DESIGN OF THE "TERRAMAGE" FOR OFF-THE-ROAD LOCOMOTION IN ETHIOPIA

by

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Dedicated to

my wife, Zenaye,

and

our children Yosias, Hebret,

Saba, and Dagmawy.

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INTRODUCTION

The term "terramage" is an Ethiopian word connoting step by step motion. This name describes the machine in general and it is the writer's wish to make "terramage" useful for transportation and draft requirements in Ethiopia.

As a means of justifying the need of the "terramage" in Ethiopia or in any other country that has similar problems for that matter, the writer wishes to give a little background as regards to mechanization and transportation in his country. Ethiopia is one of the oldest countries to be inhabited by people who retained their independence and way of life for a considerable length of time. The Ethiopians are a people who developed a culture which produced able statesmen, generals, and politicians; but contributed very little in producing engineers and other people bent towards technical fields. It was only quite recently that motivation in the technical fields has been aroused. Such skills as blacksmithing, leathercraft, woodcraft and others were considered of inferior type and thus a class was given to people of such trades. It was common not long ago, to consider people belonging to one of the above named trades as inferior to the other groups. This led to the general stagnation in the populace when it came to any type of skill. The effect of such neglect of skill earlier is very much evident today in that the farmer has not changed his way of doing things just like his forefathers did a long time ago. Thus, the Ethiopian farmer is presently found without having harnessed wind power, water power, and power from the minerals. He is not only unable to use the above enumerated sources of power but remains with very limited labor saving devices at his command. The main sources of power on his farm remain his muscles and those of oxen and donkeys that he may own. In general the Ethiopian farmer is a subsistent farmer remaining outside of cash economy. It has been variously estimated that about 90 per cent of the Ethiopian people derive their livelihood from agriculture.

Ethiopia is a mountainous country with many fertile valleys. The main farming region is the plateau located at some 6000 to 8000 feet above sea level. The location of the country west of the Red Sea makes it favorable to receive moisture laden wind which gives the country its abundant rainfall. The average rainfall for the whole country is 40 inches annually while the agricultural regions receive well over 40 inches. Practically speaking, Ethiopia has two seasons namely, the wet and the dry. The dry season lasts for about seven to eight months during which a limited amount of rainfall is received. The wet season is a season of very heavy rainfall concentrated in about a four months period. The two seasons determine the activities of the farmer. The dry season is a season of harvest, travelling, and limited land preparation since the ground remains hard and difficult to plow. It is during the dry season that merchants venture further away from their immediate districts. Whatever produce the farmer has to sell is sold during the dry season and that is if the farmer lives within about two days walk from a small village located on one of the very few highways in the country. The farmer may also be lucky to live near a trail which may occasionally be used by a motorized vehicle. Generally mules, ponies, and donkeys are used to transport goods and people.

The wet season is a season of limited movement by people in the interior of the country. During this season the rivers and even normally dry brooks overflow their banks. The soil becomes very soft and sticky thereby hindering motorized transportation and limiting natural transportation namely walking by man or animals. Contrary to one's expectation the farmer increases his activity on his farm during the initial stages of the rainy season. He prepares his land during the beginning of the wet season and terminates his work after sowing which is towards the middle of the rainy season. The sowing season may be in the wettest period for some crops notably "teff" which is the staple food of the Ethiopian people.

Presently Ethiopia is served by a few highways and about three rail lines which total 700 miles (12). Five major highways radiate out from the capital city, Addis Ababa, which is located in the center of the country. Only two of the highways reach the border, while the others terminate at about 200 to 300 miles from the border of the country. Feeder highways are very limited. It may be estimated that on the average the Ethiopian farmer lives within 100 miles of a highway. Thus he has to depend on his traditional method of transportation namely walking and/or mule back riding. By this method he may cover the 100 mile distance in about three days. Should he have to transport a few pounds of grain, his speed may be reduced since he needs to advance at the pace of the loaded donkey (Plate II, Fig. 1 and Plate III, Fig. 1)

The present mode of transportation known to the Ethiopian farmer has not been modified or changed for generations. The wheel seems to be unknown to him even though he may observe its use on vehicles for transport. Dr. W. F. Buchele of Iowa State University made a brief visit to Ethiopia after his tour of the orient, India and Egypt. During his tour he made an observation to the effect that the bicycle to be the fore-runner of mechanization. Upon his arrival in Ethiopia, however, he found bicycles to be very limited in number in the cities and non-existant on the farms.

Ethiopia is fortunate enough to have a good internal air service. Remote areas inaccessible to wheeled vehicles are reached by airplane. The airplane serves to transport both people and the produce of such localities. Specifically coffee and hides find their way to the market by airplane (7). The introduction of the airplane has markedly improved communication within Ethiopia but it has hardly scratched the surface in meeting the needs of the farmer. Due to the prohibitive cost and limited number of airplanes as well as air strips, the airplane cannot serve adequately in revolutionizing transportation in Ethiopia.

Transportation is the central problem of Ethiopia today. As a result of inadequate transportation, mechanization has lagged considerably. Presently, not over two to three thousand tractors exist in the country. The present source of the farmer's power can hardly leave any room for hope in his ability to increase food production in order to meet the staggering food shortage in the world. Ethiopia is an agricultural country and one blessed with a climate that allows food production the year round. All these privileges will be of no value unless the farmer can be reached. The farmer cannot be easily reached as road construction is slow and requires a large capital outlay which the country does not have. A faster and cheaper method to reach the farmer must be sought in order to hasten Ethiopia's progress. Not only must the Ethiopian farmer be reached, but he must be provided with better tools to increase his efficiency and effectiveness. Therefore with the present problems of Ethiopia in mind, it is the expressed purpose of this thesis to suggest a method of reaching the farmer and providing him with a tool such that he may participate in raising the economy of his country.

PROBLEM AND OBJECTIVE

It was pointed out in the previous paragraphs that the Ethiopian farmer is very much limited in his ability to increase his production and get his produce to the market. As far as this thesis is concerned the problems that the Ethiopian farmer faces are mainly classified into two categories. One group of problems is the lack of adequate transportation. The second group arises from lack of power on the farm. The two groups of problems are discussed in some detail under their respective headings.

Transportation As It Affects Progress in Agriculture

Agriculture is the main economic strength of Ethiopia. Even though few modern factories like the cement, brewery, textiles, meat packing, sugar making and oil seed processing are being built, the Ethiopian government depends heavily on land taxation as a source of its revenue. Land is classified as fertile, semi-fertile and unfertile; and the taxes are levied according to the above classification. However, the terms used in land classification do not describe the inherent fertility of the soil but merely indicate the extent of farming done irrespective of the farmer's income and the type of crop grown. The extent of farming done is directly dependent upon whether the region has good outlet for its produce or not. A farmer may own a large section of land which may inherently be very fertile. However, due to lack of adequate transportation in his region he may develop a few acres of his land leaving the rest untouched. Of course, this will directly reduce the government's revenue and also make the farmer lose interest and incentive in his farming operations.

Unlike many areas of the world where roads were built through regions of economic importance, almost all of the Ethiopian roads were built through regions lacking in economic importance but highly important strategically. This happened during the Italo-Ethiopian war. Presently road planning and construction is of a different nature. The socio-economic importance prompts the construction of roads in many regions of the country. It also includes the reconstruction of the already existing roads.

Ethiopia is spending millions of dollars for the maintenance and reconstruction of the existing roads as well as the construction of new ones.[1] Presently Ethiopia is served by some 5000 miles of all-weather roads which may be divided into about 90% major highways and 10% feeder roads (Plate I). The terrain and heavy seasonal rainfall make road construction and maintenance very costly. The cost of road construction varies according to the terrain over which roads are constructed. In flat areas the cost ranges between \$10,240 to \$22,400 per mile while in rugged areas the cost is \$128,000 per mile. Cost of maintenance per mile ranges between \$1600 to \$1984 (15).

Lack of capital will always beset Ethiopia's endeavour to reach inaccessible agricultural regions. Wherever road transportation improvement has been made, one sees a definite awakening of the people. Business flourishes, extent of farming increases,

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[1]Ethiopia depends very heavily on foreign loans to finance the construction of its highways.

number of schools increase, and people start to move about. Such was the experience of the writer some years ago. In 1952, the writer had to travel by bus to a rich agricultural region where coffee grows wild. A distance of 210 miles took fourteen hours to cover. After the road was improved, however, the time was reduced to five hours and the bus service increased from once a week to three buses a day. The population of the town (the terminus) doubled within about four years.

Today the bulk of the farmer's produce is moved by pack animals mainly donkeys (Plate III, Figs. 1, 2, and 3). The donkey can at most carry 100 pounds of grain during the dry season. Such limited load-carrying capacity of the donkey makes it necessary to own or hire many donkeys to move to market any appreciable amount of the farmer's produce. Furthermore the farmer has to depend on the mule or the pony for his own transportation. Here again the mule or the pony is limited to carrying one person. Should it be desired that about ten people have to travel together, the number of ponies or mules required about equal the number of people. This is why the total animal population on the farm other than cattle is 42,000,000 (7).

Power As It Affects Progress in Agriculture

In Ethiopia today the farmer uses a wooden plow with steel point, the hand sicle, the hoe, and the axe (Plate IV). The plow is a digging type tool cutting a very narrow furrow. The soil is not cut, pulverized and inverted to expose the roots of weeds as done by the modern plow (8). Such limitations of the

Ethiopian plow increases the time the farmer spends in his field. The farmer has to plow the same field four times before it is ready to accept seeds. Even then large clods remain in the field. (6). After the crop emerges the farmer weeds the same field four times by hand (Plate V).

