, operability by one individual, simplicity and ruggedness. Although the design concept is still evolving, as is the supporting theory, a description of the device at its present stage of development and results of its demonstration at the Workshop are here presented.

This paper deals only with penetrometer tests in deep snow rather than shallow or crusted snow in support of tracked vehicles. Deep snow situations are most favourable for testing because bottom boundary conditions do not intrude on the full development of test performance. If one wishes to obtain a wider experience with various snow property constraints, shallow or crusted snow performance can be examined. The present test procedure, however, ignores the significant influence of bottom boundary condition on the control of performance of both vehicle and test tool.

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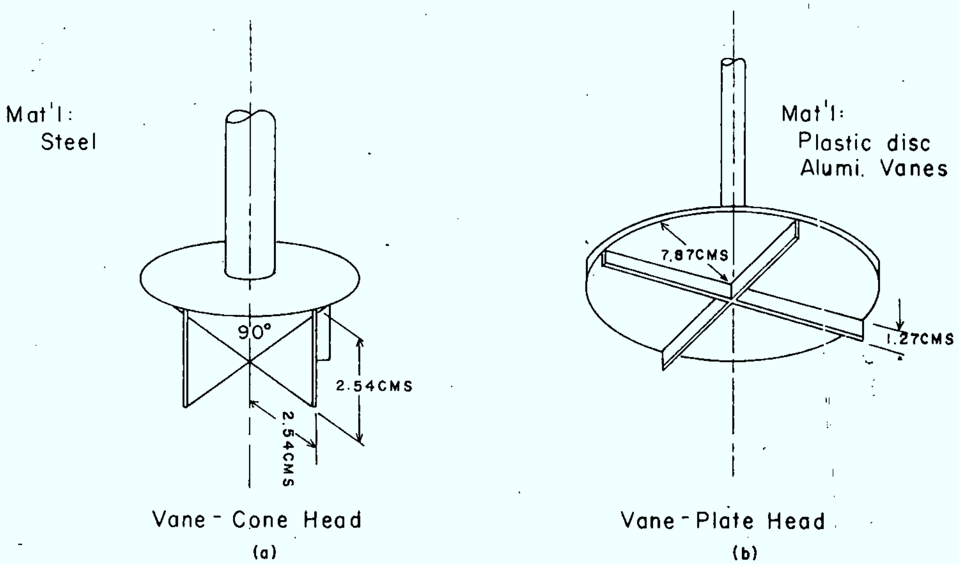

FIG. 1. Schematic presentation of vane-cone and vane-plate penetrometer devices.

## DESCRIPTION OF THE HAND-HELD PENETROMETER

Two types of sensing head attachments to the penetrometer are in current development and use. Sketches are given in Fig. 1. Figure 1(a) is that of a cone in combination with four orthogonally placed vanes. The application of such a device in soils has been described elsewhere [1]. For the second head type, the cone portion is replaced by a plate in the version of Fig. 1(b) while retaining the vanes.

## VANE-CONE PENETROMETER

In order to simulate the action of a track on snow, a sequence of snow compression followed by shear is used. The snow surface is preloaded vertically with a circular plate with an applied pressure equal to the mean maximum footprint pressure of the tracked vehicle under consideration. To minimize problems of scale, the plate diameter should be as large as can be handled by one person. Sizes of plate usually vary up to 20 cm. A conveniently slow increase in load (and corresponding plate sinkage) until the predetermined value of plate pressure is reached, reduces problems of rate effect and usually establishes repeatable results of pressure vs sinkage. The simplest means of recording data is by visually noting the indication on a hydraulic gauge or on a dial and proving ring combination. The stem of the penetrometer should be extendable and bear graduations for purposes of reading plate sinkage in snows of widely varying depth. The variables associated with the plate penetrometer are intended to correspond to the pressure and sinkage of tracked vehicles operating at maximum dynamic drawbar pull.

The plate is then exchanged for a vane-cone head. In the present experiment the cone angle used was 90°. The head is pushed into the pre-compacted snow to a depth of one vane-cone height so that the base of the cone is flush with the compacted snow surface. While maintaining the head at this position, a torque is applied until a maximum torque, at snow breakaway, may be read. A maximum torque reading is also taken in undisturbed snow at the same sinkage depth. Torque may be measured with a torque meter or spring scale and torque arm combination.

