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The Air-Cell Suspension System— A Solution to Off-Road Mobility Problems

G. H. Howe and C. G. Wells
LTV Aerospace Corp.

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INTRODUCTION

DESIGNERS OF agricultural, construction, and military vehicles share a common problem, that of providing vehicles with the required mobility to traverse unprepared ground surfaces. These designers work toward practical methods of solving the off-road mobility problem, but their approaches differ according to the specialized requirements of the applications for which they design.

Fundamentally, the solution to the problem lies in the proper matching of vehicle characteristics with soil characteristics so that the vehicle does not become immobilized in the terrain in which it is expected to operate. The agricultural tractor usually operates at relatively slow speeds on previously worked acreage during plowing, planting, and harvesting. These terrain characteristics are generally consistent in nature and well known to the operator; thus immobilization can be anticipated through operator knowledge of the land and the capability of the vehicle. This type of vehicle does not require a suspension system, but does incorporate features for aggressive traction.

Construction equipment, which is used under more rigorous conditions (conditions encountered in road building, for example), requires a degree more of complexity. Larger tires and powerplants afford the mobility necessary for traversing primitive terrain, and more effective suspension systems allow somewhat higher cross-country speeds than are needed for farm equipment. However, as in the case of the agricultural tractors, a good knowledge of the land and relatively slow speeds enable the operator to anticipate and avoid mobility problems.

Military vehicle designers, on the other hand, must provide the capability for high speed off-road travel under adverse conditions and often in unfamiliar territory. These requirements present a continually increasing challenge to the suspension and traction system engineers, since each new vehicle created for a military application must be more mobile and operate at higher cross country speeds than the vehicle already in the military system. These requirements have brought about evolutionary changes in military vehicle suspension design and have forced designers to look for new and better ways to advance the state of the art.

For the majority of military applications, the choice of tractive elements is limited to tracks and wheels; hence, the choice of suspension designs is similarly restrictive. Test experience and actual use have shown most tracked vehicles to be more mobile than wheeled vehicles on unprepared surfaces. Although recent track and suspension

ABSTRACT

Recent studies by Missiles and Space Division-Michigan, LTV Aerospace Corp., have quantitatively verified that the air cell track/suspension concept originally applied to the pneumatic all-terrain amphibian (PATA) vehicle offers a unique solution to off-road mobility problems of tactical vehicles. Analog computer simulation techniques were employed to determine ride characteristics and experiments with scaled models were conducted to analyze air cell performance in water and soft soils. This paper covers current efforts to develop and perfect the air cell concept, concentrating on analytical studies and recent significant design improvements that promise improved suspension capabilities.

developments have brought about a high degree of performance for such vehicles, there are still limitations for the following reasons:

1. Because of the large number of components, tracked vehicles are expensive to manufacture and maintain.
2. The traction and suspension elements are generally very heavy.
3. Reliability and durability are low compared to wheeled suspensions.
4. Cross country speed is limited, owing to severe ride.
5. Tracked suspensions lack flotation capabilities for swimming or for operation over extreme marginal terrain.

In recent years, LTV Aerospace Corp. has been involved in the research and development of suspension systems, with the objectives of overcoming tracked vehicle limitations and solving off-road mobility problems. A suspension system embodied in a track was conceived as a possible breakthrough. This new system is an assembly of inflated rubber air cells connected together on a continuous belt to form a track/suspension system.

This paper summarizes the development of the air cell track/suspension system and describes current findings about air cell behavior which indicate that this type of system may become the optimum solution to military off-road mobility problems.

EARLY DEVELOPMENTS

In the early 1960s, LTV Aerospace Corp. conceived the air cell track/suspension system as a possible solution to the Army's need for an off-road, marginal terrain vehicle. As defined by the Army, the vehicle that might employ this suspension system would be used for general purpose, amphibious, logistics resupply missions, and for operations in extreme off-road areas such as swamps, rice paddies, tundra, and muskeg, as well as on prepared roads. In other words, the vehicle would be expected to do just about everything but fly.

It was determined that no existing vehicle configurations could perform the desired mission; a new concept was needed. The requirement for operation in water and extremely soft soil dictated flotation characteristics that standard tracks would not provide. Swamp and rice paddy requirements demanded aggressiveness and obstacle negotiation capabilities unavailable in existing systems. The high cross country speeds required for logistics resupply operations necessitated a reasonably "soft" suspension to isolate the driver from the terrain and enable him to maintain vehicle control.

