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WITH THE PRESENT state of technology, the achievement of maximum transport efficiency on highways and roads, or smooth, hard ground, calls for the use of wheeled vehicles. Conversely, when faced with a requirement to operate in the severe terrain conditions encountered off the road, experience has shown that tracked vehicles will generally outperform wheeled vehicles. But, of course, they are not well adapted to extended, high-speed travel on improved surfaces.

For several decades now, various attempts have been made to combine in a single vehicle the performance and efficiency of a wheeled vehicle on improved surfaces and mobility equal to, or better than that of a tracked vehicle in soft-soil environments, such as mud, swamps, marshland, tidal flats, and intensively irrigated agricultural land. The majority of these designs have reflected emphasis on off-the-road mobility, as evidenced by the use of some type of track system -- conventional, spaced-link, pneumatic, air-supported, and so forth. Consequently, the goal of achieving the performance and efficiency of a wheeled vehicle on improved surfaces has not been completely attained, because tracks, of whatever design, are not fully compatible with the highway and road environment. At the higher speeds not only possible but demanded for this use, track wear is greatly accelerated, maintenance of adequate control becomes difficult, and the driver, passengers, cargo, and vehicle structure are exposed to possibly damaging levels of shock and vibration.

Several years ago we undertook to determine whether there was a practical way to avoid the dilemma of "wheels or tracks" by providing a third alternative. The basic consideration guiding development was to utilize some type of running gear on improved and hard surfaces which would enable us to obtain wheeled vehicle efficiency in those environments, and, by virtue of the configuration of the running gear and incorporation of the ability to drive it in an unorthodox fashion, to obtain or surpass tracked vehicle mobility in soft soils. The result of this effort is the TerraStar locomotion device -- essentially a new type of wheel called a major/minor wheel. The following discussion traces the development of this wheel, or locomotion device, from conceptual design to its use on full-scale experimental vehicles.

ABSTRACT

Many off-the-road mobility development programs have had as the principal objective a substantial improvement in soft-soil performance. This paper describes the evolution of the TerraStar marginal-terrain amphibian, which represents an effort to achieve this improvement without sacrificing "roadability." The TerraStar concept is based on the use of a new locomotion device called a major/minor wheel. Essentially an "interrupted" wheel, this device works down in soft soils much like a spaced-link track, and also provides wheeled vehicle performance on roads and highways, or hard ground.

Aspects of the program related here include the use of scale-model tests in natural soils for preliminary design, the development of full-scale experimental vehicles, and the early results of field tests of the full-scale vehicles.

DESIGN PHILOSOPHY

Except for the spaced-link type, the popularity of tracks for soft-soil work results from their ability to provide good flotation, thereby minimizing motion resistance, and to generate relatively high thrust in low-strength conditions by developing soil failures in shear of extensive proportions. Unconventional track systems, such as tubular or cellular pneumatic types, or roller tracks with low-pressure tires, are intended to enhance these characteristics. With these, in near-fluid soils, the large contact area and low ground pressure typical of tracks are augmented by the inherent buoyancy of the track components to provide excellent flotation. The aggressive configuration of the ground-contact elements produces the necessary level of thrust to overcome what little motion resistance is encountered working on top of the soil.

With the goal, however, being a vehicle which would operate efficiently on highways and roads as well as in adverse terrain, track systems were eliminated as a possible approach, since, in our opinion, none, regardless of type, offered completely satisfactory "roadability."

On the other hand, the conventional wheel offered no possibility of a solution either, so a compromise was reached and the design based on the functional characteristics of a spaced-link track with a physical form something like a wheel. As is well known, the spaced-link track operates quite differently in soft soils than a conventional (or unconventional), closed track. Flotation plays no real part in its ability to move a vehicle in low-strength conditions. Rather, high thrust is developed by efficient soil shearing action, augmented by the capability of reaching down into the soil to act against firmer material. While the sinkage experienced would be expected to result in very high levels of motion resistance, the open design of the track largely avoids this.

From the standpoint of soft-soil performance then, implicit in the design decision was the discard of the guidelines of low ground pressure, high flotation, and the avoidance of sinkage normally followed to assure gaining thrust and avoiding motion resistance in low-strength conditions. It was proposed to achieve the same results in a unique way which would also make it simpler to get good roadability.

CONCEPT DESCRIPTION

In the TerraStar concept, conventional wheels and tires are replaced by "major-wheel" assemblies. These assemblies each consist of "minor wheels" mounted on secondary axles located radially about, and at some distance from, the major-wheel axle by means of large spokes rigidly attached to the major-wheel axle. The minor wheels carry wide-base, low-profile, low-pressure tires. A gear-train housed in the spokes on one side of the major-wheel assembly carries power to the minor wheels from a drive shaft located inside the tubular major-wheel axle (Fig. 1). A clutch assembly is incorporated on the drive-shaft so it may be engaged, or

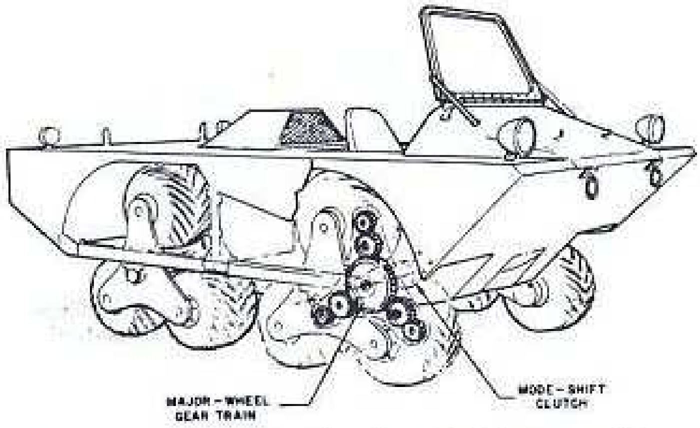

Fig. 1 - Major-wheel and mode-shift clutch assembly

Fig. 2 - Road operation at convoy speeds

locked-up with the major-wheel axle and drive it directly, causing the entire major-wheel assembly to revolve.

