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40p. $1.00

U. S. ARMY
TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

TRECOM TECHNICAL REPORT 64-7

RESEARCH ON A LIGHT-TRUCK HIGHWAY TRAIN

Task 1D543006D40405

Contract DA 44-177-AMC-1(T)

March 1964

prepared by:

DAVIDSON LABORATORY
Stevens Institute of Technology
Hoboken, New Jersey

[illegible]

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HEADQUARTERS
U S ARMY TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

The U. S. Army Transportation Research Command concurs in the recommendations of the contractor.

However, no funds are available to implement any of the recommendations.

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TASK 1D543006D40405
CONTRACT DA44-177-AMC-1 (T)
TRECOM Technical Report 64-7

March 1964

RESEARCH ON A LIGHT-TRUCK HIGHWAY TRAIN

Report No. 995

Prepared by

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U. S. ARMY TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

FOREWORD

This report completes the requirements of Contract DA-44-177-AMC-1 (T) and presents the results of a program to design, construct and test a second-generation Light-Truck Highway Train. A first-generation train, which was built, tested and reported on in 1961, established the necessary engine control characteristics.

The program was a joint effort of the Davidson Laboratory of Stevens Institute of Technology (DL Project 2706/444) and Wilson, Nuttall, Raimond Engineers, Inc., of Chestertown, Maryland. The work was done under the technical supervision of Mr. I. O. Kamm of the Davidson Laboratory. Mr. R. B. Schwartz (DL) performed the model tracking tests. Mr. C. J. Nuttall (WNRE) supervised the design and Mr. C. W. Wilson (WNRE) the construction and proof-testing of the train. Field testing and evaluation were conducted jointly by personnel of Davidson Laboratory and Wilson, Nuttall, Raimond Engineers, Inc. A short synopsis of the field tests was submitted earlier in the form of a motion picture.

The authors greatly appreciate the assistance during the program given by Dr. I. R. Ehrlich and Mr. H. Dugoff of Davidson Laboratory and their critical review of this report and the motion picture covering the test program.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

SUMMARY

The primary objective of this program was to design, fabricate, assemble, install, and engineering-test a pneumatic system to control simultaneously the engines of an individually powered, four-unit, 1/4-ton truck train. Secondarily, the tracking characteristics of the train were to be compared with those predicted from scale-model data obtained with a geometrically similar "Tractrix" model.

The control features provide the driver in the lead unit of the train with direct and essentially simultaneous control of the throttles and service brakes of all units. The lead unit is directly steered by the driver; following units are steered in the path prescribed by the hitch of each preceding unit. The drawbars interconnecting the units are longitudinally soft-sprung and well-damped. Automatic torque-converter transmissions were installed to eliminate the necessity for remote control of the transmissions.

All control systems proved to be highly successful under the conditions tested. On dry smooth roads, stable operation of the four-unit train at speeds as high as 35 mph was possible. Safe panic stops were made from up to 20 mph on dry pavement and from 10 mph on firm dirt. The vehicles are capable of transmitting substantial assisting forces when traversing obstacles and difficult slopes. Coupling and interchange of the units are convenient and quick, allowing the four-unit train to be assembled in approximately three and one-half minutes.

During the estimated ten hours of train operation, all control systems demonstrated their safety and reliability under conditions representative of every type of field operation, without mishap or breakdown of any of the contractor's funished and installed items.

CONCLUSIONS

On the basis of the very limited test program conducted during this study and performed over terrain and in environment which may not be considered severe, the following conclusions can be drawn:

1. Pneumatic engine control is sufficiently precise for the intended purpose.

2. Pneumatic engine and brake controls function reliably under field conditions and are suitable for servicing by military field maintenance personnel.

3. Coupling and control systems have been devised which allow convenient and complete unit interchangeability.

4. For moderate maneuvers of the four units tested, the tracking characteristics of the "Tractrix" model and of the prototype are comparable. The percentage of error increases with the number of vehicles and this could lead to a large error for long trains. In tight turns, intervehicle forces can influence the prototype tracking pattern considerably.

5. Significant gains in stable train speed have been made by reducing lost motion in all steering and coupling linkages and by more properly proportioning and locating the hitches and drawbars and their attachment points.

6. Conversion of the units for both direct and remote control can be done inexpensively, utilizing off-the-shelf items primarily. The drawbars and their attachment brackets were the only specially produced items.

7. At this point in the program, there have been no indications of difficulties with either the control or the coupling systems, which would preclude application of similar techniques to a train consisting of more than four units and/or to larger and heavier vehicles.

RECOMMENDATIONS

1. Additional field tests should be conducted to demonstrate the off-road mobility capabilities of the train in terrain (hills, mud, snow) too difficult for a single jeep to negotiate.

2. Further tests should be performed to establish firmly the on-road stability behavior, especially under difficult weather and pavement conditions (wet surfaces, ice, snow).

3. Prototype lateral stability should be correlated with laboratory data of a dynamically similar scale model, to establish safe prototype limitations and to study the effects of changes.

4. A laboratory model should be used in exploratory tests to determine train performance over obstacles which may prove to be too severe for safe prototype negotiation.

5. Investigation should be made of the tradeoffs involved in reducing interunit compressive forces by applying the braking signal from rear to front at the expense of one additional intervehicle air hose and some additional time lag.

6. The factors which presently prevent accurate model-to-prototype tracking correlations should be determined so that the model may become a more useful tool for predicting the tracking characteristics of longer trains.

7. Four additional jeeps should be converted for train use in this same manner. Thus, with six- and eight-unit trains, factors limiting train length can be studied.

8. The train concept should be applied to larger vehicles (2-1/2-ton and 5-ton trucks) to study their operational characteristics and usefulness in train configurations. Standard vehicles of these classes exist, already equipped with compressed air systems and automatic transmissions, which reduce conversion costs.

INTRODUCTION

Under Contract DA44-177-TC-390, Stevens Institute of Technology, jointly with Wilson, Nuttall, Raimond Engineers, Inc., had previously investigated, built, and experimentally operated a vehicle train composed of four individually powered but centrally controlled 1/4-ton trucks, called the Jeep Train.[1, 4] The purpose of that project was to study the engine control systems necessary to operate a highway train under various terrain conditions without unduly encouraging jackknifing tendencies. Engine control was accomplished by an electronic servo system allowing for a wide range of control modes, from simple master-slave throttle-position control and engine-rpm matching system to those which would automatically compensate for differences in vehicle output or power requirements by responding to a drawbar-sensed positional signal. In addition, each of the two more simple servo systems could be modulated by the drawbar signal. The train was also equipped with positive steering-action drawbars which were designed to satisfy geometric tracking requirements and incorporate air-hydraulic features that permitted variable telescoping effect by adjustment of spring and damping rates. The brakes in the train incorporated the standard hydraulic system with master-controlled air actuation.

The major conclusions drawn from the construction and testing of this train were:

1. The simple master-slave throttle-position system provided the best overall train power-control characteristics.

2. The relatively soft-sprung, highly damped drawbar provided the best linkage characteristics for both highway and cross-country operations.

3. The simple master-controlled brakes were satisfactory.

4. Dynamic lateral stability would need further examination. Severe snaking made operation at speeds above 18 mph impossible.

5. The highly sophisticated, variable electronic control system components, with their frequent failures and costly maintenance problems, proved to be unsuitable for general rough field use.

6. The useful lives of the reclaimed surplus trucks used in the conversion had ended.

In the studies of tracking mechanisms and couplings for a combat support train concept performed by Southwest Research Institute for TRECOM,[2, 3] one of the conclusions reached was that there was mutual antagonism between the geometric modifications made to the steering and coupling mechanism to increase dynamic lateral stability and those made for the purpose of giving the vehicle better tracking characteristics. Thus, there was a need for more quantitative data on both tracking and lateral stability characteristics which could not be satisfied with the original jeep train.

