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GROUND TRANSPORTATION FOR POLAR OPERATIONS - 16-WHEEL LOW-GROUND-PRESSURE VEHICLE (LGPV-16)

By

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NAVAL FACILITIES ENGINEERING COMMAND

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Transportation operations at remote sites in polar regions require specialized equipment due to the climatic and terrain conditions. Design criteria was developed for a multipurpose, 5-ton-capacity, high-flotation-tired, prototype vehicle to move personnel and cargo and to provide fire-fighting/crash-rescue capabilities to aircraft operations. Contracts were awarded for the design and fabrication of a 16-wheel low-ground-pressure vehicle (LGPV-16). After delivery of the vehicle in late 1970, initial testing indicated the

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need for a tire with better flotation and traction capabilities. After new tires had been installed and minor modifications made to the suspension system, the vehicle was retested before shipment to Antarctica. During the Antarctic testing the vehicle did not fulfill performance requirements set forth in the design criteria, mainly because the complete drive-train system is underdesigned for the severe operational conditions when driving over deep snow. The vehicle was returned to the continental United States where the decision has been made to discontinue further development.

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INTRODUCTION

A major requirement for operating in and around polar coastal stations is a fast, dependable transportation system for movement of personnel and cargo over snow, ice, and frozen ground. Light, tracked vehicles are effective for operating over unprepared snow fields but generally travel at slow speeds under most conditions. Also, they are subjected to considerable track wear and resulting high maintenance cost if used on ice, frozen ground, or dirt, and in mud. Wheeled vehicles with standard-sized rubber tires are capable of fast transportation over most hard surfaces but become immobile in deep, soft snow. To improve the performance of wheeled-vehicle operation for the Naval Support Forces Antarctica (NSFA) in and around McMurdo Station, Antarctica, the Civil Engineering Laboratory (CEL) has adapted and introduced to the transportation system a variety of vehicles with high-flotation tires [1,2,3]. This has extended the operation of wheeled vehicles to outlying station areas, such as Williams Field, located on the deep snow of the Ross Ice Shelf. However, to achieve full utilization of the flotation-tired vehicles it has been necessary to prepare snow trails and snow roads for such vehicle travel in the deep snow areas. Heavy-haul vehicles require well-prepared snow roads, but lightweight vehicles operate satisfactorily over snow trails, which require minimum preparation effort. Operation is even satisfactory over natural snow surfaces, under certain conditions.

This report describes a multipurpose, 5-ton, 16-wheel, high-flotation-tired, prototype vehicle designed by CEL to extend the high-speed wheeled transportation system to include traveling over unprepared, natural-snow surfaces. This capability would greatly enhance logistic support in polar operations.

BACKGROUND

In fiscal year 1969 CEL completed feasibility and preliminary design studies to develop criteria and fabrication specifications for a flotation-tired vehicle that would negotiate rough, low-ground-bearing terrain and deep snow fields. During a later phase of the CEL study airfield safety was studied by those responsible for fire-fighting/rescue technology and equipment for remote polar airfields. Operation of airfields in polar regions such as Williams Field at McMurdo, Antarctica, presents many problems regarding climate and terrain where the use of standard procedures and equipment is not possible.

Williams Field Air Facility, the air terminal for all United States air raft entering and leaving the Antarctic continent, basically consists of 1) camp, (2) aircraft control facility with fire-fighting and rescue service, (3) ice runway for wheeled aircraft, and (4) a snow runway for ski-equipped aircraft. The largest logistical aircraft supporting the Antarctic operation is the C-141, which utilizes the ice runway. The study indicated that because of the flight density and type of aircraft using the field, the facility fell under a Gross Weight Category-4 (GWC-4) designation with respect to required fire-fighting/rescue capability. As a result of the study, an immediate effort was launched to upgrade the existing fire-fighting equipment, which at that time consisted of fire-rescue equipment mounted on tracked vehicles. Beyond the interim procurement of new equipment, certain criteria were established for the development of new equipment. CEL incorporated as much of the fire-fighting/rescue vehicle criteria as possible into the development of a rough-terrain vehicle. However, it was recognized that compromise was necessary between the performance of the ideal, fire-fighting/rescue vehicle and of that which could be achieved. Experience with wheeled-vehicles traveling over rough, low-ground-bearing terrain indicated that a speed of 45 mph could not be expected.

DESIGN

The criteria, listed below, were established as the target objectives for the design and fabrication of a prototype vehicle resulting from the feasibility study and preliminary design performed under Navy contract N62399-69-C-0003 by Fabco Division, Keysey-Hayes Company, Oakland, California.

1. Vehicle curb weight: approximately 18,000 pounds
2. Payload: 5 tons
3. 16 rubber-tired driving wheels: with near equal weight distribution
4. Vehicle ground bearing pressure: in the range of 3 psi
5. Travel speed: up to 35 mph
6. Engine: gasoline powered
7. Transmission: automatic shift
8. Front and rear steering: with capability for compound and crab operation
9. Front-mounted winch: with 10,000-pound pull
10. Fuel supply: for 30 hours of continuous operation
11. Over-all body dimensions: no greater than 8-1/2 feet high by 9 feet wide by 30 feet long for shipment in C-130 aircraft

12. Size of cargo deck: not less than 8 by 12 feet

13. Winterized cab: for crew of six with escape hatch in roof

Concept

The vehicle would be designed around two basic principles: (1) simplicity of design and utilization of as many off-the-shelf components as possible and (2) a vehicle capable of producing a uniform ground-bearing pressure.

The preliminary analysis indicated that 16 wheels would be required to obtain sufficient ground contact area. This requirement was based on the tire manufacturer's indication that 19.75 x 20-inch flotation tires would provide approximately 500 square inches of contact area when inflated at 5- to 6-psi pressure. To achieve uniform ground pressure, the wheels would be grouped in clusters of eight at the front and the rear of the vehicle. Each group of eight wheels would be subgrouped into four wheels connected by a wobbly-axle, walking-beam assembly to provide flexibility for the individual wheel to follow the surface contour of the terrain. The two subgroups of four wheels, each forming the eight-wheel cluster, would be assembled to a turntable which would be attached to the front and rear deck frames that would be swivel-connected at a transverse break in the deck.

The turntable configuration would permit maneuvering the vehicle by independently steering each set of eight wheels for fore-and-aft directional control in turning and crab steering. The wheel suspension would not include the complicating mechanism of a shock-absorbing system, but for a smooth ride would rely on tire flexing and the flexible linkage of the walking-beam, wobbly-axle arrangement.

Equal weight distribution would be achieved by locating the cargo deck space in the central portion of the vehicle, with the personnel cab mounted forward and the drive engine at the rear. This configuration would provide easy access by the crew, if the vehicle carried fire-fighting equipment, and also ease of drive-engine maintenance by mounting the engine on the deck top-side. Power from the engine would be transmitted through a torque converter into drive shafts and gear boxes to a differential at each eight-wheel cluster. From this point each set of two wheels in each subgroup of four wheels would be chain-driven from the differential. The preliminary analysis indicated the wobbly-axle would have to be limited to 6 degrees of movement to avoid an over-twist in the roller-type drive chain; also, the walking-beam should be confined to 12 degrees movement to minimize vehicle height and avoid tire interference with the deck framing.

The cab would be designed to seat six passengers, including the driver. Three would be seated forward in individual bucket seats, and a bench seat at the rear would accommodate the remaining crew. This area could also be convertible to storage of equipment and protective clothing needed in crash/rescue operations, if crew requirements were less than six.