For operation on highways, roads, or natural, hard surfaces, the minor wheels are driven and the vehicle is propelled by the eight minor wheels bearing on the surface, much the same as any conventional, all-wheel drive vehicle (Fig. 2). The only characteristic tending to distinguish the TerraStar in this mode of operation is the use of a skid-steering system like that found in tracked vehicles. When soft soils are encountered in adverse terrain, where bearing capacity and shear strength are so low that sinkage and slip of the minor wheels could result in immobilization, the minor-wheel drive shaft is clutched to the major-wheel axle. The power on the major wheels causes them to revolve, with the minor wheels successively brought into contact with, and separated from, the soil in something like a "stepping" or "walking" method of locomotion. How does this enhance mobility?

Assuming that a vehicle is not power limited, the maximum tractive effort that can be developed in adverse terrain is determined by the ultimate strength of the soil in which it is operating. The vehicle's ability to propel itself

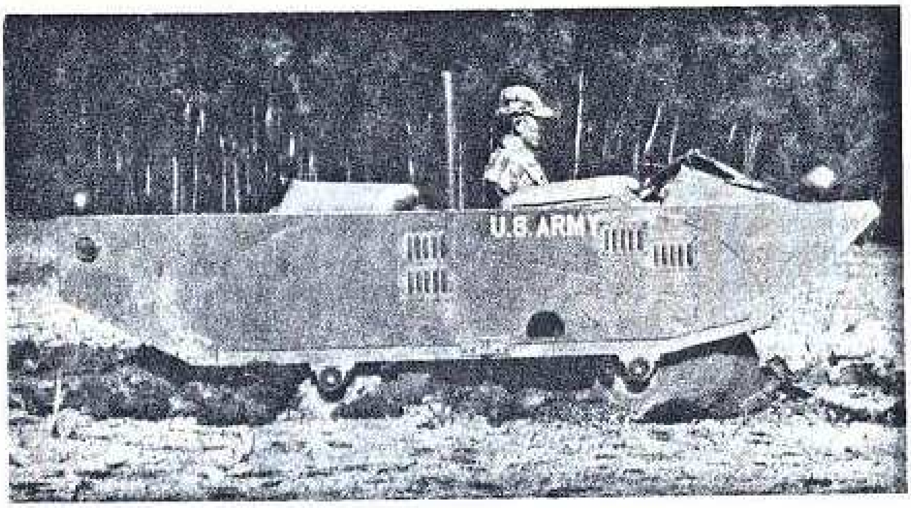

Fig. 3 - Multipass operation in heavy clay

and do useful work is, further, a function of the relationship of tractive effort and motion resistance. Expressed in its simplest form, gross tractive effort may be roughly evaluated as

$$H = Ac + W \tan \phi \qquad (1)$$

where:

- H = Gross tractive effort, lb
- A = Ground contact area of the vehicle's tractive elements, sq in.
- c = Measure of the stickiness of the soil expressed as a coefficient of cohesion, psi
- W = Load on the vehicle's tractive elements, lb
- ϕ = Apparent angle of internal friction of the soil

This expression takes into account the resistance to shearing resulting from both the cohesive and frictional characteristics of natural soils. Drawbar pull has traditionally been used as an indicator of a vehicle's mobility. It is approximated by evaluating the expression

$$DP = H - R \qquad (2)$$

where:

- DP = Drawbar pull, lb
- H = Gross tractive effort, lb
- R = Total motion resistance, lb

In detail, R is the sum of bulldozing resistance, compaction resistance, and drag. So long as a positive value can be realized for DP, a vehicle will continue to move; the greater the value of DP, the greater the vehicle's capacity to do useful work (1).*

As can be seen from Eq. 1, within practicable limits, the larger A can be made the more reactive thrust that could be developed for a given value of c. Similarly, the larger W is the more reactive thrust that could be developed for a given value of ϕ. Consequently, to develop the greatest possible gross thrust in low-strength conditions, where the values of c and ϕ are very low, a desirable arrangement would be one in which the tractive elements of a vehicle would induce shear over large areas and would also provide high concentrations of weight. With something approaching maximum thrust achieved, to gain the final goal of a high value for DP, as represented in Eq. 2, motion resistance would, at the same time, have to be held to a minimum. These are the things that have been attempted with the TerraStar's major/minor wheel (2).

As explained before, in adverse soft soils, each major wheel is powered directly causing it to revolve, with the minor wheels successively brought into contact with and separated from the soil in a stepping fashion (Fig. 3). The massive grouser action of the wheel develops soil failures over an exceptionally large area, and large load concentrations occur on a cyclical basis as the vehicle weight at the axle is borne by a single minor wheel three times during each major-wheel revolution. Thus, thrust is maximized in low-strength conditions. Since the major wheel advances by "picking up" its minor wheels and displacing them forward as it revolves, unlike a conventional wheel or track which is pushed through the soil, bulldozing resistance is practically eliminated and compaction resistance is kept low so that total motion resistance is minimized.

PRELIMINARY DESIGN

Rather than the customary concerns of weight growth, vehicle envelope size, power train efficiency, and so forth, preliminary design on this project entailed basic, concept decisions and the resolution of design conflicts. While it now seems natural for the major wheels to have three minor wheels each, there was originally a question as to why not two, or four, or five? There was discussion whether it would be advantageous to continue to drive the minor wheels when

*Numbers in parentheses designate References at end of paper.

the vehicle was in the major-wheel mode of operation, either forward or in reverse, or to lock them up. Consideration had to be given to the question of suspension for the major wheels and, if no suspension were provided, should they be free to rock about their center axle when the vehicle was in the minor-wheel mode of operation? There were also conflicts to be resolved between the advantages of a mechanical, hydraulic, or electrical final drive.

Finally, there was the fundamental question as to whether the major-wheel method of locomotion would really prove as effective in adverse soft-soil conditions as rudimentary, theoretical analysis indicated it would.