For these reasons, a second-generation (more rugged) vehicle train was planned; compressed air would be used to control not only the brake but also the engine and proper emphasis would be given to the steering system. Reported here are the results of this program, including the design and installation of pneumatic control systems fulfilling the above requirements, with special attention to engine control. The resulting vehicle is shown in Figures 1 and 2. Emphasis in the report is on: (1) the conduct of engineering trials to prove the components, (2) the short field test program to establish lateral stability characteristics, and (3) the special tests which were conducted to compare the tracking. ability of the jeep train with that of a one-eighth scale tracking model.

CONTROL SYSTEMS

Transmission System

The original three-speed manual transmission and clutch were replaced by a Borg Warner torque-converter automatic transmission, and the transfer case was relocated exactly as in the earlier train.[4] Before getting underway, selection of transmission (forward or reverse) is done manually in each unit as is the proper selection of the transfer case range.

Drawbar System

Each vehicle is equipped with a specially constructed, double-acting, telescoping, mechanically sprung and shock-absorbing drawbar (Figure 3). Each drawbar is permanently attached, free in pitch and yaw, to the rear of each unit (Figure 4) and coupled in a fixed position to the steering input socket of the following unit (Figure 5). Freedom in roll is within the telescoping drawbar.

Steering System

In this system, a drawbar angle displacement in yaw positively steers the front wheel of the following unit by transmitting the motion of the drawbar socket via a bell crank to the steering linkage (Figure 6). Due to the limitations imposed by the existing design of the jeep, a slightly unsymmetrical relationship between drawbar and wheel steering angle resulted. (See discussion of this problem in the section on tracking test results.) However, the main objective of selecting steering geometry was to devise a workable steering system which would compromise a minimum of cut-in or encroachment in a tight turn, with proportions of drawbars and linkages and locations of their attachment points which correspond to qualitative experience gained in a stability investigation conducted under a separate study.[5]

Pneumatic System (Figures 7-9, Table 2)

Each vehicle is equipped with its own independent compressed air system consisting of an engine-driven compressor with evaporator, storage tank, and moisture ejector. When connected in a train configuration, the several systems are manifolded together into a single system which supplies air to the master brake and throttle controls at the lead vehicle (Figure 8). A schematic of the pneumatic system is presented in Figure 9.

These controls are commercial air-control pressure regulators which supply modulated pressures to matching commercial pressure-sensitive actuators, one each at the throttle and the brake, and permit their action to be controlled either from within the vehicle or remotely from another vehicle. For transmission of the remote control signal in train operation, the vehicles are linked by three air hoses, one each for brake control, engine control, and manifolding of the air systems of all vehicles joined. When in train configuration, the throttle and service brake controls in the individual following vehicles are inoperative.

In order to make the control systems fail-safe, special consideration was given to the design, so that:

1. Loss of manifold pressure line (or the loss of all air pressure for any other reason) will apply all brakes and close all throttles.

2. Loss of throttle control line will return all throttles to idle.

3. Loss of brake control pressure line will automatically "dump" manifold pressure when the foot brake is next operated, thus applying all brakes and closing all throttles as though the manifold line were lost at that moment (see #1 above).

Brake System (Figures 7 and 8)

Brakes in all vehicles, whether solo or in train hookup, are operative. The standard hydraulic service brake system of the jeep is actuated pneumatically in a fail-safe fashion so that the brakes are applied by spring force over a differential systems-to-brake line air pressure. A combined parking brake and emergency stop control (panic button), which is operative at all times, is provided in each vehicle. Actuation of this device will apply brakes in all vehicles in the train.

Engine Control System (Figures 7 and 8)

All engines are running at all times and providing power to the train. The throttle linkage of each jeep is connected to a pneumatic actuator in such a manner that the hand throttle is still operative. Control of this actuator is by a standard foot-pedal controller. When in train hookup, all throttles are moved simultaneously. Manufacturer's specifications state that the angular position accuracy of the controller is within ± 2 per cent of full displacement.

TRACKING TESTS

The off-tracking of the four-unit vehicle was investigated principally during the execution of a quarter-circle turn following motion in a straight line. Upon completion of the quarter circle, the lead vehicle proceeds in a straight path as in negotiating a street corner (Figure 10) - one of the more common maneuvers made in actual operations. Such a study gives an indication of the performance in more complicated maneuvers such as U-turns, full circles, and S-turns.

The model used by Southwest Research Institute in their studies for Reference 2 was obtained and set up to approximate the steering characteristics of the 1/4-ton trucks (Figure 10). This model, however, is wagon-steered as compared to the Ackerman system used in the jeeps. An additional error is introduced because the M-38 A-1 steering ratio (the ratio of the drawbar angle to the wheel angle) is neither constant nor symmetrical for left and right turns (see Figure 11). Nevertheless, the results, as will be shown, give reasonably good agreement for determining the off-tracking of the vehicle trains in those configurations where intervehicular forces are small.

For the tracking tests, the one-eighth scale model was first placed with the center of its front axle at the entrance to the 90° curve and with the body parallel to the entrance tangent. The model was then moved along the circular course so that the front axle remained perpendicular to the course with its center directly over the course. A trace was made of the rearmost point of the model, which corresponded to its hitch point. The model was then set up to represent the second unit of the train; it was placed parallel to the straight approach tangent with its drawbar attachment point directly over the start of the hitch trace made previously. It was then drawn along the path with the attachment point kept directly over the first trace. The paths of successive train units were plotted in a similar manner; the attachment point of the drawbar was guided over the trace made by the hitch point of the previous unit.

For the prototype tests, a similar course was marked off on a level blacktop surface. The units were first aligned parallel to the approach tangent. The operator then proceeded at a very slow speed, keeping the left front wheel of the first vehicle on a chalked circular line (Figures 12 and 13). Measurements of cut-in were made as each of the following seven axles of the vehicle crossed radii representing the start of the curve, the end of the curve, and 22-1/2°, 45°, and 67-1/2° through the curve. It was observed that the accuracy of these tests was influenced by the ability of the driver to regulate the throttle and brakes so that the vehicle was halted and started very gradually at each of the points where measurements were made. When this was not done, noticeable vehicle drift occurred. Earlier, excessive vehicle drift had caused the cancellation of plans to conduct the tracking on a surface covered with sand which would record the vehicle tire tracks.

A comparison of model and prototype data is presented in Figure 14. A larger discrepancy between the results for the full-scale and the model tests was noted for the tests performed at the 27.3-foot radius than for the test performed at the 34.3-foot radius. This is very likely due to the fact that the steering characteristics of the model and prototype differ more for the smaller radius than for the larger one, since larger wheel angles are required in negotiating a smaller radius turn (see discussion at the beginning of this section and Figure 11).

Perhaps the most significant reason for the discrepancies existing between the tracking test conducted with the model and that with the prototype is that no intervehicle forces were acting in the model simulation, whereas small forces were transmitted by the drawbars in the full-scale tests. The result of these interunit forces is to cause the vehicle tires to drift sideways, whereas the model "tires" are knife edges and hence drift very little. The effect on cut-in of tensile or compressive forces in the drawbar is illustrated in Figure 15. This figure illustrates the results of three full-scale tests. In the first, the last three vehicles were in neutral; in the second, the engines in the first three vehicles were in neutral; but in the third, all units were powered. In the first test, all drawbar forces were in tension; in the second, all were in compression. It may be seen that greater cut-in is experienced when the drawbar forces are tensile than when they are compressive.

FIELD TESTS

Only the most cursory field test program was included, mainly for the purpose of demonstrating the workability and reliability of the components installed in the jeep train (Table 1 and Figure 16). The vehicles were operated by various drivers for several hours over all types of dry roads at speeds up to 38 mph. At 38 mph, the first warning signs of incipient lateral instability were detected. Model tests conducted by the contractor in other studies[5] and the limited experience obtained with the prior jeep train gave good indication of what happens when a train becomes unstable. Therefore, it was not considered safe to exceed this speed.

