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COMPACTED SNOW AS A TRANSPORT SUBSTRATUM

BY

B. H:SON AGER

FROM
NORRLANDS SKOGVÅRDSFÖRBUNDS TIDSKRIFT, (3): 293 - 388, 1956

TRANSLATED BY

E. PEREM

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Translator: E. Perem

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* SDA = Forestry Society and Royal Domain Administration, Research Section.

PREFACE

Although snow roads are of economic interest in Canada, particularly to its pulp and paper industry, there is as yet very little published information on their construction and performance which is generally available in English to engineers.

As one contribution toward solving this problem the National Research Council, through its Associate Committee on Soil and Snow Mechanics, is cooperating with Professor Seheult of the University of New Brunswick, on a project to evaluate current practice in the construction and use of snow roads in Canada and other countries of the world. One of the first steps has been to translate into English the more pertinent publications available on the subject.

Sweden, through experiment and field practice has gained much valuable experience on the construction of snow roads. This translation is the first of a series of reports to be translated which describe this Swedish experience.

Ottawa,
February 1960

R.F. Legget,
Director

COMPACTED SNOW AS A TRANSPORT SUBSTRATUM

Foreword

For a number of years SDA has been engaged in intensive experiments aimed at the establishment of rational methods of construction and maintenance of compacted snow roads. A summary of previous experiments and experience in this field has been published by Crown Forester A.C:son Leijonhufvud, Chief of the SDA[12].

For the winter 1955-1956 both SDA and the Army Field Engineering School (under Major Tore Rahmqvist) had planned studies on compacted snow roads. These studies were coordinated and were carried out at Lycksele and in Alsbäcken, approximately five Swedish miles (50 km) northwest of Lycksele. The Department of Theory of Work of the State Institute of Forestry Research (Professor Ulf Sundberg, Director) also cooperated in the studies of certain fundamental problems associated with the methods of measurement.

Since one part of the test results seemed to be of certain value for future research in this field, the test procedures and the probable errors in the test results have been reported in detail, a fact which makes reading of the article wearisome. The writer has attempted to compensate for this by making the chapter "Views on the opening and maintenance of compacted snow roads", which is based on the test results and on the practical experience of the recent winters, somewhat fuller.

The present report is a complement to and an extension of the previous publications and therefore does not claim to be a summary of present knowledge in this subject. For the fundamental properties of snow, general rules for the use of compacted snow roads etc., the reader is referred to other SDA publications.

On behalf of the initiators of this study the author wishes to acknowledge the support given to these experiments. Great interest in this study has been shown by Stora Kopparbergs Bergslags AB and Mo och Domsjö AB. The officials of these companies have made many valuable contributions to the work. The contacts with

Statens Väginstitutet (State Institute of Highways), Mellan och Sydsvenska Skogbrukets Arbeitstudier (MSA) (the Institution of Work Studies of the Forestry Association for Central and South Sweden) and with Sveriges Meteorologiska och Hydrologiska Institut (the Swedish Institute for Meteorology and Hydrology) have also been valuable.

I wish to acknowledge personally the good advice and valuable comments given to me by my chief and my co-workers at the SDA, by Crown Forester Nils Nätterqvist, Inspector Rune Östberg and by licentiate in technology Rune Eriksson.

The Object of the Study

The aim of the research activities of the SDA in the field of compacted snow roads is to establish effective methods for the use of a snow substratum as an alternative to the conventional methods of construction and maintenance of roads for different types of timber transport. Two phases can be clearly distinguished in this field of research. The first phase includes fundamental studies of the demands made by different types of transport on the bearing properties of a snow substratum, the securing of information on the variations of the bearing properties under different conditions and the establishment of methods of construction and maintenance to meet the requirements of the various forms of transport. The second phase falls entirely within the category of applied research. Its aim is to modify in practice the principles of construction and maintenance to suit the requirements of the different types of traffic and to compare the new techniques with the prevalent ones from the economic point of view. This second phase of the research is naturally a long-term project. The conditions vary tremendously from year to year for the different methods, and experiences of several years are required before a given method can be recommended or before the approximate limits can be determined for the application of the different methods. Good progress has been made in this phase of research for some forms of transport. For hauling by horse for example, methods of opening and maintaining compacted snow roads have been developed which compare favourably from the economic point of view with the method of deep ploughing. For other forms of transport, for example hauling by trucks, we still are in the first phase of research, although some methods of processing snow have been developed which suggest possibilities of improving the bearing strength of a substratum of snow.

I. Measuring Instruments Used in Experiments

The hardness of snow was determined by a proctor needle (see Fig. 3). During the winter another apparatus for measuring the hardness of snow was also developed. This instrument is described in a separate chapter.

The density of compacted snow was determined by weighing samples of snow taken with the aid of a cylinder 10 cm long with an inside cross-section of 30.9 cm^2. For loose snow a graduated (in cm) tube, 150 cm long with an inside cross-section of 16.6 cm^2, was used.

The drawbar pull of a vehicle was registered with the aid of a dynamometer, PM-dynamometer (see Fig. 1).

The traction resistance of the loaded timber sledge was determined with a "work recorder" (Fig. 2). This instrument is coupled between the vehicle and sledge. Traction resistance is recorded on a strong steel ring and the distance travelled on a measuring wheel which runs on the surface of the road. These two factors, traction resistance and the distance travelled, are recorded with the aid of two planimeter mechanisms, each of which is connected to its own counting mechanism. On these counting mechanisms the product of the traction resistance and the distance travelled are recorded, indicating the total work done. The distance travelled is also recorded separately on a counting mechanism connected to the measuring wheel. From these values the average drawbar pull of the vehicle = traction resistance of the sledge, can be calculated for the whole distance covered.

The particle size of the snow was determined with a magnifying glass and a millimetre scale.

The temperature and the relative humidity of the air were measured constantly during the whole period of experiments with a thermo-hygrometer, enclosed in a ventilated case which protected it from radiation. The case was placed 1.2 metres above the compacted snow surface.

The temperature of the snow was recorded with thermistors. The type of thermistor used in the tests consisted of two small metal plates separated by a semiconducting material. A thermistor changes its electrical resistance with temperature in accordance with definite laws.

II. Determination of Snow Hardness

1. Proctor needle

When a few years ago SDA started its field experiments with compacted snow roads, one of the first tasks was to find an instrument which would measure the bearing strength or the "hardness" of snow under various conditions. The proctor needle was selected for this purpose (see Fig. 3). A proctor needle is a spring balance which records the force exerted on a disc when pressed against a substratum. In measuring the hardness of a snow road the stress is recorded at the moment the plate penetrates the substratum. The load is measured in kilograms and the area of the plate in cm^2. The bearing-strength values are thus expressed in kg/cm^2.

(a) Relationship between hardness and the size of the plate

The different sizes of plate gave different values for the maximum load or "breaking" load per unit area on the same substratum, greater values always being obtained with smaller plates. The relationship between the area under load and the breaking load has been discussed and explained by R. Eriksson[9] and A.C:son Leijonhufvud[12]. Before bearing-strength values obtained with plates of different size can be compared quantitatively, an adjustment of the values to a uniform size of plate must be carried out. In a previously published SDA investigation, Eriksson[9] recorded unadjusted breaking loads in kg/cm² and the sizes of plates used, but Leijonhufvud[12] and the author of this article[1] reported values which were adjusted to a uniform plate size of 32 cm². The adjustments were made according to the results of a specific relationship study.

Through a contact with the State Institute of Highways it was learned that in recent years the proctor needle has been used for determining the bearing strength of clays. The findings of this work have been published by F. Rengmark[16] and A. Olhagen[6]. Olhagen has demonstrated the existence of a rectilinear relationship between the mean breaking load and the reciprocal of the plate diameter. This relationship can be expressed as follows:

$\omega = \tan \alpha(a + \frac{1}{D})$, where (see Fig. 4)

ω = mean breaking load

D = diameter of the plate

α and a are constants which vary with the characteristics of the clay.

The angle α increases with increasing hardness of the substratum. From measurements in which different plate sizes were used on a large number of clay surfaces Olhagen found that the curves tended towards a more or less constant value of a between 0 and $1(\frac{1}{\text{cm}})$. The best value was $\frac{1}{2}$. In computing the value of a the scatter of this value for the different plate sizes was taken into account. On a given substratum the scatter of the values from individual observations increases as the size of the plate is decreased. The values obtained with the smaller plates were therefore given less weight in the calculations than those from the larger plates. Olhagen demonstrated that the empirically determined relationship was also theoretically sound.

A re-examination of the relationship found for clay between the breaking load and the size of plate was required for snow. During the late winter of 1956 a series of measurements was therefore carried out with different plate sizes on compacted snow roads of different bearing properties. In each substratum 25 observations were recorded for each plate and a mean value was calculated for each plate. A graphic representation of the data showing breaking loads (= ω kg/cm^2) on the ordinate and the reciprocal values of the plate diameter on the abscissa showed that the relationship between these two variables could be expressed in comparatively rough approximation as a straight line. When the reciprocal value of the plate diameter was replaced by the reciprocal of the plate area ($\frac{1}{S}$), the straight line seemed to fit the test data better. In order to find out if the relationship could be expressed in the form of a pencil of rays, the following calculations were made:

Different paired values of ω and S were assumed to be the points of origin of the different pencils of rays. For each such pencil of rays the sum of the squares of the deviation of the calculated ω value from the experimental value was found. The sum of the squares (Q) was thus employed as a criterion for the correctness of the adjustments. The minimum sum of the squares (Q_{min}) was obtained by graphical interpolation, for the point $\omega = 1.1$ and $\frac{1}{D}$ - 1.75. The corresponding Q value was approximately 12.4. In order to find a simple expression for ω, the possibility of placing the point of origin of the pencil of rays on a point on the abscissa was studied. Q_{min} for $\omega = 0$ was 12.6 when $\frac{1}{S} = -2.06$, or in other words the pencil of rays originating from this point showed almost as good agreement as that from the "best" point with an arbitrary ω value. For comparison it may be mentioned, that the Q value for a parallel pencil of rays was as high as 35.2.

The best expression for the relationship between the maximum load per unit area and the size of plate for the observations made thus seems to be:

$$\omega = \tan \alpha(2.06 + \frac{1}{S}).$$

In order to demonstrate graphically the agreement between the derived relationship and the observed values a few curves drawn from the point $\omega = 0$, $\frac{1}{S} = -2.06$ are compared in Fig. 5 with the results from the test data. The agreement seems satisfactory for the higher values of ω, which represent a range of breaking strengths for which only plate sizes of 4 cm^2 or less can be used. The agreement for the larger plates seems to be less satisfactory. It has to be mentioned, that all plates were given the same weight in the calculations. Had the larger plates been given a greater weight on the grounds that their mean values have smaller coefficient of variation, the agreement would have been better for the low bearing-strength values and poorer for the high values. Since the most common sizes of plate used in such studies are 0.5 - 4 cm^2, and since the agreement within this range was satisfactory when unweighted mean values were employed, an adjustment was not considered necessary.

In order to eliminate the influence of plate size on the measured bearing strength values, Olhagen introduced a term "proctor bearing strength" = mean bearing load in kg/cm^2 obtained with a plate size of 6.45 cm^2 or 1 square inch. This unit was selected for certain practical reasons.

As mentioned above, the bearing-strength values in the more recent experiments carried out by SDA have been converted to the plate 32(cm^2).

As will be shown later, the possibility of subjective errors by the person carrying out the proctor needle measurements on a substratum of snow are too great to allow comparison of the results of different experiments where the measurements have been made by different persons. The values of measurements made by proctor needle ought to be taken only as relative values applying to a given study in which the bearing strength of snow is involved. The author therefore considered it unnecessary to use the same unit for the computation of the snow hardness as was used in the previous studies[1,12].

In the experiments reported in this article, plate sizes 1 and 2 were chiefly used, and in a few cases also sizes 0.5 and 4 cm^2.

For reasons associated with the calculations, the 1 cm^2 plate was chosen as the standard. For breaking loads obtained with this size of plate the term "proctor value" is applied. What will be the conversion factor by which the values obtained with other plate sizes have to be adjusted? In discussing this problem the results of the calibration tests reported by Leijonhufvud (1951 and 1955 series) are compared with Olhagen's data on clay and with the results described above by the author (1956 series). In all four series the plate size 1 was given the value 1.00 and the values for the other plate sizes were indicated in relation to this figure. The comparison for plates 0.5 to 4 cm^2 is shown in Table I.

The variations in the values from the different series are probably due to many causes. The series of the years 1951 and 1955 were obtained from mid-winter snow, while those of the year 1956 were from the coarse-grained snow of late winter. These two types of substratum probably affect the values of the series. The experimental results reported here were obtained almost entirely under mid-winter conditions. Since Olhagen's series have an intermediate position between the two mid-winter series, the author has chosen these data as a basis for rendering the values for the different plate sizes comparable.

(b) Possibilities of error

A compacted snow road in which the snow has been well mixed before compacting shows increasing hardness with increasing depth below the snow surface. When the hardness of the upper layer of the snow is measured with a proctor needle, no definite break-through point is obtained, since at constant load the plate first penetrates a relatively thin layer and is then stopped by the harder layer of snow beneath. If the load is increased, the plate breaks through this latter layer, but is stopped by the next layer, etc. The same phenomenon is probably encountered if the hardness of snow is uniform in the vertical direction throughout the snow cover. Since the plate has compressed the snow beneath, a much greater load is in all probability required in order to reach the breaking limit and to achieve a step-by-step break-through with increased loading as the plate is forced through the snow cover[23]. In most cases, however, such a definite failure is produced in the layer for which the hardness value is to be determined that the reading can be taken without hesitation. Occasionally, however, the question of which break-through to read may arise and, of course, the greater the increase of the hardness from the surface to the bottom layers the more difficult the choice will be. At the same time it can be assumed that different observers may obtain different values for the same substratum. Another source of error is associated with the rate of loading up to the breaking limit. In order to clarify these sources of error two persons were asked to carry out measurements on the same substratum. The measurements were performed at noon when the temperature of the air was 0°C. The previous night had been extremely cold and thus the warmed up surface layer was relatively loose and the hardness of the road bed increased toward the bottom, which was still cold due to the night time cooling. The conditions were thus most unfavourable for proctor needle tests. Both observers had had previous experience with the proctor needle, had received the same instructions, but they did not have the same training. The measurements were carried out on two different roads. The results are shown in Table II.

As indicated in the table, observer G.B. generally obtained higher values than B.A. and in two out of three cases the differences were considerable. Although the test conditions were the worst imaginable and while it might be possible to obtain greater agreement from observers who had had the same training, these experiments showed clearly that <u>when the snow hardness is determined with a proctor needle, measurements for the same comparative study should not be made by different people</u>. On the basis of the results of these experiments one would tend to disapprove entirely the use of the proctor needle for comparative measurements of the hardness of a substratum of snow. However, in the hands of a person who carries out measurements consistently, the proctor needle is a sufficiently reliable instrument. In the SDA experiments on compacted snow roads all measurements during the recent years have been carried out by one and the same person.

2. Other methods of measuring snow hardness

The obvious disadvantages of the proctor needle have resulted in a search for other methods of determining snow hardness aimed at the development of a more objective method. In determining the strength properties of the different types of soil several methods have been employed. Most of these are complicated and designed for laboratory use. A study of the literature in this field has directed the attention to the simple drop device shown in Fig. 6.

Description: A stand which is supported by an iron ring is provided with a vertical aperture through which passes a metal rod. An impact body is screwed onto the threaded lower end of this rod. In order to provide the freely movable part of the apparatus with the desired weight for experimentation, an additional weight is fastened to the lower part of the rod and is locked in position against the impact body. On the upper end of the bar is a millimetre scale, 0 - 150 mm, mounted in such a way that the zero mark on the scale is in line with the upper edge of the aperture (reading index) when the tip of impact body is touching the surface of the substratum. The vertical aperture has a latch mechanism which engages in notches on the rod thus locking the rod at a certain height. The notches determine the height of fall in 5 cm intervals from 0 to 40 cm. When the latch mechanism is released, the impact body drops vertically toward the substratum.

First a wedge with an edge angle of 30° and an edge length of 40 mm was tried as an impact body. Then two cones with generating angles of 30° and 60°, respectively, were tested. The method is based on the same principle as the cone method of the Geotechnological Commission[10] and F. Rengmark's drop wedge method[16], which, however, are designed for laboratory use. The dimensions of the tested cones and the wedge were in part selected on the basis of those of the above-mentioned instruments. The weights of the three impact bodies were chosen so that the movable part (impact body, additional weight and rod) would weigh approximately 5 kg.

As in the case of proctor needle and most other instruments for measuring the bearing properties of a substratum, a great number of physical properties of the substratum determine the value of the snow's "hardness" as measured by this method.

The proctor needle and the drop device with the two cones and the wedge were compared under different conditions, always using two or more methods for the same substratum. For example, the following experiment was carried out. At the beginning of April the differences between the temperature during day time and that during the night were extremely high. A snow road (A) was compacted early in the morning when the temperature of the air was -21°C. The snow was first gone over with a track-type tractor and then compacted with a rail-roller and a sliding pontoon (see Fig. 8). By using the same method another road (B) was compacted in the afternoon when the temperature was -4°C. The next day the hardness of the surface layer of the two roads was measured by all four methods. Twenty-five observations were recorded for each road and each method. Plate 1 was used with the proctor needle, the height of fall was 10 cm for all the three impact bodies. The results are summarized in Table III. The average values are given in kg/cm² for the proctor needle and in millimetres of penetration for the impact bodies.

In general, all four methods led to much the same conclusion in this test, namely, that the differences in the bearing properties of the two roads were not significant.

Additional measurements were carried out on different snow roads by using two or more methods simultaneously. For each series of tests on the same substratum the standard error was calculated as a percentage of the mean from 20 observations for each method (Table IV).

Table IV indicates that, as a rule, the impact bodies give a smaller standard error than the proctor needle for the same number of observations. However, the "sensitivity" of the different methods must also be taken into consideration. In Fig. 7 the relationship is shown between the proctor value and the penetration in millimetres of the wedge for a drop of 10 cm. From this relationship certain conclusions as regards the "sensitivity" of the two methods can be drawn.

If the "sensitivity" of the different methods is taken into consideration, the proctor needle was found to give more reliable bearing-strength values below the range of 15 to 20 kg/cm^2, while the impact bodies seemed to give more reliable mean values for substratums of higher bearing strength. When the different impact bodies are compared with each other, the 30° cone seems to be more suitable than others for the substratums to which these measurements were applied. The wedge showed a greater standard error and showed a less uniform performance than the cones. For the range of hardness which is commonly found in the compacted snow roads, the 30° cone seems to be more suitable than the 60° cone.

What scale should be used for measuring the strength of a substratum? The Geotechnological Commission[10] has set up a scale of relative strength values in which a relative number of 10 is assigned to a substratum into which a 60° cone, weighing 60 grams, penetrates 10 mm. The weight of a 60° cone which is required to produce a 10 mm penetration in another substratum is then expressed in relation to 60 gm. In his tests with a wedge Rengmark[16] has used the term "wedge-strength value", which indicates "the total work calculated in mechanical work units (kilogram-metres, etc.), which is required to produce a penetration of 10 mm into a soil sample by a freely falling wedge with a 30° edge angle and a 40 mm edge length". The work (A) is expressed as the product of the weight of the wedge (G) and the drop distance. The drop distance is the sum of the height of the fall (F) and the depth of penetration (N). Rengmark found that for any given substratum there was a rectilinear relationship between $\sqrt{G \cdot (F + N)}$ and N and that this relationship held for a wide range of N, G and F values. When this relationship was calculated for the different degrees of hardness and transferred to a system of coordinates, a pencil of rays with a common point of intersection at the origin was obtained for various types of cohesive soils.

In this way the "wedge-strength value" for any drop distance, any wedge weight and any penetration can be calculated from a simple expression. The rectilinear relationship between the total work and the penetration, however, presupposes a homogeneity of the substratum which is seldom found in a compacted snow road where the hardness often varies with the layer depth in the road. If one wishes to use a scale such as the above "wedge-strength value", which is tied to a certain N value, the actual measurements have to be in the vicinity of that N value. The proper way is to take one A value on each side of that N value and then interpolate between these two, assuming that the $\sqrt{A}$,N-curve is a straight line within this range of N values. This can be done, of course, provided that the weight of the wedge and the drop distance can be varied within a wide enough range so that for every actual substratum a penetration is obtained which is close to the N value to which the strength value is tied. For the 30° cone, 40 mm seems to be a suitable penetration to be used with the drop apparatus employed in this study.

The simplest way to obtain a snow hardness measurement with a drop apparatus is, of course, to employ a constant height of fall and to measure only the penetration into the substratum. In choosing the weight of the cone and the distance of the fall it is necessary to reconcile two opposed aims. If a small weight and a small height of fall are chosen a wider range is achieved for the apparatus, but the method becomes relatively insensitive at higher degrees of hardness. With a greater weight and height of fall the apparatus becomes more sensitive but the range is reduced. According to experience gained from measurements during the winter, a cone weight of 3 kg combined with the height of fall of 10 cm seemed to be the most suitable.

3. Summary of views on apparatuses for measuring hardness

The results of measurements of a snow substratum with a proctor needle are often greatly influenced by the person performing the tests. Therefore, all the hardness measurements taken with that instrument in the course of a given experiment must be carried out by the same person if the different phases of the experiment are to be comparable. A certain degree of experience also seems to be desirable in order to secure consistent readings of the instrument under different conditions. Where different sizes of plate are used in the different phases of an experiment to be compared with each other, a source of error has to be taken into account when the measured values are adjusted to a single plate size. This source of error is eliminated if only one plate size is used during all phases of the experiment. A limiting factor here is, however, the load range for a given plate size. The readings are difficult on the parts of the scale indicating the highest and lowest values. If the scale range is from 0 to 50 kg, the plate size must be chosen so that the readings will fall within the limits of 5 and 40 kg.

In addition, the instrument must be calibrated from time to time since its spring may be subject to fatigue.

If the above-mentioned requirements are taken into consideration a proctor needle is sufficiently reliable for comparative measurements of hardness. The instrument is easy to handle and is relatively sensitive. The source of error due to the person who uses it is, however, a great disadvantage for the method and may render any objective and detailed comparison between the test results of different workers impossible.

The simple drop apparatus which was constructed during the winter makes possible an objective recording of the snow hardness. Of the different impact bodies tested, a cone with a 30° acute angle seemed to be the most suitable. The type of scale needed for evaluation of the snow hardness could not be determined as the data collected for this purpose were too limited. Two possibilities are discussed. One is to record the resistance, calculated in kilogram-metres between the snow and the cone for a given penetration after free fall. As a standard, a depth of 40 mm is recommended. For the second method, a constant wedge weight and a fixed fall distance (3 kg and 10 cm, respectively, have been recommended) are used and the penetration in millimetres is recorded as the hardness.

The present design of the drop apparatus limits its use to flat or only slightly sloping ground. The possible errors arising from a cone falling against a steep slope are not known.

The drop apparatus is not as convenient as the proctor needle and the working speed is slower.

The drop apparatus was not completed before the end of the test period. The hardness measurements reported below were therefore made entirely with the proctor needle. Every reported hardness value in this paper is a mean value from 25 observations and is expressed in kg/cm^2, adjusted to the plate size of $1\ cm^2$, unless otherwise indicated. All the measurements were carried out by the same person.

The term "bearing strength" below refers to surface hardness expressed as the proctor value.

III. Different Methods of Processing Snow

One of the aims of the experiments on compacting snow carried out by the SDA has been to find simple and inexpensive methods and equipment for the construction of snow roads. In the traditional method the snow is first processed throughout the road bed with a deeply penetrating track-type tractor and then dragged. With this method a certain time must generally be allowed for the snow to harden between compacting and dragging, otherwise the drag penetrates too deeply into the snow, producing an inferior road surface and at the same time requiring more pulling power.

Leijonhufvud[12] has reported and discussed the earlier experiments employing different methods of processing of snow and has demonstrated empirically the great importance of breaking up and mixing the snow before compacting it where the road is established directly in deep snow. The research activities are directed towards the development of a tractor-driven combine in which the mixing is performed by one part of the equipment and the compacting by another. The aim has been to make a road in one pass. The work has been continued and the results of the tests carried out during the last winter are reported below.