Some questions could be satisfactorily resolved by further analysis. For example, the optimum number of minor wheels to have on each major-wheel assembly. It could be readily demonstrated geometrically that going from two to three minor wheels -- a one-third increase in complexity -- would provide almost a 70% increase in ground clearance for normal, wheeled vehicle operation and decrease the stepping height in the major-wheel mode of operation by approximately 50%. However, going from two to four wheels, doubling the complexity of the assembly, would increase ground clearance by only 20% more and further decrease the stepping height by not much more than an additional 10%. Obviously this was a case of diminishing returns, and three minor wheels on each assembly would be the optimum configuration.

Other questions, such as the selection of the final drive, were settled by circumstances. There was no "off-the-shelf" hydraulic or electrical final drive available with an input/output capacity and a physical size compatible with the installation requirements of the TerraStar, so there was no alternative to a mechanical drive.

However, in considering questions on the modes of operation and mobility performance, it soon became obvious that no purely analytical approach would provide fully satisfactory answers. Yet, before making the final commitment of money and time required to construct a full-scale experimental vehicle, it was desirable to gain additional evidence that the new locomotion method offered distinct advantages over conventional wheels or tracks in soft soils. A good way to get this evidence appeared to lie in the testing of geometrically and dynamically scaled vehicle models in natural, cohesive, and frictional soils.

Both 1/4 scale and 1/5 scale, electrically powered, "free" models of the TerraStar were used in these tests (Fig. 4). Two natural soils -- one predominantly cohesive and one predominantly frictional -- were prepared in tanks, the strengths of the soils being varied by changing their moisture contents for each successive test. A simple shear vane, with provision for varying the normal load, was used to determine values for c and ϕ in situ. Values for c and ϕ were also obtained from soil samples by shear-box tests at the same time laboratory soil analyses were made to determine soil specific weights and moisture contents for each model test. The test setup included apparatus for measuring model drawbar pull and determining slip. Unladen weight distribution

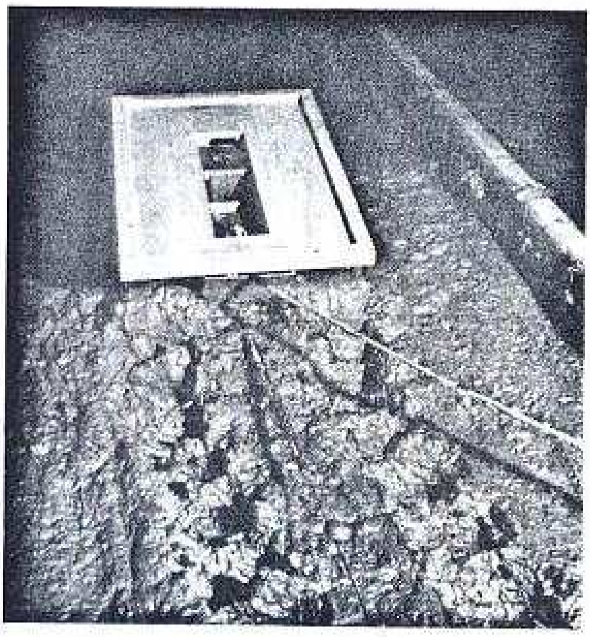

Fig. 4 - Drawbar-pull test with dynamically similar model

of the models approximated that of the planned, full-scale vehicles. The test weights of the models were determined on the basis of evaluating Pi terms evolved from dimensional analyses accomplished by other investigators in the locomotion mechanics field (Ref. 3). For tests in the predominantly cohesive soil the model loading was determined by evaluating the expression

$$W_m = \frac{W_{fs}}{cL^2} \qquad (3)$$

where:

W_m = Model weight, lb

W_{fs} = Full-scale vehicle weight, lb

c = Coefficient of cohesion of the soil, psi

L = Characteristic length or scale factor, either 4 or 5 in the case of the models used.

When tests were conducted in the predominantly frictional soil, the model loading was based on an evaluation of

$$W_m = \frac{W_{fs}}{\gamma L^3} \qquad (4)$$

where W_m, W_{fs}, and L are as defined above and γ is the test soil's specific weight, lb/cu in.

At first, attempts were made to obtain independent performance data from the vehicle model tests which could be directly correlated to full-scale vehicle performance. Un-

