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Two Pennsylvania Plaza, New York, N. Y. 10001

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IN THE EARLY 1960's Lockheed began an intensive study of the requirements and current limitations of military combat vehicles. This new program was one of several in the company's long range business plan for diversification into technological areas outside the aerospace field which, at that time, was the company's primary area of activity. Actually, work had been going on for some time in the design and development of advanced ground handling equipment and transporters for missiles and spacecraft. Certain in-house tactical warfare studies provided a foundation for expansion of this effort. Both wheeled and tracked vehicles were investigated during preliminary "Missile B" study efforts and LMSC's NATO MMRBM Study, providing much insight into the problems of global, all-terrain mobility requirements. Also, an extensive survey of light tank and tank-destroyer vehicles contributed significantly to an understanding of vehicle limitations, vehicle performance tradeoffs, and modern tactical vehicle requirements. Each successive effort pointed up the limitations that existed in obtaining good cross-country speed while maintaining acceptable ride quality and platform stability at these higher speeds.

A feasibility study was conducted to determine the possibility of designing a vehicle that would result in at least 2 to 1 improvement in military vehicle performance. The new concept, based upon an 8-wheel all-wheel drive, two-bodied articulated configuration, appeared to meet this ambitious goal. Subsequently, the Twister Project was established as an in-house, company funded development program in February 1965. Nine months later, in October 1965, design, fabrication, and assembly of a testbed were completed. Since that roll-out date, more than 3 years of engineering and field testing have been conducted. The test results have proved conclusively that Twister has met or exceeded expectations and appears to represent a significant step forward in the state-of-the-art for high-performance, off-road vehicles. Three developmental vehicles have been contracted for by the Army to assess the military potential of the Twister configuration. This paper covers the Twister testbed development program from design concept and hardware fabrication through the current test and evaluation program, with an appropriate overview of test results.

DESIGN PHILOSOPHY

One of the basic limitations to current military vehicles is their speed over rough terrain. In this environment the limits of human tolerance are soon reached due to forces transmitted through a vehicle during high-speed operation. If these forces could be reduced and the vehicle made to accommodate the higher external forces, then safe, de-

ABSTRACT

A new, high-performance ground vehicle known as Twister has been built and tested. The vehicle incorporates features designed to meet military needs for a substantial increase in cross-country speed, all-terrain mobility, and platform stability. The design of TWISTER is based upon a dual body joined by a unique pivot yoke permitting three degrees of freedom between the bodies. Significant departures from current practice have been made in the application of a dual power supply, individual walking beam suspension, coordinated Ackerman/yaw steer and unique tire design and application.

Aspects of the Twister development program presented in this paper include the design and development of a full-scale testbed and the results of three years of test operations in both engineering and natural terrain environments.

pendable high-speed movement could be achieved. It was decided that no single-bodied vehicle could meet this objective. An extensive investigation of various multi-wheeled articulated configurations was begun, since they appeared to possess the potential capability to conform to the extremes in terrain to be encountered. An articulator has the obvious advantages of reducing body "torquing" and allowing greater effective wheel movement without using up the basic suspension travel so necessary to absorbing dynamic loads. An articulator also insures a more continuous tire-to-ground contact, particularly in rough terrain; and therefore, we were convinced that the effectiveness of the tire-to-ground contact would ultimately determine the overall vehicle performance. It was recognized that a major improvement in tire configuration was also mandatory.

We were convinced that articulation in itself was not enough to insure an effective operational vehicle. High-speed operations result in significantly higher basic loads being fed into the suspension system. A soft, high-displacement suspension system on an articulated body with the resultant high effective wheel movement can go a long way toward "damping" the loads felt by the occupants.

Walking beams, due to their basic configuration, are extremely effective in the reduction of transferred loads. Hence, a front body configured as one large walking beam and a rear body incorporating independently sprung walking beams was selected to minimize vertical accelerations and pitch rate at the driver and crew positions. We were confident that such a configuration would result in a more stable rear platform and excellent overall ride qualities.

Our combat effectiveness studies had shown that we could no longer depend entirely on fighting from behind several inches of armor plate in slow-moving vehicles. Technological advances in armor-piercing weaponry have resulted in kill capabilities from weapons that can easily be carried on a soldier's back. It appeared that a new concept of "shoot and scoot" had merit and that the ability to move fast with lightly armored fighting vehicles would eventually replace the apparent advantages of the heavier armored but slower fighting vehicles of today.

The low horsepower-to-weight ratios of existing military vehicles we felt sure would restrict maximum utilization of this new concept. The use of two engines to obtain the required high horsepower-to-weight ratio fits very well with Twister's two-body configuration. In addition to the greater acceleration, higher sustained speeds and good vehicle response rate, a greatly improved-get-home capability was automatically provided since the loss of one power source only partially degraded the vehicle's total performance capability.

It was realized that high-speed movement also required a fast steer capability. Vehicle steering in the conventional manner lacked the rapid response, short-turning radius, and ease of handling required. Therefore, in a major breakaway from tradition, the time-proven Ackerman steer was combined with a yaw steer system to produce a highly responsive and stable vehicle control system.

The last, and certainly the major consideration, was that the basic configuration should be applicable to a wide range of vehicle weight classes without degrading the overall performance objectives. Subsequent in-depth studies and operational experience have verified this.

PRELIMINARY DESIGN

Following the establishment of the design philosophy, a general study plan was developed to do sufficient analysis of Twister's general arrangements, sub-systems, and componentry to provide definitive characteristic data for a cost-effectiveness comparison with the more advanced combat vehicles in service or under development. Upon completion of the initial study plan, preliminary performance comparisons and combat-effectiveness analysis, as compared with the best current and planned wheeled and tracked vehicles, indicated such a superiority potential for the new concept that the entire plan was re-examined. A decision was made to bypass the more comprehensive parametric design cost-effectiveness evaluation and proceed immediately to the design of a full-scale testbed vehicle.

This course of action was based on the premise that analytical methods for determination of performance, handling characteristics, and general functional suitability would not be adequate for such an unconventional vehicle configuration. Actual testing of full-scale hardware at the earliest possible date was recognized as the only practical way to obtain conclusive verification of the apparent capability improvement both for Lockheed's own evaluation of Twister's product potential and for a realistic evaluation of its value by the military.

