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ENERGY TRANSFER, MECHANISMS AND TRACTION PERFORMANCE

by

R.N. Yong, E.A. Fattah, A.F. Youssef and P.V. Janiga

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FOREWORD

THE following three papers which constitute this report, **ENERGY TRANSFER, MECHANISMS AND TRACTION PERFORMANCE**, have been prepared and presented as follows:

1. *Influence of Contact Characteristics on Energy Transfer and Wheel Performance on Soft Soil.* R. N. Yong and E. A. Fattah. 5th International Conference, International Society for Terrain-Vehicle Systems, Detroit, U.S.A. June 1975.

2. *Vane-Cone Measurements for Assessment of Tractive Performance in Wheel-Soil Interaction.* R. N. Yong, A. F. Youssef and E. A. Fattah. 5th International Conference, International Society for Terrain-Vehicle Systems, Detroit, U.S.A. June 1975.

3. *Considerations in Vehicle-Ground Interaction in Off-Road Mobility in the Canadian North.* R. N. Yong and P. V. Janiga. Symposium on Canadian Mobility and Environment, Canadian Society for Terrain-Vehicle Systems, Ottawa. June 1974.

THE above papers represent the results obtained in the overall study of the problems associated with the production of tractive effort through wheel or track systems. The work performed was under Contract arrangement with the Department of Supply and Services of Canada under Contract Nos. SUI.7090084 Serial No. 2SU3-0547 and 03SU-CD-7090014 Serial No. 2SU4-0105, with project monitoring by the Earth Sciences Division, Defence Research Establishment Ottawa. Mr. I. S. Lindsay was the Project Officer for the studies.

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INFLUENCE OF CONTACT CHARACTERISTICS ON ENERGY TRANSFER AND WHEEL PERFORMANCE ON SOFT SOIL

by

R. N. Yong* and E. A. Fattah**

INTRODUCTION

The items of interest with regard to the evaluation of powered or towed wheel performance on soft soil centre around:

a] characteristics [and requirements] of drawbar-pull development for powered wheels, and

b] pull requirements for towed wheels for maintenance of continuous motion for cases where sinkage is less than vehicle clearance.

By and large, it is noted that commonly used methods for analysis and assessment of performance of off-road wheel systems rely on experimentally established pressure-sinkage and shear deformation relationships as a base for generation of theoretical, semi-theoretical or empirical tools - for use in predicting expected drawbar-pull of the wheel system. Since the soil pattern of deformation under the test plate, cone, or shear ring device and the wheel are different, it is apparent that for predictive purposes, theories based on experimentally

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derived pressure-sinkage or shear deformation relationships should be carefully used if performance prediction is desired. In order to circumvent some of the problems associated with relating dissimilarity of the deformation fields, performance assessment may be predicted by studying wheel-soil interaction.

In this paper, the performance of a wheel is evaluated in terms of maximum useful energy [work] that can be developed in view of the wheel contact surface characteristics and soil properties - from a known or specified energy input. In essence, with appropriate conditions the wheel may be examined as an equivalent stable system - with the characteristics and properties of wheel contact surface and subsoil properties defining interface relationships as a mutual interacting system. Figure 1 shows the regions associated with the energy components participating in defining the stable system. The dissipation of the parasitic energy components [i.e. interfacial and deformation] can be seen in Figure 2. It is apparent that if the characteristics of the energy dissipation curve can be altered, wheel performance can be correspondingly changed. The parameter of useful interest, in a non-changing soil substrate system would be one concerned with the contact surface and the resultant development of interface relationships. This study examines the results obtained from tests on a rigid wheel with three surface conditions:

a] smooth,

b] rubber coated, and

c] V-shaped treads,

in the light of the development of energy transfer at the interface - and resultant drawbar-pull.

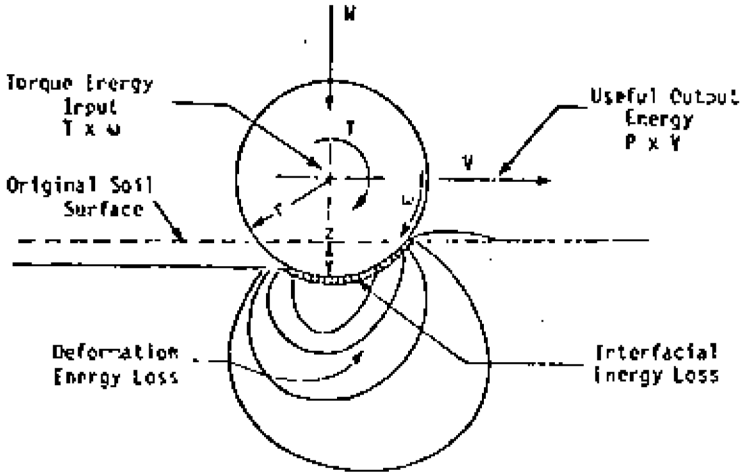

Fig. 1 - Types of Input and Output Energy

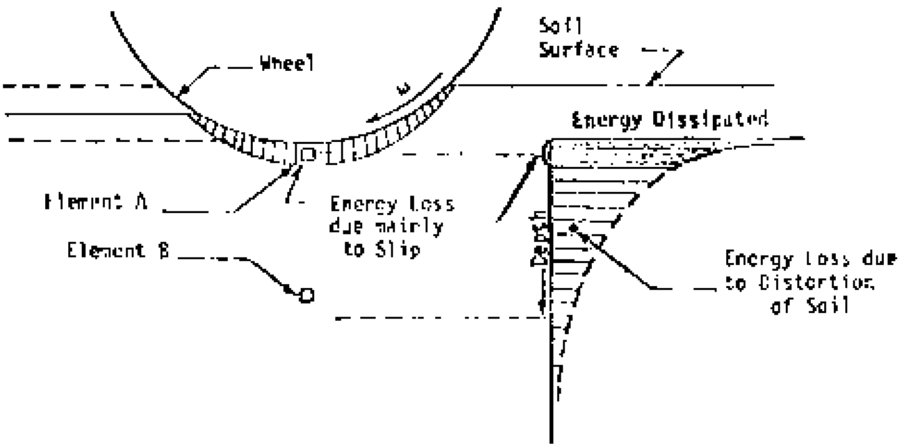

Fig. 2 - Energy Dissipation in Substrate due to
Wheel Soil Interaction [after Yong 1973]

ENERGY TRANSFER AND DRAWBAR-PULL

An evaluation of actual wheel performance in regard to sub-soil deformation as influenced by variation of wheel contact surface characteristics may be performed at different degrees of slip in terms of the energy transfer mechanism at the interface. Intuitively one would expect that subsoil distortion and disturbance with depth may be directly associated with wheel slip and contact characteristics. The indications are that the relationships can be evaluated in terms of energy transfer mechanics. The component of energy transfer which is associated with sub-soil deformation must obviously depend on the mechanics of transfer at the interface,and is thus seen to be related directly to the interface energy component. The procedure for examination requires an analysis for the overall problem in terms of the rationale for partitioning of the components of parasitic energy.

As indicated previously [Yong and Webb (1969)] and as seen from Figs. 1 and 2, the energy balance formula may be written as

$$T\omega = PV + RV + E_f \tag{1}$$

where

T = input torque

ω = angular wheel velocity

V = translational velocity

R = rolling resistance

E_f = interfacial energy loss

P = drawbar pull

Equation (1) may be written as

$$E_i = E_\omega + D + E_f \tag{2}$$

where

E_i = input energy

E_ω = useful output energy

D = deformation energy

D and E_f are the components of parasitic energy i.e. energy lost to the soil. For ease and simplicity in comparison between the different wheel surface conditions, the energy balance equation should be described in terms of wheel travel speed and wheel diameter.

Thus,

$$\frac{T\omega}{V} = P + R + \frac{E_f}{V} \tag{3}$$

or

$$\dot{E}_i = \dot{E}_\omega + \dot{D} + \dot{E}_f$$

where the dot superscript indicates rate.

Examination of immediate response and resultant subsoil deformation and distortion using flash X-ray techniques similar to those described by Yong and Webb (1969), can confirm expectations in regard to dependency between soil distortion slip/contact characteristics. The test results indicate that no direct independent generalized relationship between the different rate of energy parameters [input, useful output and losses] and degree of slip can be written. It appears that each energy component or parameter is a function of the interdependent nature of the different wheel-soil parameters.

The deformation energy rate is seen to be a function of wheel load and soil response. In turn, this is a function of the stress-strain behaviour of the soil,and the loading rate. The rate of interfacial energy loss is a function of the tangential stresses developed, contact area and slip velocity. The dependence of slip performance on wheel parameters is obvious. An examination of the components or factors contributing to input energy indicates that input torque is dependent on the resultant tangential stresses developed at wheel-soil interface. The influence of wheel surface characteristics and angular velocity may be seen in the changes in developed tangential stresses, since useful work is a function of both input and parasitic energies and the interdependent nature of wheel-soil parameters.

EXPERIMENTATION AND ANALYSIS

The laboratory soil bin experiments were conducted to provide information on drawbar-pull input torque, angular velocity, translational velocity, dynamic sinkage and the displacement pattern within the soil mass beneath moving rigid wheels. The test facility, utilizing a flash X-ray technique has been described previously by Yong et al. (1967), (1969). The technique consists essentially of recording by flash X-ray techniques, the positions of lead markers embedded in the subsoil at various times corresponding to various instantaneous positions of the moving wheel. With multiple recordings, it is seen that this procedure provides information which may be used to trace the "distortion" motion of each embedded marker. From linear superposition, it is possible to provide for velocity and displacement fields in the soil - as a result of wheel motion. The developed procedures have been reported previously by Windisch and Yong (1970).

To provide for a simple rational approach in the analysis of results, the experiments conducted considered the following factors:

a] three different wheel loads - using a rigid wheel with constant radius, b] constant water content and density of the clay subsoil,

c] constant wheel translational velocity, with varying angular velocity and torque to provide for slips varying from the towed point [zero torque] to 80 per cent slip,

d] varying rigid wheel surface characteristics [smooth, rubber coated and V-shaped treads affixed to the rubber surface as seen in Fig. 3].

The effect of the above factors and variables on wheel performance and subsoil deformation behaviour constitutes the basis for the analysis and discussion stated hereafter.

Interfacial Energy

The interfacial energy, E_f, previously defined as the energy dissipated at the wheel-soil interface may be expressed as

$$E_f = \sum_{\substack{\text{total}\\ \text{area}\\ \text{of}\\ \text{contact}}} \text{tangential stresses x elemental area x elemental slip velocity} \qquad (5)$$

Two methods were used to determine the associated tangential stresses developed at wheel-soil interface. The choice of each method depended on the amount of slip obtained. For low slips - up to 45 per cent, the method for determination of interfacial stresses required determination of the contact stresses at wheel soil interface. This was obtained with experimental data and knowledge of

a] the resultant instantaneous stress field beneath the moving wheel,

b] the instantaneous strain and strain-rate fields developed in the subsoil, and c] soil deformation patterns [see Windisch and Yong (1970)].

By applying a suitable yield criterion [i.e. Tresca] and the associated flow rule, the interfacial stresses can be determined using the method of characteristics as shown by Yong and Windisch (1970).

For high degrees of slip [i.e. above 45 per cent] the tangential, or interfacial, stress may be predicted by using a skid test to obtain the relationship between slip velocity and frictional stresses as shown in Fig. 4.

Wheel Performance

From previous studies, [Yong and Webb (1969)], it has been successfully established that with the use of the visioplasticity technique, the subsoil response to surficial wheel loading may be expressed in terms of dissipative energy fields, subsoil stresses, interfacial stresses, strain rate fields, through appropriate experimental and analytical procedures. In this study, the subsoil response behaviour may be examined in relation to the characteristics of wheel input, i.e. wheel load, input torque and slip rate, as shown for example, in Figs. 5a through 5c. It is pertinent to note that only direct subsoil response is given by the figures, and that the effect of wheel surface condition on the wheel performance is not directly described. Indirectly, however, one would expect that the velocity and energy fields reflect transfer characteristics at the surface.