Prototype Design

Navy contract N62399-70-C-0015 was negotiated with Fabco Division, Keysey-Hayes Company, for fabrication of the prototype vehicle. The vehicle was delivered to CEL in December 1970, after undergoing acceptance test at the contractor's plant in Oakland, California. During the design and fabrication, it was found necessary to substitute materials from that considered in the preliminary design. The major deviations from the preliminary design concept were a change from gasoline to a diesel-fueled drive engine, a change in cab fabrication from fiberglass to steel, and a weight increase in the chassis (necessary for strength). This resulted in a vehicle-curb-weight increase from the target weight of 18,000 pounds to an actual weight of 24,630 pounds. Government-furnished material consisted of 16 tire-and-wheel assemblies. The tires, 19.75 x 20, 18-ply nylon cord, Martin Ultra Flo, were manufactured by Marin Tire Company of Wichita, Kansas.

The dimensions and weight distribution of the vehicle are shown in Figure 1.

Engine, Transmission, and Power Train. Motive power is provided by a Cummings diesel engine Model V-470P of 470-cubic-inch displacement. The engine is rated 155 hp at a governed speed of 3,400 rpm. It is connected directly to an Allison model MT42 automatic transmission, which provides six forward speeds and one reverse speed. The transmission is coupled by a short propeller shaft to a miter gear box, which drives the rear set of wheels through a modified Dana, model 70HD, rear axle assembly. The wheels are driven through a series of roller chain and sprocket drives from the axle assembly. The front set of wheels are similarly driven by a propeller shaft extended forward from the miter box. Fuel supply is provided by two 80-gallon tanks under the deck between the front and rear sets of wheels.

Suspension and Steering. The front and rear wheels (dolly assemblies) are nearly identical. Each consists of a turntable assembly which permits the dolly to turn for steering purposes. Mounted on each turntable are two walking beams. Each walking beam pivots about its centerline, with the rotation restricted to a 12-degree up-and-down tilt. At each end of the walking beam is a transverse shaft, which carries one wheel at each end. The shaft is pivoted at the center to permit up-and-down movement of each wheel. This movement is restricted to 4 degrees each side of neutral position. The combined articulation of the wheel shaft and walking beam permits each wheel to carry a uniform load over irregular terrain.

The rotation of the front and rear dolly assemblies provides the steering; two hydraulic cylinders on each dolly provide the required torque. Hydraulic oil under pressure is directed to the cylinders on the front dolly through a valve controlled by the steering wheel in the cab. Also located in the cab is a valve which controls the flow of oil to the cylinders on the rear dolly. Actuation of this valve turns the rear dolly to the right or left. The rear dolly can also be mechanically locked in the straight-forward position. A coordinated operation of the steering wheel and the rear dolly control valve results in high maneuverability, tight turning, and a crab-steering capability.

Brakes. The vehicle is equipped with four hydraulic brakes. They are located on the axles in the front and rear turntable assemblies and apply braking effect to all wheels through the drive chains. The vacuum-boost hydraulic system is split, with the front brakes separated from the rear brakes.

Cab and Controls. The cab was designed for separation at approximately midheight. Provision for removal of the upper section was necessary to maintain a vehicle height limitation of 8-1/2 feet for shipment in C-130 aircraft. The electrical wiring harnesses were made for plug disconnection at this point, and the cab doors were made for easy removal.

Operating controls, all located in the cab within reach of the driver, include: steering wheel, brake pedal, parking brake lever, throttle pedal, transmission shift control, rear dolly steering, rear dolly steering lock handle, winch control valve, heater controls, engine starter switch and lock, windshield wiper control switches, windshield washing control, window defogging switches, light switches, headlight dimmer switch, turn and hazard-warning switch, dome light, spotlights, and power take-off control for hydraulically operated winch.

Electrical System. The vehicle is equipped with a 24-volt electrical system. Energy is supplied to the batteries by a 45-ampere alternator driven by the engine. Instruments are on a 12-volt system, which is fed through a voltage-reducing resistor located under the instrument panel.

INITIAL TEST

Following delivery of the vehicle to the Civil Engineering Laboratory at Port Hueneme, California, the first vehicle operation was over dirt and sand areas (Figure 2). These tests were conducted to familiarize the operator with the vehicle's handling characteristics and to observe its general performance. After some experience with the steering control system the operator developed the necessary skills for executing the maneuvering capability of the vehicle through the coordinated operation of the front and rear steering systems. It was observed that the vehicle could turn a full circle with an inside tire track of 28 feet in diameter. The top vehicle speed on a flat, level dirt course at governed engine speed was found to be 3[illegible] mph.

To check the ground-bearing pressure of the vehicle, tests were conducted to determine the ground-contact area of a single tire at various inflation pressures and loads. Using a tire and wheel from the vehicle, tests were performed in a large materials testing machine with the wheel mounted in a special support frame. Tire contact areas for various inflation pressures and loads on a flat surface with no tire penetration are given in Table 1. Calculating the vehicle ground-bearing pressure based on the test data in Table 1 (assuming the minimum operating tire pressure would be 5 psig) and using the actual vehicle weight data in Figure 1, the unladen vehicle weight distribution results in a ground pressure of approximately 6.2 psi on the front tires and 8.6 psi on the rear tires. The addition of the 5-ton load increases the vehicle ground pressure by approximately 3.0 psi on the front and rear tires. The vehicle obviously far exceeded the design criteria of approximately 3-psi ground pressure if zero tire penetration performance is considered. At 4-inch tire penetration, based on manufacturer's data for a similar-sized tire, the above calculated ground pressures would be reduced by about 50%. Prior to the first snow test at Mammoth, California, this vehicle was equipped with a Kim Hotstart Model BC 110X engine coolant preheater and a Model OL6315EP lube oil heater.

MAMMOTH AREA SNOW TESTS

Adequate snow for the tests was found at levels above 8,000 feet in the California Sierra Mountains with access to the area at the Mammoth ski-run location. The test area was covered with snow ranging up to 6 feet deep.

The first tests were run with 7-psi tire inflation pressure and an 8,000-pound payload. Attempts were made to negotiate a 20% slope which also had a side-hill effect. The vehicle had adequate power to climb the slope but would lose traction and slide sideways. After repeated attempts, traction was obtained in the packed snow, and the vehicle proceeded up the slope.

On the next test, the vehicle covered approximately 200 yards on a flat, level area before becoming immobile in the soft snow (Figure 3). The front wheels had penetrated 8 inches and the rear wheels 12 inches. Disturbance of the snow by the front wheels and the slightly higher axle load on the rear wheels contributed to their deeper penetration.

Several runs were made at this location by backing up after the vehicle had become immobile and proceeding forward in a new track. Very little additional tire penetration was observed when backing over the existing tracks; however, each trip of forward travel through undisturbed snow was halted at about the same 200-yard distance.

With the 8,000-pound load removed and the tire inflation pressure lowered to 5 psi for the next test, there was little observable improvement in vehicle performance in undisturbed snow; however, travel over the previously tire-compacted test area, which was now covered with 6 to 8 inches of new wet snow, caused no problem. The wet snow easily compacted for added vehicle support. Further testing over a 3-mile trail with grades ranging from 4 to 20% indicated once an initial pass had been made there was little additional tire penetration, even when carrying the 8,000-pound load. Reducing the tire pressure to 3 psi had little effect in improving vehicle performance.

A 2,500-foot test course was measured and marked to determine vehicle speed. Slope measurements were determined to be 4% over the measured distance. Fifteen runs were made over the test course, at an average attainable speed of 15 mph when climbing the slope and 20 mph going down. The 8,000-foot elevation was a contributing factor to the slow speeds; horsepower loss at this altitude is estimated to be 24% on a diesel engine without a turbocharger.