Lateral instability is that condition under which road and/or driver-induced course disturbances fed into the system no longer damp out but rather amplify; this results in a snaking of the trailing units which rapidly becomes so severe that control over the train is lost. This phenomenon is most pronounced at the rearmost unit of the train and develops so rapidly that the driver, situated in the first vehicle, cannot at once be aware of it.

Although the tests performed to determine the lateral stability of the jeep train on the highway were accordingly limited, repeated attempts were made to induce instability at lower speeds by introduction of a random steering input at the first unit. Up to 30 mph, steering inputs comparable to the drivers' reactions in avoiding obstacles on the road did not produce any amplification of lateral motions in the following vehicles.

Emergency stops were performed on dry pavement from speeds up to 20 mph; no tendency of the vehicles to jackknife was observed. With wide-open throttle, the vehicle train accelerated from 0 to 35 mph in 11 seconds. During the acceleration, drawbar forces were estimated from drawbar displacement to be in the order of 20-25 pounds in tension. There are no perceptible intervehicle forces when cruising at 35 mph. During emergency stops from 10 mph, the drawbar compressive forces were approximately 400 pounds, 300 pounds, and 75 pounds between vehicles 1 and 2, 2 and 3, and 3 and 4, respectively.

Interchangeability tests proved that any vehicle can function as the lead vehicle. The time required to build up from a completely bled pneumatic system to the minimum operational air pressure of 60 psi is an average of 46 seconds for all vehicles. In special time trials, the time required by two men to make up a four-unit train from individual jeeps parked side by side with all engines running and air pressure up is approximately 3 minutes 20 seconds. In another test, 3 minutes 50 seconds was required to uncouple the last unit and couple it into the lead position.

Subsequent to the road test, the train was operated over a variety of off-road terrain and over obstacles ranging from 9 inches in height to 7 inches in depth. Engine and brake control systems and steering functions performed satisfactorily throughout. No further modifications to any of the contractor's installed components proved necessary.

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1. Finelli, J. P., and Nuttall, Jr., C. J., "Control Systems for Highway Trains: Phase I: Final Report", Davidson Laboratory Report 801, September 1960, USA TRECOM Contract DA44-177-TC-390, J. O. #4
2. Jindra, F., "Tracking Mechanisms and Couplings for a Combat Support Train Concept, Phase II-A: Off-Tracking of Trailer Trains", Southwest Research Institute Report EE-443
3. Jindra, F., "Tracking Mechanisms and Couplings for a Combat Support Train Concept, Phase II-B: Lateral Stability of Trailer Trains", Southwest Research Institute Report AR-467, U.S. Army Transportation Research Command Contract DA44-177-TC-631
4. Kamm, I. O., Nuttall, Jr., C. J., et al, "Control Systems for Highway Trains: Phase II: Final Report", Davidson Laboratory Report 867, November 1961, TCREC Technical Report 61-128, Contract DA44-177-TC-390, J. O. #4
5. U.S. Army Contract DA30-069-ORD-3731

TABLE 1. CHARACTERISTICS OF FOUR-UNIT TRAIN

Overall Length	59-1/2 feet
Overall Width	62 inches
Width of Track	49-1/4 inches
Wheel Base (each unit)	81 inches
Length (each unit)	142 inches
Weight (approx., each unit)	3000 pounds
Tires	Size - 7.00 x 16 NDCC Inflation - 25 psi (all)
Ground Clearance	10 inches
Approach Angle	26 degrees
Departure Angle	27 degrees
Break Angle (under drawbars, on level)	12 degrees
Engines	Willys' Hurricane Brake Horsepower: 72 at 4000 rpm Displacement: 134 cubic inches
Transmissions	Borg-Warner Model AS4-5AG Three-Speed Automatic with Torque Converter Ratios: 1st - 2.40:1 2nd - 1.47:1 3rd - 1.00:1
Axles	Spicer Front: Model 25 - 5.38:1 Rear: Model 44 - 5.38:1
Transfer Cases	Spicer, Manual Ratios: High - 1.1:1 Low - 2.4:1

TABLE 2. SPECIFICATIONS OF PNEUMATIC SYSTEM

(Cross-Reference Fig. 9)

1.	Compressor	Bendix-Westinghouse 226342
2.	Governor	Bendix-Westinghouse 226342
3.	Reservoir	Bendix-Westinghouse 209026 (kit)
4.	Evaporator	Bendix-Westinghouse 209434
5.	Moisture ejector	"Monroe" Moisture Ejector
6.	Tractor protection valve (modified)	Bendix-Westinghouse 224939
7.	Quick release valve	Bendix-Westinghouse 205000
8.	Safety valve	Bendix-Westinghouse 205105
9.	Throttle control valve	Westinghouse Air Brake P52971
10.	Brake control valve	Bendix-Westinghouse 225834
11.	Two-way valves	Bendix-Westinghouse 229467
12.	Pressure indicator	Westinghouse Air Brake (0-160 psi)
13.	Directional-flow control valve	Westinghouse Air Brake Colorflow F-600F, P-53025-2
14.	Directional-flow control valve	Westinghouse Air Brake Colorflow F-600F, P-53025-2
15.	Service brake	Bendix-Westinghouse 279300
16.	Park and safety brake actuator	Bendix-Westinghouse 279300
17.	Throttle actuator	Westinghouse Air Brake 536194
18.	Coupling	Snaptite VHC 6-6-H
19.	Parking brake valve	Bendix-Westinghouse 226821
20.	Shuttle check valve	Bendix-Westinghouse 227177