TESTBED VEHICLE

DESIGN CRITERIA - In establishing design criteria for the Twister the most important and most difficult to be made was whether or not the vehicle would be configured as a testbed or represent a specific military configuration. The latter would have the advantage of immediately showing the intended customer the proposed hardware he might buy and result in minimum changeover time in going from testbed to development vehicle status. The disadvantages were the longer design period and significantly higher development costs. At the onset of this program there was no approved QMR for a vehicle in the Twister category. Designing for one of the military requirements that might eventually be established was considered too risky at this point in the program. Also, it was decided that overall effectiveness of the "hardware" would be restricted if a specific military configuration was built rather than staying with the more flexible testbed configuration. The testbed concept would also ease the task of component and system revisions and modifications that inevitably develop in a program of this type.

It was futher decided that the initial objective after vehicle roll-out would be to demonstrate to company management and to the customer the capabilities of this unique configuration. Once additional knowledge was gained through a comprehensive test and evaluation program, mockups of one or more military configurations could be constructed, based upon more definitive information regarding proposed customer QMR's. There was also an awareness that the introduction of a new military vehicle concept into the military supply line is a long and arduous task. A testbed configuration would be more effective through this long period and would permit maximum utilization and exposure to a wide variety of customer interests.

Once this decision was made, it was necessary to define the basic design criteria futher. The following specific design goals were established:

1. Versatility - Provide as much flexibility as possible for variation of vehicle characteristics to permit optimization during test. This included, but was not limited to, possible changes in damping and spring rate characteristics, steering mode and configuration, tire size, overall power train ratio, and articulation limits.

2. Low Development Cost - Wherever possible, existing components and proven designs would be used in order to confine development activity to features peculiar to the Twister configuration.

3. Realism - While meeting other specified criteria, weight, weight distribution, articulation, suspension, steering structure, and power train design should be kept within the range of a producible design so that the testing and development, when accomplished on the testbed, would have direct applicability to next-generation military pilots and eventual production vehicles.

As much emphasis as possible, consistent with the overall program objectives, would be placed upon maintainability, human factors, and reliability/durability features. However, the prime objective was to investigate vehicle performance and potential capabilities, since it was obvious that time and money constraints would not permit all areas to receive equal emphasis.

Three years of experience with the testbed have shown that the design criteria and other initial decisions were sound. Under similar circumstances today, the original ground rules would be followed again.

DESIGN - Design of the testbed began with the establishment of a proposed characteristics and performance chart,

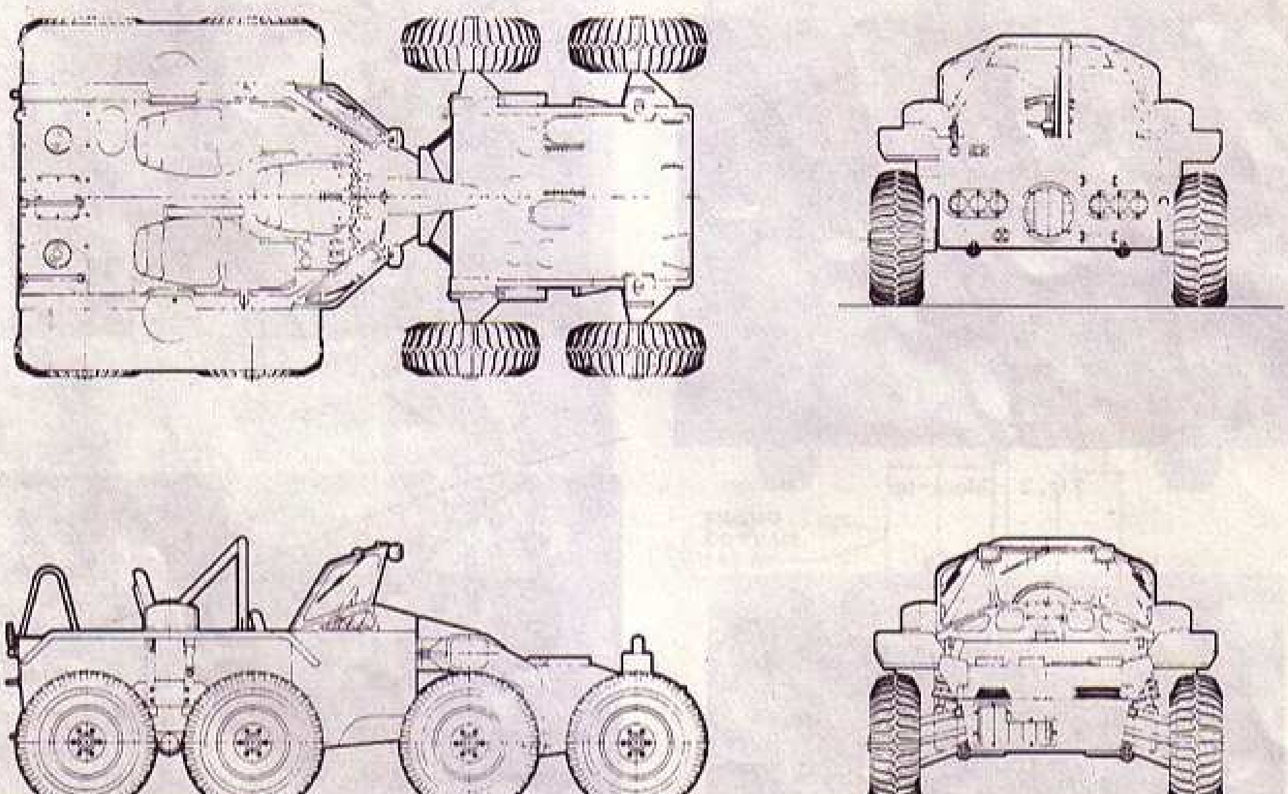

Fig. 1 - Test bed, general arrangement

and basic load and structural design criteria. Of these, the basic loads were the most difficult to establish since no other vehicle employed a configuration similar to Twister, nor was any other vehicle capable of the high cross-country speeds with attendant high external suspension loads. Subsequent vehicle operation showed that certain loads were considerably higher than had been anticipated and component design changes were required for greater strength. This condition was particularly evident in the drive train area where there is usually a tendency to underestimate the high loads encountered during the extremes in articulation with resulting large changes in individual wheel loadings.