The air cell track/suspension was created to meet all these requirements. It provided the tractive elements needed for locomotion, flotation for water and extreme soft soil operation, and all requisite suspension characteristics for a high speed, cross country ride. Since the air cell track/suspension system was totally different in concept from any state-of-the-art suspension system, it imposed many unique new design problems, the most critical being in the areas of:

1. Reliability.
2. Understanding of the air cell dynamic response.

In order to overcome these problems, a test bed program and an air cell evolution program were pursued. The air cell evolutionary process and the results of operation of the test bed are discussed in the following sections.

AIR CELL METAMORPHOSIS - To demonstrate the functional characteristics of the original air cell track/suspension system concept, a four-tenths scale, one-man test bed was fabricated. This test bed, shown in Fig. 1, incorporated the inflated air cells mounted on wide belts. The system required none of the ordinary suspension elements such as torsion bars, road arms, or road wheels. The unique capabilities of the tread system, as demonstrated by the test bed, provided the justification for later construction of a full scale test bed, which was given the name "Pneumatic All-Terrain Amphibian (PATA)."

The air cell used on the four-tenths scale test bed is shown in Fig. 2. Note that it is a completely closed construction. The pattern on the side of the cell results from the internal stays used in an attempt to force the cell to hold its shape. The cells were mounted to V-shaped cleats on an endless belt and connected together through a hinging arrangement near the top of each cell.

This system had distinct advantages over a conventional linked track: flexibility when operating over cross country terrain, and buoyancy to provide propulsion in water and extremely soft soil. The cell design also permitted a nesting effect so that each cell interlocked with the next. This system was adequate for use on the scaled test bed, but because of its complex design, was too costly for use on larger vehicles.

Upon completion of tests on the four-tenths scale model, a contract was signed to build and test a full scale vehicle. Because of the inadequacy of the original air cell concept for a large vehicle, a second air cell concept, shown in

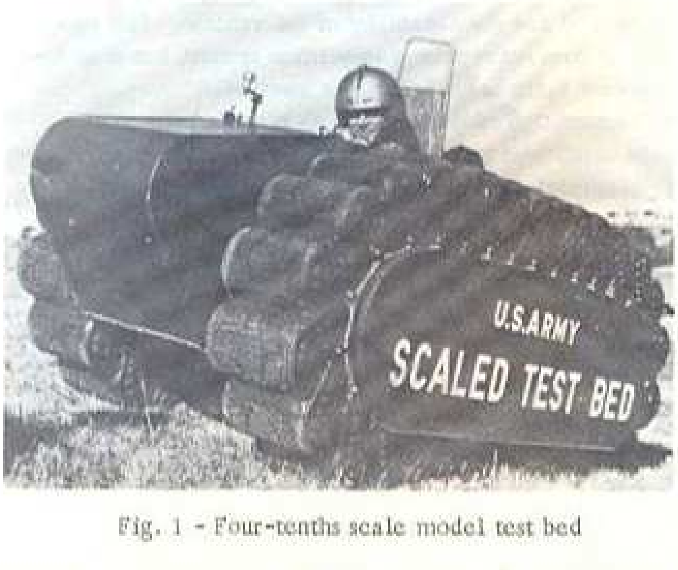

Fig. 1 - Four-tenths scale model test bed

Fig. 3, was created. These cells were designed to permit a two-piece construction. A small triangular intercell was mounted close to the belt, and a larger cell with a similar shape was mounted above the small cell. The large cells were attached to the V-cleats on the belt and connected to one another with webbing, and the smaller cells were inserted between the larger cells.

This system also included a new manifolding arrangement between the cells, which was connected to a central air supply to inflate the cells, maintain pressure, and overcome the effects of leaks. The system had problems. First, the cells tended to separate from one another when rounding the drive wheel. Second, the manifolding system could not be kept airtight. Third, when inflated, the cells tended to bulge on the sides and interfere with the adjoining structure. Because of these problems, it was decided to change the configuration.

The third in the evolutionary series of air cell concepts is depicted in Fig. 4. The two-piece construction, similar to that of the second air cell, was maintained, but the size of the lower cells was increased to overcome the separation problems. Both the upper and the lower cells were reinforced with internal stays to reduce the bulging effect. The method of mounting the cells was essentially the same as before.