Soil Particle Path

To obtain a better appreciation of contact and interface relationships, representative soil particles at some subsoil depth may be examined - vis-a-vis soil motion under load. The soil particle paths shown in Fig. 6 express the motion of soil particles due to the surface motion of the wheel. Since the experimental wheel moves with

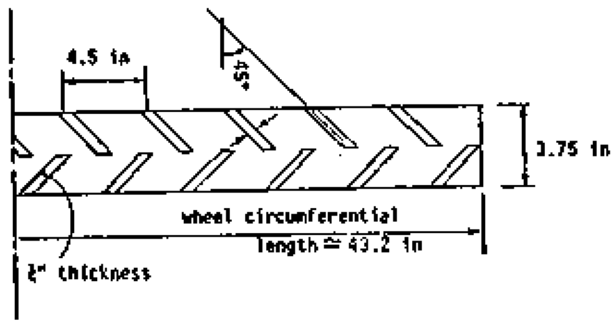

Fig. 3 - Tread Arrangement unfolded on Horizontal Plane

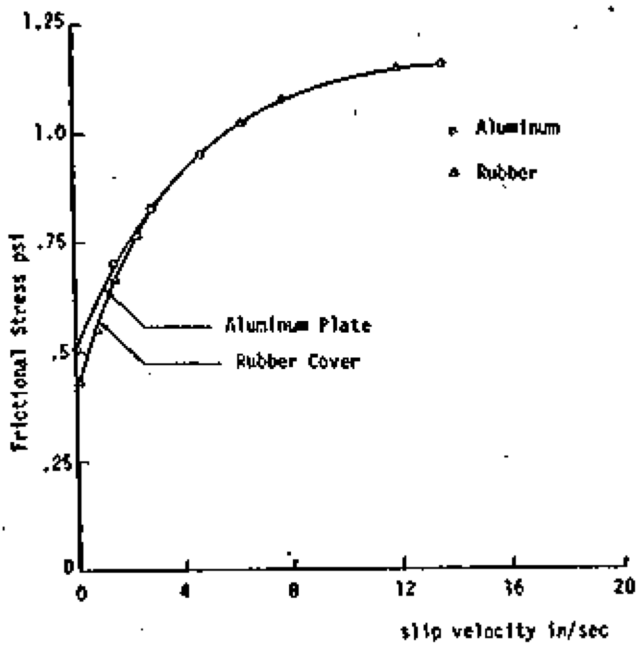

Fig. 4 - Effect of Slip Velocity on Frictional Stresses in Skid Testing

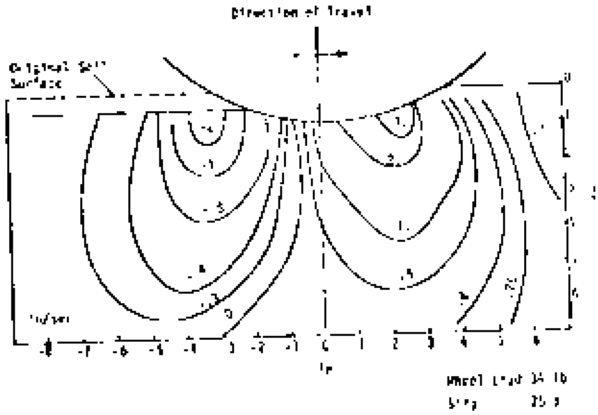

Fig. 5a - Vertical Velocity Contours [Rubber coated Wheel]

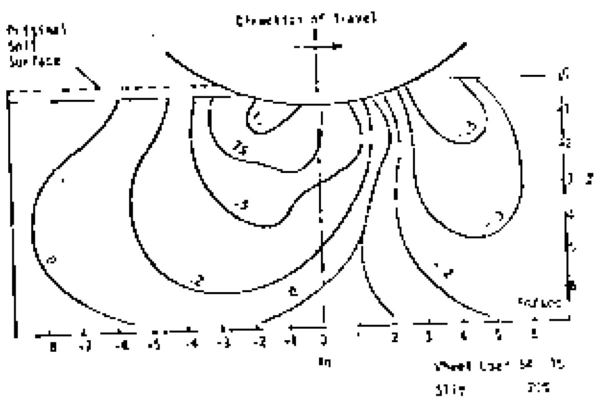

Fig. 5b - Horizontal Velocity Contours [Rubber coated Wheel]

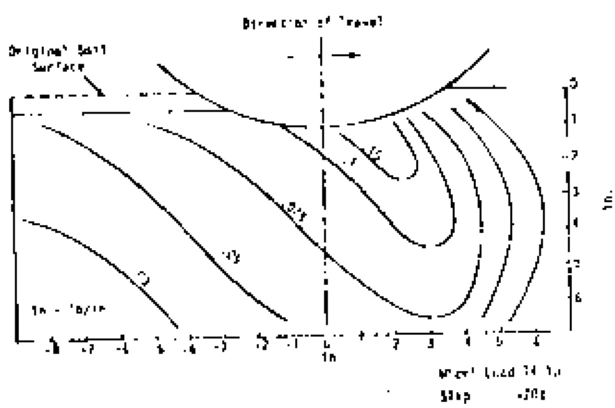

Fig. 5c - Deformation Energy Contours [Rubber coated Wheel]

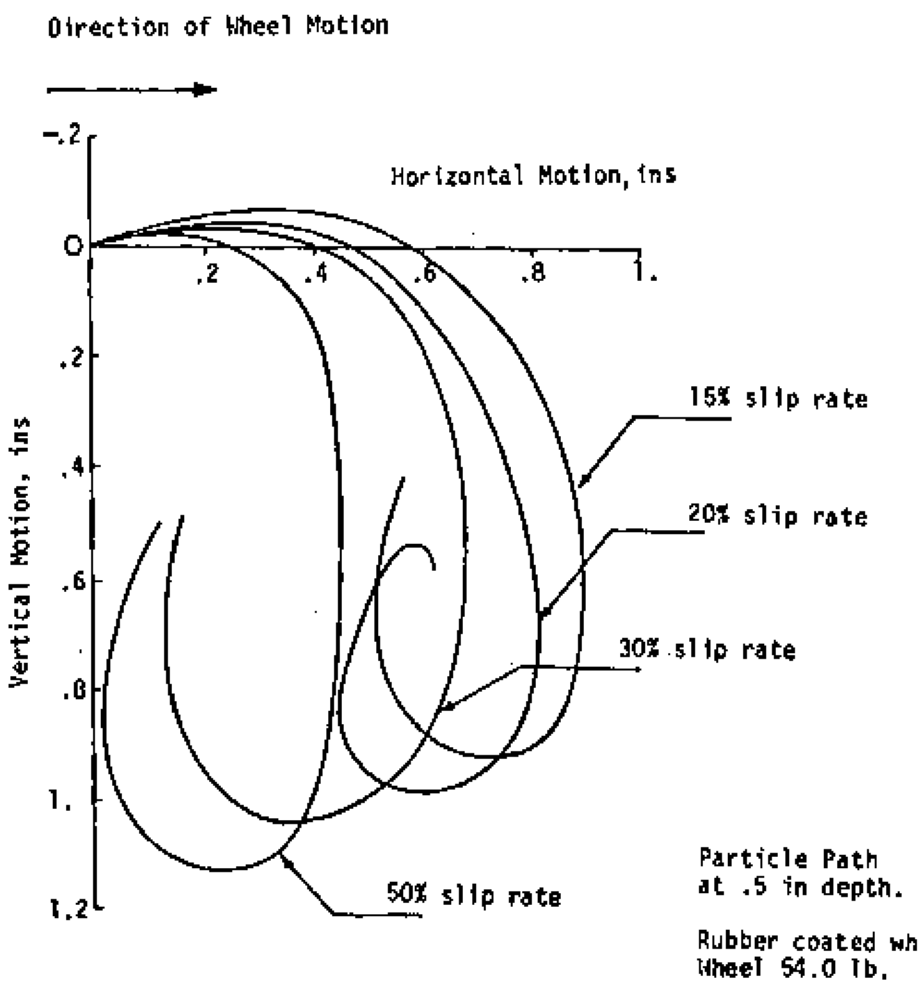

Fig. 6 - Soil Particle Path as Influenced by Slip Interface

constant translational velocity and if the soil is homogenous, it is expected that the particle paths for typical soil elements at the same depth should be similar.

In Fig. 6 the resultant particle paths developed under a moving rigid wheel for rubber contact surface conditions are given. Analysis for other conditions of loading reveals that the shape of the particle path can take various forms - depending on load and transfer characteristics. In a similar vein, the same type of argument can be applied for examination and evaluation of subsoil performance expressed in terms of particle velocities, deformation energy and subsoil stress contours, e.g. Figs. 5a through 5c.

Dynamic Sinkage and Deformation Energy

Figure 7 shows the results of the dynamic sinkage for two specific wheel contact surface conditions. It was found that the sinkage remained relatively constant at low loads - slightly sensitive to slip. At higher loads, there was evidence of higher dependency on degree of slip with additional increase in dynamic sinkage noted with roughness of the wheel contact surface.

Interfacial Energy

The test results demonstrate the expected dependencies between wheel load and developed interfacial energy as conditioned by wheel contact surface, soil type and degree of slip. It is interesting to note that after a well-defined degree of slip [60 per cent] the interfacial energy appears to be a function only of slip, i.e. independent of wheel load and contact surface characteristic, as shown in Fig. 8. As explained in the next section, the rubber surfaced wheel does indeed have an apparent smoother surface - due primarily to the properties of clay-rubber interaction. Similar curves and relationships can be obtained for other wheel loads and contact surface characteristics - and also for other subsoils. The characteristic singular point of slip

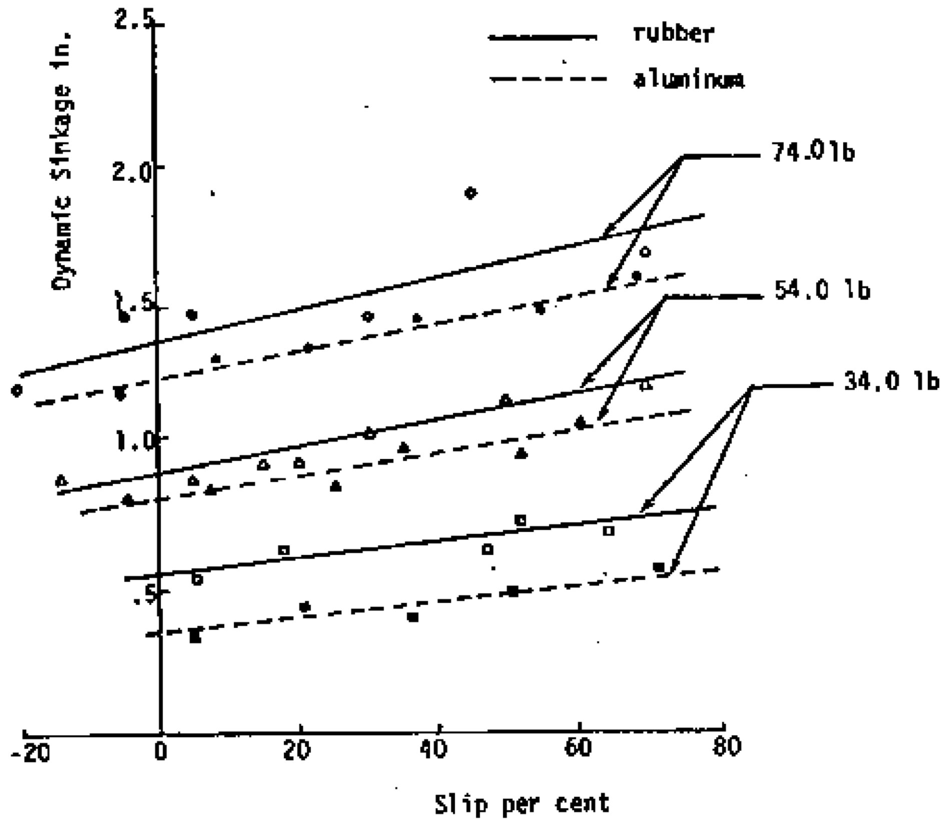

Fig. 7 - Dynamic Sinkage and Degree of Slip

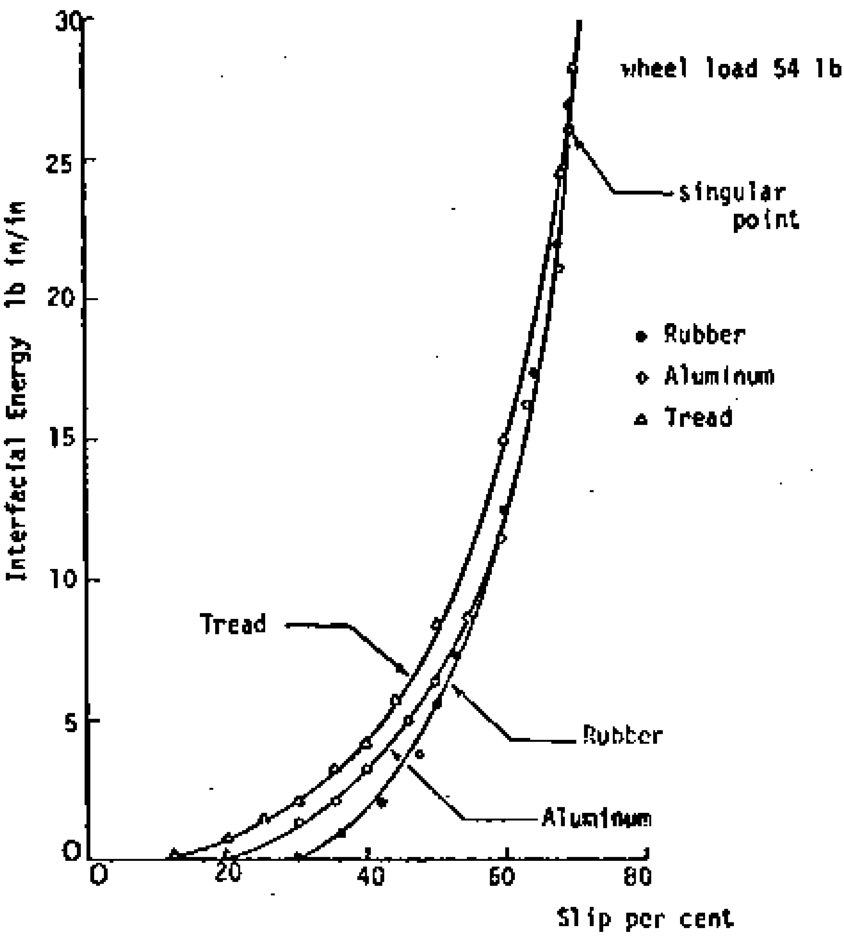

Fig. 8 - Interfacial Energy and Slip

which establishes the single valued relationship between slip rate and interfacial energy is seen to be dependent on the factors and parameters associated with loading surface and subsoil.