The above procedure should be repeated for statistical accuracy. In addition, by varying the preconditioning pressure of the plate penetrometer, a classification of the snow pack with regard to strength and trafficability may be obtained. This classification may take the form of profiles of (a) applied pressure vs plate sinkage and (b) maximum torque in both pre-loaded and unloaded snow vs plate sinkage.

The relationship used for the prediction of drawbar pull has been based directly on principles of energy conservation [2].

Useful work = input energy — (energy losses due to sinkage, slip, and drag).

or

$$F = \frac{T_{\max}\, n.b.L}{\Pi\left(\frac{d^2 h'}{2} + \frac{d^3}{6}\right)} - \left[\frac{W}{L} Z + \frac{T_{\max}\, n.b.L}{\Pi\left(\frac{d^2 h'}{2} + \frac{d^3}{6}\right)}\, i + \frac{2T'_{\max}\, .n.L.h}{\Pi\left(\frac{d^2 h'}{2} + \frac{d^3}{6}\right)}\right] . \qquad (1)$$

*Nomenclature*

| | |
|---|---|
| $F$ | vehicle drawbar pull |
| $n$ | number of tracks |
| $b$ | contact width of one track |
| $L$ | contact length of each track |
| $h$ | grouser height at the outside edges of each track |
| $W$ | vehicle weight |
| $Z$ | plate penetrometer sinkage |
| $d$ | cone base diameter |
| $h'$ | vane height |
| $i$ | assumed slip where $0 < i < 1$ |
| $T_{\max}$ | maximum applied torque of the vane-cone penetrometer in preloaded snow |
| $T'_{\max}$ | maximum torque in undisturbed snow. |

For the determination of the absolute maximum value of drawbar pull, set $i = 0$.

The supporting assumptions are as follows:

1. the tangential and the normal pressure distribution beneath each track are uniform;
2. the grousers are fully embedded in the snow;
3. the sinkage beneath the plate and the track are the same for the same normal pressure;
4. calculations are made to predict the maximum traction and maximum drawbar pull.

## VANE-PLATE PENETROMETER

Interest in the vane-plate penetrometer device was based on the need for an improved simulation of track action on soft snow. The snow is pre-loaded as before. The second step is to apply torque slowly while maintaining constant load. Maximum torque at break-away is noted. In order to correct for friction effects the above two steps are repeated using a plate without vanes. For drawbar pull prediction the following formula is given

$$F = \frac{T_{\max}\,(nL)\,(b+2h)}{\Pi\left(\dfrac{d^2\,h'}{2}+\dfrac{d^3}{6}\right)} - \left[\frac{W}{L}\,Z + \frac{T_{\max}\,n.L.(b+2h)}{\Pi\left(\dfrac{d^2\,h'}{2}+\dfrac{d^3}{6}\right)}\,i\right]. \tag{2}$$

The symbols are as defined above with the following exceptions: $d$ = vane-plate diameter; $h'$ = height of the vanes; and $T_{\max}$ = corrected value of maximum torque applied to the vane-plate.

## EXPERIMENTAL CONDITIONS

The use of the snow penetrometers followed the testing of five tracked vehicles in the deep snow of the Albion basin both on level terrain and on grades. Undisturbed snow was tested in both locations using the procedure just described. Atmospheric conditions at the time of tests consisted of overcast skies, intermittent snowfall and, little or no wind. The upper 30 cm of the snow cover was light and of low strength. Details of the snow classification may be obtained from the Workshop proceedings [2]. It is to be noted, however, that at 20 cm depth, there were consistent differences between snow on level ground where vehicle drawbar pull tests were carried out and snow on a nearby slope of 12–18° where gradability tests were conducted. See Table 1.