This new concept solved some of the problems of its predecessor, but the individual cells still tended to separate when rounding the drive wheel. Additionally, durability problems arose at the location of the cleat: The cleat separated from the drive belt and the air cell, in turn, separated from the cleat. Also, stresses induced at the hinge points caused failures. Further development was attempted to resolve these problems.

It was decided at this point to completely revamp the configuration of the air cell. The shape was changed from triangular to straight-sided, and the new two-piece construction consisted of an external shoe and an inner tube. This configuration is shown in Fig. 5. Note that the cells are still attached to the belt with a triangular cleat arrangement. This system represented an improvement but still presented certain problems. The durability of the cell had improved, but the durability of the mount remained unchanged.

Fig. 2 - First air cell concept

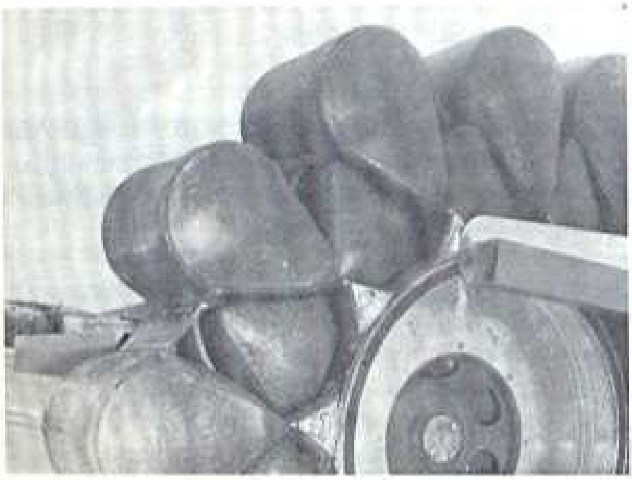

Fig. 3 - Second air cell concept

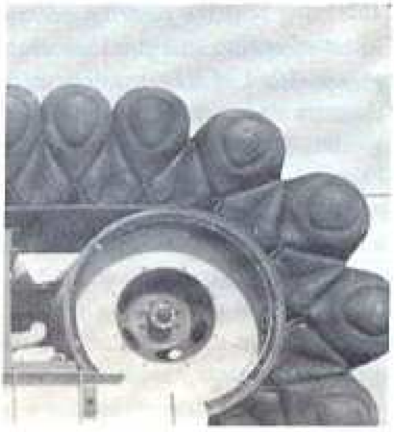

Fig. 4 - Third air cell concept

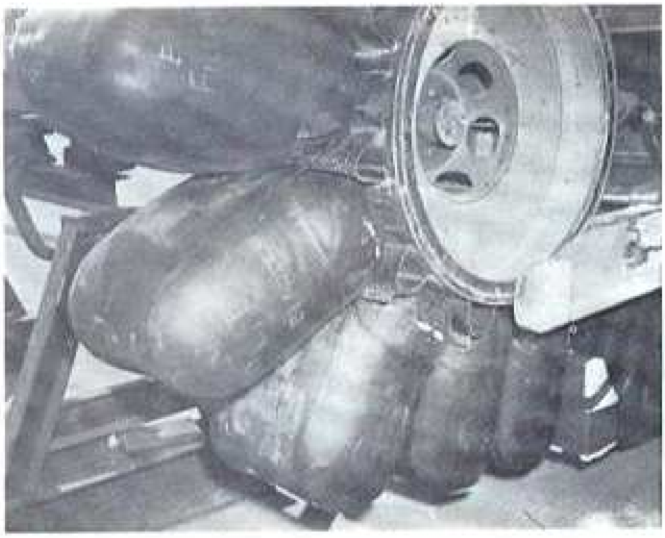

Fig. 5 - Fourth air cell concept

This configuration, at first, did not employ a hinge attachment at the upper end of the cell; however, such an attachment was later incorporated into the design to relieve some of the load on the triangular mounts. This change resulted in air cell concept 5 in the evolutionary series, which is shown in Fig. 6.

In order to provide hinging near the top of the cell and to improve performance in water and soft soil, the cell was inclined with respect to the drive belt. Also, the ground contact surface was formed into a kidney shape. The triangular attachment to the belt was maintained, but the manifolding system was eliminated and each cell was individually inflated. The durability of the mounts improved as a result of this configuration change.

