SUPPLEMENTAL INFORMATION
TO
CONCEPT STUDY

DEVELOPMENT CHARACTERISTICS
FOR
TRACKED AMPHIBIAN PERSONNEL AND CARGO CARRIER

BY

HYDRONAUTICS INC.

PREPARED FOR

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HULL FORM STUDY SUPPLEMENT

To inject fresh and knowledgeable ideas into the problem of water performance, the services of Hydronautics, Incorporated, hydrodynamic consultants of Rockville, Maryland, were retained. Their investigations were directed toward reducing the hull resistance, and increasing the propulsive efficiency of propelling means of a generalized, barge-form, track-laying vehicle, with a minimum of restrictive conditions placed on their method of attaining these ends.

Since possible LVT displacement-hull speeds lie in the range of Taylor quotients, $\frac{V}{\sqrt{L}}$, from 1.1 to 1.4, wherein residual resistance due to wave-making is a substantial portion of the whole, this loss received corresponding attention. The modifications proposed, pictured in Figure 1, were tow-tank tested for qualitative effects. When compared with the basic model, the bow change reduced the resistance at 7 MPH by 50%, while the modified 5 foot transom stern alone gave a 25% reduction. Other changes such as the hydrofoil wave-depresser and side blisters indicated incremental reductions of 5% when tested separately, however, the savings were not accumulative.

The ladder of turning foils at the transom was not tested, although a single foil, when tried, proved detrimental in that it increased the drag, the entire character of the wake was changed from stagnant to free-flowing, demonstrating the foil to be a powerful tool worthy of further inquiry. Disregarding the practical aspect of the foil cascade (it would be, of necessity, retractable), its philosophy is interesting. The cascaded passages act as diffusers, reducing the high potential flow velocities to create a thrust which offsets their drag while turning the flow into the stalled region abaft the submerged transom. Essential to this function is the successively reduced angle of incidence of the lower foils.

An independent quantitative tank-model study made at Pacific Car and Foundry Company led to the present hull lines which incorporate the most practical of the above modifications and their correlative advantages.

In summary, the resistance of a hull with extended bow and rounded bottom-transom corner is halved, and added buoyancy is provided forward of the power train weights to correct the trim and reduce nose-diving in the surf. Its frontal armor gains effectiveness from the obliquity. On the debit side, the ability to climb wall-type obstacles may be reduced, although the degree is hard to determine.

WATER PROPULSION

Use of the tracks for water propulsion has so many advantages for LVT's as to virtually preclude other means from consideration. The main disadvantage of its poor efficiency is excessive fuel consumption.

The limiting efficiency of practical screw propulsion is of the order of .5, approximately four times that of a conventional LVT track. Thus, a wide margin for improvement exists encouraging Hydronautics to make a mathematical analysis of track propulsion. The enclosed report reveals the inherent character of a submerged-return track that agrees with practical tests to a remarkable degree in view of the single assumptions made for the derivation.

The first modification to this basic concept assumes that the drag coefficient of the return track is reduced to .5 of that of the lower track. In a very practical manner, this same effect is obtained by shrouding the return track paddles, restricting flow at the sprocket and return wheel by the close approach of the sponson, and recovery of energy from entrained water by hydrovanes. This is accomplished by fixed elements compatible with the land-going requirements. The complication of additional mechanisms (retracting shrouds, venting pumps, etc.) necessary to the more efficient means proposed, is judged incompatible with simplicity in a vehicle waterborne only 20% of its useful life.

The potential of the return track as the pumping element of a jet propulsion system can only be realized by development of an efficient diffuser within the sponson-return track space or close-coupling the track paddles to the hydrovanes. The value of this system warrants prompt investigation.