Energy-slip Curves

In Fig. 9 the energy-slip curves under one wheel load for the three specific contact surfaces are given. The differences noted between the curves relate to changes in surface conditions. It is pertinent to observe that the characteristic performance of any wheel can be identified by three points on the energy-slip curve. These are identified as zero slip [condition], selfpropelled and maximum drawbar-pull points. The negative value of the drawbar-pull at the zero slip towed point is a measure of the rolling resistance of the wheel. Tests show that this value increases with increasing wheel load, and can be envisaged as being directly related to the resultant increasing value of dynamic sinkage. Whilst the negative drawbar-pull results at zero slip for the tests shown in Fig. 9 appear to demonstrate insensitivity to wheel contact surface, test results indicate that this is fortuitous. Intuitively, one would expect that contact surface characteristics would influence rolling resistance. This has been substantiated by Yong and Fattah (1975).

Taking the self-propelled point as the point on the energy slip diagram where the drawbar-pull is equal to zero, it is seen that this point is a property of the powered wheel. It is apparent that in order to develop sufficient traction to maintain the wheel in motion at this point, the circumferential wheel velocity should be larger than its translational velocity, i.e. the slip at this point always has a positive value. As seen from Fig. 9, this is obviously a function of wheel load and contact surface characteristic. The degree of slip at the self-propelled point decreases with increasing roughness of the wheel. The justification for characterizing the rubber surface as smoother than the aluminum surface may be established as:

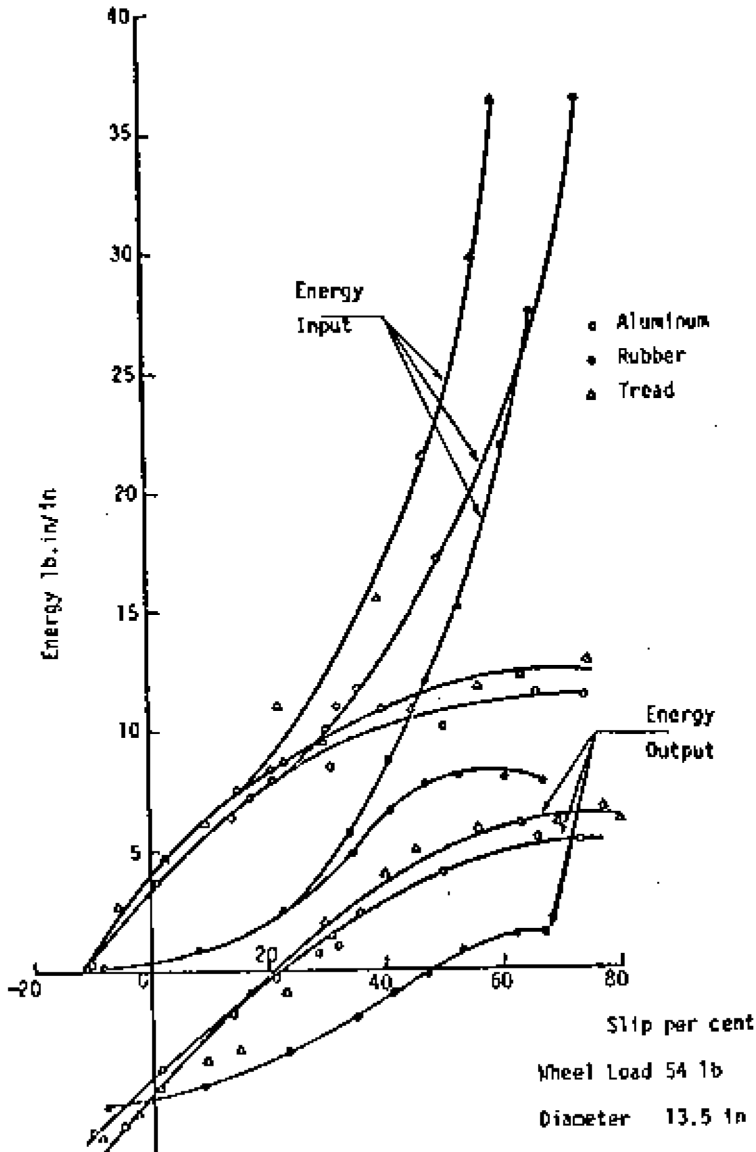

Fig. 9 - Energy Balance for Rigid Wheel

1] the supporting results shown in Fig. 8, and

2] the clay-rubber interface adhesion is smaller - probably due to the less than smooth nature of the rubber and the smaller clay-rubber cohesion value.

The maximum drawbar pull for all the tests appear to occur at high degree of slip - generally around 65 to 75 per cent. The test results indicate that the drawbar-pull increases by increasing the roughness of the wheel surface - with a corresponding increase in required input energy. It is interesting to note that at high slips, a thin clay layer appears to coat the surface of the wheel and thus it is expected that the tangential stresses developed would be between the clay layers, i.e. at high slips, there would be little effect of wheel contact surface characteristics on the drawbar-pull.

A useful point for examining effectiveness of surface transfer of energy is the establishment of the critical slip point. The critical slip point is defined as the point of maximum [optimum] slip at which the interfacial energy remains sensibly zero. The slip at this point appears to be consistently positive and generally occurs before the self-propelled point. As seen from Fig. 9, the critical slip points for the three types of wheel contact surface are sufficiently different - both in terms of slip and in terms of input energy, when interface energy loss becomes significant. The usefulness of such a critical slip point as a measure of contact surface effectiveness for development of drawbar-pull and interface energy [surface disturbance?] can be seen. However, it is obvious that in view of the limited amount of data available, much remains to be done before a proper characterization of this critical slip point can be obtained. The factors and parameters needed for consideration in the need for characterization would include carcass stiffness, tread configuration, subsoil properties, contact area and pressure, etc. The advantages to be gained in establishing the critical slip point relate to

a] development of drawbar-pull in view of wheel and tire constraints, and

b] present awareness and conscious need for minimization of surface disturbance in off-road mobility; - the reduction of interface energy loss is seen to be directly linked to the reduction in surface disturbance.

SUMMARY AND CONCLUSIONS

The results in Fig. 9 also show that the amount of input energy that can be developed for production of drawbar pull, is intimately tied into the properties of the contacting bodies - wheel and soil surfaces. The smoother surfaces would apparently restrict energy input because of the high slip loss at the interface. With increased intimate relationships at the interface, the amount of energy lost at the interface increases and thus the input energy that can be developed becomes correspondingly larger. With a constant subsoil condition, it is apparent that drawbar-pull can be increased thereby - as noted from Fig. 9 in the aluminum and tread wheels.

The statements relative to input energy development perhaps should be further explained - in terms of interdependencies. Whilst it may not be immediately obvious, input energy is not a quantity that can be specified as an independent, known and predetermined quantity. Its inter-relationship in terms of wheel-soil interaction is established as a function of available interface and subsoil response properties. Thus for example, given similar subsoil response characteristics but totally dissimilar surface layer properties - e.g. dry as opposed to slippery surfaces, it is evident that both resultant maximum drawbar-pull and input energy required to achieve maximum drawbar-pull will be changed.

The examination of wheel performance in terms of interface performance - established through contacting surfaces, and through knowledge of development of the two component parasitic energies provides for an appreciation of the amount of control exercised in the surface layer of the subsoil vis-a-vis wheel contact surface and load. With application of energy transfer relationships, resultant subsoil performance can also be evaluated - to show the effective performance or contribution from wheels and their surfaces.

ACKNOWLEDGMENTS

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5th Int. Conf. International Society for Terrain-Vehicle Systems, Detroit, U.S.A. June 1975.

VANE-CONE MEASUREMENTS FOR ASSESSMENT OF TRACTIVE PERFORMANCE IN WHEEL-SOIL INTERACTION

by

R. N. Yong*, A. F. Youssef** and E. A. Fattah***

INTRODUCTION

The problem of assessment of tractive performance in wheel-soil interaction can be examined in terms of soil response and associated strength parameters at the critical near-surface region - especially in view of the slip between wheel and soil surface. In situations where actual physical slip is large or excessive, it becomes necessary to distinguish wheel immobilization as a result of flotation instability developed through disturbance and strength loss in the surface layer because of high slip performance. This type of immobilization which can be identified as slip-support immobilization is not uncommon in situations where excessive surface wetting of the ground occurs thus providing for slippery and soft surface layers. Because the subsoil beneath the surface layer may not be affected, it is necessary to identify surface layer immobilization as a phenomenon separate from instability immobilization which occurs through lack of flotation as a direct result of poor and insufficient overall bearing support - identified as sinkage immobilization. This latter kind of performance characteristic is in essence insensitive to slip simply because when sinkage immobilization occurs, surface layer immobilization through

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excessive slip is non-existent because physical forward movement of the wheel becomes impossible.

In previous studies [e.g. Yong (1973)] it has been well-established that energy transfer from surficial wheel loading is dissipated through interface slip and subsoil distortion and deformation. The associated parasitic energy components have been identified as slip energy and deformation energy losses. Intuitively, one might expect that the operative shear strength parameters in the surface layer wherein slip energy loss occurs will be different from those in the subsoil because of the manner of surface layer distortion under high slip. Thus, in view of the need for assessment and proper analysis of tractive capability of moving wheels where slip is a relevant consideration, it is apparent that appropriate accounting for separate soil response behaviour be given. This study is concerned with the use of a vane shear device in combination with a cone which is intended to provide simple strength data input for analyses which recognizes the need for separation of excessive surface layer distortion [mechanisms] due to slip, and subsoil deformation/distortion performance due to surface loading. By evaluating the soil response to slip-shear distortion using a vane shear type of test, and by obtaining the bearing capability of the subsoil through knowledge of the deformation resistance of the soil [from a cone penetration type of performance], the two kinds of mechanism contributing to wheel-soil interaction are suitably accounted for. With linear superposition, it is hoped that initial prediction of drawbar pull might be available - so long as the forces and parameters involved in the two mechanisms are properly identified.