This design was deemed satisfactory for use on the vehicle for evaluation testing. Work proceeded on the design of the PATA test bed, using this air cell configuration. On completion of the design work, the test bed was fabricated and then tested to evaluate full scale performance.

FULL SCALE TEST RESULTS - Testing of the PATA test bed by MSD-Michigan substantiated that it was capable of good performance in adverse marginal terrain, snow, and water. The test bed experienced only rare instances of difficulty in maintaining positive steering control when operating in some areas of severe marginal terrain. The soil, in these instances, consisted of a bottomless mixture of clay silt; difficulties were encountered only when the tracks were operating in a soil mixture of inconsistent compaction. When the soil shear strength under one track was less than under the other, PATA tended (as will any tracked vehicle) to turn toward the track that developed less traction.

During the tests, the payload was shifted fore and aft to determine what effect CG shift had on steering control on such soft soil. These tests substantiated the theory that steering control in bottomless mud is decidedly improved by a weight shift forward, which maintains a bowdown attitude. The obstacle mobility of a tracked vehicle is normally limited by the height from the ground to the centerline of the front idler or wheel. However, the PATA vehicle demonstrated the ability to negotiate obstacles of considerably greater height than the distance from the ground to the sprocket centerline. During testing in the swamp areas, PATA negotiated obstacles of 4-5 ft heights without difficulty.

Fig. 6 - Fifth air cell concept

Righting-moment calculations indicated that the PATA would be stable in water at roll angles beyond 60 deg. The calculations were checked by testing through a roll angle of 41.5 deg (test equipment precluded higher angles). At this angle, the vehicle had a righting moment of 5500 ft-lb. Dynamic tests revealed that with full power and minimum turning diameter, a maximum roll angle of only 15 deg was developed.

The results of the tests can be summarized as follows:

1. During cross country testing, the vehicle ride was exceptional at speeds up to 25 mph.
2. A water speed of 6.4 mph was measured at a vehicle weight of 9300 lb, which exceeded the performance of most tracked vehicles.
3. The turning diameter in the water was 18 ft at full engine power.
4. During water stability tests, a roll angle of 41.5 deg was reached with no evidence of instability.
5. PATA demonstrated the ability to traverse waterways covered with 7 in. of ice without damage to the vehicle or loss of control. The vehicle could climb out of the water on top of the ice edge.
6. Testing in a 15 in. accumulation of snow demonstrated PATA ability to operate over deep snow with a maximum penetration of only 5 in. There was no tendency for the vehicle to accumulate snow in the track system.
7. During gradeability tests, the vehicle successfully negotiated a wet, grassy, 70% slope.
8. In swamps and marshy areas, PATA demonstrated the ability to negotiate terrain such as soft, slippery mud; heavy swamp vegetation; and deep, fast flowing streams. Entrance and egress were demonstrated over slippery banks up to 70% in slope, and over dikes that simulated conditions existing in southeast Asia.
9. In operation through heavily vegetated marsh, speeds over 16 mph were recorded; in tidal mud, speeds up to 9 mph were obtained. The vehicle actually floated on its tracks in mud.

Upon completion of the testing by MSD-Michigan, the vehicle was delivered to Fort Eustis, Virginia, for military potential testing. The significant results of the military potential tests were the following:

1. PATA was capable of transporting the driver, assistant driver, and ten combat equipped personnel over highways, semiimproved roads, water, marshes, tidal mud flats, and cross country terrain.
2. As a cargo carrier, PATA was capable of transporting 2500 lb of cargo over the same range of terrains.
3. Ride characteristics were good, with little or no shock transmitted to the cab or cargo compartment.

4. The empty vehicle was able to develop a maximum speed of 8.78 mph on tidal mud flats with cone penetrometer readings of zero to 18 in. depths. When carrying a 2500 lb payload, the vehicle developed a speed of 8.18 mph.

5. The empty vehicle had an average swimming speed of 5.75 mph. When carrying a 2500 lb payload, the vehicle achieved a swimming speed of 5.19 mph.

The PATA test program showed better than expected performance with respect to cross country mobility, cross country ride, and soft soil mobility. However, shortcomings in the reliability of the drive train components and the durability of the air cells were encountered. The power demands, which were underestimated in the original design, caused the drive train problems. These were easily corrected.