HYDRONAUTICS, INCORPORATED

TECHNICAL REPORT 236-1

PERFORMANCE OF TRACKED
PROPULSIVE SYSTEMS

by

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PERFORMANCE OF TRACKED PROPULSIVE SYSTEMS

INTRODUCTION

Under Pacific Car and Foundry Company Purchase Order No. GCT-455, HYDRONAUTICS, Incorporated, has carried out an investigation directed toward improving the waterborne performance of the LVTPX11 tracked vehicle. Since the propulsive efficiency of existing tracked vehicles is so low (about 10%), it seemed likely that the greatest gains in the overall waterborne performance could be achieved by improvements in the propulsive efficiency. In order to reveal possible areas of improvement in such propulsive systems, a simple preliminary analysis of track propulsion was carried out. This report is a summary of the results of the analysis.

ANALYSIS

A typical tracked vehicle is illustrated in Figure 1. The vehicle has a track speed relative to the vehicle equal to V_T. The forward speed of the vehicle is denoted as V_o. A skirt is assumed to extend over some portion of the upper track as illustrated. Flow enters the area above the upper track through the clearances along the side and ends of the track. It will be shown that the efficiency of the resulting propulsion system is greatly dependent on the upper track-skirt system and that significant increases in vehicle waterborne performance may probably be achieved by inventive design of the upper track system. A simplified analysis of the propulsion of tracked vehicles considering two methods of treating the upper track system are given in the following sections.

CASE I. UPPER TRACK MOVING IN DEAD WATER: If the clearances at the end of the tracks are very small, and the skirt extends about halfway down to the wheel axes, water will flow into and out of the space above the track through the side clearance and the grousers only. The relative velocity of the upper track will then be just equal to the track speed. The energy put in by the upper track is expended in turbulence and no net thrust is achieved by the upper track.

The relative velocity of the lower track is $(V_T - V_o)$ and the net thrust on the vehicle is given by the following equation:

$$T = C_D \tfrac{1}{2} \rho \, (V_T - V_o)^2 \, S_1 \qquad [1]$$

where C_D is the drag coefficient (based on unit projected track area)

and S_1 is the effective propelling area of the track approximately equal to the twice the product of one track width and the level length of the lower track (neglecting the small thrust of the track on the drive wheels).

The resistance of the track is approximately given by the following equation

$$R_{Track} = C_D \tfrac{1}{2} \rho \left[(V_T - V_o)^2 \, S_1 + (V_T - V_o)^2 S_2 + (V_T^2)(S_1 + S_2) \right] \qquad [2]$$

The resistance of the drive and bogie wheels has been estimated and found negligible compared with the track resistance.

For equilibrium forward motion the drag of the vehicle must be equal to the thrust developed. Thus, if the drag coefficient of the vehicle is defined as

$$C_D = \frac{D}{\tfrac{1}{2} \rho V_o^2 \, S_1}$$, and D is taken equal to the thrust T,

as given by equation [1], then

$$\frac{C_{D_{Vehicle}}}{C_{D_{Track}}} = \left(\frac{1-\frac{V_o}{V_T}}{\frac{V_o}{V_T}}\right)^2 \qquad [3]$$

The propulsive efficiency of the track system may be written as

$$\eta = \frac{T\,V_o}{R\,V_T} = \frac{C_D\frac{1}{2}\rho\,(V_T - V_o)^2\,S_1}{C_D\frac{1}{2}\rho\left[(V_T-V_o)^2S_1+(V_T-V_o)^2S_2+(V_T)^2(S_1+S_2)\right]}\,\frac{V_o}{V_T} \qquad [4]$$

or simplifying

$$\eta = \frac{(1-\frac{V_o}{V_T})^2\,(\frac{V_o}{V_T})}{(1+\frac{\ell_2}{\ell_1})\left[(1-\frac{V_o}{V_T})^2+1\right]} \qquad [5]$$

where ℓ_1 and ℓ_2 are the track lengths indicated in Figure 1. It may be shown that equation [5] has a maximum value at $(\frac{V_o}{V_T}) = .405$, so that the maximum possible efficiency for the case being considered is

$$\eta_{max} = \frac{.107}{(1+\frac{\ell_1}{\ell_2})} \qquad [6]$$

Since $\frac{\ell_1}{\ell_2}$ will be about .1 the maximum efficiency attainable within the assumptions made in the analysis is about 10%.