Several tests for mobility were made with turns off the traffic-packed areas up side slopes and between the tree growth lining the test area. Maneuvering between the trees was accomplished by using the crab and compound steering of both front and rear wheels (Figure 4). In these areas the snow supported the loaded vehicle, except in the soft drifts. The vehicle would become immobile with wheel penetration of 4 to 8 inches and loss of traction. Backing out of the drifts was accomplished by remaining in the same tracks. On two tests the wheels penetrated 12 to 14 inches, and the vehicle became completely immobile.

Snow density tests were attempted, but the snow was so stratified with both loose snow and ice lenses from daily thaw-and-freeze cycles that the data had little value. The shear values were so low that test equipment available could not obtain readable results.

Rolling resistance caused by wheel penetration and wheel slippage allowed by the smooth-tread design of the tires were the main causes of the vehicle becoming immobile in soft snow. A more aggressive tread would have improved forward movement capability at the tire-penetration depths encountered during these tests.

A summary of the test results follows:

1. A new tire with thinner sidewall construction, greater ground contact area, and a more aggressive tread was required.

2. Mechanically, operation of this vehicle was acceptable.

3. Steering characteristics of the vehicle were acceptable.

4. Engine power would be adequate at lower elevations, but turbocharging should be considered for use at elevations above 3,000 feet.

5. The cab was roomy and comfortable for six people dressed in winter clothing.

6. The ride was somewhat stiff but would probably improve with more flexible tires.

MODIFICATIONS

After completing the Mammoth snow tests the vehicle was fitted with new tires to reduce tire ground pressure and improve vehicle traction. The largest tire the vehicle would accommodate was a 48 x 20.00 x 20, high-flotation Goodyear Super Terra-Grip. It was of 4-ply sidewall construction and would operate with a minimum inflation pressure of 4 psi. According to manufacturer's specifications, ground contact area is 280 square inches at no penetration and 590 square inches at 4-inch penetration. The new tires also required new wheels with lockbead rims to eliminate tire-rim slippage at the low inflation pressures. To use the tire also required reversing the wheel drive chains to eliminate the chain link pin ends' rubbing against the tire sidewall. Figures 5 and 6 show the difference in tread design between the original and replacement tires.

Inspection of the vehicle indicated weld failure had occurred in both the front and rear structural members (bolsters) that support the walking beam. Several cracks had developed in welded joints. The vehicle manufacturer assessed the problem as inadequate design and corrected it by adding stiffener tie rods and rewelding the gusset stiffeners that had pulled loose. Subsequent testing of the vehicle on dry pavement, sand (Figure 7), and rough terrain (Figures 8 and 9) indicates this modification had corrected the problem, which was attributed to rough terrain and steering operations.

POINT MUGU AREA MUD TEST

The LGPV-16 with the new Goodyear Super Terra-Grip tires was tested in mud and wet sand in a marsh-lagoon area at Naval Air Station, Pt. Mugu, California. This terrain is an area subject to tidal flooding with the soil consisting of a thin top layer (4 to 6 inches) of mud mixed with vegetation and debris that overlays a silt and organic mixture with high water content. Table 2 is an analysis of the soil up to 24 inches. Table 3 is a summary of the penetrometer tests. These tests were limited due to the difficulties of getting support vehicles and equipment into and out of the area.

The vehicle, loaded with 10,000 pounds and tire inflation of 10 psi, had adequate flotation and traction to traverse this area on an initial pass (Figure 10) with tire penetration of 1 to 5 inches. However, on a repeat pass over the same area the tires penetrated 5 to 10 inches more into the mud until the walking-beam suspension arms dragged, completely immobilizing the vehicle (Figure 11) due to loss of traction. The vehicle successfully traversed the wet sandy beach areas with tire penetration of 1 to 2 inches. All steering modes - compound, crab, and front-only - were accomplished without difficulty during these tests.

TRUCKEE AREA SNOW TEST

In mid-January 1972 the LGPV-16 vehicle fitted with the 48 x 20.00 x 20 Goodyear Super Terra-Grip tires was transported to the Sierra Mountains test area near Truckee, California, for further snow testing. On the flatlands the snow depth ranged from 18 to 25 inches and was soft and wet. Air temperatures during this phase of testing ranged from 20^{o} to 38^{o}F.

Tire pressures were set to 10 psi, and the vehicle was loaded with 10,000 pounds. The vehicle easily traversed the level terrain in this area (Figure 12), and steering was very responsive on both the front and rear wheels. Steering modes, including compound, crab, and front-only, were handled with ease; the 8-inch penetration of the wheels did not appreciably affect the steering.

Over the rough areas of the course, a severe bounce from the flexing of the tire sidewalls was experienced. When the speed of the vehicle was held constant, this bounce would become more severe as a harmonic frequency seemed to develop; but the bounce was reduced considerably when speed was decreased. The bounce tendency increased in severity when tests were performed at lower tire-inflation pressures of 6 and 8 psi. As the flexing of the tire sidewall is the only shock-absorption capability built into the suspension system, this feature will be a limiting factor in high-speed operation.

A barranca was found which was 60 feet wide and 8 feet deep and had banks with slopes up to 60%. Several runs were made with approaches directly into, and at angles to, the slope. The vehicle traversed slopes up to 50% but lost traction on 60% slopes. Side slopes up to 30% were traversed with little difficulty.

Speed tests were run on a 1,500-foot measured course where the average snow depth was 24 inches. Initial passes over untraveled snow, with tire penetration of 8 inches, were made at an average speed of 7 mph. Subsequent runs over the same area with zero penetration on the packed snow were made at an average speed of 12 mph. Loss of power due to elevation (6,000 feet) was noticeable during these tests, and the speed was also reduced to some extent by the bounce caused by the tires.

The vehicle was then driven to another test site, with newly fallen snow ranging from 34 to 48 inches deep. Here, the air temperature reached a low of $0^{\circ}F$. The vehicle traversed slopes up to 22%, with tire penetration in the new, powder snow averaging 12 inches. The new tires provided good traction, and the terrain was easily traversed. Speed over the deep snow and following the hilly terrain averaged about 5 mph. Both the front and rear steering was required to maneuver around the trees in this area (Figure 13).

Density tests of undisturbed snow and of snow compacted under the front and rear wheels are given in Table 4. Tire contact areas for different inflation pressures are given in Table 5. It should be noted that the observed contact areas are appreciably less than the 590 square inches specified by the manufacturer for 4 inches of penetration. The manufacturer is possibly quoting an implant type of contact, which would be appreciably greater than that produced by a rolling tire that compacts the surface, where material such as snow, does not remold itself to the tire shape.

The following list is a summary of the results of the tests conducted at the Truckee snow area:

1. Traction with the 48 x 20.00 x 20 Terra tires was very good.

2. Flotation with the new Terra tires was better than the original Martin tires but still does not meet the requirements set forth in the design criteria.

3. Top speed of the loaded vehicle will not approach requirements set forth in the design criteria.

4. Structurally, the vehicle is satisfactory for the load requirements. The new tie rods installed between the walking beams reduced the loading in the support brackets, and no weakness was discovered during these tests.

5. Power loss due to altitude (about 18%) limited the climbing ability and speed of the vehicle. Subsequent investigation indicates that a limitation to torque on the gear-train will not allow for installation of a turbocharger to increase power.

6. The low-pressure tires and lack of shock absorbers contributed to the bounce encountered during the speed runs. Redesign of the suspension system would be required to eliminate this problem.

7. The fuel-fired cab heater is difficult to start and maintain; however, when working properly, the heater maintains a comfortable cab temperature.