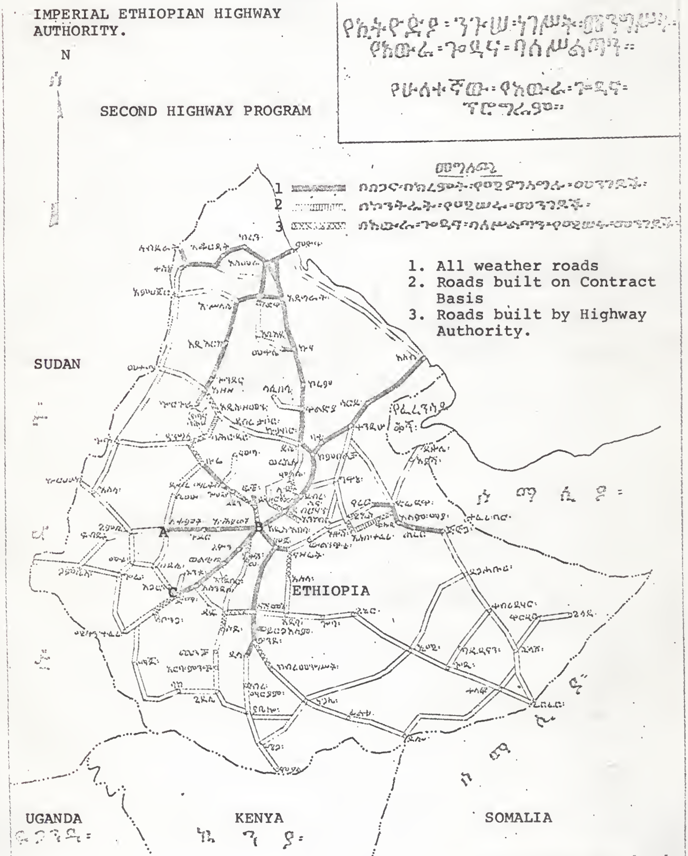
When it comes to harvesting, the farmer depends on his hand sickle. He harvests a handful at a time until the entire field is covered. Such is the method that his forefathers handed down to him. Threshing too, as one of the farmer's operations, has not changed from generation to generation. Presently the farmer uses oxen to trample the grain after which direct wind power is used to separate the seed from the straw (16).

The progress of agriculture in Ethiopia hinges on two factors namely (1) availability of an adequate transportation and (2) availability of adequate power on the farm. Power and transportation must receive due attention in order to utilize the rich agricultural resources of Ethiopia so that the Ethiopian people can lead a better life. With the present problems of Ethiopian agriculture in mind, the objective of this thesis was to design a machine suited for off-the-road transportation and draft requirements on the farm with a minimum of power expenditure.

EXPLANATION OF PLATE I

Second Highway Program

PLATE I



IMPERIAL ETHIOPIAN HIGHWAY AUTHORITY.
N
SECOND HIGHWAY PROGRAM
1. All weather roads
2. Roads built on Contract Basis
3. Roads built by Highway Authority.
SUDAN
ETHIOPIA
A
B
C
UGANDA
KENYA
SOMALIA

EXPLANATION OF PLATE II

Figure 1 - A typical all weather highway.

Figure 2 - Truck and trailer on a highway near the capital.

Figure 3 - Part of the Addis Ababa plateau.

PLATE II

Fig. I

Fig. 2

Fig. 3

EXPLANATION OF PLATE III

Figure 1 - Grain transported to market.

Figure 2 - "Teff" straw on the way to the market.

Figure 3 - Donkeys laden with grain.

PLATE III

Fig. 1

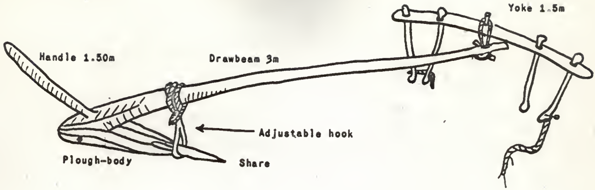
Fig. 2

Fig. 3

EXPLANATION OF PLATE IV

The Ethiopian Plow

PLATE IV



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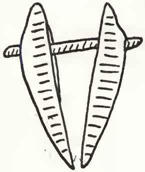
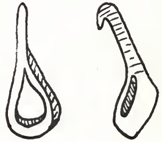
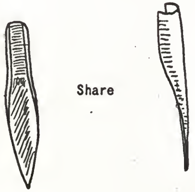


Wooden shanks of plough-body



Adjustable hook, iron



Share

EXPLANATION OF PLATE V

A farmer preparing seedbed for "teff".

PLATE V

LITERATURE REVIEW

The planet earth has complex physical features that make movement from place to place very difficult for the creatures that inhabit it. Its rugged mountains, deep seas and oceans, the jungles, the sandy deserts, the snow covered regions, and wet lands require different means to traverse them. This is made necessary due to the fact that the creatures that inhabit the earth have such a small size compared to that of the earth itself. Should the earth be inhabited by such an imaginary creature that can stand somewhere in the Atlantic Ocean and can reach with its long and huge arms the continents of Africa, Europe and South and North America, locomotion (actual displacement of the creature) would be unnecessary. Fortunately or unfortunately as the case may be, man and other creatures have to move about in search of food and shelter. Specifically man seems to move about more and this is clearly shown by his efforts to create machines that enable him to go places faster and carry a heavier load. Of the machines that man has developed for his own transportation, only those that enable him to move over rough terrain are considered here. The writer thus wishes to review off-the-road locomotion briefly under the following two headings

Off-the-Road Locomotion by Animals

Animals were designed to fit their environment. Their environment is very much diversified that one sometimes wonders how it may be possible for them to so easily adapt to it. Their size makes it necessary to cross deep gorges, climb steep and rugged hills, pass over very soft and weak soils, avoid such obstacles as boulders and trees, and pass over snow covered terrain. The higher forms of animals are able to walk, run and leap.

Bekker (3,4) has shown the power requirement for the different modes of locomotion by animals. The equations[2] that Bekker proposed for leaping, running and walking are

$$(P)_{leap} = 0.91 \frac{V}{\sin\alpha \cos\alpha} \quad \text{HP/ton} \quad (a)$$

$$(P)_{run} = 0.91 \; V \tan\alpha \quad \text{HP/ton} \quad (b)$$

$$(P)_{walk} = 3.63V \frac{L_w}{p_w} \left[1 - \sqrt{1 - 0.25 \left(\frac{p_w}{L_w}\right)^2} \right] \quad \text{HP/ton} \quad (c)$$

In equation (a) above Bekker defines 0.91 as a factor that expresses the conversion of the units of power into units of horsepower per ton, V as the speed of locomotion in feet per second, and α as the angle at which the trajectory of leaping is inclined with respect to the horizon. The factors in equation (b) are similarly defined. In equation (c) L_w denotes the leg length and p_w denotes the step length.

Bekker (3,4) considers that in leaping the total kinetic energy is lost while in running only the vertical component is lost. Walking (Plate VI) entails the consumption of power in

[2]Equations (a), (b), and (c) are respectively equations (1), (2), and (5) shown in Reference number 3.

order to raise the center of gravity. Comparison of the different modes of animal locomotion as well as tracked vehicles, the truck, and railroad cars is shown by Figure 1 in Reference 3 and Figure 12 in Reference 4. This was done after assigning values to factors shown in the equations for the different modes of locomotion.[3] Figures 1 and 12 cited above show the relationship of speed in miles per hour versus power requirements in horsepower per ton over soft, smooth ground and hard smooth ground. According to either graph walking is considered to be the most efficient in the use of power for locomotion off the road. Moreover, when the terrain changes from hard to soft the power requirement for walking remains practically the same while the change in the terrain is accompanied by a marked increase in power requirements for other modes of locomotion. However, when it comes to locomotion on man-made (the railway line and the highways) surfaces, the train is considered highly efficient in power consumption per unit weight.

Mechanized Off-the-Road Locomotion

Man's desire to conquer the remotest part of the earth made him invent the modern vehicles of transport. He has made great strides in the development of air, space, rail, road, and sea travels. In his effort to improve land transportation he built

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[3]The speed, V, was assigned a value of 20 mph, $\alpha = 45^{\circ}$, and $L_w/p_w = 1.65$.

[4]The speed is shown for a hard, rough ground.

beautiful highways and rail lines. He not only improved the terrain (the environment) for his vehicles of transport, but built faster cars, buses, trucks, and locomotives. Such improvements hinged on adapting the terrain to his vehicles rather than adapting his machines to the environment (3). The trend of adapting the environment to the vehicles of transport is a costly proposition as nature does not provide man with a ready-made highway or the rail line. Such prohibitive cost has made him look elsewhere in order that he may go to areas where highways do not exist. Thus he started to conceive mechanized off-the-road locomotion.

Man has turned to such engineering materials as concrete and steel to lay his highways and rail lines. However, when it comes to off-the-road locomotion he has to rely on the constituents that make up the terrain he wants to traverse. He encounters soils that must support weight when he moves across them or soils that he works to raise food. Soils as engineering materials have complex properties that change according to their water content. Thus man tried to characterize soils as engineering materials using emperical equations. The basic equation that defines the shearing strength of soils is:

$$S = C + p \tan \phi \qquad \text{(d)}$$

where S denotes the shear stress of the soil, C denotes stress due to cohesion, p is the normal stress, and ϕ is known as the angle of internal friction. Such equation is known as Coulomb's equation (14). Equation (d) is for an average soil having the cohesive as well as frictional properties. Equation (d) is written as:

$$S = C \qquad (e)$$

for a frictionless soil while for cohesionless soil equation (d) becomes

$$S = p \tan \phi \quad . \qquad (f)$$

Multiplying equation (d) by A (contact area) gives:

$$A\,S = AC + Ap \tan \phi \qquad (g)$$

which becomes:

$$H = AC + W \tan \phi \qquad (h)$$

where H is known as the thrust developed, and W is the weight of the vehicle crossing the soil. According to equation (h) knowledge of the values of C and ϕ are necessary in order that the off-the-road locomotion engineer can determine whether locomotion can be negotiated in such coil. However, equation (h) does not indicate how much the soil can be compacted by the vehicle. This calls for another equation that relates sinkage and normal pressure. Bernstein (3) used the equation in the following form:

$$P = Kz^{1/2} \qquad (i)$$

The same equation was written by Russian investigators as:

$$P = k\,z^{n} \qquad (j)$$

wherein K denotes a modulus of soil deformation while n is the exponent of deformation (3). The civil engineer uses another equation relating sinkage and the pressure on the soil. This equation is written as:

$$P = [B/b + C] z \qquad (k)$$

in which B represents a modulus of deformation related to the cohesion of the soil while C is a modulus associated with the frictional part of the soil (3). When equation (k) is modified, it is written as:

$$P = (k_c/_b + K_\phi)\ z^n \qquad (L)$$

in which b represents the smaller dimension of the area of loading (3).

When wheels or tracks pass over soils, the soils deform horizontally. This phenomenon cannot be described by equation (1). Bekker (3,4) proposed an equation that defines horizontal shearing strength, S, of the soil in terms of d (soil deformation), C (cohesion), ϕ (friction), and P (ground pressure). The equation is written as:

$$S = (C + P \tan \phi) \Big/ Y_{max}$$

$$\{ \exp\left(-K_2 + \sqrt{K^2{}_2 - 1}\right) K_1\, d - \exp\left(-K_2 - \sqrt{K^2{}_2 - 1}\right) K_1\, d \} \qquad (m)$$

where K_1 and K_2 are known as slip parameters while Y_{max} represents the maximum value of the part within the brackets.