The poor durability of the air cell was directly related to the use of manufacturing technologies that were undeveloped at the time of air cell fabrication. Additional problems were uncovered during the test program in the area of water propulsion and steering. To overcome these problems, it was decided to consult with manufacturers of rubber products and to perform further research, using model tests and theoretical analysis. The following sections describe the current research efforts.

CURRENT FINDINGS

Based on observations made during cross country testing and the results from the performance tests, an attempt was made to develop a thorough understanding of the air cell dynamics by predicting the ride qualities of a new vehicle concept with the air cell track/suspension installed.

ANALYTICAL AIR CELL STUDIES - The ride characteristics observed in both the scaled and the full sized vehicles were much better than predicted during the early research studies. More recent analytical studies of the dynamics of the air cell revealed that the smooth ride results from the nonlinearity of the air cell's spring rate, which increases with increasing deflection. In a linear system, the frequency of free oscillations is independent of amplitude. In a nonlinear system, however, it is amplitude dependent.

Thus, since the natural frequency of the system is a function of air cell spring rate, the frequency of oscillation depends upon the amplitude of the deflection. This type of system, therefore, has no discrete natural frequency.

The advantage of the nonlinear spring rate is further demonstrated in Fig. 7, which compares the responses of lightly damped linear and nonlinear spring systems. Curves of amplitude versus forcing frequency are plotted for a constant force amplitude and constant damping. For some frequencies, the response curve (refer to Fig. 7) of the nonlinear spring system is triple valued.

This fact leads to a "jump" phenomenon. If a given force amplitude is maintained as the forcing frequency is slowly changed, the response amplitude follows the usual response curve until point A is reached. The region between points A and C in Fig. 7 corresponds to the unstable condition; an increase in frequency above point A causes the amplitude to jump to that corresponding to point B. A similar condition occurs when frequency is slowly decreased; the jump then occurs between points C and D.

From this description, it can be seen that if an excitation condition approaches the resonant frequency of the vehicle suspension system and the amplitude of vibration begins to increase, the natural frequency of the system changes and the resonance condition disappears. Since the unfavorable effects of resonance on the vehicle are diminished, the driver's comfort while operating the vehicle over cross country terrain at high speeds can be theoretically improved. Thus, operation at higher speeds would be possible.

Spring Rate Determination - The spring rate of the air cells was derived from Boyle's law, which describes the relationship between the pressure and the volume of a gas, assuming constant mass and temperature:

$$PV = \text{constant}$$

where:

P = Internal pressure

V = Volume

Since the air cell can be considered as an air container with uniform cross-sectional area and constrained by adjacent cells, a vertical deflection will cause a proportional change in volume. Thus, the rate of change of the pressure depends on the deflection and can be related to the force causing the deflection. The spring rate can be determined as follows:

$$P'_1 V_1 = P'_2 V_2$$

$$P'_2 = P'_1 + \frac{W}{A}$$

where P'_1 and P'_2 are absolute pressures.

Combining the two expressions above gives (14.7 psi = atmospheric pressure)

$$(14.7 + P_1)V_1 = \left[(14.7 + P_1) + \frac{W}{A}\right] V_2$$

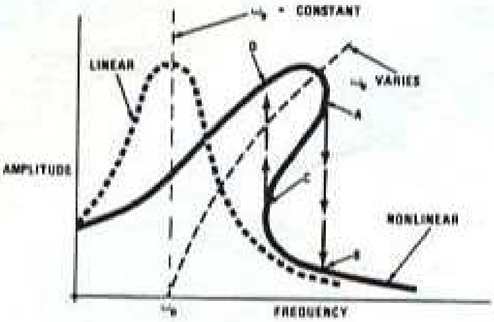

Fig. 7 - Comparison of response of linear and nonlinear systems

This equation can be rearranged as

$$W = A(14.7 + P_1)\left(\frac{V_1}{V_2} - 1\right)$$

Since

$$s = \frac{V_2 - V_1}{A}$$

and

$$K = \frac{W}{s}$$

we have

$$K = \frac{A^2(P_1 + 14.7)[(V_2/V_1) - 1]}{V_2 - V_1}$$

where:

P_1 = Initial inflated pressure of air cell, psi
P_2 = Pressure of air cell under load, psi
A = Cross-sectional area of air cell, in.^{2}
W = Load applied to air cell, lb
V_1 = Initial volume of air cell, in.^{3}
V_2 = Loaded volume of air cell, in.^{3}
s = Vertical deflection, in.
K = Spring rate of air cell, lb/in.