1. Comparative experiments with certain equipment and methods

During the winter of 1955-56 the following equipment was tested.

Roller of Finnish type (See Fig. 8): The roller consists of three circular wooden discs mounted on a common axle and joined together on their circumferences by rails along the generating surface of the drum. The roller is attached to a frame made of U-beams which serves as a tow gear. It is provided at the rear with hooks for the suspension of weights. The effective width of the roller is approximately 2.0 m. This type of roller is used in Finland and has also been tested in Sweden by the Stora Kopparbergs Bergslags AB for construction of compacted snow roads. It mixes and compresses snow. In this paper it is referred to as the rail-roller.

Power-take-off driven rotary tiller (Settergren tiller) attached to a Ferguson tractor (see Fig. 9): The tiller has a prong mechanism mounted on a rotating axis placed at right angles to the direction of motion of the tractor and connected to a hydraulic hoisting mechanism. The working depth is controlled by an adjustable runner. The tiller has an effective width of 75 cm and is operated at a speed of 500 rpm. Its function is to stir and mix the snow.

SDA sliding pontoon (Fig. 8): The sliding pontoon (earlier known as "packoped") consists of an iron plate with a parabolic curvature mounted in a frame. In the model used in the experiments the position of the iron plate was adjustable so as to produce various specific pressures against the substratum. The pontoon can be loaded with additional weights. The model used during the experiments had an effective width of approximately 2.0 m and weighed 180 kg. It levels and compacts the snow.

Closed roller. By covering the above-described rail-roller with corrugated sheet-metal which could easily be removed and replaced during the experiment, a roller, which had a compacting effect only, was produced. In this report it is referred to as a closed roller (plåtvält).

Conventional wooden drag (see Fig. 10): The test drag had three blades. The total contact-area of the blades was approximately 4000 cm². The total weight, including the additional weights, was 142 kg, the pressure of the drag against the substratum being thus approximately 0.035 kg/cm².

The above-described equipment was combined in the various ways described below and roads 10 to 15 m long were compacted.

Methods

1. An Oliver OC3 tractor was driven three times "track to track" over the section of road to be compacted, thus working the snow down to the bottom. After a certain time the drag was towed once over the road by the same tractor. The time between processing and dragging was three hours if the temperature was below -10°C, and approximately 24 hours if the temperature was higher.
2. The snow was worked over with the Oliver OC3, "track to track", after which the tractor towed a closed roller and sliding pontoon once over the section of road.
3. The Oliver OC3 first made a track and then towed a rail-roller with sliding pontoon once over the section road.
4. The Oliver OC3 made a track and then towed first a rail-roller and afterwards a closed roller once over the road.
5. The Oliver OC3 made a track and then towed a rail-roller once and afterwards a rail-roller with sliding pontoon once over the section of road.

6. The Oliver OC3 made a track and then towed a rail-roller once and closed roller with sliding pontoon once over the road segment.
7. The Oliver OC3 towed a half-tracked Ferguson tractor with rotary tiller attached once back and forth over the section of road. It then pulled a sliding pontoon once over the road.

It should be mentioned that not all the above-described equipment and methods are considered ready for practical use. The purpose of these experiments was to compare different processing principles. The comparative tests were carried out in a swamp at the SDA Experiment Station in Lycksele from January 9th to January 21st 1956.

The experiments were arranged in such a way that two or more combinations were tested more or less simultaneously. This was repeated several times. Every repetition was designated as a series. In every series method 1 was included as a control method, as it had hitherto been the most common method of constructing compacted snow roads.

The depth of snow increased during the experiments from 70 to 90 cm. The Oliver OC3 was equipped with standard tracks and could not pull the equipment immediately in the loose snow. It was first necessary to open a track.

In the experimental road, sections constructed by the above-described methods the snow hardness was determined with a proctor needle both at the surface of the road (bearing strength) and at a depth of 20 cm. In each series the hardness values at the surface and at 20 cm depth for method 1 were given a relative value of 100. The respective hardness values obtained with the other methods for each series were expressed in relation to the method 1 value. In cases where the deep snow was considered to have been processed by the special equipment used and by the tractor, the hardness at the 20 cm depth was determined between the ruts of the vehicle. The results are summarized in Table V. It should be emphasized that in the comparisons the bearing-strength values and the snow-hardness values at a depth of 20 cm are dealt with separately. Data on the significance of the difference between the values of different methods have been recorded in the same table.

It can be seen from Table V that in some respects the results are relatively uncertain, resulting from too few comparisons in some cases, but are decisive in many other instances. The following conclusions have been drawn, taking into consideration only the strength values which were determined.

Methods 3 and 4 gave approximately the same bearing-strength values as method 1, whereas methods 2, 5 and 6 gave values approximately 40 percent above those of the basic method (method 1). The rotary tiller and sliding pontoon combination gave considerably higher bearing-strength values.

At 20 cm depth the same hardness was obtained by processing snow with the tractor in both method 1 and method 2, although a closed roller and a sliding pontoon were used as compacting equipment in method 2. If a snow cover is exposed to a certain load, the stress decreases in the substratum with increasing depth of the snow[22]. Figure 11, reproduced from SIPRE Report 13, illustrates this phenomenon. At a depth of 20 cm only a fraction of the initial surface stress is present. As compared with processing by the tractor, the rail-roller produced a definitely lower hardness in the snow at a depth of 20 cm. When the rail-roller is pulled twice over the road instead of only once, the hardness of snow at this depth seems to increase but little (compare 3 and 5). The rotary tiller produced a considerably greater hardness of snow even at the depth of 20 cm.

What conclusions of practical importance can be drawn from the results of these experiments? It is known that basic method 1 generally produces roads of adequate bearing properties for horses and track-type tractors. Of the two methods which produced almost the same bearing-strength values (methods 3 and 4) method 3 seems to be preferable because of its simplicity. Is the hardness at the greater depth, however, sufficient to produce a bearing strength comparable to that of method 1? Here Fig. 11 can be consulted again - it shows that the primary and deciding factor, up to a certain limit, is the surface hardness of the road. This limit is, however, sometimes exceeded by the traffic on roads which have been compacted by the "Weasel" tractor. Such roads develop, as a rule, a hard surface layer, but the unprocessed bottom layer consists of loose- and coarse-grained snow(12). When the surface layer becomes loose, during mild weather, the vehicle may break through this layer. On the basis of data published by Leijonhufvud(12) and the results of the experiments of 1954/55, a road compacted by the "Weasel" in January or later (when the coarse-grained layer of the loose snow in the bottom layer has become relatively thick) may be expected to have a hardness of 20 to 40 percent of that of a road produced by method 1. Since the corresponding figures obtained with a rail-roller and a sliding pontoon are 60 to 70 percent, the depth processing by this method can be considered satisfactory. The traditional method produces a hardness in the deeper layers which is unnecessarily high for horses and track-type tractors.

Of methods 2, 5 and 6, all of which are superior to methods 1 and 3, method 2 seemed to be the most practical as far as the compacting effect is concerned. The possibilities of using this method will be discussed later.

The method employing a rotary tiller and a sliding pontoon was superior to all other methods. It produced a road which had a great hardness throughout. It is obvious, that this method produces roads with adequate bearing strength for horses and track-type tractors. This bearing-strength requirement however, can be satisfied with considerably simpler and less expensive methods. In order to find out if the method produces roads with adequate bearing strength for wheeled vehicles also, including cases where the road is established directly in snow of considerable depth, specific tests were carried out, the results of which are to be reported in a later chapter.

It should be pointed out that the rail-roller and rotary tiller both reduced considerably the depth of the undisturbed snow, 40 to 50 percent in the first case and 50 to 60 percent in the latter. The bearing strength of the snow is increased substantially if these implements are followed by compacting equipment.

The rail-roller and sliding pontoon combination was considered almost ready for practical use, and the properties and working principles of these were studied in detail.

2. Testing the rail-roller and sliding pontoon combination

In order to study the operation of the roller in snow the following experiment was carried out. A winch was used to pull a rail-roller and sliding pontoon over an undisturbed snow cover. Next to this area a Weasel tractor towed the same equipment over the snow cover after first producing the tracks. This experiment was repeated using a deep-penetrating track-type tractor, a Fiat OM* equipped with Alfta tracks. The depth of the snow was then measured in the prepared test areas. The results are shown in Figure 12.

The graph shows clearly that the compacting capacity of a rail-roller with a sliding pontoon in deep snow depends strongly on the vehicle used for towing the equipment. The compacting capacity of the equipment alone in unmixed snow is rather limited. When it is pulled by a vehicle which does not penetrate deeply into the snow, the ruts probably give some support to the processing equipment, making the performance of the equipment unsatisfactory. When pulled by a deep-penetrating vehicle, however, a substantial compacting effect is obtained. Nevertheless, it seems that the working depth of the rail-roller was not sufficient for mixing the coarse-grained snow in the bottom layer. The bearing strength of the experimental road area was relatively low.

A few tests were carried out with different working angles and with different loads on the sliding pontoon in order to find out to

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* A track-type tractor with Diesel motor which when equipped with Alfta winter-tracks, weighed approximately 4 metric tons.

what extent these factors affect the bearing strength of the road. Three series of tests were performed. The results are summarized in Table VI where the bearing-strength values are expressed as relative figures. For each setting of the sliding pontoon the bearing strength obtained with an unballasted pontoon 24 hours after compacting has been given the numerical value of 100, and the bearing-strength values recorded for pontoons with a given ballast are expressed in relation thereto. Secondly, the bearing-strength value obtained with the sliding pontoon set at an intermediate working angle for each test load is taken as 100 and the strength values obtained with large and small working angles for this test load are recorded in the table as relative values. The bearing-strength values referring to working angles are given in the table in parentheses.

Although the variations were relatively great, mainly due to the difficulties of creating similar conditions for each test, the results have generally provided answers to the questions formulated. The compacting effect of a sliding pontoon was improved considerably when the weight of the pontoon was increased. Also, in almost every case a lower surface hardness was obtained with a medium working angle than with either the largest or smaller possible working angle of the experimental sliding pontoon. For practical reasons the use of the smallest working angle is not feasible. In that position the front edge of the pontoon is forced downwards and pushes some snow ahead of it. This is probably why a high bearing strength is obtained after compacting with a pontoon set at a small working angle.

3. Traction resistance

Traction resistance studies were carried out in connection with test series 3 using the above-described compacting equipment. A dynamometer was coupled between the tractor and the compacting equipment, consisting of a sliding pontoon set at different working angles and provided with different test loads. The PM dynamometer enabled readings to be made to the nearest

25 kiloponds*, but values could be estimated to within 10 kp. The traction resistance estimates were naturally very approximate, but the only purpose of the study was to obtain general information on the problem involved. Series 3 was later supplemented with traction resistance measurements carried out under similar conditions (series 4). The results are recorded in Table VII.

The results show that the traction resistance is at a minimum at the intermediate working angle of the sliding pontoon. The high traction resistance at the smallest working angle is due to the penetration of the edge of the pontoon into the snow. It is obvious that the traction resistance also increases when the working angle of the pontoon is increased.

Side by side with the compacting tests, experiments were carried out with different types of vehicles for the purpose of comparing the behaviour of the vehicles in loose and compacted snow under different conditions. This included a test of the pulling power of the vehicles in deep loose snow. The test was conducted by mounting a dynamometer on the braking vehicle and making a reading at the moment the tracks of the pulling vehicle began to slip. The drawbar pull up to this limit had increased continuously from 0 kilopond to the reading at which the tracks lost their grip on the substratum. The pulling vehicle was braked the whole time, keeping it stationary. Three tests were made for each gear position which brought about slipping of the tracks. These experiments were carried out on a flat substratum of loose snow, 90 - 95 cm deep on February 8. The following approximate maximum values (with "best gears") of drawbar pull were recorded for some of the most common tractors:

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* 1 kp (kilopond) = 9.80665 Newtons (N)

Tractor	Drawbar pull at the moment of slipping
Fiat CF and Cletrac HG 42, both equipped with Alfta winter-tracks.........	400 - 500 kp
Fiat OM with Alfta winter-tracks and Fordson Major with SDA wheel-tracks..	800 - 1000 kp
Vessla ("Weasel"), original............	600 - 700 kp
Nordwerk snow tractor..................	approx. 800 kp

It must be emphasized that these results represent only a single experiment and as such have to be regarded as examples of the pulling power of the vehicles in deep, loose snow. They cannot, therefore, be compared directly with the traction resistance values of the compacting equipment recorded in Table VII. However, since the depth of snow was approximately the same, and the properties of the snow did not differ too greatly in the two experiments, certain conclusions can be drawn from the approximate orders of magnitude for the respective experiments. Only a certain proportion of the drawbar pull recorded during the above-mentioned tests is available for pulling the snow-processing equipment in the snow. A great deal of this force is required for moving the pulling vehicle itself, because of the resistance of the snow to the vehicle. The proportion of the total pull lost by a given vehicle in this way depends on the bearing properties of the snow.

The drawbar pull of the small tractors (Fiat CF 25 and Cletrac) equipped with commercially available tracks seems to be adequate for pulling a rail-roller and an unloaded sliding pontoon on level ground at the depths of snow mentioned above.

For the larger tractors there seems to be a certain margin for loading the pontoon on level ground. However, it must be pointed out that the drawbar pull of the vehicle decreases rapidly in loose snow with increasing uphill grade. For example, a Fiat OM was able to move only with great difficulty in a depth of snow of approximately 100 cm with unballasted equipment up an estimated 2 - 3 percent grade. Although this difficulty may be eliminated in many cases in practice by equipping the vehicle with a winch, it is evident, that the drawbar pull of the common vehicles which are used in snow, is a restricting factor in using the tested compacting equipment. In a depth of snow of less than 50 - 60 cm this difficulty usually vanishes because most of the above-mentioned vehicles make contact with the ground when they lose traction on the grade and are thus able to continue on their way.

Appraisal of methods on the basis of the experimental results. Since the various combinations constitute heavy loads in rotation to the drawbar pull of most of our tractors in loose snow, the desired production of a road in a single pass can be realized only if the snow is less than 50 - 60 cm deep. Up to this depth light tractors, even the lightweight "snow-weasel", can be used to tow the compacting equipment. Beyond this depth, heavier deep-penetrating tractors must generally be used to pull the present-day rollers. A larger tractor is required for greater drawbar pull, and a deep-penetrating vehicle is needed for the efficient use of the processing equipment. Shallow ruts prevent the roller from penetrating deeply into the snow and mixing it properly. If the depth of the snow is more than 90 - 100 cm, the compacting equipment produces roads of low bearing strength no matter what type of vehicle has been employed.

The sliding pontoon should be loaded to the limit of the vehicle's drawbar pull. The bearing properties of the road will be greatly improved. The working angle of the pontoon with respect to the snow should be quite large.

4. The power-take-off driven roller

The limiting factor for the use of the relatively simple and practical combination of rail-roller and sliding pontoon has been the drawbar pull of the tractor. In preparing the SDA winter experiments in Vinliden, Crown Forester C.E. Malmberg (SDA) proposed the idea of making the roller power-take-off driven. The relatively poor grip that the tracks of a tractor have on loose snow means that only part of the total engine output is utilized for the progress of the vehicle. If a power-driven roller is used, the roller does not have to be pulled and the "surplus-power" of the engine, because of the good ground traction of the equipment, can be utilized for the progress of the tractor. The Sandbergs Mekaniska Verkstad in Stensele took up this idea and in the late winter produced a prototype of such a roller (see Fig. 13). This working model was similar in principle to the rail-roller described above. The snow processing part, however, was made of plate iron and the effective width of the roller was only 136 cm. The drum axle was driven from the drive shaft of the tractor. The tractor was fitted with a specially constructed power-take-off behind the gear box and the roller was operated synchronously with the tractor in all gears. The coupling was made in such a way that the periphery of the roller had approximately 10 percent higher velocity than the tracks of the tractor. This was done in order to bring about a more intensive processing of snow by the roller[5].

The roller was tested during the late winter only. It seemed to fulfill expectations with regard to assisting the forward motion of the tractor even in great depths of snow, while at the same time the processing of the snow was more intense than with a rail-roller pulled by a tractor.

It would seem appropriate to give the roller a greater effective width (the working model tested was intended for roads for horse-drawn traffic) and to add a sliding pontoon or some simpler compacting tool to the equipment, because the bearing strength of the road thus can be improved considerably as compared with treatment by roller alone.

5. Other methods of processing snow

Most of the known methods of snow processing have been described by Leijonhufvud[12] who has also reported on those methods which were tested by the SDA during the winter of 1954-55. No detailed descriptions of these methods will therefore be given here.

Interest in compacted snow roads has been very high in the U.S.A., Canada and Russia for various reasons. The conditions for mechanization in these countries are at present different from those here. Relatively large and complicated machines have been used there which process the snow intensively and are followed up by large closed rollers weighing several tons. Such equipment is in general use for the construction of airfields in arctic regions. The author recently found in the literature a short description of an apparatus for building airfields of snow. This machine is called "Pulvimixer" and is described in an American journal* as follows: "The Pulvimixer, with its tilter-like prongs, tears up several inches of the surface snow and throws it into the flames of eight huge blow torches. The snow is partially melted and returned to the ground to be smoothed by a rear drag blade of the Pulvimixer. Immediately behind come wobbly-wheel pneumatic rollers and corrugated-iron rollers which compress the snow as it refreezes." It is mentioned in the article that an aircraft equipped with wheels landed on the airfield 72 hours after the compacting.

Although these methods seem too complicated and expensive for our conditions, the processing principles ought to be taken into consideration in future research.

IV. Hardness of Compacted Snow under Various Conditions

The basic physical processes in a snow cover, both in the natural condition and in the compacted condition, have been described by Eriksson in the forestry publications(9). Leijonhufvud(12) and the author(1) have also reviewed these briefly so that it is unnecessary to do so again. In the course of reporting on observations made during recent winters the author hopes to explain some of the important processes which take place in a road bed.

The experiments described below were, unless otherwise stated, carried out in Alsbäcken, approximately five Swedish miles northwest of Lycksele. Almost all the experiments were performed in a small, relatively wind-protected area during the month of February

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* Snow airfield construction. The Military Engineer Vol. XLVII, No. 317

and the beginning of March, 1956. The snow conditions were almost uniform over the whole area owing to its protected location. This fact, and the relatively stable prevailing climatic conditions, facilitated comparison of the various experimental methods.

1. Density of snow, temperature and period of time after compacting

On the experimental area in Alsbäcken four roads were compacted on the 14th of February at a temperature of -19°C and a relative humidity of 87 percent, as follows:

Road No.	Method of compacting
1	The snow was first mixed. A Fiat OM (with Alfta winter-tracks) pulled a Ferguson (half-tracked) to which a tiller was subsequently attached. The Fiat OM then pulled a rail-roller and a sliding pontoon loaded with a 300 kg ballast once over the road section.
2	The Fiat OM processed the snow by repeated "track-to-track" treatment and then pulled a rail-roller and a sliding pontoon with a 300 kg ballast once over the processed snow.
3	The Fiat OM pulled a rail-roller and a pontoon with a 300 kg ballast directly over the untreated snow.
4	A rail-roller with unballasted sliding pontoon was pulled directly over the untreated snow by means of a winch. The depth of the snow was 100 cm.

The temperature, hardness and density at the surfaces of these roads were then determined. The temperature was measured with a thermistor which was inserted in the road so that the upper edge of the thermistor was level with the surface. The hardness was measured with a proctor needle and the density in the upper 10 cm was determined with the sampler described on page 5. These measurements were carried out as the opportunity arose during the "waiting periods" between the tests, generally in order to "see what was happening". Whenever fresh snow fell on the road it was immediately swept off.

The analysis of the test data showed that the density of snow had increased during the period of measurement in all test roads (see Fig. 14). The density of the snow is recorded as the mean value of four measurements for each test, with the exception of the first series of determinations where only three measurements were taken for each road. The high variability of the results for road No. 1 is due to the extreme hardness of this road which made the sampling very difficult.

The causes of the increase in the density of the snow are, of course, open to discussion. Consolidation of the upper layer of the snow due to melting must be ruled out, since the temperature during the period of measurement was never above the freezing point. Nor could condensation of water vapour from the atmosphere in the upper layer of the road be claimed, since during the winter the sublimation of snow generally exceeds the condensation of moisture. The author believes the increase in density in the upper layers to be due mainly to the transport of material from the lower layers upward. This transport takes place in form of water vapour originating in the relatively warm bottom layers of snow and the substratum, and freezing again in the colder upper layers of the road. The prerequisite for such a condition is a decrease in temperature from the bottom towards the surface - a temperature gradient - which is practically always present during the winter. The water vapour thus ascends, so to speak, step by step through the road bed as a result of this gradient. In principle, water vapour moves away from high vapour pressure conditions to lower vapour pressure conditions, and the vapour pressure of ice decreases with decreasing temperature (snow consists of ice particles mixed with air). Water evaporates most easily from the highly convex surfaces of the snow particles, such as open corners and edges, and refreezes on slightly convex, plane and concave ice surfaces, or in other words, on the individual large crystals and at their common bonds. During the previous winter the author proved experimentally that the above-mentioned movement of moisture is one of the reasons for the hardening of a road after compacting. These measurements were carried out during the time when the road was "freezing-solid", i.e., as a rule during the 24 hours following compacting[1].

In order to determine whether the increase of density during the 20-day period of measurements was accompanied by an increase of hardness during the same period, the following experiment was carried out. Two road sections were compacted on the 4th of March in the experimental area at a temperature of -13°C and a relative humidity of 85 percent using approximately the same methods of compacting described above for test roads No. 1 and 2. The depth of snow was 90 to 95 cm. During the 24 hours following the compacting treatment the weather was clear to partially clear and showed fluctuations in the temperature. During this 24-hour period the temperature and the surface hardness were repeatedly measured in both roads as the temperature increased from the minimum to the maximum and again as it decreased from the maximum to the minimum. This was done in order to avoid any systematic error due to the hardening lagging behind the temperature change or to some similar phenomenon. The results are shown in Fig. 15. The roads are designated as 1-a and 2-a. The temperature ranged during the measurements from -9.7 to 29.5°C. The relationship between temperature and bearing strength for both roads during this period of time could be expressed as a straight line.

Road 1-a: $P = 6.84 - 0.63\ t$

Road 2-a: $P = 4.04 - 0.33\ t$, where p is the proctor value and t is temperature in degrees centigrade.

In order to test the utility of this approximation the following procedure was applied: During the second half of February several test roads were prepared in the experimental area in the same way as roads 1 and 1-a. The surface hardness and the temperature of these roads were determined by the routine methods used for roads 1 and 1-a as a rule 24 hours, but sometimes 48 hours, after compacting. The results of these measurements together with data of the first measurements for road 1 (48 hours after compacting) were also included in the graph on Fig. 15. With few exceptions, the values are concentrated satisfactorily along the straight line and its extension on the graph.

Applying the relationship between surface temperature and surface hardness found to exist for roads 1-a and 2-a, a test was made to determine if an increase in hardness had taken place in roads 1 and 2 during the period of measurement. This was carried out by expressing each proctor value obtained for roads 1 and 2 as a relative value of the corresponding proctor values for roads 1-a and 2-a. For example, eleven days after compacting a hardness value of 33.5 kg/cm^2 was measured for road 1 at a temperature of -20°C. According to the equation P = 6.84 - 0.63 t a hardness of 19.4 kg/cm^2 will be obtained for road 1-a at this temperature. The relative value is thus:

$$\frac{33.5}{19.4} \cdot 100 = 173.$$

The results are shown in Fig. 16, where the relative hardness values are indicated on the ordinate and the number of days counted from the time of compacting on the abscissa. There is a clear increase in hardness. An attempt was made to smooth the curve graphically. The temperature for each measurement is also indicated on the graph. Deviations from the curve seem to bear no relation to the temperature values. The level indicated on the graph by 100 represents the hardness of the roads 1-a and 2-a approximately 24 hours after compacting and holds only approximately for the roads 1 and 2. No additional examination of possible errors is required. The only purpose was to determine whether an increase of hardness had taken place during the period of measurement and this question was considered satisfactorily answered.