TABLE 1. SNOW PROPERTIES AT 20 cm DEPTH

| Location | Time (h/m) | Air temperature (°C) | Snow temperature (°C) | Density (kg/m³) | Canadian hardness test |
|---|---|---|---|---|---|
| Grade | 12 : 00 | −4 | −7 | 220 | 10 |
| Level snow | 16 : 30 | −10 | −8 | 172 | 1 |

Note that the nominal track pressure $P_n$ represents the pressure applied to the terrain surface *if* the track is a flat rigid plate of dimensions represented by $L \times b$. Since the vehicles were all two-tracked vehicles, the nominal track pressure calculated was $W/2bL$. However, from a realistic point of view, the actual effective track pressure is greater than $P_n$—dependent on the type of grouser used and the amount of real compression sinkage.

Table 2 shows pressure calculations for 1.25 $P_n$ to 2 $P_n$ situations. Laboratory experiments using a range of grousers (including those used on the 302) have shown that a useful approximation of the actual effective track pressure can be obtained with a knowledge of the height $h$ of the grousers. The greater $h$ is, the greater (by and large) is the effective pressure. The laboratory measurements show that the effective pressure $P_n$ can vary from 1.25 $P_n$ to 3 $P_n$ and sometimes as high as 5 $P_n$ if the terrain surface is relatively stiff. It follows that if the terrain surface is hard, and if no grouser penetration is obtained, $P_e$ can be many times larger than 5 $P_n$.

TABLE 2. VEHICLE SPECIFICATIONS

| Dimension and pressures | Thiokol* 3700 | Thiokol Spryte | Thiokol Imp (1450 model) | Bombardier 302 | Bombardier Bombi |
|---|---|---|---|---|---|
| $W$ (Newtons) | 55,603 | 35,808 | 16,014 | 40,034 | 11,121 |
| Track $L$ (cm) | 323 | 302 | 295 | 300 | 152 |
| Track $b$ (cm) | 145 | 114 | 91 | 135 | 58 |
| Track $h$ (cm) | 8.38 | 8.64 | 2.54 | 10.67 | 6.10 |
| *Nominal pressure* | | | | | |
| $P_n$, N/m$^2$ | 6067 | 5171 | 2965 | 4964 | 6274 |
| 1.25 $P_n$, N/m$^2$ | 7584 | 6481 | 3723 | 6205 | 7791 |
| 1.5 $P_n$, N/m$^2$ | 9101 | 7791 | 4482 | 7446 | 9308 |
| 1.75 $P_n$, N/m$^2$ | 10,618 | 9032 | 5171 | 8687 | 10,894 |
| 2 $P_n$, N/m$^2$ | 12,135 | 10,342 | 5929 | 9792 | 12,411 |

* Use of trade names in any context in this paper is not to be interpreted in any way as an evaluation of the vehicle. Only the penetrometers and their associated methodology should be considered for evaluation.

## RESULTS AND DISCUSSION

The raw data obtained with both penetrometers operating in previously undisturbed snow are presented in Tables 3 and 4. These were used throughout subsequent calculations of drawbar pull. A distinction was made between (a) penetrometer data from level snow where vehicle drawbar pull tests were carried out, and (b) penetrometer data from the snow grade where gradability tests were done.

TABLE 3. VANE-CONE PENETROMETER IN UNDISTURBED SNOW

| Preloading plate pressure (N/m$^2$) | Plate sinkage (cm) | | $T_{\max}$ ($N-m$) | | $T'_{\max}$ ($N-m$) | |
|---|---|---|---|---|---|---|
| | From level snow | From grade | Level | Grade | Level | Grade |
| 3998.96 | 9.4 | 10.16 | 0.14 | 0.38 | 0.0 | 0.0 |
| 6894.76 | 12.70 | 13.97 | 0.34 | 0.56 | 0.1 | 0.0 |
| 10,342.14 | 17.78–19.05 | 17.78 | 0.56 | 0.98 | 0.0 | 0.0 |
| 14,478.99 | 21.59–22.86 | — | 0.79 | — | 0.0 | 0.0 |

