Snow-Removing Performance of the Snowplow Truck

Yasuyuki Tanaka

Field studies of the performance of a 4-wheel-drive truck with snowplow produced the following results: (a) Working resistance of the truck consists of the truck's rolling resistance that varies with its speed, sliding resistance of the snowplow, and snow accelerating resistance expressed as a square of the truck speed; (b) at a truck speed of less than 7.5 mph, snow-removing performance of the one-way plow is not effective because the plow pushes snow without throwing; (c) snow-removing efficiency of the plow falls as the square of the truck speed; (d) the distance snow is thrown increases with the square of the plow speed; and (e) the plow with a conical surface performed better than one with a cylindrical surface.

In order to remove new snow from the surface of roads and runways, many straight plows mounted on 7- to 10-ton capacity trucks of 4-wheel-drive are used in Japan. Tests were conducted in the winters of 1965-1966 and 1966-1967 to ascertain the performance of a truck equipped with a snowplow having the capability of removing snow 5 to 20 cm deep at speeds of 15 to 30 km/hr. The tests were carried out on the test road at the Institute of Snow and Ice Studies located at Nagaoka in Niigata Prefecture. Tests were made on National Highway Route 17 running along Yuzawa, also in Niigata Prefecture, and at Aomori Airport in Aomori Prefecture. Because of the difficulty of controlling natural conditions such as snow density, air temperature, wind, and road surface condition, considerable scatter appears in the data. This report presents chiefly the results obtained in Aomori Prefecture.

TEST CONDITIONS

Truck and Snowplow Used in the Test

The truck used for the test was a dump truck modified for the attachment of a snowplow and equipped with a small hoist to facilitate the changing of test plows. The principal dimensions are given in Table 1.

Three types of snowplows were used. Type A, most commonly used, is a one-way plow with conical surface. Type B is an angling plow with cylindrical curved surface whose plow angle may be changed horizontally. Type C is an angling plow with a cylindrical curved surface whose plow angle and also throw-out angle may be changed. The tests were chiefly made by using Types A and C. Table 2 gives the principal dimensions of each plow.

Items and Methods of Measurement

Force required for removing snow was determined by measuring the hydraulic pressure of the cylinders attached to the 2 plow push bars. The engine horsepower was calculated from the reading of a torquemeter by employing wire strain gages and a tachometer attached to the drive shaft. The truck speed was measured by a fifth wheel. These data were recorded on a recorder located inside the truck cab.

Density, temperature, and volume of snow on the test area were measured in advance of the test. After a test run was made, the volume of any residual snow was measured and deducted from the volume that had been measured in advance. Measurements were taken every 5 to 10 m of running distance.

TABLE 1

SPECIFICATION OF TEST TRUCK (WITHOUT PLOW)

HINO ZH 10D Dump Truck	HINO DS 30 Diesel Engine
Length, 8,010 mm	Rated horsepower, 150 hp at 2,400 rpm
Width, 2,450 mm	Maximum torque, 50 kg-m at 1,600 rpm
Shipping weight, 8,330 kg	Transmission, 8 speeds forward and 2 speeds reverse
Total weight (with measurement device), 8,900 kg	Drive, 4 by 4, all-wheel
Maximum speed, 69 km/hr	Tire size, 1000-20, 14 PL
Turning radius, 9.7 m	Crane capacity, 2-ton hydraulic

TABLE 2

SPECIFICATION OF TEST PLOWS

Item	Type A	Type B	Type C
Plow	One-way	Angling	Angling
Snow clearing width, mm	2,550	2,940 at 60-deg angle	2,600 at 60-deg angle
Plow height, mm	1,150 left, 600 right	1,080	1,100 at 50-deg throw-out angle
Plow angle, deg	55	30 to 70	50 to 70
Throw-out angle, deg	-16.5	19	20 to 60
Plow weight, kg	450	638	400
Plow surface shape	Conical	Cylindrical	Cylindrical

The length of run was varied according to the working speed, but generally, it was 10 to 40 m. Distance required for a high-speed test reached 300 m to provide an accelerating distance, a preparatory measure section for attaining power balance, a measurement section, and a braking distance.