Actually if the upper track is confined by the skirt at the edges so that there are very small clearances at the edges, the grouser vanes will not operate effectively and their drag coefficient may be expected to be only about one-half of their unconfined value. If the upper track drag coefficient is reduced by 50%, the equation for efficiency becomes

$$\eta = \frac{\left(1-\frac{V_o}{V_T}\right)^2\left(\frac{V_o}{V_T}\right)}{\left(1+\frac{S_2}{S_1}\right)\left(1-\frac{V_o}{V_T}\right)^2+\frac{1}{2}} \qquad [7]$$

The maximum value of equation [7] occurs at a value of $\frac{V_o}{V_T} = .555$ so that

$$\eta_{max} = \frac{.169}{1+\frac{S_1}{S_2}} \qquad [8]$$

Since the assumptions made in determining equations [7] and [8] are probably typical of the present LVTPX11 configuration, an efficiency of about .15 at a slip, $\left(1-\frac{V_o}{V_T}\right) = .45$, is about the maximum efficiency that can be obtained with the present configuration.

Values of $\frac{C_{D_{Vehicle}}}{C_{D_{Track}}}$ and $\eta\left(1+\frac{S_1}{S_2}\right)$ (for both cases of upper track drag coefficient) are plotted against $\frac{V_o}{V_T}$ in Figure 2. For a given track geometry the value of $C_{D_{Track}}$ may be obtained from experimental tests. For the present side grouser vanes the drag coefficient based on vane area is estimated to be about 1 for a vane spacing of one chord. It is probable that this value of unity is close to the maximum achievable for an individual vane.

Therefore, a rough estimate of $C_{D_{Track_{max}}}$ may be obtained from the following equation.

$$C_{D_{Track}} = 1 \frac{\text{Vane area} \times \text{No. of vanes}}{\text{Projected track area}} \qquad [9]$$

Equation [9] does, of course, show that variations in vane area may be used to alter the value of $C_{D_{Track}}$ so that for a given $C_{D_{Vehicle}}$ and available horsepower, the slip may be selected so as to operate at maximum efficiency.

Since the present LVTPX11-3 operates with a value of $\frac{V_o}{V_T} = .55$, which is near the value for optimum efficiency, it appears that increasing or decreasing the track drag coefficient from its present value will tend to decrease the vehicle performance.

The foregoing remarks apply only to the case under consideration; that is, the upper track moves in dead water. Obviously if the upper track drag could be eliminated, great increases in performance are possible. For example, if the upper track drag is zero, equation [4] simplifies to

$$\eta = \frac{V_o/V_T}{\begin{matrix} S \\ (1+\frac{2}{S_1}) \end{matrix}} \qquad [10]$$

Since the upper track contributes no thrust, the thrust of the vehicle is not altered. Consequently for the present LVTPX11-3, $\frac{V_o}{V_T}$ would remain about .55 and the efficiency of the system would be about .5. Equation [10] shows that, for this case of zero upper track drag, optimum efficiency occurs at zero slip; that is for $V_o = V_T$. Thus if $C_{D_{Track}}$ were increased by an increase in vane area or by adding more effective vanes on the lower surface, V_o/V_T and the efficiency will be increased.

One method of reducing the upper track drag is to provide close clearance upper track passages for the grousers. Since the suspension system is not rigid, such close clearances along the top are probably not permitted. However, it may be possible to provide a mechanism for folding back the grousers as they enter the upper region and so reduce the upper track drag.

A unique method for reducing the upper track drag which should be investigated is to provide a skirt which extends about half-way down to the axles and which has very small side clearances at the axle elevation. Pressurized air from an outside source might then be supplied to the space enclosed by the skirts and so remove most of the water from the upper track region. The feasibility of such a system depends entirely on the quantity of air required and thus on the skirt clearances.