8. The load platform is stable on 30% slopes, but the height required to clear the large tires gives the appearance and feeling of being top-heavy.

MODIFICATIONS

After completing the Truckee snow tests and before shipping the vehicle to McMurdo Station, Antarctica, in September 1973 for additional testing, the following modifications were made:

1. An upshift inhibitor was installed on the transmission. This electric solenoid is activated to hold the transmission in the lowest gear of each gear range, thus eliminating automatic upshifting when the vehicle traverses soft snow at slow speeds.

2. The engine and transmission housing was modified to permit easier access to the units for repair or maintenance.

3. The output shaft oil seal on the rear right-angle-drive gear box, which had failed once during the tests, was found to be leaking. The seal and bearing retaining flange was modified by the vehicle manufacturer to accept a larger seal and bearing.

4. The rear-steering control valve was modified to a self-centering valve for ease of operation.

ANTARCTIC (MCMURDO AREA) TESTS

The Antarctic testing program, started in February 1974, was designed to evaluate the vehicle under various conditions of tire pressure, payload, and snow cover. To assist in evaluating the operational characteristics of the LGPV-16 vehicle, a Nodwell Model FN100TT Water Trotter cargo vehicle (empty weight 15,000 pounds) was obtained from NSFA at McMurdo to provide performance comparison.

Compacted Snow Road - 1974

The first tests were speed trials on the compacted snow road, running the vehicles without payload. Over a 5,000-foot measured course, in gear range 3-4, the LGPV-16 (with ground pressure of about 4.6 and 6.4-psi front and rear tires, respectively, at no penetration and operating in fourth gear at the governed engine speed of 3,400 rpm) covered the 5,000-foot course in 2 minutes, 15 seconds (approximately 25 mph). In gear range 3-5 the engine could not maintain governed speed in fifth gear and the resultant time was 2 minutes, 25 seconds. The test in gear range 3-6 was not completed, as the transmission would not stay in sixth gear, due to low engine rpm. By comparison, the Water Trotter, operating in third gear, covered the same test course in 2 minutes, 37 seconds (approximately 22 mph). The Water Trotter, with its larger, softer tire (ground pressure about 4.7 psi at no penetration) and short wheelbase, has a very severe bounce even when operating on a relatively level surface. In comparing the speed trials of the two vehicles, the LGPV-16 was operating at its upper mechanical ability and was restricted very little by the bounce, while the Water Trotter was severely restricted because of safety and operator discomfort.

Undisturbed Snow - 1974

For the first test of the LGPV-16 over undisturbed snow, the vehicle was unloaded and operated at tire inflation pressure of 15 psi. The snow characteristics were typical of deep snowfields, containing both hard-packed drifts and very soft areas. The vehicle negotiated the hard-packed drift areas with little trouble but quickly became immobile in the soft snow areas. By remaining in the same tracks the vehicle could usually be backed up; however, at times, towing assistance was required.

The tire inflation pressure was then lowered to 5 psi for the next test. This lower tire pressure somewhat improved the vehicle flotation characteristics but not sufficiently to prevent becoming immobile. Both the LGPV-16 and the Water Trotter could negotiate the hard, windpacked drifts with little trouble, leaving only shallow ruts. The performance difference in soft snow areas was observed. The Water Trotter could slowly chew its way through the soft snow by constant slippage of the tires. Conversely, the LGPV-16 would rut into the soft snow with little tire slippage until the rolling resistance overcame forward momentum, causing the tires to slip and the vehicle to become immobile (Figure 14). The high ground clearance of the Water Trotter enabled it to continue chewing its way through the soft snow, while the low axles and walking beams on the LGPV-16 would drag in the snow, increasing the rolling resistance.

During this test run, while trying to maneuver the LGPV-16 out of the soft snow, the rear differential failed and because repair parts were not available, further testing was halted until the next test season in 1975.

Before beginning the tests in January 1975 the following repairs and maintenance were required:

1. Rear differential that failed during initial testing was replaced. Inspection revealed teeth on both the ring gear and pinion gear were broken. Also, one differential side bearing and bearing cap had failed.

2. The batteries were frozen and had to be replaced. Only two batteries of that type were locally available and replaced the original four. This reduced the ampere-hours capacity but was adequate for starting after the engine was preheated with the oil and coolant heaters.

3. The alternator was inoperative and could not be repaired because parts were not available. The battery charge was maintained by an external source during nonoperational hours.

4. The brakes were adjusted. Fabrication of an adjusting tool and enlarging the entry holes were required to make the adjustment.

During the initial checkout of the vehicle following repair, an additional operational problem was encountered. The transmission's override control (a solenoid type of up-shift inhibitor that prevents automatic shifting out of the lowest gear of the selected gear range) had shorted out. This control had been installed during Continental United States (CONUS) tests when it was found that the engine torque requirement changed rapidly with variable tire penetration, resulting in erratic gear-shifting as related to engine rpm. Automatic gear shifting occurred when engine rpm reached 2,400 to 2,600. The vehicle had to be operated during the 1975 tests with this limitation because a replacement part was not available.

Inclined Ramp

The vehicle, driven over and around snow berms 10 to 12 feet high, had adequate power in first and reverse gears to climb 20 to 25% slopes. The walking-beam/wobbly-axle combination allowed the tires to maintain ground contact, except at points where rapid slope change occurred. Here, either the front or rear tires would momentarily leave the surface as the vehicle passed over the slope change (Figure 15).

Winch Operation

The front-mounted, hydraulically driven winch was tested by attempting to pull a 20,000-pound gross-weight truck immobilized in soft snow. The winch would not pull this load but held while the LGPV-16 pulled the truck out. The winch would pull the truck through soft snow, except when completely immobile.

Compacted Snow Road - 1975

A 1,000-foot test course was marked off on the snow road for rolling-start speed tests. The LGPV-16 was loaded with 6,000 pounds (weight of the Ansul-type fire-fighting unit), and all tires were inflated to 5-psi pressure. With this load, the ground contact pressure was about 5.3 psi for the front tires and 7 psi for the rear at no penetration. For operational comparison, arrangements were made with NSFA to use a Nodwell Model FN100TT Water Trotter crash-and-rescue vehicle (Figure 16), which weighs 21,600 pounds and has a ground contact pressure of about 6.7 psi at no tire penetration.

In gear range 1-2, operating in second gear at an engine speed of 3,400 rpm, the LGPV-16 covered the test course in 52.6 seconds (approximately 13 mph). In gear range 3-4, operating in third gear at 2,200 rpm, the time was 41.0 seconds (approximately 16.6 mph), and in gear range 3-5, operating in fourth gear at 2,300 rpm the time was 52 seconds (approximately 13 mph). Attempts were made in gear ranges 3-5 and 3-6, operating in fifth and sixth gears, but were discontinued; the transmission would not stay in fifth gear, and sufficient vehicle speed was not attained for sixth-gear operation.

The Water Trotter covered the 1,000 feet in fourth gear, high range, in 28 and 26 seconds (approximately 24.3 and 26.2 mph). The engine was running at close to maximum rpm; however, the tachometer was broken, and the actual rpm was unknown. Because of the roughness of the ride, the operator had to let up on the throttle at times but maintained maximum throttle as much as possible.

It was observed that maximum obtainable speed of the LGPV-16 was regulated by mechanical limitations. Its speed would be improved if shift points of the transmission could be manually controlled for the particular surface condition. The speed of the Water Trotter while running at close to maximum was somewhat restricted by operator comfort and safety.