The behavior of the removed snow was also analyzed by high-speed 16-mm motion pictures, and the cast direction and distance were measured by marking the snow with ink.

SNOW-REMOVING PERFORMANCE OF SNOWPLOW

Resistance on Snow-Removing Truck

In addition to the running resistance general traffic vehicles have, snow-removing trucks have added the resistance caused by snow removing. The resistance is classified for practical purposes into 3 kinds: running resistance of the truck body itself, R_r; resistance of the snowplow sliding over the snow face, R_s; and resistance of snow-casting (snow-removing resistance), R_p.

Of these resistances, R_r is composed of rolling resistances, aerodynamic resistance, grade resistance, and accelerating resistance, as in all vehicles. The grade and accelerating resistances are transient, and aerodynamic resistance is also when it is outside the speed limit of a snowplow truck. Because it is 3 percent or less, it is excluded here. The rolling resistance is usually expressed by the following formula:

$$R_r = \mu_r W_T \qquad (1)$$

where

R_r = rolling resistance;
μ_r = coefficient of rolling resistance; and
W_T = weight of vehicle.

μ_r is dimensionless and changes according to the tire pattern, inflation pressure, road conditions, and speed; it is usually 0.1 to 0.2 for an automobile tire. In the present test where 4-wheel-drive and chains on all tires were used, it is presumed that the values will be quite large compared with those for normal trucks.

Sliding Resistance of Plow

The resistance in sliding over the road surface may be expressed as

$$R_S = \mu_S W_S \tag{2}$$

where

R_S = sliding resistance of snowplow;
μ_S = coefficient of sliding resistance of snowplow; and
W_S = weight upon cutting edge or shoe of snowplow or both.

μ_S has different values according to road conditions and the form of the plow contacting the ground. In the present test, the ground contacting part was a cutting edge only, and no shoe or caster touched the ground. The tests were made under different conditions where snow or ice lay over the entire or partial roadway. It is known that μ_S between the snow and a snow sleigh is 0.2 or less.

Snow-Removing Resistance

The snow-removing resistance is composed of the resistance required for cutting the snow and the reaction force due to the work required to accelerate the disaggregated snow particles. Because these 2 actions are continuously and simultaneously carried out, it is difficult to separate them, and in the test both are measured together. However, at least theoretically, the two should be clearly separated. In another test series performed at the same time, the snow-cutting resistance of a knife-shaped cutting edge was obtained by using models. The results show that cutting resistance increases proportionately to the increase of cutting speed, and a cutting resistance of 0.7 kg/cm of cutting edge length was found at a speed of 18 km/hr. Although this value is considerable with a plow whose effective cutting width is 250 cm, it is necessary to reflect that the snow used in the cutting test was harder than that used in the plow test.

The snow hitting the plow moving at a high speed is accelerated as it passes over the plow surface and is thrown from the plow. The energy required for its acceleration comes from the reaction force of the plow and its speed. Therefore, the resistance for acceleration constitutes, among all resistances, the sole useful force. Snow particles fly up in the air by the energy of motion that they possess when leaving the plow and then fall on the ground; the distance of movement is influenced not only by the speed but by the direction as well, and therefore the velocity vector should be considered in order to send snow particles flying a greater distance.

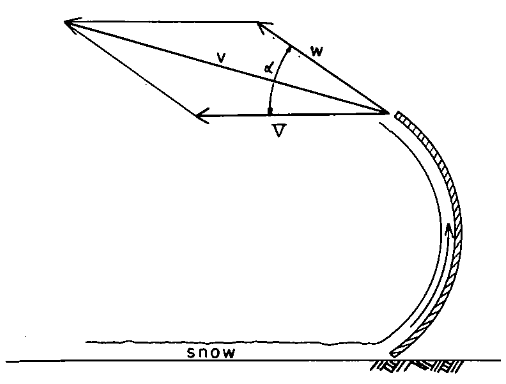

Figure 1. Velocity diagram of plowed snow.