Another method of removing a major portion of the upper track drag can be devised if the side grousers are eliminated and only bottom grousers used. In this scheme, water would be taken in through a forward facing scoop or scoops, energized with an axial flow pump (probably one per track), the flow then passed over the upper track, from the rear forward, at the track speed and then diverted aft through a system similar to the proposed PCF hydrovanes. The hydraulic losses associated with such a scheme are difficult to estimate without actually designing the configuration. A rough estimate indicates that 2-15 horsepower pumps (1 per side) should be adequate for the proposed system. A similar pump propulsion system which utilizes the upper track itself as the pump is described in the following section.

CASE II. <u>UPPER TRACK USED AS PUMP TO SUPPLY THRUST</u>: In Figure 3 a linear pump propulsion system is illustrated. The propulsion system moves from left to right at a speed of V_o. Flow is taken in at the left at a relative speed of V_o, accelerated and turned vertically into a cascade of lifting vanes moving from right to left at a velocity, V_T, normal to the inflow velocity V. The pressure of the liquid is increased as a result of the energy imparted by the blades. The flow leaving the vanes is then turned aft and ejected at a velocity $V_o + \Delta V$ consistent with conservation of mass and energy. A resultant thrust is produced which propells the vehicle to the left as a result of the increased momentum of the flow passing through the system.

It is clear that such a linear pump propulsion unit may be devised for a tracked vehicle by utilizing the upper track grousers as the pump vanes. The lower intake and turning vanes may be incorporated in the skirt of the vehicle and a system similar to the proposed PCP propulsion hydrovanes utilized as the exhaust. A simple analysis of such a propulsion system combined with the normal lower track propulsion is presented in the following paragraphs.

The efficiency of the linear pump may be expressed in terms of the blade lift and drag as

$$\eta_{pump} = \frac{1-D/L \tan \beta}{D/L + \tan \beta} \tan \beta \qquad [11]$$

where $\tan \beta = \dfrac{V_{in}}{V_T}$.

For reasonable values of D/L (approximately .1), maximum efficiency of the pump is attained at blade angles approximately equal to 45° so that best efficiency is obtained for $V_{in} \approx V_T$. The anticipated pump efficiency (neglecting track drag inboard of the grousers) is about 75%. The maximum blade lift coefficient without separation is about 1. Denoting the total blade area to projected blade area ratio as (BAR) the pump will produce a pressure $\Delta p \cong \frac{.7}{(BAR)} \rho V_T^2$. If some losses are assumed in passing through the upper exhaust system the total pressure increase available to increase the momentum of the fluid is $K \frac{.7}{(BAR)} \rho V_T^2 (K < 1)$. The blade area ratio of the existing LVTPX11-3 is about 1.4. Using a value of 1.4 for BAR, it may then be shown that $\Delta V \cong K(\sqrt{V_o^2 + V_T^2} - V_o)$ and the thrust produced may be given by the following equation:

$$T = K \rho V_T S_g \left[\sqrt{V_o^2 + V_T^2} - V_o \right] \qquad [12]$$

where S_g is the area of the blade passage. The power put into the system is given by the equation

$$\text{Power}_{in} = \frac{\frac{1}{2} \rho V_T^2 S_g}{\eta_{pump}} \qquad [13]$$

Now the efficiency of the total track propulsion system may be computed as follows:

$$\eta = \frac{\left\{ C_D \frac{1}{2} \rho (V_T - V_o)^2 S_1 + K \rho V_T S_g \left[\sqrt{V_o^2 + V_T^2} - V_o \right] \right\} \frac{V_o}{V_T}}{C_o \frac{1}{2} \rho \left[V_T - V_o)^2 S_1 + (V_T - V_o)^2 S_2 + V_T^2 S_2 \right] + \frac{1}{2} \frac{\rho V_T^2 S_g}{\eta_p}} \qquad [14]$$