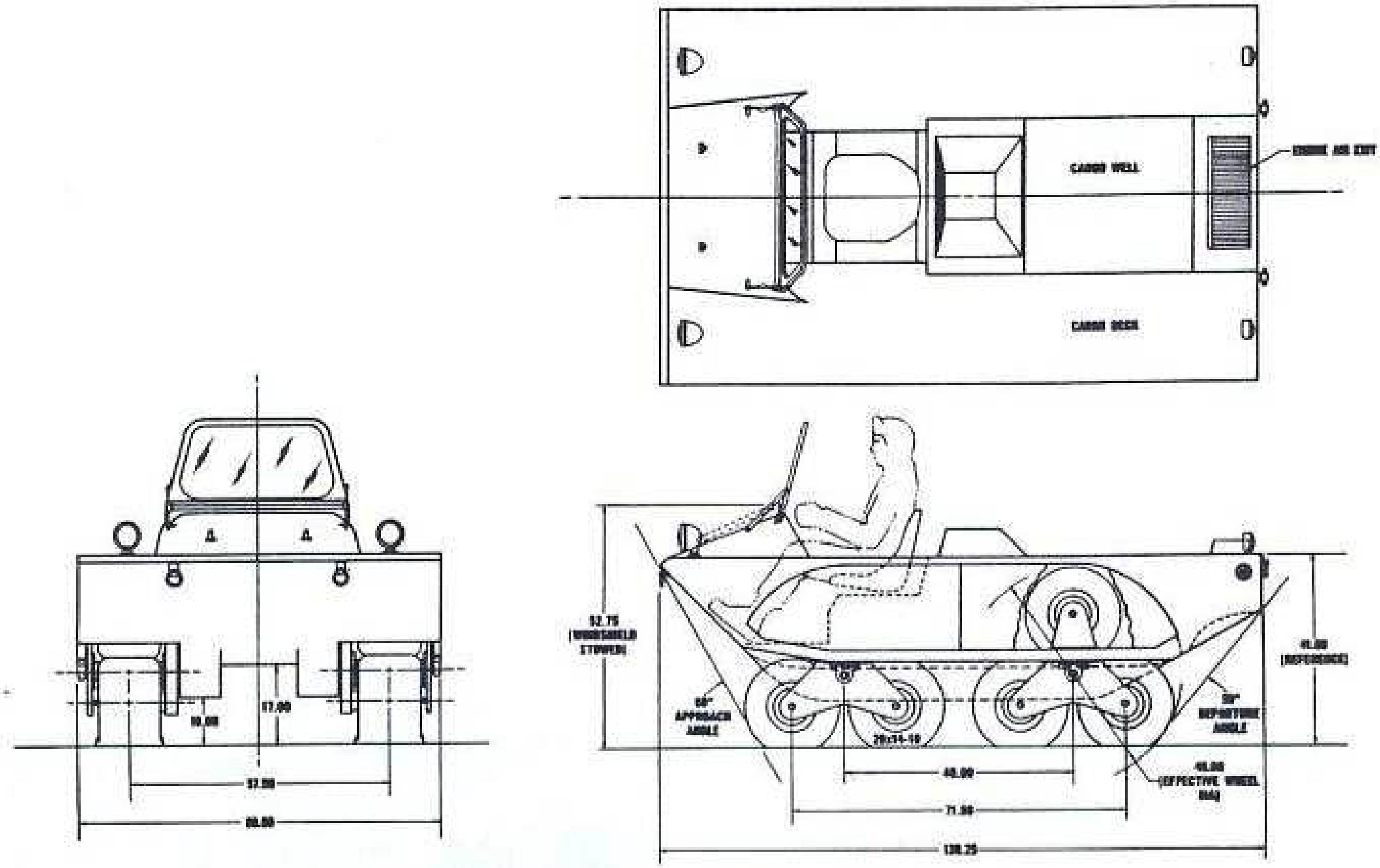

Fig. 5 - Dimensional drawing of experimental TerraStar

fortunately, while it was practicable to do this in the predominantly cohesive soil over a wide range of moisture contents, it was found impossible, with the simple test setup employed, to achieve the high loads required for correct dynamic scaling in the frictional soil and yet stay within the physical size limits of the model imposed by geometric scaling.

The effort to obtain independent data was, therefore, discontinued and we resorted to a series of tests in the cohesive and frictional soils in which identical models were equipped with major/minor wheels and various types of conventional running gear so that comparative performance data could be obtained. The drawbar-pull/slip curves generated from the data showed the TerraStar method of locomotion to be markedly superior to conventional running gear in soft soils. Ultimately, tests of the full-scale TerraStar experimental vehicles provided corroboration of the results of the comparative model tests.

The scale-model work also provided opportunities to determine the desirability of driving or not driving the minor wheels when operating the vehicle in the major-wheel mode, of providing or not providing a conventional suspension at the major-wheel axles, and to reach conclusions on other basic questions on the concept which could not be readily answered on the drawing board. Essentially, then, scale-model tests constituted a major part of preliminary design on the TerraStar.

EXPERIMENTAL VEHICLES

With confidence in the new locomotion concept greatly strengthened by the performance demonstrated by the scale-models, Lockheed immediately undertook the design and construction of a full-scale, TerraStar experimental vehicle in a nominal 1/2-ton payload size (Fig. 5). Shortly after completing this vehicle, and prior to the completion of extensive testing, Lockheed was awarded a contract by the U.S. Army Limited War Laboratory for the design, development, and construction of another full-scale, experimental vehicle for Army evaluation of the locomotion concept.

As will be noted in the tables of characteristics, the vehicles are dimensionally similar (Tables 1 and 2). They also have somewhat the same external appearance. However, they differ substantially in detail design and subsystems.

TerraStar I (Fig. 6) was designed to be built quickly and economically and this is reflected in the use of a simple, welded steel frame under an aluminum sheet skin, the use of rough, built-up, major-wheel, gear-train housings, utilization of readily available components, and, generally, a disregard of the niceties of weight-saving and long-life design techniques. While not as light or agile as it might have been, TerraStar I incorporated all the characteristics and was, and is, capable of demonstrating all the features of major/minor wheel locomotion. The relatively limited tests carried out with this vehicle proved invaluable in im-

Table 1 - TerraStar I Characteristics

Length	126.25 in.
Width	78.00 in.
Deck height	39.00 in.
Curb weight	3100 lb
Gross weight	3700 lb
Engine	41 hp
Transmission	4-speed manual
Steering	Braked differential
Tires	16 × 14.50-6
Frame construction	Steel
Performance:	
Maximum speed, land	25 mph
Maximum speed, water	4 mph
Gradeability	60%
Steering	Pivot

Table 2 - TerraStar II Characteristics

Length	130.25 in.
Width	80.00 in.
Deck height	41.00 in.
Curb weight	2600 lb
Gross weight	3600 lb
Engine	53 hp
Transmission	4-speed manual
Steering	Clutch-brake
Tires	20 × 14-10
Frame construction	Aluminum
Performance:	
Maximum speed, land	35 mph
Maximum speed, water	6 mph
Gradeability	60%
Steering	Pivot

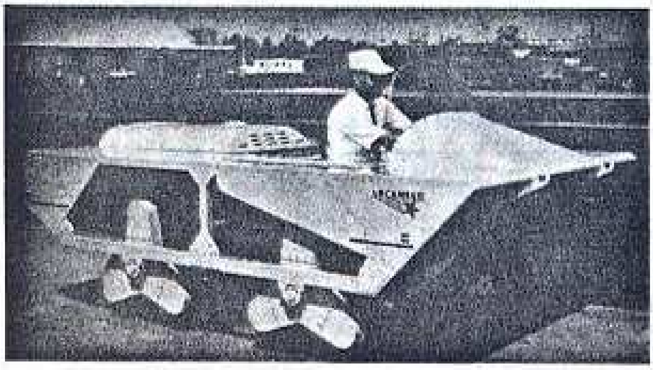

Fig. 6 - Original TerraStar research vehicle

Fig. 7 - U. S. Army Limited War Laboratory vehicle

proving the detail design of the Army's experimental vehicle, TerraStar II (Fig. 7).