A mockup of the proposed configuration was fabricated following completion of the initial design layout (Figs. 1 and 2). The mockup served to pinpoint a number of potential problem areas prior to the detailed design stage. It also permitted on-the-spot engineering decisions, articulation clearance checks, vision analysis, and necessary configuration changes that otherwise would have taken many manhours of design time to fully investigate.

Principal elements of the vehicle system as originally designed are described in the following paragraphs. Subsequent modifications to the system are discussed in the "Field Testing" portion of this paper.

Articulation and Steering - The steerable front body is united with the load-carrying rear body by a joint or coupling which provides an unusual degree of freedom in pitch, roll, and yaw (Figs. 3-5).

The installation of the patented pivot yoke linking the front and rear bodies provides the unique articulation capabilities basic to the Twister concept. Functionally, the yoke is as much a part of the primary structure as the suspension and carry-through structure. Variable stops are provided to limit articulation to any desired value of pitch and roll. The yaw mode is normally powered. However, it can be disconnected to "trail" or locked in the straight-ahead position to simulate a conventional 8 x 8.

The four front wheels of the Twister design are power steered in conjunction with a controlled and patented front body yaw steering system (Fig. 5). When the yaw articulation and front wheels are turned to the maximum angle possible, turning radius is a short 19 ft. The vehicle is controlled by a conventional steering wheel which is easily turned by one hand throughout its full 2.5 turns from lock to lock. The ratio is varied by changing the steering hand pump. The turning action of the forward body wheels is actuated by hydraulic power. The steering geometry is designed along conventional Ackerman principles. Yaw action is produced by a double-rod hydraulic cylinder mounted inside the pivot yoke and connected to the yoke by tension

Fig. 2 - Mock-up

Fig. 4 - Twister roll

Fig. 3 - Twister pitch-up

Fig. 5 - Twister, yaw

chains. The control signal to the yaw actuator is provided by hydromechanical slave linkage which continually compares front wheel position and yaw angle and automatically compensates for any deviation from the ideal geometric combination.

SUSPENSION - The front suspension employs unequal length wishbones with coil springs damped by hydraulic, double-acting, telescoping shock absorbers. The number one axle utilizes a coil spring and shock absorber outside the body shell (Fig. 6). The number two axle suspension is similar but the coil springs and shock absorbers are inside the body shell. A total wheel excursion of 12 in. is provided at each wheel to permit maximum wheel movement and load attenuation prior to engaging the rubber jounce and rebound stops.

The four wheels of the aft body are mounted tandem in pairs on two walking beams, one beam on each side of the vehicle (Fig. 7). Each walking beam responds independently of the other. In principle, the concept is conventional; however, on Twister, the beam is unrestrained at its pitching axis, permitting 12 in. vertical wheel movement. The suspension spring for each side provides 6 in. vertical movement at the trunnion in addition to the travel permitted by the pitching motion of the beam. The suspension spring is mounted integrally with an extendable hydraulic cylinder which raises the rear body to a maximum of 10 in. for greater ground clearance as required. Shock absorbers are provided for both the vertical walking beam movement and the pitching movement. Rubber stops are provided to limit overall pitch travel. Shaft power to the wheels is independent for each wheel.

POWER TRAIN - Each body contains its own complete and identical power train package (Fig. 8). No mechanical means of interconnecting the front and rear power units is provided, nor considered necessary. All wheels are driven all the time under normal operating conditions. It is pos-