SUBSOIL DEFORMATION/DISTORTION PERFORMANCE AND ASSESSMENT

Figure 1 shows input energy and both predicted and measured drawbar pull results illustrating the fact that a proper separation of energy transfer mechanisms can be successfully made - as shown

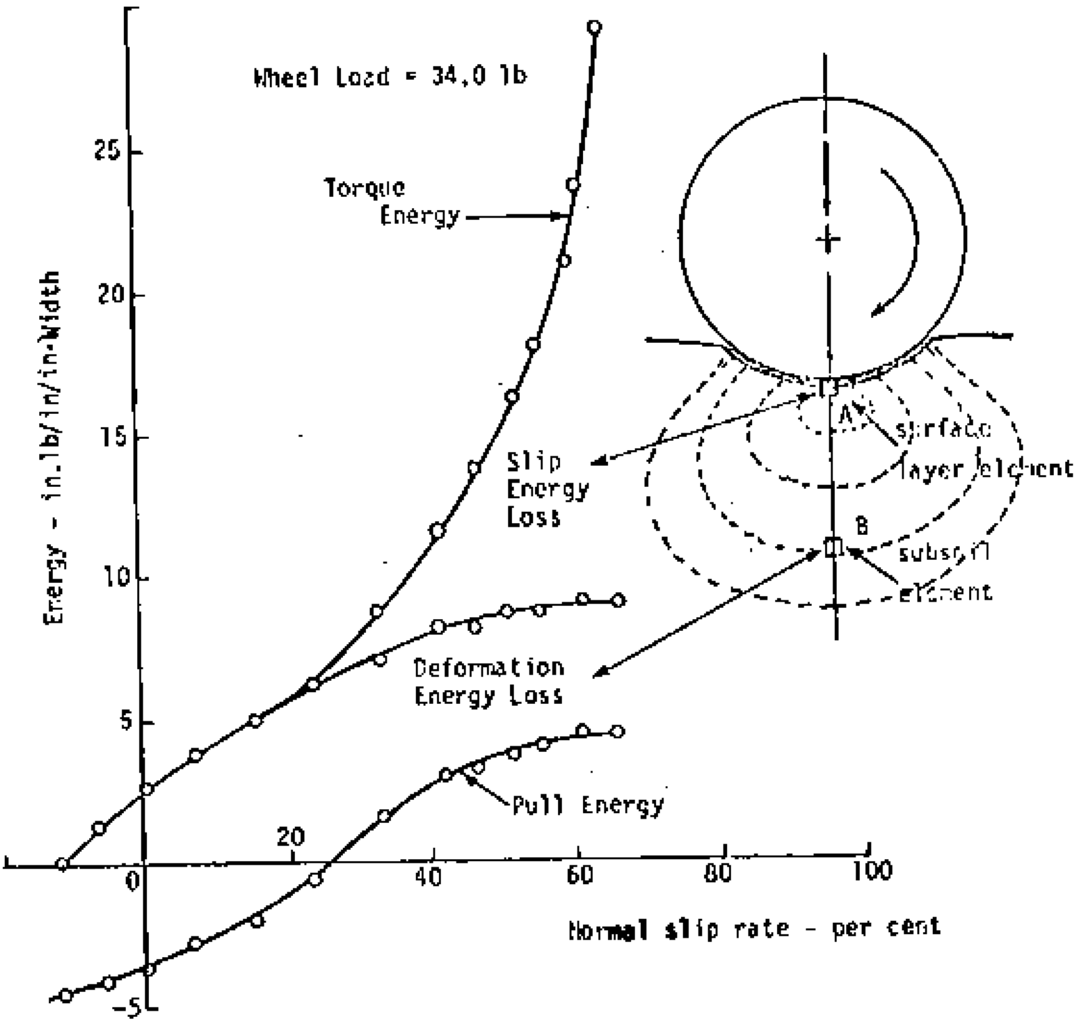

Fig. 1 -- Energy Dissipation in Production of Drawbar Pull

Note that the parasitic energy components are identified as slip energy and deformation energy.

previously by Yong and Webb (1969). As noted in the Figure, the slip energy loss occurs as a result of interface slip between wheel surface and soil. The deformation energy loss component occurs in the subsoil [supporting] region.

For measurement of the deformation characteristics of the soil - leading to evaluation of deformation energy relationships, it is apparent that some form of compression resistance test would be necessary. In view of widespread usage and as demonstrated previously, the cone penetration device serves to provide a measure of resistance of subsoil to deformation forces. The application of such a device for provision of relevant strength data input must recognize

(a) the dissimilar distortive mechanisms applied to the subsoil between cone and wheel, and

(b) the different boundary conditions [both physical and mathematical] between cone and wheel.

The above notwithstanding, it is apparent that for correlations between interpreted data from cone measurements and wheel performance to be realized, the concept of <u>subsoil deformation energy equivalence</u> needs to be applied. This concept states that in the case of two dissimilar kinds of distortive and deformation mechanisms [i.e. cone and wheel], since the specific resultant energy dissipation in the reactive medium [i.e. subsoil] for each applied action is a scalar quantity, comparisons on the basis of equivalent energy dissipation between the two can be performed. It is understood that actual physical modelling of like situations is not necessarily accomplished. Thus, insofar as predictive capability is concerned, the ideal requirements for correspondence between physical and mathematical modelling must still be met.

Recognizing the above concerns, it is apparent that applicability of results from cone measurements to wheel performance can best be achieved when slip energy loss is insignificant. From Fig. 1, we observe that one could use the cone data to compare equivalence in deformation energies for the wheel up to the selfpropelled point.

Subsoil Deformation Energy Loss from Wheel Loading

To provide the basis for comparisons, rigid wheel tests were performed in the laboratory - using flash X-ray recording and standard soil bin experimental techniques previously described by Windisch and Yong (1970).

The analytical method used for calculation of the total energy of deformation in the subsoil has been used by Yong and Fattah (1975) and is similar to that used by Yong and Webb (1969). The coordinate position of representative soil particles under the wheel [and penetrometer] are identified and the measured rates of deformation in the vertical and horizontal direction are used in the analytical treatment as follows.

Since the derivatives of the velocity components with respect to distance are generally small, the Cauchy strain rate tensor [Eq.1] is used in preference to the Lagrangian strain rate tensor, i.e.:

$$\dot{\epsilon}_{ij} = \frac{1}{2}\left[\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right] \qquad (1)$$

Writing Eq.(1) in an unabridged notation, the strain rates can be expressed as:

$$\dot{\epsilon}_{xx} = \frac{\partial u}{\partial x}$$

$$\dot{\epsilon}_{yy} = \frac{\partial v}{\partial y} \qquad (2)$$

$$\dot{\epsilon}_{xy} = \frac{1}{2}\left[\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right]$$

where

u and v = displacements in the x and y directions respectively

$\dot{\epsilon}$ = strain rate

Invoking the Levy-Mises incremental theory of plastic flow written in terms of the strain invariant, we obtain:

$$\dot{\epsilon}_{xx} = \frac{1}{k}\cdot\sqrt{I_2}\,\sigma'_x$$

$$\dot{\epsilon}_{yy} = \frac{1}{k}\cdot\sqrt{I_2}\,\sigma'_y \qquad (3)$$

$$\dot{\epsilon}_{xy} = \frac{2}{k}\cdot\sqrt{I_2}\,\tau_{xy}$$

where

$k^2 = J_2$ = second invariant of the deviatoric stress tensor

k = shear strength in simple shear

σ = stress

I_2 = second invariant of strain rate tensor

$= \frac{1}{2}\left[\dot{\epsilon}^2_{xx} + \dot{\epsilon}^2_{yy}\right] + \frac{1}{4}\left[\dot{\epsilon}^2_{xy}\right]$ in plane strain and the primed stress values denote deviatoric components

Since the rate at which plastic work is done in plane strain $\dot{W}$ [that is, the power of deformation in plane strain] may be expressed as:

$$\dot{W} = \sigma'_x\,\dot{\epsilon}_{xx} + \sigma'_y\,\dot{\epsilon}_{yy} + \tau_{xy}\dot{\epsilon}_{xy} \qquad (4)$$

Where the primed stress values again denote deviatoric stress components, one can obtain:

$$\dot{W} = \left[\sigma_x'^2 \sqrt{I_2} + \sigma_y'^2 \sqrt{I_2} + 2\tau_{xy}^2 \sqrt{I_2}\right] \cdot \frac{1}{k}$$

$$= \frac{\sqrt{I_2}}{k}\left[\sigma_x'^2 + \sigma_y'^2 + 2\tau_{xy}\right]$$

$$= 2\,\frac{\sqrt{I_2}}{k} \cdot J_2 = 2k\,\sqrt{I_2} \qquad (5)$$

Thus, the total work done, and hence the energy dissipated in accomplishing plastic deformation in the subsoil due to movement [on the surface] of the wheel deformation, is found to be:

$$\dot{D} = 2\,b \int_{t_1}^{t_2} \int_{x_1}^{x_2} \int_{y_1}^{y_2} k\sqrt{I_2}\, d_x\, d_y\, d_t \qquad (6)$$

where

$\dot{D}$ = rate of deformation energy dissipation per unit of wheel width.

Applying the above for analysis of wheel experiments, we note from Table I the normal slip rate at the selfpropelled point [obtained from graphical representation as in Fig. 1] and the specific deformation energy loss expressed in unit width of wheel. The specific deformation energy at the selfpropelled point for the representative test results for the larger wheel given in Table I can be examined in relation to the dynamic sinkage - as shown in Fig. 2. It is observed that a linear relationship is obtained - through the origin of axes. This confirms the validity of test measurements and analytical treatment.

VANE-CONE PENETRATION AND SUBSOIL DEFORMATION

Figure 3 shows the combined vane shear device and cone penetrometer - identified as a vane-cone device. With simple insertion into the ground, the device is meant to act as a cone. With rotation

TABLE I

Normal Slip Rate and Deformation Energy Loss at Self Propelled Point

Wheel Diameter in.	Wheel Width in.	Vertical Load lb.	Normal Slip Rate %	Specific Deformation Energy Loss in.lb/in/in.Width
13.5	3.75	79	35.0	12.0
13.5	3.75	51	23.9	7.20
13.5	3.75	34	16.0	3.36
9.0	2.50	23.5	27.7	7.22

TABLE II

Vane-Cone (30°) Depth of Penetration Required to Predict Deformation Energy Loss at the Self Propelled Point

Wheel Load lb.	Wheel Diameter in.	Self Propelled Slip Rate %	Specific Deformation Energy Loss in/lb/in/in.Width	Depth of Tip Penetration in.
79	13.5	35.0	12.00	4.403
51	13.5	23.9	7.20	3.380
34	13.5	16.0	3.36	2.69
23.5	9.0	27.7	7.29	3.380

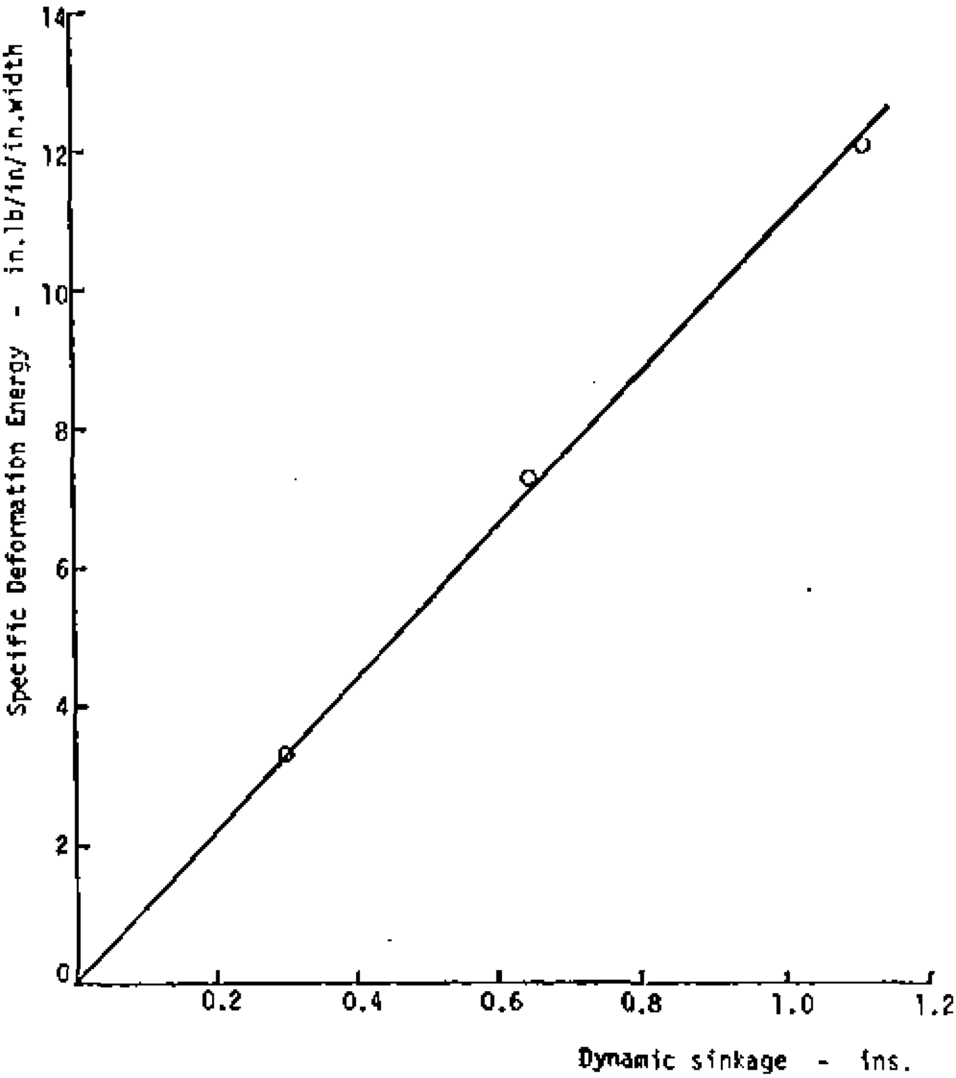

Fig. 2 - Variation of Specific Deformation Energy with Dynamic Sinkage for a Rigid Wheel at the Self Propelled Point