The first vehicle incorporated a braked-differential, skid-steering system. On emerging from a swamp or similar soft-soil area it was found that the differential in the drive train made it possible for the wheels without good traction on one side to "spin out," wasting power. This, of course, is not a new or unusual phenomenon; however, correcting the condition by braking the spinning wheels caused unwanted steering just when it was desired to keep the vehicle straight on to the bank.

The braked-differential steering system also resulted in a greater loss of power to the wheels on the driving side, or outside, of a turn than had been anticipated. While there was no noticeable degradation of performance, it was apparent that steering response could be improved. To effect this improvement and also provide for better control in soft soils, a clutch-brake steering system was installed in TerraStar II. This gives full power in turns and gets all the torque to the wheels that can use it in adverse terrain. However, while not as complex or costly as a geared, regenerative steering system, the clutch-brake system was not as simple as the equipment used in TerraStar I and presented problems in obtaining satisfactory components.

While operating TerraStar I in near-fluid, soft soils at Aberdeen Proving Ground, it was observed that possibly a larger radius at the lower portion of the front of the hull would reduce soil buildup at that point. It also appeared that a larger diameter tire and reduction of the rpm of the major-wheels to obtain a more deliberate stepping action would enhance performance. Accordingly, TerraStar II is equipped with a more efficient hull form, incorporates provisions to accommodate 16 or 20 in. diameter tires, and has a total reduction in low gear, major-wheel mode of operation, of 98:1 instead of the 72:1 reduction used in TerraStar I.

Of course, the major improvements, and the ones most difficult to achieve in the second vehicle, were the use of an all-aluminum, welded frame with a riveted, aluminum sheet skin, and the change from built-up, major-wheel, geartrain housings to cast-aluminum housings. The aluminum frame and skin provided a light, rugged vehicle hull, but initially created problems with respect to engine and drive-

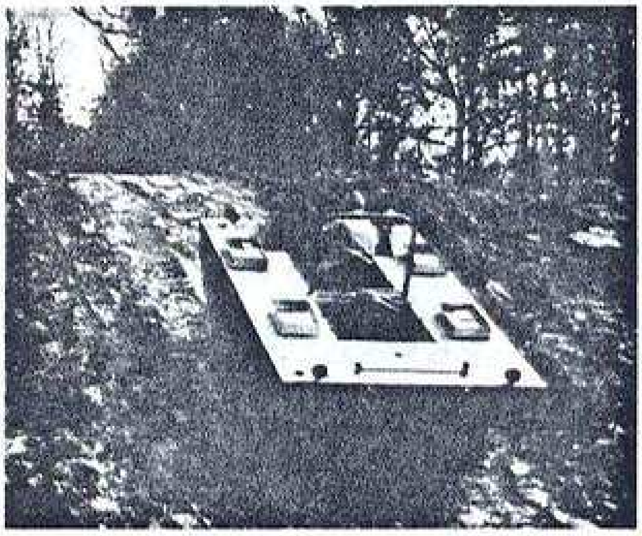

Fig. 8 - Climbing a wet, clay slope

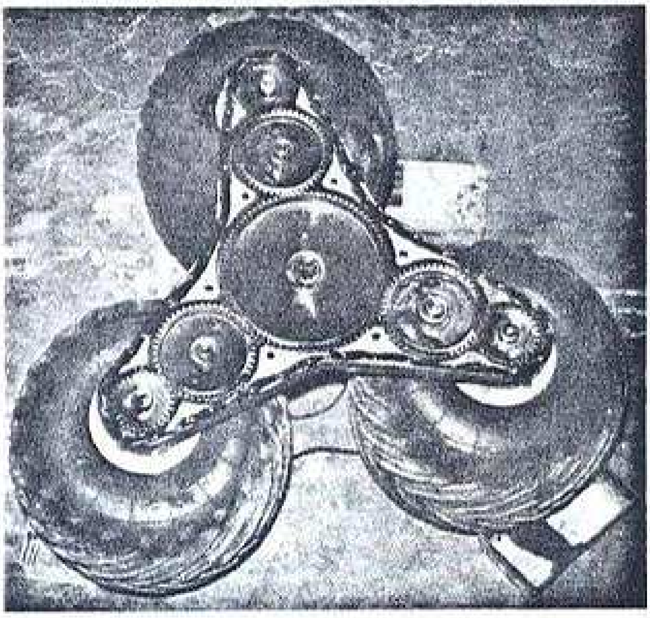

Fig. 9 - Major-wheel gear train

train mountings and attachments. Although the cast-aluminum housings at first caused some concern with respect to their ability to take high impact loads and continuous abrasion in soft soils, they have successfully withstood numerous encounters with sharp rocks, boulders, roots, and sunken logs and still show no appreciable wear. And it proved worth while to accept these early problems and misgivings because the much lighter TerraStar II is an agile, maneuverable vehicle with a very substantial overall performance superiority over the first experimental vehicle (Fig. 8).

So far in this discussion the emphasis has been on the features and functioning of the TerraStar concept in soft-soil environments. There is also much of interest regarding the characteristics and operation of the TerraStar on roads, highways, natural, hard surfaces, and in the water. These are common to both experimental vehicles.

The desire to achieve maximum simplicity and the special requirements for power transmission in the major-wheel assemblies led to selection of a planetary gearset (Fig. 9) for the final drive to the minor wheels. The sun gear is mounted on the input drive shaft which extends out to the gear housing through the tubular major-wheel axle. An intermediate gear transmits power to the planet gears which are mounted on, and drive the minor-wheel axles. In addition to the final-drive function, this simple mechanism provides the TerraStar with many of its unusual characteristics and capabilities.

When the vehicle is operated in the minor-wheel mode, the final-drive gearset cuts the overall gear ratio to one-third that of the total reduction used in direct, major-wheel drive so that adequate speeds can be achieved for highway and road use.

The major-wheel assemblies are not restrained from independently rocking about their center axles, or even full rotation, when the vehicle is in the minor-wheel mode. Suspension of the vehicle is thus derived not only from tire deflection but also from the fact that each wheel assembly is, in effect, a two-axle bogie suspended at a single point; a walking beam suspension for each pair of minor wheels in ground contact, with its action mechanically damped.