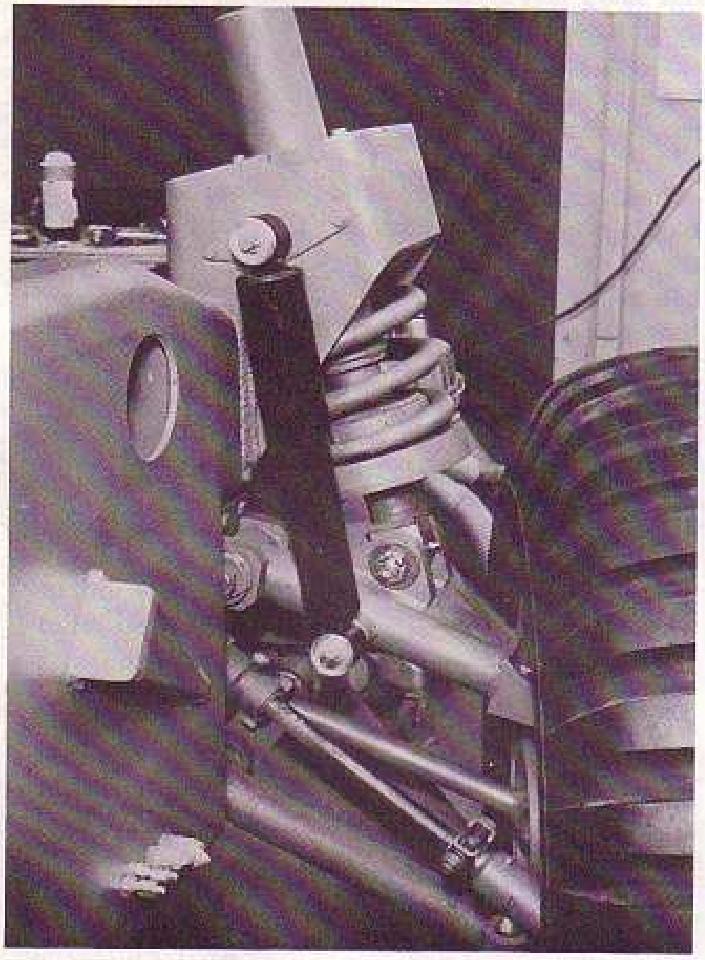

Fig. 6 - Suspension, right front

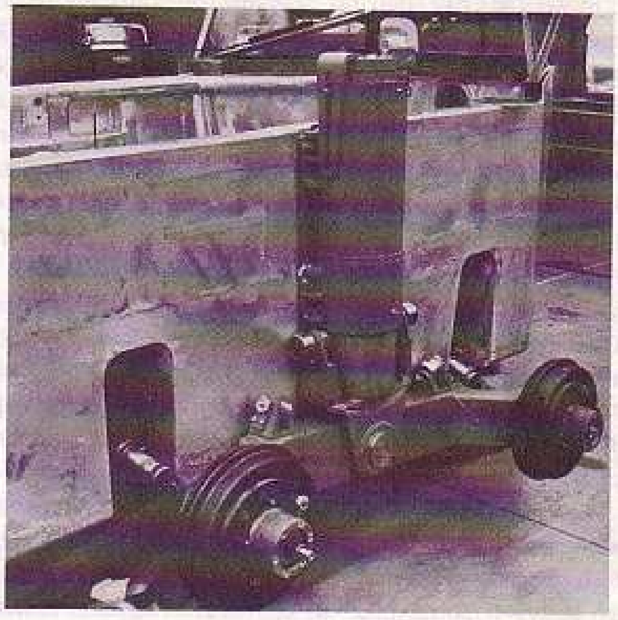

Fig. 7 - Suspension, right rear

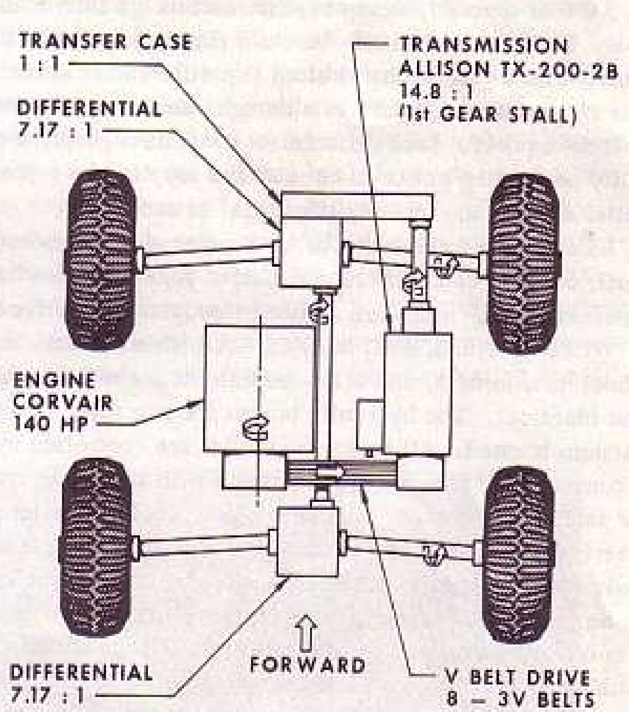

Fig. 8 - Front drive train schematic

sible to operate with either power train shut down in emergency conditions. Each engine throttle is controlled from a common accelerator pedal in the driver's compartment.

Two Corvair engines delivering 140 gross horsepower at 5200 rpm are utilized in stock condition except that the carburetors and oil pans are modified for extreme slope operations. These engines were chosen for the ease and economy with which they could be used in the test bed. The application of two engines results in a horsepower-to-weight ratio in excess of 50. This is significantly higher than existing military vehicles and results in an unusually responsive vehicle with excellent acceleration capabilities.

The engine drives the transmission through an eight-strand matched V-belt system. This system was chosen because of the ease with which ratios could be changed. No problems have been encountered with this system. The transmission is an Allison TX-200-2B, six-speed automatic transmission with a torque converter and manual shift, which provides excellent ratio coverage and a full power shift capability. The transmissions are rated for approximately twice the maximum available input torque from the Corvairs. However, this additional weight penalty is offset by the excellent durability and good performance characteristics already mentioned. Separate manual gear selector levers in the driver's compartment permit simultaneous shifting, or the selection of different ranges, for each transmission depending upon the operating conditions.

The transmissions are mechanically coupled to specially designed aluminum transfer cases having a fixed 1:1 ratio. The transfer cases bolt directly to the front differential of each body. A power take-off is provided on each transfer case and is utilized in the rear body only for the mechanical parking brake.

All four specially designed differentials are interchangeable. They feature an off-the-shelf ring gear and modified pinion with a proprietary limited slip differential assembly. The ratio selected is 7.17:1, although other ratios are available as required. Each differential has a through-drive capability permitting power to be split and supplied by a propeller shaft to the second differential in each body.

Independent axle shafts, made from modified production parts, connect each differential output yoke to each wheel. Conventional U-joints are utilized throughout the drive train.

WHEELS, TIRES, AND BRAKES - All wheel assemblies, wheel hub, spindle, and brake assemblies are off-the-shelf and identical. The hydraulic brakes are two shoe, 12 × 2 in. vacuum boosted. All brake assemblies are controlled by a conventional foot pedal actuating a split hydraulic system for safety. The brakes are mounted on specially designed steering knuckles on the front body axles and on the rear body walking beams. An open brake of this type was known to be subject to contaminants, but this potential problem was offset by availability and low cost. The mechanical parking brake is used on level surfaces only. A separate hand-actuated electrohydraulic system is built into each body brake system to permit full brake lockup and effective holding power during severe slope operations.

The initial tire used on Twister was a production 14-18, 6-ply rating, bias ply with a nondirectional, cross-country tread design. This tire was selected because of its good flotation characteristics due to low static loading of the tire. Operating characteristics of a special 16-20 radial ply type and a 38 × 20 flotation type were also determined. All tires were tubeless to maintain a low suspension sprung-to-unsprung weight ratio. The 14-18 tires are mounted on steel 14.00 × 11 drop center rims.