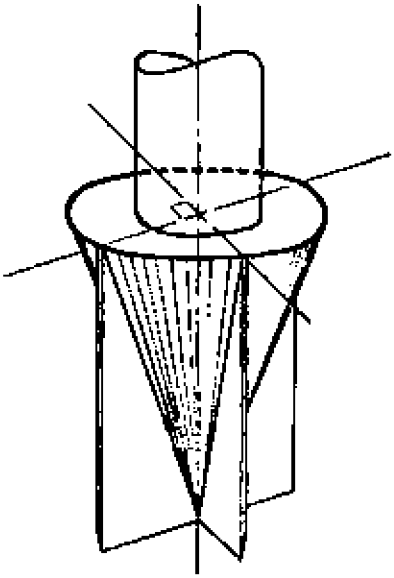

Fig. 3a - Vane-Cone Device

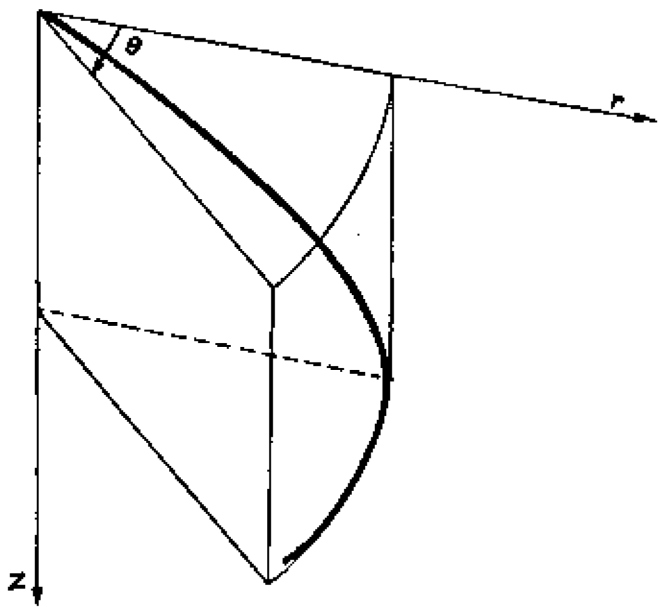

Fig. 3b - Typical Particle Path for Soil Element - resulting from initial penetration followed by subsequent rotational shear.

of the vane at any particular depth, the vane shear strength of the sub-soil can be determined. By rotating the vane-cone device at high speeds, a measure of soil resistance similar to that in slip performance can be obtained. The trace movement of a representative soil element due to initial penetration of the device followed by subsequent rotational shear is also shown in the Figure. The penetration results from a typical cone and the vane-cone device have been interpreted in terms of dissipative energy using Eq. (6) and are shown in Fig. 4 in relation to depth of penetration. It is observed that as penetration depth increases, there is no difference in penetration readings between the two. In actual fact, both tools give almost identical results.

The depth equivalence for cone and vane-cone penetration to realize the corresponding specific deformation energy loss due to the wheel loading tests shown in Table I is given in Table II. The results obtained from cross plotting for dynamic sinkage y_0 and tip penetration may be seen in Fig. 5. The linear relationship obtained is given as:

$$d = my_0 + k \tag{7}$$

where

d = depth of tip penetration

y_0 = dynamic sinkage

m = phenomenological coefficient depending on the tip angle

k = constant depending on the vane-cone penetrometer height [approximately equal 0.7 of total height]

In this case m and k are obtained as 2.08 and 2.0 respectively.

It is obvious that the relationships obtained pertain to the particular sets of constraints set in the experimental programme [i.e. soft clay, and rigid model wheels] and that application to field performance remains to be investigated. It is expected that the general class of relationships shown in Figs. 4 and 5 should prevail in appli-

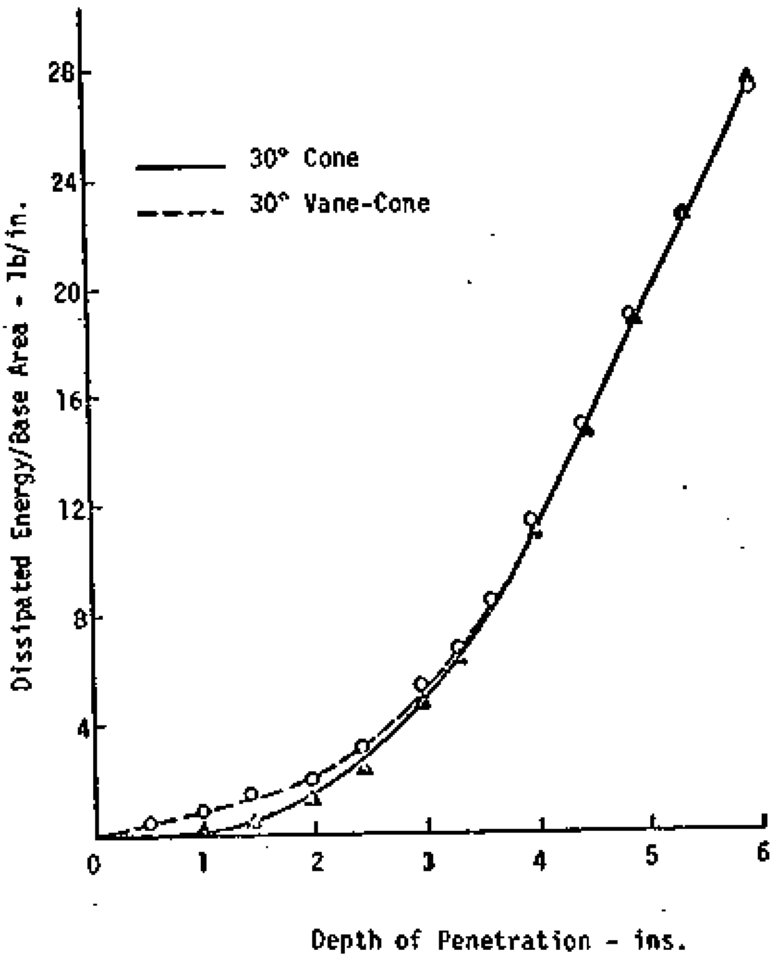

Fig. 4 - Dissipated Energy per Unit of Base Area vs. Depth of Penetration for 30° Cone and Vane-Cone Penetrometers

cation to other tests.

For conditions where slip performance becomes significant - e.g. above the selfpropelled point, it is apparent that additional accounting for energy dissipation at the interface must be available. In essence, the slip energy loss component must be incorporated into analyses of total energy dissipation from wheel energy input as seen in Fig. 1. The use of the vane component of the vane-cone device can now be considered at this stage for evaluation of slip energy loss contributing to the total energy loss.

INTERFACIAL SLIP AND ENERGY DISSIPATION

From geotechnical engineering tests and previous experience, it is not unreasonable to expect that a vane shear device would be most appropriate for assessment of energy lost in the surface layer due to excessive distortion in the layer from wheel slip at the interface - especially if the remoulding effect from high vane shear rotation is utilized. A close similarity in shear distortive effects between wheel and vane slip might be expected in view of the constitutive behaviour of soil.

The vane component of the vane-cone device shown in Fig. 3 is designed to be used to provide for soil response performance characteristics of high shear distortion in the subsoil or surface layer. Vane shear test measurements using conventional vanes and the vane-cone device on laboratory prepared soil in relation to tangential velocities [at outer edge of the vanes] are shown in Fig. 6. We note that both the effects of remoulding and rotational speed [reflected in terms of tangential velocities] are shown. It is apparent that the differences in shear stress between conventional vanes and the device are relatively small, and that at higher rotational speeds the differences become insignificant - as can be expected. As noted from

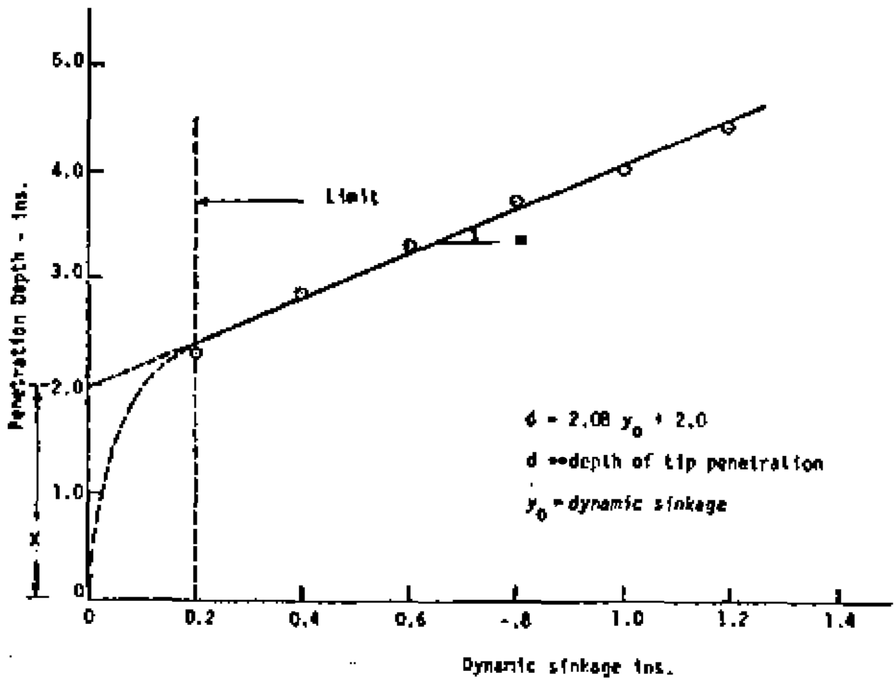

Fig. 5 - Dynamic Sinkage vs. Penetration Depth at the Self Propelled Point

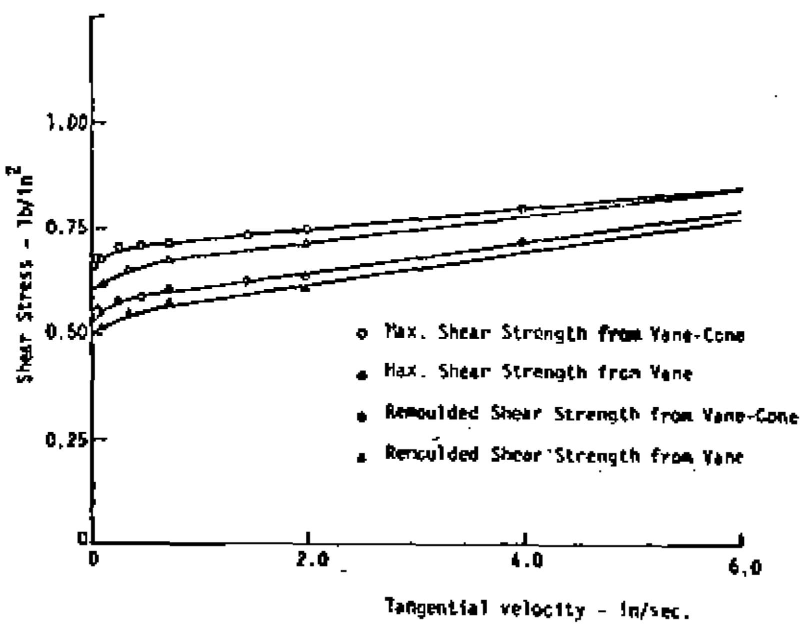

Fig. 6 - Shear Strengths obtained from Vane-Cone and Vane Devices vs. Tangential Velocity

the results, the shear stress values asymptote at high rotational speeds. The asymptotic shear stress value τ_{max} can be taken from Fig. 6 and may be considered as the operative stress value acting in the surface layer where high shear distortion due to wheel slip occurs.