To verify the calculated spring rate, a model air cell was tested to determine its actual spring rate. The experimental results were found to agree with the calculated results within experimental error. The full size spring rate data to be used in the computer model can be calculated at various inflation pressures by using the stated equations. Fig. 8 is a typical spring rate curve.

Damping Constant Determination - The damping constant of the air cell was determined by further experiments with the scaled model of the air cell at 1 psi inflation pressure. The cell was loaded with a laboratory weight and excited into vibration. The amplitude and period were recorded. The data obtained from the experiment were reduced, and the damping decrement was used to obtain the damping constant. This approach assumed linear damping, but the numerical value was expected to be very low and the error therefore insignificant.

Quantitative Prediction of Ride Characteristics - To predict cross country ride, we inserted the assumed vehicle constants and the computed spring and damping constants into a hybrid digital-analog computer program. The computer output plots predicted vertical acceleration at the driver's seat in g's as a function of speed over three terrain types: flat grassland, mild cross country, and severe cross country. The ride qualities at the driver's seat were selected as the criteria for determining maximum cross country speed because the driver of a tactical vehicle will operate at the highest speed at which he can maintain vehicle control.

During a computer run at any one vehicle speed, a range of accelerations is predicted because of the irregularity of the terrain amplitude shape and wavelength. To overcome the data handling problems, we decided to reduce the data to statistical form. For example, if the probability that a certain level would be met were 0.95, the acceleration could be assumed to be constantly recurring.

Fig. 9 is a plot of the data computed by this technique. Note that for this case, the driver will be able to operate the vehicle over mild cross country terrain at speeds up to a maximum of 27 mph before the ride becomes intolerable, forcing him to limit the speed.

The air cell rate and vehicle ride studies were a part of a total performance analysis. The other phases of this study will not be discussed. Since all data required for accurate soft soil and water performance predictions was not available from full scale testing, a model test program was initiated. The next section briefly describes that program

EXPERIMENTAL MODEL AIR CELL STUDIES - The PATA model testing program was conducted in two phases. The first phase involved the collection of data on water performance. The second phase involved the collection of additional data in soft soil to estimate full scale performance and power requirements.

The water performance of the full scale vehicle showed problems in obtaining suitable forward thrust and steering

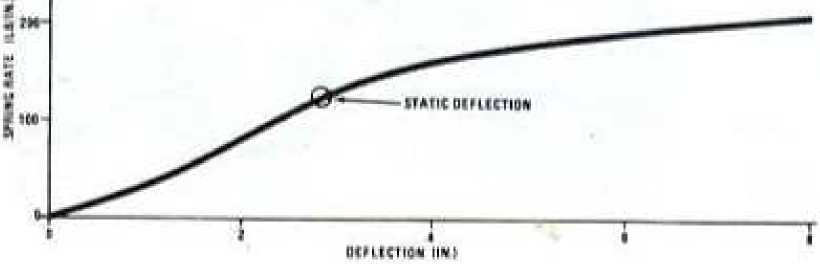

Fig. 8 - Spring rate versus deflection

control. A quarter-scale, self-propelled model was constructed, based on the physical characteristics of the PATA test bed. This model, shown in Fig. 10, was made to accept adjustable reactor vanes, which were designed to redirect the vertical "rooster tail" off the rear of the tracks into a horizontal thrust stream and correct the steering and propulsion vectors.

Fig. 11 is a view of the full scale test bed operating in the water, illustrating the rooster tail. The reactor vanes were designed to convert the downward thrust on the vehicle stern, caused by the rooster tail, into an upward thrust that would provide additional propulsive and steering force.

The model tests in water predicted a full scale vehicle speed of 6 mph with 100 hp and indicated that 7 mph with 150 hp was feasible. After installation of the vanes on the full sized vehicle, the model test results were verified. Steering control was much improved and water speed closely approximated the prediction based on the model test results.

The second phase of quarter-scale model testing was conducted to evaluate the performance of the pneumatic track on extremely soft soil (swamp type of terrain). The same model that had been used for the water tests was employed, permitting good correlation of data. The model was instrumented to measure torque and speed at the drive shaft. A special tank for mud testing was constructed and loaded with screened Macomb County, Michigan, farm soil (clay loam) to a depth of 12 in. Tests were conducted with soil moisture content varying from 7 to 25% and at several model weights and track speeds.