BODY STRUCTURE - The vehicle hull structure consists of the separate front and rear bodies connected by the pivot yoke interconnecting structure. Both bodies are a semi-monocoque design incorporating hard points and box beams to accept and distribute concentrated loads. The shape of the forward body is dictated primarily by aspects of power train packaging, wheel and articulation clearance, and driver visibility. The rear body shape is constrained by the two-body interface, walking beam and wheel clearance, and the established angle of departure of 90 deg. Both front and rear bodies are constructed from high-strength 5083 H113 alloy aluminum. All major access panels form a part of the stressed body design. The yoke suspension members, and other highly stressed parts, were fabricated from alloy steel.

ELECTRICAL SYSTEM - The electrical system is a conventional 12 V type made up of commercial components. One heavy-duty battery and one high-output alternator are used with each engine package. For reasons of schedule and cost, provisions for waterproofing and static supression, normally utilized on a production military vehicle, were not supplied.

HYDRAULIC SYSTEM - The testbed vehicle has three active pump-powered hydraulic systems in addition to the closed-loop system for controls. The front body system consists of a constant delivery steering pump driven by a V-belt and pulley arrangement off the engine. The integrated pump and reservoir system provide pressurized hydraulic fluid power to operate the wheel steering system actuator and is sized to provide nominal lock-to-lock steering in under 2 sec.

The rear body system consists of a constant delivery double pump driven by a double V-belt and pulley arrangement off the engine. The pumps are sized to provide full stop-to-stop front body yaw in 2-1/2 sec and rear body lift of 10 in. approximately 7 sec. A common 2 gal reservoir with integral filter is provided for both pumps. Adjustable relief valves are provided which give a range of 800-2000 psi for both steering systems.

FUEL SYSTEM - A separate fuel supply system for each engine is provided in the rear body of the vehicle. Each system includes a 17.5 gal fuel tank. An interconnecting line and valve between the tanks and shut-off valve at each tank makes it possible to draw fuel from either or both tanks for both engines. Each line is equipped with a filter, with the line to the front engine having an electrical booster pump. The normal fuel pumps on the Corvair engines are also used.

FABRICATION AND ASSEMBLY - In April 1965, fabrication of the vehicle began, following the freezing of the basic design after the mockup had been thoroughly evaluated. A minimum of hard tooling and holding fixtures were used and most of the components and subassemblies were fabricated by Lockheed.

Final assembly and checkout of the vehicle power train, hydraulic system, instrumentation, controls and electrical wiring was started in early October. On Oct. 22, 1965, the vehicle was completed and given its initial shakedown run. The time required from start of fabrication to shakedown was slightly less than 6 months.

FIELD TESTING

Following the initial shakedown period, the task of developing a meaningful quantitative engineering test program and qualitative performance and mobility evaluation was begun. Several engineering objectives were established:

1. Determine capabilities of overall Twister concept in a variety of operating conditions and environments.
2. Perform parametric testing to improve the existing configuration.
3. Evaluate design and componentry and effect design improvements as required.

Since the accumulation of extensive engineering information without input from the potential customer is usually not sufficient, a concurrent program was developed to demonstrate Twister's capabilities to the customer, first at the Sunnyvale Test Course and later at offsite locations. From these demonstrations have come much information vital to the matching of capabilities with requirements in the complex military market place.

Two years after the start of these tests, a development contract for military versions of Twister was received. Another year of company funded testing has since been completed concurrent with the contract program. The following is a summary of the 3 years of LMSC-sponsored test operations from January 1966 through the fall of 1968. An overview of the results of these tests is presented in chronological order to give perspective to the total developmental program.

PRELIMINARY PERFORMANCE TESTING - The initial tests defined the performance characteristics of the testbed and served as a baseline for later, more comprehensive tests and modifications.

Vehicle acceleration at wide open throttle was evaluated at various tire pressures with the 14-18 tires. A maximum acceleration rate of 0-40 mph in 17 sec with the tires at 6 psig was recorded. These results confirmed the substantially better acceleration characteristics of Twister over current military vehicles. The high horsepower/weight ratio was a principal contributor to this improved performance.

Drawbar pull and rolling resistance tests were completed. Discussion of these two areas will be deferred until later in the paper.

Brake performance tests were run at various hydraulic system pressures, tire pressures, and with one and then the other body brake system deactivated. Extensive additional data were gathered under a variety of conditions. The net result was that the vehicle showed a capability to stop in a distance of 18 ft from a speed of 20 mph, thus exceeding the standard military requirements. One potential problem area was noted during the test program. The front body tended to pitch downward, severely reducing the ground clearance at the front, and the tires at the No. 2 axle tended to lift off the ground (Fig. 9). Some form of pitch damping was obviously required. This problem was analyzed in considerable depth in later tests.

A series of tests was performed to study the vibrational response of the rear suspension and rear body to various external inputs. Tests were run with variations in spring rates and damping characteristics of shock absorbers over various fixed obstacles. Timbers of various sizes were negotiated at specific speeds to give controlled and reproducible external inputs to the vehicle. While sharp-edged obstacles are not usually encountered in a normal operating environment, they did permit reproducible test results. These data formed a baseline for many subsequent suspension analyses in the parametric test program. The net result was a more ideal rear-body spring and shock absorber selection. Comparison data of rear body acceleration with other military vehicles led to the conclusion that the testbed exhibited significantly better ride characteristics and a more stable rear body platform than existing military vehicles.

A series of load tests was performed to substantiate the structural load criteria used in designing the testbed. Structural loads were measured with strain gages while the vehicle performed a series of 33 different maneuvers. Strain gages were located on such components as suspension arms, walking beams, and yoke assembly. Maneuvers included driving across 6 × 6 in. timbers at speeds to 40 mph, across 8 × 8 timbers at speeds to 30 mph, across 12 × 12 timbers at speeds to 21 mph, and running into an immovable object with the front wheels at 2.0 mph. The results indicated that the working loads in several of the components were in excess of those designed for. The design factor of safety, however, provided adequate margin to preclude structural failure. Although most of the loads measured were approximately what had been anticipated, it was apparent that Twister's high speed capability resulted in unusually high loads during certain extreme operating condi-

Fig. 9 - Braking test

tions. It was determined that additional and more extensive basic load determinations should be conducted in order to characterize Twister's total loading spectrum.