With this absence of restraint of the major wheels and the planetary gearset arrangement, it is probably obvious that, should the load go off the minor wheels for any reason, the input torque will begin to rotate the major-wheel assembly automatically, even though the mode-shift clutch is not engaged to lock its center axle to the drive shaft. This autorotation into major-wheel mode enables the vehicle's wheels to bridge ditches while moving cross-country. It is also valuable in permitting the vehicle to climb a vertical elevation of greater height than half the effective diameter of the major wheels. The leading minor wheels on the front wheel assemblies contact the base of the elevation. The tractive effort, gained primarily from the rear wheel assemblies, forces the vehicle ahead and the forward wheel assemblies autorotate into the major-wheel mode, bringing the top minor wheels over to catch the edge of the elevation as they move around and down. Once the front of the vehicle is started over the elevation, then the tractive effort is gained principally from the front wheels and the rear wheel assemblies are pulled over the elevation as they, in turn, are made to autorotate. A somewhat analogous series of actions occurs when the vehicle makes an exit from water over an abrupt bank.

The autorotation feature also has other advantages when the TerraStar is operated in the water. The best control, achieved by identical driver inputs to those used on land, the best maneuverability, and satisfactory speeds are obtained when the vehicle is left in the minor-wheel mode. On entering the water (Fig. 10), as soon as the buoyant force starts to support the hull, the load comes off the minor wheels and the wheel assemblies autorotate into the major-wheel mode, automatically providing the "paddle-wheel" action which propels the vehicle. Coming out of the water, the autorotation in major-wheel ceases as soon as the minor

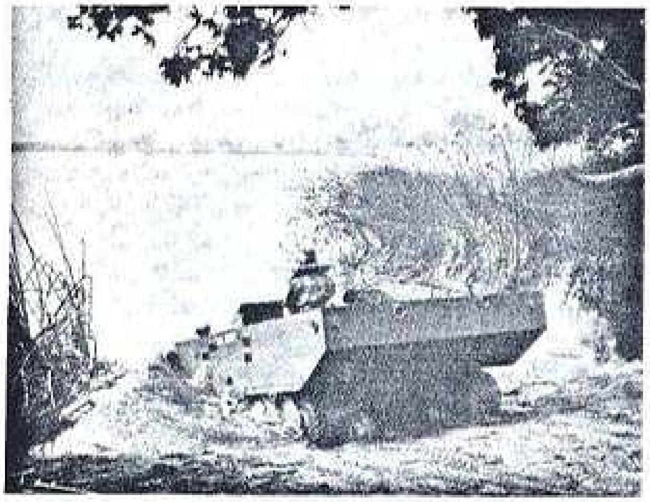

Fig. 10 - High-speed water entry

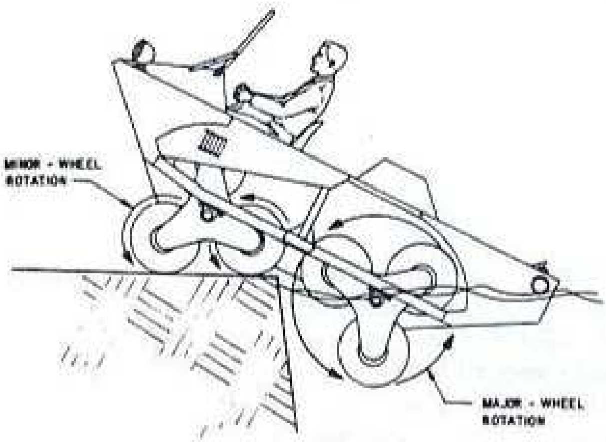

Fig. 11 - Wheel action during water exit

wheels contact a firm footing and pick up the load (Figs. 11 and 12). The advantage of this type of operation is most obvious when the vehicle is "swimming" in areas where underwater obstacles are common. As can be seen, if the wheel assemblies were locked in the major-wheel mode the impact loads, on striking an obstacle, would be high. Whereas, with the vehicle in the minor-wheel mode, and the wheel assemblies autorotating, when an obstacle is struck the impact load is substantially lessened by the assembly's ability to rock back on itself as the minor wheels pick up the load.

There are other, less obvious basic advantages or characteristics of the TerraStar resulting directly from use of the unorthodox major/minor wheel. Two of these contribute greatly to its potential value as a military vehicle (Fig. 13).

First, there is the inherent simplicity of the concept. This is evidenced by the absence of conventional suspension components, half-shafts with slip joints, universal joints, transfer cases, and multiple use of differentials. It is also demonstrated by the uncomplicated, straightforward char-

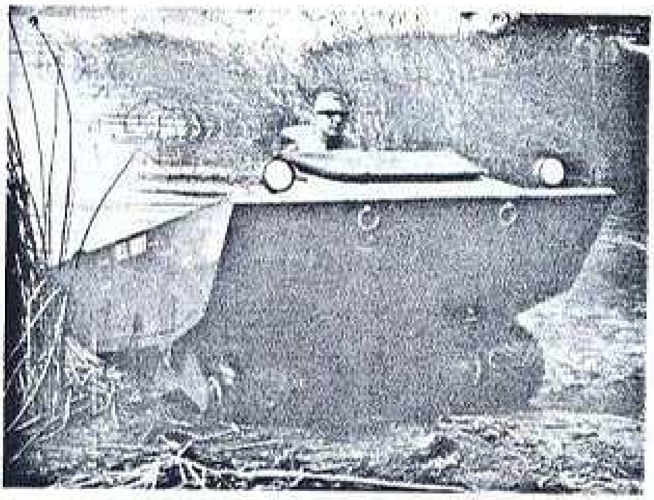

Fig. 12 - Water egress over a near vertical bank

Fig. 13 - Artist's concept of three TerraStars delivered by CH-47 helicopter

Fig. 14 - Major/minor-wheel shift lever

acter of the driver's controls -- simple steering levers like those of a tracked vehicle, the usual brake, clutch and accelerator, and conventional instruments. The only unique feature is the mode-shift control (Fig. 14) enabling selection of the minor-wheel or major-wheel mode of operation. As mentioned previously, control of the vehicle is accomplished by identical driver inputs on both land and water.