This form of hardness and density increase answers a question which was raised several times during the experiments, i.e., whether a road can be established even when the temperature remains between -5 and -10°C for a relatively long time after compacting. During the two recent cold winters such temperatures have been rare during the time that most of the roads were constructed. On this question the answer is in the affirmative, assuming that the right construction technique has been used for the type of traffic to be carried. It is believed that if the methods of compacting recommended for the given type of traffic are applied the road will be ready for use a few days (e.g. 3 to 5 days) after compacting under the above-mentioned temperature conditions.

The test results obtained for the above-described roads have also been used in an attempt to illustrate the interrelation between density, temperature and hardness. First, relationships with respect to surface hardness between simultaneously compacted test roads 1 - 4 were studied. This is shown in Fig. 17. The hardness value of road 1 has been given the relative value of 100 for each time of measurement and the corresponding hardness values for roads 2 - 4 are shown in relation to the value for road 1. The hardness of road 2 tends to decrease compared with road 1, but in the roads 3 and 4 the hardness tends to increase. No definite tendency is, however, present. The distributions of experimental values were graphically represented by straight lines. For the sake of brevity the dependence of the relative hardness values on the temperature was examined by determining "average temperature values" for the points above the straight line and for the points below the line. No tendency of the relative hardness value to change with temperature could be traced in the material, and for that reason it was not considered necessary to carry out a more detailed examination of the data.

The author then wished to analyze the relationship between density, temperature and hardness in roads 1 - 4, 24 hours after construction. A period of time of 24 hours was chosen for the following reason. In a road which has been compacted during a moderately severe cold period, the warm snow of the bottom layers is mixed with the cold snow of the upper layers producing a temperature of the snow which is higher than that of the air above the snow. "The coldness of the air" thus finds its way into the snow. The coldness, however, spreads rather slowly downward and in a deep road bed it may take up to 24 hours before the temperature in the body of the road achieves a state of equilibrium. During this first phase the road hardens probably "from two directions", partly and primarily from above due to cooling, and partly from below as a result of the movement of moisture brought about by the existing temperature gradient. Other processes, such as regelation, moisture movement from cold regions to warmer ones in the mixed snow immediately after compacting, and similar processes[9,22] naturally contribute also to the hardening of snow, but they are believed to be of secondary importance[1]. The author has suggested earlier[1] that the increase of snow hardness on cooling is due mainly to condensation of moisture from the saturated atmosphere of the road body on the individual snow crystals and their points of contact. The results of experiments published recently by Yosida et al.[23] seem to indicate, however, that the interrelation of the various factors involved in this process is rather complex. It seems absolutely certain that condensation is a factor contributing to the increase of snow hardness, but it is very likely that certain other factors also play an important part. Further studies seem to be required in order to explain this process fully.

Whatever the reasons, the hardness of the road seems to reach an equilibrium (the upward movement of material through a snow cover takes place as long as there is a temperature gradient) relative to a given constant temperature of the atmosphere during the 24-hour period following compacting. Hence a period of 24 hours was chosen as a basis for comparing density, temperature and hardness for the test roads 1 - 4.

<u>The densities</u> of the four test roads 24 hours after compacting were derived graphically from the adjusted curves in Fig. 14.

<u>The relative hardness</u> of the roads 24 hours after compacting, in relation to the hardness of test road 1 was obtained by graphical extrapolation from Fig. 17.

Finally it was assumed, that the relationship between temperature and hardness obtained for test road 1-a, P = 6.84 - 0.63 t, was also applicable to road 1. With this equation and the existing differences in hardness values of the different roads, hardness values were calculated for all four test roads for a number of different temperatures. These values, together with the snow densities, are shown in Table VIII.

On the basis of this "skeleton material" the nomogram shown in Fig. 18 was devised.

The possible errors in the relationships indicated in Fig. 18 will be discussed here briefly. The assumption that a linear relationship exists between temperature and hardness is undoubtedly a rather rough approximation.

The error involved in supposing that the relationship obtained for test road 1-a is also valid for road 1 is unimportant in this connection. Whether the whole "skeleton" in Fig. 18 is shifted somewhat upward or downward is of little importance.

The hypothesis that the interrelation between the hardness values of the different roads does not change noticeably with varying temperatures is not ruled out by the experimental results (see above).

The graphical derivation of densities and relative hardness values 24 hours after compacting obviously involves some uncertainty. Leijonhufvud has reported a relationship between relative density and relative hardness values(12). He designated the density and the hardness obtained by a certain method of processing as 100, and expressed corresponding results obtained by other methods of processing as relative values. Such relative values were computed for each of the many test series carried out with various methods of compacting from January to March during the winter of 1954/55. The author's results agree satisfactorily with Leijonhufvud's relationship.

Density, however, is not the only factor which differentiates the test roads. There is also a difference in the size of snow particles. In road 1 the coarse-grained bottom snow and the fine-grained surface snow had been well mixed. In road 2 the mixing was less complete, in road 3 still less, and in road 4 the results of mixing were almost insignificant. The average size of snow particles in the upper layers of the test roads decreases thus from road 1 to road 4. The influence of this fact on the hardness of the road could not be established.

Finally, the methods of compacting which produced certain snow densities are indicated in Fig. 18. The methods which produced certain densities for roads 1 - 4 have been used as reference points. During the experiments in Alsbäcken, test roads were compacted at different times by the following methods: (a) rotary tiller - rail-roller - sliding pontoon, (b) processing by tractor - rail-roller - sliding pontoon, and (c) rail-roller - sliding pontoon. The densities were determined for several of these roads. From the data of these tests and the results of previous experiments with different methods of compacting, three different categories of treatment were distinguished from the standpoint of the snow density. The relation between the different categories of processing is believed to be applicable over a relatively wide range. On the other hand, it is obvious that a given method of processing will produce different densities under different conditions (see also the chapter on compacting at different times during the winter). In a given snow different densities will probably be obtained with a given method of processing if compacting is carried out at different temperatures. This has been pointed out by Russian scientists in cases where the snow was only compressed[22]. For the methods of processing which were employed in this study, this phenomenon was not clearly evident. In order to leave a margin for this and other variables, a certain range of density values for the different categories of processing has been indicated.

In spite of its inherent shortcomings the nomogram of Fig. 18 gives a good indication of how significant the two most important factors - density and temperature - are for the hardness of a compacted snow road. It shows also the approximate density values that were obtained or could be expected to be obtained by the different methods of compacting under the conditions prevailing in the Alsbäcken experimental area during the period of testing.

The absolute values are naturally related entirely to the conditions existing during the experiments. The relation between the different processing categories, which is obvious in spite of the margins allowed to each category, is believed to be valid within a wide range.

The nomogram indicates, among other things, the effect of an increase of density on the bearing properties of snow. If for a given form of transport a proctor value of, for example, 8 kg/cm^2 at the road surface is required before the road can be opened to loaded vehicles 24 hours after compacting, the temperature has to be -20°C or lower if a rail-roller and a sliding pontoon have been used but probably only -5°C if the road has been compacted with a rotary tiller and a sliding pontoon.

It is difficult to form an opinion on expected hardness of a road which is established at temperatures higher than -5°C. When there is a decreasing temperature gradient from the ground to the surface, the road will harden, but if the temperature at the ground level is, for example, -1°C and that on the surface of the road -2° or -3°C then the hardening will, of course, take a long time. If the temperatures at the surface of the road and at the ground are approximately the same a comparatively long period of waiting will probably ensue before the road can be used. Such situations however, are no doubt exceptional in the climatic regions where compacted snow roads are being used.

2. Compacting at different times during the winter

These experiments were carried out in a swamp close to the SDA experimental station in Lycksele. Compacting was carried out by one standard method at different times during the winter. The method consisted of processing the snow with an Oliver OC3 tractor ("track-to-track" treatment), after which the tractor pulled a wooden rail-roller (weight approximately 400 kg) and simple sliding pontoon ballasted with 300 kg over the test roads. The bulk of the resulting observations are shown in Table IX. Unfortunately, only four tests could be carried out, the compacting being done on December 20, January 23, March 3 and April 4, respectively. On each occasion two roads were compacted by the above-mentioned method (except on March 3 when, owing to an accident, only one road was compacted) and the values shown in Table IX are the average values of all measurements on each pair of roads.

On April 6 still another pair of roads was compacted at Lycksele using the rotary tiller - rail-roller - sliding pontoon combination, i.e., the same method with which equation $P = 6.84 - 0.63\ t$ was obtained for road 1-a, which was compacted on March 3. The compacting and measurement of the two roads (of March 3 and of April 6) were carried out under practically identical weather conditions. At a surface temperature of -26°C a surface hardness of 15.44 and 17.32 kg/cm^2, respectively, were recorded for the roads compacted on April 6, approximately 20 hours after compacting. A corresponding surface temperature will give a hardness value of 22.22 kg/cm^2 for road 1-a.

In Fig. 19 the particle size in the different layers and the density, both in untreated snow, is shown for different times of the winter in the experimental area in Lycksele. The particle sizes are expressed as diameters of the largest particles found in the respective layers. In connection with the last observation (April 25th) a road was compacted by tractor processing followed by treatment with rail-roller and sliding pontoon, at temperatures a few degrees above the freezing point. During the night the temperature dropped to -5°C and the road became particularly hard. When the temperature rose during the next day to 5 - 6°C above freezing point, the road disintegrated completely and the bonds between the individual coarse-grained snow particles disappeared almost entirely.

In order to obtain a detailed picture of compacting results with different methods at different times of the winter, considerably more observations are required than the ones reported here.

It is undoubtedly true that a road can be constructed without difficulty during early and late winter. It is again true that the hardness at 0 cm depth in the "December road" was relatively low, probably due to the fact that fine-grained snow is difficult to compress at the low temperatures prevailing at the time of compacting. It is believed that the good bonding capacity of fine-grained snow during early winter produces very good roads. On the other hand, the opinion has been expressed that satisfactory roads cannot be obtained in "March snow" (this applies to continental and northern parts of Norrland). It is possible that this opinion results from compacting with a "Weasel" during the late winter. In the course of the winter a coarse-grained layer forms at the bottom of the snow cover. Such snow which has very inferior bearing properties, is frequently referred to as depth hoar. As the winter progresses the thickness of this layer increases (see Table XII). If the snow is merely compressed, as is generally the case when compacting is performed by the "Weasel", a relatively thin bearing surface layer is formed while the extensive layer of depth hoar remains more or less as before[12].

If the snow were mixed and treated during compacting with the aid of a deep-penetrating tractor, a rotary tiller or similar equipment, roads of some bearing capacity could probably be produced even in late winter. Such roads, however, are inferior to roads which have been compacted earlier, since the size of snow particles increases as the winter progresses and the possibilities of bond formation between individual particles is thus reduced. After the melting of snow has actually started, the snow particles become too large and too rounded to produce strong roads even if the snow is processed intensively. However, the construction of new roads so late in the winter is hardly ever required.

3. The effect of traffic

Once a road has gained sufficient hardness so that it can be opened for traffic the increase of the hardness of the road depends on the traffic itself. Increased hardness in a road used by wheel tractors has been reported by Leijonhufvud[12].

The effects of traffic on two roads compacted differently with respect to the intensity of processing were compared in Alsbäcken. One road was compacted by rail-roller and sliding pontoon, the other by rotary tiller, rail-roller and sliding pontoon. Compacting was performed on February 15 in snow approximately 100 cm deep. Both of these roads were then used by track-type tractors with ballasted sledges for a period of two weeks. The density of the upper layer and the temperature and hardness of each road at various depths were determined before and after this period of traffic. The temperature during the period of time between the two measurements never rose above the freezing point.

Unfortunately, after the roads were in use for two weeks the hardness of the snow at some points of measurement at 0 and at 5 cm depth exceeded the capacity of the proctor needle. In calculating the average values each measured value which was higher than the maximum reading of the proctor needle was given this maximum value. The sign > (greater than) was added to such average values and the number of individual observations which exceeded the reading capacity of the proctor needle was also recorded. This procedure makes the comparison of roads more difficult, but on the basis of the figures thus obtained and of the density determinations it can be stated that both roads obtained almost the same degree of surface hardness as the result of traffic. Traffic by track-type tractors, however, could not even out the already great differences in the interior of the road bed. The relative hardness had indeed increased more in the slightly compacted road, but the hardness values at 15 and 25 cm depth, respectively, of the road treated by the rotary tiller were still 33 and 40 percent higher than those of the former.

The rate of hardness increase due to traffic depends, of course, on the vehicles and the sledge loads driven over it. The average density and hardness values for roads exposed to various types of traffic have been reported by Kragelski (1945). His figures are reproduced in Table XI.

The hardness values in kg/cm^2 recorded by Kragelski are probably not comparable with those of the author. How these values were obtained has not been explained. Kragelski's values do however show the extent to which the roads can be compacted by exposure to wheeled traffic. Wheeled vehicles, as a rule, pull heavier loads, a fact which also contributes to the compacting effect.

4. Formation of depth hoar in compacted roads

Leijonhufvud[12] has shown that depth hoar does not form in roads which have been exposed to traffic by wheeled tractors and in which either the snow had been well mixed before compacting or which had been first compacted to the bottom. According to other authors[22], such depth hoar forms in roads from the bottom, as in an untreated snow cover, and thus undermines them. In order to determine, if such deterioration takes place in roads exposed to light-weight traffic only, the following observations were made on a snow road compacted for horse-drawn traffic. The road was compacted in the district of Björksele, four Swedish miles northwest of Lycksele on January 11, 1955. An Oliver OC3 tractor processed the snow by "track-to-track" treatment, after which the road was dragged. The depth of the snow was approximately 60 cm. The road was then used for horse-drawn traffic until March 25.

At different points along the road tests were made constantly both in the untreated snow cover and in the road bed to determine the changes in snow particle size. The first and the last measurements at one of the observation points are shown in Table XII. The size of particles is expressed as the diameter of the largest snow grain observed in each respective layer. The boundary line between depth hoar and other types of snow is indicated in the table by a broken line.

Table XII shows that the increase of particle size had been considerable in the untreated snow cover but insignificant in the road bed. This held true for all the observation points.

Provided the snow is well mixed during the compacting process, there does not appear to be sufficient depth-hoar formation in the snow road to have an adverse effect on its bearing strength. This seems to hold true for roads exposed to either light or heavy traffic.

V. Drawbar Pull Tests

1. Drawbar pull tests with different types of tractors on compacted snow roads of various bearing strength

In order to determine the hardness requirements of compacted snow roads to be used by wheel tractors and track-type tractors, and to study how the darwbar pull of these vehicles varies with the hardness of the road, a number of experiments were carried out in the experimental area in Albäcken.

The following tractors (gasoline-driven) were used in the tests:

	Total weight
Ferguson TE-A 20 with "Combi-Triumph" anti-skid device (see Fig. 20)	1236 kg
Ferguson TE-A 20 equipped with Bombardier half-tracks	1570 kg
Ferguson TE-A 20 equipped with SDA's wheel tracks	2000 kg

The method of testing was the same as that used in the traction resistance tests in loose snow described above (see page 25 and 26).

A heavy tractor was used as the braking vehicle. The tractor under test was braked with the help of a cable. The latter was fastened to the braking vehicle and then passed around a pulley attached to the tow hook of the test vehicle and then back to a dynamometer (PM dynamometer) mounted on the tow hook of the braking vehicle, where it was secured. The drawbar pull of the test vehicle was increased gradually with the tractor in low gear by letting the clutch out slowly. This continued until the tractor lost its grip on the substratum and the wheels or tracks started to slip. The tractor's momentum was thus not utilized; the tractor merely applied pulling force up to the constant slipping. By this method the maximum drawbar pull of a vehicle at the instant of slipping gives the pulling power of the tractor in a stationary position.

Apart from differences of engine design, this drawbar pull depends on the capacity of the wheels or tracks to grip the substratum and on the size of the load imposed on the wheels or tracks, as the case may be.

When hauling timber the tractor's drawbar pull is put to the test mainly in two different situations, driving uphill and starting out after loading to capacity. When driving uphill the factor which limits the size of the load is the maximum drawbar pull under hard pulling conditions. This limiting aspect of the pulling capacity of a tractor can thus be reproduced by the above-described test with a stationary tractor. However, the initial start after loading the sledges with timber is often made difficult by the freezing of the runners to the substratum during loading. The starting friction may be as much as ten times the running friction[7]. This starting friction can be overcome, for example, by applying an "elastic pull", i.e., utilizing the momentum of the tractor. Attempts were made to determine the magnitude of such a pull experimentally by allowing the test vehicle a certain "jerk distance" corresponding to an "elastic pull". However, neither the method of testing nor the measuring instruments proved capable of producing reliable results.

The results of the drawbar pull tests for the three types of tractors on substrata of various hardnesses are shown in Fig. 21. Each point on the diagram represents the mean value of three tests on the same substratum. For general information regarding the reliability of these mean values, it should be mentioned, that the difference between the highest and the lowest individual values (range of scatter) was less than 100 kiloponds for 30 percent of the data, 100 kiloponds for 50 percent and more than 100 kiloponds for

20 percent. The readings on the instrument could be measured with an accuracy of 50 kiloponds.

The hardness values for freshly compacted, unused roads, varied as a rule between 0 and 20 kg/cm^2, while the hardness of the roads exposed to traffic under different conditions was over 20 kg/cm^2. Two tests were also carried out on bottom ploughed roads which were in use. The results of this test are shown on the extreme right of the diagram.

The tractor with wheel-tracks was superior to the others because of its greater weight and its greater area of contact with the substratum. At the highest drawbar pull value recorded by this tractor, the motor stalled without any slipping of the tracks. This means that the maximum pull of the tractor relative to the engine output was somewhat over 1600 kg.

On a loose substratum the tractor equipped with half-tracks had a higher drawbar pull than the wheeled tractor, but with increasing substratum hardness the difference was reduced. On the two hardest roads the wheel tractor actually had a higher drawbar pull than the tractor equipped with half-tracks. The half-tracked tractor seems to have an optimum drawbar pull at hardness values between 20 and 50 kg/cm^2. Such values correspond to relatively high temperatures in roads subjected to traffic. It also appears that the tractor with wheel-tracks had its optimum drawbar pull within the range of hardness values employed in the experiment. On substrata with values of 43 and 63 kg/cm^2 the engine stalled, whereas slippage occurred on the two bottom-ploughed roads which gave the hardest substrata of all the roads.

The author tried, during the experiments, to estimate the lowest hardness value at which a given vehicle could be expected to start hauling on a snow road over level ground. A few spot tests were carried out with loads up to 3 tons. The estimated limits are indicated in Fig. 21. A few comments are, however, necessary. The pull which was recorded in the above-described tests was the propulsive or frictional force, which depends on the grip of the driving parts on the substratum and on the load imposed on these parts. In forward motion, however, the tractor has to overcome a resistance which is produced mainly by the fact that the wheels or tracks penetrate the substratum and must perform work of deformation. This resistance, called rolling resistance, increases with decreasing hardness of the substratum[8,21]. If the rolling resistance is higher than the propulsive force, the tractor does not move ahead, but digs itself into the substratum. This happened with the wheel tractor at a hardness value of 3 - 5 kg/cm². In order to start hauling loads therefore, a road hardness is required which will make it possible to secure a certain surplus of drawbar pull.

If these hardness value limits are entered in the nomogram of Fig. 18, the following may be noted. Under the conditions which prevailed during the test period intensive processing with the rotary tiller, rail-roller and sliding pontoon had produced roads on which wheel tractors could start hauling operations 24 hours after compacting, provided the temperature from the time between compacting until the start of traffic had been from 5 to 10 degrees below freezing point, even when the method had resulted in relatively low snow densities. Where low density values were expected from treatments "B" and "C", temperatures of 20 to 25 degrees below the freezing point would be required for treatment "B" and still lower ones for treatment "C", before the road could be opened to wheel tractors 24 hours after compacting.

To obtain strong roads by methods described under "B" and "C" the roads must be allowed to harden a certain period of time first before being used at relatively high temperatures.

Treatment "B" had probably produced strong roads for traffic by half-tracked tractors after a waiting period of a few days.

Where method "C" was applied a temperature of -5°C during the period between compacting and use had apparently been adequate for tractors with full tracks, although the compacting results were relatively poor (low density).

Even if one is critical of this schematic application of the test results, it must be admitted that it clarifies the demands made by the different types of vehicles on the snow roads and it shows which techniques should be used to establish roads which will meet these demands under various conditions.

The above-described tests were carried out with light tractors. In connection with the previously described experiments with different vehicles tested by the SDA concurrently with the snow compacting tests reported here, drawbar pull tests were made with a great many different vehicles, using the same testing methods.

The tests were performed on a large snow field which was compacted and worn in by different vehicles under more or less identical conditions. During the experiments hardness was measured with a proctor needle in different parts of the field at different times. The mean values from 25 observations varied between 15 and 22 kg/cm^2. The temperature during the whole period was about -13°C and the density of the substratum surface layer was approximately 0.51 gm/cm^2.

In order to connect up the drawbar pull values for the tractors used in the snow-compacting tests with those of some other vehicles, the three Ferguson tractors, equipped as described above, were tested concurrently with the other vehicles. The results are shown in Table XIII in which the maximum pull (drawbar pull at the instant of slipping of a stationary tractor in the "best" gear) is recorded for the different tractors on the substratum described above.

The drawbar pull values recorded in Table XIII cannot, of course, be used for general comparison of the different vehicles and the different types of tracks; they merely indicated the approximate orders of magnitude.

2. Drawbar pull tests with various anti-skid devices and extra loads on a wheel tractor

As a part of the winter experiments, a few of the most common commercial anti-skid devices were compared during late winter in Lycksele. The following anti-skid devices, fitted to a Diesel-driven Ferguson 1320 kg tractor, were tested: Convention snow chains (weight 64 kg, see Fig. 22), "Combi-Triumph" (116 kg, Fig. 20), "Ceve" (77 kg, Fig. 23), "Perfekt"* (251 kg, Fig. 24), "Mudmaster" (192 kg, Fig. 25) and half-tracks of Bombardier type for Ferguson (approximately 450 kg).

Drawings of the anti-skid devices and tracks tested on the tractors can be found in Appendix 1.

The maximum drawbar pull for the various anti-skid devices was determined by the method described above. For each type of anti-skid device the drawbar pull was measured both for the unballasted tractor and for the tractor carrying extra loads of 250, 500 and 750 kg. The latter were placed above the tow hook of the tractor as close to the rear axle as possible.

The experiments were carried out on two different categories of roads characterized by different hardness values. The roads of one category had been exposed to some traffic and had hardness values of 25 - 35 kg/cm^2. The other roads were newly compacted, with a hardness of 10 - 15 kg/cm^2. The test results are summarized in Table XIV. Each value in the table represent the mean value from five tests on the same substratum. It should be noted, that this Ferguson tractor was Diesel driven, while the tractor which was used for the previous drawbar pull tests was gasoline driven. The last mentioned type could pull only 1600 kp in a stationary pull before the engine stalled, while the Diesel-driven tractor attained drawbar pull values up to almost 2000 kp without stalling.

(a) Comparison of different anti-skid devices. For comparison of the different anti-skid devices the drawbar pull for the conventional snow chains was assigned a value of 100. This was based on the fact that conventional snow chains are at present the most commonly used anti-skid device. The drawbar pull values of the other anti-skid devices on different roads and for different extra loads were then expressed as values relative to the corresponding values for the conventional chains. The results are shown in the form of a diagram in Fig. 26. The large brackets on the diagram

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* Equipped with an extra rim on each plate for hauling on snow substratum.

indicate the range of variation of the individual relative values, and the corresponding mean value is shown in parentheses. It can be seen from the diagram, for example, that the tractor equipped with "Perfekt" devices, had between 43 and 121 percent (average 77.5 percent) more drawbar pull than with conventional snow chains. An approximate value of drawbar pull obtained with rubber tires has also been included in the diagram, chiefly as a matter of curiosity (this value was obtained from a test on a hard-compacted road at a different time from the tests reported here).

It is apparent from the diagram that the variation of the relative values was very high. Besides the error in measurement and the possible errors due to changing conditions during the different parts of the experiment, this variation was caused, among other things, by the fact that the relationship between the drawbar pull values for the different anti-skid devices varied somewhat with the size of the extra load and with the hardness of the road. For the purpose of evaluating the different anti-skid devices, the data are, however, fully usable. Additional tests have confirmed this classification according to efficiency of the different anti-skid devices.