Figure 1 shows how snow lying on the ground begins movement along the plow surface when it is cut by a plow moving at a velocity V. When it is forced along the plow surface, assuming that no crushing, cutting, or plow surface friction takes place, the relative velocity of snow particle and plow becomes equal to plow velocity V. Generally speaking, considering the lowering of velocity, the relative velocity of the snow particle w to the plow at the instant of leaving the plow is

$$\frac{w^2}{2g} = \frac{V^2}{2g} - \frac{V^2}{2g}\epsilon \tag{3}$$

where

V = velocity of plow;
g = acceleration of gravity; and
ϵ = coefficient expressing the loss in velocity energy.

Because the velocity v of snow particles against the ground is the combination of V and w,

$$v^2 = 2V^2\left(1 + \sqrt{1-\epsilon}\cos\alpha - \frac{\epsilon}{2}\right) \tag{4}$$

where α is the snow throw-out angle formed by truck direction and plow blade.

When the density of snow on the ground is taken as γ, a cross-sectional area of snow removed as S, and the reaction force of the plow as F_o for a snow mass of $(\gamma S/g)V$ per unit of time accelerated from rest, then

$$F_oV = \frac{\gamma S}{2g} V v^2 = \frac{\gamma S}{g} V^3 \left(1 + \sqrt{1-\epsilon}\cos\alpha - \frac{\epsilon}{2}\right)$$

$$F_o = \frac{\gamma S V^2}{g}\left(1 + \sqrt{1-\epsilon}\cos\alpha - \frac{\epsilon}{2}\right) \tag{5}$$

In the present study, allowance is made in Eq. 3 for energy loss expressed as $V^2\epsilon/2g$, while in Eq. 5 the energy loss is excluded; but this loss is caused by plow surface and therefore, in the force R_p, which is the force exerted by the truck on the plow, it is necessary to make allowance for this loss. The assumption here is that this loss is not caused by the plow surface but all is taken outside as the kinetic energy of snow, as $\epsilon = 0$. If the reactionary force of the plow then is taken as F_p, Eq. 5 will be

$$F_p = \frac{\gamma S V^2}{g}(1 + \cos\alpha) \tag{6}$$

F_p plus the snow-cutting reaction represents the value of snow-removing resistance R_p.

The sum of the running resistance R_r of the truck, sliding resistance R_s of the plow, and the snow-removing resistance R_p is the resistance suffered while in operation. Accordingly, it is expressed as the square of truck speed, and the horsepower required for removing snow is the cube of truck speed.

Snow-Removing Efficiency

The power efficiency of removing snow is obtained from the ratio of the work done to snow to the power applied. Therefore, various kinds of efficiency may be considered according to the way of assigning these values, but, in the present case, plow efficiency η_p indicating acceleration of snow in the plow and snow-removing efficiency η_r giving the distance of cast are considered.

Plow efficiency η_p is

$$\eta_p = \frac{F_o}{R_p} \tag{7}$$

For F_o the value expressed in Eq. 5 is used, while for R_p the measured value is used. There are many difficulties in obtaining the coefficient expressing energy loss in Eq. 5. As shown in Eq. 3, ϵ is the value obtained by measuring the velocity w of snow flying out from the plow; w has not yet been measured, despite the numerous attempts so far made. For this reason, instead of Eq. 7, the following formula in which $\epsilon = 0$ is used:

$$\eta_p' = \frac{F_p}{R_p}$$

The snow-removing efficiency η_r in which the snow-casting distance L is considered may be obtained in the following way. The snow-casting distance L_o at initial velocity V_o and horizontal angle β is

$$L_o = \frac{V_o^2}{g} \sin 2\beta \qquad (8)$$

The plow reaction force F_o, which is necessary for accelerating the snow at initial velocity V_o, is (from Eq. 6)

$$F_o = \frac{\gamma S}{2g} V_o^2 \;(1 + \cos \alpha)$$

Accordingly,

$$L_o = \frac{2F_o \sin 2\beta}{\gamma S \;(1 + \cos \alpha)} \qquad (9)$$

When actual snow-casting distance is assumed to be L,

$$\eta_r = \frac{L}{L_o} = \frac{L\,\gamma S \;(1 + \cos \alpha)}{2F_o \sin 2\beta} \qquad (10)$$

Measuring snow-casting distance L is difficult as compared with measuring the distance casting by a rotary snowplow, owing to the fact that the direction of snow throwing does not form a right angle with respect to the direction of progress, and furthermore the snow thrown is scattered over a wide area. Accordingly, η_r has large errors and poor practical use.