Second, although the TerraStar is a wheeled vehicle -- a highly unconventional one -- its vulnerability, with respect to tires, is exceptionally low. Each major-wheel assembly carries a working spare. Should a tire be damaged, the wheel assembly is simply rotated to get another minor wheel on the ground, so the vehicle's roadability in the minor-wheel mode is not impaired. It has also been determined that the loss of a tire on one or more of the wheel assemblies has little effect on the vehicle's performance in soft soils or in water.

FIELD TESTS

While tests and evaluation of the full-scale, TerraStar experimental vehicles are not yet complete, enough work has been done to determine the validity of the concept. The highlights of these tests further illustrate the unusual nature of the vehicle.

Since a fundamental aim with the concept was to obtain good road and highway performance and a capability to negotiate rough terrain, this type of operation received considerable attention in early tests. Road speeds of 30 mph and higher, with excellent directional control, were readily obtained, the limiting factor being, as it turned out, unnecessary concern over tire wear. Running over hard, broken ground, the vehicles exhibited exceptionally good stability and provided a relatively smooth ride at 15 mph. The damping action on the major wheels proved far more effective than had been expected. It was also shown that full revolutions of the major-wheel assemblies, caused by encounters with severe obstacles at reasonably high speeds, caused no control or stability problems. An original shortcoming of TerraStar I was an inability to make tight maneuvers on concrete and asphalt; this was corrected, after some experimentation, by replacing the drum-type, steering brakes with disc brakes of the same type subsequently used in TerraStar II. As touched on previously, one impressive result of the tests, in view of the skid-steering system and the generally rough treatment given both vehicles, is the durability of the low-pressure tires. Only one tire has failed because of a puncture. Except for this, the vehicles are still running on the original tires, and they show no appreciable tread wear.

Most of the water performance tests of both the TerraStar I and TerraStar II vehicles were accomplished by Lockheed at the U.S. Naval Ordnance Laboratory, Corona, Calif. These confirmed the anticipated high propulsive efficiency of the major wheels in water where they act much like paddle wheels, demonstrated the good water speeds that could be achieved without the added complexity of an auxiliary propulsion system, and provided opportunities to work out the best arrangements for baffles to control water flow in the wheel wells and obtain maximum thrust (Fig. 15). The tests also resolved a long-standing question on the TerraStar's ability to travel through dense surface and subsurface marine vegetation. Instead of the major wheels becoming entangled and bound up as they turned, the material was dragged into the wheel wells, chopped up as it passed between the wheels and structure, and expelled (Fig. 16) -- the whole process increasing reactive thrust.

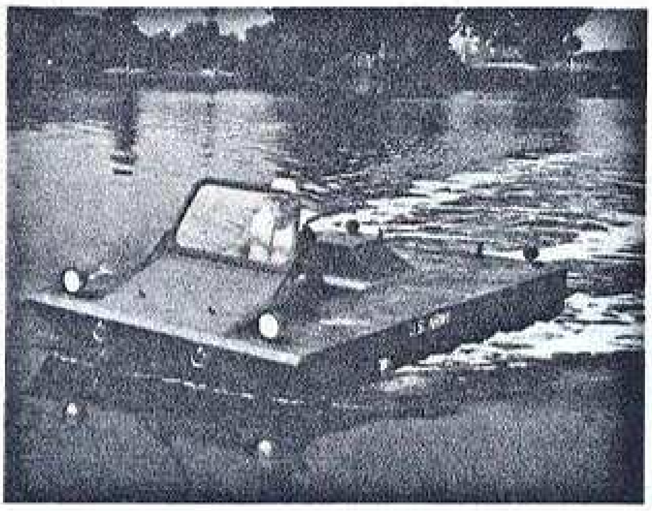

Fig. 15 - Completing a lake crossing

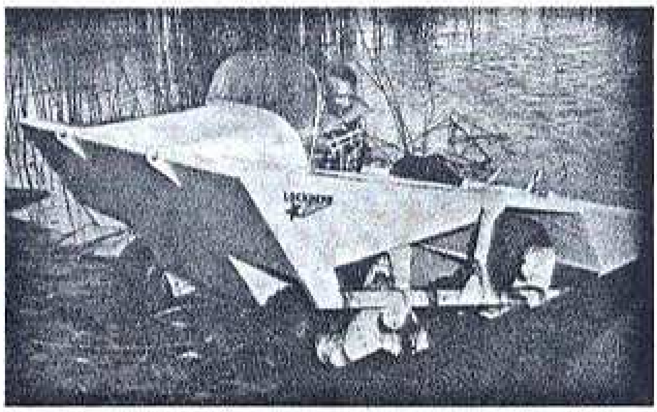

Fig. 16 - Research vehicle after 5 hr in dense marine vegetation

Of all the soft-soil tests accomplished with the TerraStars, the most revealing of the concept's performance were those run by the U. S. Army Limited War Laboratory in a rice paddy (Fig. 17) and in so-called "twilight-zone" conditions at Aberdeen Proving Ground, and the trafficability tests in clays conducted by the Waterways Experiment Station (WES) at Vicksburg, Miss.

The twilight zone (Fig. 18) describes an area in which a near-fluid soil with shallow surface water is not able to support a vehicle's ground contact elements and yet the water is not of sufficient depth to provide full buoyancy for an amphibian. With more or less conventional marginal-terrain amphibians, the wheels or tracks sink deeply into the soil and, because of the soil's lack of shear strength, cannot develop sufficient thrust to overcome the increase in motion resistance as the hull "bottoms out." Both experimental vehicles have demonstrated their ability to operate successfully in such conditions. An interesting sidelight on this