Undisturbed Snow - 1975

A 1,000-foot test course on undisturbed snow near Williams Field was marked off for speed tests. The LGPV-16, loaded with 6,000 pounds and tire inflation pressure of 5 psi, covered the course in 3 minutes, 43.5 seconds (approximately 3.1 mph) in gear range 1-2 with the transmission frequently shifting between first and second gear (a previously described problem). The Water Trotter, in first gear, high range, covered the course in 4 minutes 28 seconds (approximately 2.5 mph). During a second test the engine speed of the LGPV-16 was varied in an effort to eliminate upshifting of the transmission into second gear. The vehicle covered the course in 2 minutes, 50 seconds (approximately 4 mph). During this second test the Water Trotter was run in second and third gear, low range, covering the course in 4 minutes, 35 seconds (approximately 2.5 mph).

The performance characteristics of the two vehicles were considerably different. The LGPV-16 was faster but inconsistent, while the Water Trotter was slower but maintained a steady speed. At times the LGPV-16 penetrated only 1 to 4 inches, but frequent penetrations of 8 to 12 inches would slow the vehicle almost to a stop. The Water Trotter left ruts 6 to 8 inches deep the full length of the course but maintained a constant speed.

The LGPV-16 was then driven over other areas of undisturbed snow to determine steering capabilities, using front or rear steering modes. By using compound steering of both front and rear wheels, a turning radius of 18 feet 9 inches was obtained. When operating in crab-steer position (rear wheels tracking to one side of the track of the front-wheels), the rear wheels left ruts 3 to 6 inches deeper than the front wheels because of higher axle load.

During tests on undisturbed snow it was observed that when the LGPV-16 was stuck, the wheels spun and stopped repeatedly, even though the engine was maintained at a constant speed. Closer inspection found that the cross members supporting the right-angle-drive gear boxes were twisting, allowing the gear boxes to twist 2 to 3 inches. The slack in the drive train, differentials, drive shafts, and chains (plus the twisting of the cross member) caused the wheels to stop momentarily when tire traction increased. With this observation, all testing was discontinued, due to the possibility of cross-member failure, which would cause major damage to the drive train. Inspection also revealed leaks in two of the power steering cylinders, the input-shaft of the rear right-angle gear box, and the right rear differential axle seal. The vehicle was returned to CONUS.

Summary of Results

1. Speed tests in 1974 indicated the LGPV-16 vehicle with no load could attain a maximum speed of about 25 mph over a hard-packed snow road surface. For comparison, the cargo Water Trotter vehicle attained a maximum speed of about 22 mph.

2. Limited tests on undisturbed deep snow before the rear differential failed, concluding the 1974 tests, indicated that poor mobility performance could be expected over such surfaces.

3. Speed tests in 1975 indicated the LGPV-16 vehicle loaded with 6,000 pounds could attain a maximum speed of about 17 mph over a hard-packed snow road surface. For comparison, the crash/rescue Water Trotter vehicle traveled the same distance at about 25 mph.

4. Over the undisturbed deep snow the LGPV-16 vehicle labored with great difficulty to negotiate the terrain, traveling a measured distance at about 4 mph. For comparison, the crash/rescue Water Trotter traveled the same distance at about 2.5 mph.

5. Inspection of the LGPV-16 vehicle during the undisturbed-snow tests resulted in an early end to the testing; failure of the framing members supporting the drive train appeared inevitable if testing continued. The inspection also located numerous hydraulic fluid and oil leaks in the power steering system and drive train gear boxes.

6. The inoperative override solenoid installed on the automatic transmission to prevent gear-hunting caused some constraint on the 1975 performance of the LGPV-16 vehicle.

DISCUSSION

The performance of the LGPV-16 did not meet the objectives set by the criteria. The ground pressure of the prototype vehicle - appreciably higher than that specified by the criteria - prohibited what could be considered satisfactory vehicle performance over low-ground-bearing (snow field) terrain. The undisturbed Antarctic snow was more difficult for the vehicle to traverse because of the snow's dry-base, granular texture, which flows with the tires. The moist CONUS snow, with its higher moisture content tends to compact under traffic. To maintain mobility, a wheeled vehicle has to overcome such resistances as: (1) basic hard-ground rolling resistance; (2) sinking or compaction resistance, which relates to work done compacting the surface; (3) bulldozing resistance, which relates to the work done displacing the material ahead and to the sides of the tires; (4) tire hysteresis due to flexing of the tire; and (5) grade-climbing resistance.

In the development of the criteria for the 16-wheel vehicle, not enough consideration was given to these mobility factors. The mobility success of the vehicle was further compromised during the design and fabrication, when the vehicle weight had to be increased from that initially planned, but with no increase in tire size. It would be well for the future designer to pretest the prospective tire at planned inflation pressure and loading to determine actual contact area for the intended terrain usage, as opposed to accepting the manufacturer's general specifications. In the case of the 16-wheel vehicle, the prototype would accept a tire only slightly larger than that originally specified. A review of current literature indicates that off-road, low-ground-bearing, rough-terrain vehicles should be designed for ground pressures in the range of from 0.5 to 2 psi for effective mobility capability.

In regard to high-speed travel, the specification that the vehicle should be capable of 35 to 40 mph over rough terrain was extremely unrealistic. Operating experience from the current high usage of rough-terrain vehicles indicates such vehicles seldom attain speeds greater than 8 mph, due to the wave profile of the terrain, which promotes vehicle pitching with its resulting driver fatigue.

CONCLUSIONS

1. The LGPV-16 does not have sufficient flotation to be considered a satisfactory off-road transportation vehicle capable of negotiating low-ground-bearing terrain, such as the deep, undisturbed snow fields in the Antarctic.

2. For travel over hard surfaces such as compacted snow roads, the LGPV-16 vehicle, compared with more conventional, less complex vehicles presently available, does not have sufficient speed for crash/rescue operation or high-speed cargo movement.

3. The LGPV-16 vehicle has adequate power for low-speed, relatively hard-surface, rough-terrain operation, such as that demonstrated in its beachsand operation; however, its drive train is underdesigned for a continuing high-torque-demand operation.

4. The ability to steer the LGPV-16 vehicle by independent front and rear steering made the vehicle highly maneuverable; however, the separate controls made steering awkward and inconvenient for the operator.

5. The uncommon, somewhat unique, chain-drive and walking-beam suspension performed well, except that less restriction of walking-beam rotation is necessary to avoid tire overload as the vehicle passes over an abrupt slope change.

6. In general, the vehicle as designed would require high maintenance, due in part to the present underdesign of the drive train.

RECOMMENDATIONS

Though the vehicle design concept does have merit, it is recommended that further development of the vehicle be discontinued, because of its relatively limited cargo-carrying capability and the high cost of development of a more rugged drive train for greater endurance.

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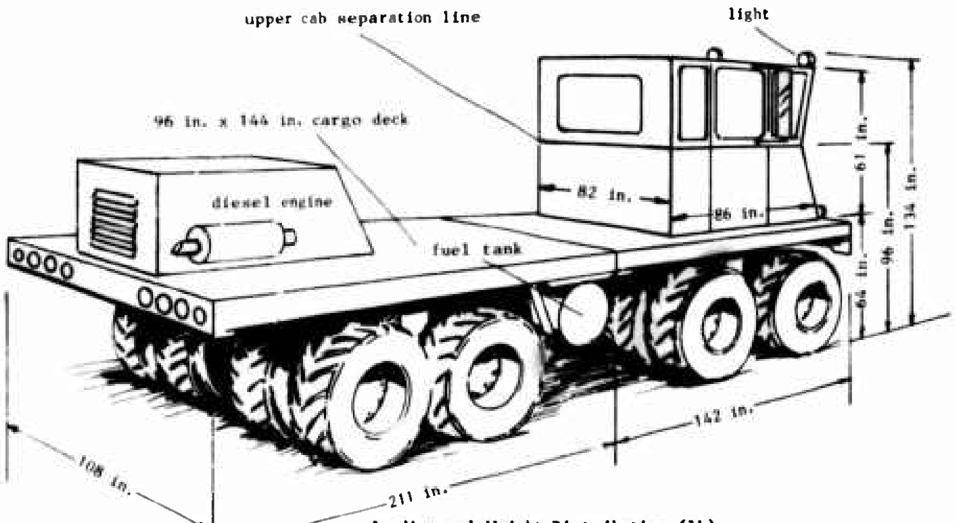
2.________. Technical Report R-409: Polar transportation equipment - six by six truck tractor and 20-ton semitrailer with high-flotation tire, by W. H. Beard and G. E. Sherwood. Port Hueneme, CA, Oct 1965.