The differences cannot be ascribed solely to differences in the grip of the anti-skid devices on the road. They are influenced to some extent also by the differences in weight of the various devices. With the aid of the graphically adjusted relationship between extra loads and the drawbar pull values for each anti-skid device, an estimate was made of the drawbar pull values which are purely the effect of the weight difference between conventional snow chains and other anti-skid devices:

Conventional chains	Combi-Triumph	Ceve	Mudmaster	Perfekt
100	107	101	112	128

The relationship between half-tracks and conventional snow chains was not considered comparable in this connection, since half-tracks provide a considerably greater area of contact with the substratum. These relative figures are therefore not included.

An interesting point concerning the form of an anti-skid device will be discussed in this connection. The plates of the "Perfekt" are normally mounted in such a way that the higher lug of each plate grips the substratum before the shorter one. An anti-skid device was first tested in which every second plate was reversed with respect to the relative position of the lugs. Fig. 27 shows how the anti-skid device looked after a short period of driving. The reversed plates were full of compressed snow and had lost a great deal of their gripping capacity, while the unreversed plates were relatively free from snow.

The test results show that <u>the choice of anti-skid devices and their design is of great importance for the pulling capacity</u> of the tractor. It should be pointed out, however, that the various anti-skid devices have been evaluated only on the basis of the drawbar pull of the tractor. The other properties of the anti-skid devices have not been taken into consideration.

(b) <u>Relationship between drawbar pull and extra loading</u>. In order to determine the extent of the increase in drawbar pull due to an increase of load on the wheels of the tractor, the drawbar pull value at zero load for each anti-skid device and for each road was assigned a value of 100. The drawbar pull values for other loads were then expressed in terms of this value. The highest gain in drawbar pull was recorded for conventional snow chains on the road which had been exposed to traffic. The tractor with an extra ballast of 750 kg showed a 162 percent increase in drawbar pull over the unballasted vehicle. The smallest gain was obtained with Mudmasters on the traffic-worn road, where the corresponding figure was 62 percent. Moreover, the increase of drawbar pull due to extra load was almost always greater on traffic-worn roads than on loose, newly compacted roads.

The average approximate increases for all types of anti-skid devices and on both types of roads were 32% for an extra load of 250 kg, 63% for 500 kg greater and 95% for 750 kg applied to the tow hook.

The test data do not permit a more detailed analysis with respect to the different types of anti-skid device. The figures reported here serve as a rough indication of the effect of ballasting on the drawbar pull of a tractor on a substratum of compacted snow.

3. The optimum bearing strength of a road bed of snow in relation to drawbar pull

According to Fig. 21 the optimum drawbar pull of a half-tracked tractor seems to be obtained somewhere within a range of hardness values of 20 to 50 kg/cm^2. A similar optimum was also obtained for a tractor equipped with wheel-tracks but not a wheel tractor with "Combi-Triumph". It seems obvious, that for practically every type of anti-skid device or track there is an optimum bearing-strength value in relation to drawbar pull. One need only consider the extreme cases of loose snow and glassy ice. The optimum hardness lies at the point at which the substratum lets the gripping apparatus penetrate deeply while at the same time showing the greatest possible resistance to the shearing stresses exerted by the gripping devices. This optimum hardness value (on traffic-worn roads for a constant load on the driving wheels) apparently increases with decreasing size of the gripping parts of the anti-skid devices or tracks (lugs, etc.), and, for any given type of anti-skid device, with increasing load on the drive wheels. Here we ignore the engine output as a limiting factor.

Before the above-described, more or less detailed tests were carried out in Lycksele, a few preliminary drawbar pull tests were performed on the experimental field in Alsbäcken with a gasoline-driven Ferguson tractor equipped with various anti-skid devices at various extra loads on compacted roads of various hardness. Among others, a wheel tractor with conventional chains, with "Combi-Triumph" and with "Perfekt" devices were compared with tractors equipped with half-tracks and wheel-tracks. The tests were carried out on a road which had been exposed to traffic and had a hardness value of 43 kg/cm^2 at a temperature of -5°C on the surface of the road. Before the experiments the road was driven over approximately

50 times by a track-type tractor with ballasted sledges. The results are shown in Fig. 28. Each point in the graph represents the mean value of three tests on the same substratum. In the cases where the engine stalled without any skidding of the wheels, the values have been marked with circles. It should be mentioned that the highest drawbar pull values for the tractors tested were obtained as a rule in low gear and that this gear was therefore used in every test. Fig. 28 shows that "Perfekt" produced such a good grip on the road that the tractor could pull until the engine stalled without having any extra ballast on the driving wheels. This was also true of an unballasted tractor equipped with wheel-tracks and one equipped with half-tracks when ballasted with an extra weight of 450 kg. The fact that the wheel tractor developed a lower maximum drawbar pull than the tractors equipped with wheel-tracks and half-tracks may be due to differences in engine tuning or possibly to failure to warm up the engine of the wheel tractor before the test. As a rule, the tractor was warmed up properly before each test. It seems, however, that this substratum had a hardness which was close to the optimum value for an unballasted Ferguson tractor equipped with "Perfekt" anti-skid devices. With the other two types of anti-skid devices slipping occurred even with the maximum tractor ballast.

It thus seems that <u>tractors equipped with either wheel-tracks or half-tracks and wheel tractors fitted with anti-skid devices having prominent lugs have the optimum drawbar pull values on roads which have been exposed to traffic at relatively high temperatures. This applies to the light-weight tractors tested. The optimum drawbar pull of heavier vehicles is probably displaced towards higher hardness values and lower temperatures</u>.

It can also be assumed, that with certain anti-skid devices a better grip can be obtained on a road bed of snow than on a hardened, bottom-ploughed road which has been exposed to traffic.

As far as anti-skid devices and extra ballast on wheel tractors are concerned, <u>the old belief that the drawbar pull of a tractor can be thus increased has been verified. The experiments have shown</u>

that a light wheel tractor with a good anti-skid device and a relatively small ballast on the drive wheels can in certain cases grip a substratum of compacted snow sufficiently well to attain the limiting drawbar pull value determined by the engine output.

VI. Traction Resistance Tests

1. Driving on new-fallen snow over a hard road bed

The main argument of horse drivers against the compacted snow roads has been their belief that loads are harder to haul on such roads than on bottom-ploughed roads. Their complaint seems to be justified when considering the methods of maintenance commonly in use for compacted snow roads. When new-fallen snow or drift snow comes to the road surface, it is, as a rule, compacted by the help of a roller or the road is simply driven over and then dragged. It is generally known, that new-fallen snow and fine-grained drift snow cause higher draught resistance. This has been pointed out by Eriksson in his relatively extensive study of sledge runner friction on snow and ice[7].

In order to clarify these factors further, some traction resistance tests were carried out on the experimental area in Alsbäcken. A tractor drove with loaded sledges several times over a road which had been subjected to traffic but which was covered on one occasion with 7 cm snow and on another with 1 cm of new-fallen snow. After a certain number of passes the traction resistance was measured with the instrument described on page 5. A Fiat OM with Alfta winter tracks was used for pulling; the sledge was a "Stensele" type (runner width, 15 cm). The total weight of the load was 3060 kg on the first occasion and 1645 kg on the second. The driving speed was 1 m/sec. The traction resistance is expressed as a percentage of the gross weight. The results in Fig. 29 indicate that on 7 cm of new snow the traction resistance tended to attain a constant value only after approximately 10 passes had been completed. When hauling timber in practice the road is also used by unloaded vehicles and it can therefore be stated that a snowfall of the indicated magnitude may increase the traction resistance to double the normal value on the first trip, and cause some increase for at least the first five round trips after a snowfall.

A 1 cm thick layer of new-fallen snow caused an insignificant increase in traction resistance during the first passes.

These test results cannot be applied directly to the case where hauling is done by horse. The tracks of a tractor process the snow while driving, and it is difficult to say what effect this has on the traction resistance. It is obvious, however, that new snow and drift snow on a road bed increase the traction resistance substantially even when the hauling is done by horse.

In order to get some information on the frequency and amounts of precipitation in winter, some data were obtained from the Swedish Meteorological and Hydrological Institute (SMHI) for their stations in Stensele, Forse (Ångermanland) and Särna. These data have been summarized in Table XV, which shows the number of days with precipitation of various magnitudes for each month and station. The amounts of precipitation are given in millimetres and have been divided into four classes. When "converted to snow" 1 mm equals approximately 1 cm. The figures represent average values for the years 1911 to 1940.

Assuming that a snowfall of more than 1 cm increases the traction resistance to a point where the load must be reduced, since pulling strength of the horse on a traffic-worn road is in any case taxed to the maximum, it is found that at all the three stations such amounts of precipitation occur 9 - 11 times in January, the frequency decreasing in the course of the winter to 7 - 8 times in March. In addition to the snowfalls, snow sometimes drifts onto the road, so that obviously the road will often become heavy for hauling, especially if maintenance is restricted to the use of a roller or simply to driving over the road. It is clear that maintenance techniques have to be adapted to such conditions at least for horse-drawn traffic in which the drawbar pull is generally the limiting factor for the size of the load. How this problem can be solved in practice will be discussed later.

2. General considerations with respect to traction resistance on a compacted snow road

The traction resistance also varies, of course, with the hardness of the substratum. At low hardness values the runners of the sledge penetrate into the snow and they have to perform considerable work of deformation during forward motion. A few traction resistance tests were carried out on roads of different hardnesses in order to clarify this aspect. The above-mentioned Stensele sledge was used. The total weight of the load, including the sledge, was 3060 kg. The sledge was drawn over the road by a winch. In the experiments, carried out at a temperature of -8°C, traction resistance, runner penetration depth and road hardness were recorded. The results are shown in Table XVI. The traction resistance tests of experiment No. 3 were unsuccessful.

The runner width of the tested sledge was approximately twice that of the commercial sledges. Relatively wide runners are recommended for use on compacted snow roads[12] and they are especially advantageous under the conditions prevailing when a road is first opened to traffic.

What traction resistance values should be used for estimating the load sizes on compacted roads? A summary of a number of friction studies will be found in the Skogsteknisk Handbok (Handbook of Forest Technology) published by the SDA. The average approximate mean values for winter are given as 3.5 percent for a "hard compacted snow road" and approximately 7 percent for a road covered with new snow or for a loose and slushy road. The first value applies to haulage roads for horses in which the ruts have become icy. If a track-type or wheel tractor is used for hauling, the ruts formed by the sledge runners at each pass are usually broken up by the tractor. A higher traction resistance may therefore by expected on such road than on a haulage road for horses, where the ruts are not deformed. On the road on which a track-type tractor pulled a loaded sledge, the traction resistance test gave a value between 4 and 7 percent where the size of load varied between 1.5 and 7 tons and the range of temperatures was from -1° to - 14°C. On the basis of the results of previous studies, and to some extent also on the basis of the values reported here, it is believed that a traction resistance value of 5 - 6 percent can be taken as an approximate "standard value" for track-type and wheel tractors on haulage roads.

VII. Traffic Intensity Tests

The author also conducted some experiments with wheeled trailers. Since these experiments threw some additional light on the properties of snow roads they will be discussed here briefly. The tests were carried out during the second half of February in the Alsbäcken experimental area.

The purpose of the study was to determine the hardness which is required for the use of a tractor towing a two-wheeled trailer at a given level of traffic activity.

Trailer data:

Total weight	520 kg
Load at coupling loop	225 kg
Tire size	6.00 - 20

The trailer was normally equipped with rubber-tired wheels but could also take wheel runners. Two different types of wheel runners were tested.

Wheel-runner data:

	Length	Width	Area
Wide type	160 cm	31 cm	4950 cm^2
Narrow type	158 cm	12.5 cm	1980 cm^2

Gasoline-driven Ferguson tractors equipped with wheel-tracks, half-tracks and with Combi-Triumph devices were tested alternately.

As a road hardness requirement it was decided that the road should withstand 15 passes of the tractor and the trailer driven in the same ruts 24 hours after compacting. The load on the trailer during the test was 900 kg. The gross weight of the loaded trailer was distributed as follows: 490 kg on the hook and 930 kg on the axle of the cart.

The experiment was carried out on level ground at a snow depth of 90 to 120 cm. A number of test roads were compacted by different methods. Approximately 24 hours after compacting the roads were tested with a number of different vehicle combinations. The necessary meteorological observations were made for the period of time between compacting and driving. The hardnesses and temperatures of the surface layers of the roads were determined immediately before compacting.

It was soon established that the bearing properties were slightly better for the narrow type of wheel runners than for wheels alone, and that under moderately cold conditions neither the rail-roller and sliding pontoon used directly in unmixed snow nor tractor, rail-roller, sliding pontoon treatment would produce a road capable of standing up to traffic by wheel tractors and tractors with half-tracks. The tractor equipped with wheel-tracks, however, did not require such low temperatures with these methods for completing 15 passes. Since the main interest was directed to the behaviour of wheel tractors and tractors equipped with half-tracks, no attempt was made to determine the range of hardness requirements for tractors equipped with wheel-tracks on these test roads. The tests therefore continued on the roads compacted with rotary tiller, rail-roller and sliding pontoon. As mentioned previously, the combination was employed for technical reasons instead of the rotary tiller - sliding pontoon combination. The relative effect of a rail-roller on the compacting results seems to be small.

For this method compacting approximate limiting values for hardness and temperature were obtained for the conditions prevailing in the experimental area. These values are shown in Fig. 30. The temperature values are for the period of time between compaction and the opening of the road to traffic. These boundary values were not directly established during this experiment, of course, but were obtained by interpolation of various test results. The possibility of error in reporting a certain hardness at a certain temperature for a given method of compacting is approximately the same as that mentioned in connection with the construction of the nomogram of Fig. 18. Since the tests reported here were carried out within a relatively limited range of temperatures the values given in Fig. 30 would appear to be somewhat more reliable. At the "limit of hardness" the road was considered to be completely broken up, with ruts up to 30 cm deep. The depth of snow in the roads was 40 - 55 cm.

The following conclusions, we believe, can be drawn from these experiments. The rail-roller - sliding pontoon method of compacting used directly in deep, loose snow produces roads which stand a high level of traffic activity relatively soon after compacting even when tho road is used by wheel tractors. Hauling of timber certainly makes greater demands on the roads than the vehicle combinations tested here, but the intensity of traffic activity in timber hauling is not as great as it was during these experiments.

VIII. Some Timber Hauling Experiences on Compacted Snow Roads in the Recent Winters

In 1955 Leijonhufvud[12] reported the results of practical experience with compacted snow roads under various conditions. The recent winter seasons have provided us with some additional results, some of which will be reported here. These will be described here partly in the form of short reports on a few driving experiments and partly as summaries derived from various sources.

1. Hauling with horse and with track-type tractor

In the district of Älvdalen, Stora Kopperbergs Bergslags AB, the rail-roller and sliding pontoon combination was tested for establishing main hauling roads for horses and crawler tractors.

A road was supposed to be established on January 25 in a depth of snow of 70 - 95 cm with the above-mentioned equipment pulled by a Cletrac tractor with Alfta tracks. It was found, however, that the tractor could not pull the equipment directly in such deep snow even when the tractor had rutted it immediately before compacting. The tractor then opened up ruts of double width on the whole road by moving back and forth, after which the ruts were left to harden overnight. The next morning the equipment was pulled back and forth over the road without difficulty, the tractor being driven in second gear. The temperature was -20°C. Four days after compacting the same tractor hauled a full load consisting of 9 cu metres (solid measure) of debarked pulpwood over the road. The temperature during the first pass was -12°C. The road was maintained basically by driving over it. On one occasion approximately 15 cm and on another approximately 20 cm of new snow and drift snow covered the road. The snow was then treated with a rail-roller and a sliding pontoon, and the day after compacting full loads were hauled again. Hauling continued until April 16 without any reduction of loads due to mild weather or the like.

With a Nordverk snow tractor a road was compacted on January 24 by the same method as that used for the Cletrac road. The depth of snow was again 70 - 95 cm and the temperature -23°C. Two days after compacting the first load of approximately 6 cu metres (solid measure) of debarked pulpwood was hauled with the Nordverk tractor at a temperature of -18°C, and starting the third day after compacting, full loads of 16 cu metres (solid measure) were carried. As the only maintenance measure a homemade drag equipped with a steel ice scraper was towed behind the tractor in the course of regular traffic. This was used once or twice a week. Both the above-mentioned new snowfalls were treated as follows: For a whole day following the storm, loads were reduced to 70 percent of normal, but the usual number of trips were made. The next day the road was dragged, after which full loads could again be hauled. Hauling continued until April 24 without appreciable reduction in the size of the loads.

A main hauling road for horses was compacted as late as March 9 using the same method of processing as for the above two roads. The depth of snow was 55 - 85 cm and the temperature -8°C. One detail in establishing roads for hauling by horses should be pointed out. By opening ruts of double width in such a way that the inner edges of the two pairs of ruts are in contact with each other, a thorough processing of snow by the tracks of the tractor and by the roller and sliding pontoon is obtained in the portion of the road which later becomes the path for the horse (cf. methods 2 and 3 in Section III, "Different methods of processing snow"). The day after compacting, 15 cm of snow fell on the road and this snow was treated with compacting equipment. Hauling was started five days after compacting at a temperature of -6°C. For the period of time between compacting and hauling the temperature stayed at -5 to -6°C. The first load consisted of 2.5 cu metres (solid measure) of pulpwood. From the third day on full loads of approximately 4 cu metres (solid measure) were hauled. The road was maintained with the aid of a wooden plough, which was used after snowfalls and when the road became slushy. According to haulers, ploughing creates good embankments for the road. Hauling was completed on April 26. During the period of hauling no reduction in the size of loads was observed, although the temperature stayed for a long time at about -2°C.

In the district of Nå (Stora Kopparbergs Bergslags AB) a Fordson Major tractor equipped with SDA's wheel-tracks opened a road directly in snow 45 - 65 cm deep using a rail-roller and sliding pontoon. The compacting was carried out on January 30 at a temperature of -28°C. Nine days after compacting the Fordson tractor hauled the first load of 450 cu ft of green, freshly cut timber at a temperature of -18°C. The road was maintained with the aid of a drag (see the SDA's booklet entitled "Road Equipment"). The dragging was carried out, as a rule, during trips with empty vehicles. Difficulties of dragging on banked sections were solved by welding pieces of steel to the runners of the drag so as to prevent slipping. During the period of hauling dragging was carried out on six occasions. The size of the loads, approximately 450 - 550 cu ft of green timber, was kept constant until the end of the hauling operation on April 25, without reduction due to weather or wind. On Wednesday, March 21, during a visit to the area, the author measured the hardness at different levels of the road. The temperature was $\pm 0°C$, the snow depth 25 cm and the following proctor values were recorded: At the surface 62.6 kg/cm^2, 5 cm from the surface - 44.4 kg/cm^2, 10 cm from the surface - 11.8 kg/cm^2 and 20 cm from the surface - 10.4 kg/cm^2. The low hardness values for the lower strata of the road indicate that transport of moisture from the lower layers to the upper strata had weakened the former and that traffic by tractors equipped with wheel-tracks pulling loaded sledges had compacted the upper layers only, in spite of the relatively heavy loads on the sledges. The depth hoar layer at the bottom was approximately 2 - 7 cm thick. It was proabably already present before compacting, since the method of compacting generally leaves such a layer of depth hoar unmixed. The bearing properties of the road did not, however, seem to have been affected by the weakening of the bottom layers. Although the temperature during the last week of the hauling operation rose to 5 to 15 degrees above freezing point every afternoon, full loads were in effect. On April 25, however, the road became bare on a slope with southern exposure and hauling had to be discontinued.

The district of Lycksele, Mo och Domsjö AB, has had considerable experience with compacted snow roads, expecially for horse-drawn traffic. The method of maintaining the roads by compacting only the new-fallen snow has been more or less discarded there. Light-weight wooden ploughs and rut cutters have been included in the maintenance equipment for snow roads. The maintenance measures can thus be adapted to suit the amount of new snow on the surface of the road. This snow can be either removed by ploughing or compacted, and thus the advantages of a bottom-ploughed road can be combined with those of a compacted snow road.

2. <u>Hauling with wheeled tractors</u>

An interesting hauling operation with a wheeled tractor was carried out in the district of Lycksele, Mo och Domsjö AB. One road was compacted at the end of December and two others at the beginning of January, using the method of processing the snow with a tractor by "track-to-track" treatment and then dragging the road. On the first occasion a Cletrac tractor was employed and on the second a Volvo T 31 tractor equipped with SDA wheel-tracks. The roads were not used until the middle of March, when 30 - 35 cm loose snow covered them. A Ferguson wheel tractor equipped with conventional snow chains then hauled a load of 200 - 250 cu ft of timber over the roads. After this the road was dragged. The roads were maintained afterwards with the aid of a drag and a plough. On March 27 to 29 a heavy thaw occurred, but the hauling of full loads of 400 cu ft unbarked timber was continued. On the second day of the thaw the tractor broke through the road bed almost to the bottom, and ruined the road completely. The road was then dragged the same evening and it hardened during the night in spite of temperatures above the freezing point (effect of radiation?). The day after, full loads were hauled again. The road was again broken up and was dragged in the evening. Then colder weather set in and the road became very hard. Previous experience also indicated that a road which is broken up during a thaw, if dragged afterwards, will become considerably harder than it was before. Hauling on the test roads was continued with unreduced loads until April 24. The snow depth in the roads on April 21 was approximately 40 cm.

During the two recent winter seasons a special method of constructing road beds of snow for traffic by wheeled tractors and even for traffic by trucks has been used in the forest district of Särna. For example, a Fiat CF 25 equipped with Alfta tracks tows a BM-35 wheel tractor and a sledge directly over untreated snow, whatever the depth of snow may be. The same combination of vehicles then drives over the road with a few logs on the sledge. During the following passes successively increased loads are employed. The road is then dragged, after which hauling is continued with wheel tractors, since the road has become very hard. After wheeled tractors have used the road for a while even trucks are driven over it. The trucks could operate on the roads even during mild day-time conditions. The method of establishing the snow road consisted in first thoroughly processing the snow cover and then leaving the development of the necessary hardness to the trucks. One road was compacted by the above-described method as late as April of this year and a road bed of adequate bearing strength was obtained.

IX. Views on the Opening and Maintenance of Compacted Snow Roads

On the basis of test results and recent practical experience the author has attempted to present certain views on establishing and maintaining compacted snow roads for various types of timber transport. Certain fundamental principles can be stated.

In establishing a road, obviously, "no greater force should be used than the need justifies". For a wheeled tractor a considerably harder road, and consequently a more intensive processing, is required than for one intended, for example, for horse-drawn traffic. In order to adapt the technique of establishing snow roads to their requirements with respect to bearing properties, something must be known about the range of bearing strengths obtainable by different methods of compacting and the variation of bearing properties under various conditions. It is also necessary to understand the effects of the most important variables such as the compacting temperature, the time elapsing between compacting and use of the road, the time of compacting, etc., on the properties of road, so that the necessary bearing properties can be attained with minimum effort. With the help of such knowledge a choice can be made, for example, between two alternative methods of establishing the road, on the basis of the bearing-strength requirements for a given type of traffic. If compacting is carried out only a day or a few days before the hauling operation is started, an intensive and expensive processing of snow will probably be needed in order to obtain the necessary hardness in the road. On the other hand, if compacting is carried out a week or more before hauling operations begin it should be possible to employ a simple method of compacting and still attain the same hardness, since the hardness of the upper layer of the road increases with the interval between compacting and the use of the road. However, a certain risk is involved in the latter case. If a heavy snowfall occurs immediately after compacting, the layer of new snow will insulate the road bed from the cold air above and the hardening process will be retarded. The extent of maintenance required on a given road depends, among other factors, on whether or not the drawbar pull is the limiting factor for the size of loads. A haulage road for horse-drawn traffic, if it includes some uphill sections, will require careful maintenance in order to minimize the traction resistance, since the drawbar pull of the horse is normally the limiting factor for the size of loads. In a level road for hauling by tractor on the other hand, other factors such as the type sledges employed, may determine the size of maximum loads. On such roads a given tractor will have some surplus pulling capacity which can be utilized when the road conditions deteriorate. Such a road requires but slight maintenance. The maintenance measures also depend on the extent to which the sledges deform the road bed, the exposure of the road to weather and wind, etc.