The performance of the rubber tire is one of the least predictable and least understood of any component in an off-road vehicle system. However, it is generally acknowledged that the tire is an extremely important subsystem and that tires of different types can alter substantially the performance of a vehicle. Three different sets of tires were acquired (Fig. 10) to study the effect of different types on the Twister testbed. The tire types were 14-18 bias ply with modified tread, 16-20 radial ply, and the very wide 38 x 20 flotation tire with bias ply and aggressive tread.

Certain basic measurements were made on each set of tires in a specially designed tire test rig. This test rig permitted the analysis of both static and dynamic tire spring rates, flat plate projected tread area with varying loads and tire pressures, as well as a number of other important tire characteristics. The data from these tests, as well as the all-important subjective analysis of the varying vehicle performance in the various environments, formed the basis for ultimate tire selection later in the test program.

SANTA CRUZ OPERATIONS - In May 1966, the vehicle engaged in the first of a series of offsite tests, conducted at the 4500 acre Lockheed Santa Cruz Test Base in the rugged Santa Cruz Mountains of California. This area gave us an excellent opportunity to study the operation of the vehicle in a natural rugged terrain environment. High-speed runs on surfaced roads yielded a top speed capability of 65 mph. Vehicle handling characteristics at the higher speeds were considered acceptable but it was generally felt that a steering system with less high-speed sensitivity would be desirable. Runs over secondary roads and narrow trails indicated that the vehicle's highly responsive steering system and small turning radius were important attributes in maintaining relatively high vehicle movement rates. Very steep (40-60%) natural dirt slopes were negotiated periodically throughout the test period. Twister was able to operate

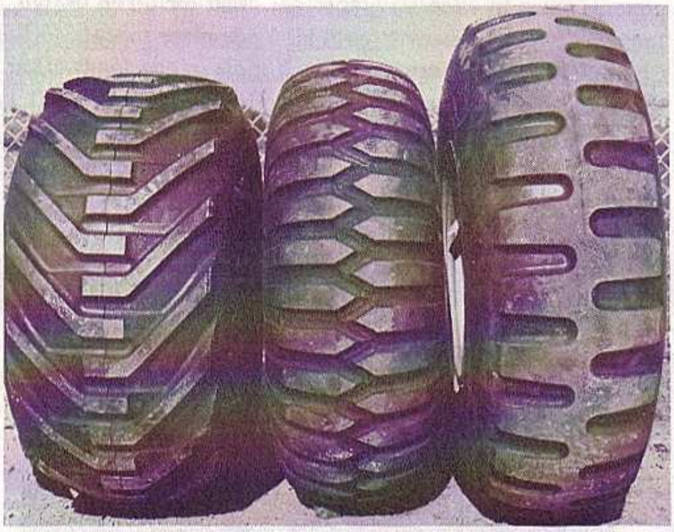

Fig. 10 - Three different tire configurations

successfully on all slopes encountered. A considerable number of runs were made in an organic bog located along a creek bed. The vehicle made many successful crossings in the area but became immobilized on two different occasions in an unusually soft sand bar. Overall operating characteristics in this area were considered satisfactory.

Most of the tests run at Santa Cruz were with the 14-18 tire. A limited number of runs were made with the 16-20 tire. This tire's characteristics were such that the vehicle ride and handling were improved; however, the greater tractive effort that could be developed resulted in failures in the power train shafting. Test results with the larger tires stimulated the desire to determine their full capabilities when improved shafting could be provided.

Other problems noted during these operations included: front engine "miss" when operating on steep slopes; front wheels tended to lift off the ground as the vehicle climbed extreme slopes; cooling for both engines and transmission was inadequate; open brakes were easily contaminated. Additional power steering boost was also required. Nonetheless, the Santa Cruz operation served to confirm that Twister had mobility, agility, and movement rates superior to standard military vehicles.

Following the Santa Cruz operation, it was apparent that certain problems required immediate attention to insure the required testbed performance and durability. A few of the more significant modifications were: the addition of a higher output steering pump to reduce the driver hand force required; the addition of improved power train shafting in the rear body; the addition of pitch dampers on the front body; improved engine cooling air ducts; and the installation of engine oil coolers and front body cooling fans.

RICE PADDY OPERATIONS - A test to determine vehicle performance while operating under rice paddy conditions was performed in September 1966. The test area, located north of Sacramento, Calif. was leased for this purpose. The area consisted of fully grown rice standing 36-48 in. high (Fig. 11). Dikes throughout the area maintained a water depth of 3-6 in. The loose surface soil in which the rice grew was about 6 in. deep. Beneath the soil and root structure was a hard pan which effectively precluded further tire sinkage.

Numerous runs were made with both the 38 x 20 tires and the 16-20 tires. The more serious challenge to vehicle operation in the paddies was caused by slipperiness rather than excessive tire sinkage. Relatively soft dikes,

Fig. 11 - Twister rice paddy operation

which ranged 16-30 in. high, created some difficulty when the vehicle's tires tended to sink into the dikes, causing underbody dragging. The flotation tires with their very aggressive tread resulted in slightly less wheel slip as compared with the 16-20's; however, the 16-20 tire tended to get over the dikes easier without excessive dragging of the vehicle's underbody. The overall performance of the vehicle during these tests was considered satisfactory.

WESTERN NEVADA OPERATIONS - In November 1966, three weeks of intensive testing were conducted in western Nevada. This operation was conducted under contract to the Nevada Automotive Test Center (NATC), headquartered in Carson City. The purpose of this testing was to verify and supplement existing performance data obtained at the Sunnyvale Test Course, conduct instrumented comparative tire tests, and operate in a new type of "real world" terrain in order to evaluate the vehicle's mobility and speed characteristics.

The first week of vehicle operations at NATC was spent conducting rolling resistance and drawbar performance tests on a dry alkali lake bed which provided a flat, unobstructed area. Rolling resistance to gross vehicle weight ratios were comparable with existing wheeled military vehicles.

Drawbar tests were performed on the dry alkali with 16-20 tires at 60 psig pressure. A maximum steady drawbar of 10,300 lb was developed. This is an apparent coefficient of friction of 0.93 and shows the improved effectiveness of tire-to-ground action for the 16-20 tires. Under these extremely high torque conditions, failure occurred in the power train shafting. Further dry surface tests were cancelled in deference to the power train which had been designed for the smaller 14-18 tires.