3.________. Technical Report R-507: Polar transportation - analysis of wheeled vehicles for McMurdo, Antarctica, by D. Taylor and N. E. Pierce. Port Hueneme, CA, Jan 1967.

4. T. N. W. Akroyd. Laboratory testing in soil engineering. London, G. T. Foulis for Soil Mechanics, Ltd. 1957.



Loading and Weight Distribution (lb)

	Front Dolly	Rear Dolly	Total
Weight unladen	10,300	14,330	24,630
Payload	5,000	5,000	10,000
Weight, laden	15,300	19,330	34,630
Load per tire, unladen	1,290	1,790	
Load per tire, laden	1,910	2,410	

Figure 1. Weight and dimensions of the prototype low-ground-pressure, rough-terrain, 16-wheel vehicle (LGPV-16).

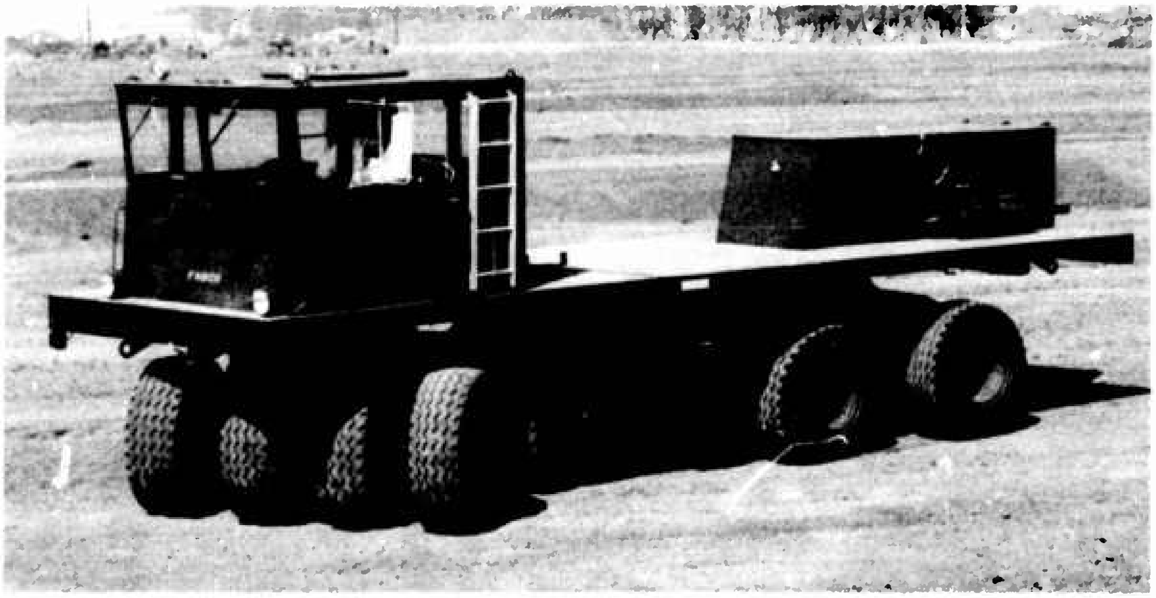


Figure 2. LGPV-16 vehicle as received from manufacturer.

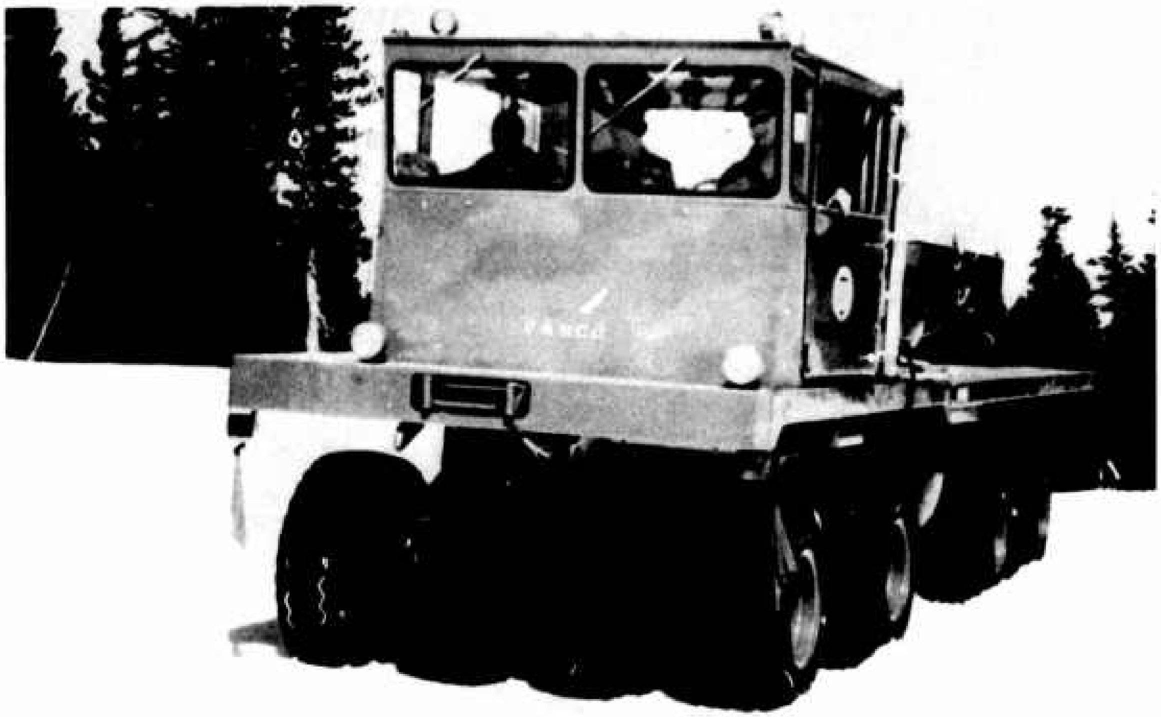


Figure 3. Operation of vehicle over undisturbed snow at Mammoth.