Computation of slip energy loss $\dot{S}$ can now proceed according to:

$$\dot{S} = \int_{Area} \tau_{max} V_s dA \qquad (8)$$

where

V_s = elemental slip velocity = $r\omega - V_{soil}$

dA = differential area of interface contact

r = radius of wheel

ω = angular velocity of wheel

V_{soil} = elemental soil velocity

Taking values for τ_{max}v-c and applying to Eq. (8), one obtains the predicted soil-soil slip shear curve shown in Fig. 7. It is stressed that the predicted curve represents shear resistance between soil and soil which may not necessarily occur throughout in a wheel-soil interface slip situation. At the actual interface, slip occurs between soil and wheel surface material. Thus the operative shear strength is $\tau_{w/s}$ - i.e. shear stress between wheel and soil. However, at a very small distance away from the wheel surface, slip occurs between soil and soil in the highly disturbed surface layer. Thus, τ_{max} becomes the operative shear strength beyond the first contact region.

We note the close correspondence in Fig. 7 between the predicted [calculated] interfacial slip using the value of τ_{max} from

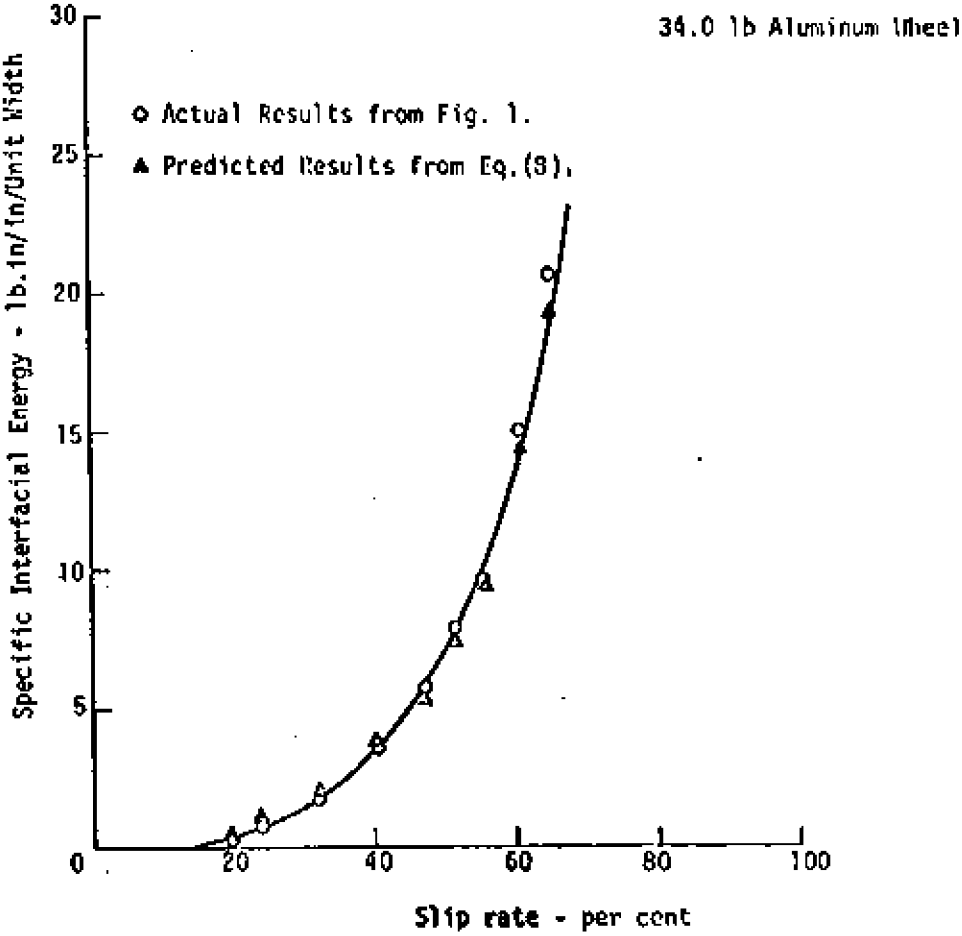

Fig. 7 - Actual and Predicted Specific Interfacial Energy vs. Slip Rate

Fig. 6 and Eq. (8), and the experimental values as obtained from Fig. 1 [slip energy loss]. It is recalled that the measured slip energy values are obtained by subtracting deformation energy [computed as in Yong and Webb (1969)] and measured drawbar pull from measured input energy. Thus, the close agreement shown in Fig. 7 indicates validity of vane shear strength input.

By taking the predicted results as shown in Fig. 7 and combining with the computed specific deformation energy [also using the vane-cone device], the drawbar pull curve shown in Fig. 8 can be obtained - with knowledge of the input energy. The close agreement between predicted and measured values, shown by superposing predicted results of slip energy loss from vane measurements using the vane-cone, plus deformation energy losses using again the same tool, demonstrates the potential usefulness of the tool. The philosophy which requires recognition of the two energy loss components thus appears to be correct.

SUMMARY

It is evident that for simple prediction of drawbar pull from soil testing, both compression and slip shear behaviour must be evaluated. This study represents an attempt at an initial appraisal through simple testing with a view to obtaining a direct knowledge of the properties of the soil in the near surface region. The vane shear device tested in this study is used to provide for an assessment of the operative shear strength in terms of compression behaviour in the subsoil through application of the cone concept, and the slip shear performance characteristics in the surface layer through use of the rotating aspects of the vane.

The inference of slip generation in the surface layer region is seen to be correlated in terms of the effective stress parameter which is developed in terms of strain rate dependence. As shown, with knowledge of the component which accounts for flotation given in terms

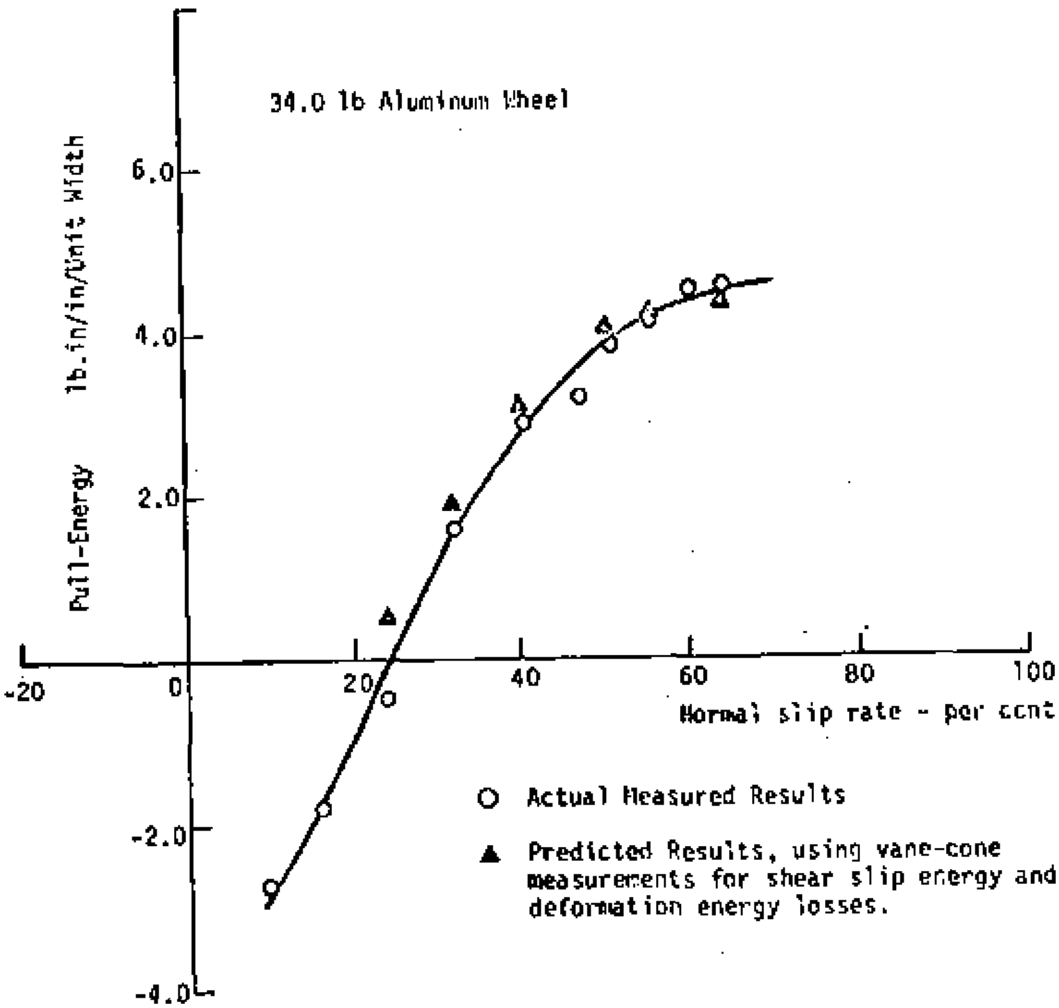

Fig. 8 - Actual and Predicted Drawbar Pull for 34.0 lb Wheel Loads and 13.5 in. Diameter

of bearing support, and with direct compression deformation correlation to cone penetration measurements, an assessment of drawbar pull performance can be obtained. The combination of the vane and cone measurements, through the use of a combined device which includes both these features, provides for a realistic means for assessment of tractive performance in wheel-soil interaction in view of the approach to modelling wheel-soil action. The specific relations developed which provide for correlations between the analyses generated from the vane-cone measurements, and actual performance characteristics,can be noted in terms of the results shown in Figs. 7 and 8 and in terms of soil and wheel characteristics, and now remain to be further investigated for application to other soil conditions and field situations.

ACKNOWLEDGMENTS

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CONSIDERATIONS IN VEHICLE-GROUND INTERACTION IN OFF-ROAD MOBILITY IN THE CANADIAN NORTH

by

R. N. Yong* and P. V. Janiga**

INTRODUCTION

In view of the need for operating in the northern regions of Canada - for purposes of development of resources and maintenance of communication, transportation and habitation, it is necessary to provide the wherewithal which ensures that the quality of the environment is both preserved and protected. Since both air transport and overground transport constitute the primary means of achieving portability of goods, etc. and since the present attention is focussed on overground transport, it then becomes necessary to provide a "protective" or "sympathetic" grouser/track or wheel system for overland vehicles for operation on snow covered surfaces and on soft ground which would -

1] Ensure zero or minimal surface cover disturbance for maintenance of original surficial environmental quality.

2] Produce productive drawbar pull whilst fulfilling [1].

3] Produce good "flotation" qualities in addition to fulfilment of points [1] and [2].

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INITIAL CONSIDERATIONS

Because of its size and continental position Canada experiences a wide spectrum of climates, i.e. from maritime, through continental, alpine to the arctic, which are in turn superimposed on a similarly varied physiography.

In view of this variation it is useful to recognize also the characteristic common to this country: in that its political boundary with the U.S. is also the approximate limit of northern cold regions. These are characterized by low temperatures and snowfall throughout part of the year, resulting in a variable snow cover duration. In general, the duration of snow cover increases with latitude and altitude. It can be said that in Canada [excluding some of the coastal and southernmost regions] snow covers the ground at least four months of the year. The variation of ground snow cover during and subsequent to formation and deposition is beyond classification with respect to vehicle mobility. We note for example some of the factors affecting the properties and characteristics of ground snow cover:

1] the nature and form of precipitated crystals,
2] the extent of crystal formation during precipitation,
3] changes in the snow cover with time, temperature and humidity,
4] changes in the snow cover due to solar radiation,
5] nature and quantity of foreign matter in the snow,
6] anisotropism due to deposition, and
7] wind forces.

Whilst the above factors may tend to create pessimism in regard to the needed detailed knowledge for characterizing and assessing snow performance, experience has shown that it is necessary <u>but not sufficient</u> to distinguish the following snow characteristics with respect to over-snow vehicle performance evaluation:

1] shallow from deep snows,

2] low density from high density snows,

3] wet from dry snows, and

4] new from old snows.

In addition to snow cover and properties, it becomes necessary to take into consideration the nature of ground surface cover - other than snow. The limited plant growth period in northern temperate and subarctic regions requires that particular attention be paid to sustaining available plant growth - as an integral part of the surface environment. Thus, when traction devices are imposed on ground surfaces, care must be exercised to ensure that these devices do not destroy the plant growth or surface cover.

Surface cover is important in:

a] ecological considerations [i.e. in establishment of the natural inter-relationships between specific organisms and their surficial environment], and

b] in natural control of the micro-meteorological inter-relationships at the interface which in turn impact on the subsurface thermal regime [i.e. geothermal profile].