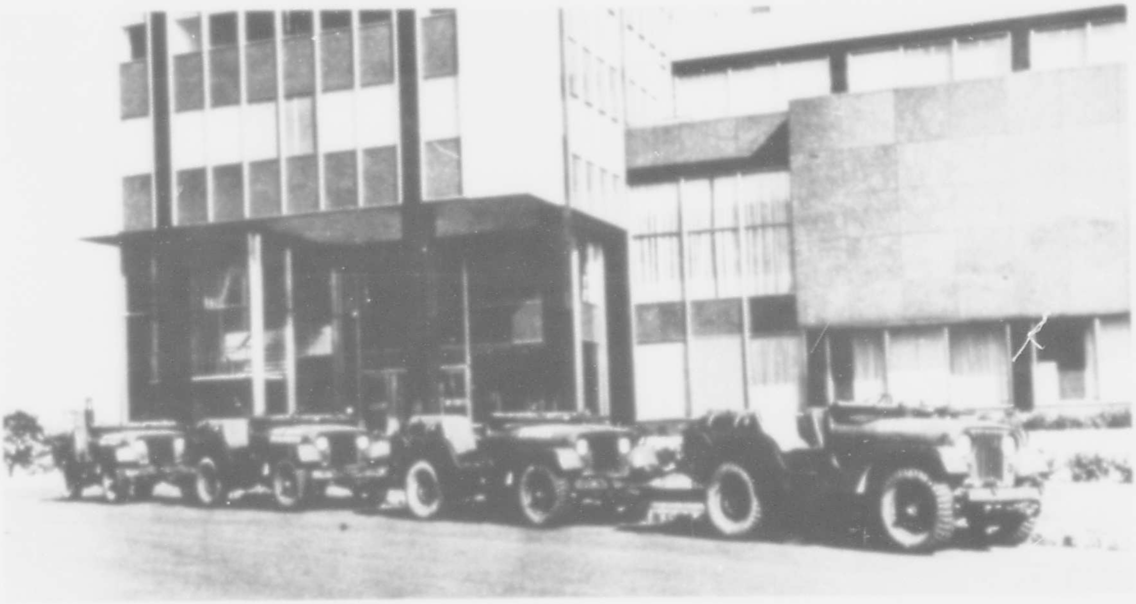

FIGURE 1. LIGHT-TRUCK HIGHWAY TRAIN

FIGURE 2. TRAIN EXECUTING A RANDOM MANEUVER

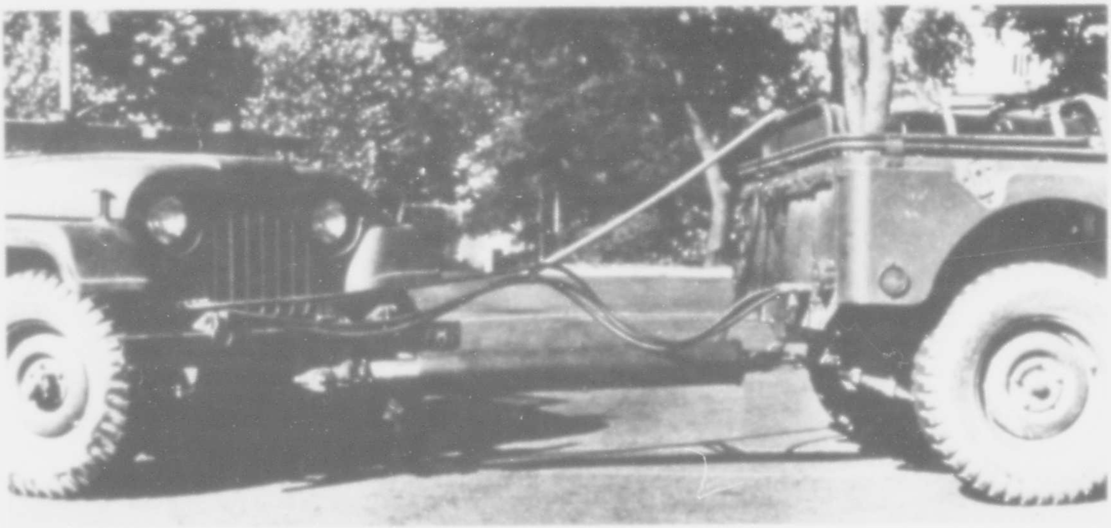

FIGURE 3. INTERUNIT DRAWBAR HOOKUP

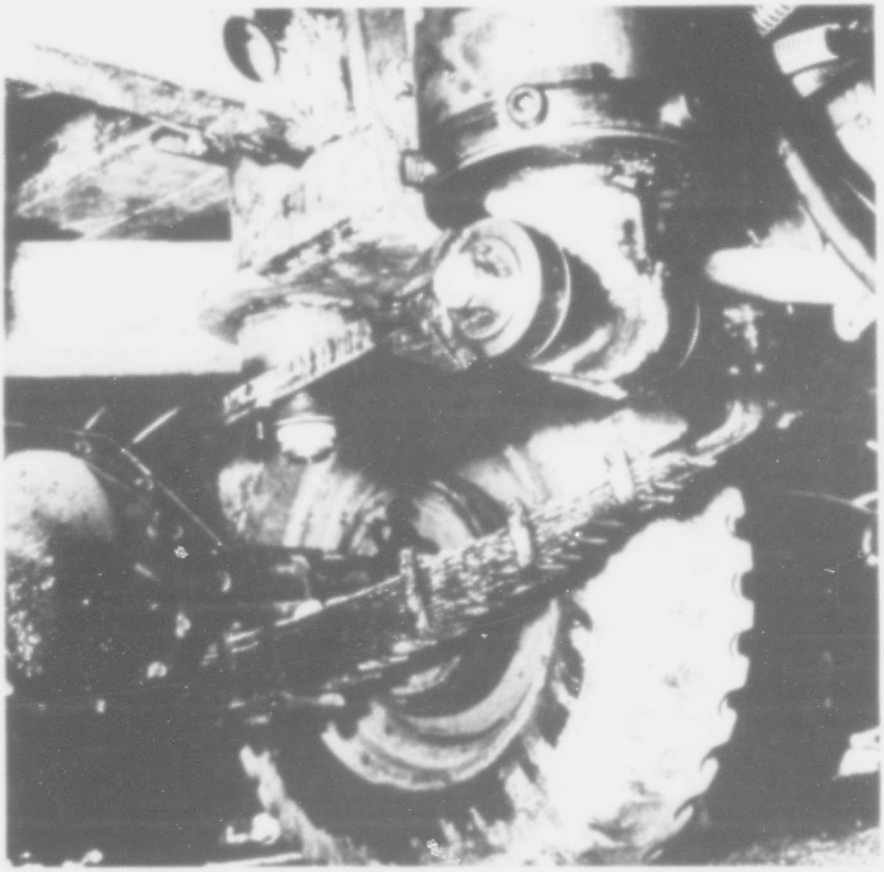

FIGURE 4. DRAWBAR ATTACHMENT POINT AT REAR OF UNIT