Based on equations (d), (L), and (m) there are several parameters namely C, ϕ , n, K_c, K_ϕ, K_1 and K_2 that must be known in order that one may know whether locomotion can be negotiated over soils in question. Up until quite recently the tire and the track were the only devices used for the mechanized off-the-road locomotion. This is because designers of transportation vehicles still adhere to the idea of adapting the environment to the vehicle rather than adapting the vehicle of transport to the environment. Any improvement in the off-the-road locomotion vehicles is based on the improvement of the conventional road vehicles. The farm tractor is a little exception in that it is provided with non-conventional tires. Even then the improvement made in the farm tractor was made paralleling that of the road vehicles. This is specifically true when one considers the increase of power per unit. All improvements made in the off-the-road locomotion vehicles seem to center around the power plant (3). This appears to be a reason why the above enumerated parameters are of importance.

Equation (d) ($H = AC + W \tan \phi$) shows the thrust that can be developed in a soil. The thrust, H, can be increased either by increasing the contact area of the wheel or track or the weight of the vehicle. This is true for an average soil. In a cohesive soil (ϕ=0) the weight cannot serve to generate thrust and therefore thrust can be increased by increasing the contact area only. In a cohesionless soil (C=0) the contact area does add to thrust improvement and thus only the weight should be increased to increase thrust. When a frictionless soil ($\phi=0$) is encountered the contact area can be increased by increasing either or both dimensions of a rectangular track or the diameter of a wheel. However, limitations in increasing the dimensions of the contact area are discussed later in this thesis.

The thrust generated in the soil cannot be fully used to do useful work. However, part of it is utilized to overcome the external motion resistance due to compaction of the soil, bulldozing and dragging of soil particles caught by the suspension and protuding parts of the vehicle (3). Bekker proposed an equation that shows motion resistance due to compaction. Such an equation is:

$$R_c = \frac{1}{(n+1)(K_c+bK_\phi)1/n} \left|\frac{W}{L}\right|^{\frac{n+1}{n}} \qquad (n)$$

wherein b is the smaller dimension of a rectangular track while L is the larger dimension. The ability of a vehicle to move depends upon the difference between soil thrust and motion resistance. As soon as motion resistance equals soil thrust, locomotion of the vehicle ceases. The difference between soil thrust and motion resistance gives the drawbar pull (3).

It was discussed earlier that engineers try to improve the locomotion of off-the-road vehicles by improving the traction devices, namely, the tire and the track. Accordingly one sees the appearance of terra tires on the market. However, one wonders how far it is possible to go in improving the coefficient of traction[5] of off-the-road vehicles using the present trend of vehicle concept.

When using the tracked vehicles one cannot increase the width or the length of each track at will in order to improve the ratio of the drawbar-pull to weight. Bekker (3) indicates to the effect that the width of a track cannot be further increased due to the limitations imposed by road gauges and vehicle belly. Similarly the length of a track cannot be increased due to steering problem. In regards to the wheel, one needs to increase its diameter to increase the length of the ground contact area. Here again Bekker (3) indicates the limit as follows:

> "...Nowadays 10-ft-diameter tires have already been built without satisfying all the requirements of mobility. Are we going to increase the diameter further? Without answering this question directly, one may agree that this avenue of approach is also nearing a dead end."

The conventional off-the-road vehicles are limited in many ways. Their ground clearance has not changed such that they may fail while corssing a rough and soft terrain. Furthermore rough terrain imposes a limit on the speed of off-the-road vehicle even though it does not lack power. Limitations of off-the-road vehicles is further magnified by Bekker in the following statements (3).

> "Present development trends have reached their ultimate and no radical change in performance of motor vehicles may be expected. Certain

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[5]Coefficient of traction is the ratio of the drawbar-pull to the vehicle weight.

> readjustments and improvements of performance within the existing vehicle concept are quite possible, however, and may be achieved by analyzing the soil-vehicle systems. A study of a number of possible combinations of soils and vehicles, or their elements, must be performed in order to select the optimum solution. This must be based on a knowledge of soil values and on the mathematical representation of soil-vehicle relationships.
> Future radical progress cannot be expected when following the approach of prevailing concepts. New vehicular concepts are needed..."

In order to improve off-the-road locomotion, a symposium was held at Auburn University in October, 1964. The symposium dealt with (a) moon locomotion, (b) machines that hop, walk or crawl, (c) tire and track efficiency, (d) new agricultural engineering responsibility. The meeting was attended by 90 scientists representing industry, universities, and government agencies. Bekker gave two lectures on a subject entitled "Methods of Approach for Research in Off-the-Road and Lunar Locomotion" (10).

Lunar explorations and military needs have increased interest in off-the-road locomotion. Such names as the "walking truck", "quadruped transporter", and the "moon walker" are appearing in various sources of literature. These machines are reviewed by the writer in the following paragraphs (1,2,9,13).

The Quadruped Transporter (Plate VII) is a vehicle that is developed to meet military needs. The "walking truck" as it is also known is designed to mimic the movements of the arms and legs of man. The operator becomes the brain of the machine. Whatever movement the operator makes is made by the truck. This means that the operator selects where the feet should be placed. Advanced levers, control linkages, and servomechanisms are used to make the vehicle operate.

The "walking truck" uses hydraulic systems to operate its jointed legs. The legs stand six feet while the length and width of the truck are respectively 10 feet and 4 feet. Presently the "walking truck" is claimed to carry a load of 500 pounds at a speed of up to 5 miles per hour. It is also considered that this vehicle is able to traverse terrains that cannot be traversed by the conventional vehicles.

Unlike the wheeled vehicles that continuously compact the soil they pass over, the "walking truck" compacts the soil only at the points where its feet come in contact with the ground. Thus it is considered that there is a saving of power over the conventional vehicles. Besides meeting the military needs in the way of transport, the "walking truck" is anticipated to serve in reaching isolated logging camps and assist in the maintenance of power transmission where roads do not exist.[6]

The "Moon Walker" is another off-the-road locomotion vehicle that was originally designed for lunar locomotion. Specifically it was aimed to land on the moon with Surveyor space craft. The original design provided for six legs, however, after it was rejected by NASA, the design was changed to include eight legs, and

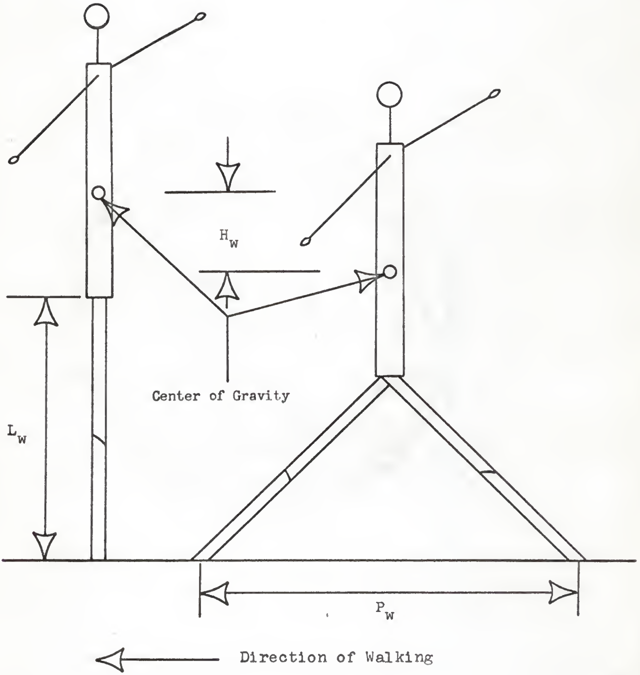
[6]Information was provided by the General Electric Company.

thereby serve for locomotion of cripple children. Even though detailed information is not available to the writer, the "Moon Walker" has jointed legs in which one pair of legs swing forward or backward while the second pair is in contact with the ground supporting the weight. According to one report, the "Moon Walker" can be steered easily and is also able to climb a 30° slope, cross rough fields, and pass over an 8-inch curb. (1,13).

EXPLANATION OF PLATE VI

Diagram of a walking man as
he progressively moves from right to left.

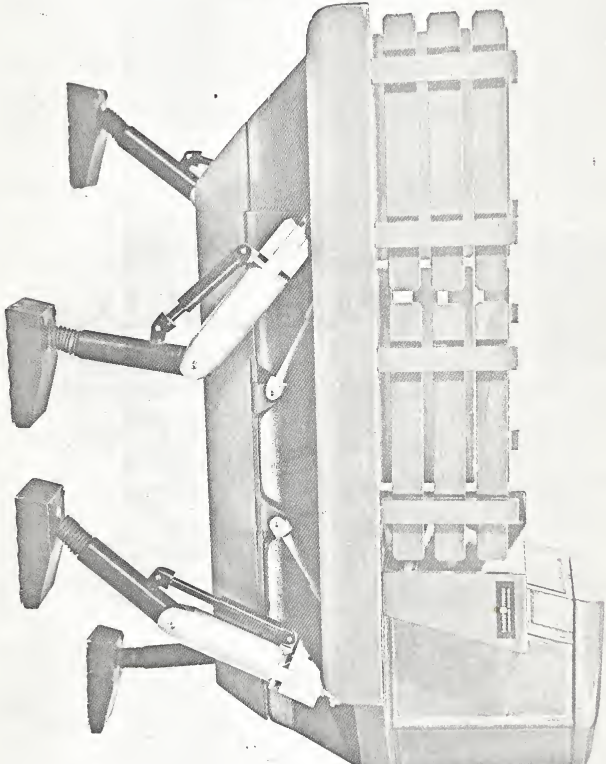
PLATE VI



EXPLANATION OF PLATE VII

Quadruped Transporter ("Walking Truck")

PLATE VII



ORDNANCE DEPARTMENT
GENERAL ELECTRIC

PHOTO #NOD 27203 - UNCLASSIFIED - QUADRUPED TRANSPORTER - MANIP. MISC. - 2-23-66

DESIGN OF THE "TERRAMAGE"

The "Terramage" consists of two frames, a power car, and six legs. One of the frames (Plate VIII, B) is 1 foot high, 10 feet long, and 3 feet and 7 inches wide. The second frame (Plate VIII, A) is 2 feet high, 7 feet long and 4 feet and 4-1/2 inches wide while the power car is 1 foot high, 4 feet wide and 5 feet long. Three legs are attached to frame A while the other three are attached to frame B (Plates VIII and IX). The three legs on each frame form an imaginary triangle.[7] Plate VIII shows frame B in contact with the ground through the media of its three legs while frame A is off the ground and is ready to move forward. This means that frame B is supporting the power car and frame A. Frame A moves forward (displacement = 2 feet) on frame B by rollers resting on frame B (Plate VIII, 7 and Plate IX, 5) and the side rollers (Plate IX, 6). At this time the power car (Plate VIII, 2) also moves on the stationary frame B by the wheels contacting frame B (see Plate VIII, 6 and Plate IX, 4). After frame A is displaced two feet to the left (Plate VIII), it lowers its legs and is then ready to support the weight of the power car and frame B which must be displaced 2 feet to the left after frame A is completely in contact with the ground. Frame B moves on frame A by means of the rollers resting on frame A (Plate VIII, 22 and

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[7]Introduction to Bekker's theories on off-the-road locomotion in Advanced Farm power and Machinery class taught by Dr. G. H. Larson coupled with the staggering transportation and power problems at the farm level in Ethiopia motivated the writer to conceive the design of the "terramage" as of September 22, 1965.

