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TEST AND EVALUATION OF AN EDDY CURRENT CLUTCH/BRAKE PROPULSION SYSTEM

George J. Adams

FEBRUARY 1975
FINAL REPORT

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16. Abstract

This report covers the Phase II effort of a program to develop and test a 15 hp eddy-current clutch propulsion system. Included in the Phase II effort are the test and evaluation of the eddy-current clutch propulsion system on board a test vehicle. The test vehicle was designed and built to be compatible with an existing monorail track and was instrumented for the conduct of the test program.

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PREFACE

The research, development, and testing studies documented in this report were carried out as a part of the New Systems Development Engineering Program for Personal Rapid-Transit (PRT) Systems, conducted by Mobility Systems and Equipment Company of Los Angeles under contract DOT-TSC-357 for the Transportation Systems Center, Department of Transportation, Cambridge, Mass., under the auspices of the Urban Mass Transportation Administration, Department of Transportation, Washington, D.C.

The work at Mobility Systems and Engineering and at the test site was carried out under the general supervision of George J. Adams, P.E., Frank Gaarde, P.E., Mathew Alexander, and Darrell Watkins.

The ride quality tests were conducted with instrumentation supplied by the Transportation Systems Center. Analysis of this data was conducted by Dr. Cheryl Burnette of the Measurements and Instrumentation Division, and Mr. Joseph Herlihy of the Ground Systems Programs Division at the Transportation Systems Center.

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LIST OF ABBREVIATIONS

A	amperes
AC	alternating current
amps	amperes
C	centigrade
DC	District of Columbia
DOT	Department of Transportation
ECC	Eddy Current Clutch
F	fahrenheit
FM	frequency modulation
fps	feet per second
ft	feet
FY	fiscal year
hp	horsepower
Hz	hertz
i. e.	that is
in.	inches
KHz	kilohertz
kVA	kilovolt-amperes
kvar	kilovolt-amperes reactive
kW	kilowatts
LACF	Los Angeles County Fair
lb	pound
MS&E	Mobility Systems and Equipment Company
ma	milliamperes
min	minutes
mm	millimeters
ms	milliseconds
P. E.	Professional Engineer
PF	power factor
PRT	Personal Rapid Transit
rpm	revolutions per minute
TSC	Transportation Systems Center
UMTA	Urban Mass Transportation Administration
v	volts
vs	versus
ϕ	phase
Ω	ohms

FOREWORD

Contract DOT-TSC-357 was awarded to Mobility Systems and Equipment Company of Los Angeles, California, by the Department of Transportation, Transportation Systems Center, Kendall Square, Cambridge, Massachusetts. The contract was sponsored by the Department of Transportation, Urban Mass Transportation Administration, Office of Research and Development, Washington, DC.

Phase 1 of the contract required the development, fabrication and laboratory testing of a variable speed eddy-current clutch-propulsion system in a form suitable for installation in an experimental vehicle. The work on Phase 1 is reported in Report No. UMTA-MA-06-0027-73-1 "Development and Test of an Eddy-Current Clutch-Propulsion System - Final Report", Oct. 1973. This report is available to the public through the National Technical Information Service, Springfield, Virginia 22151 (No. PB-225093).

Phase 2 of the contract required the installation of the eddy-current clutch-propulsion system in an experimental vehicle in which the propulsion system could be tested while the vehicle was in motion. This report presents data on fabrication of the experimental vehicle, installation of the propulsion system, the tests conducted and the results obtained in the tests.

1.0 Program Review and Summary

1.1 Review of Phase 1 Accomplishments

In performing Phase 1 of Contract DOT-TSC-357 Mobility Systems and Equipment Company (MS&E) was required to design, fabricate and evaluate a propulsion system consisting of a 15-hp, 3-phase induction motor, an eddy current clutch and an eddy current brake. These components were to be suitable for incorporation in the suspension system of a vehicle to operate on an existing monorail guideway. Control circuits for the propulsion system were to be packaged in a form suitable for installation in a test vehicle.

At the time that Phase 1 of the contract was placed there was no vehicle propulsion system with an eddy current clutch (ECC) drive larger than 7 1/2 hp. The details of the propulsion system design and evaluation tests for Phase 1 are given in final report for Phase 1, Report No. UMTA-MA-06-0027-73 "Development and Test of An Eddy-Current Clutch-Propulsion System", dated October 1973. The report is available to the public as document number PB225093 through the National Technical Information Service, Springfield, Virginia 22151.

In summary, during Phase 1 a variable speed propulsion system of a 15-hp, 460-V, 3-phase motor with an eddy current clutch and eddy current brake was completed. The design of this propulsion system was consistent with possible future installation in a test vehicle to be suspended from an I-beam rail. A control unit and an operator's console providing four programmed speeds were assembled in units suitable for the test vehicle. This variable speed ECC propulsion system was tested using a fly-wheel to simulate the inertia of the vehicle and an electric dynamometer to simulate drag forces of the vehicle. The propulsion system was tested with loading to simulate operation of a 9000 lb vehicle on the Jetrail Track at Love Field, and with loading to simulate a 16,000 lb vehicle making random runs between stations on an "optimized" track creating heavier loading. The tests of the propulsion system during Phase 1 were completed successfully.

1.2 Program Objectives for Phase 2

The program objectives for Phase 2 were:

(1) Design and build a test vehicle having features essential for testing the ECC variable speed propulsion system built in Phase 1.

(2) If necessary, adapt an existing track so it could be used for testing.

(3) Install the test vehicle on the track.

(4) Test the ECC propulsion system and determine its characteristics

(5) Assess the test results.

1.3 Chronology of Phase 2

The Phase 2 schedule is shown in Figure 1.1. The establishment of a test program plan is a continuing effort throughout the first part of the program. It will coincide with the design and fabrication of the test vehicle and also with the modifications to the test site. The test program will commence with the conclusion of the vehicle fabrication and site modification, according to the test plan.

1.4 Significant Results of Phase 2

The eddy current clutch propulsion system was installed in a vehicle for testing on a monorail track. Figure 1.2 shows area view of the test vehicle in operation during one of the tests on the test track. The monorail track that was used is located at the Los Angeles County Fairgrounds, where it is used as an amusement ride during the time the fair is open. A series of tests were conducted providing performance data on the propulsion system and of the vehicle. Analyses of the tests have been prepared, and the results are presented in this report.

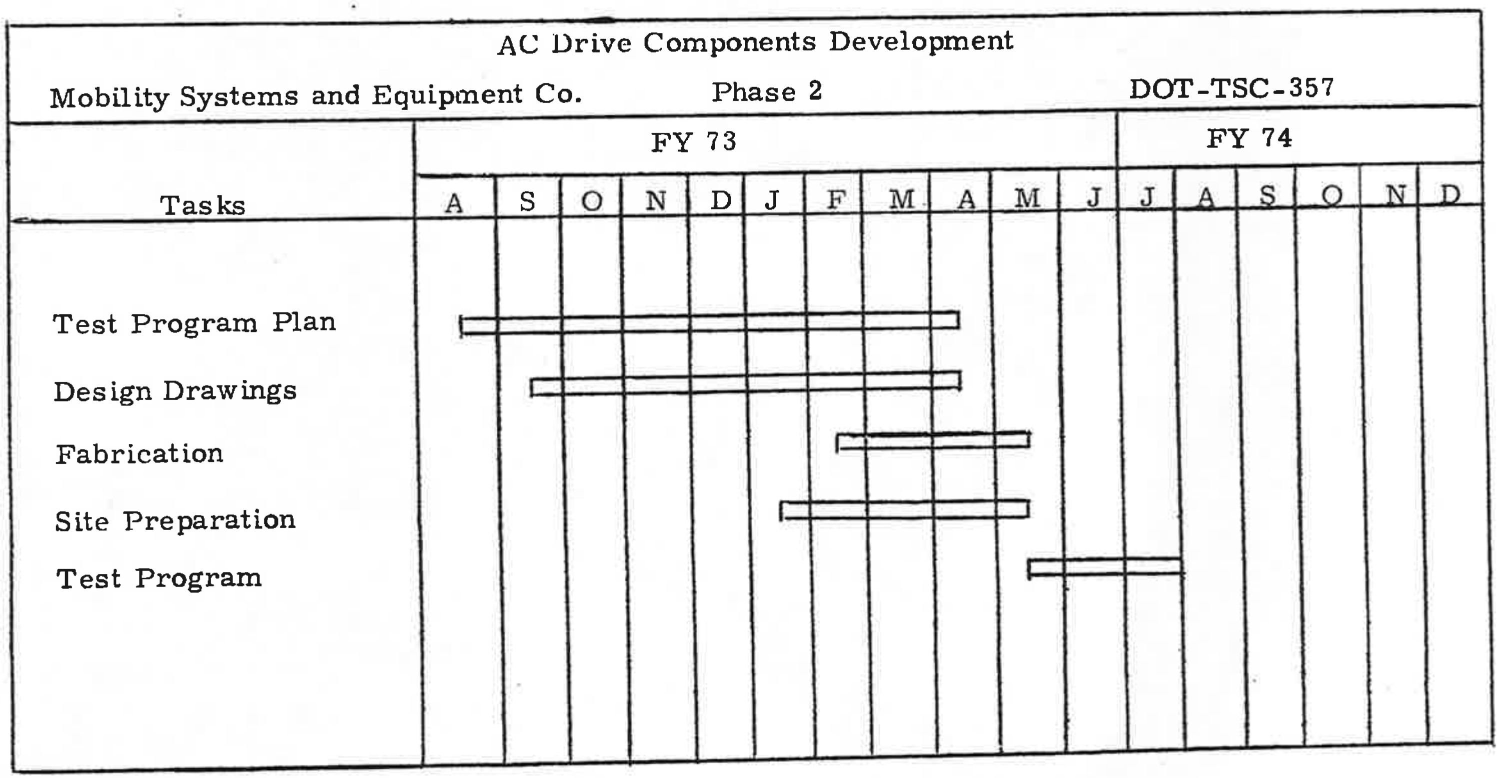


Figure 1-1. Schedule for Phase 2.

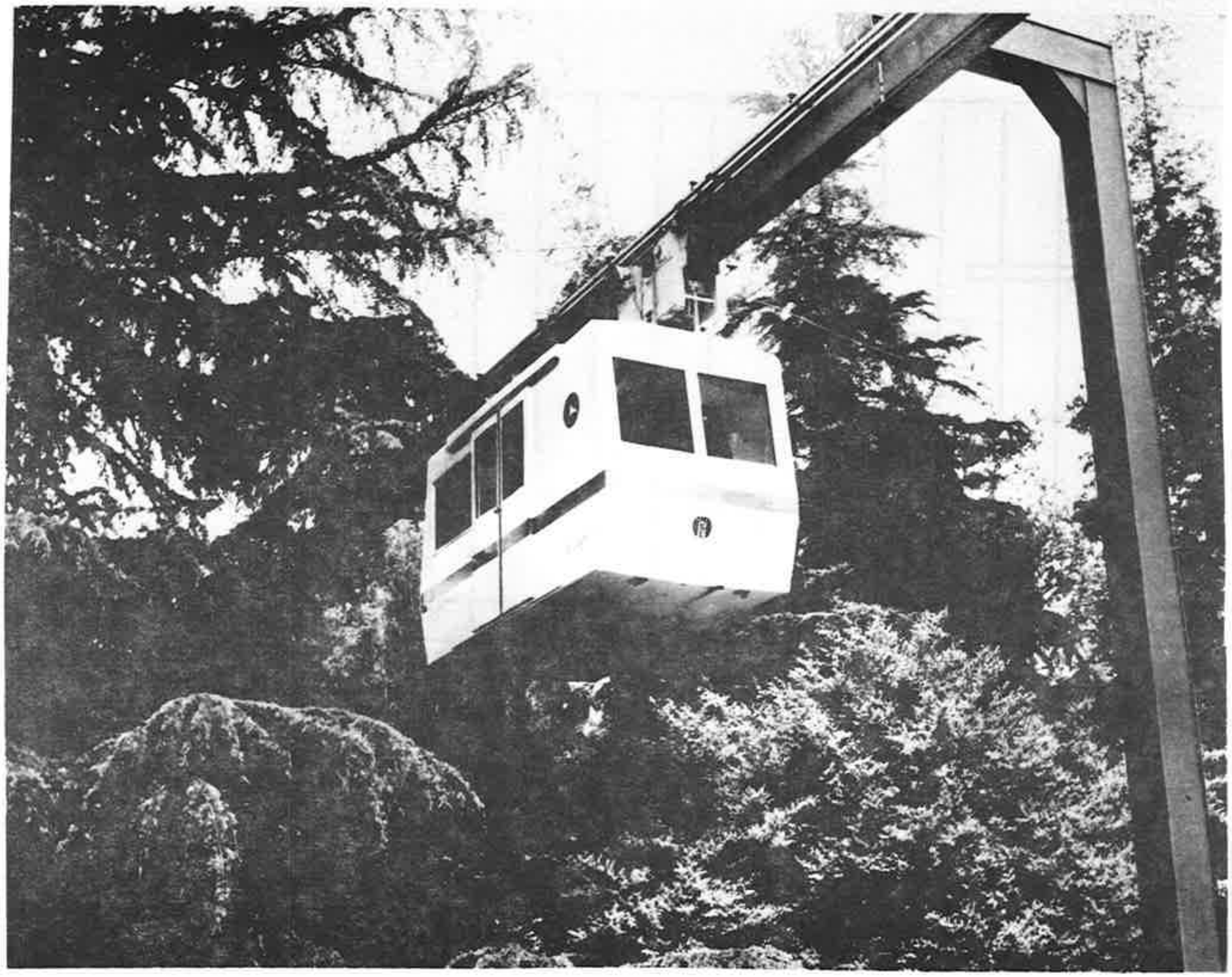


Figure 1-2. Test Vehicle in Operation

2.0 Test Vehicle Description

2.1 Basic Design

In constructing a test vehicle to evaluate the ECC propulsion system it was desired to have a realistic simulation of the conditions the propulsion system would encounter in an operational monorail. The Braniff Jetrail at Love Field was used as a guide, leading to the following vehicle specifications guidelines:

Vehicle Size: (passenger compartment only)

13 ft 7 in long
7 ft 3 in wide } Outside dimensions
7 ft 7 in high

Vehicle Suspension:

To be supported by two bogies, one near each end of the vehicle. Each bogie to have four weight bearing wheels and four guide wheels.

Propulsion Equipment:

To be mounted on the roof between the bogies, and arranged to drive two wheels of one bogie. Gear ratios and wheel sizes to be selected for a maximum speed of 22 ft/sec.

Gross Weight: 9000 lbs.

A sketch of the vehicle assembly is shown in Fig. 2.1.