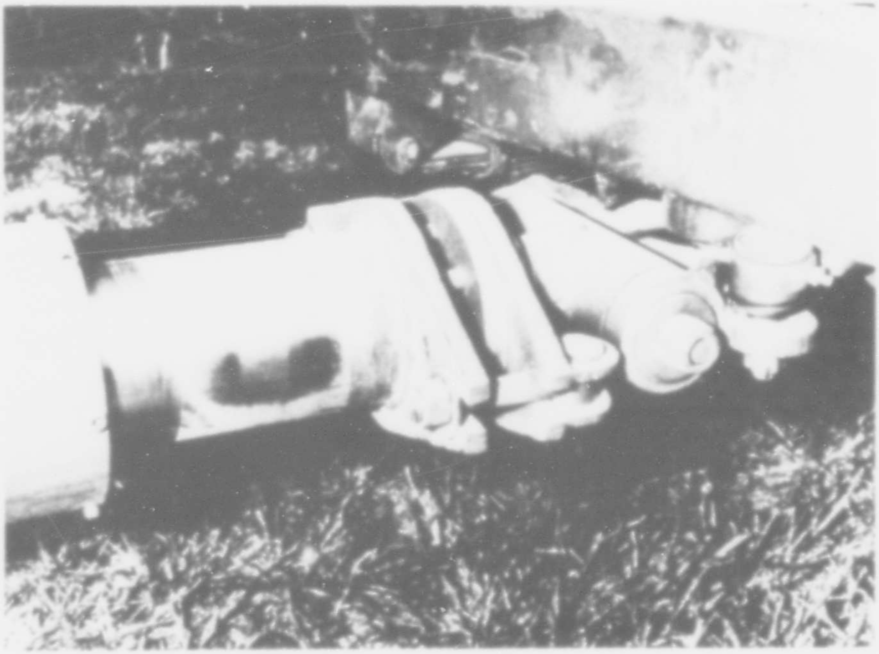

FIGURE 5. DRAWBAR CONNECTED TO STEERING INPUT SOCKET AT FRONT END

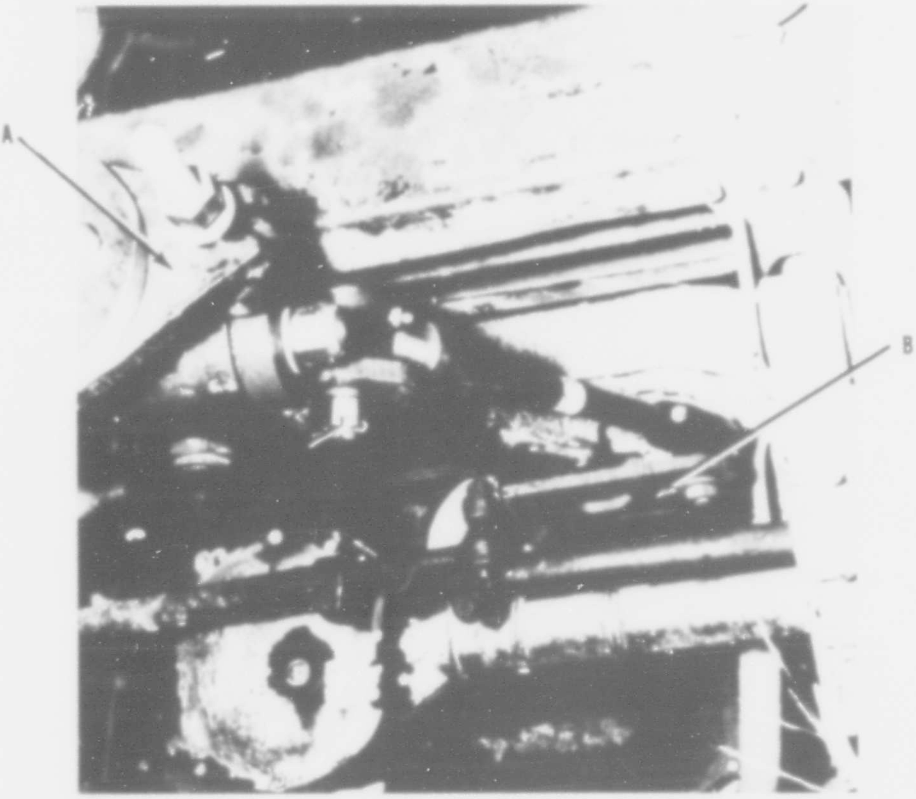

FIGURE 6. STEERING INPUT LINKAGE
a) Drawbar attachment socket
b) Bell crank

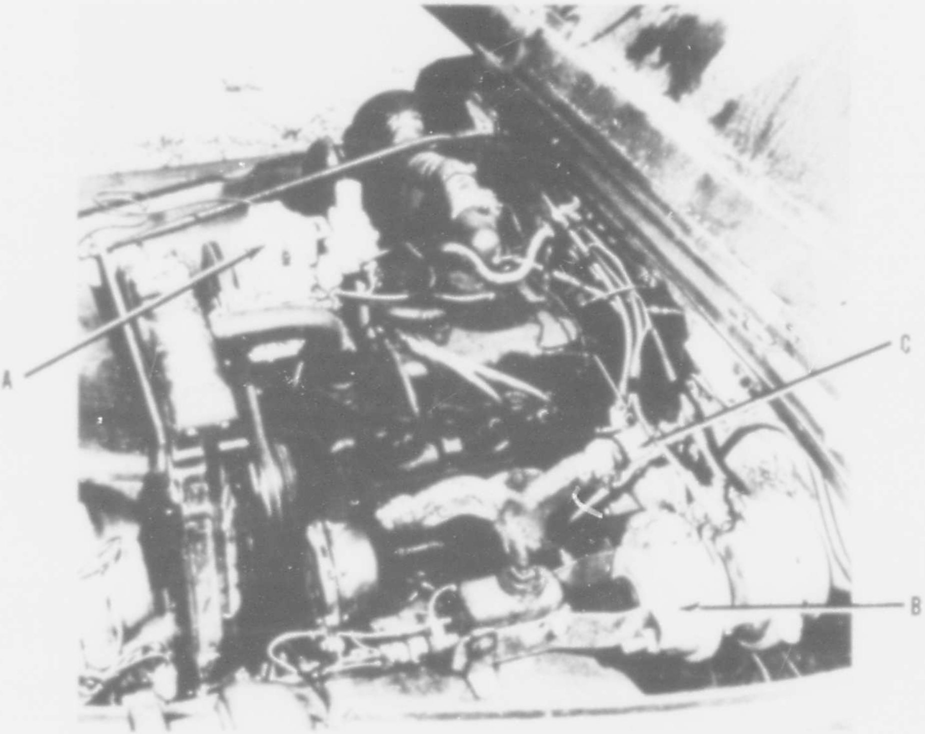

FIGURE 7. PNEUMATIC COMPONENTS

a) Compressor