Plate IX, 10) and the side rollers (Plate IX, 6). The power car then moves on frame B by means of the wheels resting on frame B (Plate VIII, 5 and Plate IX, 3). The power car is also supported by the side rollers shown by number 20 in Plate IX. This means that the power car is continuously moving while frames A and B take turns in supporting it. Basically the "terramage" can be considered to be a vehicle that carries its road. Either frame is displaced to the left at a speed which is twice the speed of the power car.

The above paragraph indicates that the "terramage" moves as a result of a sequence operations. When frame B contacts the ground by its legs (Plate VIII), frame A is displaced to the left by means of a hydraulic cylinder shown as number 8 in Plate VIII and number 7 in Plate IX. The piston is attached to frame B at its ends while the cylinder is attached to frame A. Oil is introduced to the left port and the pressure pushes on the left and inner surface of the cylinder thereby moving frame A to the left since its legs are off the ground. After frame A is fully displaced, its legs are lowered to the ground. Next frame B raises its legs and then oil is introduced to the right port such that the pressure pushes on the surface of the land (shown as part of the piston in Plate VIII) thereby moving frame B to the left. While this sequence operation is taking place, the power car (Plate VIII, 2) is continuously powered by means of an alternate power supply to the rear wheels in contact with the stationary frame. This indicates the fact that the wheels are powered and depowered as the case may be. The sequence operation carried out by means of hydraulic systems is discussed in detail in the following paragraphs.

The key to the function of the "terramage" is the master control which like the brain controls the timing and the various functions. Plate X, Fig. 3 shows the master control and the components it directs. Before the full function of the master control is discussed the components it controls need to be described.

The "terramage" utilizes hydraulic valves and cylinders to perform the various functions that constitute the sequence operation. Altogether there are nine hydraulic cylinders and nine 4-way, two solenoid, spring centered directional control valves with each valve directing the operation of its respective cylinder. Plate X, Fig. 3 shows the electric and hydraulic systems jointly for performing a function: Number 7 in Plate X, Figure 3 shows the hydraulic cylinders that operate the legs on frame B while number 6 shows hydraulic cylinders that operate the legs on frame A. Number 4 is a hydraulic cylinder that moves either frame A or B. Numbers 2 and 3 show hydraulic cylinders that are used to power and depower the wheels on the power car. Plate X, Figure 1 shows the mechanism that makes powering and depowering of the wheels possible. Figure 2 (Plate X) also shows the linkage and hydraulic cylinder that prompts the powering and depowering of the wheels on the power car. In order to give the complete operation of the master control, knowledge of the complete sequence operation is necessary. The following sequence operation shows step by step how the "terramage" moves forward.[8]

(A-I) Wheels referred to by numbers 5 and 6 in Plate VIII are both powered.

(A-II) Wheels shown by number 5 in Plate VIII are depowered.

(A-III) Legs on frame A (Plate VIII) are lifted.

(A-IV) Frame A moves forward.

(A-V) Legs on frame A (Plate VIII) are lowered.

(A-VI) Wheels to which number 5 refers in Plate VIII are powered.

(B-I) Wheels numbered 5 and 6 (Plate VIII) are both powered.

(B-II) Wheels shown by number 6 (See Plate VIII) are depowered.

(B-III) Legs on frame B (Plate VIII) are lifted.

(B-IV) Frame B moves forward.

(B-V) Legs on frame B are lowered.

(B-VI) Wheels indicated by number 6 in Plate VIII are powered.

The master control shown by number 27 in Plate X is a circular plate mounted on a shaft to which a rotating arm is attached. The plate is divided into arc lengths according to the length of time the operation in question requires. Arc A-I (see Plate X, Fig. 3) for instance represents the time it takes to power or depower the wheels on the power car, while arc A-III represents the time needed for the legs on frame A to be lifted up. Between each

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[8]The sequence operation is to be studied by assuming that in the beginning both frames A and B have their legs on the ground. It should also be studied by referring to Plate X, Figure 3.

step there is a gap (see Plate X, Fig. 3) which corresponds to the time that is necessary so that any two adjacent steps do not overlap. The master control is designed in such a way that power is made available only when it is on the non-gap arc.[9]

The driving (powering and depowering) mechanism shown in Plate X, Figure 1 consists of the clutch assembly, hydraulic cylinder and a simple linkage. The belt (number 11, Plate X, Fig. 1) transmits power from the engine. The sheave (number 10, Plate X, Fig. 1) rotates on the shaft by means of a bearing. Power is transmitted from the pulley (sheave) to the shaft and finally to the driving wheels (number 9, Plate X, Fig. 1). Number 12 in Figure 1 shows a clutch plate in contact with the sheave surface. The spring (number 13, Fig. 1) presses the clutch plate against the sheave. The clutch plate transmits power to the plate on the shaft (see number 14, Fig. 1). The plate shown as number 14 in Figure 1 is welded to the shaft such that rotation of the plate brings about rotation of the shaft. The power is cut off from the shaft when the clutch plate disengages the sheave surface. This is known as depowering of the wheels (see number 9, Fig. 1). The depowering of the wheels is accomplished by the cylinder shown as number 2 in Figure 3, number 16 in Figure 1,

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[9]According to Plate X, Figure 3, the rotating arm is on arc A-IV such that power is provided to the right solenoid of the valve which controls the hydraulic cylinder (Plate X, 4) that moves frame A forward. This is accomplished by the fact that when the switch (Plate X, 25) is closed current flows to the right solenoid and then to arc A-IV passing to the rotating arm. From the rotating arm the current passes to the shaft which is ground thereby returning to the battery (Plate X, 24).

and number 22 in Figure 2 (see Plate X). In Figure 2 the bar shown by number 21 has one of its ends attached to the hydraulic cylinder (number 22). The other end of the bar is connected to a handle attached to the assembly shown as number 15 in Figure 1. The bar is pivoted at a point shown by number 20 in Figure 2. When the piston extends it pushes the bar to the right (see Fig. 2). This action makes the opposite end of the bar move to left thereby moving the assembly shown as number 15 to the left in which case the clutch plate is disengaged. At this time the spring (number 13, Fig. 1) is compressed. When the piston retracts, however, the spring pushes against the clutch thereby engaging it with the surface of the sheave.

Plate XI shows an example of how the hydraulic and electrical systems operate. The schematic must be studied along with the leg detail in Plate VIII since the hydraulic cylinder shown in Plate XI is one of the legs shown in Plate VIII. Before any further discussion is made of the two systems, it is necessary to describe how the control valve (number 16, Plate XI) operates.

The valve is a 4-way, spring return, solenoid operated directional control valve (11). The spool has three lands (see Plate XI) which control the three ports of the valve.[10] The center port is for the supply of oil while the left and right end ports are for exhausting (discharging) the oil which then returns

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[10]Plate XI shows the valve with the lands centered. Even though it is not shown clearly on the drawing, the valve is overlapped.

to the reservoir (see number 10, Plate XI). Oil cannot enter while the valve is centered. If the legs were to be lifted, oil must be supplied to the upper port of the hydraulic cylinder (number 2, Plate XI). This is accomplished by first energizing the right solenoid (number 18, Plate XI) which moves the spool to the right thereby allowing oil to enter the supply port and directly flowing to the upper port of the hydraulic cylinder (number 2, Plate XI). The solenoid is energized as long as the rotating hand (shown more clearly as number 26 in Plate X) is on the arc A-III (see also Plate IX). As soon as the solenoid is de-energized the spring (number 15, Plate XI) centers the valve. On the other hand if the legs were to be lowered, the left solenoid is energized pulling the spool to the left such that oil flows to the lower port of the hydraulic cylinder. By the same token when the solenoid is de-energized the valve is centered by the left spring.

Lowering of the legs is a different operation than the lifting of the legs. The "terramage" is designed in such a way that each leg be lowered independently of the others. This is necessary in order to make the legs fit the terrain since the points where the legs contact would have different elevations. In order to avoid leg settlement which can be brought about by the additional weight from the power car and the moving frame, each leg is lowered with a force about equal to its own share of the anticipated maximum weight it is to support. As soon as the force with which the leg is lowered is exceeded due to the upward push of the ground the leg ceases its displacement downward. This is accomplished by a mechanism provided in the pad on the leg. Plate VIII shows the details of the pad. Part number 18 is a rubber facing attached to an aluminum plate (number 19). A pipe (number 20) is welded to the aluminum plate while another pipe (number 15) is welded to the upper portion of the pad which is in the shape of a frustum of a cone. Number 13 is a guide post for the spring (number 14) shown compressed. Number 17 is a flexible joint also shown compressed to allow free movement up or down of the lower portion of the pad. Number 16 shows a two-way pressure switch wired in with either solenoid (see Plate XI). One set of contacting points of the pressure switch opens while the other set closes when the ground pushes up with a force greater than the force with which the leg is lowered. This action breaks the circuit thereby deenergizing the solenoid in question even though the rotating hand is still on the respective arc. The closed points assure the flow of current at the time the legs are to be lowered.

It was discussed in the introduction that the "terramage" is intended to serve for transportation and draft. Plate XII shows a design of the "terramage" which is adapted to meet the draft requirement. The power car (number 7) is shown close to the ground in order to facilitate mounting of the implement. The attachment of the legs on frame A (number 1, Plate XII) is varied such that instead of two legs in front as shown in Plate VIII, the two legs are at the rear. This design is also different than the one shown in plate VIII, because the height of the "terramage" has been reduced.

The design shown in Plate XII is also very useful from the standpoint of steering. The "terramage" is so radically different that none of the steering methods used on the conventional vehicles apply. Plate XIII shows a method for steering the "terramage". The "terramage" is steered by the frame in contact with the ground. The frame pivots on the front leg while its rear moves on the curved beam attached to the rear legs. The solid outline of the frame shows the initial position while the dotted outline shows its position after the frame is displaced from its initial orientation. After the frame is in its new position (see dotted outline), the other frame can lower its legs and then carry the weight of the power car. This means both frames are oriented at an angle of θ to the original direction. In the next step the frame that was on the ground first lifts its legs after the weight is transferred to the second frame. When the legs are lifted off the ground, legs A and C swing back in position under their respective frame. This can be accomplished by the use of hydraulic cylinders.