As pointed out in the Case I discussion, C_D based on the lower track grouser blade area is approximately 1. Therefore, C_D based on the total lower track area S may be taken as approximately $\frac{S_g}{S_1} \times$ BAR. Using a blade area ratio 1.4, C_D may be replaced by $1.4 \frac{S_g}{S_1}$ so that equation [14] becomes

$$\eta = \frac{(1 - \frac{V_o}{V_T})^2 + \frac{2K}{1.4}\left[\sqrt{(\frac{V_o}{V_T})^2 + 1} - \frac{V_o}{V_T}\right] (\frac{V_o}{V_T})}{(1 - \frac{V_o}{V_T})^2 + \frac{\ell_g}{\ell_1}\left[(1 - \frac{V_o}{V_T})^2 + 1\right] + \frac{1}{\eta_p 1.4}} \qquad [15]$$

If reasonable care is taken in the intake and exhaust ducting a value of K of about .7 may be achieved. Furthermore the pump efficiency η_p has earlier been shown to be about .75 and $\frac{S_g}{S_1}$ may be taken as about .1. Using these typical values the efficiency of the proposed system is plotted as a function of $\frac{V_o}{V_T}$ in Figure 4. Figure 4 shows that the maximum efficiency occurs at zero slip and is equal to .4. The actual value of $\frac{V_o}{V_T}$ required to propel the vehicle will probably be about .7 where the efficiency is .35. The ratio of vehicle drag coefficient to track drag coefficient for the proposed system is

$$\frac{C_{D_{Vehicle}}}{C_{D_{Track}}} = (\frac{V_T}{V_o} - 1)^2 + \frac{2K}{1.4} \frac{V_T}{V_o}\left[\sqrt{1+(\frac{V_T}{V_o})^2} - 1\right] \qquad [16]$$

Equation [16] is also plotted in Figure 4 and may be used with equation [15] to estimate the terminal velocity of the vehicle for a given input power.

CONCLUDING REMARKS

The foregoing analysis is intended only as a preliminary investigation directed toward uncovering possible areas of improvement in track propulsion. The analysis is admittedly incomplete and necessarily relies on assumed values of geometry and hydrodynamic force coefficients and losses. All of these factors are subject to more detailed analysis but the expenditure of the time required to carry out such an investigation does not presently seem warranted.