In what follows the possibilities of employing compacted snow roads as an alternative to existing practice for conventional types of timber transport, are discussed.

1. <u>Hauling over forest trails by horse and by track-type tractors</u>

In districts subject to heavy snowfall timber is usually taken out in winter to the forest trails. The hauler collects timber on these trails and hauls it to a main road or directly to a stockpiling point on a highway, waterway or similar location. The trail is usually prepared by the haulers themselves, by smoothing off the untreated snow with their vehicles. The deeper the snow, the more difficult the hauling operation, partly because the horse or tractor cannot proceed so easily, and partly because more time is consumed in putting the road into a condition that will enable full loads to be hauled. In deep snow the forest trails are generally smoothed off by the empty vehicles on their way to the felling area, but when hauling starts the hauler cannot immediately take on full loads. He must first make a few runs with reduced loads. Had the road been completed before the start of hauling operations, fewer runs would have been required to transport a given amount of timber. There is thus a "hidden" road cost involved in this method.

In some places "Weasel" tractors are used for "compacting" such trails when the snow depth is too great. The question of whether it would not be profitable to "precompact" a system of trails needs further clarification. The use of a power-take-off driven rail-roller (page 27-28, Fig. 13), which processes the snow and at the same time assists the progress of the tractor in deep snow, seems to offer possibilities of establishing roads at a relatively low cost. By assisting the forward motion of the tractor even in relatively deep snow, the equipment will compact a forest trail in a single pass provided the roller is wide enough. As mentioned previously, an implement which compresses and levels the surface of the road should be attached to the rail-roller. This will increase the hardness of the road considerably.

The system of forest trails should be compacted only a short time before hauling is started, but at the same time the roads have to be allowed to harden for an adequate period of time. That is to say, if the operation is to pay, the compacting equipment can only be transported to the district once, but if the compacting is carried out a long time before hauling begins, new snow may fall on the roads and impair the hauling conditions. Even if compacting is carried out a relatively short time before hauling, new snow may nevertheless be expected to fall sooner or later. However, if the snow has been compacted once, the haulers themselves should be able to keep the road in good condition by occasional treatment in the course of their empty runs on the way to the felling area.

2. Hauling on main roads by horse

The old "standard method" has been found reliable for opening main haulage roads for horse-drawn traffic. It consists of processing the snow with a deep-penetrating tractor equipped with tracks, such as a Fiat CF 25 or Cletrac. The snow is processed by "track-to-track" treatment and then dragged. It should be mentioned that probably the most effective "compacting-drag" is a debarked round timber of the type usually available in the felling area. During recent winter seasons a new combination consisting of a "rail-roller" (Finnish type) which breaks down and mixes the snow cover, and a "sliding pontoon", which levels and compacts the road, has been developed (Fig. 8) and tested under practical conditions. It is believed, that most of our light-weight tractors could establish a road by hauling this equipment only once over it and back again, provided the snow depth is less than 50 - 60 cm. On fairly steep uphill grades the tractor may have to use its winch (a compacting tractor should, as a rule, be so equipped). The effectiveness of this method in deep snow is limited by the low drawbar pull of tractors in loose snow and by the fact that the rail-roller in its present design does not process the snow deeply enough. The ruts can be opened with a light-weight, but relatively deep-penetrating tractor and are left to harden for a few hours or overnight, depending on the prevailing temperature. These hardened ruts enable the tractor to tow the equipment with ease. To establish a road in snow more than 50 - 60 cm deep by towing the equipment directly back and forth over the snow cover, heavy deep-penetrating tractors are required. If the depth of snow is greater than 90 cm the compacting results with the combination rail-roller and sliding pontoon will become unreliable.

The idea of making the rail-roller power-take-off driven probably points to an excellent solution to the problem of insufficient drawbar pull. However, the method has to be studied further before a final decision can be made.

Apart from whether the rail-roller is to be take-off driven or not, two details must be borne in mind. When the tractor is driven back and forth on the road it must produce ruts of double width with the inside edges of each pair of ruts touching each other. In this way the road will be made especially hard in the location of "horse tracks", where it is exposed to the severest strain. Secondly, the sliding pontoon has to be ballasted as far as the drawbar pull of the tractor will permit.

It is of course difficult to express an opinion on how soon after compacting hauling may be started. As a general rule of thumb the hauling operation may be started 24 hours after compacting if the temperature has been lower than 10 - 15 degrees centigrade below freezing during the period between compacting and hauling (where the road has been compacted by the above-described methods). If the temperature has been higher than mentioned above, and if the new snow has fallen on the road bed, a certain period of waiting is required between compacting and hauling.

For the <u>maintenance</u> of compacted main haulage roads for horse-drawn traffic the best combination at present seems to be a road rutter (see Fig. 31) and a wooden roller (see Fig. 32). The design details of the equipment, however, are not yet fully clear. The road rutter should be used when a comparatively small amount of snow falls on the road. If it is used too often, or after a heavy snowfall, high embankments will be formed along the sides of the road and drift snow will pile up on the road in places where it passes through swamps and similar areas. One of the advantages of the compacted road is thus lost. The rail-roller has to be used when larger amounts of snow fall on the road bed. Normally the rail-roller is used more frequently during the early part of the hauling season when it snows often and in great quantities, and when there is a greater tendency for drift snow to pile up on the road. During the later part of the season the snowfalls are less frequent and the road may, as result of surrounding drift snow, have attained the same level as the rest of the snow cover, so that no accumulation of drift snow on the road surface occurs.

Obviously, drags, simple wooden ploughs, and other maintenance equipment can also be employed.

It is important for the road rutter and drag to be light enough in weight to be carried on a loaded sledge, so that they can be used for dragging and rut cutting during the return runs with empty sledges. The compacting equipment can be ballasted with a rear sledge or similar equipment.

3. Hauling on main haulage roads with track-type tractors

The track-type tractors are at present employed only to a limited extent for hauling on main haulage roads. Since it is expected that they will be used more in the future, and in view of the present attempts to develop full-tracks for our wheeled tractors, the use of track-type tractors is discussed here briefly.

Establishing roads can be generally carried out in accordance with the same principles and methods outlined above in connection with hauling on main haulage roads by horse.

The problem of maintenance can be probably solved with the aid of the drag. Whether the drag can be attached to the sledge, or whether extra passes are required for dragging, depends on the drawbar pull of the tractor, the slope of the road and similar factors. At the relatively high speeds which are attained, for example, with a tractor equipped with wheel tracks, the sledges tend to skid sideways on the curves, and it has been observed, that skidding damages the road. Such places should perhaps be ploughed occasionally so as to bank the road and thus guide the movement of the sledges wherever dragging does not form large enough embankments for guidance purposes.

4. Hauling on main haulage roads by wheel tractors

The safest method so far developed for establishing compacted snow roads for traffic by wheel tractors has been "bottom compacting"[12]. Bottom compacting consists in compacting the road early in the season at a relatively small snow depth, followed by further compacting operations as fresh snow accumulates and repeating this until hauling operations begin. The method is very reliable, but relatively expensive. The previous experiments carried out by SDA, and the case from the district of Lycksele, Mo och Domsjö AB, of the last winter (page 61) show that strong roads for wheel tractors can be produced directly in deep snow if the roads are processed by a tractor and then dragged or treated with a rotary tiller. Such roads, however, have to harden for a certain period of time before hauling can be started, except in cases where the temperature has been very low.

A new method of compacting, consisting in the processing of the snow with a rotary tiller (Fig. 9) followed by a sliding pontoon, has been thoroughly studied during the experiments. The treatment results in sufficient road hardness so that hauling with a light-weight wheeled tractor is possible 24 hours after compacting even at moderately low temperatures and even when the road is established in a depth of snow up to 110 - 120 cm. The method, however, is not yet ready for practical application, the limitation in the drawbar pull of our tractors in deep, loose snow being one of the obstacles still to be overcome.

The question of how quickly the power-take-off driven roller and sliding pontoon combination can produce a road with adequate hardness for traffic by wheeled tractors is still unanswered. By allowing a certain waiting period between compacting and hauling, however, strong roads should be obtained by this method.

It is difficult to decide, which is the proper method of maintenance for compacted snow roads for wheel tractors. In many cases maintenance can be limited to the use of a drag. If used properly, a plough is probably a suitable complementary piece of equipment even for roads for wheeled tractors (reduced traction resistance, embankments for guidance, etc.). Experience in the work carried out in the district of Lycksele, Mo och Domsjö AB, indicate, that drift snow will not accumulate on the road if the relatively small embankments formed by the plough are modified somewhat with the aid of a special spreading wing. The plough should be used, however, with discrimination. During the late winter the upper layers of the road easily becomes loosened as a result of the higher day-time temperatures and the intense solar radiation. Under such conditions a snowfall may greatly improve the hardness of the road (as found, for example, in hauling operations for many years at Nordmalings Sawmills on compacted snow roads).

The amount of maintenance required also depends on the choice of anti-skid devices. Tests performed during these experiments showed that considerably higher drawbar pull is produced when anti-skid devices equipped with traction rims a few centimetres high are used as compared with conventional snow chains. The traction rims, however, damage roads more than snow chains, an inconvenience which is especially evident at high temperatures, and will thus necessitate more intensive maintenance. If the additional capacity for load pulling that an anti-skid device with proper traction rims provides to a tractor can be fully untilized, this advantage will probably more than compensate for the disadvantage of increased maintenance work.

If a wheeled tractor is equipped with half-tracks, the minimum requirements for the establishment and maintenance of roads are somewhat lower, although considerably higher than for track-type tractors.

5. Hauling on main haulage roads by trucks

As the experience of Nordmalings Sawmills Ltd.[12] indicates, trucks can be used on a road which is compacted according by the "standard method" after it has been used previously by large track-type tractors with heavy sledges, provided the temperature has been below -10°C. Experience in the Särna forest district has shown that a road which has been thoroughly processed during compacting and then used by wheeled tractors, can be used by trucks even under mild day-time conditions (provided the nights are relatively cold). The trucks can thus be brought into use in the hauling operations on a compacted road if they are preceded by other vehicles. An intensive "bottom compacting" (see above) should also produce roads of adequate bearing strength for truck traffic[12].

Whether an effective method can be developed for directly producing snow roads of sufficient strength for truck traffic, especially in rather deep snow, is difficult to predict. Fundamental studies have to be made on this subject. It is possible that some method of mixing snow, perhaps combined with a simple method of using fire or heat in order to bring about partial melting of snow, may produce roads of the desired bearing strength.

6. Some concluding remarks

Beyond the above-described principles of establishing and maintaining compacted snow roads the author makes no attempt to give final answers to the problem. For information on the basic procedures for the establishment of snow roads and for certain general rules the reader is referred to SDA Bulletin No. 56* (A.C:son Leijonhufvud, 1955).

Furthermore, the rough indications given here should be adapted to the local climatic and other conditions which vary considerably from year to year. The rapid development of techniques also makes it difficult to give any complete and satisfactory instructions.

X. Summary

This paper deals with some of the problems relating to the bearing strength of compacted snow from the transport point of view. An analysis was made of the bearing-strength values obtained by using various methods of snow processing, the variation of the bearing strength under different conditions and the way in which various forms of transport affected the bearing strength of compacted snow.

In these experiments the snow hardness was measured with a proctor needle. The hardness was expressed as a "proctor value", defined as the maximum load in kg per cm^2 that the road bed is

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* Obtainable from SDA, Fleminggatan 37, Stockholm K.

capable of bearing with a disc surface of 1 cm^2. The sources of error of this method were investigated. As a consequence it was found that the measuring results obtained with a proctor needle on a snow cover depend to some extent on the person making the observation, and this generally results in a systematic error. In a given experiment, therefore, all hardness measurements are carried out by a single person when a proctor needle is used on a snow cover. This practice was also followed in the present investigations. The need for a more objective method of measurement led to the construction of a simple drop device (Fig. 6). Various drop bodies were tested and a cone with a generating angle of 30° appeared to be the most suitable. With this apparatus the hardness of a snow cover can be stated either in terms of the number of mm of penetration by the cone at a given height of drop, or in kilogram-metres as a measure of the work performed by the cone during its penetration. A summary of the conclusions concerning both the mentioned methods of hardness measurement of a compacted snow cover will be found on page 16.

Different snow-processing principles and the bearing strength produced thereby in a road bed of snow were compared. As a basic method, and one to serve as a basis of comparison, we chose the one hitherto most frequently used in the opening of compacted snow roads. This consisted in first processing the snow with a deep-penetrating track-type tractor "track to track" and then dragging. Experience has shown that this kind of processing produces a road bed that can be exposed to traffic by track-type tractors a short time after compacting. A simple implement combination (Fig. 8) comprising a "rail-roller" (Finnish type) which mixes and compacts the snow and a "sliding pontoon" which smoothes and compacts the road bed gave almost the same bearing strength as the basic method. The method was thoroughly tested both experimentally and in practical application. The possibilities of application are limited by the drawbar pull of our present-day tractors in loose snow. The idea advanced by C.E. Malmberg, SDA of making the roller power-take-off driven (Fig. 13) promises to overcome this difficulty and at the same time such a roller can probably process the snow more intensively than a towed roller. However, additional tests of the power-take-off driven roller are necessary for a final appraisal of the method.

The processing of the snow with a rotary tiller (Fig. 9) and a sliding pontoon gave by far the highest bearing-strength values of all methods. It is estimated that a road compacted by this method can be exposed to traffic by a light wheeled tractor as early as 24 hours after compacting, even at moderately low temperature and even when the road is opened up directly in deep snow. However, the method must be developed further before it can be applied in practice.

The relationship between density, temperature and bearing strength of compacted snow was later shown and discussed on the basis of a number of investigations. With the aid of a series of measurements the author has tried to give a schematic picture of this relationship in the form of a nomogram (Fig. 18) for the case where the snow had hardened approximately 24 hours after compacting. The nomogram also shows the densities resulting from or expected to result from different processing methods under conditions similar to those prevailing at the time of measurement. The absolute values shown apply, of course, only to the conditions prevailing on the test field. The nomogram gives a good picture in summary form of the interplay of the factors principally involved in the bearing strength of compacted snow during the first phases of the snow's hardening after processing.

In a snow road that was exposed to the atmosphere but had not been driven over, it was found that the density and hardness of the surface layer increases with increasing time after compacting. The hardness increase was ascribed to a transport of moisture from the ground and from the lower layers of the road as a result of the surface layer generally being cooler than the ground or the bottom layers. The ground generally had a temperature of ±0 to -2°C at the time of compacting. If a certain waiting period is allowed between compacting and exposure to traffic it is thus possible to obtain the necessary bearing strength so that it is possible to begin driving over it with a certain type of tractor even at relatively high winter temperatures.

Once traffic on the road begins the bearing strength is largely determined by this traffic. However the traffic primarily affects the surface layer of the road. If a given form of transport requires a road bed of great hardness in the lower layers then intensive deep processing is necessary when the road is first opened.

A loosening and reduction of hardness in the bottom layers of the road due to material transport from the bottom to the surface layers does not appear to take place to such an extent that it endangers the bearing strength of the road even when the latter is exposed only to light traffic. This applies, however, only when the snow has been deeply processed at the beginning.

Drawbar pull tests on snow roads of various bearing strength were carried out with a light wheel-tractor equipped alternatively with anti-skid devices, half-tracks or full-tracks (Fig. 21). These three alternatives were examined and discussed from the standpoint of bearing strength. An example is also included showing the drawbar pull of the three vehicle combinations compared with the pull of other vehicles on compacted snow (Table XIII).

The drawbar pull of a light wheel-tractor equipped with various anti-skid devices and with various extra loads on the drive wheels of the tractor was investigated. The importance of these two factors is best illustrated by the following example: In an experimental series the best anti-skid device combined with a ballast of 750 kg applied to the drawbar gave about three times as much pull as a conventional anti-skid device without any ballast.

The relationship between drawbar pull and bearing strength was also analyzed. Each form of track or anti-skid device shows an optimum bearing-strength range in relation to the drawbar pull. Approximate values for this optimum could be obtained experimentally for some of the tracks and anti-skid devices tested.

On the basis of earlier experience, together with some new experiments, the traction resistance of sledges on a road bed of snow was studied. The objection of horse haulers to compacted snow roads, namely that transport on the roads becomes heavy as a consequence of frequent new snow falls on the road bed, were clarified with the aid of experiments and meteorological data. These disadvantages can probably be eliminated by modifying the maintenance techniques hitherto applied.

The approximate bearing strength needed for certain traffic intensities with various types of light tractors was determined. As a complement to the results of the experiments data were collected on some hauling operations on compacted snow roads used under practical conditions and were analyzed.

Finally, from the results of the investigation and from practical experience the author attempts to lay down some rules for the opening and maintenance of compacted snow roads for different types of timber transport.

It should be pointed out that most of the above experiments were carried out under relatively uniform conditions in order to facilitate comparison between the various experiments. The absolute values apply only for the conditions prevailing at the time of the experiments. In many cases, however, the relative values obtained from the experiments, e.g. the relationship between the compacting method and the relative bearing strength, the relative bearing strengths required by different vehicles etc., would hold approximately from winter to winter and from place to place in the parts of Sweden in which compacted snow roads can be used.

References

1. Ager, B.H:son. The compacted snow road. II. Climatic consideration. SST (2): 201-230, 1955. (SDA Meddelande no.54) (NRC TT-816).

2. Ager, B.H:son. Compacted snow roads for transport of timber. "Skogsägaren", July 1956.

3. Ager, B.H:son. Experiments with horse-drawn transport on a compacted snow foundation road. SDA-redogörelse no. 6, 1956.

4. Bader, G.m.fl. Snow and its metamorphosis. Geotechn. Ser. Hydr., Lief 3, Bern 1939.

5. Bengtsson, Å. Snow processing implements. SDA Aktuell Information av intern natur, no. 108, 1956.

6. Bruzelius, Nils G. Study of the bearing capacity of roads. Statens Väginstitut, 1951.

7. Eriksson, R. Friction of sleigh runners on snow and ice. NST 1949: II, III. (SDA Meddelande no. 34-35).

8. Eriksson, R. The roadway from the standpoint of transport. NST 1952: II.

9. Eriksson, R. The compacted snow road. I. Properties of the snow. SST no. 2, 1954. (SDA Meddelande no. 56) (NRC TT-849).

10. Geotech. Comm., 1922, Statens järnvägars geotekniska kommission 1914-22. Final conclusions. Geotekniska medd. 2. Stockholm.

11. Hedegård, Bo. Engine powers and pulling strength - a number of fundamental concepts. NST 1952: II. (SDA Meddelande no. 44).

12. Leijonhufvud, A.C:son. The compacted snow road. III. Field tests and practical applications. SST no. 4, 1955. (SDA Meddelande no. 56) (Being translated for NRC TT series).

13. Leijonhufvud, A.C:son. The compacted foundation snow road. SDA Aktuell Information no. 30, 1950.

14. Putkisto, K. The compacted snow road for horse-drawn transport. Metsäteho medd. no. 89.

15. Putkisto, K. The compacted snow road for horse-drawn transport. Metsäteho medd. no. 101, 1954.

16. Rengmark, Folke. The conical ram. A new method of investigating the bearing capacity of soils and gravel roadways. Statens Väginstitut medd. 57, 1938.

17. Samset, Ivar. Agricultural tractor on compacted snow. Skogeieren, 1951.

18. Seligman, G. Snow structure and ski fields. London, 1936.

19. Sundberg, Ulf. A study of forestry transports. SST 1952: 4, 1953: 1. (SDA Meddelande no. 48).

20. Sundberg, Ulf. Data on wheel and crawler tractors for timber transports in winter. NST 1952: II.

21. Söderlund, J. and Frieberg, B. The wheel tractor in transport work. SST 4, 1954.

22. Taylor, A. Snow compaction. Jan. 1953, SIPRE Report 13.

23. Yosida, Zyungo and Colleagues. Physical studies on deposited snow. II. Mechanical properties. (1). - Contributions from the Institute of Low Temperature Science, (No. 9, 1956), Kokkaido University, Sapporo, Japan.

SST = Svenska Skogsvårdsföreningens Tidskrift.

NST = Norrlands Skogsvårdsförbunds Tidskrift.

SDA = Föreningen Skogsarbetens och Kungl. Domänstyrelsens Arbetsstudieavdelning.

Table I

Size of disc vs. relative breaking stress for different substrata

	4	2	1	0,5 cm²
1951 års serie på snö series on snow	1,54	1,24	*1,00*	0,78
1955 års serie på snö	1,43	1,20	*1,00*	0,83
1956 års serie på snö	1,33	1,19	*1,00*	0,75
Olhagens serie på lera Olhagen's series on clay	*1,48*	*1,25*	*1,00*	*0,79*

Table II

Proctor needle measurement on the same substratum by two persons GB and BA

Väg Road	Platta Disc	Antal obs. per pers. No. of observ. per person	Medeltal kg/cm² Mean kg./cm²		Differens Difference	Diff:s medelfel Standard error of diff.	Signifikans Significance
			GB	BA			
I	1	25	8,44	6,40	2,04	± 0,849	*[1]
I	8	25	37,04	35,36	1,68	± 1,806	ej s. no sign.
II	1	25	18,08	15,12	2,96	± 1,065	**

[1] * sannolikheten 95/100
** probability 99/100
*** „ 999/1000

Table III

Comparison of the surface hardness of two roads measured by using different methods

Metod Method	Medelvärde Mean Väg A Road A	Medelvärde Mean Väg B Road B	Diff.	Diff s medelfel Diff. stand.-error	Ant. frihetsgr. No. of degrees of freedom	t	Diff. i % av A Diff. in % of A	Signifikans Significance
Pr. nål ... Pr. needle	11,28	11,20	0,08	± 0,738	48	0,108	0,71	ej s. no sign.
Kil .... Wedge	41,88	39,40	2,48	± 1,940	48	1,278	5,92	»
Kon 30°... Cone 30°	53,56	53,00	0,56	± 1,926	48	0,291	1,04	»
Kon 60°... Cone 60°	33,52	32,32	1,20	± 1,278	48	0,939	3,58	»

Table IV

Standard error as a % of the mean for 20 observations with different measuring devices. Each experimental series comprises simultaneous measurements with two or several measuring devices on the same substratum

Försöksserie nr Experimental series no.	Proctorvärde Proctor value	Proctornål Proctor needle — Plattstorlek cm² Disc size cm² 0,5	1	2	4	8	Kil Wedge — Fallhöjd cm Height of fall cm. 5	10	20	30	Kon 30° Cone 30° — Fallhöjd cm Height of fall cm. 5	10	20	30	Kon 60° Cone 60° — Fallhöjd cm Height of fall cm. 5	10	20	30
114	19,7	4,33	3,34	2,85	—	—	2,74	2,00	1,74	1,73	—	—	—	—	—	—	—	—
119	14,1	—	—	3,24	—	—	2,41	2,34	2,08	1,54	—	—	—	—	—	—	—	—
120	13,9	—	—	2,43	—	—	—	—	—	—	—	—	—	—	2,13	1,65	1,51	1,30
121	4,8	—	9,49	5,73	5,45	4,86	—	—	—	—	1,53	2,05	1,24	0,75	—	—	—	—
122	17,9	—	4,02	—	—	—	—	—	—	—	—	—	—	—	1,52	2,05	1,79	—
123	18,2	—	5,32	—	—	—	—	—	—	—	—	2,14	2,95	2,16	—	—	—	—
125	13,5	—	3,82	—	—	—	—	—	—	—	2,94	—	1,87	1,55	—	—	—	—
126	13,4	—	4,06	—	—	—	—	—	—	—	—	2,33	—	—	—	2,83	—	—
127	9,6	—	—	5,17	—	—	—	—	—	—	2,95	2,02	1,11	—	—	—	—	—
129	16,6	—	—	4,18	—	—	—	2,42	—	—	—	1,80	—	—	—	2,56	—	—
130	11,2	—	5,21	—	—	—	—	3,89	—	—	—	2,87	—	—	—	3,13	—	—
131	11,3	—	5,17	—	—	—	—	3,66	—	—	—	2,84	—	—	—	3,01	—	—
132	15,1	—	3,83	—	—	—	—	—	—	—	2,28	1,78	2,51	1,72	—	—	—	—