Drawbar pull was increased in increments by adding weights to a pulley arrangement attached to the model until 100% slip was attained. Fig. 12 shows the model during a typical run in the test fixture. During each test run, driveshaft torque and speed, model speed, sinkage, and drawbar pull were recorded. Fig. 13 shows drawbar pull over weight with slip varying from 0 to 100%. We scaled up the data for this illustration, using model laws, to represent 10,000 lb gross vehicle weight (GVW). These tests were carried out in 25% moisture content soil.

CONCLUSIONS DRAWN FROM WORK TO DATE - Upon completion of the initial phases of air cell track development (that is, concept, design, installation, test), the following conclusions were made:

1. The use of the air cell in a track/suspension concept is entirely feasible and provides improved ride characteristics.

2. The inherent buoyancy of the air cell track/suspension system provides unique flotation and propulsion characteristics for soft soil and water operation not found in conventional track systems and represents a state-of-the-art improvement in suspension design.

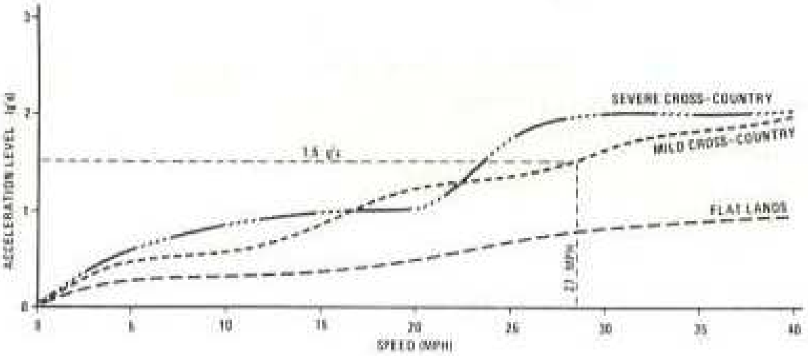

Fig. 9 - Acceleration versus speed

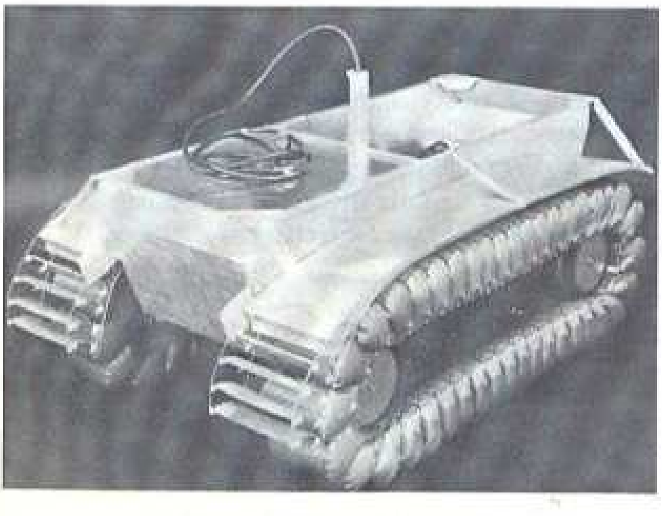

Fig. 10 - View of test model

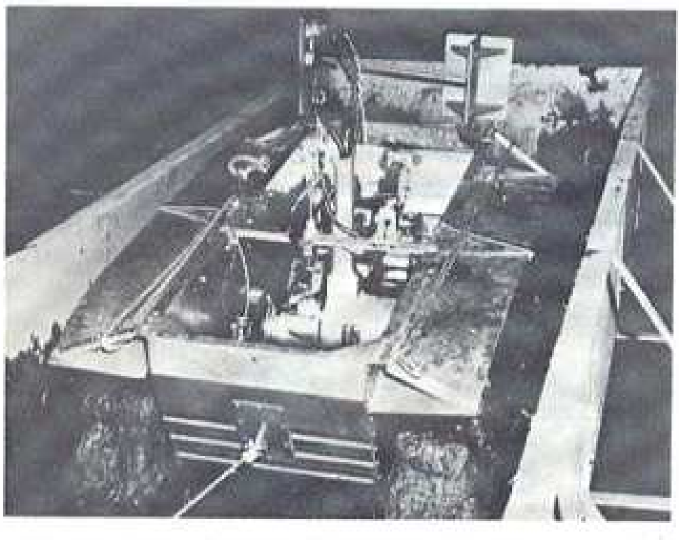

Fig. 11 - View of PATA test bed showing "rooster tail"