TABLE 4. VANE-PLATE PENETROMETER IN UNDISTURBED SNOW

| Applied plate pressure (N/m$^2$) | Plate sinkage (cm) | | $T_{\max}$ ($N-m$) | |
|---|---|---|---|---|
| | From level snow | From grade | Level | Grade |
| 4343.70 | 10.80 | 10.16 | 3.69 | 3.69 |
| 6687.91 | 14.22 | 13.97 | 5.34 | 5.60 |
| 13,100.04 | 20.32 | 20.32 | 6.50 | 7.15 |

Predictions of drawbar pull for the five vehicles are given in Tables 5 and 6. They are also plotted in Figs. 2 and 3 against plate pressure although only three vehicles (3700, Spryte, and 302) were successfully tested. The graphs of drawbar pull vs pressure allow for interpolation using nominal values of vehicle footprint pressure $P_n$ or any other effective pressure for the particular vehicle under consideration. The graphs are intended merely to show trends in the data since careful estimates of experimental error have not been undertaken. Note in Fig. 2, drawbar pull is plotted using only data from the level snow for clarity of presentation. Figure 3 shows the full range of prediction with the uppermost boundary of any given range corresponding to snow on a grade while the lowermost is for snow that is level.

For all calculations $i = 0$. Observers of the workshop advised that vehicle slip was very small at the point of maximum dynamic drawbar pull. In addition, slopes were variable. Hence for uniformity of procedure in calculations and for purposes of obtaining a prediction of the absolute maximum of dynamic drawbar pull regardless of slip value and local slope, the above simplifying assumptions were made.

TABLE 5. PREDICTION OF DRAWBAR PULL USING VANE-CONE (NEWTONS)

| Preloading plate pressure ($N/m^2$) | 3700 | | Spryte | | Imp | | 302 | | Bombi | |
|---|---|---|---|---|---|---|---|---|---|---|
| | From level | From grade | Level | Grade | Level | Grade | Level | Grade | Level | Grade |
| 3998.96 | 6632 | 13,505 | 4347 | 10,173 | 3745 | 8318 | 5133 | 11,957 | 721 | 2189 |
| 6894.76 | 15,031 | 21,120 | 10,987 | 21,093 | 9622 | 16,983 | 12,829 | 24,759 | 2180 | 4844 |
| 10,342.14 | 27,579 | 41,253 | 20,569 | 37,481 | 14,003 | 29,905 | 24,172 | 43,953 | 4519 | 8905 |
| 14,478.99 | 39,224 | — | 29,220 | — | 23,629 | — | 34,324 | — | 6583 | — |

TABLE 6. PREDICTION OF DRAWBAR PULL USING VANE-PLATE (NEWTONS)

| Preloading plate pressure ($N/m^2$) | 3700 | | Spryte | | Imp | | 302 | | Bombi | |
|---|---|---|---|---|---|---|---|---|---|---|
| | From level | From grade | Level | Grade | Level | Grade | Level | Grade | Level | Grade |
| 4344 | 13,460 | 13,572 | 10,382 | 10,502 | 7762 | 7798 | 12,335 | 13,225 | 2366 | 2411 |
| 6688 | 19,710 | 20,831 | 15,186 | 16,098 | 11,303 | 11,903 | 18,029 | 20,133 | 3523 | 3762 |
| 13,100 | 23,438 | 26,156 | 18,100 | 20,253 | 13,576 | 15,057 | 21,512 | 25,559 | 4061 | 4622 |

Table 7 shows a comparison of predicted and measured drawbar pulls on level terrain. Pull to weight ratios predicted with the penetrometers on level terrain are listed with the measured values of each performance related to nominal pressure $P_n$, and estimated actual effective track pressures equal to 1.25 $P_n$ to 2 $P_n$.