A series of mobility and speed evaluations were conducted over established NATC courses. The first timed run was made over Test Course 2 which is 9 miles in length and consists almost entirely of cross-country trails through rolling, sage-covered, sandy terrain with some natural slopes to 60%, side slopes in excess of 40%, and dry wash canyons. The course permits an evaluation of cross-country speed, maneuverability, and ride and suspension characteristics. Runs were made with the 14-18 tires at 6 psig. Twister performed well in this area and easily halved the elapsed time of the comparison M-38 Jeep. The vehicle's suspension system and articulation tended to envelop the obstacles with the result that the drivers felt confidence in maintaining the high speeds without exceeding the structural capabilities of the vehicle. Numerous tight turns were easily negotiated due to the short turning radius. The ease with which Twister could be controlled was especially noticeable; the winding course required constant steering redirection. Only one obstacle over the course had to be avoided. This was a 60% natural, soft sand slope which might have been negotiated with the 16-20 tires.

One dry wash on the course was particularly narrow and winding (Fig. 12). Twister negotiated the wash forward and backward (in reverse gear) by keeping tires on one side of the vehicle in the bottom of the wash and the others up on the steep sides. The good side slope capability and tight turning radius permitted unhindered operation.

A second timed run was made over NATC Course 1 which is 16.5 miles in length and consists primarily of secondary roads and unimproved trails with some cross-country operation. The course permits an evaluation of vehicle control and handling characteristics, high speed performance, and cross-country mobility and maneuverability. Operations over the secondary roads presented no problems to Twister or conventional types of vehicles. Operation over the unimproved trails was impressive even though the trail was quite often fairly narrow. Twister, with its greater lateral wheel spacing and responsive steering, was able to straddle the tire ruts. The soft suspension and low pressure tires permitted the rocks and other natural obstacles to be enveloped without a serious reduction in speed. Maneuverability in the narrow areas, tight turns, and switchbacks was unimpeded due to the tight turning radius. Operation over the high-speed portion of the course was uneventful except that some reduction in steering sensitivity would have been desirable. Only two obstacles over the course had to be avoided, a narrow wooden bridge, which was marginal in its load-carrying capability, and a 60% loose soil, natural slope.

This timed run was terminated about three-quarters of the way through the course when the rear suspension walking beam failed due to hitting a rock outcropping. The left number three wheel assembly and hub were badly smashed. As a result, the walking beam was severely yielded in the area of the wheel spindle. Due to inaccessibility in the narrow canyon, it was necessary to drive the vehicle out under its own power. This operation displayed a good "get-home" capability after severe suspension damage.

Up to that point, Twister had easily outpaced the comparison M-38 Jeep that had started at the same time. The course rules are set up to assure safe and representative operations of test vehicles. Since part of the course is on public roads, a test vehicle must always be capable of safely stopping within a reasonable distance. Hence, Twister's potential could not be fully assessed on the secondary roads. However, soon as cross-country conditions were encountered, the rate of speed of Twister more than doubled that of the Jeep. Up to this time, the M-38 Jeep had set the best times over this course.

Fig. 12 - Twister, dry wash operation

In order to get a comparison of tire performance, part of the course was traversed with the larger diameter 16-20 tires. The improvement in vehicle ride was quite significant. It was estimated that the vehicle could have improved its average speed over this entire course by about 30% if time and power train shafting strength had permitted a rerun with the larger tires.

The last series of mobility evaluations took place in Nevada's Sand Mountain area. This is a geological phenomenon consisting of loose sand dunes up to about 700 ft high. The area permits a complete evaluation of vehicle performance in desert-type dunes. Test operations were started with the 14-18 tires; however, it soon became evident that these tires would not provide the desired performance in this area. A switch was made to the 16-20 tires and overall performance improved considerably. The extra flotation and long footprint permitted the tires to stay on top of the sand and to develop more tractive effort. Subsequently, the tire pressure was reduced from the normal 6 to 4 psig. Vehicle performance improved even more. It should be noted that vehicle operation with the larger tires did require careful power application to avoid power train failures. Even with care, one front axle was "torqued" while negotiating a 60% slope. The vehicle's side slope stability showed up as it was operated at an angle down 60% sand slopes. The large underbody clearance and responsive yaw steering contributed to the vehicle's ability to traverse the tops of sharp-edged sand slopes by straddling the edge and moving where other vehicles would have had extreme difficulty (Fig. 13). Overall sand operation was considered very satisfactory.

SNOW TRIALS - In March 1967, Twister was subjected to a winter environment. These snow trials were conducted in the High Sierras south of Lake Tahoe, Calif., under contract with the Nevada Automotive Test Center. All three types of tires were tested in the snow. The tires exhibiting the best overall performance were the 16-20 radial ply tires. Extensive experimentation with tire pressures indicated they could be operated satisfactorily at 40% deflection which was equivalent to 2-1/2 psig in the front body tires and 3 psig in the rear body tires. Twister negotiated virgin snow-covered terrain in the 7,000-9,000 ft elevation levels of NATC Winter Test Area 4 without being immobilized. Snow depths were in excess of 4 ft and drifts were estimated to be in excess of 9 ft deep. The vehicle ranged freely off the established route and could be driven with confidence over unfamiliar terrain. Soft snow grades of up to 27% could be negotiated. Side slopes of up to 42% were traversed with the front body yawed up the slope to keep the vehicle from sliding sideways (Fig. 14). Twister's articulation allowed it to traverse steep embankments and range freely through boulder-strewn fields and timber areas (Fig. 15). Instrumented testing showed that a drawbar pull of 5000 lb could be achieved on a test course of hard-packed, glazed snow-ice.

The primary problem noted during the snow trials was the excessive transmission oil temperatures reached during low-speed, full-throttle operations at ambient temperatures as low as -10 F. One power train shaft failed in this operation.