Snow-Removing Performance Rate

The performance of snow-removing equipment is ascertained by giving a few practical numerical examples.

The ton/hr and m^3/hr, which represent the amount of snow removed per hour in weight (ton) and volume (m^3), are often used in the case of rotary snowplows. The ton/hr is a value showing power limitation, while m^3/hr shows volume limitation.

The value called the relative snow-removing resistance is useful for indicating performance. This is given by $R_p/\gamma S$ (in which R_p is the reaction force acting on the snowplow, S is the cross section of snow removed, and γ is the density of snow) and is the ratio of plow reaction force against snow weight per unit of snow-removing length. Now, by ignoring the cutting resistance of snow and taking $R_p = F_p$ from Eq. 6,

$$\frac{R_p}{\gamma S} = \frac{V^2}{g} \;(1 + \cos \alpha) \qquad (11)$$

This value has the dimension of length, which is presumed to be related to the distance of snow-throwing. Accordingly, when 2 or more relative snow-removing resistances are compared, it is necessary to consider working speed V as an index.

As a similar method of representation, there is ton-hp/hr, whose value is often used in the case of rotary snowplows and is the value obtained by dividing the weight of snow removed per hour (ton/hr) by the power (hp) required for removing the snow. Because this value also has the dimension of length, it is necessary to take vehicle speed as an index.

TABLE 3

SLIDING RESISTANCE OF PLOW

Test Location	Coefficient of Sliding Resistance	Sliding Resistance (kg)
Nagaoka (Concrete)	0.47	188
Aomori (Asphalt)	0.39	161
Mean	0.41	167

RESULTS

Truck Running Resistance

Running resistance of the truck with the plow clear of the ground, all tires chained, and all wheels driven, on thin hard-packed snow on a paved road is obtained from the following equation:

$$R_r = W_T\,(0.00123V + 0.050) \qquad (12)$$

where

R_r = running resistance of truck (kg);
W_T = weight of truck (with plow 9,520 kg); and
V = truck speed (km/hr).

This value is somewhat larger than values for other vehicles; the difference of 30 percent or more depends on the type of test truck. Therefore, it is necessary to obtain data from many types of trucks.

Sliding Resistance of Plow

Before the snow-removing test was started, the sliding resistance of the plow was measured by making the plow slide on the snowless section that had been cleared during the previous test. Small differences in road surface conditions greatly affect the sliding resistance of the plow and make large measurement variations. However, after an analysis of variance was made, the only significant factor found was the kind of pavement; no significance due to speed and type of plow was found. Values obtained for the coefficient of plow sliding resistance μ_s and sliding resistance R_s are given in Table 3. The plows used were Types A and C.

Snow-Removing Resistance

Because snow-removing resistance R_p is affected by cross-sectional area of snow removed S and snow density γ, the relative snow-removing resistance $R_p/\gamma S$ given in Eq. 11 is employed to facilitate the comparison of values under various conditions. In the 1965-1966 winter test, the results shown in Figure 2 were obtained by using the Type B plow. Measurement was carried out at relatively low speed. Here relative snow-removing resistance $R_p/\gamma S$ is plotted against snow-removing speed V. From this it has been proved that the relative snow-removing resistance attains a minimum value at velocity of approximately 12 km/hr. According to the analysis of high-speed 16-mm film made at each velocity, the snow is pushed sideways and rolls along the lower part of plow whenever the truck speed is 12 km/hr or less. When the speed exceeds 12 km/hr, snow rises up along the plow surface and flows outward. Because more energy is required for rolling the snow sideways than for making it flow, the relative snow-removing resistance increases as truck speed drops below 12 km/hr. This velocity