ENERGY TRANSFER AT THE INTERFACE

Considerations arising from the evaluation or assessment of vehicle impact on the surficial environment require that the design parameters be defined in relation to not only useful work output requirements, but also in relation to the immediate environment. In addition, it is necessary to examine their influence and variability vis-a-vis distribution and availability for design characterization.

Just as the snow cover is a characteristic of the cold northern region, the tracked vehicle is characteristic of conventional over snow transport. Such being the case, by and large, considerations in vehicle snow interaction will be limited to the track-snow interaction and grouser design.

Perhaps the most expedient way to obtain an appreciation of snow behaviour and for the purpose of obtaining the consequent design parameters is to compare observations of snow and soil behaviour under various loadings.

In general:

1] The $\frac{DBP}{W}$ versus slip curves for snow exhibit a lower maximum than those for soils. [This is obvious from an immediate recognition of the "strength" of snow]

2] the maximum $\frac{DBP}{W}$ is attained at a higher slip in snow than in soils. This is probably due to its compressibility and its typical collapse behaviour,

3] because the unit weight of fresh snow is about one order of magnitude smaller than that of soils, sinkage will be greater and, it is obvious that the material will be more susceptible to the effect of normal pressures,

4] because of the obvious anisotropy in snow, DBP versus slip curves shows a much wider data scatter, thus making deterministic types of interpretations difficult,

5] as opposed to soils, snows are highly time and temperature dependent in regard to performance characterization. For example, it is possible to identify

- equi-temperature metamorphism, where fabric changes will result in a re-ordering of the snow grains with growth of inter-granular bonds. As a consequence, strength will increase with time.
- temperature gradient metamorphism, where because of their position in the snow cover, some grains grow at the expense of others with the consequent loss of strength in the snow cover.
- generally, temperature tends to accelerate or attenuate the speed of the above mechanisms depending on whether it is close to 0° C or well below.

6] the dynamic response behaviour of snow is dependent on the speed of loading in a fashion opposite to that of soils. This behaviour is also coupled to the snow's time and temperature dependency for strength development,

7] the strength of snow under pure shear is nearly equal to its tensile strength,

8] snow possesses a critical unit weight $\sim$ 0.45 g/cc above which it does not apparently present a trafficability problem from the viewpoint of flotation, 9] the property of sliding friction [of snow] does not conform to the expectations expressed by Coulomb's Law in that the coefficient of friction decreases with normal load, decreases with sliding speed, increases with decreasing temperature; increases with decreasing particle size, and is highly dependent on the interface material.

10] adhesion of snow is time and temperature dependent.

To establish the characteristics of energy distribution into the ground - from torque input or load application, we examine the problem of mobility using the experience gained from wheel studies. From previous publications [Yong et al. (1972) and Yong (1973)], it has been shown that the input energy provided by a wheel for production of forward motion is dissipated in two forms - i.e. interfacial energy and deformation energy losses. These parasitic energy losses are shown in Fig. 1.

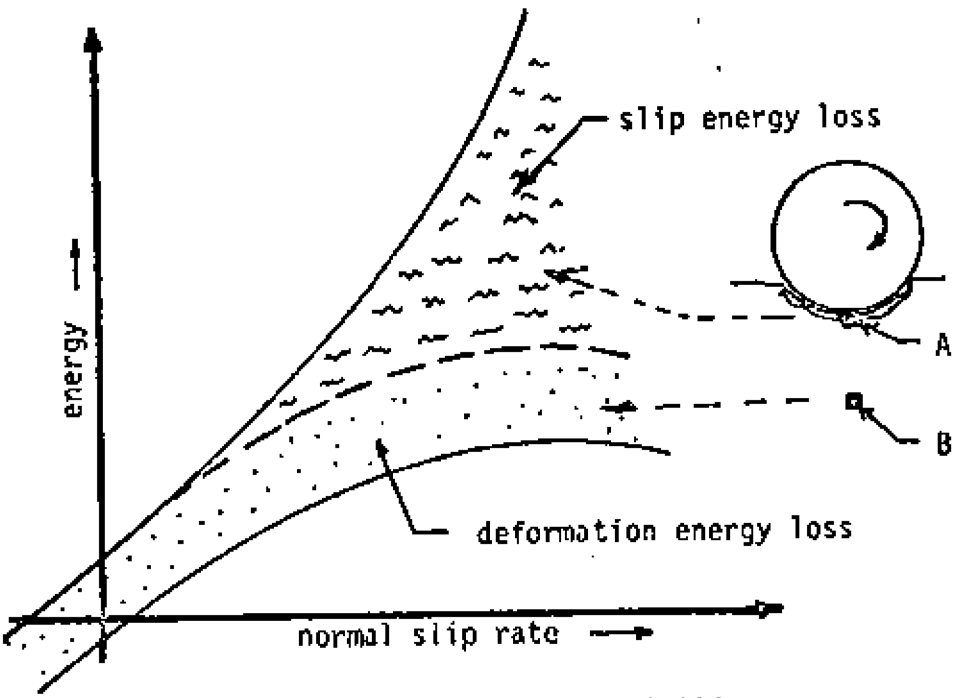
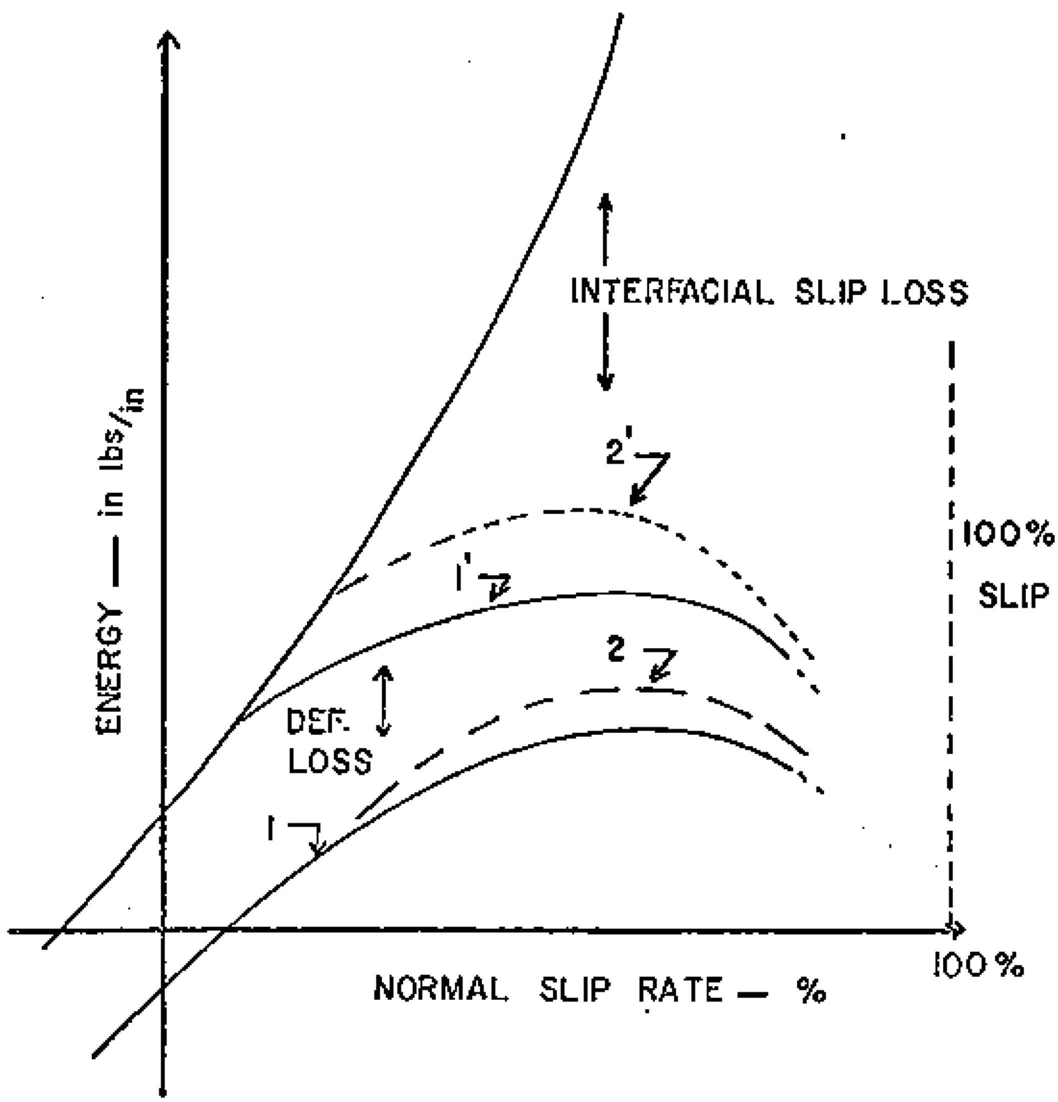


FIGURE 1 - COMPONENTS OF PARASITIC ENERGY



1 — D B P FOR SMOOTH CONTACT

1' — INTERFACIAL SLIP LOSS BOUNDARY FOR SMOOTH WHEEL

2 — D B P FOR ROUGH CONTACT

2' — INTERFACIAL SLIP LOSS BOUNDARY FOR ROUGH CONTACT

FIG. 2 — CONTACT SURFACE INFLUENCE

From Harwood and Yong
"Northland Vehicle Considerations"
Proc. Canadian Northern Pipeline
Research Conference, February 1972

The balance of energy obtained by subtracting the parasitic energy from the input energy provides the useful work done - expressed as drawbar pull. We note that if an aggressive contact system is used, more interfacial slip energy loss can be generated if energy transfer through deformation forces is not effectively achieved. Whilst this in turn would result in production of a resultant lower drawbar pull, the net effect on the surface cover is considerable alteration of the contact region because of the presence of high slip shear forces. On the other hand, if the tread design and wheel load parameters are effective in achieving maximum transfer of energy into the substrate, the curves shown in Fig. 2 will be obtained.

In a track/grouser system, a similar characteristic of energy dissipation is obtained. The values, however, will differ because of the mechanism for energy transfer. The limit equilibrium model for an angle grouser working in soil in Fig. 3 illustrates that a higher degree of surface disturbance is generated if similar slips [to wheel loading] are allowed. We observe that in a grouser-snow

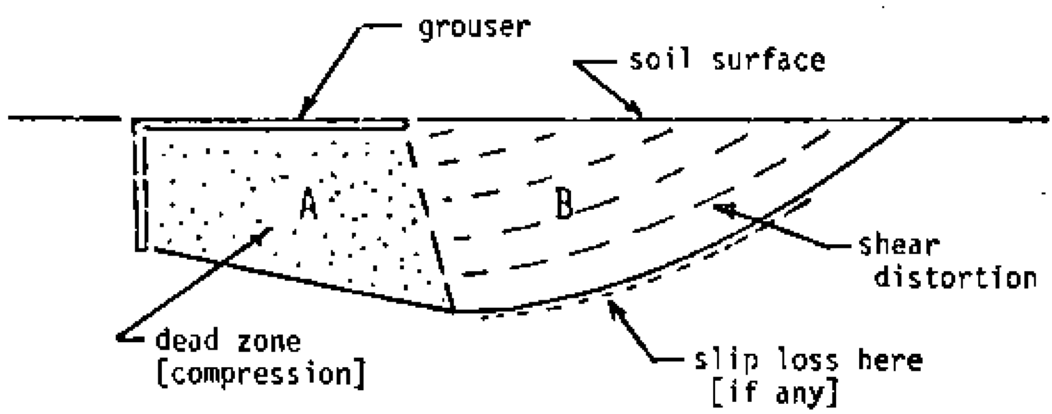


FIGURE 3 - GROUSER-SOIL INTERACTION

interaction problem, the zone identified as A undergoes much distortion [contrary to the grouser-soil model], whilst zone B remains relatively 'secure'. Volume changes in zone A are large, whilst volume changes in zone B are almost zero.