SERIES STEERING SYSTEM - In early 1968, a series steering system was jury-rigged into the testbed. This system replaced the parallel steering system to retain the very desirable fast steering response inherent in the original system

Fig. 14 - Twister, 42% side slope show

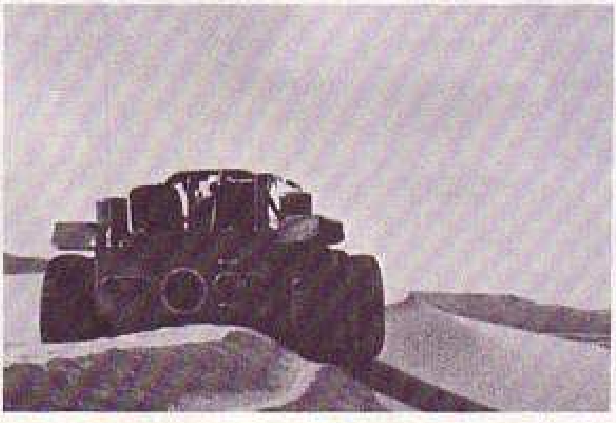

Fig. 13 - Twister, sand dune operation

Fig. 15 - Twister, tight turn, snow

but to eliminate the sensitivity to oversteer at higher speeds noted in earlier tests. Evaluation at the Santa Cruz Test Base on narrow cross-country trails as well as at high speeds on paved roads indicated that the new system substantially eliminated the problems previously noted. The testbed configuration did not permit the new system to be permanently retained; however, this new patented system will be incorporated on the second-generation Twister vehicles.

REFURBISH PROGRAM - As a result of certain continuing problems in the testbed and the pending public presentation in June 1968, the decision was made to completely refurbish the vehicle. A number of problem areas had existed since first roll-out. Our objective was to reduce or eliminate these where possible in order to prepare the vehicle for our first public presentation and subsequent demonstration to the military during two planned offsite tours. A complete redesign was performed on the power train shafting from the differential output yoke through the wheel stub shaft. Subsequent operation has indicated that this redesign has completely eleminated the shafting problem and permits full operational capabilities with the 16-20 tires. The rear body lift capability was eliminated as a result of test experience which indicated it was not necessary. A front fender configuration was finally developed and successfully applied. Engine and transmission cooling problems were essentially eliminated through a rearrangement and addition of appropriate oil coolers with forced air flow.

Fig. 16 shows the Twister configuration in its present form following the refurbishing program. Table 1 presents the current vehicle characteristics and Fig. 17 shows scale models of military configurations of the Twister concept in the roles of strike reconnaissance and antitank assault. A number of other applications are under evaluation.

CUSTOMER DEMONSTRATIONS - In June 1968, Twister was presented to the public for the first time. Up until this time, activities has been maintained on a company private status. Following public presentation, Twister was demonstrated to personnel at Fort Ord and Camp Pendleton, Calif. This was followed by an extensive tour to the east where it was shown and demonstrated to military personnel at Fort Bliss, Texas; Fort Leavenworth, Kan.; Fort Benning, Ga.; Aberdeen Proving Ground, Md.; Quantico, Va.; Fort Belvoir, Va.; and Fort Knox, Ky. This exposure has permitted many military personnel to see and drive Twister and become more familiar with the potential of this concept.

OPERATIONAL SUMMARY - During the past 3 years of testbed operations, Twister has accumulated over 400 miles in a wide variety of difficult operating conditions and environments. In addition, it has performed 121 formal demonstrations and been driven by over 525 guest drivers representing most of the military ground vehicle development and user agencies of the Free World.

With the first of the three contract vehicles scheduled to roll out in July 1969, the testbed's usefulness will continue as an important means of rapidly evaluating design changes and continuing to determine and expand the capabilities

Table 1 - Dimensions and Performance

Curb weight	11,400 lb
Length	194 in. (16 ft 2 in.)
Width	103 in. (8 ft 7 in.)
Height	6 ft 0 in.
Ground clearance	16 in.
Turning radius, center of tread	19 ft 8 in.
Roll articulation pivot angle	± 30 deg
Pitch articulation pivot angle	35 deg up; 27 deg down
Yaw articulation pivot angle	±22 deg
Forward highway speed	65 mph
Acceleration, 0-40 mph	17 sec
Gradeability	60% plus
Vertical obstacle	30 in.
Stopping distance from 20 mph	18 ft
Drawbar pull, max.	10,700 lb
Angle of approach	90 deg
Angle of departure	90 deg

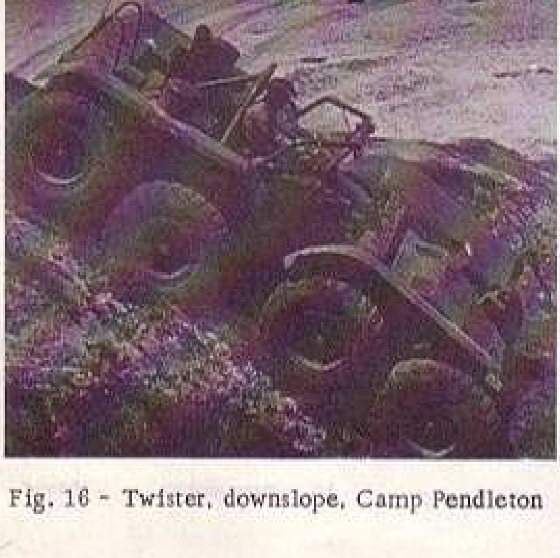

Fig. 16 - Twister, downslope, Camp Pendleton

Fig. 17 - Twister, strike reconnaissance (left), antitank assault (right)

of this exciting new mobility concept. Plans for the test-bed in 1969 include competitive vehicle testing, test support for future applications, live fire-on-the-move tests, and continued component development.

CONCLUSIONS

Three years of test operations in all types of environments indicate that the Twister concept provides a significant advancement in the state-of-the-art of military vehicles. Test results indicate that the objective of providing a quantum increase in cross-country speed was obtained. Ride and weapon platform stability indicate significant improvement over existing military vehicles. Capabilities in many environments and operating conditions have been extended beyond those formerly thought possible for wheeled vehicles. The Twister configuration offers the potential to meet a wide range of military requirements for the 1970's.

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