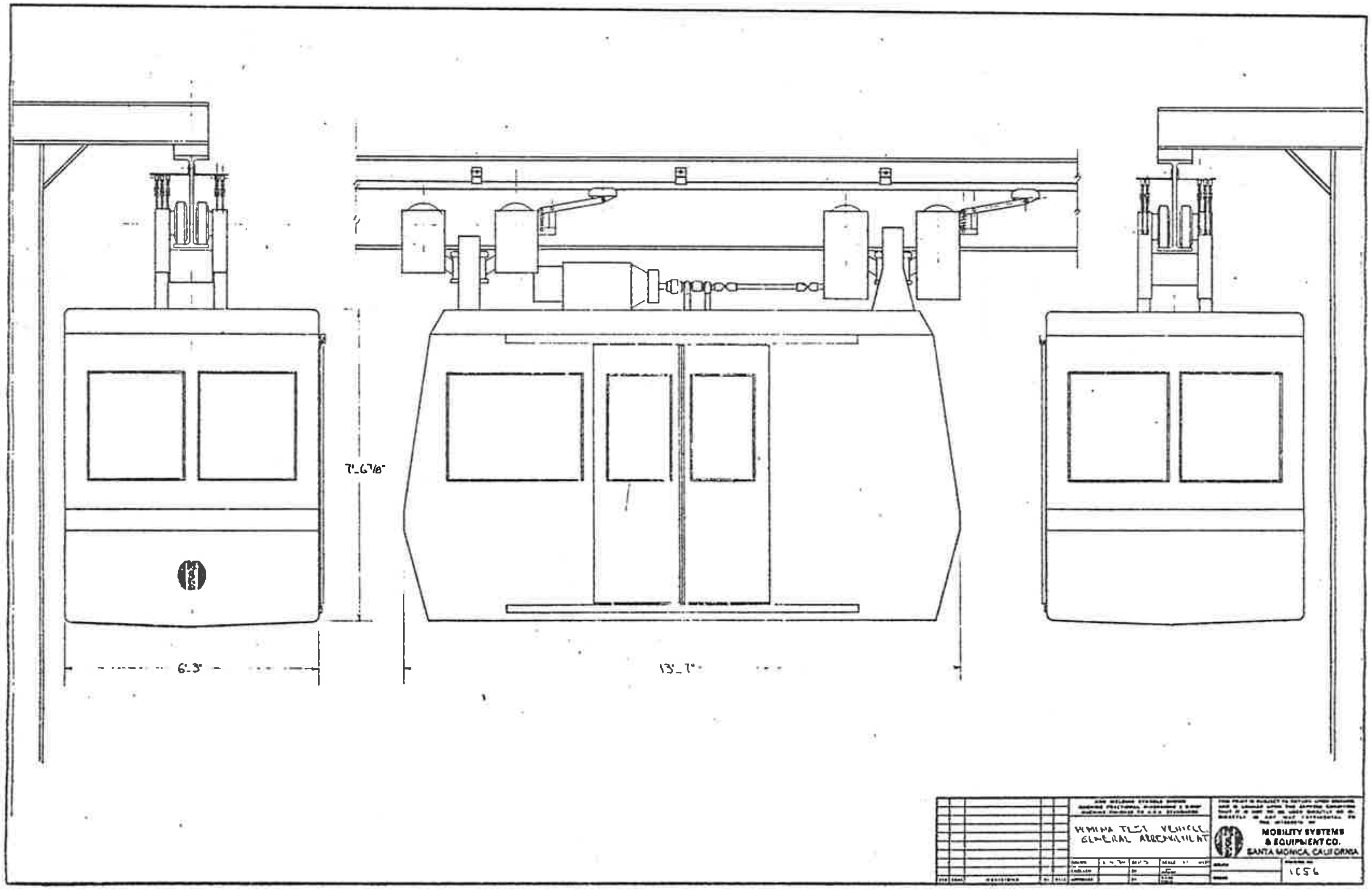


Figure 2-1. Vehicle Assembly

The test vehicle structure consisted of a weldment using structural steel square and rectangular tubing as the main frame members. The construction details of the frame are shown in Figs. 2.2, 2.3, 2.4, and 2.5. The completed frame is shown in the photograph of Fig. 2.6.

The exterior skin panels of the vehicle were 18 gauge steel rivetted to the frame. The space between frame members was filled with 2 inch thick self-extinguishing polystyrene insulation panels which were bonded to the outer skin. The inner skin for walls and ceiling was constructed of hardboard materials (masonite). Marine plywood was used for the flooring.

Windows were provided for operator visibility on front and both sides adjacent to the operator's position at the front end of the vehicle. Additional windows were provided in the rear of the vehicle. These windows were tinted plexiglass held in place with aluminum and rubber extrusions.

A double sliding door was provided at the center of the driver's side of the vehicle. The vehicle floor was located to match the platform height at the test track.

Fig. 2.7 shows the interior arrangement of the test vehicle. The console panels which had been fabricated and tested during Phase 1 were mounted just below the front windows at the operator's position. This enabled the