The ideal and proper mechanism for generating maximum drawbar pull [from Figs. 1 and 3] would require resultant zero or minimal interfacial energy loss. If this mechanism is achieved, the side benefit of surface environment protection is also obtained. For snow covered surfaces, it becomes important and necessary to consider the problem in terms of a layered system, with particular attention being paid to the snow [top layer] and the interface between snow and ground. Since the ground stratum will be frozen [more or less likely so], the energy transfer mechanism achieved at the interface will depend on the snow cover and the track/grouser system. We thus take note of the following points:

1] the high compressibility of snow necessitates that we distinguish two kinds of materials vis-a-vis the track/grouser system; one contributing to the bulldozing resistance and the other providing the reaction for tractive effort. Much also depends on the relative thickness of the snow layer - plus age, etc.,

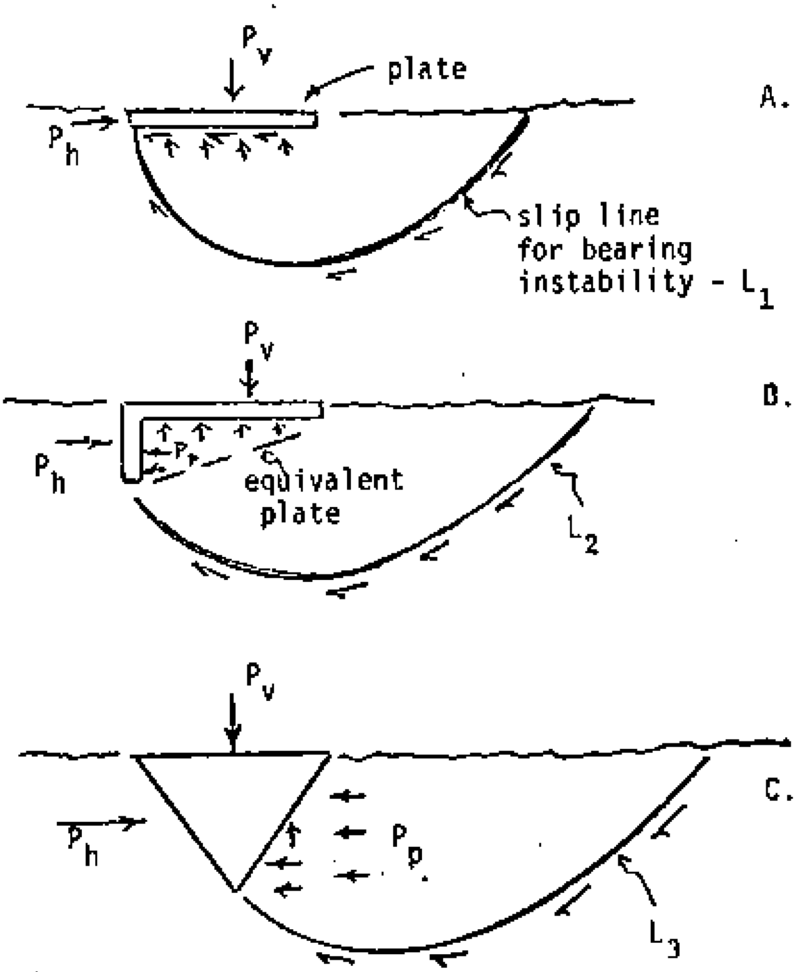
2] the choice of materials making up the track/grouser system is important in that the development of a particular failure mechanism is dependent on the interface boundary conditions.

3] the deformation field under the track and grousers is not only dependent on the stress-strain behaviour of snow but also the rate of deformation and the coupled time and temperature effects. This in turn will influence design decisions on track morphology.

3] in order to formulate a rational grouser configuration consistent with the track system, a manageable failure criterion for the snow layer needs to be formulated and tested. This criterion should span the complete tension and compression behaviour of the snow - particularly over the load-time period.

LIMIT VALUES

Using Fig. 3 as a guide for evaluation of a typical angle grouser system, we note from Fig. 4 the limit configurations for transfer of input energy into the soil [or snow] - and in turn, for generation of resultant thrust.



A. Thrust development through friction and adhesion at the interface, and shear on the slip line when bearing instability threatens.

B. Thrust development through passive pressure development P_p in substrate due to vertical face, and same mechanisms as in A.

C. Thrust development through P_p and friction and adhesion plus shear on the slip line when bearing instability threatens

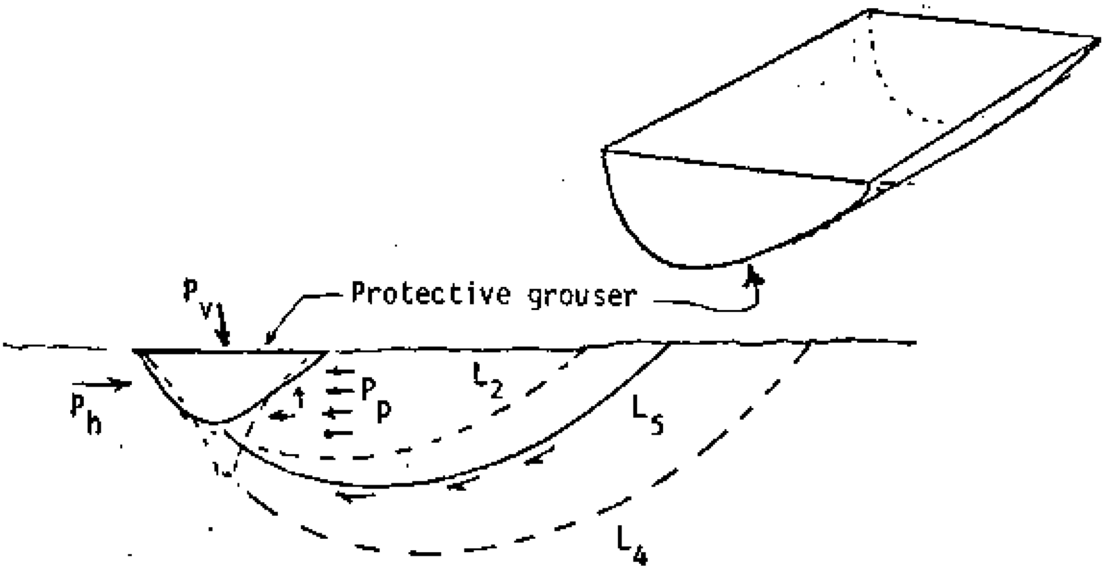
FIG. 4. THRUST DEVELOPMENT FOR SOME GROUSERS

PROTECTIVE GROUSER REQUIREMENTS

It is obvious from the previous discussions that if a track is chosen, the protective grouser system must be so designed so as not to produce excessive slip in the production of drawbar pull. In Fig. 4 the various configurations showing the limit designs for effective grouser transfer of energy into the ground would indicate that if one maintains the downward thrust of the grouser for maximum achievement of deformation energy production, whilst minimizing the surface shear slip effect, a useful protective mechanism can be built up whereby protection of surficial cover can be achieved. The design shown in Fig. 5 serves to fulfil the requirements indicated.

The rationale for choice of the design shown is given in the illustrative sketches in Fig. 5. Ideally, the angle of entry of grouser into the ground should be one where the entry face contacts the ground as a flat plate. Under these circumstances, there is no direct initial shear indentation into the soil. The rounded part of the entry face is meant to transfer the energy as the track "unwinds" and, in addition, does not allow for an exit condition which would be detrimental to the surface cover. Particular attention needs to be paid to the spacing of the grouser system and the entry and exit conditions of the grouser.

In actual production, the spacing of the grouser depends upon the kind of sprocket used. The fundamental principle however, is to provide for a contact between the vehicle through the track system, and ultimately through the grouser for production of forward motion, wherein the transfer of energy is such that if it is through

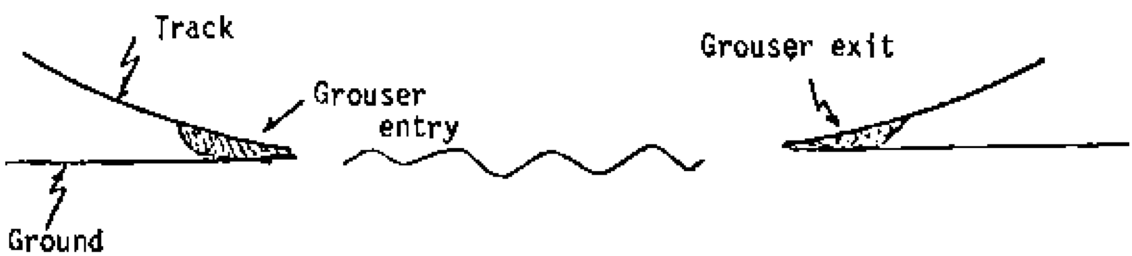


NOTE:

1. Thrust development for protective grouser is derived from passive pressure resistance in the substrate plus shear forces on the slip surface [length L_5] when bearing instability threatens.

2. For comparison, we note that L_5 is less than L_4 but is larger than L_2

3. For threatened bearing instability, the summation of shear forces on the slip line shows that the larger slip line provides for a greater thrust generation.



4. Grouser entry and exit configurations should provide for parallel arrangement with substrate.

FIG. 5 RATIONALE FOR CHOICE OF PROTECTIVE GROUSER snow, alteration and compaction of the snow would not create problems for continued establishment of growth of surface vegetative cover. This presumes that the bearing support of the subgrade will also not deteriorate under tractive and compactive disturbance conditions established by the passage of the over snow vehicle. One would expect that because of winter conditions, sufficient bearing quality exists in the substrate beneath the snow. At times, this may not be exactly true - especially in the marginal periods during thaw where the top part of the soil substrate can exist at slightly above freezing temperatures.

In the period when one encounters soft ground, because of thaw or because of poor overall subgrade quality, it is more than essential that the contact morphology established for the overland vehicle subscribe to both good flotation and minimal surficial disturbance as desirable qualities. The production of a proper track system or an alternate form of vehicle contact is seen to be most essential. In addition to the contact problem, it is understood that all the other items pertaining to the mechanical production of the vehicle, and especially to the operation of the vehicle through the performance should be properly identified and evaluated.

ENVIRONMENTAL IMPLICATIONS

Everything else being equal - and especially so for the human [driver] factor, the direct contact with the surficial environment provides for first consideration in maintenance or protection of surface quality. Recent evidence has shown that surficial scarring can occur in the northern regions of Canada to such an extent that continual thermal erosion due to stripping of the surface cover would result in the production of thermokarsts and other similar features in ice-rich permafrost. It is particularly instructive to note that visible scarring can occur due to trafficability on snow-covered terrain. With limited use of lighter tracked vehicles, it has been observed that no long-lasting disturbances occur - vis-a-vis ground surface scarring. For heavier tracked vehicles, much depends on the season within which mobility is undertaken.

From the preceding discussions on the mechanics of interaction and field experience with existing vehicles it is apparent that the mechanisms involved in vehicle-ground interaction are precisely those which would cause surficial environmental damage if the proper track or contact systems are not available, and if caution is not exercised. The significant factors to be considered in regard to mobility are:

1] disturbance and compaction of snow cover from continual mobility which will alter the thermal cover and aeration characteristics and which in turn could affect the respiratory requirements of certain sensitive plants during their dormant period. In addition, the resultant reduction of radiation through the compacted snow could also produce detrimental effects to these same plants.

2] scouring or scarring of the ground surface, either through levelling off of snow-covered terrain, or through energy transfer through the surface snow cover, thus creating plant damage and subsequent alteration to the local thermal regime,

3] high slip and shear at the ground interface creating excessive ground surface disturbance and damage leading to permanent alteration of local thermal cover,

4] water and/or ice content of soil and drainage characteristics, which in combination with the preceding three factors could create undesirable complexities vis-a-vis resultant instabilities and production of erosion in initially ice-rich slopes.

Mobility objectives for operation in the Canadian north would demand that none of the above factors be tolerated. However, there must exist a certain latitude in tolerance level in factors 1] and 2] for winter operation which could allow for successful economic operation of vehicles in the north in winter or summer. The balance that must be maintained in regard to slip production and ground or snow compression depends not only on the ground cover conditions, but also on the track or other contact morphology and the demands of the vehicle - as an overall consideration for both winter and summer operations. Load transfer characteristics can be changed if the proper contact mechanism and morphology is chosen for distribution of load whilst providing adequate tractive capability. The need for a rational approach to track and wheel requirements is obvious. The problem of economics is undoubtedly important. This must be considered, however, together with and made compatible with, other aspects of the overall problem.

CONCLUDING REMARKS

It is seen that in the operational requirements for vehicles in the Canadian north, that attention should be paid to the protection and preservation of the surface ecology especially in areas where severe subsequent ground deterioration can occur because of changes in the micro-meteorological relationships - leading to changes in the geothermal regime in the substrate. The use of vehicles for the northern regions must consider not only the very cold climatic conditions and operational hazards, but also the immediate surface topography, ground cover, and subsequent life of the environment. With the proper choice of contact morphology, the disturbance to the immediate environment can be reduced immeasurably whilst providing for a proper transport system. The ideal requirements presented herein for a grouser configuration are predicated on the fact that energy transfer from the track of the vehicle [for forward motion] should be confined to the substrate - i.e. energy transfer at the interface which is expended in terms of interface shear stress generation should be minimized.

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