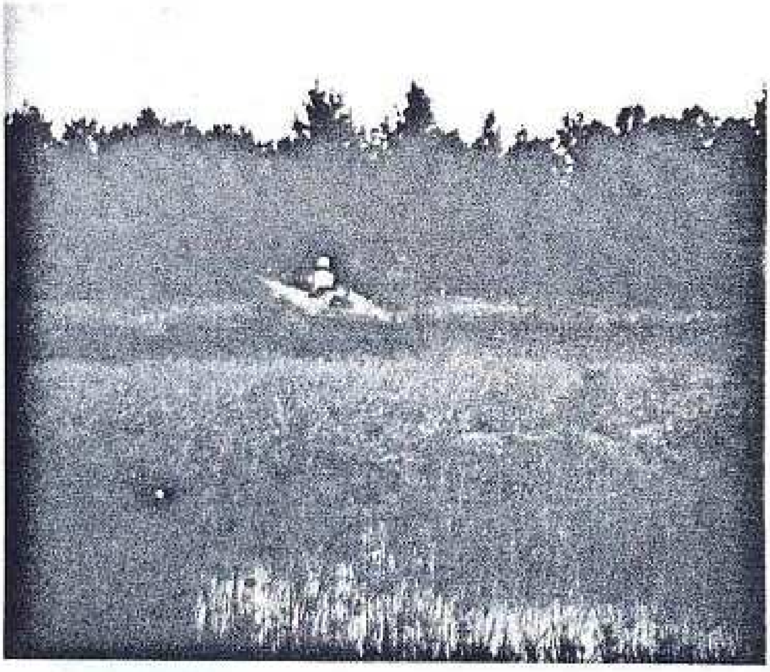

Fig. 17 - Negotiating a rice-paddy dike

Fig. 18 - Operation of TerraStar in twilight-zone

kind of testing was that directional control remained good; the favorable change in the L/T ratio when the vehicle is converted from the minor-wheel mode to the major-wheel mode is responsible for this (Fig. 19).

While complete results of the multipass, trafficability tests are not available as this is written, the TerraStar II has shown that it can operate in the major-wheel mode in clays with a Cone Index (CI, a dimensionless, comparative rating of soil strength) as low as 10. To relate this to common experience, a man on foot will rapidly sink down to his knees if he attempts to negotiate a higher strength soil with a CI of 15. A principal concern with the TerraStar concept had been the possibility of soil buildup on the major-wheel assemblies, especially when operating in clay, to the point where the wheel's ability to generate thrust would be seriously degraded. Although there was some packing of clay at the center of the wheel assemblies experienced at Vicksburg, it never approached a point where it had any effect on their function and it was quickly shed.

What has been done so far clearly shows that the TerraStar has the best type of tracked vehicle mobility in swamps, marshland, tidal flats, deep mud, and intensively irrigated agricultural land, performs very well in the water, and can be operated with the ease and efficiency normally associated with a conventional wheeled vehicle on roads and highways. These results support the theoretical concepts on which the design was based and confirm the early findings of the comparative, scale-model tests. The field tests of the full-scale vehicles have also indicated areas where improvements can be made in the design, for example, providing greater ground clearance, the use of larger diameter tires on the minor wheels, and, in conjunction with further analytical work, indicate that we will shortly be able to get the TerraStar to operate with ease in soils with a CI down to 0.

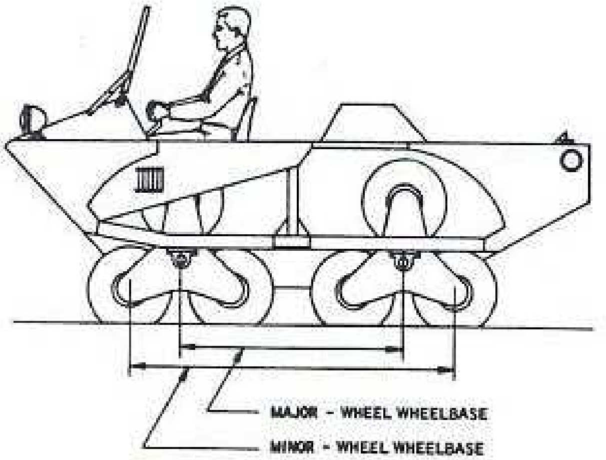

Fig. 19 - L/T ratios for major-wheel and minor-wheel mode of operation

SUMMARY AND CONCLUSIONS

An attempt has been made in this paper to provide a description of the creative and developmental processes brought into play in the evolution of an unusual, specialized ground vehicle from the first rough sketch to full-scale, experimental units. What conclusions can be drawn from the experiences with this project?

The performance of the TerraStar vehicle indicates that it may be useful to investigate further locomotion systems which negotiate soft-soil environments by working down in the medium, as contrasted with the more popular approach in which flotation is emphasized -- especially since this offers possibilities for the development of truly "roadable" marginal-terrain vehicles.

Quite possibly the full potential of scale-model vehicle testing as a working aid in preliminary design has not been realized because many efforts in this area have ultimately become elaborate and expensive. It now seems that a relatively crude apparatus and a minimum facility, while not capable of providing complete, highly accurate data, as in this instance, will, at the very least, provide valuable insights and useful directions to pursue in the early development of conceptual designs.

Simplicity is a major objective with every design. As has been repeatedly demonstrated in the past, the effort to achieve it cannot be started too soon. The early, basic decision to use a gear-train final drive in the TerraStar's major-wheel assemblies enabled subsequent simplification of controls and permitted the elimination of numerous components. And the ultimate result is unusual -- a relatively uncomplicated multienvironment vehicle.

Finally, as the TerraStar evolved into the detail design stage, it became increasingly apparent that there is a scarcity of components suitable for use in light, special-purpose vehicles. This includes engines, clutches, transmissions, steering systems, and just about everything else necessary to complete a design. As it undoubtedly has with many others, this forced compromises which did nothing to enhance performance. It appears it would benefit all of us in this field, and be especially helpful in the military vehicle area, to promote logical and timely component development programs.

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REFERENCES

1. R. C. Stewart and S. J. Weiss, "Trafficability of Soil as Related to Mobility of Vehicles." Proceedings - Separate No. 328, American Society of Civil Engineers, November 1953.

2. M. G. Bekker, "Off-The-Road Locomotion." Ann Arbor, Mich.: the University of Michigan Press, 1960.

3. D. R. Freitag, "A Dimensional Analysis of the Performance of Pneumatic Tires on Soft Soils." Technical Report No. 3-688, U. S. Army Engineer Waterways Experiment Station, August 1965.