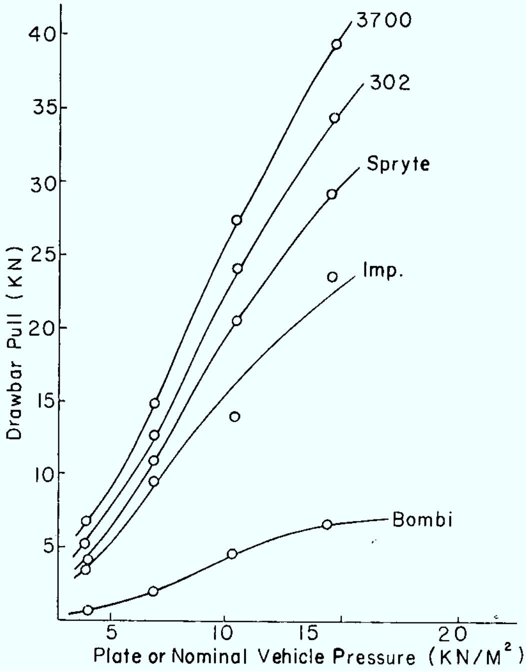

FIG. 2. Predicted curves for drawbar pull using vane-cone penetrometer.

Using the graph shown in Fig. 2, which portrays the predicted values of drawbar pull for the various vehicles at various preloading pressures ($P_n$ or multiples of $P_n$), one can begin to evaluate how well predictions correlate with actual measurements of vehicle performance. As observed from actual field measurements, the Thiokol 3700 vehicle developed a maximum drawbar pull (DBP) of 24.91 kN. From Fig. 2, if we

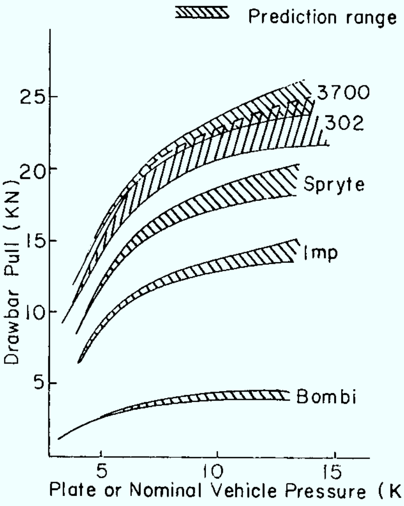

FIG. 3. Predicted curves for drawbar pull using vane-plate penetrometer.

TABLE 7. COMPARISON OF PENETROMETER PREDICTIONS FOR DRAWBAR PULL PERFORMANCE ON LEVEL TERRAIN $(DP/W)$

| Vehicle | Measured $(DP/W)$ | at $P_n$ $(DP/W)$ | at 1.25 $P_n$ $(DP/W)$ | at 1.5 $P_n$ $(DP/W)$ | at 1.75 $P_n$ $(DP/W)$ | at 2.0 $P_n$ $(DP/W)$ |
|---|---|---|---|---|---|---|
| (a) Utilizing vane-cone data from level terrain | | | | | | |
| 3700 | 0.44 | 0.21 | 0.31 | 0.42 | 0.50 | 0.60 |
| Spryte | 0.40 | 0.19 | 0.26 | 0.40 | 0.48 | 0.58 |
| Imp* | 0.44 | 0.13 | 0.19 | 0.25 | 0.34 | 0.44 |
| 302 | 0.47 | 0.20 | 0.28 | 0.37 | 0.48 | 0.56 |
| Bombi* | 0.60 | 0.16 | 0.25 | 0.32 | 0.45 | 0.52 |
| (b) Utilizing vane-cone data from slope | | | | | | |
| 3700 | 0.44 | 0.34 | 0.41 | 0.55 | — | — |
| Spryte | 0.40 | 0.36 | 0.48 | 0.64 | 0.82 | 1.08 |
| Imp | 0.44 | 0.37 | 0.47 | 0.60 | 0.72 | 0.86 |
| 307 | 0.47 | 0.39 | 0.52 | 0.65 | 0.79 | 0.94 |
| Bombi | 0.60 | 0.34 | 0.50 | 0.68 | 0.90 | >0.90 |
| (c) Utilizing vane-plate data from level terrain | | | | | | |
| 3700 | 0.44 | 0.33 | 0.37 | 0.39 | 0.41 | 0.42 |
| Spryte | 0.40 | 0.35 | 0.45 | 0.45 | 0.47 | 0.50 |
| Imp | 0.44 | 0.22 | 0.36 | 0.49 | 0.54 | 0.66 |
| 302 | 0.47 | 0.36 | 0.40 | 0.47 | 0.49 | 0.52 |
| Bombi | 0.60 | 0.30 | 0.32 | 0.34 | 0.38 | 0.38 |
| (d) Utilizing vane-plate data from slope | | | | | | |
| 3700 | 0.44 | 0.34 | 0.39 | 0.42 | 0.44 | 0.46 |
| Spryte | 0.40 | 0.36 | 0.44 | 0.49 | 0.51 | 0.59 |
| Imp | 0.44 | 0.22 | 0.36 | 0.51 | 0.57 | 0.69 |
| 302 | 0.47 | 0.38 | 0.43 | 0.52 | 0.55 | 0.57 |
| Bombi | 0.60 | 0.32 | 0.36 | 0.38 | 0.40 | 0.42 |