Table V

Summary of comparison between different methods of treating snow, January 9-21, 1956

Hårdheten på Hardness on	Metod Re Method Re	Relativ hårdhet medeltal Relative hardness mean	Antal jämförelser No. of comparisons	Antal jämför. med och utan signifikant skillnad No. of comp. with or without signific. diff.			
				***	**	*	ej sign. no signific
0 cm	1	100	—	—	—	—	—
	2	142	4	2			2
	3	115	6		1	1	4
	4	107	2				2
	5	139	6	2	1	1	2
	6	140	3	2			1
	7	463	2	2			
20 cm	1	100	—	—	—	—	—
	2	98	3				3
	3	65	5	5			
	4	74	1		1		
	5	70	5	2	3		
	6	70	2	1	1		
	7	183	2	2			

Table VI

How the compaction result (bearing strength about 24 hours after compaction) is affected by the load and working angle of the sliding pontoon in compacting with rail-roller and sliding pontoon. Figures standing by themselves refer to the load, figures in parenthesis to the working angle

Serie Series	Packad Compacted den on date	vid luft-temp. air temp.	Be-last-ning kg Load kg	Snö-djup cm Snow depth cm.	Dragare Vehicle	Relativ bärighet i vägen vid Relative surf. hardness of the road at a arbetsvinkel på packplåten working angle of the slid. pontoon: liten small	medelstor medium	stor large
1	17/1	− 9°C	0	70	Oliver OC 3 som först tog upp ett spår Oliver OC3 which had first opened a rut	100 (189)	100 (100)	100 (161)
			300			238 (300)	150 (100)	162 (174)
			600			259 (130)	377 (100)	286 (122)
2	8/2	−13°C	0	90	Vinsch, i spår av Fiat OM Winch in a rut opened by Fiat OM	100 (83)	100 (100)	100 (108)
			300			189 (115)	137 (100)	128 (101)
			575			234 (124)	158 (100)	214 (141)
3	25/2	− 7°C	0	100	Fiat OM som först tog upp ett spår Fiat OM, which had first opened a rut	100 (104)	100 (100)	100 (114)
			400			195 (130)	155 (100)	163 (119)
			650			182 (119)	164 (100)	173 (120)

Table VII

The draught resistance in kp of the compacting equipment drawn by a deep-going track-type tractor (Fiat OM) in 90 to 100 cm snow on level ground

Serie och datum Series and date	Redskap Equipment	Rälsvält + packplåt kg belastning på Rail-roller + sliding pontoon load in kg on the		Dragmotstånd Draught resistance			
		välten roller	packplåten sliding pontoon	Endast rälsvält Rail-roller only	liten small	medelstor medium	stor large
					arbetsvinkel på packplåten working angle of the sliding pontoon		
3 25/2	Rälsvält + packplåt Rail-roller + sliding pontoon	—	0	—	340	300	325
	» »	—	400	—	400	350	400
	» »	—	650	—	525	475	525
4 1/3	Rälsvält + packplåt Rail-roller + sliding pontoon	100	250	—	—	375	—
	» »	100	0	—	—	325	—
	Rälsvält .... Rail-roller	100	—	250	—	—	—
	»	0	—	200	—	—	—

Table VIII

Density and relative surface hardness of the test road 1 - 4 and surface hardness at some temperatures, calculated for about 24 hours after compaction

Väg nr Road no.	Volymvikt Density	Relativ ythårdhet Relative surface hardness	Ythårdheten vid olika temperaturer Surface hardness at some temperatures				
			−5°	−10°	−15°	−20°	−25°
1	0,494	100	9,99	13,14	16,29	19,44	22,59
2	0,470	63	6,29	8,28	10,26	12,25	14,23
3	0,437	34	3,40	4,47	5,54	6,61	7,68
4	0,408	15	1,50	1,97	2,44	2,92	3,39

Table IX

Observations made when using a standard method of compaction at different times of the winter

Packning Compaction				Observationer i vägarna Road observations						
Datum Date	Kl Time	Snö-djup cm Snow depth cm.	Luft-temp °C Air temp. °C.	Datum Date	Kl Time	Snödjup i vägen cm Snow depth in the road cm.	Volymvikt i ytskikten 0–10 cm gr/cm³ Density of the 0–10 cm. surf. layer gr/cm³	cm under ytan cm. below the surf.	Temp. Temp.	Proctor-värde kg/cm² medeltal Proctor value kg/cm² mean
20/12	15^{10}	61	—28	21/12	12^{15}	28	0,38	0 5 15	—20 —17 —14	4,08 10,79 18,01
23/1	16^{15}	83	—29	24/1	14^{30}	40	0,45	0 5 15 25	—28 —23 —18 —12	13,12 15,82 20,58 21,56
3/3	12^{00}	93	— 4	4/3	07^{40}	46	0,48	0 5 15 25	—25 —19 —12 — 8	15,15 16,32 16,88 8,49
4/4	11^{00}	70	— 4	5/4	06^{00}	40	0,47	0 5 15 25	—23 —15 — 9 — 3	9,82 10,30 8,49 8,20

Table X

Effect of traffic on two roads compacted differently, when the roads were used by track-type tractors and loaded sledges

Rälsvält + packplåt
Rail-roller + sliding pontoon

Före trafik / Before traffic				Efter trafik / After traffic				
Volym-vikt 0–10 cm / Density 0–10 cm.	cm under ytan / cm. under the surf.	temp. °C / Temp. °C	Proctor-värde kg/cm² / Proctor value kg/cm²	Volym-vikt 0–10 cm / Density 0–10 cm.	cm under ytan / cm. under the surf.	temp. °C / Temp. °C	Proctor-värde kg/cm² / Proctor value kg/cm²	[1]
0,458	0	—7,4	3,30	0,536	0	—6,2	> 52,3	7
	5	—7,1	3,41		5	—7,7	> 43,0	6
	15	—6,6	5,48		15	—7,4	23,6	—
	25	—5,2	4,88		25	—6,8	20,5	—

Fräs + rälsvält + packplåt
Rotary tiller + rail-roller + sliding pontoon

Före trafik / Before traffic				Efter trafik / After traffic				
Volym-vikt 0–10 cm / Density 0–10 cm.	cm under ytan / cm. under the surf.	temp. °C / Temp. °C.	Proctor-värde kg/cm² / Proctor-value kg/cm²	Volym-vikt 0–10 cm / Density 0–10 cm.	cm under ytan / cm under the surf.	temp. °C / Temp. °C.	Proctor-värde kg/cm² / Proctor-value kg/cm²	[1]
0,501	0	—6,8	10,88	0,545	0	—5,3	> 55,5	9
	5	—5,8	13,24		5	—7,0	> 58,1	12
	15	—4,7	16,28		15	—6,8	31,2	—
	25	—4,2	18,04		25	—5,8	28,8	—

[1] Antal observationer överstigande proctornålens mätområde.

[1] Number of observations exceeding the measuring scale of the proctor needle.

Table XI

Average densities and hardness under various types of traffic (Kragelski, 1945)

Typ av trafik Type of traffic	Volymvikt gr/cm[3] Density gr/cm[3]	Hårdhet kg/cm[2] Hardness kg/cm[2]
Hjulfordon .... Wheeled vehicles	0,625	14,0
Häst.................... Horse Drawn	0,467	7,0
Fotgängare .... Pedestrian	0,462	4,6

Table XII

Grain size in a compact snow road (main hauling road for horse-drawn traffic) and in unmixed snow cover during the winter

Vägen Road				Orörda snötäcket Untreated snow cover			
31/1		25/3		31/1		25/3	
skikt[1] layer[1]	korn[2] grain[2]	skikt layer	korn grain	skikt layer	korn grain	skikt layer	korn grain
0—3	—3,0	0—3	—3,0	0—12	—4,0	0—12	—6,0
3—17	—2,0	3—23	—2,0	12—19	—3,0	12—32	—4,0
17—28	—1,0	23—41	—1,0	19—38	—2,0	32—39	—3,0
28—33	—0,5			38—52	—0,5	39—52	—2,0
						52—64	—1,5
						64—75	—1,0

1 cm från marken. in cm from the ground.
2 största korn i mm i resp. skikt. biggest grain in mm in the various layers.

Table XIII

The maximum drawbar pull for various types of vehicles on a snow substratum with a bearing strength of 15 - 22 kg/cm^2

Fordon Vehicle	Maximal dragkraft kp Maximum pull kp.
BM-25 m. Ceve-slirskyddet ... BM-25 with Ceve anti-skid device	1,600
BM-35 m. Alfta halvbandutrustning ... BM-35 with Alfta half-tracks	2,000
Cletrac HG-42 m. Alfta vinterband... Cletrac HG-42 with Alfta winter-tracks	1,400
David Brown m. Lywe halvbandutrustning ... David Brown with Lywe half-tracks	1,800
Fiat CF 25 m. Alfta universalband ... » » » with » universal tracks	1,400
» » » m. » vinterband ... » » » with » winter-tracks	2,000
Fiat Om m. » » ... » » with » »	2,600
Ferguson m. SDA:s hjulbandutrustning ... » with SDA wheel-tracks	1,500
» m. halvbandutrustning av Bombardiertyp... » with Bombardier half-tracks	1,000
» m. slirskyddet Combi-Triumph ... » with Combi-Triumph anti-skid	800
Fordson Major m. Tegs halvbandutrustning ... Fordson Major with Teg half-tracks	3,000
Musceg, med bandmattor av Bombardier-typ ... Musceg, Bombardier	1,375
Nordverks snötraktor ... Nordverk snowmobile	1,800
Nuffield m. SDA:s hjulbandutrustning ... Nuffield with SDA wheel-tracks	2,300
Vessla, original ... »Weasel», original	1,200
Universal, med bandmattor av Bombardier-typ ... Universal, Bombardier	1,400

Table XIV

Maximum pull for various anti-skid devices and loads as applied to a diesel-driven Ferguson

I Road worn by traffic (proctor value 25 - 35 kg/cm^2)
II Newly compacted road (proctor value 10 - 15 kg/cm^2)

Slirskydd Anti-skid device	Väg Road	Dragkraft vid olika belastning Pull at various loads			
		0	250	500	750 kg
Vanlig kätting .... Conventional chain	I	470	830	950	1230
	II	560	810	820	990
»Combi-Triumph«	I	600	790	1020	1320
	II	780	970	1160	1390
»Ceve«	I	1000	1220	1760	1990
	II	980	1220	1380	1600
»Perfekt«	I	1040	1360	1990	2170
	II	870	1160	1420	1760
»Mudmaster«	I	880	1110	1260	1420
	II	800	930	1170	1340
Halvband .... Half-tracks	I	840	1050	1250	1450
	II	730	1060	1200	1310

Table XV

Number of days with precipitation at the three meteorological stations of Stensele, Forse and Särna. Average for 1911-40

Station	Månad Month	Antal dagar med olika nederbördsmängd i mm Number of days with precipitation in mm. as apparent from below			
		≥ 0,1	≥ 1,0	≥ 5,0	≥ 10,0
Stensele	Dec.	16,30	8,60	1,53	0,20
	Jan.	15,47	7,97	1,00	0,13
	Feb.	13,13	6,27	0,83	0.03
	March	12,37	6,07	1,43	0,23
	April	11,10	6,07	1,40	0,28
Forse	Dec.	10,00	8,00	2,10	0,50
	Jan.	9,07	7,37	2,07	0,47
	Feb.	7,67	6,10	1,40	0,23
	March	8,03	5,63	1,40	0,23
	April	7,53	5,83	2,00	0,60
Särna	Dec.	16,87	8,43	2,50	0,77
	Jan.	16,13	8,37	2,30	0,63
	Feb.	12,40	5,40	1,07	0,17
	March	12,27	5,63	1,40	0,33
	April	12,63	6,73	1,93	0,50

Table XVI

Example of change of traction resistance and sinking of runners when a sledge is pulled over snow covers of different bearing strengths (total weight 3,060 kg, runner surface 9,800 cm^2, temperature -8°)

Försök nr ... Experiment no.	1	2	3	4
Bärighet kg/cm^2 ... Bearing strength kg./cm^2	1,87	3,25	10,4	63
Medarnas nedsjunkning, cm ... Sinking of runners, cm	7—10	4—5	1—3	0,0—0,3
Dragmotstånd, % ... Traction resistance, %	10,0	8,5	—	5,8

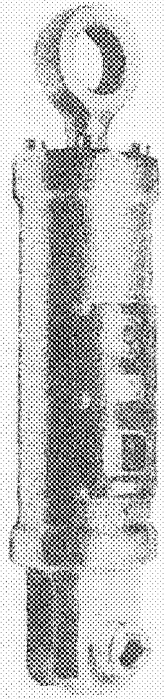


Fig. 1

The PM-dynamometer

Fig. 2

Instrument for measuring the traction resistance of sledges

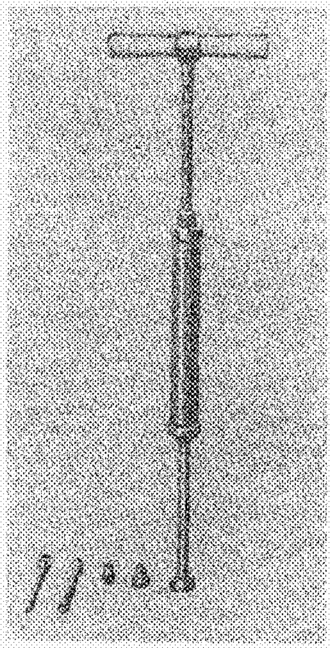


Fig. 3

Proctor needle

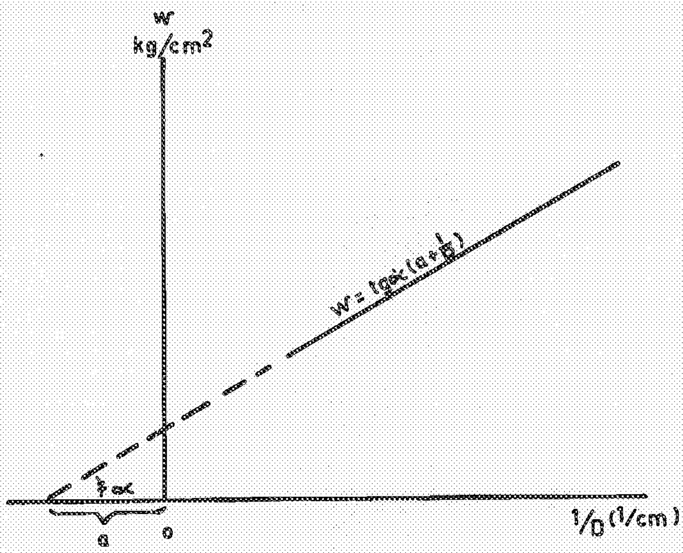


Fig. 4

Breaking stress as a function of the inverted value of the disc diameter (after Olhagen)

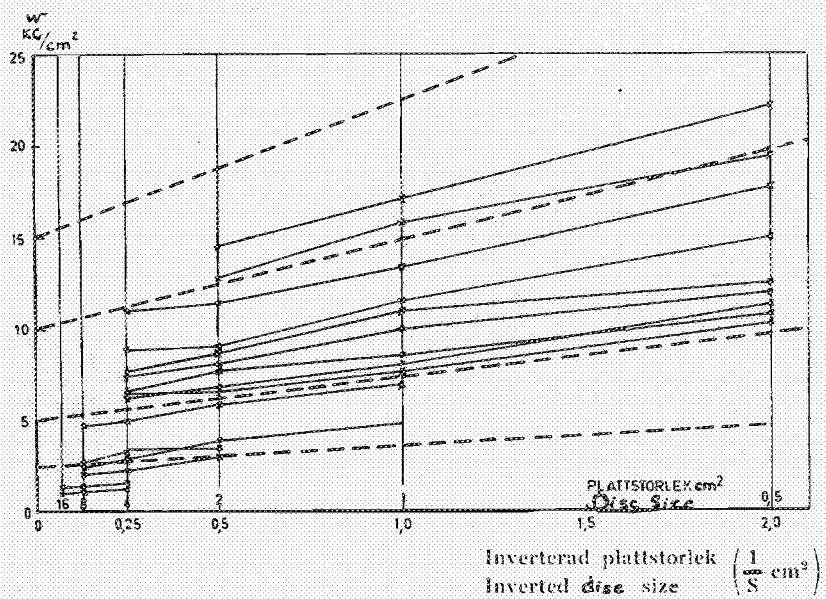


Fig. 5

Adjustment of the field observations
to a pencil of rays originating
from point $\omega = 0$, $\frac{1}{S} = -2.06$

——— field observations

------ pencil of rays

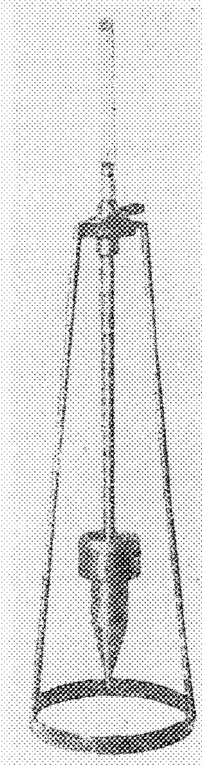


Fig. 6

The drop device with
the 30° cone

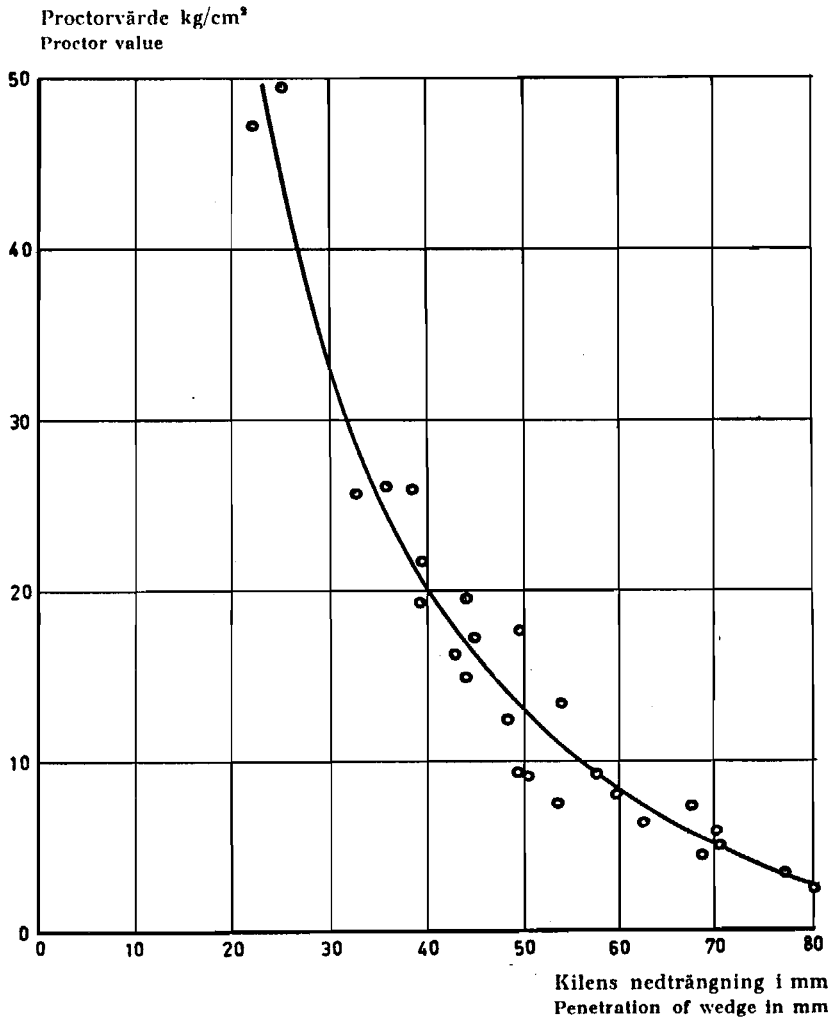


Fig. 7

Relationship of proctor value to wedge penetration at a fall of 10 cm

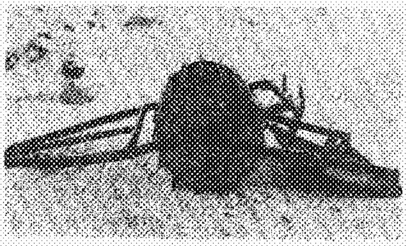


Fig. 8a

"Rail-roller" with
"sliding pontoon"

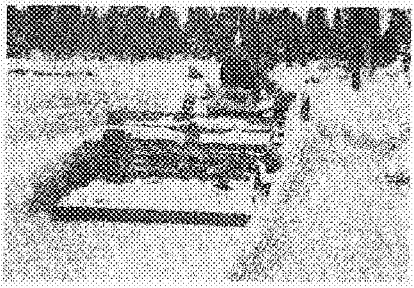


Fig. 8b

Making a snow road with
Fiat OM, rail-roller and
sliding pontoon directly
in a 90 cm deep
untreated snow

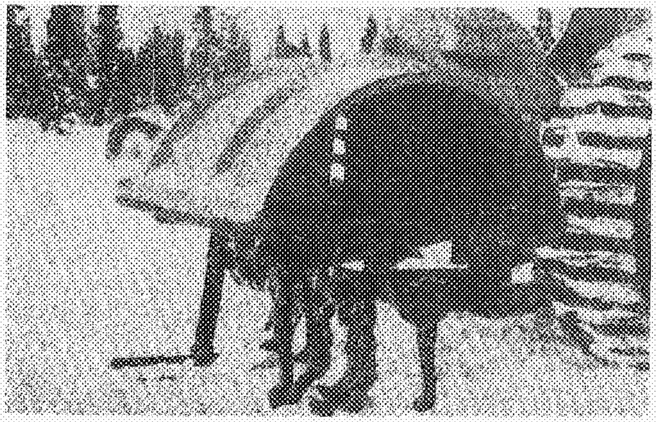


Fig. 9

The rotary tiller tested

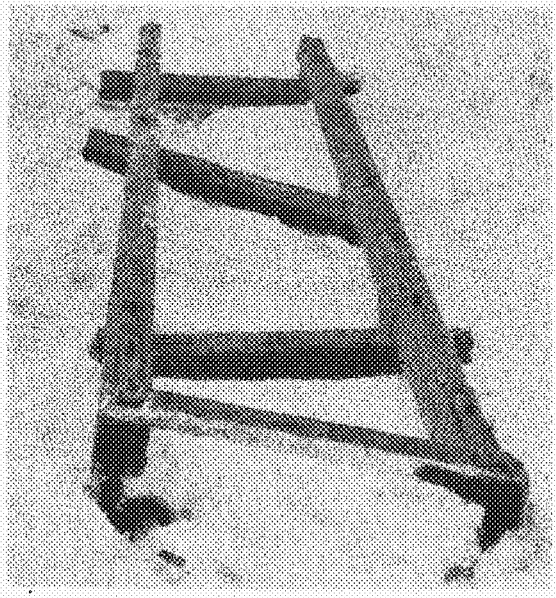


Fig. 10

The drag used in the experiments

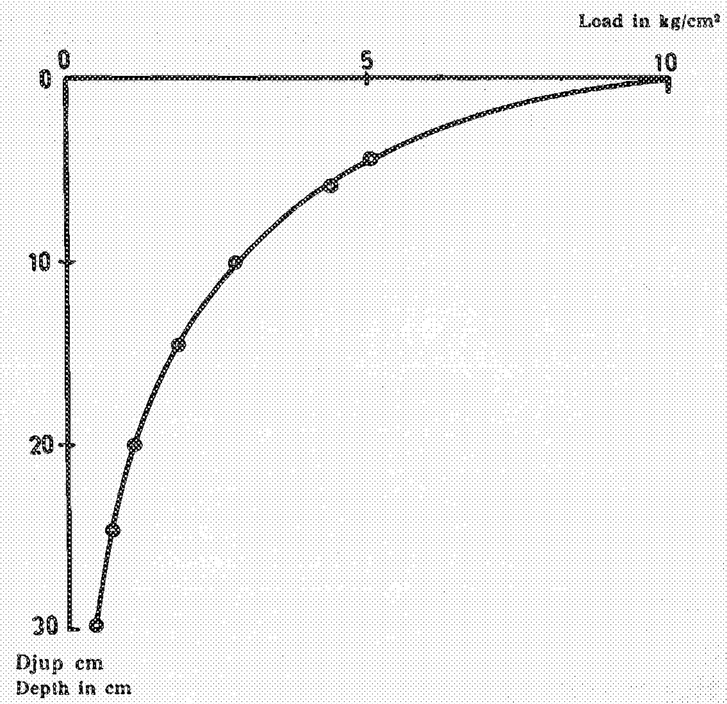


Fig. 11

Distribution of pressure in a snow cover (from the Equation of (Foeppl) (Kondratyeva, Kragelski, Shakhov, 1945)