The orientation of the frame in contact with the ground cannot be greater than an angle of θ so that the stability of the "terramage" cannot be disrupted. Plate XIII shows the legs marked as A, B and C. It is to be noted that the three legs form an imaginary triangle. If the center of gravity of the "terramage" falls within this imaginary triangle, the "terramage" would be stable (see Plate XIII).

The preceding paragraphs show that either frame A or B has a stop and go motion. In other words, the frames have to be accelerated after each of their respective stops. Since this is the case the mass of each frame is kept to a minimum by using light weight materials and by avoiding installation of parts that would add weight. Accordingly, the components of the hydraulic and electrical systems of the "terramage" are mounted on the power car which has a continous motion. On this basis the power requirement of the "terramage" is 9.8 horsepower (see Appendix A). The power requirement could have been reduced if the "terramage" were designed differently and if springs to store the energy of the frames as they come to stop are used. The stored energy would then be utilized to move the frame that is scheduled to move next. Such design changes and use of springs to store energy are discussed in the next section.

EXPLANATION OF PLATE VIII

Longitudinal Section of the "terramage".

1 - A 1/2 x 4 rectangular section 7075 aluminum used as a track for ball bearings taking a side thrust of the power car.

2 - The power car.

3 - A 2 x 4 dimensional lumber (Pine).

4 - A 2 x 3 angle 7075 aluminum.

5 - Wheel (roller) moving on frame A.

6 - Wheel (roller) moving on frame B.

A - Frame A

7 - Ball bearing supporting frame A

B - Frame B

8 - Hydraulic cylinder that moves frames A and B.

9 - One of the rear legs attached to frame B.

10 - Rear leg attached to frame A

11 - Piston

12 - Cylinder

13 - Spring guide post

14 - Spring shown compressed

15 - A guide pipe

16 - Pressure Switch

17 - Bellow (flexible material allowing up or down movement)

18 - Rubber facing

19 - Aluminum circular plate

20 - Spring guide pipe

21 - Swivel joint

22 - Ball bearing supporting frame B.

23 - A 5/16 x 4 rectangular section 7075 aluminum used to build an I-beam for frame B.

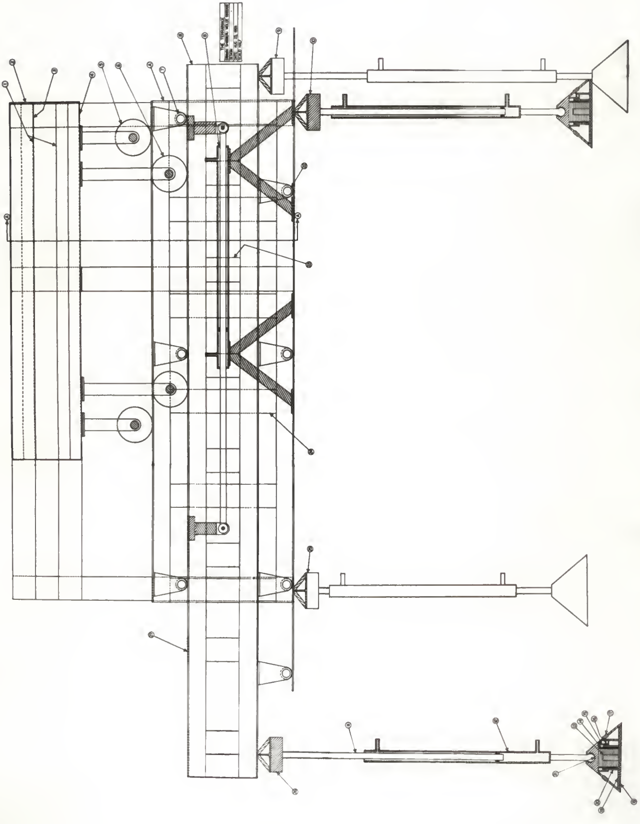
24 - A 5/16 x 4 rectangular section 7075 aluminum used to build an I-beam for frame A.

25 - One of the two front legs attached to frame A.

26 - A front leg attached to frame B

27 - A 5/16 x 4 rectangular section 7075 aluminum used to build frame B.

PLATE VIII



EXPLANATION OF PLATE IX

A Cross Section of the "Terramage"
(Section A-A of Plate VIII).

1 - A 2 x 4 dimensional lumber (Pine)

2 - A 1/2 x 4 rectangular section 7075 aluminum

3 - Wheel (roller) moving on frame A

4 - Wheel (roller) moving on frame B

5 - Ball bearing supporting frame A

6 - Ball bearing used to move frame A on frame B or vice versa

7 - Cross section of hydraulic cylinder

8 - Aluminum shaft on which bearing no. 6 is mounted

9 - Track for bearing no. 6

10 - Ball bearing to support frame B

11 - Special tee on which two legs attached to frame B are mounted

12 - A 1/2 x 4 rectangular section 7075 aluminum bracing

13 - One of the legs attached to frame B

14 - One of the legs attached to frame A

15 - A 5/16 x 4 rectangular section 7075 aluminum used to build an I-beam

16 - A 5/16 special tee 7075 aluminum

17 - Mounting for no. 19

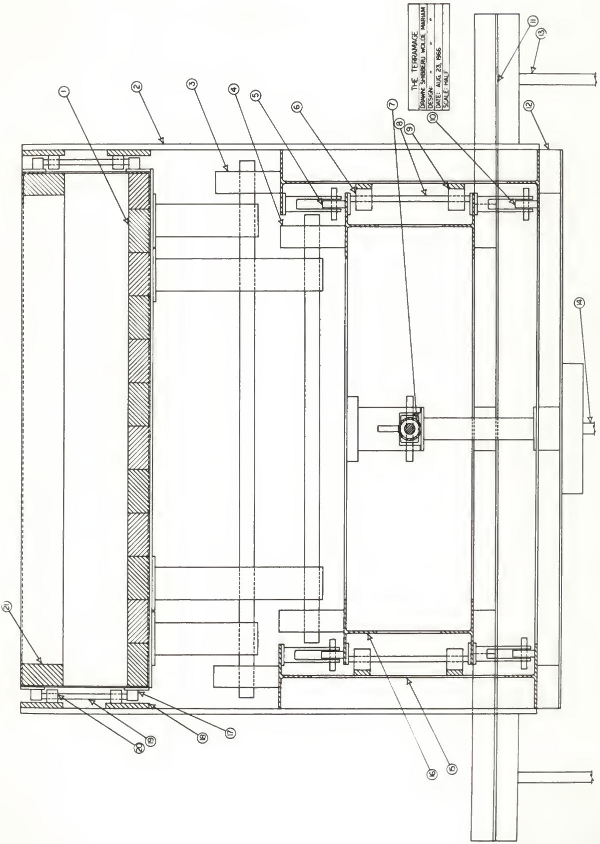
18 - Track for no. 20

19 - Aluminum shaft on which power car side rollers are mounted

20 - Ball bearing to take up side thrust of the power car

21 - A 2 x 4 dimensional lumber (Pine).

PLATE IX


THE TERRAMAGE
DRAWN: SHIBBERU WOLDE MARIAM
DESIGN: " " "
DATE: AUG 23, 1966
SCALE: HALF
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EXPLANATION OF PLATE X

Master Control and Driving Mechanism

Fig. 3.

1 - 4-way solenoid operated direction control valve

2 - Hydraulic cylinder to operate the driving mechanism related to frame A

3 - Hydraulic cylinder to operate the driving mechanism related to frame B

4 - Hydraulic cylinder to move either frame A or frame B forward.

5 - Pressure switch

6 - Legs on frame A

7 - Legs on frame B

23 - Ground

24 - Battery

25 - Switch

Fig. 1.

8 - Track (roadway)

9 - Wheel (roller)

10 - Sheave

11 - Belt

12 - Clutch plate

13 - Coil spring

14 - Backing (steel plate)

15 - Part of the linkage to operate the clutch

16 - Hydraulic cylinder to operate the driving mechanism (See Fig. 3; 2 and 3).

17 - Pivot rod

18 - Hydraulic cylinder support

19 - Power car

Fig. 2.

20 - Pivot rod

21 - Linkage bar

22 - Hydraulic cylinder to operate driving mechanism.

PLATE X

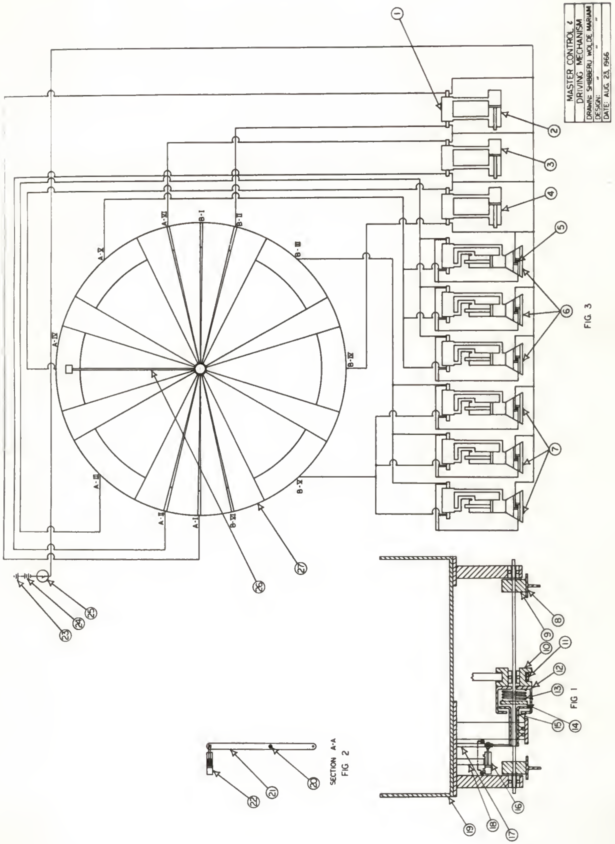
MASTER CONTROL &
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FIG 3
FIG 1
SECTION A-A
FIG 2

EXPLANATION OF PLATE XI

A Schematic Showing the Hydraulic and Electrical Systems.