b) Brake actuator
c) Throttle actuator

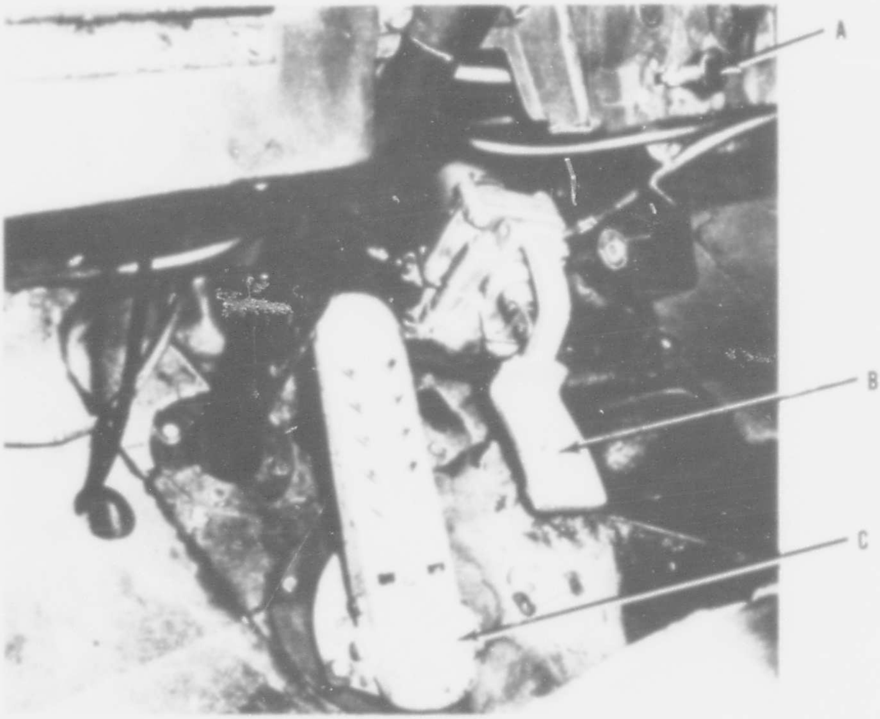

FIGURE 8. BRAKE AND THROTTLE CONTROLS

a) Air parking brake
b) Throttle
c) Brake

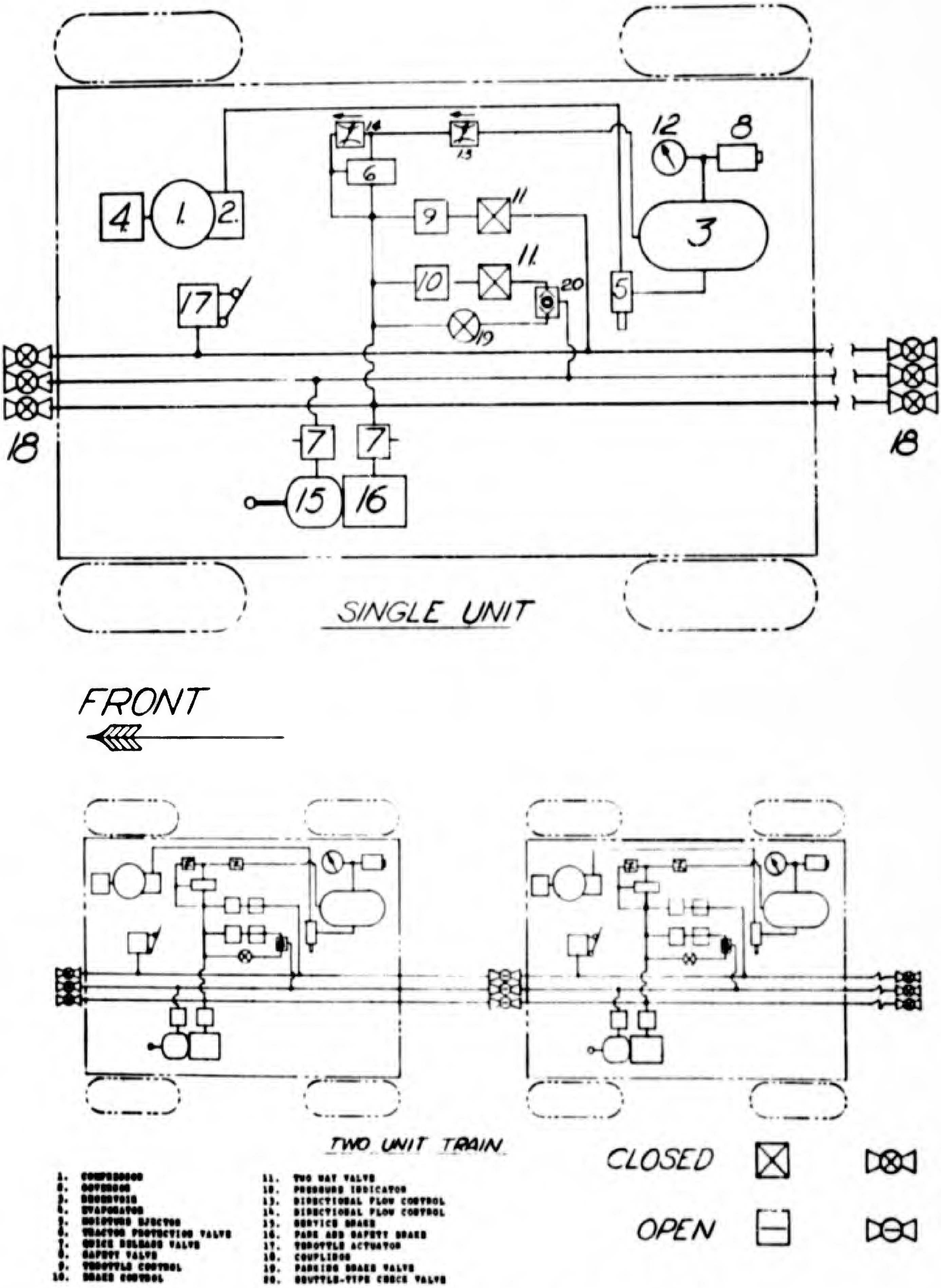

FIGURE 9. PNEUMATIC SYSTEM

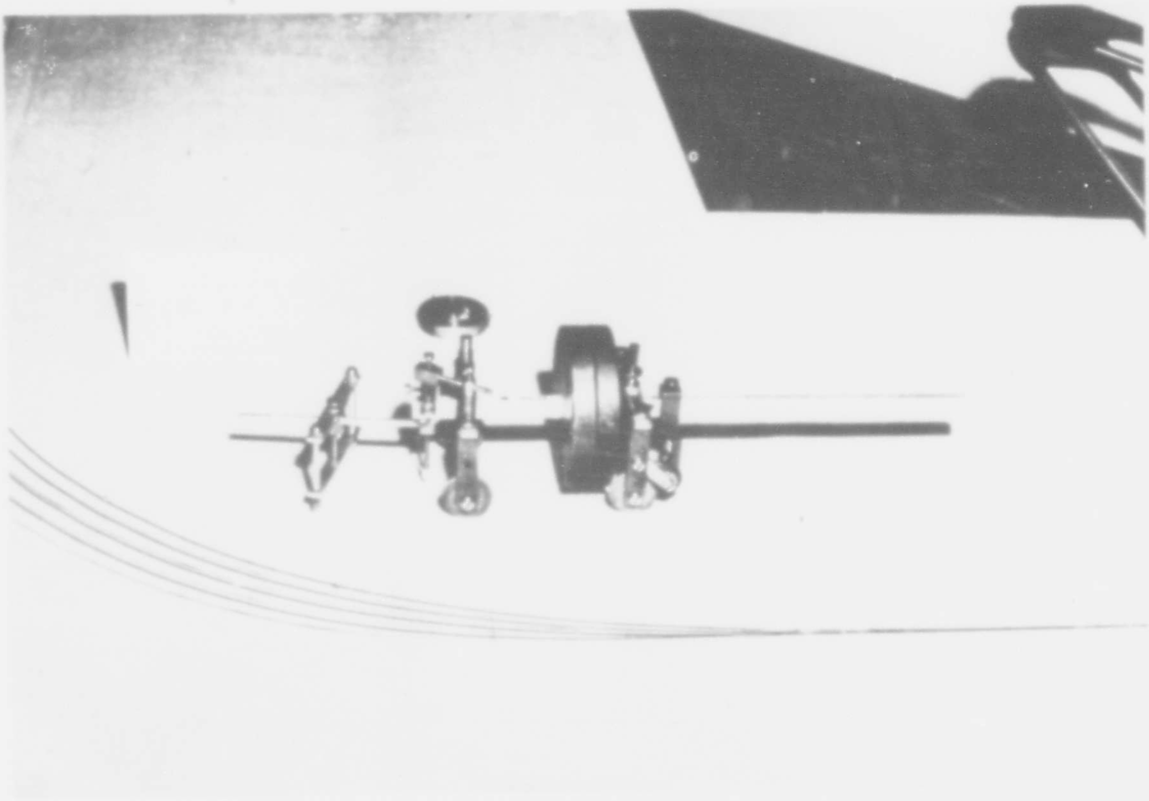

FIGURE 10. TRACKING MODEL AND REPRESENTATIVE TRACE