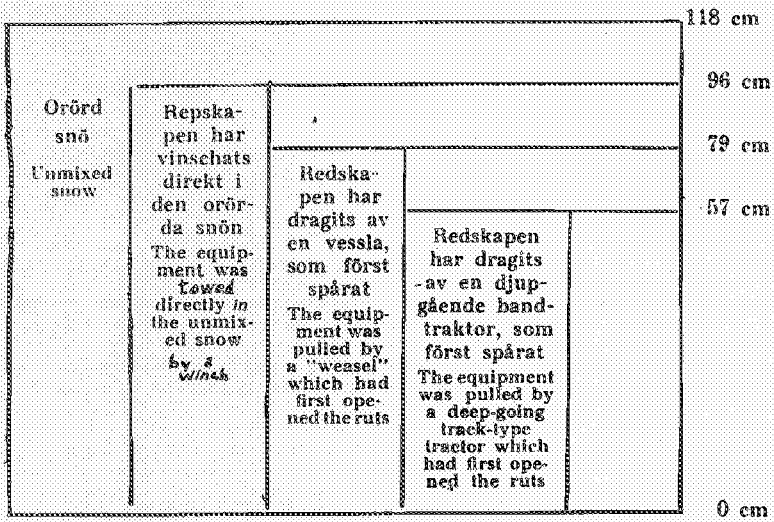


Fig. 12

The compacting capacity of the rail-roller and sliding pontoon measured according to the compression of the snow behind different towing vehicles. The experiment was conducted on Feb. 17 at an air temperature of -12°C

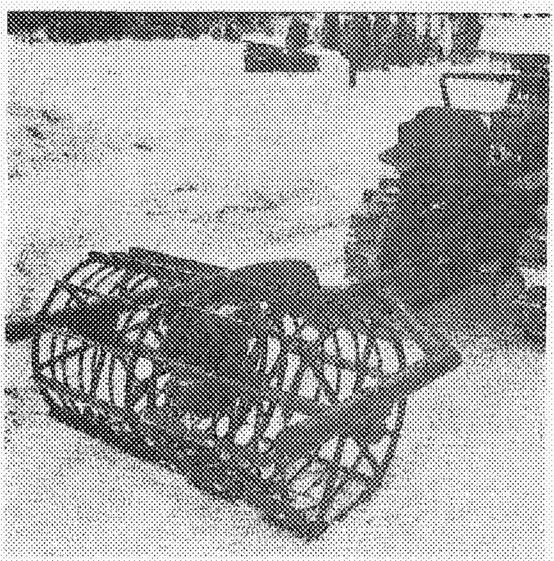


Fig. 13a

The first pilot model of power-take-off driven roller

Fig. 13b

The roller at work

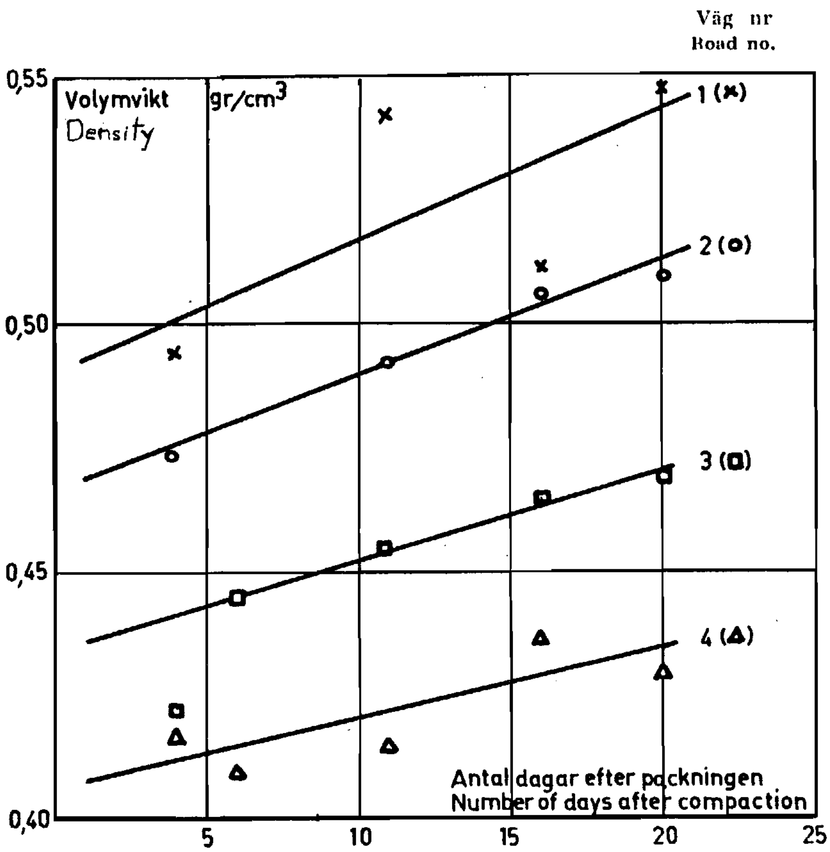
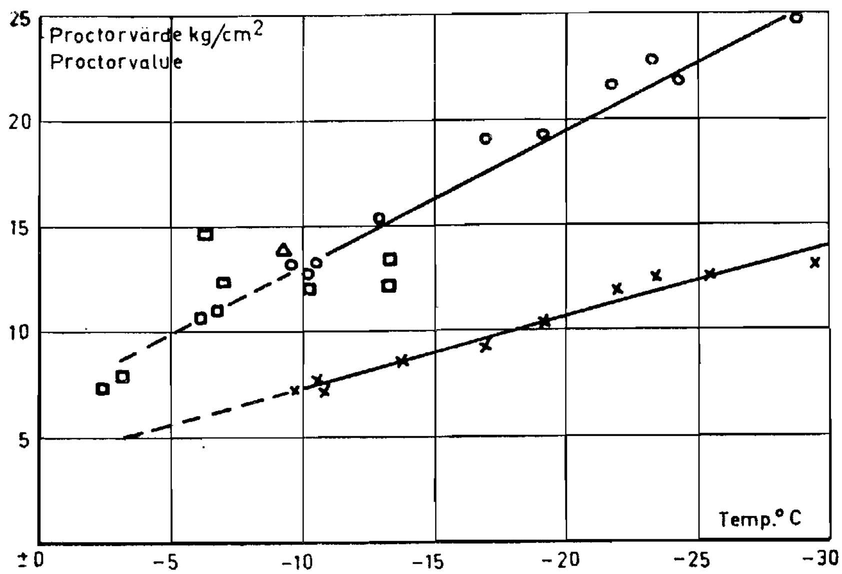


Fig. 14

The change of density in the top layers (0 - 10 cm) of the test roads with the period of time after compaction



Väg nr. - Road no.

o 1 a

x 2 a

Δ 1

□ Observationer i vägar, som packats på samma sätt som 1 och 1 a vid olika tidpunkter under försöksperioden. Varje punkt representerar temperatur och bärighet c. 1 dygn efter packningen.
Observations concerning other roads compacted in the same way as 1 a and 1 at different times during the test period. Each point represents temperature and surface hardness about 24 hours after compaction.

Fig. 15

Approximate relationship of temperature to the surface hardness of the test roads 1 a and 2 a 24 to 48 hours after compaction

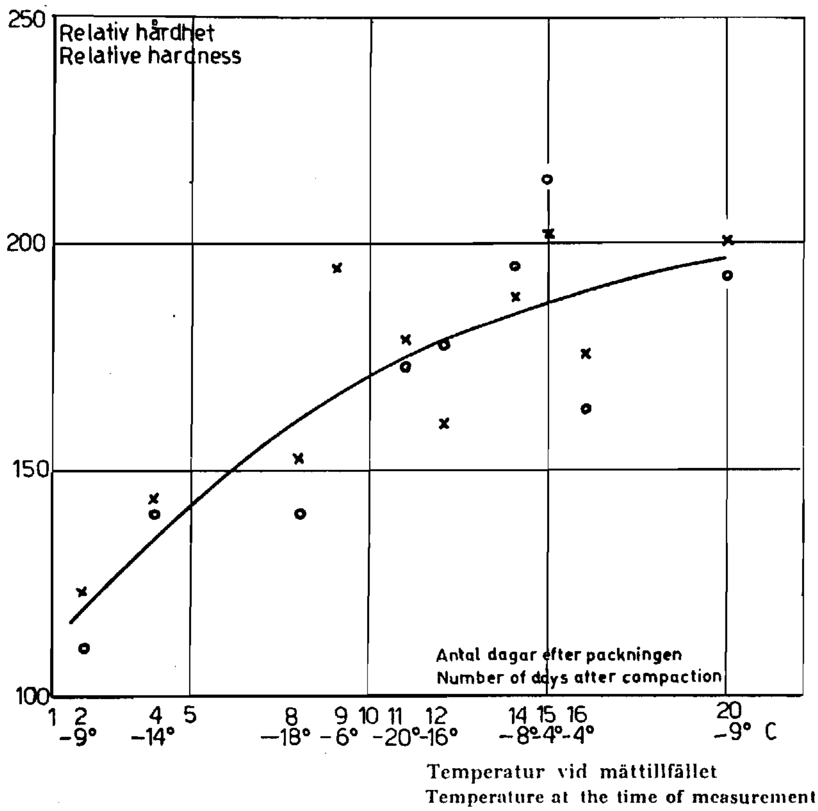


Fig. 16

Change of surface hardness at a certain temperature as a function of the period of time after compaction

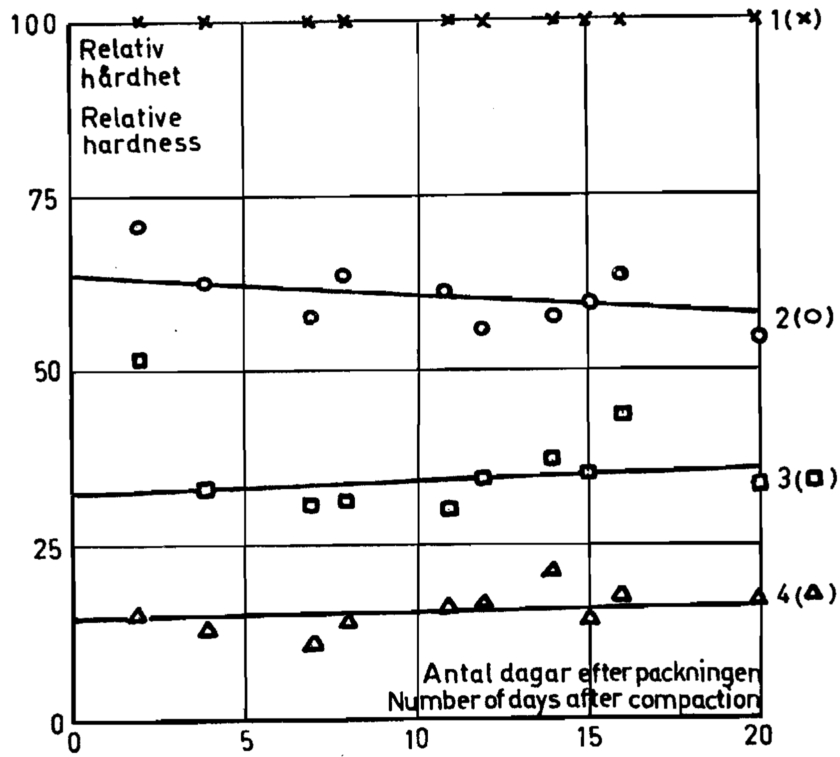


Fig. 17

Relationship of the surface hardness between the test roads 1 - 4 at different times after compaction

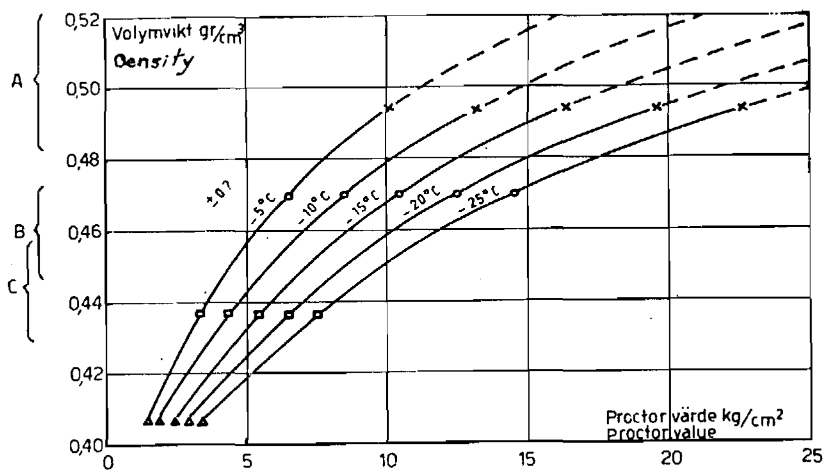


Fig. 18

Approximate relationship between density, temperature and surface hardness of the test roads 1 - 4 compacted in the experimental field of Alsbäcken. The approximate density values resulting or expected to result from different compaction methods (A,B,C) under the experimental conditions have been marked

A. Treatment of snow with rotary tiller, roller and "sliding pontoon". About the same density values can be expected by using rotary tiller and "sliding pontoon" only.

B. Treatment of snow with deep-going track-type tractor followed by compaction with roller and "sliding pontoon", or dragging with a heavy drag.

C. Treatment of snow with deep-going track-type tractor followed by dragging with a light drag or compaction with a battened roller of wood. Driving directly in untreated snow with rail-roller and sliding pontoon (in snow depths below 90 cm).

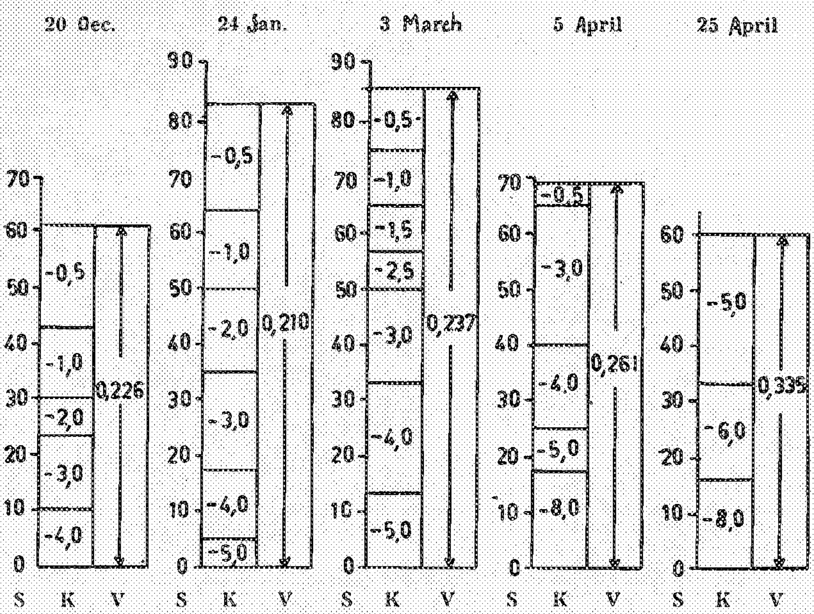


Fig. 19

Snow depth, grain size and density in untreated snow. Lycksele on peat earth 20/12 - 25/4 1955 - 56

S = Snow depth in cm. K = Diameter in mm of the biggest grain found in the various layers. V = Volume weight in gm/cm^3.

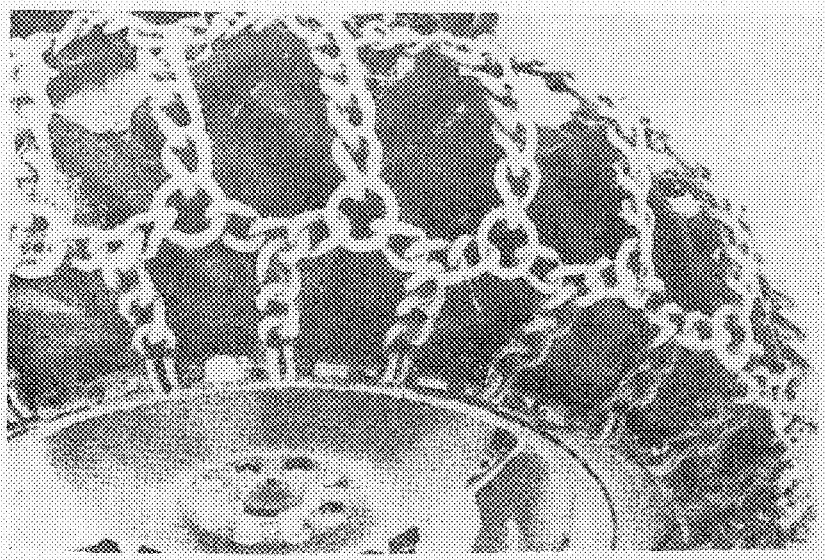


Fig. 20

Anti-skid device "Combi-Triumph"

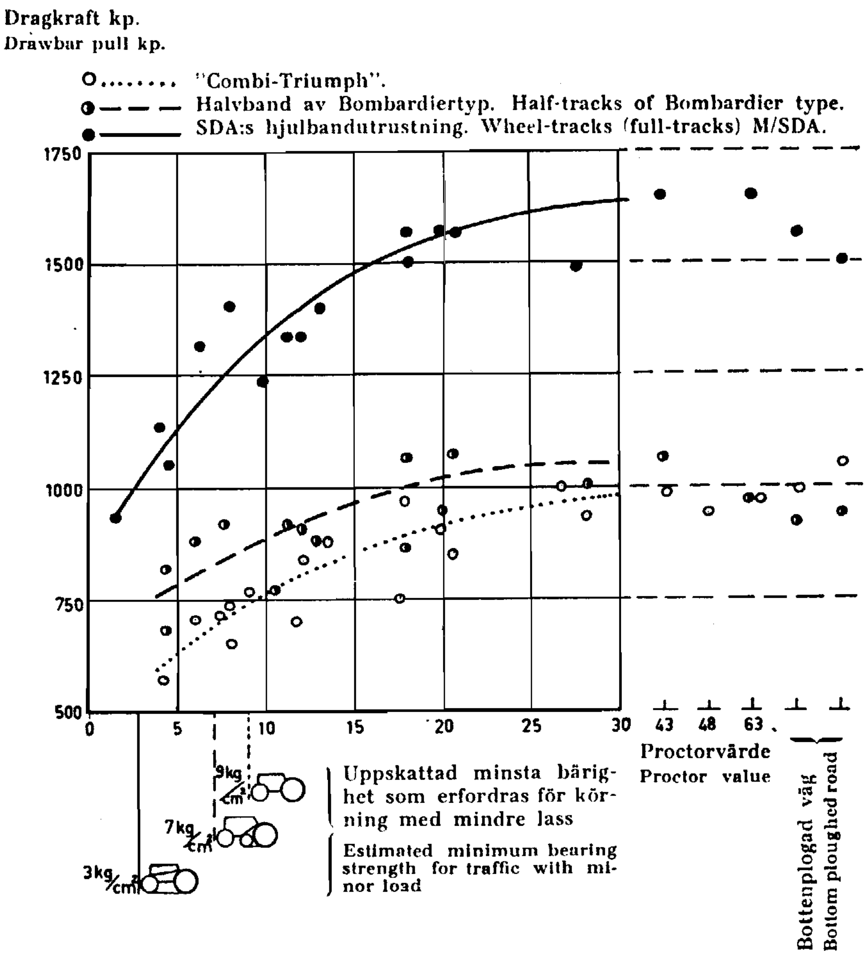


Fig. 21

Drawbar pull vs. bearing strength (surface hardness) for the tested Ferguson tractors

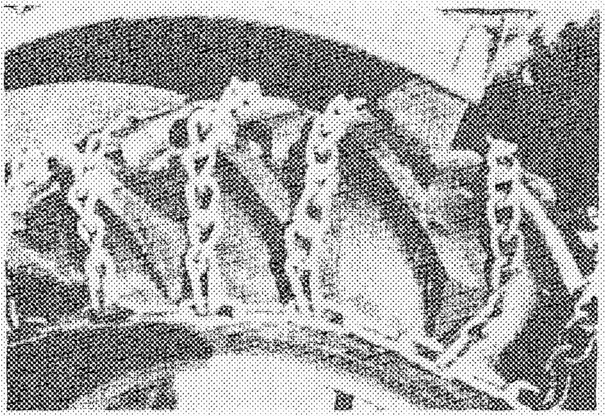


Fig. 22

Conventional snow-chains

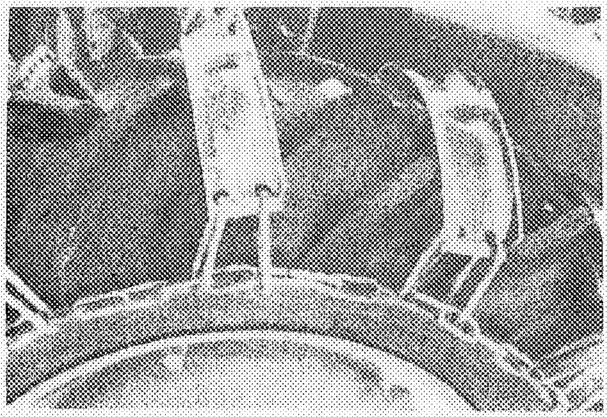


Fig. 23

Anti-skid device "Ceve"

Fig. 24

Anti-skid device "Perfekt"

Fig. 25

Anti-skid device "Mudmaster"

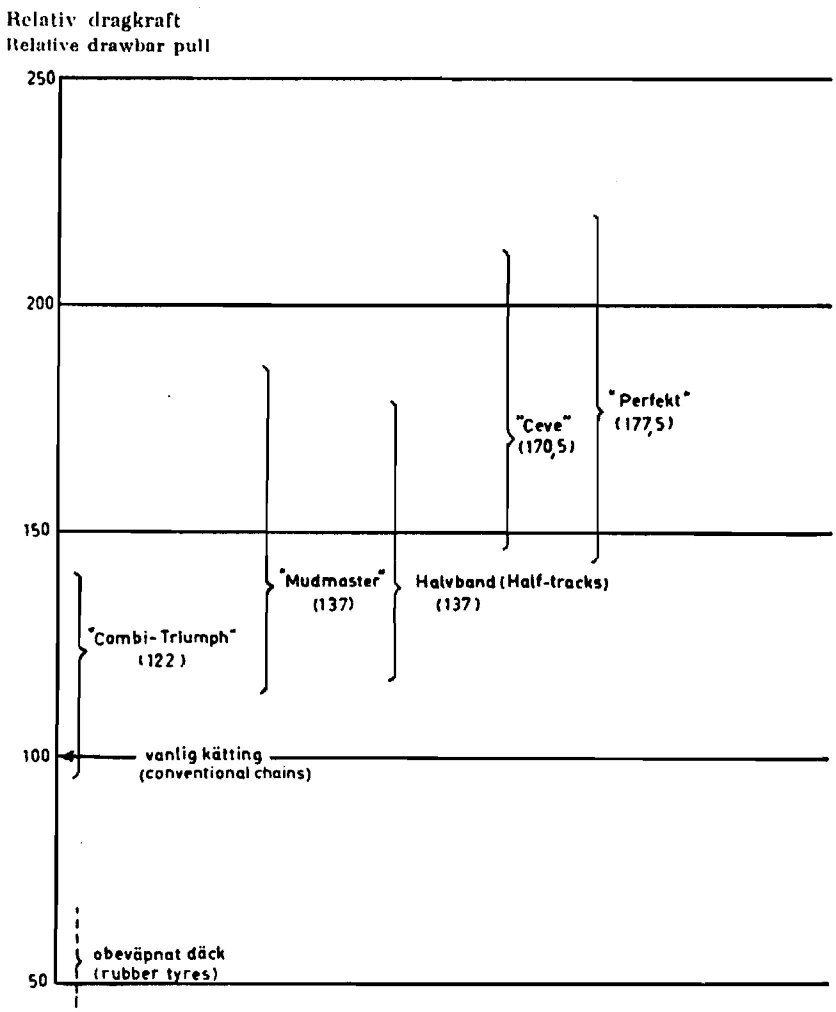


Fig. 26

The relative drawbar pull of a Ferguson wheel-tractor with various anti-skid devices. Range and mean