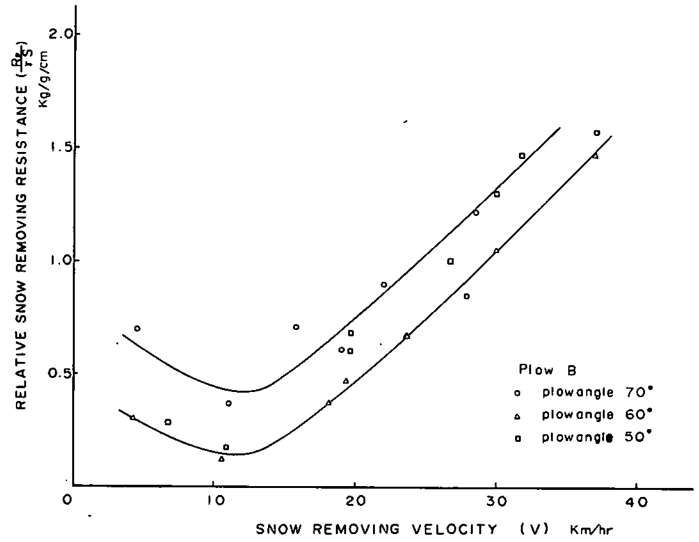

Figure 2. Relationship between velocity and resistance of snow removal.

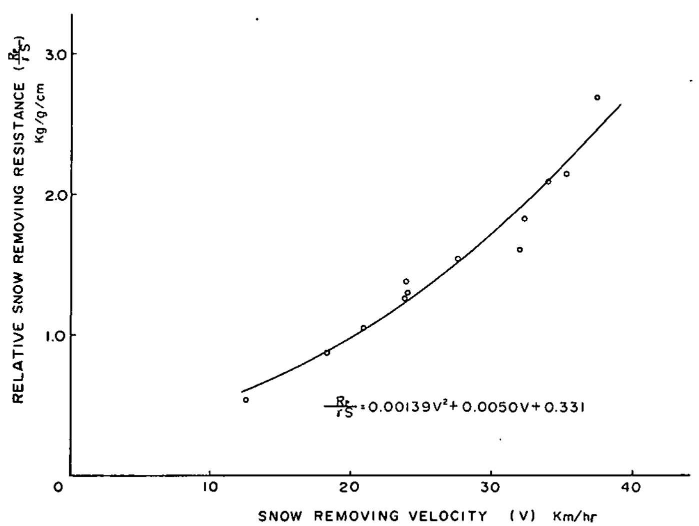

Figure 3. Relationship between snow-removing velocity and resistance of plow Type A.

limit is caused by snow rising up along the plow surface to a certain extent (30 to 50 cm) according to the truck speed.

Data for truck speeds of 12 km/hr or less were not obtained in the 1966-1967 winter tests.

Figures 3 and 4 show the relative snow-removing resistances of Type A and Type C plows plotted against vehicle velocity. The regression equations for these are

$$\frac{R_p}{\gamma S} = 0.00139V^2 + 0.0050V + 0.331 \qquad (13)$$

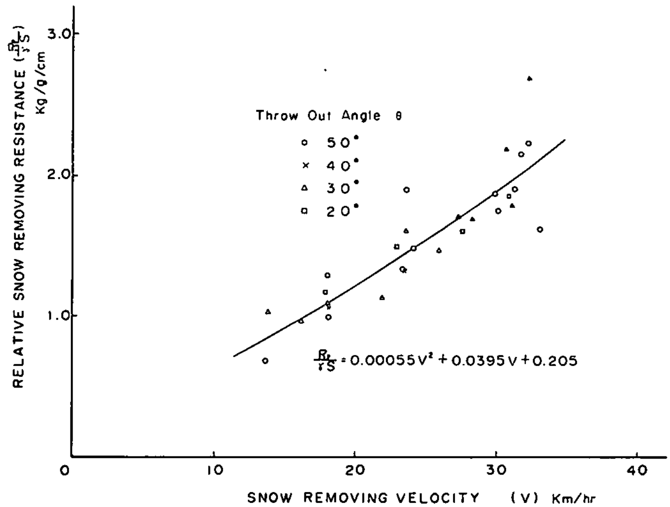

Figure 4. Relationship between snow-removing velocity and resistance of plow Type C.

for Type A plow, and

$$\frac{R_p}{\gamma S} = 0.00055V^2 + 0.0395V + 0.205 \qquad (14)$$

for Type C plow, where

R_p = snow-removing resistance of plow (kg);
γ = snow density (g/cm^3);
S = cross-sectional area of removed snow (cm^2); and
V = working speed of truck (km/hr).