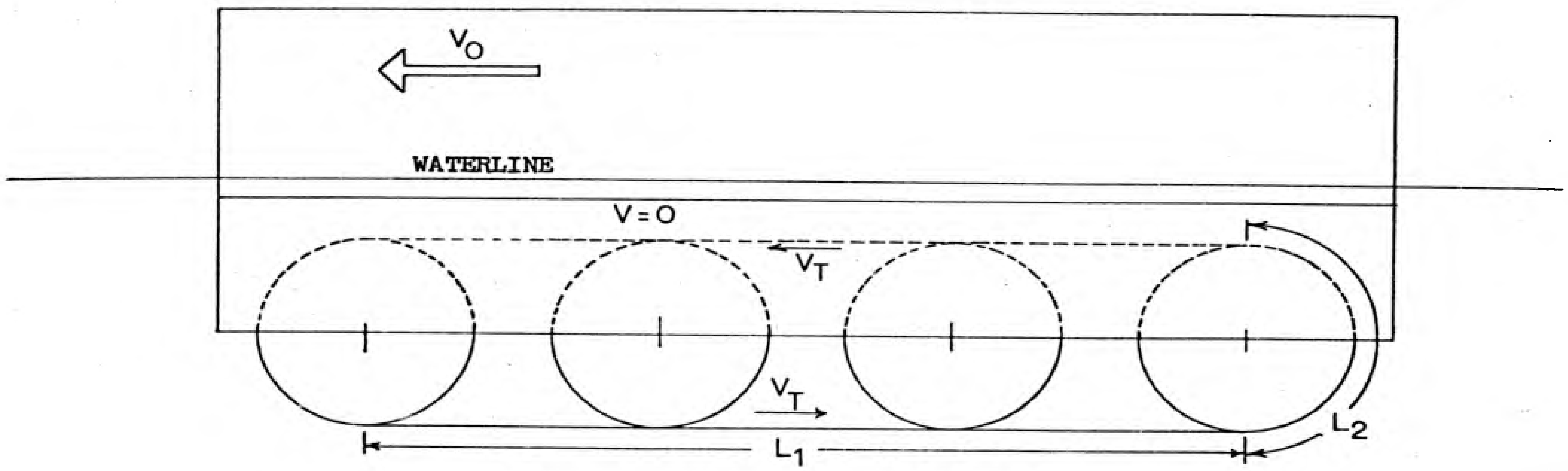

FIGURE 1. SCHEMATIC TRACK PROPELLED WATERBORNE VEHICLE

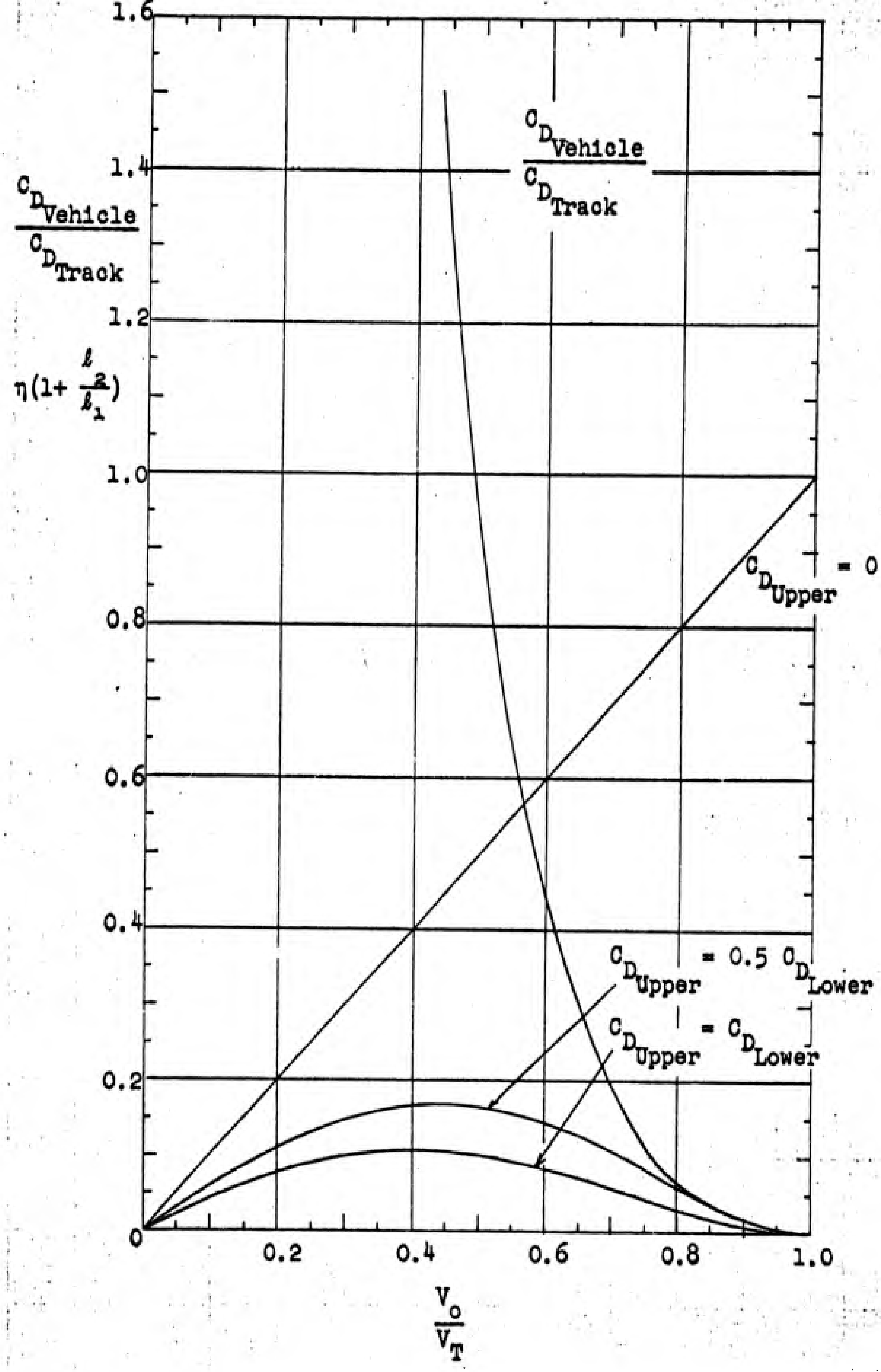