1 - Pressure switch

2 - Hydraulic cylinder

3 - Switch

4 - Battery

5 - Ground

6 - Master control

7 - Oil return pipe

8 - Check valve

9 - Filter (oil)

10 - Oil reservoir

11 - Hydraulic pump

12 - Pressure control valve

13 - Oil supply pipe

14 - Oil exhaust pipe

15 - Coil spring

16 - Four-way solenoid operated direction control valve

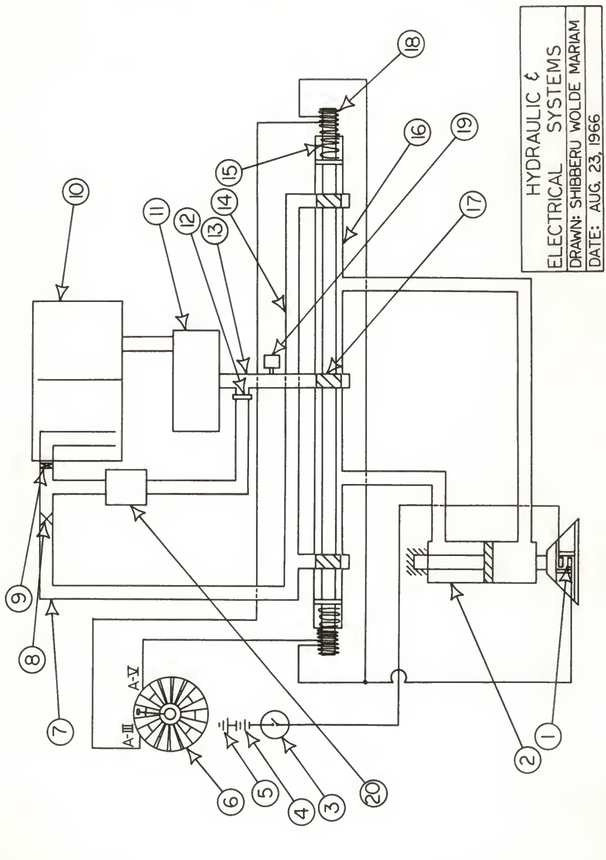
17 - Land

18 - Solenoid

19 - Accumulator

20 - Heat exchanger

PLATE XI


HYDRAULIC &
ELECTRICAL SYSTEMS
DRAWN: SHIBBERU WOLDE MARIAM
DATE: AUG. 23, 1966
A-III
A-V

EXPLANATION OF PLATE XII

A Schematic of the "Terramage" for Draft Application.

1 - Frame A

2 - Frame B

3 - Ball bearing supporting frame A

4 - Ball bearing to allow frame forward movement respectively one on the other

5 - Wheel (roller) moving on frame B

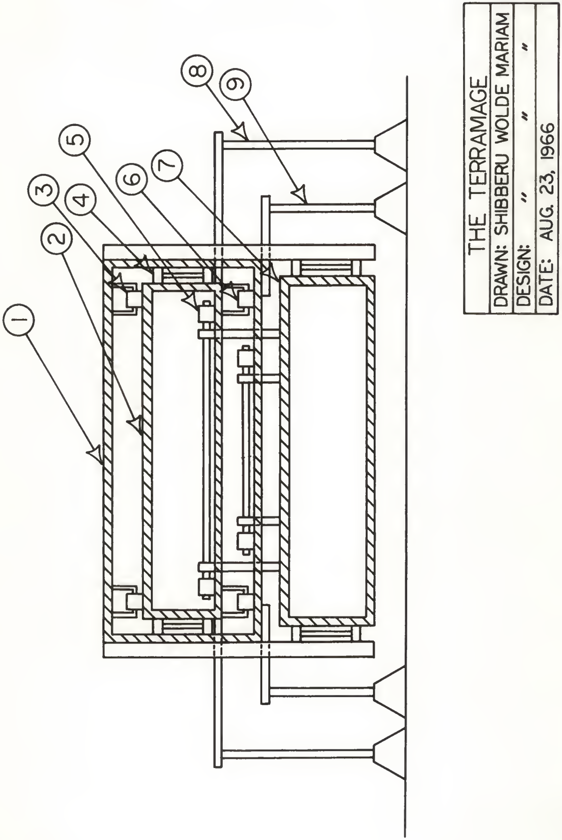
6 - Ball bearing supporting frame B

7 - Power car

8 - Rear legs attached to frame B

9 - Rear legs attached to frame A

PLATE XII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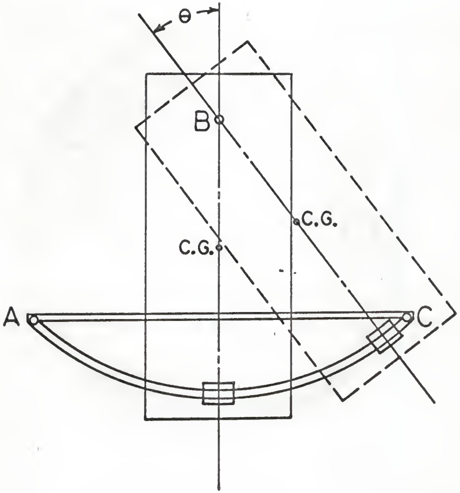
THE TERRAMAGE
DRAWN: SHIBBERU WOLDE MARIAM
DESIGN: " " "
DATE: AUG. 23, 1966

EXPLANATION OF PLATE XIII

A Schematic Showing Method of Steering the "Terramage"

PLATE XIII



DISCUSSION

The "terramage" differs from presently known off-the-road locomotion vehicles. Such vehicles as the "walking truck" and the "moon walker" are designed by imitating the locomotion of four-legged animals whereas the "terramage" does not possess jointed legs. Basically the "terramage" entails the principles of walking in a different way in that the two frames have a step by step motion which is similar to the motions the legs of animals make. This means that in the locomotion of the four-legged animals, two legs support the weight while the other two swing forward. In a similar manner one frame of the "terramage" supports the weight while the other frame moves forward.

The "terramage" is designed to combine walking and train concepts. According to Bekker (3,4) walking is the most efficient in the use of power off-the-road while the train is the most efficient for locomotion on hard and smooth man-made surfaces. The combination of the two concepts is made possible in that the frames through their legs accomplish walking and by the rails they provide to the power car make the train concept possible. The power car can be likened to a railway car moving on rails. The total weight of the "terramage" is supported by the legs which by means of the pads can provide a larger contact area than can be expected from wheels or tracks.

The unique feature of the "terramage" is the ability of its legs to fit the terrain over which it passes in such a way that its center of gravity remains unchanged. The mass that is raised is only that of the legs. In this way it is possible to save power in contrast to walking where power is consumed in raising the center of gravity. Another important feature of the "terramage" is its ability to clear obstacles in its path. This feature can be designed into the "moon walker" and the "walking truck", however, the tracked and wheeled vehicles are very much limited in this regard. The "terramage" also shares another feature with the "walking truck" and the "moon walker". Unlike the wheeled and tracked vehicles the "terramage" compacts the soil only at points where its pads come in contact with the ground thereby saving power. It must be noted further that the "terramage" incorporates another important feature which enables it to accomplish what Bekker (3) calls "surface crossing" and "subsurface crossing" of a terrain. "Surface Crossing" refers to the fact the soil is able to support a mobile vehicle without any sinkage. "Subsurface crossing" on the other hand refers to the ability of the soil to support a mobile vehicle while sinkage of the traction members of the vehicle takes place. In the case of tracked and wheeled vehicles excessive sinkage of the traction members may immobilize them. This, however, is not an insurmountable problem for the "terramage" which is able to cross soft terrain even if its legs sink. The only limits in this regard are the leg length and excessive surcharge.

Based on the present design, the "terramage" is very much handicapped in the use of power. The stop and go motion of the frames introduces large inertia forces. The power required to accelerate the frames is unnecessarily too high. Such high power requirement makes the "terramage" quite unable to compete even with the wheeled and tracked vehicles although the "terramage" is designed to go over terrain that would completely immobilize the latter vehicles. The high power requirement, however, can be overcome to a certain extent by making the "terramage" longer thereby allowing longer displacement of each frame. This reduces the need of high acceleration of each frame. Table 1 (see Appendix A) shows a trend in which the longer the "terramage" is the slower the acceleration of the frames becomes thereby reducing the power required. Yet, the "terramage" would not compete with the wheeled and tracked vehicles in the use of power even though the figures in Table 1 (Appendix A) were calculated by assuming that the mass of each frame increases at a constant rate with the increase of the length of the frames. This, then, calls for an alternative design of the "terramage" such that the power required can be reduced.

Bekker (3,4) has theoretically shown the power requirement per ton of the weight of different modes of locomotion. His calculations were based on the assumed speed of 20 miles per hour. According to his calculation walking is the most efficient requiring only 7 horsepower per ton while the tracked vehicle requires 10 horsepower per ton, and the wheeled vehicle 15 horsepower per ton. Using an alternative design of the "terramage" the power required per ton was found to be 7.3 horsepower (see Appendix A). This was made possible by incorporating springs to store the energy due to the momentum of each frame. The stored energy would be used to drive the next frame. The practicability of this method, however, will depend upon an actual test as much as walking at 20 miles per hour assumed by Bekker is subject to question until a machine is built that is capable of walking at this speed.

Another feature of the "terramage" which appears to be of academic importance is concerned with its potential energy. On a short gentle slope the "terramage" appears not to change its potential energy. In other words, the power requirement remains the same whether the terrain is level or gently sloping.

The alternative design suggested in the above paragraphs should incorporate a different driving mechanism of the frames than that shown in the present design. The longer the frames become the longer will be the displacement which calls for a long hydraulic cylinder. This, however, appears to be quite impractical, and furthermore the higher speeds may limit the use of hydraulic cylinders too. The two frames, however, can be driven by separate engines mounted on each of them. This would be accomplished by powering the respective rollers of the frames the same way as the wheels on the power car are powered.

At higher speeds the momentum of each frame becomes quite high and thus the stability of the "terramage" may be jeoperdized if the present leg design is fully retained. It is assumed that the spring will fully take up the impact and thereby store energy. However, tilting of the front legs forward and the rear legs backward along with a pad design which allows a good grip will provide a complete absorption of the impact. In this way the unnecessary shock to the driver may be fully controlled.

CONCLUSION

Heavy load transportation and higher speed requirement for off-the-road locomotion will increase interest in vehicles of off-the-road locomotion. The wheeled and tracked vehicles used today are very much limited to slower speeds due to their design. Bekker (4) describes the problems of these vehicles as follows:-

> "...In most cases, the engine power is not fully developed for most of the time because of the geometric properties of the ground surface, which create either discomfort for the riders or dynamic loads (see Figure 154) beyond the endurance of men and material... Accordingly, it appears logical to admit that the limits imposed upon speed by the geometry of the ground surface are also fixed to a large extent, since they mostly depend on the form of the vehicle, and that the present operational speeds, which, in the best cases, according to Lehr, do not exceed 10 mph, have reached a maximum which will not be easily surpassed unless all the efforts concentrate on the improvement of the suspension and form of the vehicle...The speed of the land vehicle is limited by ground waves just as the speed of a ship is often limited by rough seas rather than by the lack of power. If this conclusion is true, then the volume of efforts made by automotive engineers in the study of engines, as shown in Figure 27, is highly disproportionate and perhaps futile."