The value of Eq. 13 was the least when vehicle velocity was in the 12 to 40 km/hr range, which shows that the plow with the conical curved face is superior to the plow with the cylindrical curved face. Also, Type C plow tests were made at different angles.

The Necessary Truck Driving Force

The driving force required by the plow consists of truck running resistance R_r, plow sliding resistance R_s, and plow snow-removing resistance R_p, all put together. From Eqs. 12 and 13 and for Type A plow,

$$\begin{aligned} F_T &= R_r + R_s + R_p \\ &= W_T\,(0.00123V + 0.050) + 0.41\,W_p \\ &\quad + \gamma S\,(0.00139V^2 + 0.0050V + 0.331) \end{aligned} \qquad (15)$$

Now, on the assumption that the truck deadweight W_T is 8,900 kg, plow weight W_p is 450 kg, snow density γ is 0.1 g/cm^3, and snow-removing cross section S is 30 cm × 300 cm = 9,000 cm^2, the driving force F_T (kg) of the truck at a vehicle speed of V (km/hr) will be

$$F_T = 1.25V^2 + 15.4V + 927 \qquad (16)$$

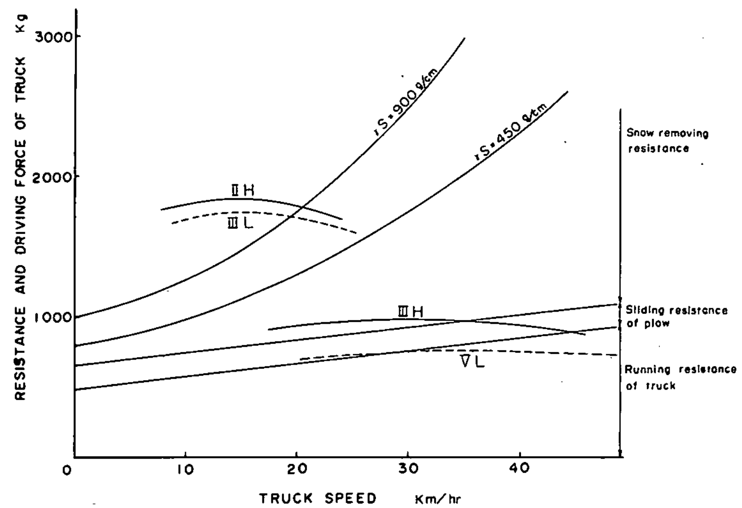

Figure 5. Resistance and driving force of snowplow truck.

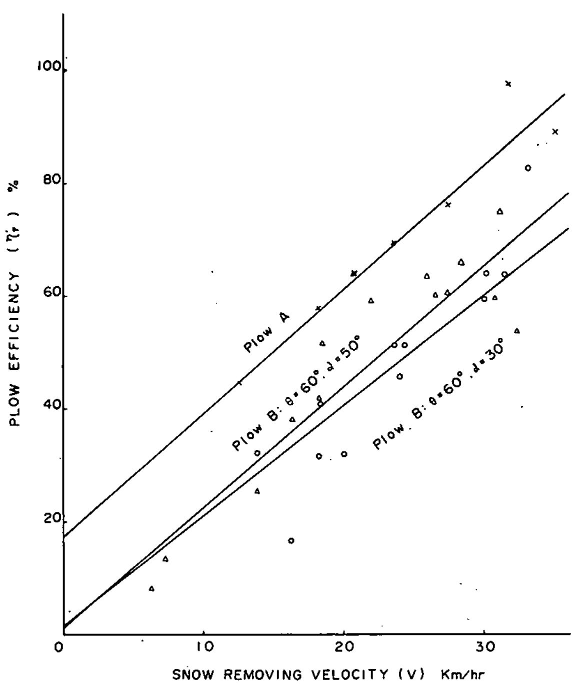

Figure 6. Plow efficiency.