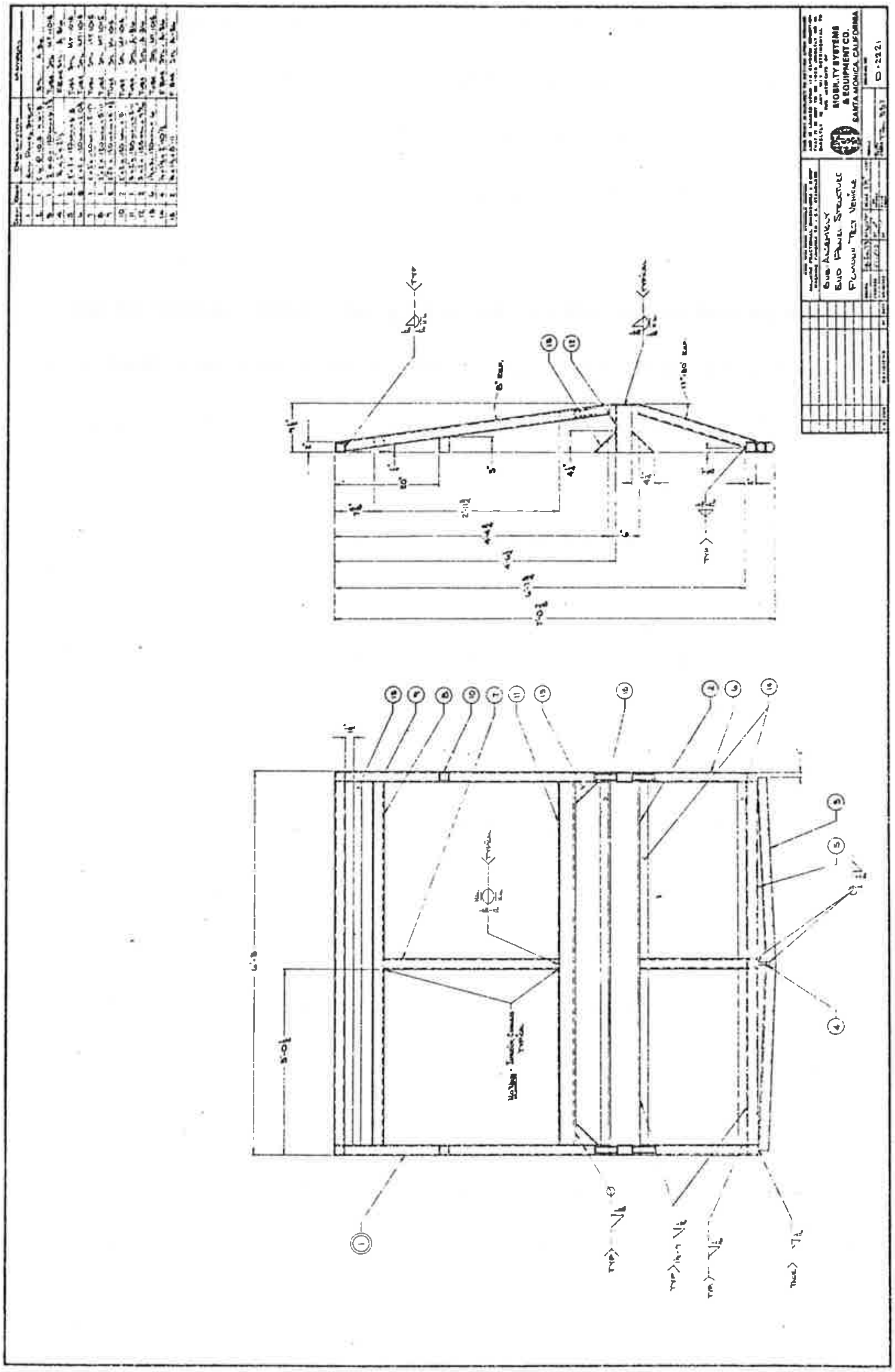


Figure 2-2. Frame Details

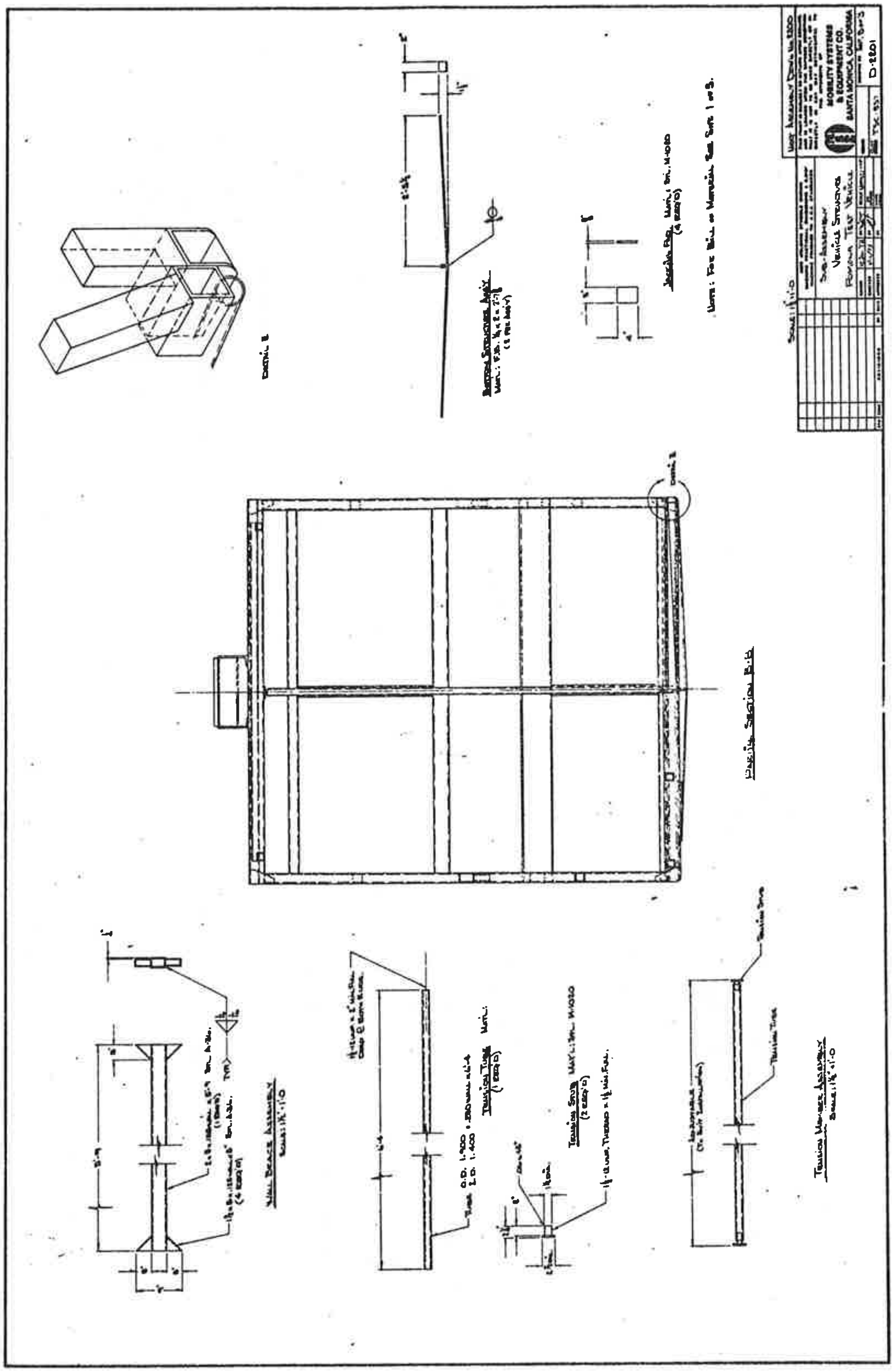


Figure 2-3. Frame Details

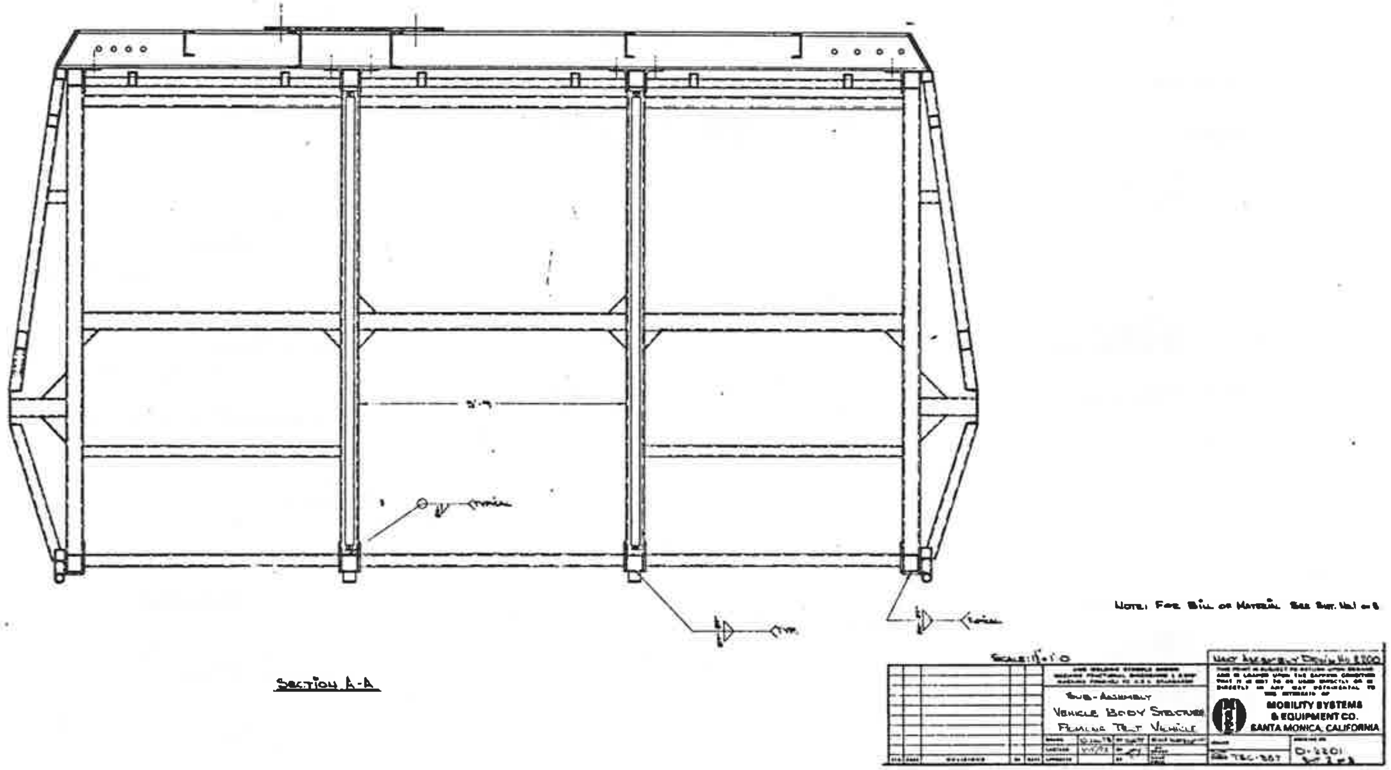


Figure 2-4. Frame Details

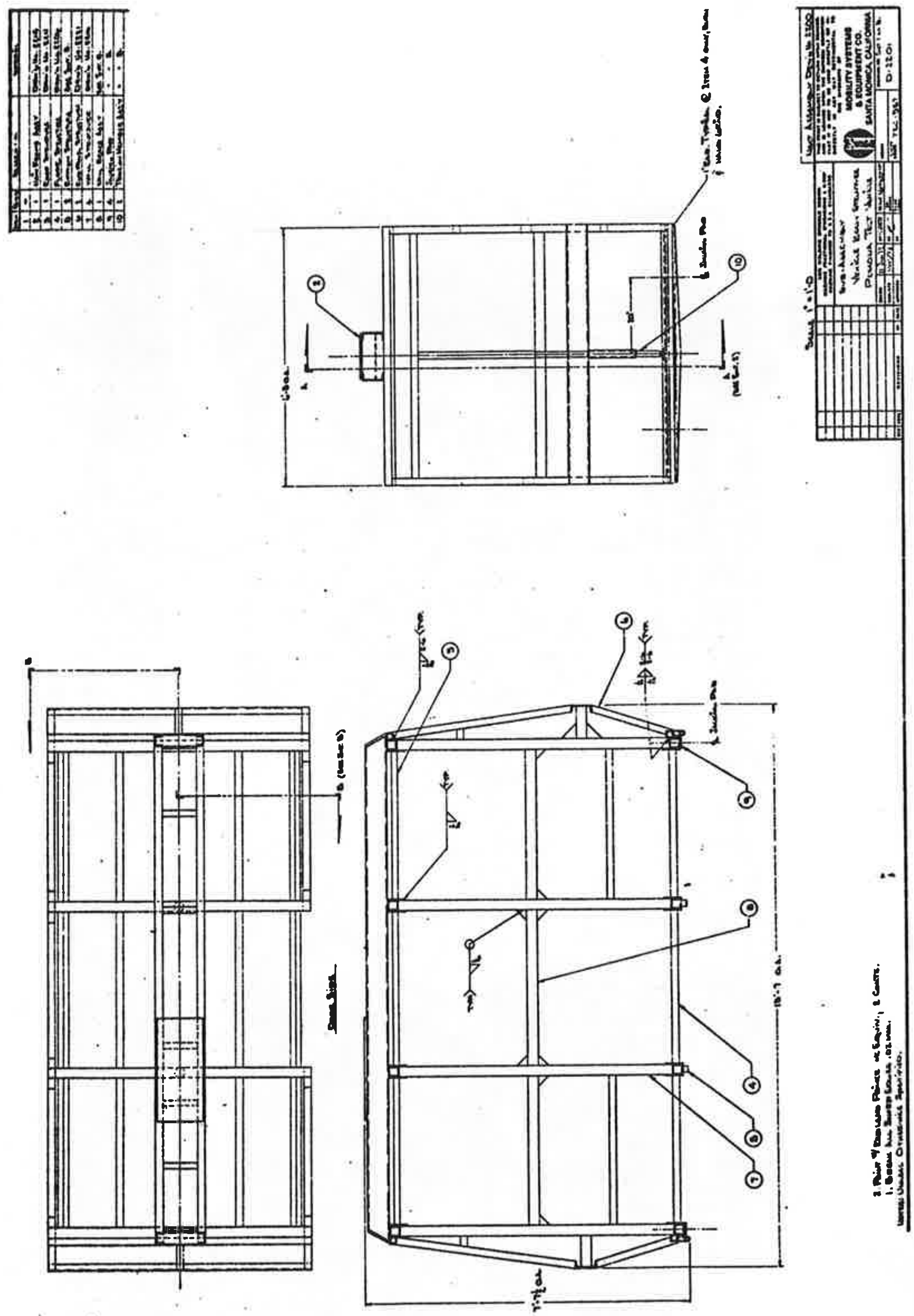


Figure 2-5. Frame Details

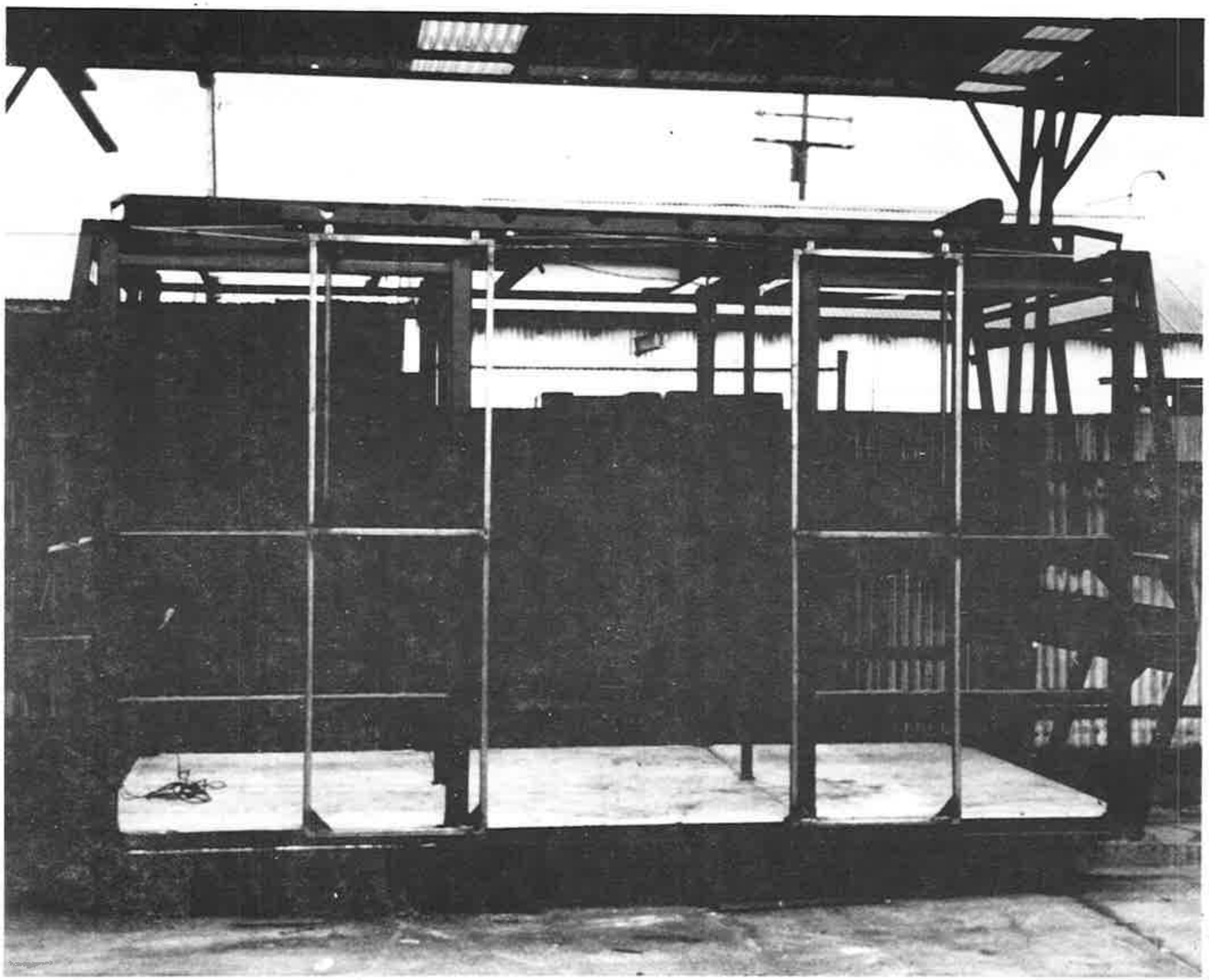


Figure 2-6. The Composite Frame

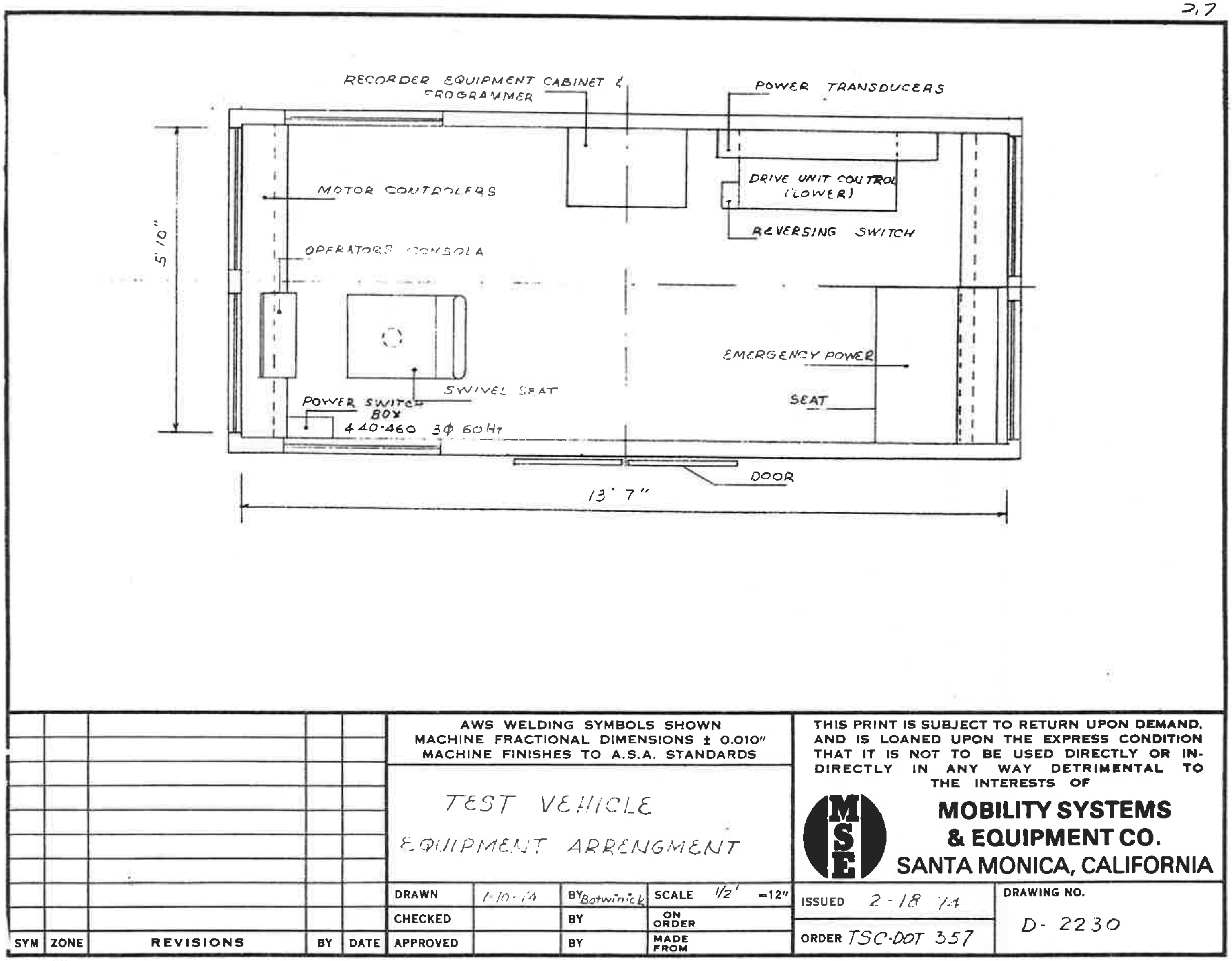


Figure 2-7. Interior Arrangement of the Test Vehicle

operator to observe track conditions ahead when the vehicle was in motion. Fig. 2.8 shows the console panels in place.

At the rear, opposite the door the main assembly of control circuits was mounted. This assembly is shown in position in Fig. 2.9. The upper panel contains sensors and transducers to measure input kilowatts and kilovars for the propulsion system. The cabinet at the bottom contains the circuits of the servo system controlling speed and torque. A 480/120-V single-phase transformer in the cabinet provides power for test instruments.

2.2 Vehicle Suspension System

The passenger compartment described above was suspended from two bogies located near the ends of the vehicle. The design concept for these bogies had been completed during Phase 1. This design is shown in Fig. 2.10 for the bogie which includes the driven wheels.

This suspension allows the bogie to rotate and to move vertically relative to the body of the vehicle on which the variable speed eddy current propulsion system and torque sensor are mounted. The universal joints in the drive shaft can flex sufficiently to allow this motion while power is being transferred to the bogie.

In the final report for Phase 1 the calculated stresses encountered by the axles, bearings, etc., of the drive system are presented. The calculations