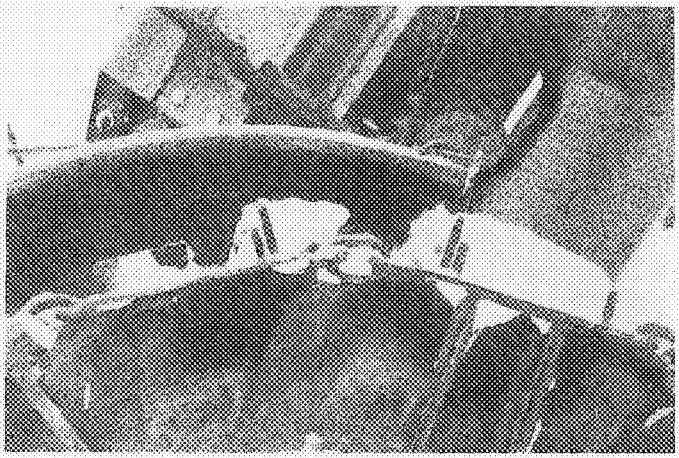


Fig. 27

The picture shows how the snow packs in the reversed plate of the anti-skid device. The correctly mounted plate is rather free from snow. Driving direction from left to right

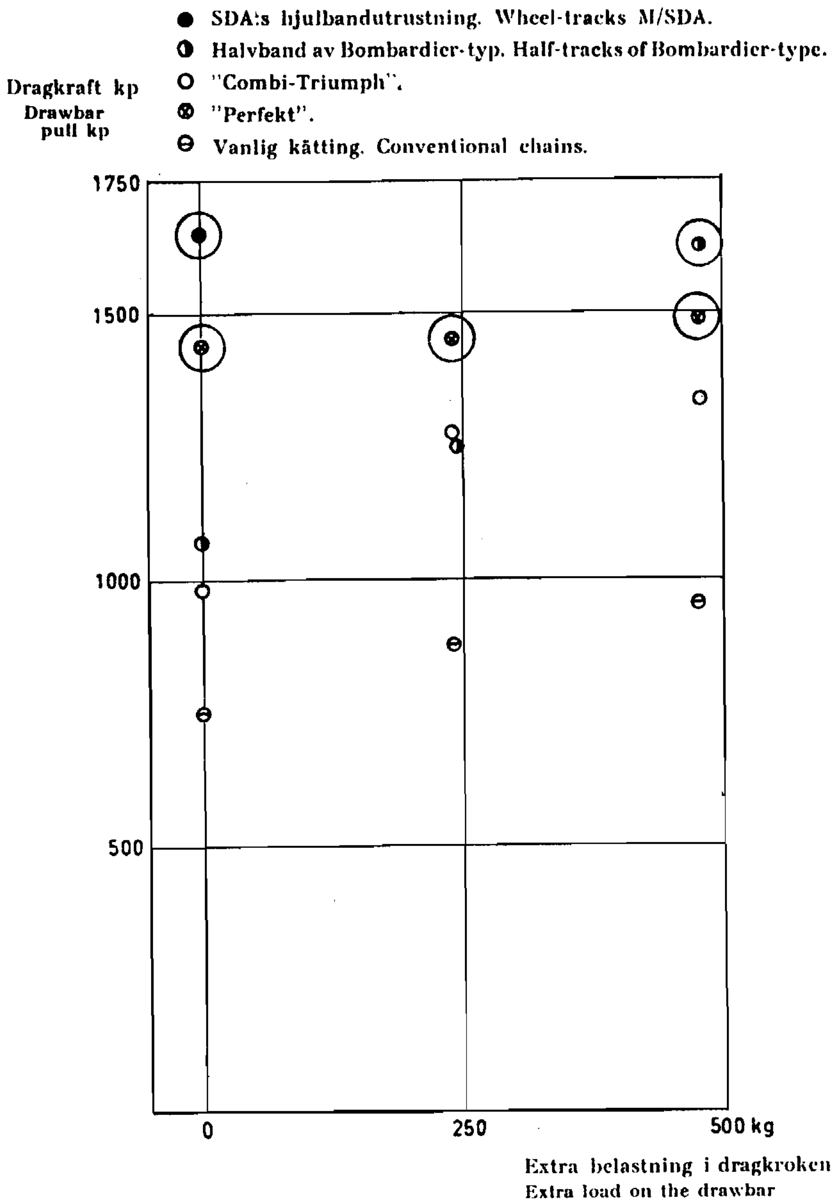


Fig. 28

Some pull tests with a gasoline driven Ferguson on a road with a bearing strength of 43 kg/cm^2

For circled points the tractor pulled until the engine stopped without slipping of wheels or tracks

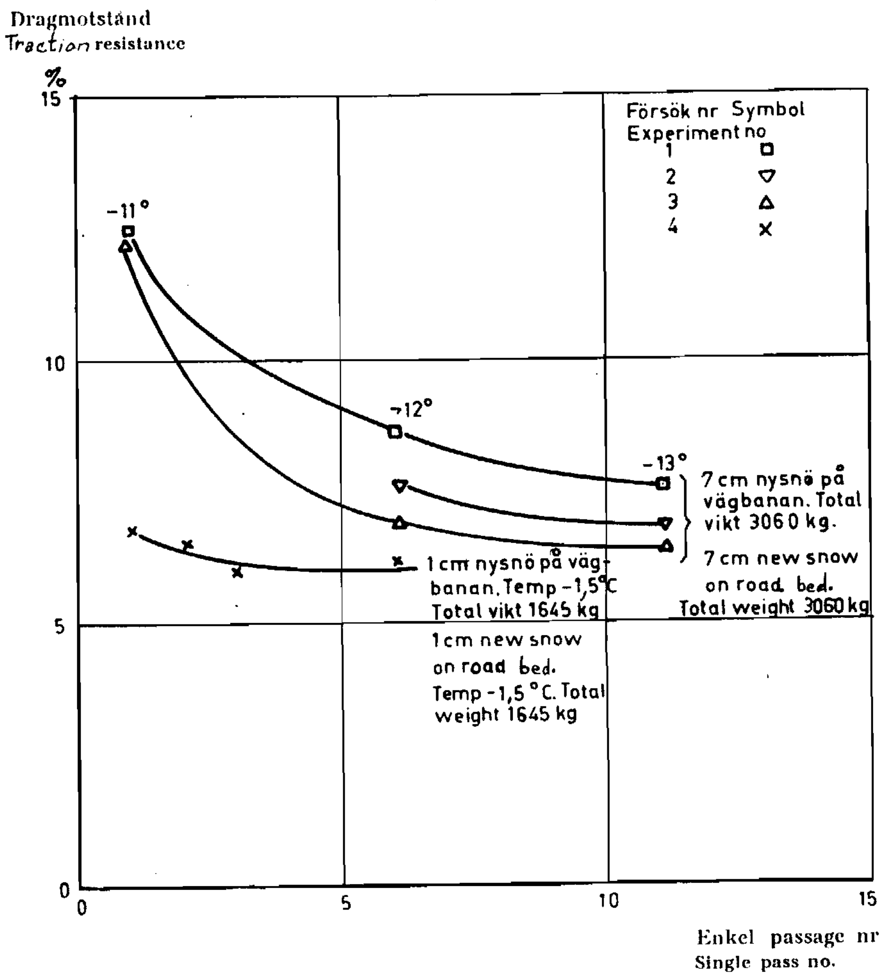


Fig. 29

The change of traction resistance with the number of passes when driving loaded sledges over new-fallen snow on a hard road bed with a track-type tractor

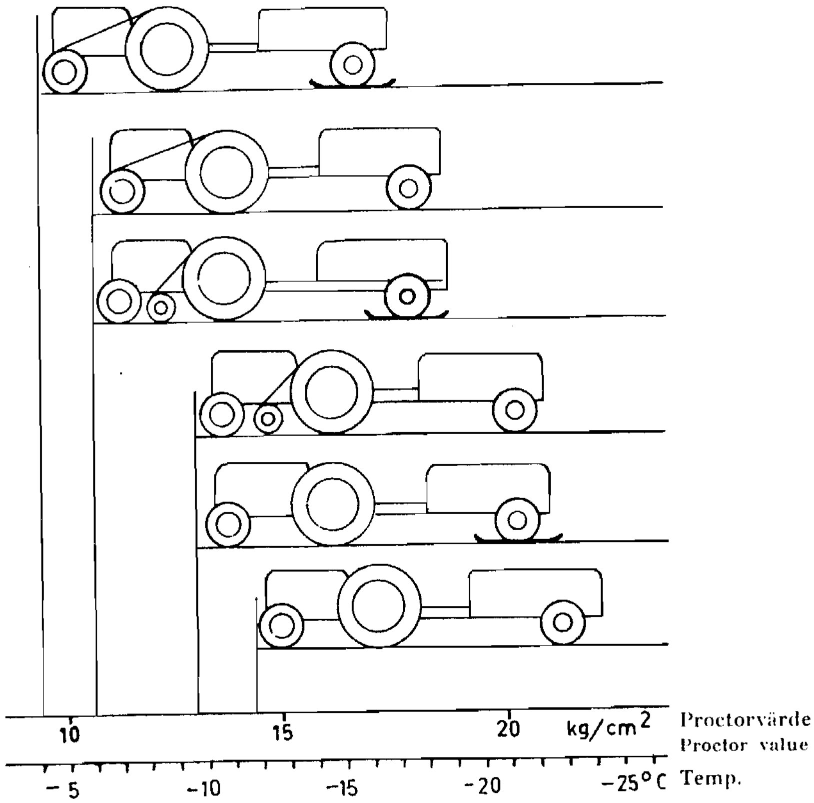


Fig. 30

Approximate bearing strength and temperature limits for intensive traffic with a varying combination of vehicles 24 hours after compaction. The temperature refers to the surface layers of the road. At a bearing strength higher or at a temperature lower than the indicated limits the combined vehicles were estimated to make at least 15 passes over the road in the same rut with a load of about 900 kg on the cart

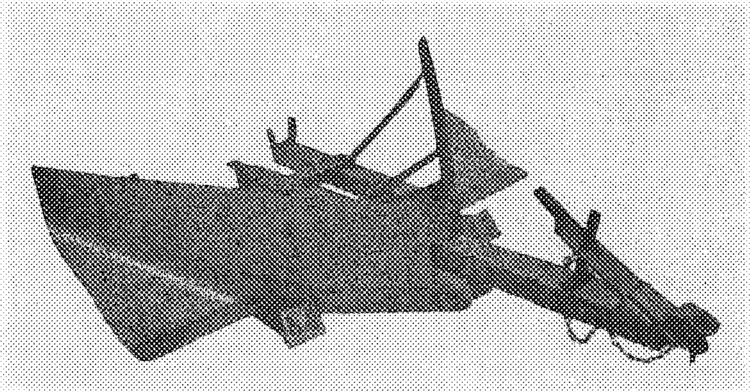


Fig. 31

Equipment for maintaining horse haulage roads. It levels the road bed and opens ruts for the runners

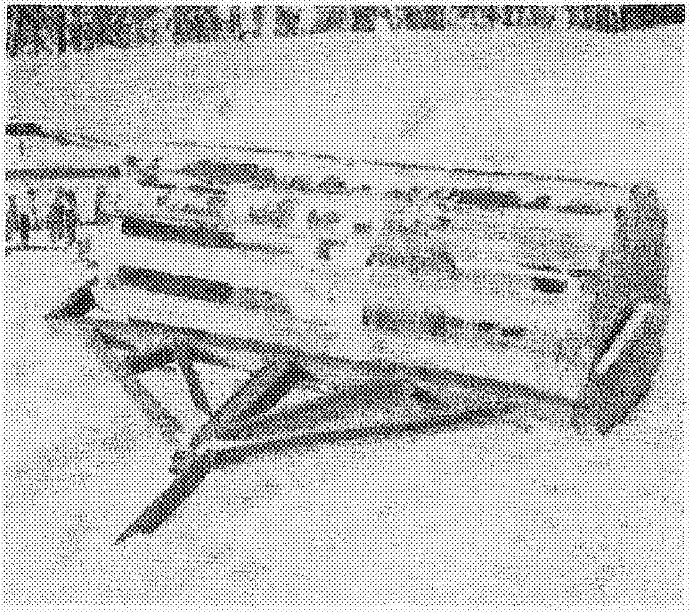
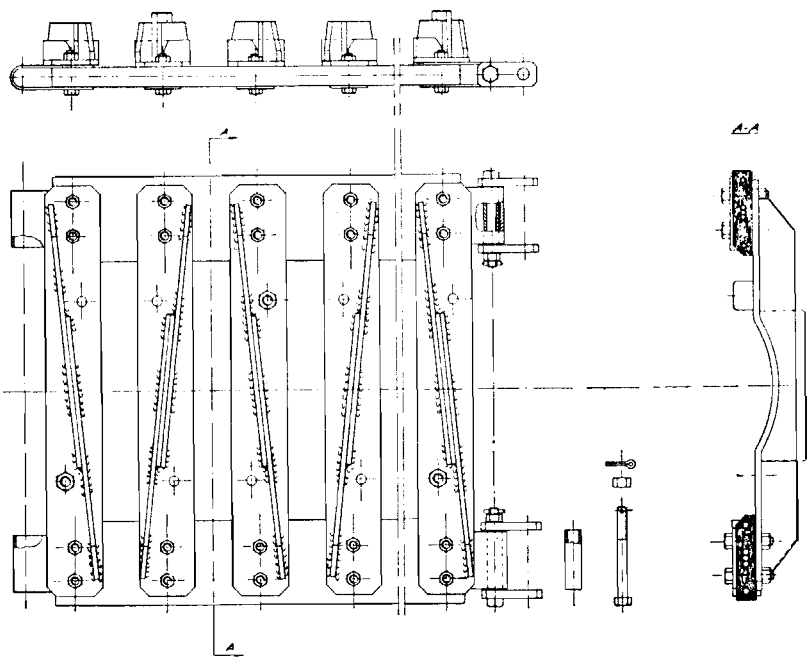


Fig. 32

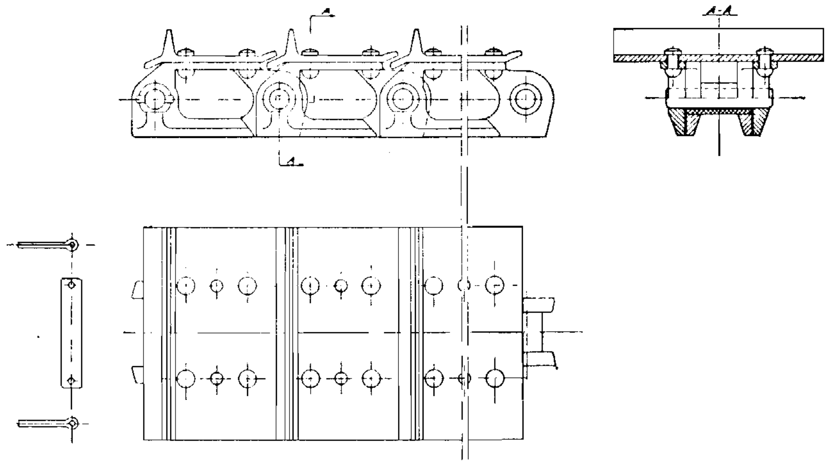
A simple roller of wooden ribs can be used for compacting loose snow (i.e. new-snow) on the road bed

Designs of Tractor Tracks and Anti-skid Devices used in the Experiments

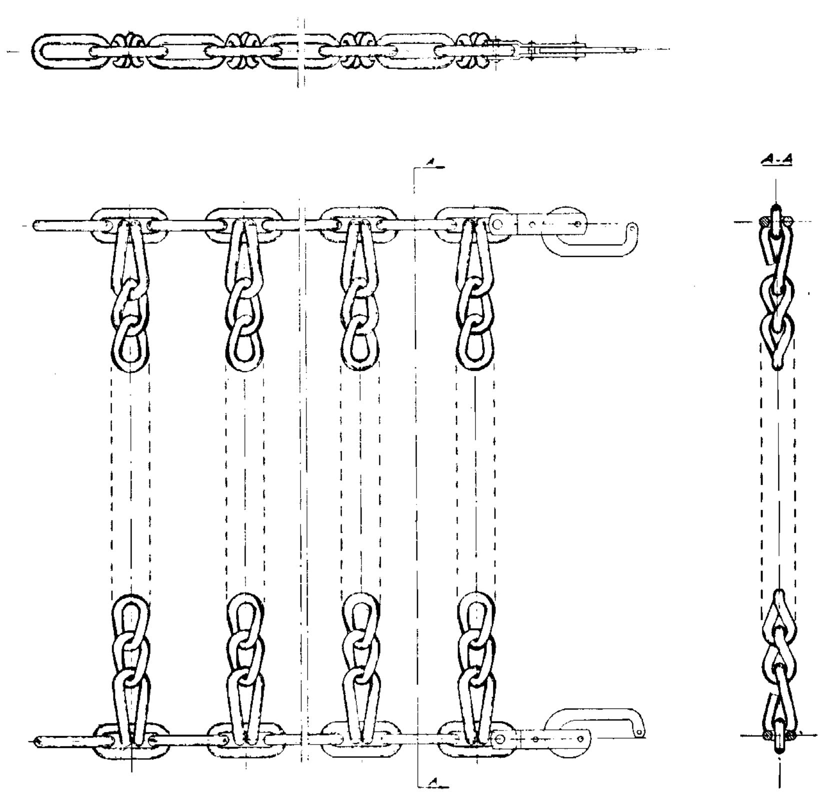
All drawings in scale of approx. 1:12



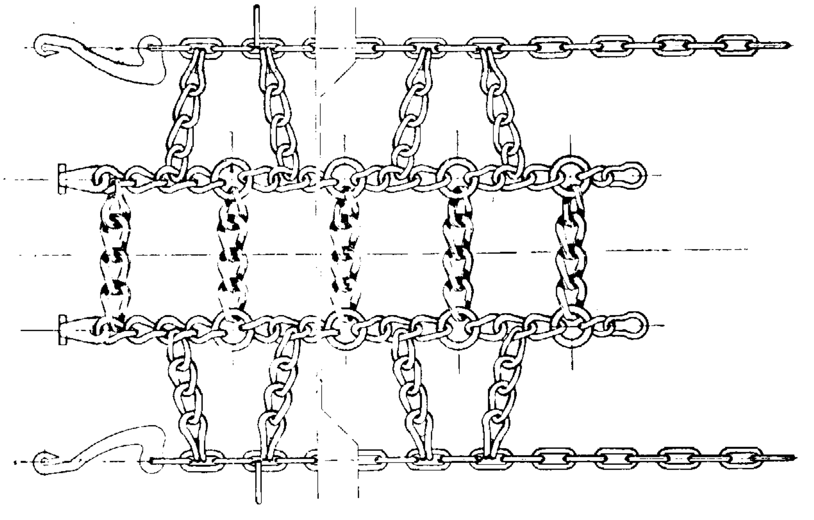
Track of Bombardier for wheel-track and half-track equipment



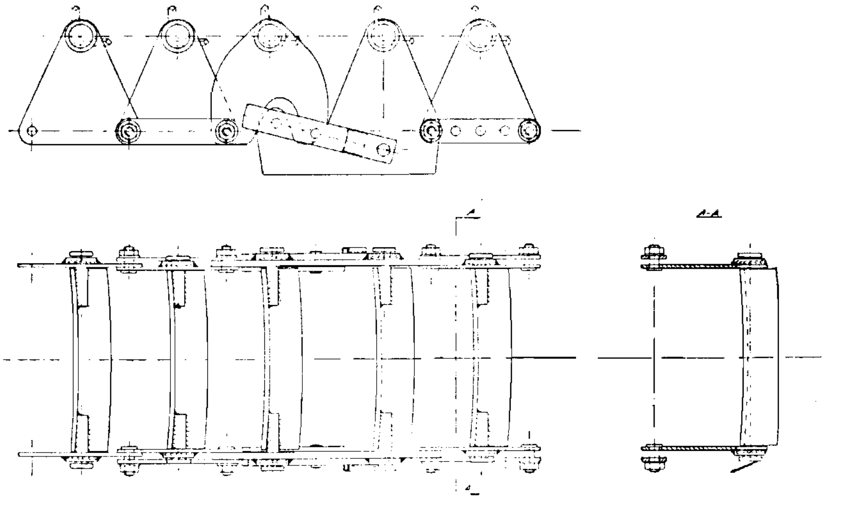
Original track for Oliver OC3



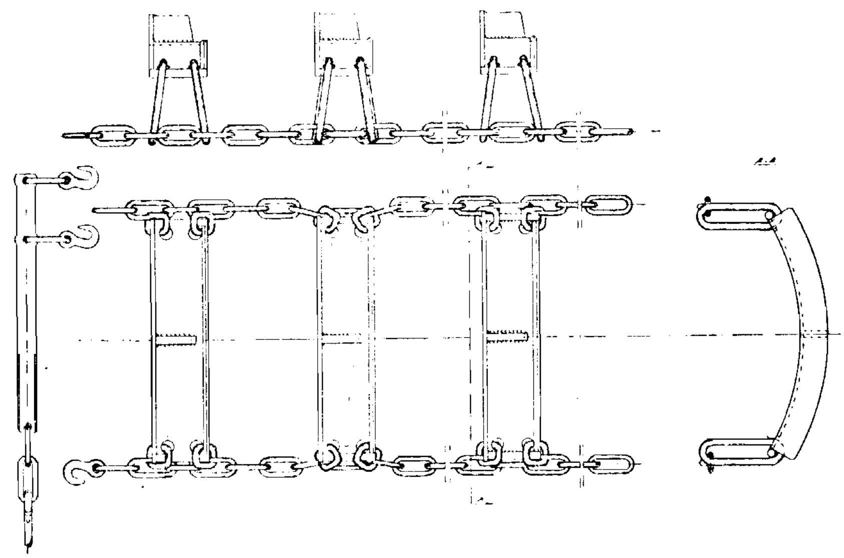
Ordinary snow chains



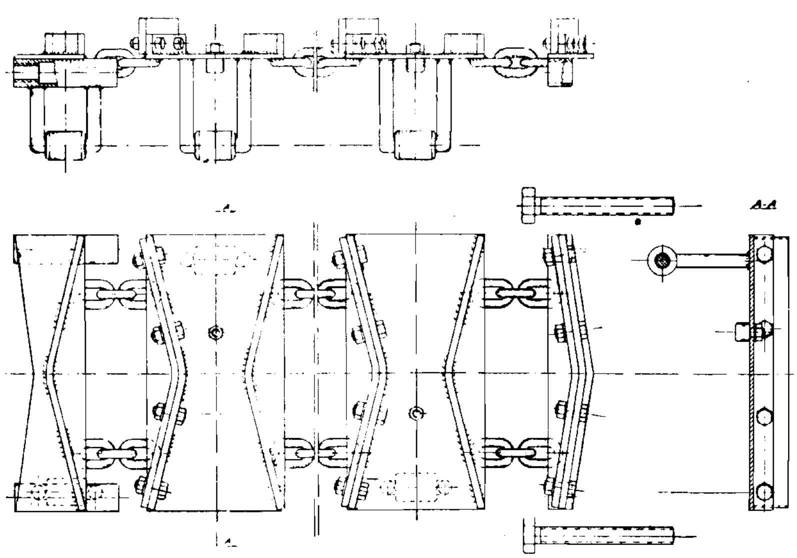
Combi-triumph



Mudmaster



Ceve



"Perfekt" with pulling lugs