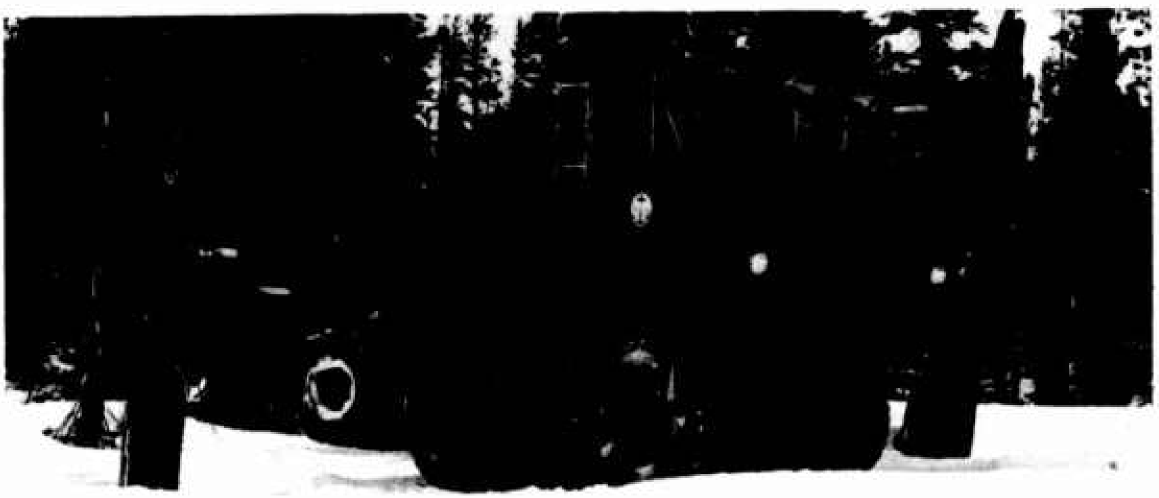


Figure 4. Maneuvering vehicle through use of independent front and rear steering systems.

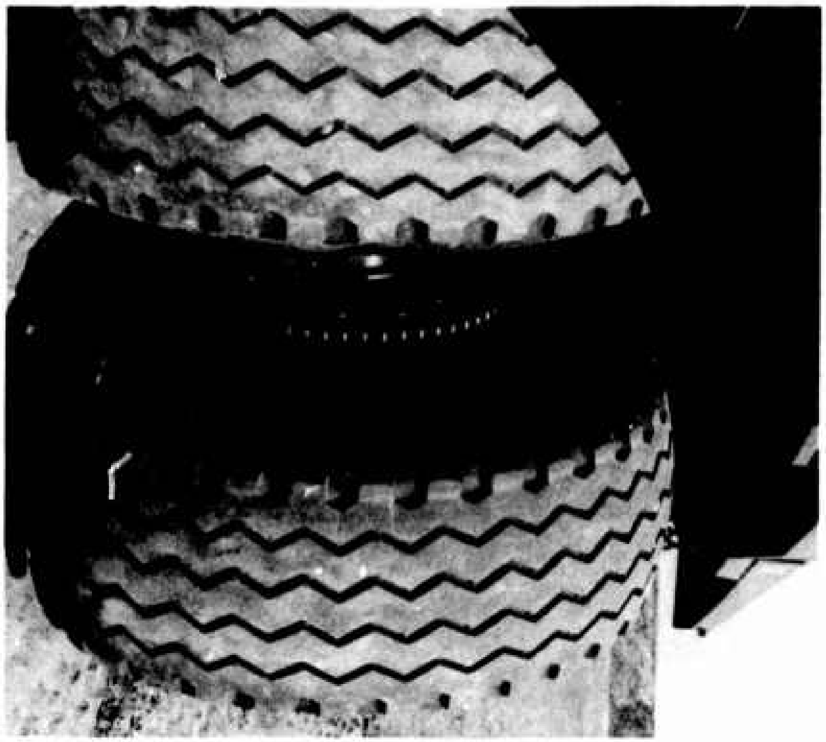


Figure 5. Martin 19.75 x 20 Ultra-Flow tire, original equipment.

Figure 6. Goodyear 48 x 20.00 x 20 Super Terra-Grip tire, replacement tire.

Figure 7. Operating vehicle on beach sand for Terra-Grip tire performance and frame modification tests.

Figure 8. Operating vehicle over sand dune area to observe rough-terrain performance.

Figure 9. Sequence view of Figure 8, showing severe loading of tire as vehicle progressed over slope.

Figure 10. Vehicle making an initial pass over Point Mugu test area.

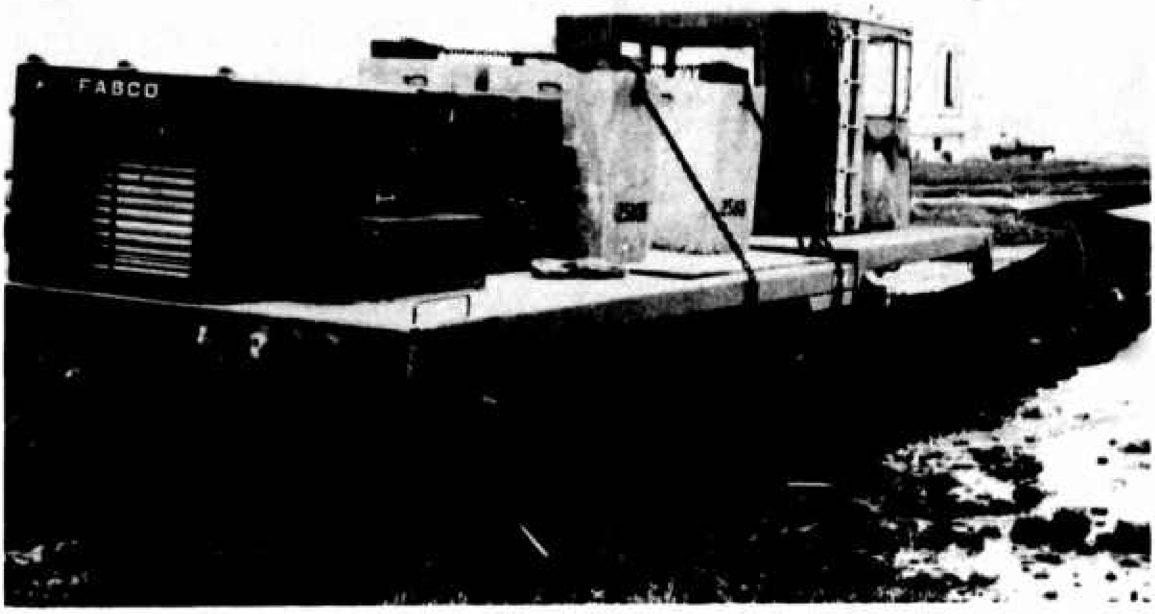


Figure 11. Vehicle immobilized in the viscid mud following tracks of initial pass.

Figure 12. Vehicle operating on level terrain at Truckee test site.

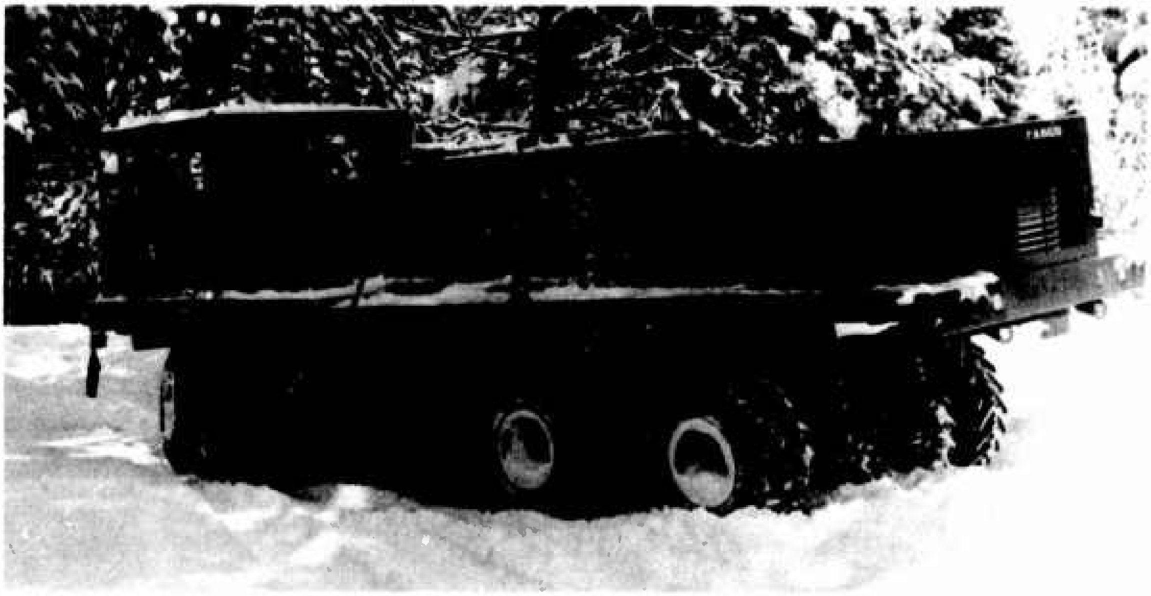


Figure 13. Vehicle operating on forest-covered hilly terrain at Truckee test site.