Bekker's analysis above no doubt paves the way for vehicles like the "terramage". The present high power requirement of the "terramage" without the use of springs to store energy may be reduced in the near future with the development of lighter and stronger engineering materials. Based on the alternative design, however, the power efficiency is highly competitive. Variation of the design of the "terramage" such as the provision of wheels that would retract like the wheels of an airplane in flight, will make the "terramage" highly versatile. The "terramage" may be used to go on highways by means of its wheels while for off-the-road locomotion its legs would be used. This combination will make the "terramage" highly desirable for various needs. The following list shows some of the functions for which the "terramage" can be used:-

1. Transportation in back country for people interested in hunting, fishing, exploration and other things of a similar nature.
2. To reach remenants of air plane accidents and areas that are cut off as a result of snow blizzard.
3. Transportation of road surveying and mineral exploring parties.
4. Serves construction crews by providing a base on which any type of rig can be mounted.
5. Transportation of minerals from inaccessible mines.
6. Transportation of cattle and sheep from remote ranches.
7. Transportation of power transmission maintenance crew.

In regards to the use of the "terramage" in Ethiopia, one needs to be reminded of the present problems that beset Ethiopia's progress. Plate 1 shows the road system of Ethiopia in which only the hatched bars show all weather roads while the non-hatched bar shows feeder highways that will have to be built. Furthermore according to Plate 1, the border provinces are without all weather roads. Unfortunately (for now at least) these provinces are the most fertile in Ethiopia and have the potential to support a large population. Absence of feeder as well as main highways increases the cost of transportation in Ethiopia to such an extent that two neighboring provinces carry on very little trade between them. For instance to go from point A to point C (see Plate 1) one needs to go through B. This means that the road distance between A and C is multiplied many times.

The "terramage" does not require the type of roads which the tracked and wheeled vehicles require. It may require clearing of heavily wooded areas and a few bridges on completely difficult rivers and gulleys. The remainder of the terrain does not need to be leveled or gravelled. Even if levelling is required at some points grass can be used in place of gravel as the "terramage" does not heavily compact or tear up the grass as do the wheeled and tracked vehicles. Specifically the dust problem that accompanies the tracked and wheeled vehicles may be non-existant and if not completely minimized in the case of the "terramage". This of course reduces the cost of road construction and maintenance.

Even though the "terramage" is definitely beyond an average Ethiopian farmer's financial abilities for individual ownership, ownership on the cooperative basis is possible. The cooperative operation in Ethiopia is clearly evident today by the actions that many communities have taken in pulling their resources together to build roads, schools and clinics. An ownership of the "terramage" by a community will aid in getting its produce to market, improve its health and improve its educational standing. The writer is of the opinion that the "terramage" will revolutionize Ethiopia's transportation and thereby accelerate its development.

ACKNOWLEDGMENT

The author is indebted to Professor Hugh F. Rouk for providing the material in Plates I, II and III, to Dr. Robert J. Robinson for his encouragement, to the Rockefeller Foundation for providing a scholarship, to Dr. Ralph O. Turnquist for his advice on the hydraulic system, to Professor Ralph Lipper for his assistance in the wiring diagram and Dr. George H. Larson for his guidance in making the "terramage" a reality.

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APPENDIX A

Dimensions of the "Terramage"

Frame A:-

Height = 2 feet

Length = 7 feet

Width = 4 feet and 4-1/2 inches.

Frame B:-

Height = 1 foot

Length = 10 feet

Width = 3 feet and 7 inches.

Power Car:-

Height = 1 foot

Length = 5 feet

Width = 4 feet

Legs:-

Fully retracted = 4 feet

Fully extended = 6 feet

Pad:-

Height = 6 inches

Base Diameter = 1 foot

Clearance between power car and frame A = 1 foot

Total height of "Terramage" = 10 feet

Other pertinent Information on "Terramage"

Operating pressure (assumed) = 1500 Psi.

Contact area of each pad = 113 square inches.

Total weight of "Terramage" = 1300 lbs.[11]

Weight of frame A = 350 lbs.

Weight of frame B = 250 lbs.

Weight of power car = 700 lbs.

Average forward speed of either frame A or B = 2 mph.

Forward speed of the Power Car = 1 mph.

Displacement of either frame A or B = 2 feet.

Maximum displacement of each leg up or down = 2 feet

Power Requirement of the "Terramage"

Power is needed for the following operations.

1. Move either frame A or B forward
2. Raise or lower legs.
3. Move power car forward
4. Steer the "terramage"
5. Power or depower power car wheels

I. Power to move frame forward:-

The heavier frame is frame A and the power required must be based on it.

V_{av} (average speed of frame) = 2 mph

$$\frac{2 \text{ miles}}{\text{hour}} \times \frac{5280 \text{ ft.}}{\text{mile}} \times \frac{1 \text{ hour}}{60 \text{ min}} \times \frac{1 \text{ min.}}{60 \text{ sec}} = 2.94 \text{ ft/sec.}$$

$V_{max} = 2 \times 2.94 = 5.88$ ft./sec.

S (displacement) = 2 feet

$$t = \frac{2}{2.94} = 0.68 \text{ sec.}$$

Area of cylinder = 1.29 in.^{2}

---

[11]The weight of the "terramage" is based on some estimate but mostly on calculation.

$$Q_{max} = 5.88 \times 12 \times 1.29 = 91 \text{ in.}^3/\text{sec.}$$

$$Q_{max} = \frac{91 \text{ in.}^3}{\text{sec.}} \times \frac{1 \text{ gal.}}{231 \text{ in.}^3} \times \frac{60 \text{ sec.}}{\text{min.}} = 23.6 \text{ gpm.}$$

Based on Elmer W. Pfeil, Inc. (Cleveland, Ohio) catalog, the pressure drop across 3/8" four way double solenoid valve is assumed to be 100 psig.

$$\text{Power} = \frac{100 \times 91}{550 \times 12} = 1.38 \text{ h.p.}$$

II. Power to raise or lower legs:-

Note that it takes more power to lower legs than to raise them and so the power requirement is based on the lowering of the legs.

Assumed time to raise or lower legs = 0.68 sec. (same as time required to move frame forward)

S (displacement) = 2 ft.

Average Velocity = 2/0.68 sec. = 2.94 ft./sec.

$V_{max} = 2 \times 2.94 = 5.88$ ft./sec.

Area of cylinder = 1.29 in.^{2}

$$Q_{max} = 5.88 \times 12 \times 1.29 = 91 \text{ in.}^3/\text{sec.}$$

$$Q_{max} = \frac{91 \text{ in}^3}{\text{sec.}} \times \frac{1 \text{ gal.}}{231 \text{ in}^3} \times \frac{60 \text{ sec.}}{\text{min.}} = 23.6 \text{ gpm.}$$

Here again the pressure drop across the valve used with the selected cylinder is assumed to be 100 psig.

$$\text{Power} = \frac{100 \times 91}{550 \times 12} = 1.38 \text{ h.p. to each leg}$$

Power to the three legs = 3 x 1.38 = 4.14 h.p.

III. Power to move power car:-

The coefficient of rolling resistance for aluminum must be assumed.

f for steel on steel = 0.002 in. (see Mark's Mechanical Engineering Hand Book)

Since E (modulus of elasticity) for steel = 30×10^6 psi and E for aluminum = 12×10^6 psi, then assume that the coefficient of rolling resistance for aluminum is 4 times the resistance of steel.

Thus f for aluminum = 0.002 x 4 = 0.008 inches

The required power to keep a power car moving is calculated based on the following formula.[12]

$$P = \frac{b}{c} w$$

where

w = weight

b = f = 0.008 in.

c = radius of roller which is 3 inches (see Plate VIII, 5 or 6)

P = force required to keep the power car moving.

$$P = \frac{0.008w}{3}$$

$$P = \frac{0.008 \times 700}{3} = 1.868 \text{ lb.}$$

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[12]See Engineering Mechanics (Statics and Dynamics by A. Higdon and W. B. Stiles, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1962.

V_{max}(for power car) = 2.94 ft./sec.

$$\text{Power} = \frac{2.94 \times 1.868}{550} = 0.01 \text{ h.p.}$$

IV. Power required to steer the "terramage":-

The stroke of the piston for steering must be less than half of the width of the wider frame. Steering is accomplished by manually operating the control valve. Frame A (see Plate VIII, A) is a wider frame having a width of 4 ft. and 4-1/2 inches.

Half of the width of the wider frame = 26.25 inches

According to Amity Merchandise Products Corporation Catalog, New York, New York, a hydraulic cylinder No. 902 has the following features:

Bore = 1-5/8 in.

Shaft = 1 in (diameter)

Stroke = 27-1/2 in.

Piston end area = 2.08 $in.^2$

According to Blackburn (5), the maximum velocity for a typical automotive steering is 3 inches per second.

V_{max} = 3 in./sec.

Area = 2.08 $in.^2$

$Q_{max} = AV = 3 \times 2.08 = 6.24 \ in^3/sec.$

$$Q_{max} = \frac{6.24 \text{ in}^3}{\text{sec.}} \times \frac{1 \text{ gal}}{231 \text{ in}^3} \times \frac{60 \text{ sec.}}{\text{min.}} = 1.62 \text{ gpm.}$$

Based on the charts in Elmer W. Pfeil, Inc. Catalog (Cleveland, Ohio), the pressure drop across a 3/8 inch 4 way double solenoid valve is assumed to be 100 psig.

$$\text{Power} = \frac{100 \times 6.24}{550 \times 12} = 0.094 \text{ h.p.}$$

V. Power needed to depower power car wheels:-

Assumed piston stroke = 2 inches.

Assumed oil delivery = 91 in^3/sec. (which is the same as delivered to each leg).

The hydraulic cylinder no. 923 in Amity Merchandise Product Corporation, New York, New York, Catalog, has the following features:

Bore = 7/8 inch.

Shaft = 3/8 inch.

Stroke = 1 to 3 inches.

piston end area = 0.60 $in.^2$

Using a stroke of 2 inches, one finds available volume to be 1.2 $in.^3$

$$\text{time} = \frac{1.2}{91} = 0.0132 \text{ sec.}$$

$$\text{velocity (max.)} = \frac{2}{12 \times 0.0132} = 12.6 \text{ ft./sec.}$$

$$Q_{max} = \frac{91 \text{ in.}^3}{\text{sec.}} \times \frac{1 \text{ gal}}{231 \text{ in.}^3} \times \frac{60 \text{ sec.}}{\text{min.}} = 23.6 \text{ gpm}$$

The assumed pressure drop across the valve in question is 100 psi (see III in this appendix).

$$\text{Power} = \frac{100 \times 91}{550 \times 12} = 1.38 \text{ h.p.}$$

It is to be noted that power is required to operate those functions that do take place simultaneously. In this case the functions that give the greatest power requirement are used in deciding the total power needs of the "terramage". Thus the functions that do take place at the same time and require the greatest power are: lowering of the legs, steering and power car motion forward.