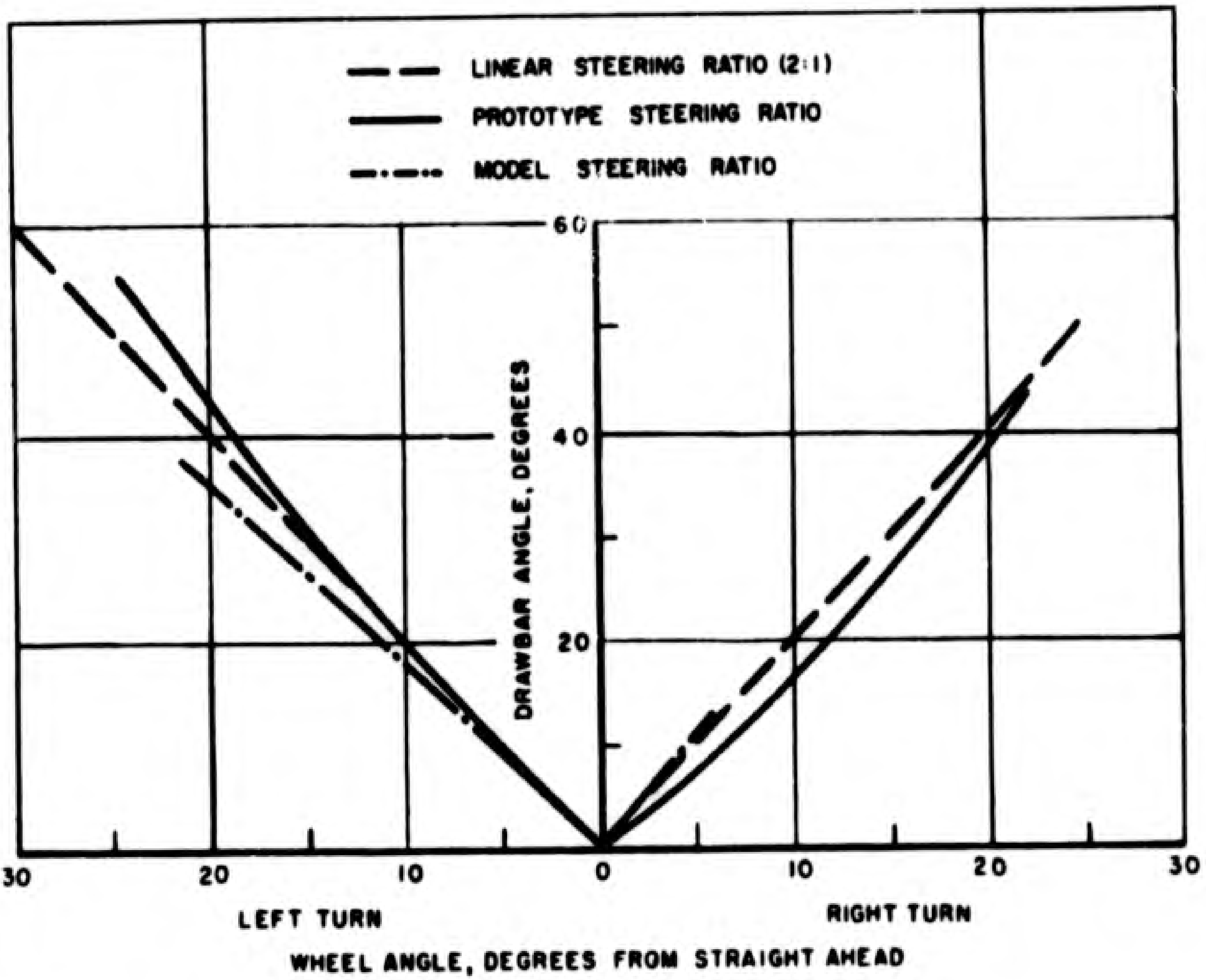

FIGURE 11. DRAWBAR-TO-ROADWHEEL STEERING RATIO

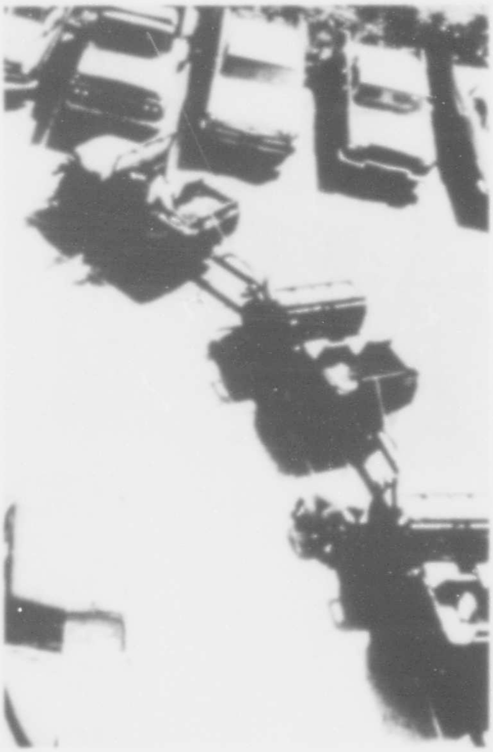

FIGURE 12. FULL-SCALE TRACKING TESTS

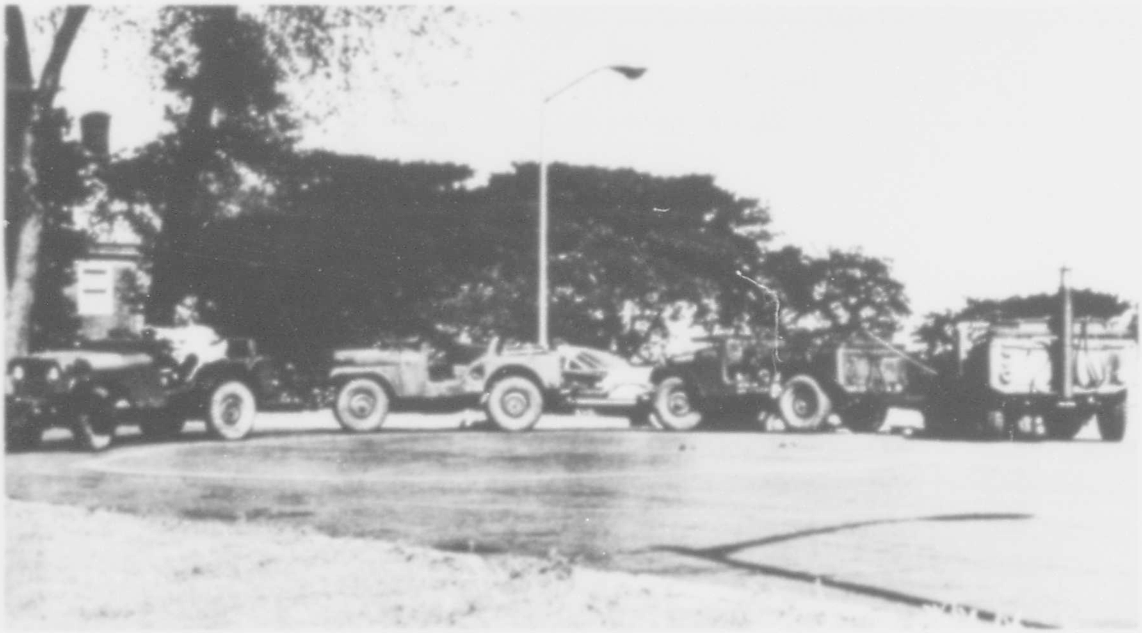

FIGURE 13. TRAIN IN MINIMUM RADIUS STEADY TURN

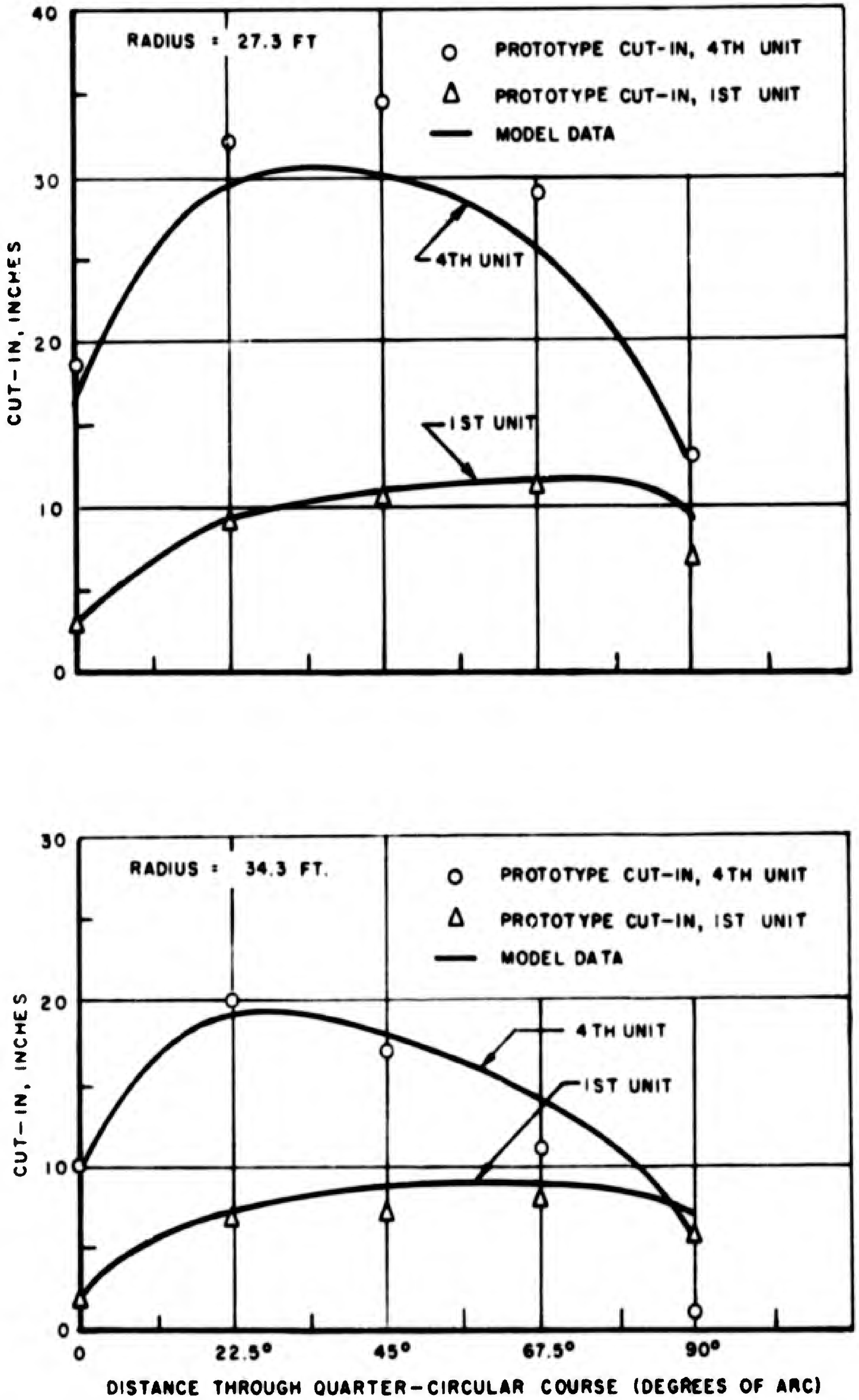