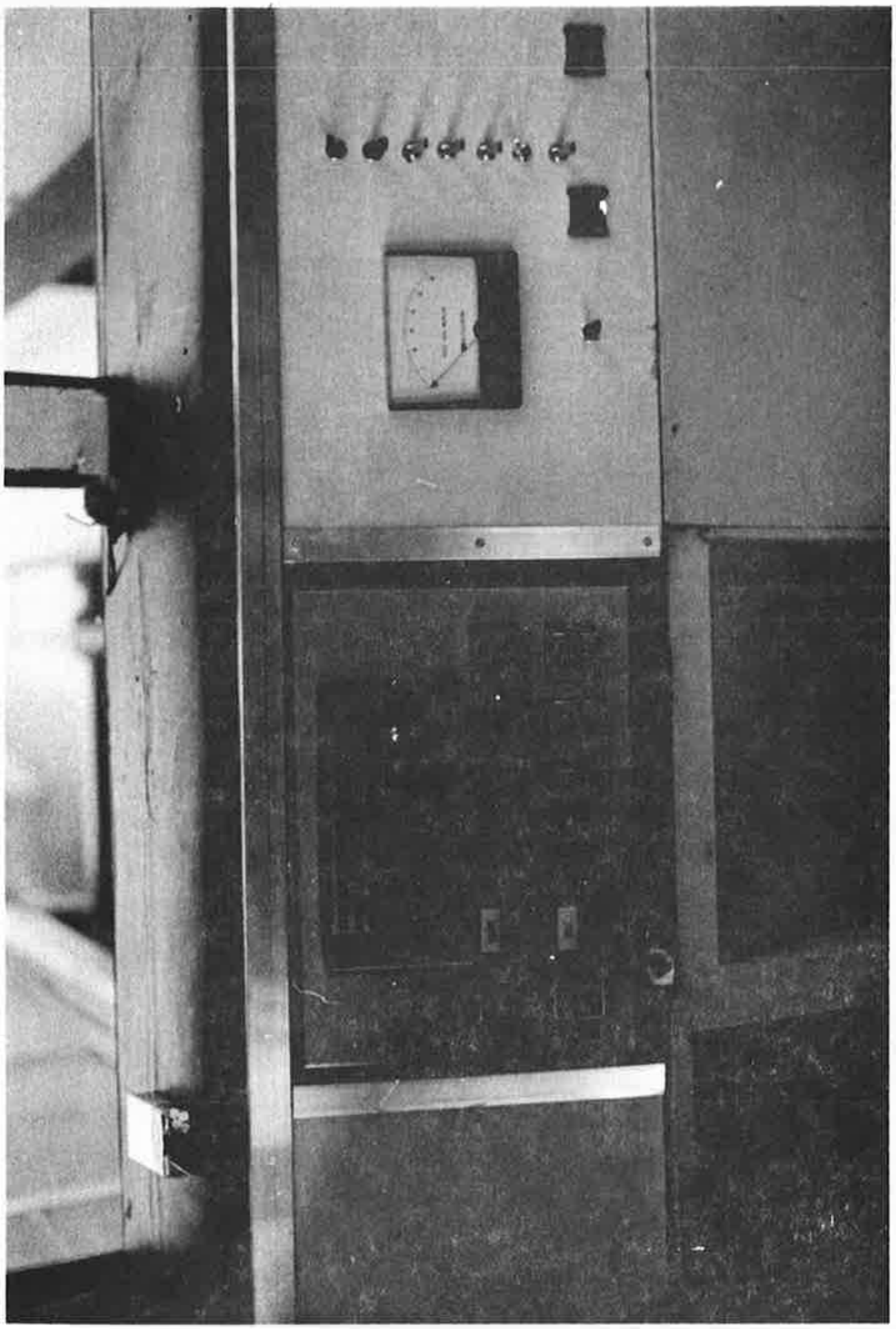


Figure 2-8. Operator's Console

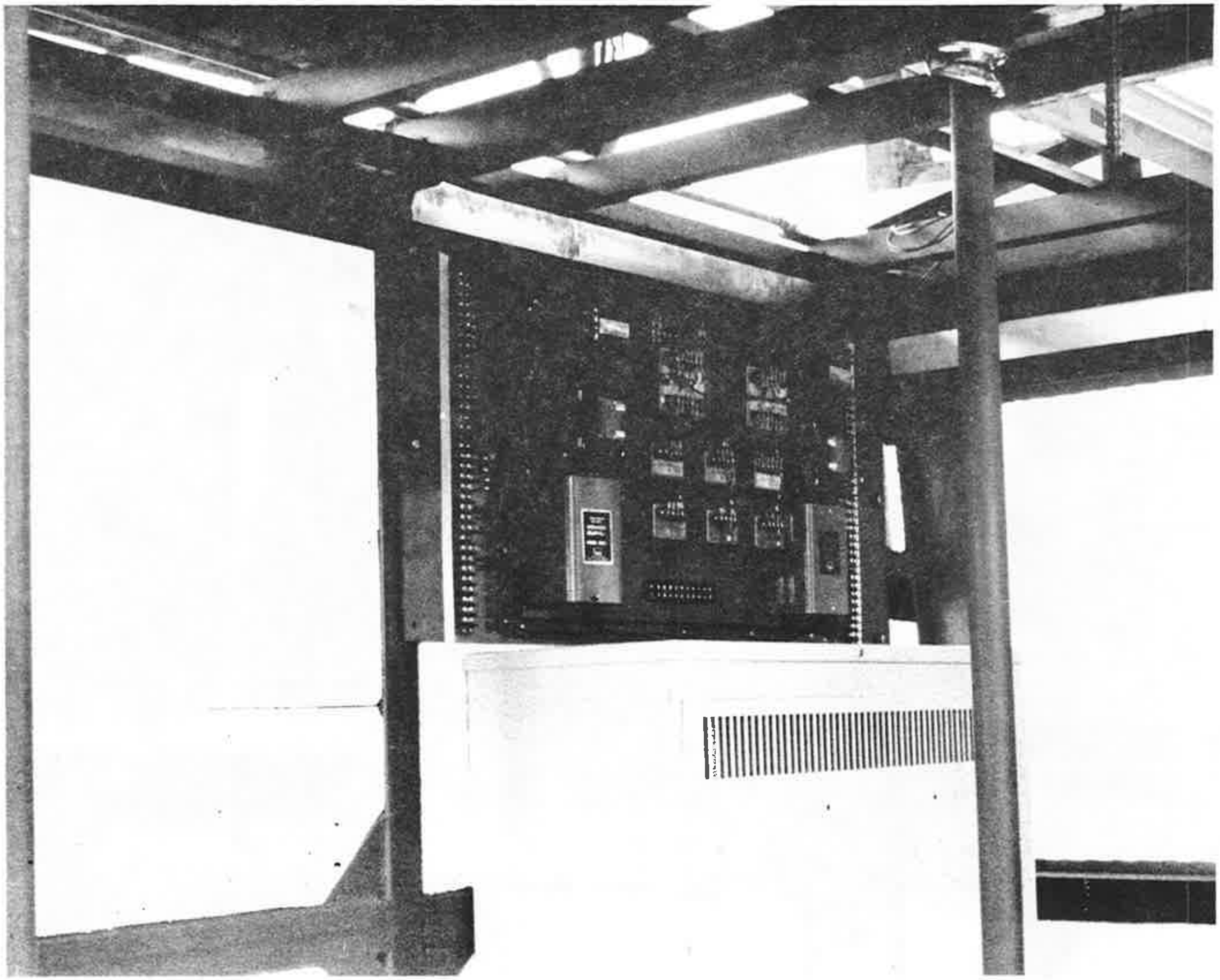


Figure 2-9. Controller Installation

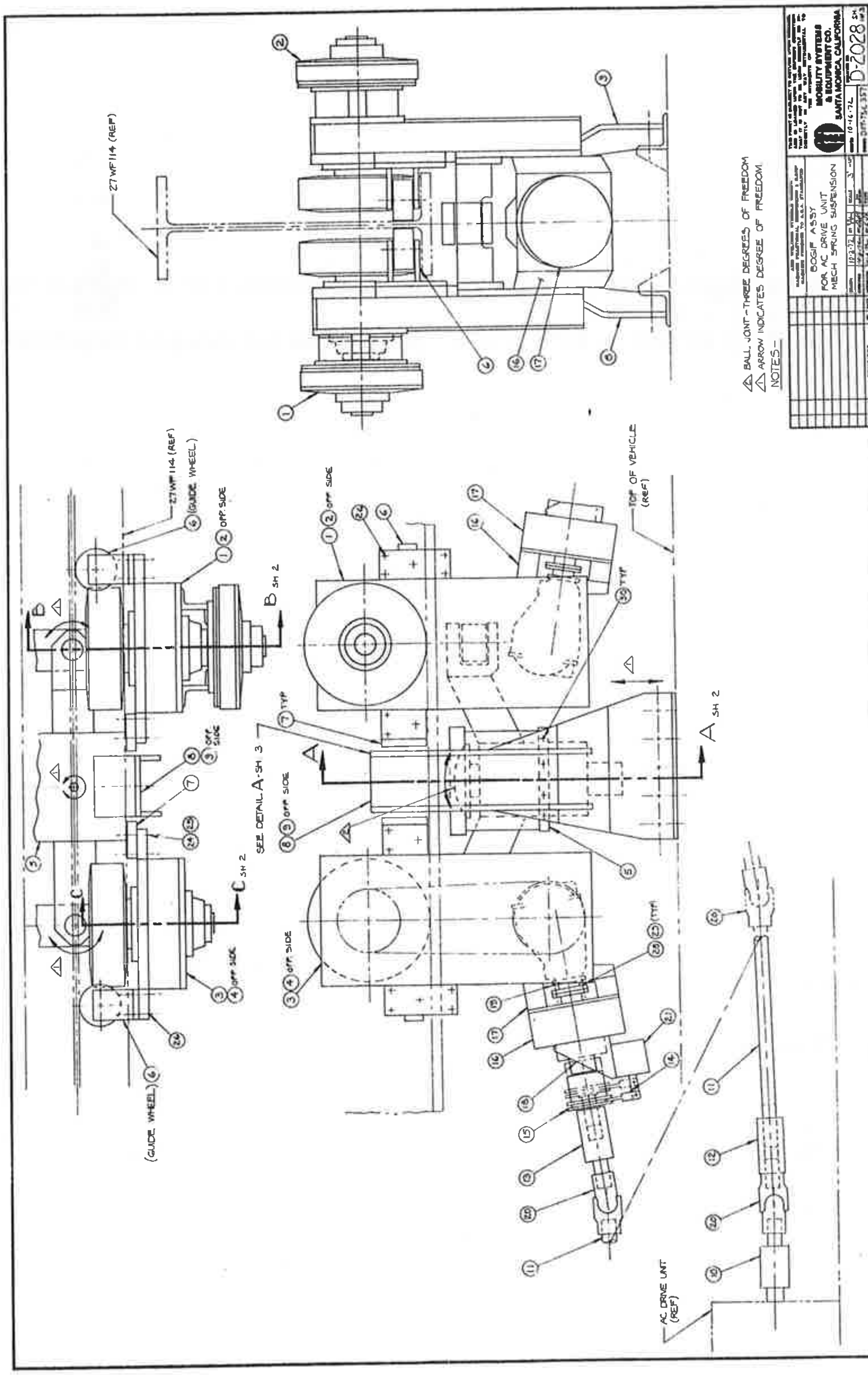


Figure 2-10. The Powered Bogie

of mechanical resonances in the running rail and the vehicle suspension system are also presented in the Phase 1 report. This report does not repeat these data.

The undriven bogie is similar in general construction except that all four weight bearing wheels are idlers with neither propulsion nor braking capability.

Power for the driven bogie is transferred from the variable speed drive and torque sensor assemblies through a drive shaft with universal joints. Output from the drive shaft passes through a differential with horizontal output shafts at right angles to the running rail. At each end of these output shafts a chain drive transfers the power to the driven axles. Hard rubber tired wheels on the driven axles provide propulsion thrust for the vehicle.

The two wheels which are not driven are mounted on similar short axles. Instead of a chain drive on the outboard ends, these axles have disc brakes which can be operated electrically.

The vehicle is suspended from a pivot located at the center of the bogie. This pivot allows the bogie to rotate relative to the body of the vehicle as necessary to follow the rail through turns. Within the pivot assembly a stack of Belleville washers in compression support the weight of the vehicle.

The washers are installed so adjacent washers have the concave side in opposite directions. Thus the weight is carried alternately at the inside diameter and outside diameter of the washers. The stack of washers act as a spring reducing the impact of track irregularities on passenger comfort.

An emergency braking system is built into both bogies. When power is available, these brakes are held in the nonbraking position. In the event of power failure offset ratchet wheels in the brake drop against the surface of the running rail. The motion of the vehicle turns the ratchet wheel in the direction which will increase the friction forces by tending to lift the vehicle. Each brake assembly has two of these offset ratchet wheels, one for each direction of vehicle movement.

2.3 Differential and Drive System

The output from the motor/ECC assembly was coupled through universal joints to a torque measuring sensor, a Lebow Model 1604-2K.

From the torque sensor a drive shaft with universal joints transfers the power to the differential which has a 4.11 to 1 speed reduction between the drive shaft and the two output shafts. The differential is an off-the-shelf unit manufactured by Spicer Division of Dana Corporation (Model A12-1). The differential does not have any devices to limit the difference in speeds of the two output shafts.

Each output shaft from the differential has a 45 tooth sprocket for chain drives to the driven axles. The sprockets on the driven axles had 38 teeth providing a speed increase in the chain drive of 45/38. Thus each driven axle has an overall speed reduction of 3.47 to 1 from the drive shaft.

The drive wheels have an effective diameter of 12 in. For a vehicle speed of 15 mph (22 fps) the drive wheels turn at 420 rpm and the drive shaft at 1458 rpm.

Fig. 2.11 shows the installation of the motor/ECC assembly, the torque sensor and the drive shaft to the differential as mounted on the roof of the vehicle.

2.4 Power Collection and Distribution

The power distribution system on board the vehicle is shown in the block diagram of Fig. 2.12. Redundant power collectors were installed on each bogie to reduce the probability of momentary interruptions in power due to contact bouncing. The power collectors used were commercial assemblies similar to those used on travelling cranes. The power collectors are mounted on arms providing freedom of motion between the structure of the bogie and the assembly of three pick-up shoes. This enables the pick-up shoes to follow the line of the power rails despite curves or irregularities in the running rail. Fig. 2.13 shows the power collector mounted on the idler bogie. A similar assembly is mounted on the driven bogie.