*The Imp and Bombi were not successfully tested at the workshop. Hence measured $DP/W$ is taken from other performance data. Comparisons may be made with this attendant limitation.

use the nominal track pressure $P_n$ of 6.07 kN/m$^2$, the predicted value is 11.57 kN. However, as noted previously, the actual effective track pressure is more likely to be between 1.5 $P_n$ to 3 $P_n$. Taking a 1.5 $P_n$ preloading condition, the predicted DBP for the 3700 vehicle is 23.57 kN—as seen from Fig. 2. This correlates well with the field measured DBP of 24.91 kN.

Since a good correlation for the 3700 vehicle with a track/grouser depth of 8.4 cm is obtained with a 1.5 multiple of the nominal track pressure, the same multiple should also be applied to the Thiokol Spryte vehicle whose track–grouser depth of 8.6 cm is close to the 3700. Thus, as shown in Table 7, the prediction of a DBP of 14.234 kN at 1.5 $P_n$ for the Spryte correlates extremely well with a measured maximum DBP of 14.68 kN.

In the case of the Bombardier 302 vehicle, the laboratory tests at McGill have shown that because of the greater depth of the track/grouser, and because of the shape of the grouser, the pressure multiple lies between 1.5 $P_n$ and 2 $P_n$, depending on the amount of sinkage. Taking a multiple value of 1.75 for $P_n$, the actual effective track pressure is obtained as 8.687 kN/m$^2$. For this preloading pressure, the predicted DBP is 19.13 kN which appears to be an extremely fortuitous exact correlation with the measured DBP.

There will always be considerable debate and discussion as to how one chooses a multiple for $P_n$. It is agreed that the use of $P_n$, the nominal track pressure, for actual assessment or correlation with measured DBP values is at best naive and at worst misleading. The quandry of what to choose as an actual effective track pressure $P_e$ nevertheless still remains. At present, for lack of a more rigorous data base, it would appear that $P_e = 1.5\ P_n$ to 1.75 $P_n$ for performance prediction in soft snow might be suitable.

Departing from the vane-cone penetrometer prediction, we observe from Fig. 3 that the vane-plate attachment approaches a maximum DBP as the value of $P_n$ exceeds 13.8 kN/m$^2$. As noted from Table 7, with a multiple of 1.5 for $P_n$ ($P_e = 1.5\,P_n$), the predicted DBP correlates well with the measured values of DBP.

Much work remains to be done to seek further clarification of the relationship between $P_e$ and $P_n$. The use of multiples for $P_n$ (1.5 and 1.75) might be satisfactory at this stage—but must be further refined and examined for more experimental/field input.

Prediction of drawbar pull for both devices was consistently higher for data obtained in undisturbed snow on the slope. This is probably a consequence of the fact that this snow was slightly stronger than that on the level, perhaps because of higher density through wind effects or faster metamorphism.

In anticipation of higher effective vehicle ground pressures, the snow could be preconditioned to a standard state. Such a state could conveniently be attained by compressing the snow to a plastic condition with a density of about 400 to 500 kg/m$^3$. If vehicles usually compress to that condition during passage then an improved simulating might be achieved with the plate penetrometer employed in a similar way.

Alternatively, by applying a range of snow preconditioning pressures that includes the standard pressure (corresponding to the standard state), a range of drawbar pull values are predicted. Any foreknowledge of how vehicle contact area or effective ground pressure varies with snow conditions will allow for the prediction of drawbar pull by interpolation as is done in the present exercise.