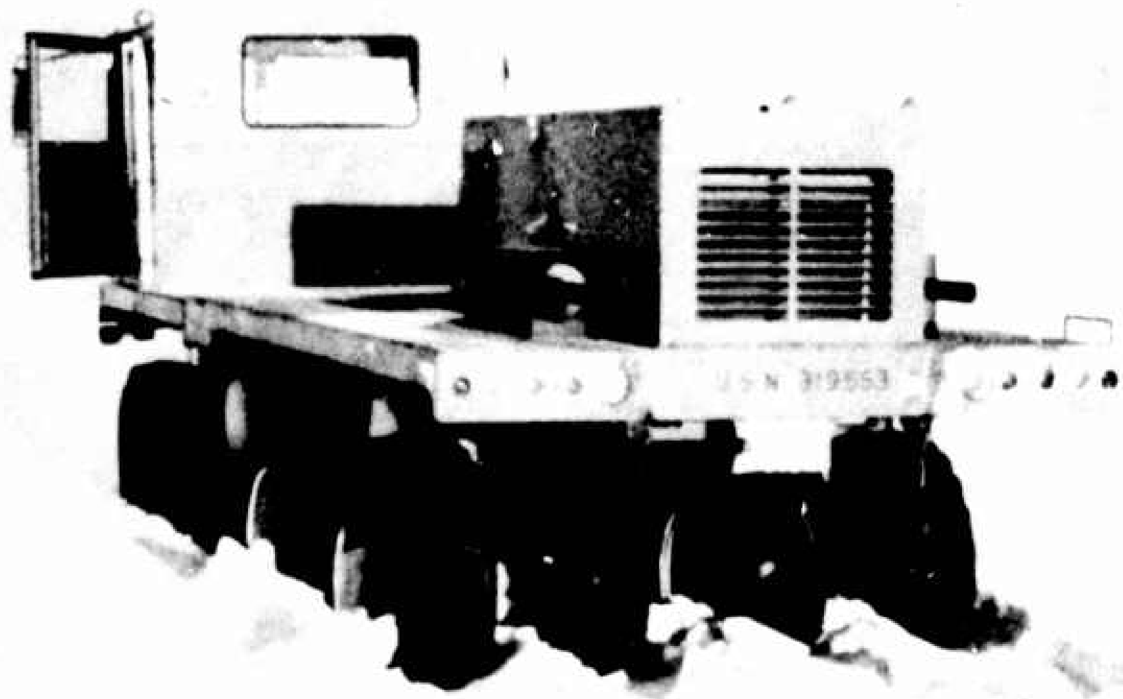


Figure 14. Testing LGPV-16 in 1974 over undisturbed snow on the Ross Ice Shelf, McMurdo, Antarctica

Figure 15. Testing LGPV-16 operation in 1975 over rough-terrain snow.

Figure 16. Nodwell Water Trotter vehicle used for aircraft crash/rescue service at McMurdo, Antarctica.

Table 1. Sidewall Deflection and Contact Area on Hard Flat Surface at Various Loads and Tire Pressures for Martin 19.75 x 20-Inch 18-Ply Tire

Tire Pressure (psi)	Deflection and Contact Area With –									
	1,000-Pound Load		1,500-Pound Load		2,000-Pound Load		2,500-Pound Load		3,000-Pound Load	
	Deflection (in.)	Area ($in.^2$)	Deflection (in.)	Area ($in.^2$)	Deflection (in.)	Area ($in.^2$)	Deflection (in.)	Area ($in.^2$)	Deflection (in.)	Area ($in.^2$)
10	0.875	40	1.250	92	1.500	130	1.750	170	2.063	185
8	1.063	70	1.500	112	1.750	150	2.063	180	2.313	204
6	1.188	90	1.625	118	1.938	160	2.250	196	2.563	220
5	1.375	104	1.688	135	2.063	170	2.438	208	2.813	236
4	1.500	110	1.938	154	2.313	197	2.688	226	3.188	262
3	1.625	118	2.063	168	2.500	210	3.063	252	3.563	286

Table 2. Soil Test Analysis of Samples Taken 15 May 1972 at Point Mugu Test Site

Depth Below Surface (in.)	Moisture Content[a] (%)	Liquid Limit (%)	Plasticity Index (%)	United Soil Classification[b]	Specific Gravity[c]	Dry Density[d] (lb/cu ft)	Organic Content[e] (%)	Gradation
0-3	111.5	54.9	4.4	OH	2.60	46	8.3	–
3-8	44.3	40.3	13.6	ML				100% passing no. 40 sieve.
8-16	51.2	52.7	26.2	CH	2.59	65	–	
16-24	47.7	43.8	21.6	ML				89% passing no. 100 sieve.

[a] Weight of water divided by dry weight of mineral and organic matter.
[b] OH – organic clays of medium to high plasticity.
ML – inorganic silts and very fine sands or clayey fine sands.
CH – Inorganic clays of high plasticity.
[c] Mineral fraction.
[d] Mineral and organic matter.
[e] Determined by hydrogen peroxide method described in Reference 4.

Table 3. Penetrometer Tests Made 19 May 1972 at Point Mugu Site

Depth Below Surface (in.)	Penetrometer Resistance (psi[a])			
	Undisturbed Site		In Vehicle Track	
0-3	35	35	20	20
3-6	25	40	30	35
6-12	40	75	45	35
12-18	100	80	60	50

[a] U. S. Army Corps of Engineers Cone Penetrometer Test, 0.5-in.[2] cone. Layman comparison – 15-cone Penetrometer Index will not support a man walking on the surface.

Table 4. Density Measurement of Snow at Truckee Test Site. [Snow depth, 34 inches; air temperature, 38°F; snow temperature, 31°F]

Undisturbed Snow		Under Front Wheels		Under Rear Wheels	
Depth Below Surface (in.)	Density	Depth (in.)	Density	Depth (in.)	Density
6	0.26	*a*	*a*	*a*	*a*
10	0.29	*a*	*a*	*a*	*a*
14	0.31	*b*	*b*	*b*	*b*
18	0.41	18	0.46	18	0.46
22	0.38	22	0.46	22	0.45
28	0.36	28	0.38	28	0.37

[a] Top 12-in. of snow compacted by vehicle tires.
[b] No measurement made.

Table 5. Tire Contact Area Taken During Truckee Snow Test with 48 x 20.00 x 20 Super Terra-Grip Tire

Tire Pressure (psi)	Penetration (in.)	Contact Area		
		Width (in.)	Length (in.)	Total (in.^{2})
10	12	19	15.5	295
8	12	19	17	323
6	11	20	18	360

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