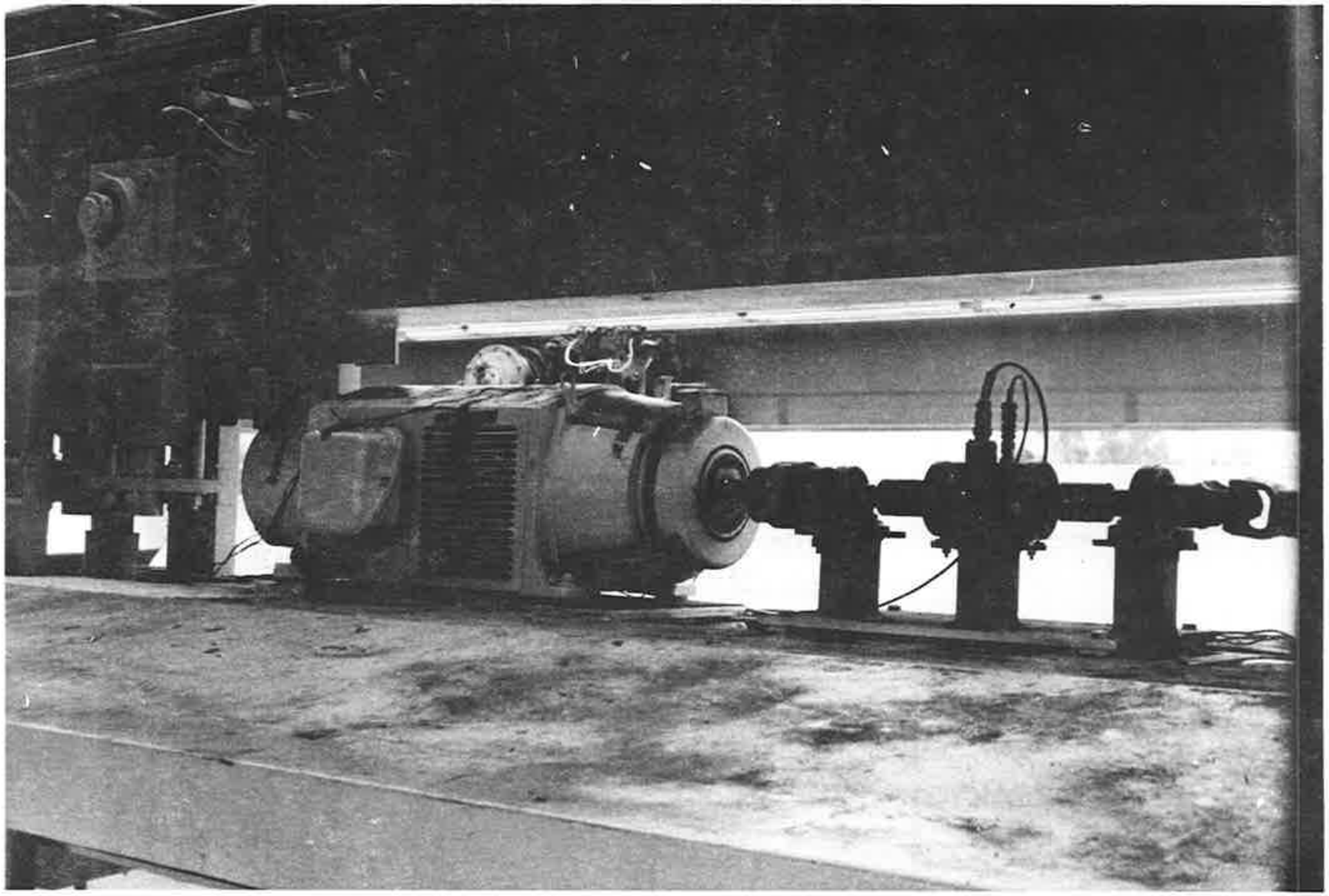


Figure 2-11. Installation of Propulsion System and Torque Sensor on the Vehicle

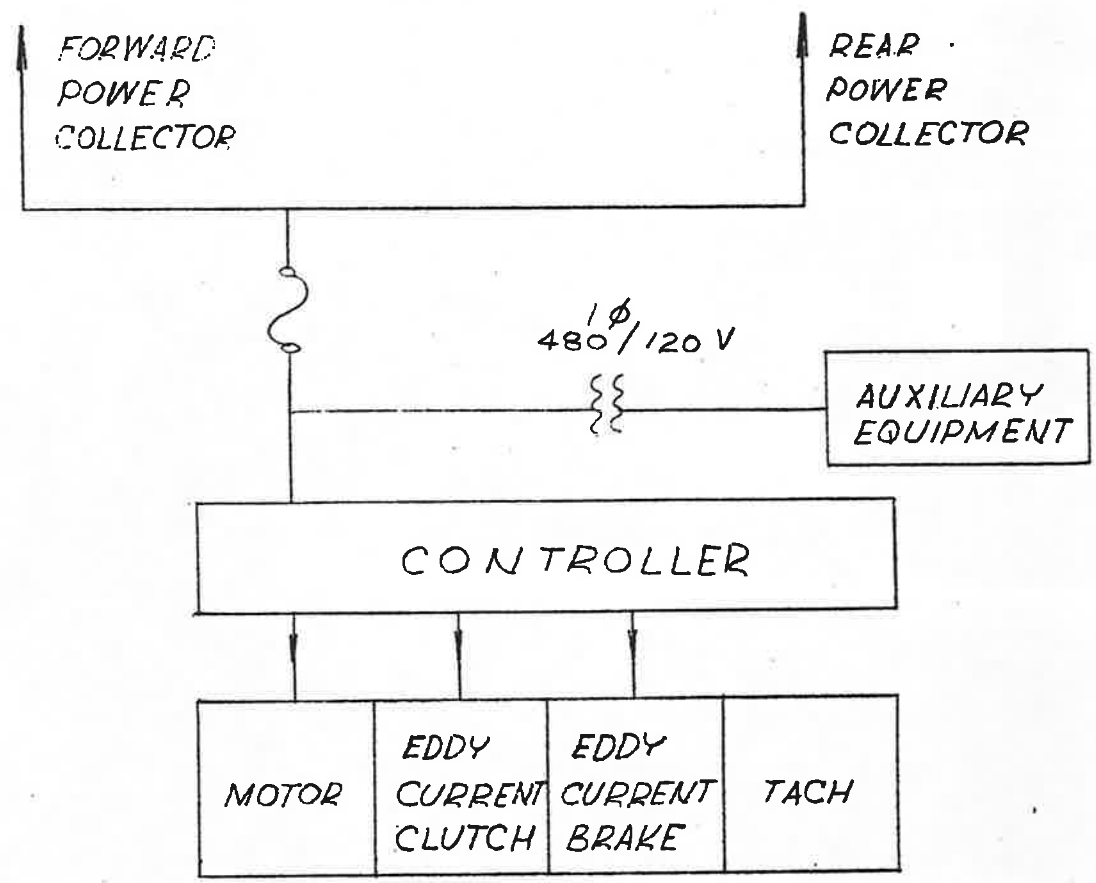


Figure 2-12. Power Distribution System in Test Vehicle

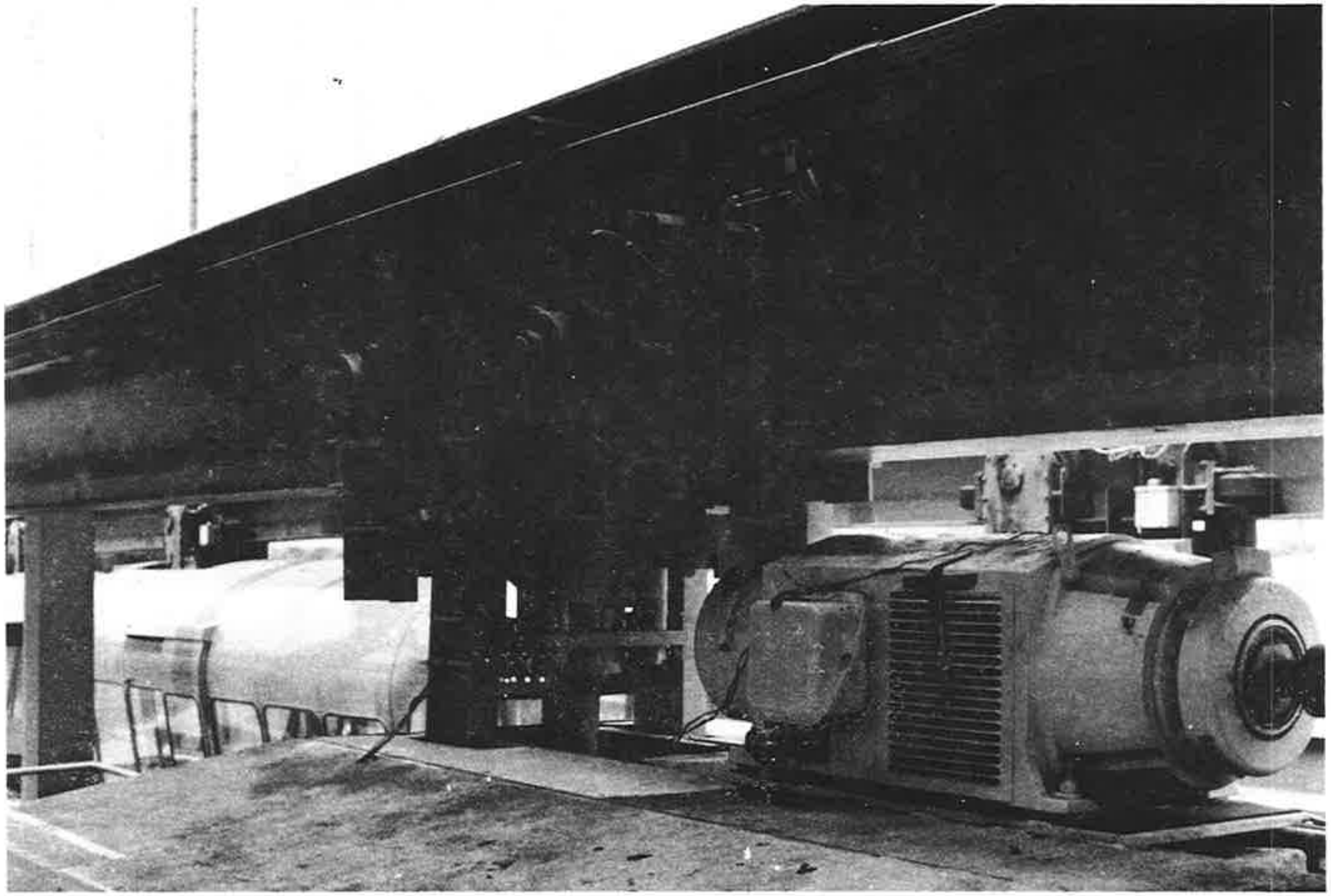


Figure 2-13. Power Collectors

3.0 Eddy Current Clutch Power Train

The complete power train installed in the test vehicle is shown in the block diagram of Fig. 3.1. The power train is constructed of three assemblies:

a. A Mobility Systems & Equipment Co. variable speed drive Model PM001MSE.

b. A Lebow Associates Inc. Model 1604-2K Torque Sensor.

c. A powered bogie.

Each of these assemblies is described below.

3.1 The Variable Speed Drive

The MS&E variable speed drive is a single assembly as shown in Fig. 3.2. Within the housing are a 15 hp induction motor, a fan, an eddy current clutch, an eddy current brake, a friction brake and a tachometer. By combining these functions into a single housing, a smaller, lighter unit has been built than would have been possible using discrete parts. The performance of the variable speed drive is described fully in the Phase 1 report. A brief description is given below.

The motor is a 60-Hz, 15-hp, 460-V, 3-phase induction motor with NEMA Class B torque-speed-current characteristics. When delivering 15-hp at nominal voltage the motor runs at 1700 rpm while delivering a torque of 46.3 ft-lbs. This is the continuous full load rating of the motor. When the

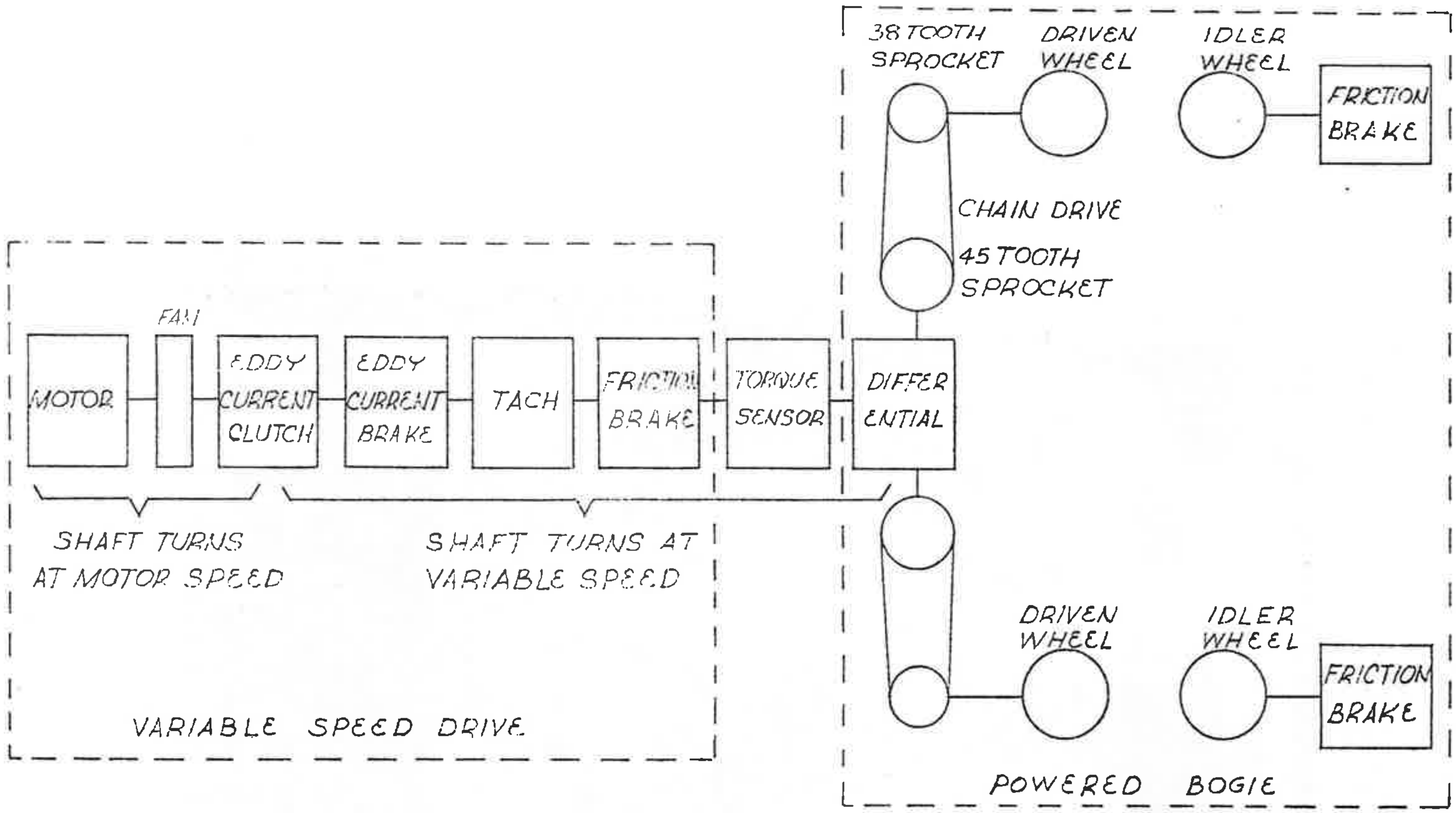


Figure 3-1. Block Diagram of Power Train

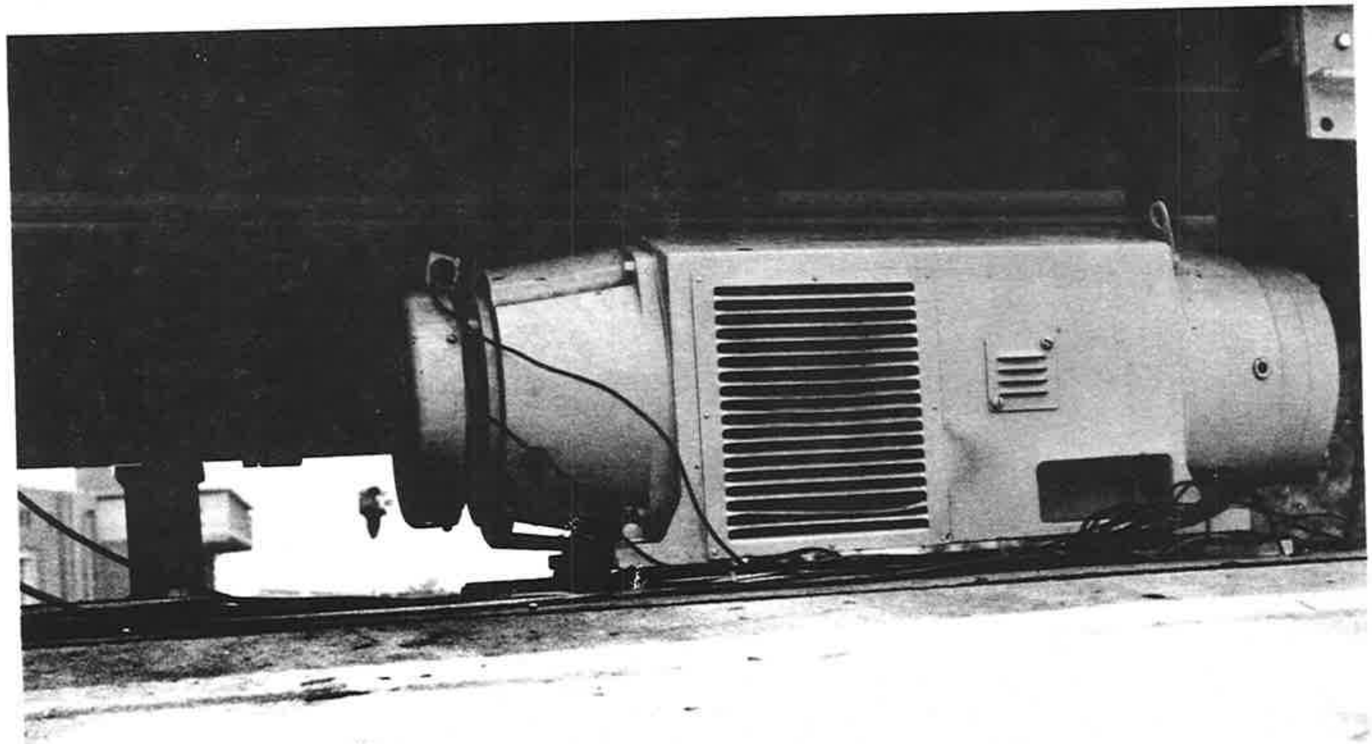


Figure 3-2. Eddy Current Clutch Propulsion System Assembly

torque demanded exceeds the continuous full load rating the motor will slow down as necessary. The motor temperature raises under these overload conditions. If damage is to be avoided the overload must be removed before the temperature becomes excessive.

The eddy current clutch built into the variable speed drive has three magnetic structures. One magnetic structure is mounted on the motor shaft and revolves at motor speed. This piece is shaped to provide the desired magnetic performance while acting as a fan to move cooling air through the assembly. The second magnetic structure is mounted on the output shaft and revolves at the variable output speed. The third magnetic structure is mounted in the frame and does not revolve. A field coil is located in the stationary magnetic structure so no slip rings are required. Changing the current in the field coil changes the magnetic flux in the three magnetic structures of the clutch. The torque transferred through the clutch depends on the current in the field coil and the difference in speed of the two rotating magnetic structures. The clutch can only transfer torque when there is a difference in speed between the two rotating magnetic structures, thus the output shaft will always revolve slower than the motor shaft when there is a load on the output shaft.