There is a suggestion in the results that with increasing plate preconditioning pressures, the plate-vane penetrometer produces a plateau of snow shear strength corresponding to the standard pressure. Such a plateau of shear strength or predicted drawbar pull could facilitate predictions. Subsequent work with both the vane-cone and vane-plate supports this view.

The prediction of sinkage appears favourable. A distinction in Fig. 4 was made between vehicle sinkage (a) as measured by the authors in the track trace and (b) as accepted by the Workshop. The curve prediction falls close to the range of values measured by Workshop participants. Hence it is suggested that despite simplifying assumptions, sinkage prediction with a plate is feasible. There is a notable discrepancy between depths of track traces and measured or predicted vehicle sinkages. Trace depth measurements are evidently subject to significant error.

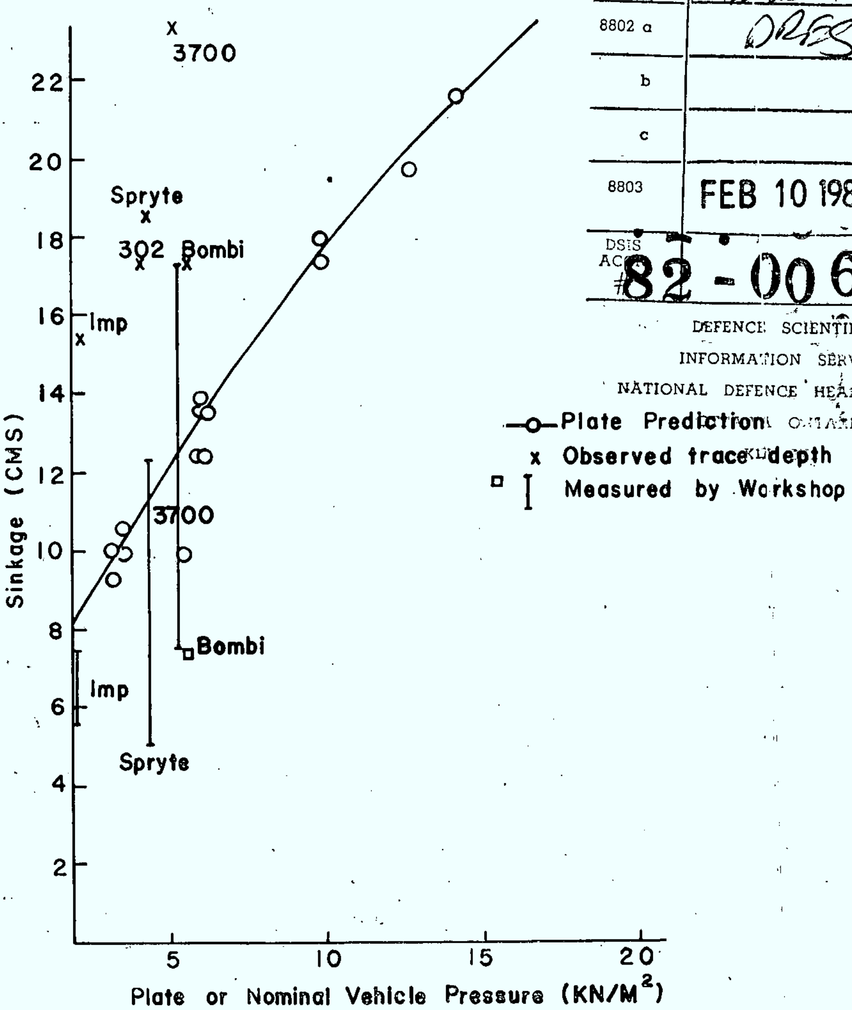

FIG. 4. Sinkage versus nominal pressure.

Time did not allow for the collection of a more extensive volume of data. Hence the demonstration of the above instruments in deep snow was necessarily limited. Future work requires a careful assessment of the repeatability and variability of torque data as well as the sensitivity of the penetrometer devices to a wide range of snow conditions. Such work, however, needs the support of vehicle testing that is precise, concurrent, and located close to the site of penetrometer testing.

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