Fig. 12 - Testing the model in 25% moisture-content soil

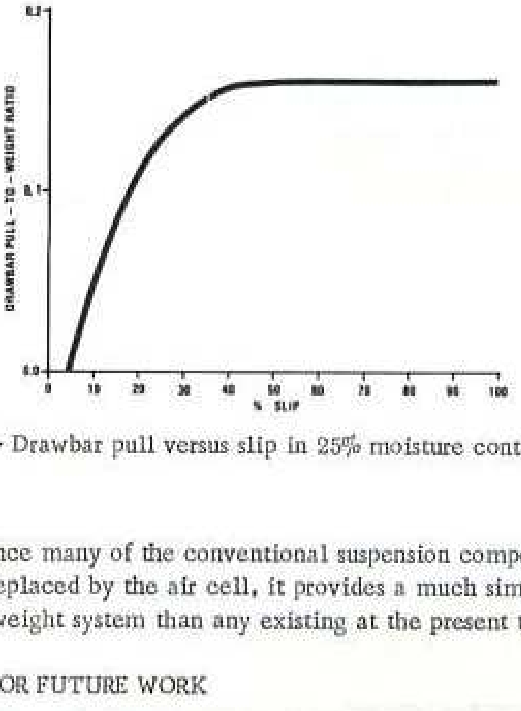

Fig. 13 - Drawbar pull versus slip in 25% moisture content soil

3. Since many of the conventional suspension components can be replaced by the air cell, it provides a much simpler, lighter-weight system than any existing at the present time.

PLANS FOR FUTURE WORK

LTV is presently involved in the second stage of track component development. The air cell is being further analyzed to gain additional understanding of its behavior, and its design is being improved through (1) consultation with rubber fabricators, (2) development of new design concepts, and (3) fabrication of test models. Through effective application of our past experience, we will build another test vehicle, incorporating the improvements necessary to achieve even better performance than the first test bed exhibited.

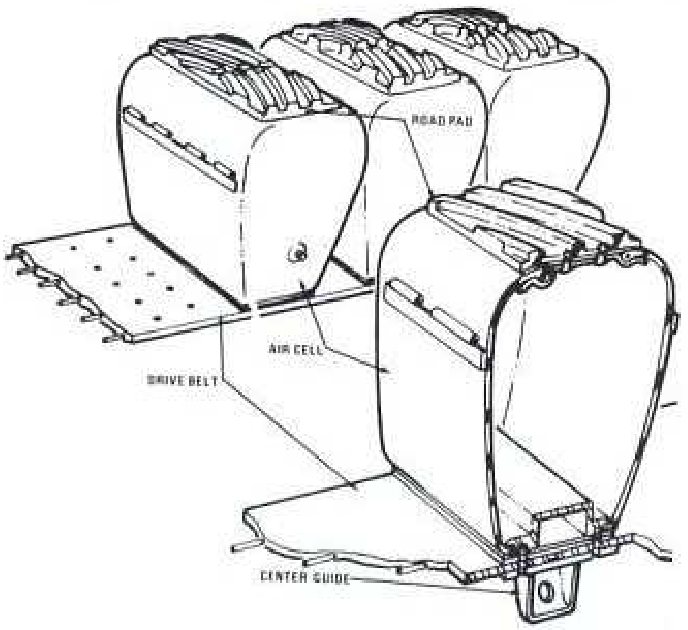

Fig. 14 - Advanced concept of flexible track air cell

As an example of a new approach, an advanced flexible track concept incorporating air cells is presented in Fig. 14. We intend to employ state-of-the-art tire fabrication techniques in the air cell development program to provide the necessary durability. Some of the more significant improvements that have been used as a guide in designing improved air cell concepts are:

1. Multiple ply, woven cording in the side wall for improved wear resistance.
2. Thicker rubber tread configurations for puncture resistance.
3. Simplified assembly techniques for improved maintainability characteristics.

SUMMARY

The air cell track/suspension system offers a solution to many surface vehicle mobility problems because it enables high speed, cross country operation, water operation, obstacle negotiation, and soft soil operation, in addition to providing highway operation capabilities. Once a few manufacturing problems are fully understood and overcome, the air cell track will be ready for tactical applications.

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