The eddy current brake has two magnetic parts. One part is mounted on the output shaft and revolves at the speed of that shaft. The second magnetic part is mounted on the frame of the variable speed drive and does not revolve. A field coil mounted in the stationary magnetic structure controls the flux in the two magnetic parts. The torque produced by the brake depends on the field current and the speed of the output shaft. The torque becomes zero as the shaft stops. The brake is therefore unable to hold the output shaft in a fixed position.

A mechanical brake is built into the variable speed drive to correct the zero speed deficiency of the eddy current brake. It is a disc brake arranged so that the brake is applied automatically when the output shaft is turning at a speed less than 265 rpm. The mechanical brake is disabled when the eddy current clutch calls for power, enabling the vehicle to start.

A permanent magnet alternating current generator is built into the assembly to act as a tachometer. The permanent magnet is mounted on the output shaft, and the coils are mounted in a small stationary magnetic structure. With no load connected to the coils the voltage and the frequency are directly proportional to shaft speed. The voltage and frequency are independent of the direction of shaft rotation.

There are three separate and independent tachometers in the drive train of which one is in the variable speed drive assembly. The tachometer in the variable speed drive provides a speed feedback signal for the circuits of the controller. The tachometer in the torque sensor was used to record vehicle speed and the tachometer on one running wheel of the bogie was used to display vehicle speed.

3.2 The Torque Sensor

The second assembly of the power train is a Model 1604-2K Torque Sensor manufactured by Lebow Associates Inc. of Troy, Michigan. The sensor is shown installed on the roof of the test vehicle in Fig. 3.3. The torque sensor was installed for test purposes only, and would not be required for an operational system.

The torque is measured by strain gauges which sense the strains introduced by torsional forces in the shaft. If the accuracy is to be maintained it is essential that the shaft of the sensor be isolated from other forces which could introduce strain. For this reason a bearing was provided on either side of the sensor. The two bearings and the sensor were mounted on a heavy base plate to maintain alignment.

A flexible coupling is provided between the torque sensor and the variable speed drive both of which are securely mounted to the roof of the vehicle. A

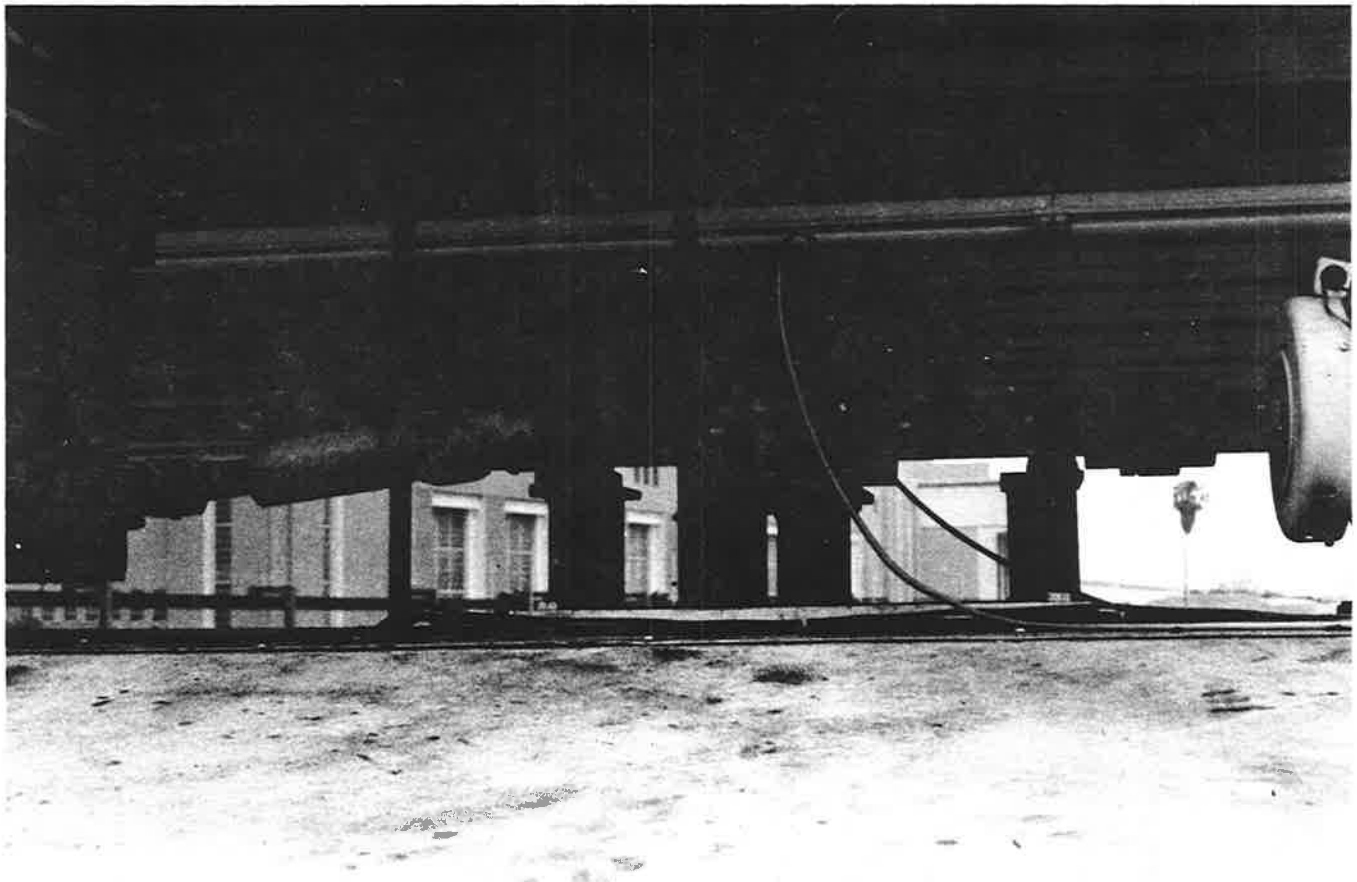


Figure 3-3. Torque Sensor Installed

univeral joint is used between the torque sensor and the drive shaft to the bogie since the drive shaft must move as required by the springing of the vehicle on the bogie, and rotation of the bogie to follow the track.

As used for the tests of the vehicle the strain gauges were excited from a 3 kHz source. The output of the strain gauges was rectified in a phase sensitive rectifier providing a dc voltage with a magnitude proportional to torque, and a polarity which depended on the direction of the torque. This dc voltage was used in the recorders.

The torque sensor includes a tachometer output providing 60 pulses per revolution. In the test vehicle this tachometer output was converted to dc to record vehicle speed.

3.3 The Powered Bogie

The features of the power train in the powered bogie are described in Section 2 of this report.

4.0 Field Test Facility

4.1 Description of Test Site

During Phase 1 of the contract a search was made to locate a suitable site to test the eddy-current clutch-propulsion system on board an experimental vehicle. Since the object was to test the propulsion system a test site was sought which would permit the tests without major expenses in building or modifying a track.

In Pomona, California, at the Los Angeles County Fairgrounds (LACF) a Monorail was constructed and first used in 1962. It has operated annually since that time. The Monorail is operated as an amusement ride during the 18 to 20 days the fair is open each year. During that period between 500, 000 and 800, 000 passengers pay a small fee for the privilege of taking a ride lasting 6 to 8 min. giving them a view of almost all of the fair. A contract was negotiated with LACF to use the track of the Monorail for the test vehicle with the variable speed eddy current clutch propulsion system.

The vehicles normally used at the fair are suspended from two bogies, one at each end of the vehicle. Each bogie has two axles which carry the weight on four 12 in. diameter hard-rubber tired wheels. In each bogie one axle is driven from a 5-hp 3-phase 460-V motor through a hydraulic transmission and a differential. The second axle on each bogie is not driven.

These vehicles carry approximately 22 passengers at speeds up to 10 mph. There are 13 vehicles available. Once they have been dispatched, they operate unattended. A block system built into the guideway maintains vehicle separation. A typical LACF vehicle is shown in the photograph of Fig. 4. 1.

4. 2 Description of the LACF Track

The LACF track is constructed using 27 WF114 steel I-beams as the running rail. As installed the web of the I-beam is vertical, with the flanges at the top and bottom. The weight of the vehicle is carried on the lower flange where the wheels roll on the inner side of the flange. The guide wheels roll on both sides of the web.

The LACF track is approximately 5000 ft long as shown on the map of Fig. 4. 2. Very little of the LACF track is level. Since fair officials could not provide data on the elevation of the track, a surveyor was engaged to measure the grades where they were greatest. The results of his measurements are shown in Fig. 4. 2. It should not be assumed that the track is level where no grade data is shown in Fig. 4. 2. Except as noted in the discussion which follows all curves have 80 ft radii and no easements are provided. The I-beam running rail has the web vertical on the curves.

Stations for loading and unloading passengers are located in the tangent labelled A on the map. Power controls for the track are also located in this area. Starting

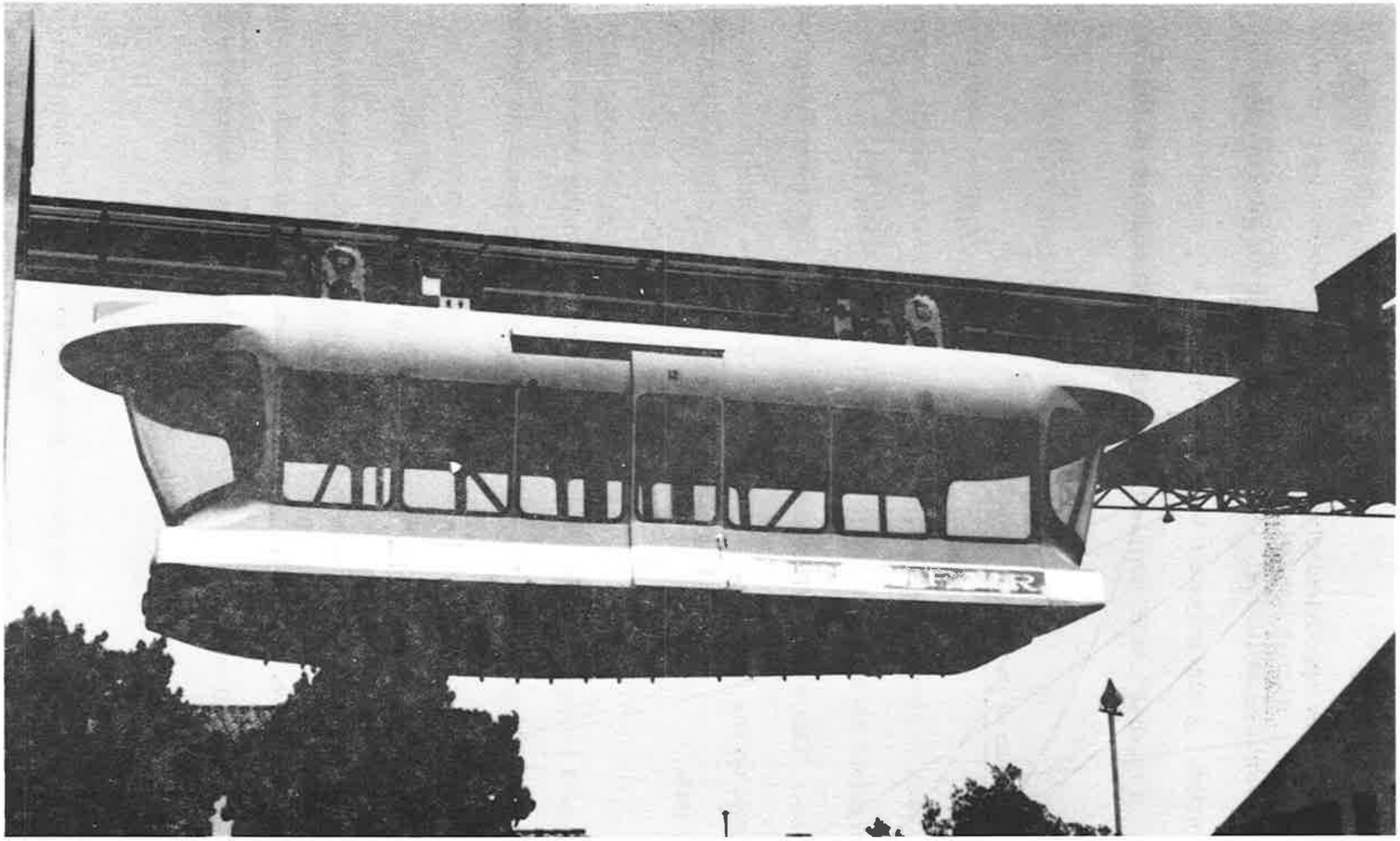


Figure 4-1. Typical LACF Monorail Vehicle

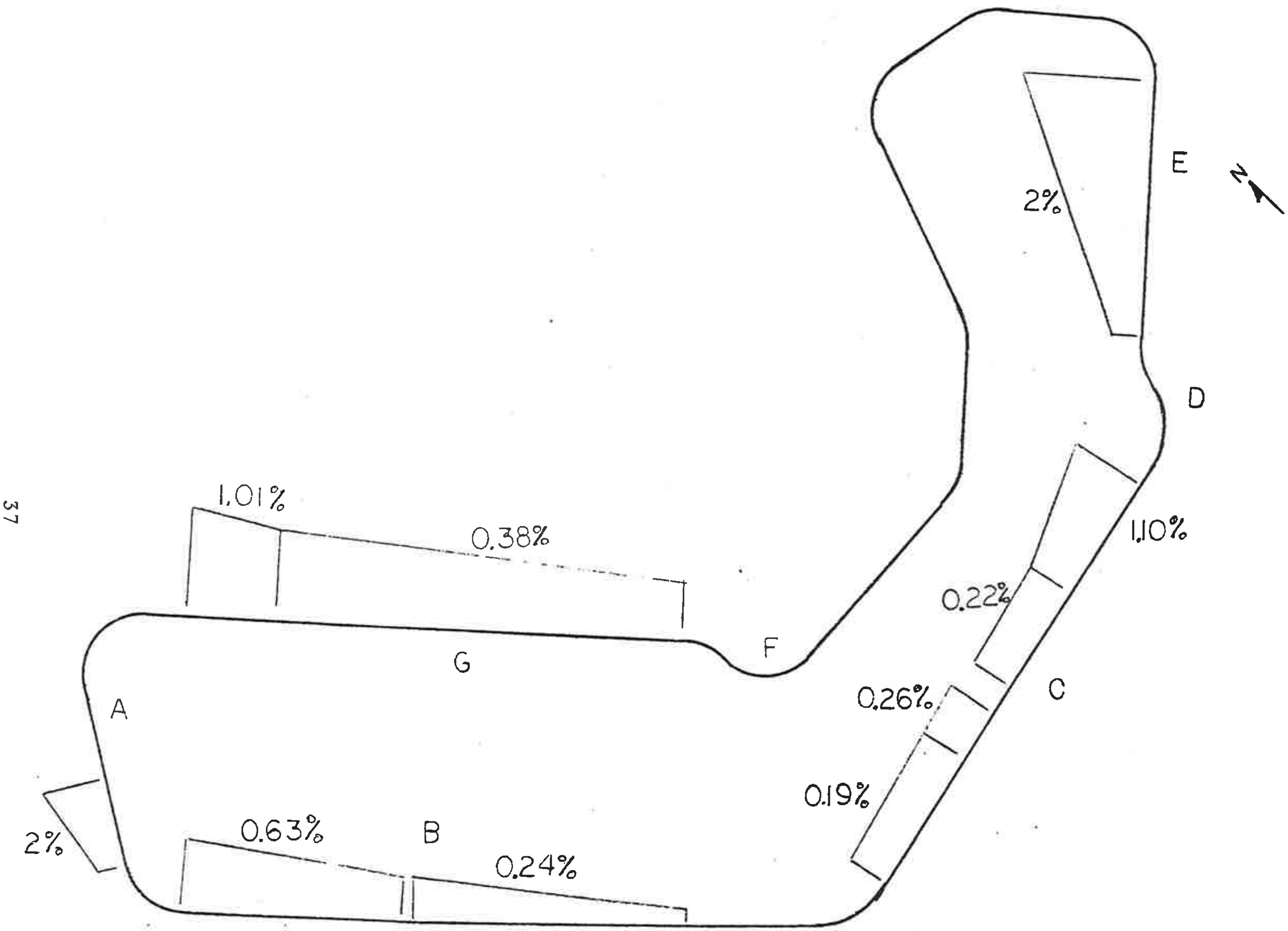


Figure 4-2. Map of LACF Monorail

counterclockwise from the station there is a short section of level rail, and then a 2% downgrade at the bottom of which there is a turn to the left which limits the safe speed on the downgrade. In area B there are two tangents, the first with a downgrade of 0.63%, the second with a downgrade of 0.24%. The slight curve between these tangents has a radius of 120 ft.