FIGURE 2. CASE I. PERFORMANCE

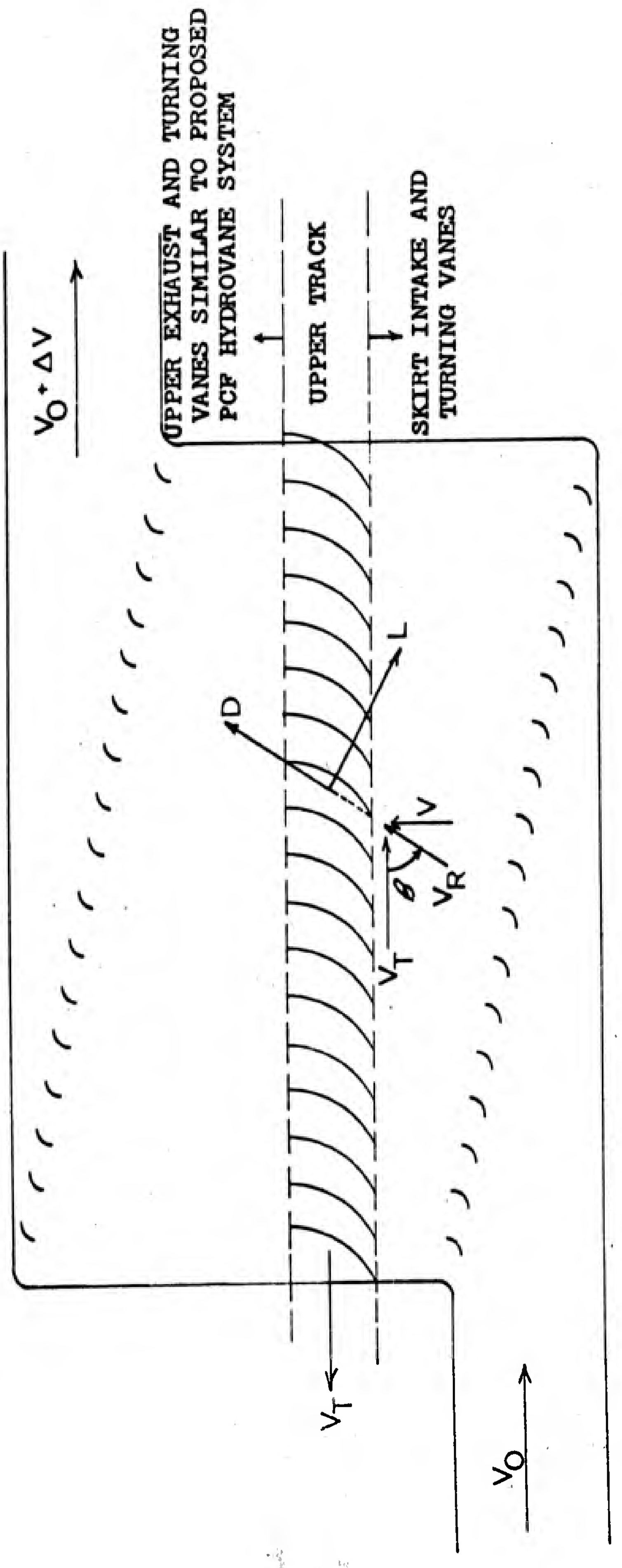

FIGURE 3. SCHEMATIC LINEAR PUMP PROPULSION.