FIGURE 14. MODEL AND PROTOTYPE TRACKING CHARACTERISTICS

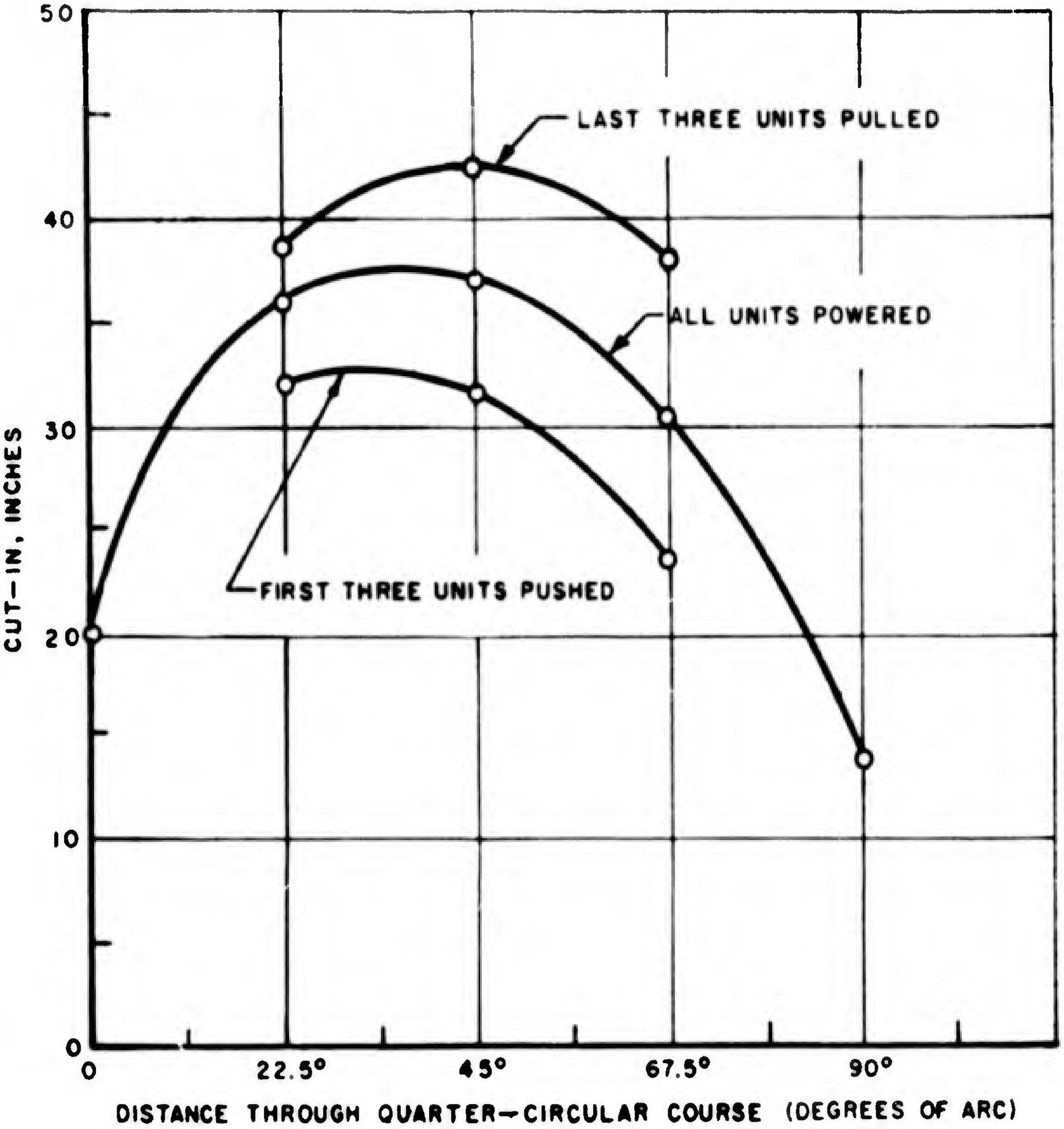

FIGURE 15. INFLUENCE OF DRAWBAR FORCES ON PROTOTYPE TRACKING

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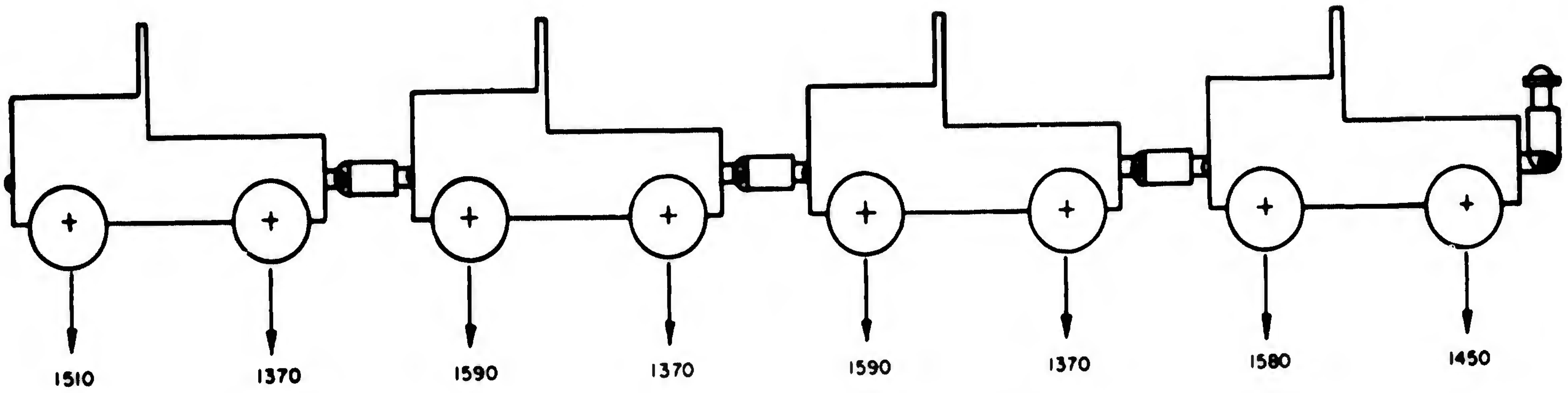

FIGURE 16. LOAD DISTRIBUTION OF TRAIN (Pounds)