The curve entering tangent C has a 120 ft radius. In tangent C various sections have four different upgrades leading into an S bend at D having 120 ft radii. This S bend limits the speed entering the 2% upgrade in tangent E.

Between tangent E and S bend F the rail is nearly level. The two turns to the right have 120 ft radii. A long tangent at G provides two different upgrades. At the upper end of tangent G a turn completes the loop.

Most tests were made with the vehicle operating around the loop in the counter-clockwise direction. The vehicle was run in reverse for additional data. Maximum speed on the steep grades was limited by safety considerations because of turns at the ends of the grade.

4.3 Test Track Power Distribution System

A 3-phase, 460-V power rail is used on the LACF track to furnish power to the vehicles on the track. The type of rail used is commonly used to furnish power to electrically operated travelling cranes. Each of the three rails consists of a heavy copper bus within a U shaped insulating housing.

The open side of the U is down reducing the amount of moisture and dirt which can accumulate, and eliminating the probability of short circuits from falling objects. Each power rail is rated for 200 A. The three rails furnishing power are mounted in a horizontal line just below the upper flange of the running rail.

A substation located near the loading/unloading station provides power to the entire track. The substation includes overload protection in the event of a fault in the power rail or in the power collector of a vehicle.

4.4 Modifications to the Test Track

In the main loop between the unloading and loading stations there is a transfer device normally used to transfer LACF vehicles to a short spur where maintenance work can be performed while the remaining vehicles continue to carry passengers. The spur was lengthened so all LACF vehicles could be accommodated leaving the main loop unobstructed for testing the ECC vehicle. The main loop of the LACF monorail track used for the tests was not modified in any way.

5.0 Test Program Plan

A test program plan was prepared to assure systematic collection of data from which the performance of the ECC drive could be evaluated. Test objectives were specified, from which test procedures were prepared. Using the test procedures, lists of necessary test equipment and diagrams for connection of the equipment were prepared.

5.1 Test Objectives

A formal test program was planned to accomplish the following:

a. Measure vehicle performance at a number of gradually increasing speeds while running at constant speed. In testing to meet this objective it was recognized that vehicle performance on sharp curves and/or on grades might limit the ability to sustain the higher speeds on a complete circuit of the test track.

b. Measure vehicle performance under transient conditions including acceleration, deceleration, and grades.

c. Measure ride quality.

d. Perform a limited life test to identify parts with high failure rates.

5.2 Test Procedures

Three groups of tests were planned, for which test procedures were prepared. These groups were:

Propulsion System Tests and Power Tests

Temperature Stability Tests

Ride Quality Tests

Propulsion System Tests and Power Tests

a. Normal Speed Tests.

During the normal speed tests the vehicle was to be run around the loop at the preset speeds. If necessary for safety, the vehicle was to be slowed for curves. During the normal speed tests the operation of the variable speed propulsion system was to be observed and measurements were to be made of power, torque vehicle speed, and temperatures. The objective was to gain data on the acceleration, cruise and deceleration performance of the propulsion system.

b. Acceleration Tests.

Start the vehicle at the bottom or top of a grade and accelerate to a preset speed with the acceleration rate controlled by the torque limiting circuits of the controller. During these tests operation of the propulsion system was to be observed, and the performance parameters were to be recorded. The objective was to determine how well the torque limiting circuits operated, and to get data on accelerating rates under various grade conditions.

c. Deceleration Tests

With the vehicle cruising at different speeds and on different grades, come to a full stop. During these tests the operation of the eddy-current brakes was to be observed and the performance parameters were to be recorded. The objective was to determine how well the deceleration limiting worked during braking, how well the mechanical brakes took over as zero speed was approached, and to get data on decelerating rates.

Temperature Stability Tests

The purpose of these tests was to determine the temperature stability point of the propulsion system.

The vehicle was to make a circuit of the loop in a simulated trip profile when it entered the station, stop for 1 minute then run around the loop again. This sequence of:

leave station
run around loop
enter station
dwell for 1 minute
leave station again

was to be continued as many times as required until the temperature just before leaving the station was the same for two successive runs. Then one more run would be made to insure temperature stabilization.

The objective of these tests was to determine whether the temperature of any part of the variable speed propulsion system exceeded safe limits during sustained operation. In addition, these tests added operating time on the system to reveal overstressed components if they were present.

Ride Quality Tests

Ride quality data was to be taken to provide baseline data for future designs of monorail suspension systems.

5.3 Instrumentation

The instruments listed below were selected and used for the tests.

Parameter to be Measured	Instruments
Torque	Lebow Model 1604-K2 Rotating Shaft Torque Sensor mounted in the drive shaft, used with a Daytronics Model 878 A Strain Gage Conditioner-Amplifier Module.
Temperature	Yellow Springs Instrument Co., Type YSI-705 Air Temperature Probes and Type YSI-709 Attachable Surface Temperature Probes, used with Daytronics Model 815 Thermistor Conditioner-Amplifier Modules.

Watts	Trans Data Inc., Model 20WS101 Watt Transducer, to be used with Westinghouse Type EMP Potential Transformers and Westinghouse Type EC1 Current Transformers.
Vars	Trans Data Inc., Model 20RS101 Vars Transducer, to be used with the instrument transformers listed above.
Line Voltage	Trans Data Inc., Model 10PS101 Voltage Transducer, to be used with the potential transformers listed above.
Line Current	Trans Data Inc., Model 10CS101 Current Transducer, to be used with current transformers listed above.
Vehicle Speed	Recorded from the tachometer output of the Lebow Torque Sensor, used with Daytronics Model 840 Frequency to Voltage Converter Module.
Demand Speed Clutch Field Current Eddy Current Brake Field Current	Recorded from sampling resistors built into the controller.
Recorders	Brush Model 260 Recorder and Consolidated Electrodynamics Corp. Recording Oscillograph Type 5-124.
Ride Quality	DOT-TSC Ride Quality Package

Performance specifications for these instruments are listed in Appendix A. The diagram of Fig. 5.1 shows the method of interconnecting the instruments and the circuits of the propulsion system.

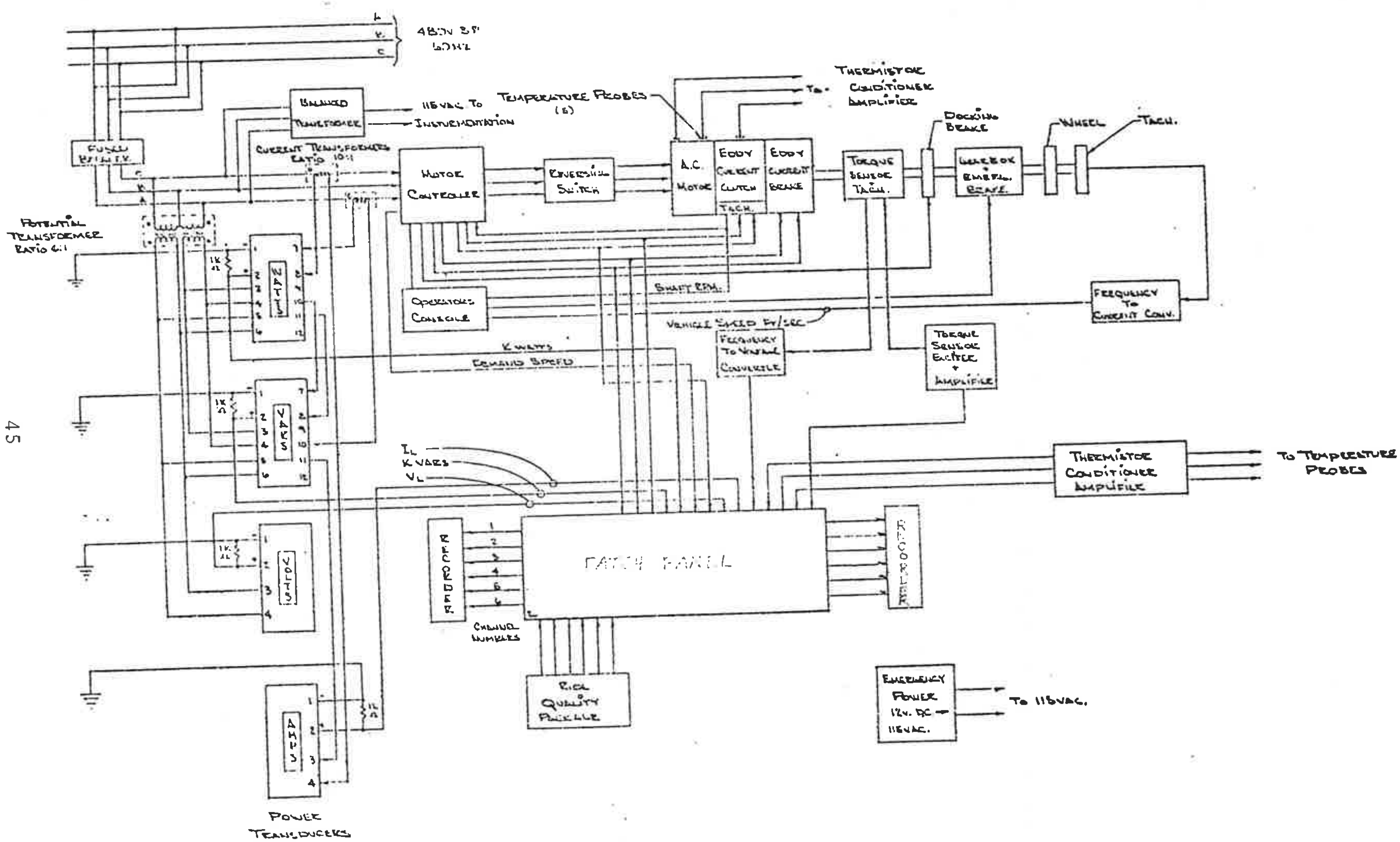


Figure 5-1. Vehicle Control Circuits and Instrumentation

6.0 Test Program

The test plans described in Section 5 of this report were followed quite closely in the actual tests. The tests are described below.

6.1 Preliminary Tests

The operator's console was designed to enable the operator to select any of four preset speeds. Prior to the preliminary test the console was modified to enable the operator to change the setting for Speed 1 while moving. This made a variable speed available for maneuvering the vehicle. Speed 2 was preset for 12 fps; Speed 3 for 16 fps; and Speed 4 for 21 fps.

During the preliminary tests the speed settings were verified using the independent speed display operated from the tachometer on the bogie wheel as a standard. At the same time the recorder channel for the four speeds was calibrated.

The transducers and recorder channels for watts, vars, current and voltage were also calibrated using laboratory standard instruments.

When calibrations had been completed several runs were made at each speed to confirm that data could be repeated under identical conditions. The repeatability was confirmed so formal testing commenced.

6.2 Propulsion System Tests and Power Tests

A series of test runs were conducted on July 25, 1973 for measurements of propulsion system performance and power demand. These tests were observed by representatives from the DOT Transportation Systems Center, Cambridge, Mass. Preliminary calculations were made at intervals during the runs to verify the data.

Run 1

This run was made at a speed of 16 fps with two people in the vehicle providing a gross weight of 9000 lbs as planned. It was not possible to maintain the planned speed through the two S bends in the track. The recordings of motor temperature, real power, reactive power, line current, vehicle speed and drive shaft torque for Run 1 are included in Appendix B.

Run 2

This run was a repeat of Run 1. The recorded data was nearly identical except motor temperature which was slightly higher at the start of the run.

Run 3

This run was made at 16 fps with five people in the vehicle making the gross weight about 9500 lbs, i. e., 500 lbs greater than planned. Results were very similar to Run 1 except there were less points with wheel slip on the S bends and on the 2% upgrade. These data recordings are in Appendix B.

Run 4

This run was a repeat of Run 3 and provided similar data.

Run 5

This run was made at 12 fps with 2 people on board. It was found impossible to maintain this speed through the S bends. The chart is in Appendix B.

Run 6

This run was a repeat of Run 5.

Run 7

This run was made at 16 fps with 3 people on board.

Run 8

This run was a repeat of Run 7.

Run 9

This run was made at 12 fps with 3 people on board. A faster chart speed was used to expand the time scale of the recording.

Run 10

This run was a repeat of Run 9.

Run 11

Prior to this run the recorder connections were changed at the patch panel to provide data on line-to-line voltage on the same chart with power data and propulsion system performance. A run was made at 16 fps with two people on board while voltage calibration vs. voltage recording was verified.

Run 12

This run was made with 2 people on board using the expanded time scale on the recorder. A speed of 12 fps was used on the steep grade leaving the station and around the first turn. A speed of 21 fps was then commanded resulting in a short period of cruising in tangent B before the vehicle was slowed to 16 fps as it approached the turn to enter tangent C. The speed was left at 16 fps until tangent G was entered when the vehicle was again accelerated to 21 fps. The vehicle was slowed for the turn entering the station.

Run 13

This run was a repeat of Run 12.

Run 14

The vehicle was positioned at the top of the grade on tangent G. It was then accelerated to 12 fps downgrade by operating the vehicle in reverse, i.e., operating in the clockwise direction on the track. The vehicle was slowed and stopped at the bottom of the grade before entering the S bend at F. The vehicle was then run back up the grade accelerating to 12 fps. The downgrade-upgrade cycle was then repeated at 16 fps. The cycle was then repeated again with a speed command of 21 fps. On the downgrade brakes were applied as soon as the speed reached 21 fps. Tangent G of the test track was too short to get complete data on upgrade acceleration to 21 fps. When a speed of 20 fps had been reached the operator applied the brakes to avoid entering the turn at the top of the grade at excessive speed.

Run 15

This run was a repeat of Run 14. The chart from Run 15 is in Appendix B.

6.3 Thermal Stability Tests

Tests were continued on July 26, 1973. Two additional runs were made during which power measurements were repeated at 12 fps and 16 fps.

A review of temperature data taken during the runs on July 25 had revealed that the exhaust air temperature was the most responsive indicator of heat losses in the variable speed propulsion system. The data also suggested that the heat losses would be greatest at lower speeds.

The motor was shut down for a period of 20 minutes before the thermal stability tests were started. At that time the temperature of the exhaust air showed 22° C and the case 24° C, i.e., both were effectively at ambient temperature.

The motor was started, and the vehicle started less than five seconds later with a command of 12 fps which was maintained throughout the run. The exhaust air temperature increased to 62° C at the top of the 2% grade, cooled some, and reached a second temperature peak of 56° C entering the station.