Total power required = 4.25 h.p.

Assumed mechanical efficiency = 87%

Assumed hydraulic system efficiency = 50%[13]

$$\text{Input Power} = \frac{4.25}{0.50 \times 0.87} = 9.8 \text{ h.p.}$$

Based on the present design the power requirement of the "terramage" is thus 9.8 h.p. The displacement of two feet of the frames would introduce very high acceleration at the speed of 20 mph in order to find the power requirement per ton of the weight of the "terramage". In this case an alternative design in which a reasonable displacement of the frames is assumed necessary. A calculation of the power required per ton of the weight of the "terramage" based on an alternative design is given below.

Power Requirement of the "Terramage" Per Ton of its Weight

Assumed:-

Length of frame A = 54 ft.

---

[13] According to Blackburn (5) hydraulic efficiency does not exceed 60%.

Length of frame B = 50 ft.

Length of power car = 25 ft.

Width of the wider frame = 5 ft.

Weight per foot of frame length = 10 lb.

Weight per foot of power car length = 140 lb.

The figure of 140 lb. is derived by dividing the present design weight of the power car (700 lb) by its length of 5 feet.

Weight of frame A = 54 x 10 = 540 lb

Weight of frame B = 50 x 10 = 500 lb

Weight of the power car = 25 x 140 = 3500 lb

Total weight of the "terramage" = 4540 lb

The power requirement per ton is calculated for a speed of 20 miles per hour that the power car should have in order to compare with the other modes of locomotion for which Bekker (5) theoretically shows the power requirement. The speed of 20 miles for the power car is the average speed which must be half of the average speed of each frame.

In this alternative design the individual frame is not hydraulically operated but on each frame an engine is mounted to provide power. Use of the hydraulic cylinder to operate the frames is impractical as the high speed and long displacement make hydraulic cylinders difficult to use.

It was discussed earlier that the power required to operate the "terramage" must be calculated based on those functions operating simultaneously and thus requiring the greatest power. Accordingly the following calculations are made by considering only those functions that can possibly be operated at the same time. The possible functions that can operate at the same time are:

(a) Frame displacement, power car displacement, and steering

(b) Lowering or raising of the legs, power car displacement, and steering.

Power required to move frame:-

V_{av} (frame) = 40 mph = 58.8 ft./sec.

V_{max} (frame) = 80 mph = 117.6 ft./sec.

$V_{av} = 1/2\ at$

$t = s/V_{av}$

where

a = acceleration in ft./sec.^{2}

s = displacement in feet.

t = time in seconds

$$a = \frac{2 \times (V_{av})^2}{s} = \frac{2 \times (58.8)^2}{25} = 276 \text{ ft./sec.}^2$$

$F = ma$

where

a = acceleration in ft./sec.^{2}

F = force

m = mass

$F = \frac{540 \times 276}{32.2} = 4600$ lb (force required to accelerate heavier frame)

In order to stop the moving frame and at the same time store energy for later use, a spring is needed.

Assumed spring efficiency = 99%

$$4600 \times 0.99 = 4560 \text{ lb.}$$

$$4600 - 4560 = 40 \text{ lb}$$

$$\text{Power lost} = \frac{40 \times 117.6}{550} = 8.55 \text{ h.p.}$$

This power must be supplied from other sources in order to move the frame.

Power to lower legs:-

Before the power required is calculated it is necessary to note that due to increased length of the "terramage", more legs are needed to support each frame. This being the case each frame is to have five legs in order to facilitate steering.

V_{max} = 5.88 ft./sec. (see II, page 71)

Area of cylinder = 1.29 in^2

$$Q_{max} = 5.88 \times 12 \times 1.29 = 91 \text{ in}^3/\text{sec.}$$

$$Q_{max} = \frac{91 \text{ in}^3}{\text{sec}} \times \frac{1 \text{ gal}}{231 \text{ in}^3} \times \frac{60 \text{ sec}}{\text{min}} = 23.6 \text{ gpm}$$

Based on Elmer W. Pfeil, Inc. (Cleveland, Ohio) Catalog, the pressure drop across a 3/8 inch 4 way double solenoid valve in question is assumed to be 100 psig.

$$\text{Power} = \frac{100 \times 91}{550 \times 12} = 1.38 \text{ h.p. to each leg}$$

Power to the five legs operating together = 5 x 1.38 = 6.9 h.p.

Power to drive power car:-

Assumed roller diameter = 2 feet.

$$p = \frac{0.008 \times 3500}{12} = 0.25 \text{ h.p. (see III, page 72)}$$

Power to steer the "terramage":-

Half of the width of the wider frame = 30 inches

Since the stroke of the piston for steering must be less than half the width of the wider frame, the same hydraulic cylinder used in the previous calculation (see IV, page 73) can be used. With the velocity of 3 in/sec. the power required for steering the "terramage" is the same as that calculated for steering as shown on page 73.

Thus power = 0.094 h.p.

Assumed hydraulic efficiency = 50%

Assumed mechanical efficiency = 87%

Power to move frame = $\frac{8.55}{0.87}$ = 9.84 h.p.

Power to drive car = $\frac{0.25}{0.50 \times 0.87}$ = 0.58 h.p.

Power for steering = $\frac{0.094}{0.05 \times 0.87}$ = 0.22 h.p.

Power to lower legs = $\frac{6.9}{0.50 \times 0.87}$ = 15.8 h.p.

It can be seen that the maximum power required to operate the "terramage" is when the power car, the steering mechanism, and the legs are operated simultaneously.

Total power = 15.8 + 0.22 + 0.58 = 16.6 h.p.

Power required per ton of the weight of the "terramage" under the above conditions is found as follows:

$$\frac{16.6}{4540} = \frac{X}{2000}$$

X = 7.3 h.p. per ton.

Table 1. A Trend in Power Requirement of the "Terramage"[14]

Length (ft)			Displacement	Acceleration ft/sec²						Power H.P.					
Frame A	Frame B	Power Car	(ft)	(a)	(b)	(c)	(d)	(e)	(f)	(a)	(b)	(c)	(d)	(e)	(f)
24	20	10	10	10.8	43.2	97.2	172.8	270.0	388.8	2.16	17.2	58.2	138.0	270.0	465.0
34	30	15	15	7.2	28.8	65.0	115.0	180.0	257.0	2.04	16.4	55.4	131.0	255.0	440.0
44	40	20	20	5.4	21.6	48.6	86.4	135.0	194.4	1.98	15.8	53.4	127.0	248.0	427.0
54	50	25	25	4.3	17.3	38.8	69.0	108.0	155.0	1.94	15.6	52.0	124.0	243.0	416.0

[14] The average velocities of each frame in miles per hour corresponding to columns (a), (b), (c), (d), (e) and (f) are respectively 5, 10, 15, 20, 25, and 30.

APPENDIX B

Information pertaining to Ethiopia:-

Population = 22,000,000 (estimate)

Area = 482,400 square miles

Altitude = 7-8000 feet (average)

Climate:- Temperature at high altitudes
Warmer along the coast and low lands.

Economical plants grown:-

"Teff", wheat, barley, corn, sorghum, coffee, cotton, sugar cane, oil seeds, lentils, peas and various root plants.

Monetary system:-

The Ethiopian dollar equivalent to $0.40 US.

The climate of Ethiopia is greatly affected by the altitude. This affects the harvesting season as well as the sowing season. Regions that may be separated by a distance of about 20 miles may be adapted to two entirely different crops resulting in different periods of plant maturity.

DESIGN OF THE "TERRAMAGE" FOR OFF-THE-ROAD LOCOMOTION IN ETHIOPIA

by

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The term "terramage" is an Ethiopian word which describes a step by step motion. The "terramage" is specifically intended to serve for off-the-road locomotion in Ethiopia and other areas with similar conditions.

Presently Ethiopia has some 5000 miles of all-weather roads which, of course, do not adequately cover the 482,400 square miles of the country's surface area. Due to the terrain and climatic conditions, road construction and maintenance is very costly thereby limiting available roads. Absence of an adequate road system is responsible for the lag in farm mechanization and improvement in both livestock and crops. It is to enhance the development of agriculture that the design of the "terramage" was considered necessary.

The "terramage" was designed after examining the current concepts of off-the-road locomotion. The theory advanced by Dr. M. G. Bekker was used in theoretically evaluating the "terramage". Dr. Bekker, in his analysis of the various modes of locomotion has shown walking to be the most efficient in the use of power off the road. Until quite recently a walking machine in the strictest sense of the word has not been known to exist. Present day interest in lunar locomotion has arroused interest in walking machines such that a symposium on the subject in which 90 scientists participated took place at Auburn University in October, 1964. Lately two walking machines referred to as the "moon walker" and the "walking truck" have been discussed in the various sources of literature. According to the available literature the "moon walker" has a speed of 2.5 miles per hour while the "walking truck" is presently limited to 5 miles per hour carrying a load of 500 pounds. The "walking truck" is able to move its legs based on the motions of the arms and legs of the operator.

The "terramage" differs from the above mentioned vehicles in that its legs are not jointed, and furthermore, it has three major locomobiles. There are two frames one inside the other and having three legs each. One frame raises its legs and moves forward while the other frame serves as a track both for the moving frame and a continuously moving power car which is one of the three locomobiles mentioned above. The various components are operated hydraulically, and a mechanism known as the master control helps in timing the various functions. Each leg is fitted with a pad to support the weight. Within the pad there is a spring that can be compressed as a result of the greater force from the ground such that the downward movement of each leg ceases as soon as the soil can support the anticipated share of the total weight that each leg must carry. The legs are independently controlled such that they can fit the terrain the "terramage" passes over thereby keeping the center of gravity of the "terramage" at the same level at all times. The features mentioned above are the advantages of the "terramage". However, due to the acceleration of the frames, the power requirement becomes excessively high. This weakness can be overcome by incorporating springs to store the energy of the moving frame such that the stored energy would serve to accelerate the next frame to move. Based on this assumption the power requirement of the "terramage" per ton of its weight was calculated to be 7.3 horsepower which compares favorably with 7 horsepower per ton power requirement for walking.

The "terramage" has features that enable it to serve in roadless areas of Ethiopia. It requires very little preparation to move it over soft and rough terrain. It may require some wood clearing and bridges to cross very difficult gulleys and rivers. Thus it is hoped that Ethiopian agriculture can be developed sooner than expected.