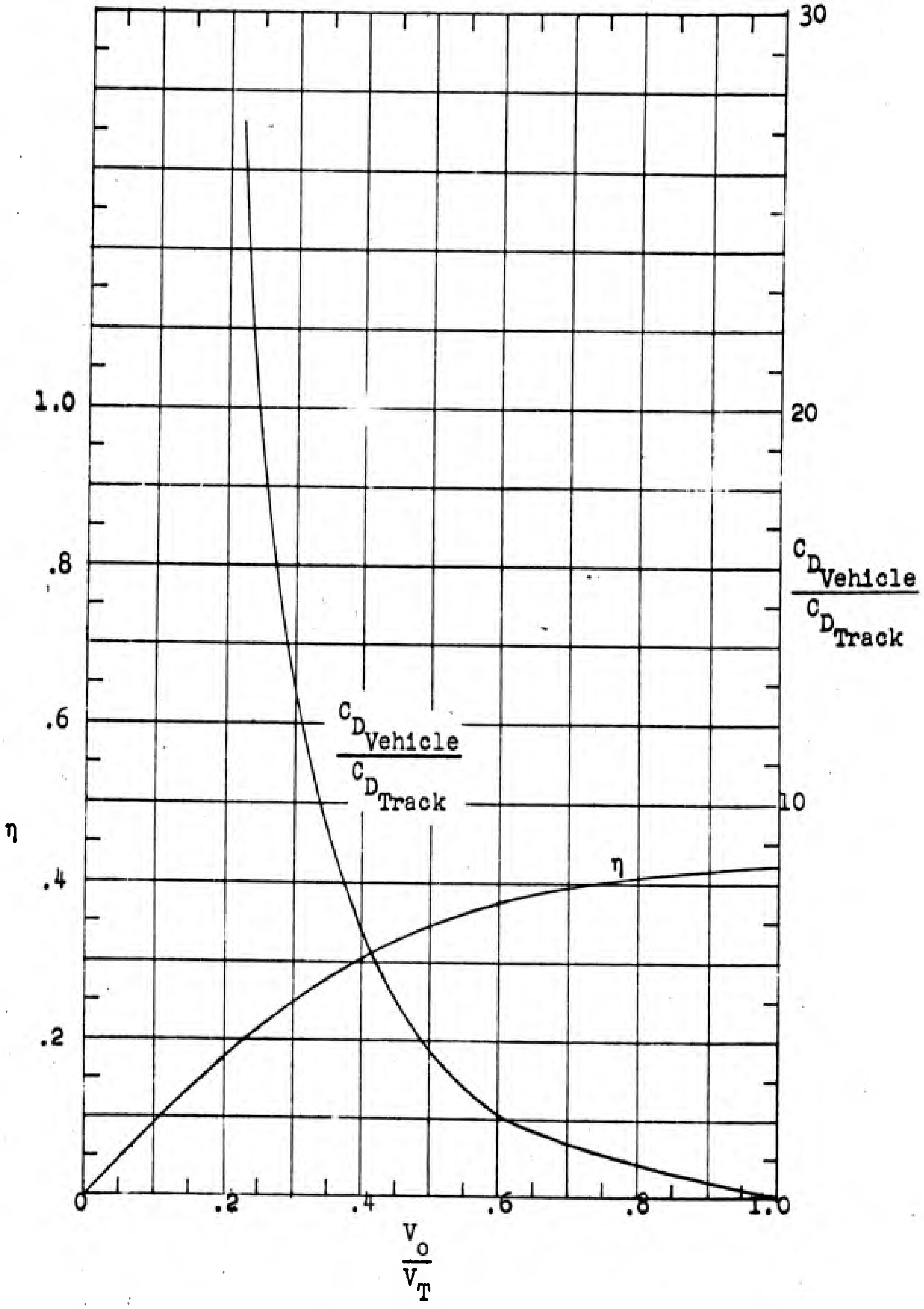

FIGURE 4. CASE II. PERFORMANCE