This is shown in Figure 5, where the driving force of a representative truck is also given. It is clear that the running resistance of the truck itself has a large value at slow speeds. So the tractive force is calculated as 3,110 kg against the truck deadweight of 8,900 kg, which is considered satisfactory because no high acceleration or climbing resistance is included in the resistance shown in Figure 5.

The lateral snow-removing resistance of the plow, measured 960 mm ahead of the truck front axle, was one-fifth or less of that in the forward direction. When this maximum value of 744 kg is calculated as movement per 4,260 mm of truck wheel base, lateral force working on the front axle amounts to 912 kg. Theoretically, when the plowing angle is taken as θ, the lateral force F_{ps} is represented in relation to reaction force F_p in the direction of progress as

$$F_{ps} = F_p \sin \frac{\theta}{2} \qquad (17)$$

In many cases, θ is 60 deg and so F_{ps} ought to be 0.5 F_p. However, in actuality, because the snow-removing resistance F_p contains the other resistances of loss and acceleration, the ratio decreases to 0.3 or 0.4. In removing snow, one must pay attention to the fact that front wheel sideslip is likely before the driving force drops because of overloading.

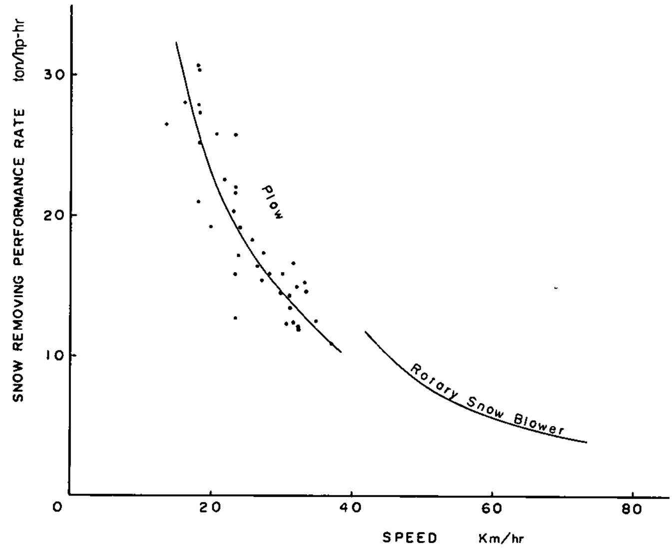

Figure 7. Snow-removing performance rate.

Snow-Removing Efficiency

The relation between snow-removing efficienty η_p' and vehicle velocity V is shown in Figure 6. η_p' clearly increases in proportion to V. This is also the case with the rotary snowblower; it is considered to be due to the fact that the snow speed is low with respect to the vehicle speed.

Rotary snowblower efficiency is 0.3 or so, but snowplow efficiency approaches 1.0 at the maximum. Therefore, it is necessary to obtain the coefficient ϵ showing energy loss and to calculate efficiency by means of η_p in Eq. 7. In Figure 6, the effect of plow throw-out angle α versus η_p' is observed. Actual measurements of snowcasting have shown that snow moves more in the direction of truck progress than in the direction tangent to the plow surface.

Snow-Removing Performance Rate

Snow-removing performance rate in tons-hp/hr plotted against truck speed V is shown in Figure 7. The curve is a hyperbola. Test results for a rotary snowblower are also shown. The speed in this case is the peripheral speed of the blower. Although the velocity range is wide, it has been proved that the snow-removing performance rate of the snowplow is inferior to that of a rotary snowblower.

ACKNOWLEDGMENT

Appreciation is expressed to the Institute of Snow and Ice Studies, which cooperated with us in carrying out these tests, and to research engineer Shigeyoshi Sawada, who aided us in the difficult tests.