The vehicle was stationary in the station for 69 seconds with the motor running during which time the exhaust air temperature stabilized at 45° C. In a second run at 12 fps the temperature reached 66° C at the top of the 2% grade and was 58° C entering the station.

During a dwell in the station of 75 seconds the exhaust air stabilized at 37° C. The third run at 12 fps showed 62° C at the top of the 2% grade and 54° C entering the station. Both these temperatures were slightly lower than the previous run suggesting that temperature conditions had stabilized.

6.4 Ride Quality Tests

Ride Quality Testing was done during the week of June 18, 1973. The data on ride quality were taken using a Ride Quality Package which was designed and constructed at DOT Transportation Systems Center, Cambridge, Mass. The Ride Quality Package is an assembly of three linear accelerometers on axes at right angles, and three rotational accelerometers on the same axes. The Package includes a Hewlett-Packard 3960 FM tape recorder on which three channels are used for simultaneous recordings from any of the accelerometers. A fourth channel in the recorder was used to record comments by the operator during tests.

The Ride Quality Package was installed in the test vehicle on the floor in the center of the vehicle. The Package was mounted with the X axis fore and aft in the vehicle, the Y axis from side to side and the Z axis vertical.

For these tests, Speed 1 was preset for a speed of 6 fps; Speed 2, 11 fps; Speed 3, 16 fps and Speed 4, 22 fps. Four runs were made around the entire test track, one with each speed setting while linear accelerations were recorded. The vehicle speed was reduced at turns when operating at 22 fps.

After changing recorder connections, four additional runs were made around the test track while angular accelerations were recorded at each speed.

The data were returned to DOT-TSC for analysis.

7.0 Data Analysis

The data taken during each of the test runs were used to prepare graphs showing the performance of the propulsion system. Typical recordings made during the tests are reproduced in Appendix B. The recordings reproduced were made with the Brush Recorder. The recordings from the optical recorder are similar.

7.1 Operation While Vehicle is Stationary

The motor of the variable speed eddy current clutch propulsion system continues to run while the vehicle stops at a station to unload or load passengers. During these stops the motor has no load except the fan on the motor shaft. The test data show the motor draws 1.4 kW of real power and 9.3 kvar of lagging reactive power or 9.5 kVA at a power factor of 0.147.

7.2 Operation at Constant Speeds

In Fig. 7.1 the real power, reactive power, apparent power and power factor of the variable speed eddy current clutch propulsion system are shown for a cruising speed of 12 fps for different grades. Apparent power and power factor were calculated from the recorded values of real power and reactive power. The data show a discontinuity at a downgrade of about 1.9%. This is the grade at which the vehicle will maintain 12 fps without power from the propulsion system. At downgrades steeper than 1.9% braking must be used if speeds are not to exceed 12 fps.

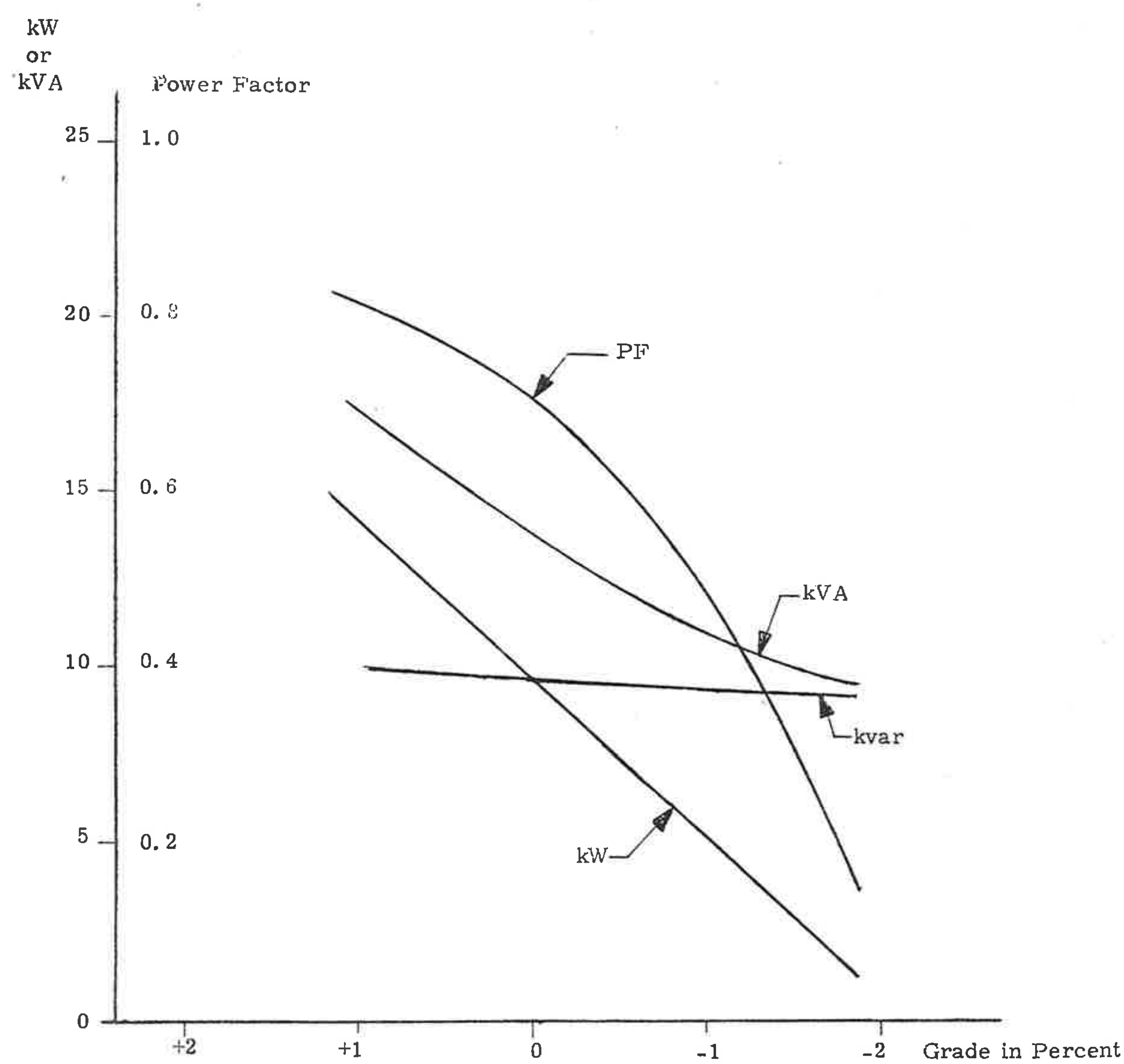


Figure 7-1. Input Power Characteristics for Cruising at 12 Feet/Second Vs. Grade

Similar data at a constant speed of 16 feet/ sec is shown in Fig. 7.2. The curves of input power do not show a discontinuity since the vehicle required power to maintain this speed even on the 2% downgrade. There was limited operation of the vehicle at 21 feet/ sec and no sustained operation on the steeper grades. The power characteristics for the 21 feet/ sec operation are shown in Fig. 7.3.

From the test data the mechanical power transferred by the drive shaft was claculated using drive shaft torque and drive shaft speed data. The mechanical power in the drive shaft was compared with the electrical power imput to determine the efficiency of the variable speed edd eddy current clutch propulsion system. The efficiency while operating at constant speeds of 12 feet/ sec, 16 feet/ sec, and 21 feet/ sec are shown in Fig. 7.4. The drive shaft torque under these same conditions is shown in Fig. 7.5

In Fig. 7.6 the efficiency of the eddy current clutch propulsion system during constant speed cruising is shown as a function of vehicle speed for various grades.

7.3 Operation During Acceleration

The controller for the variable speed eddy current clutch propulsion system included circuits to limit the torque on the drive shaft during acceration.

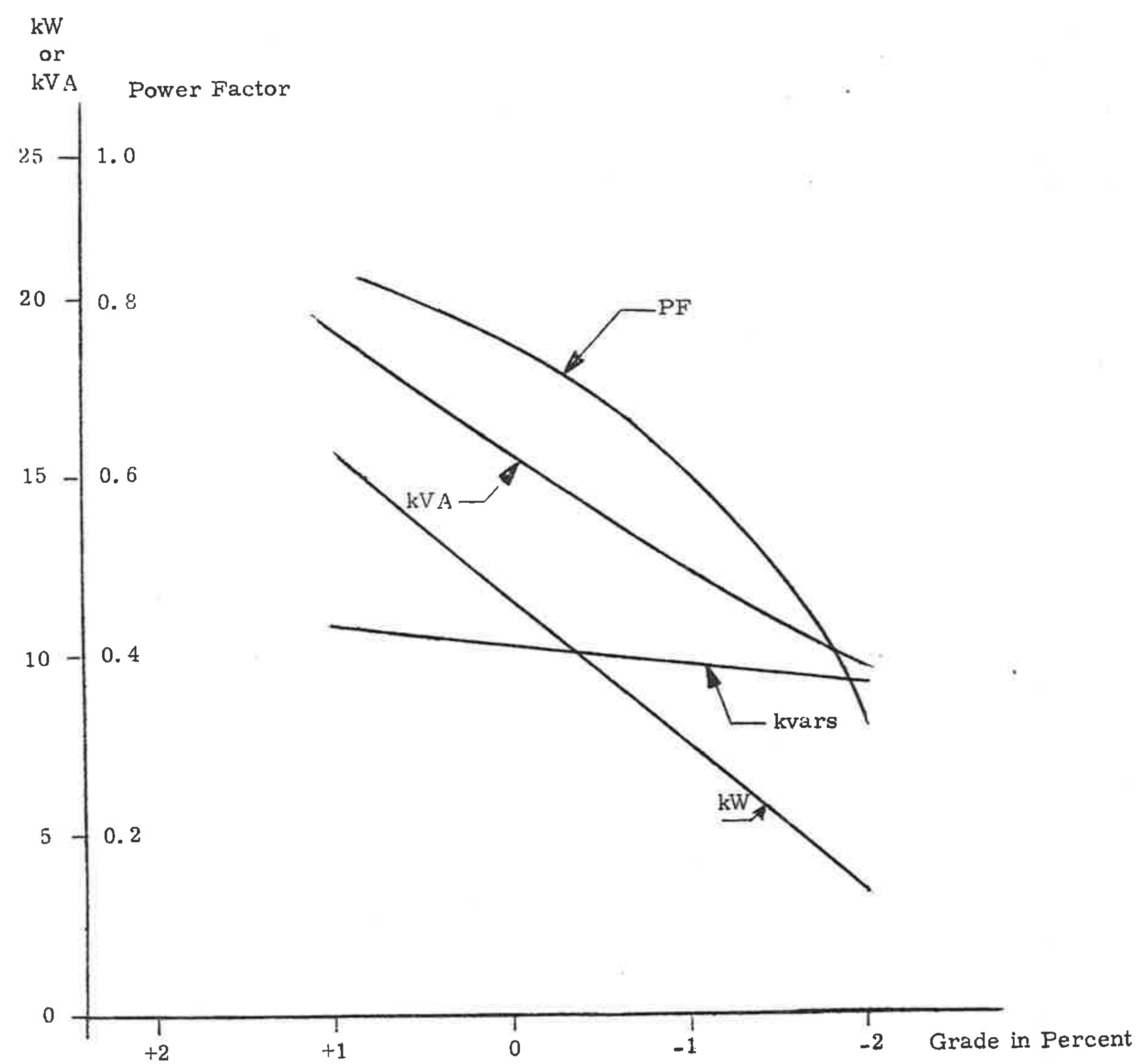


Figure 7-2. Input Power Characteristics for Cruising at 16 Feet/Second Vs. Grade

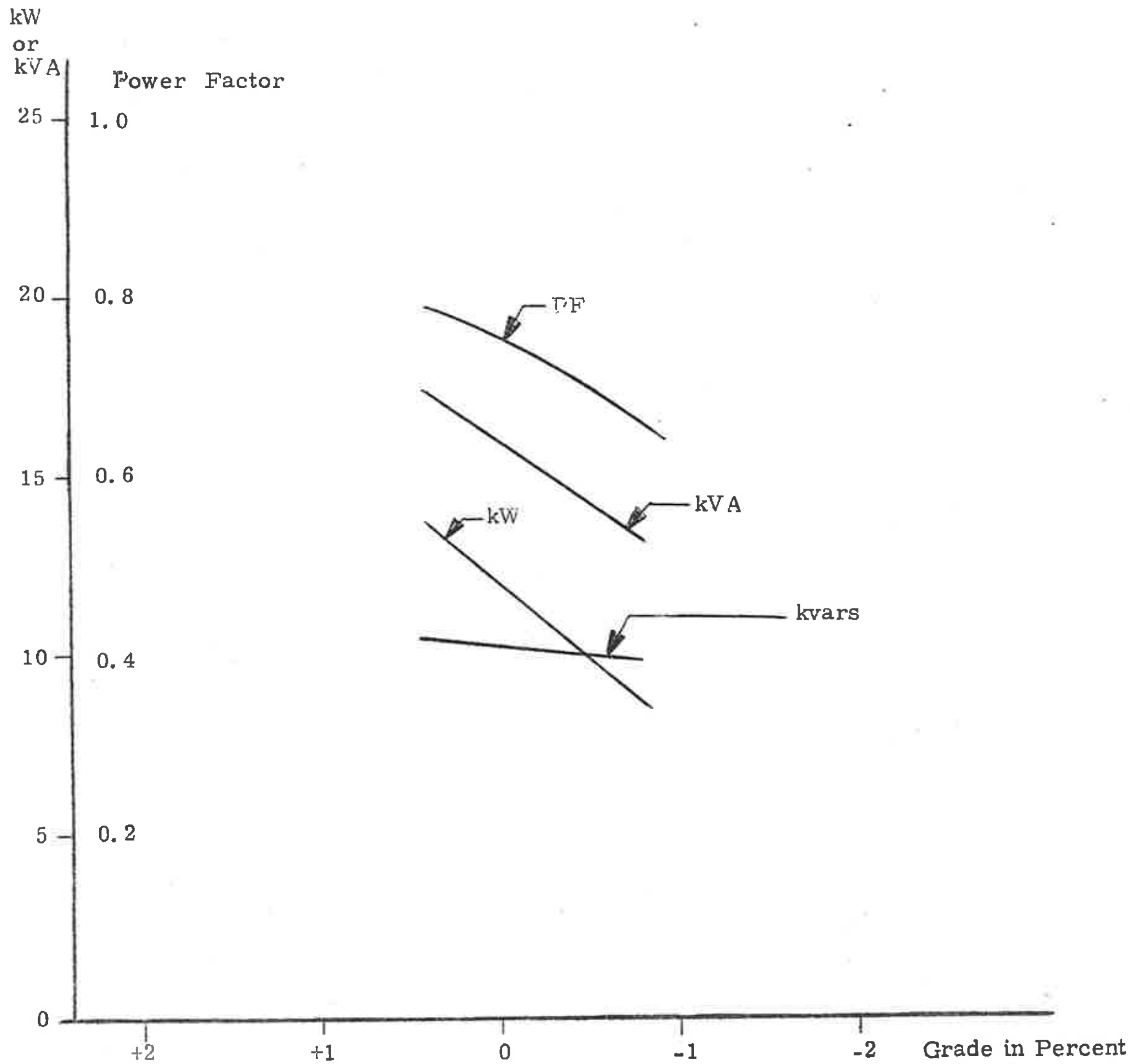


Figure 7-3. Input Power Characteristics for Cruising at 21 Feet/Second Vs. Grade

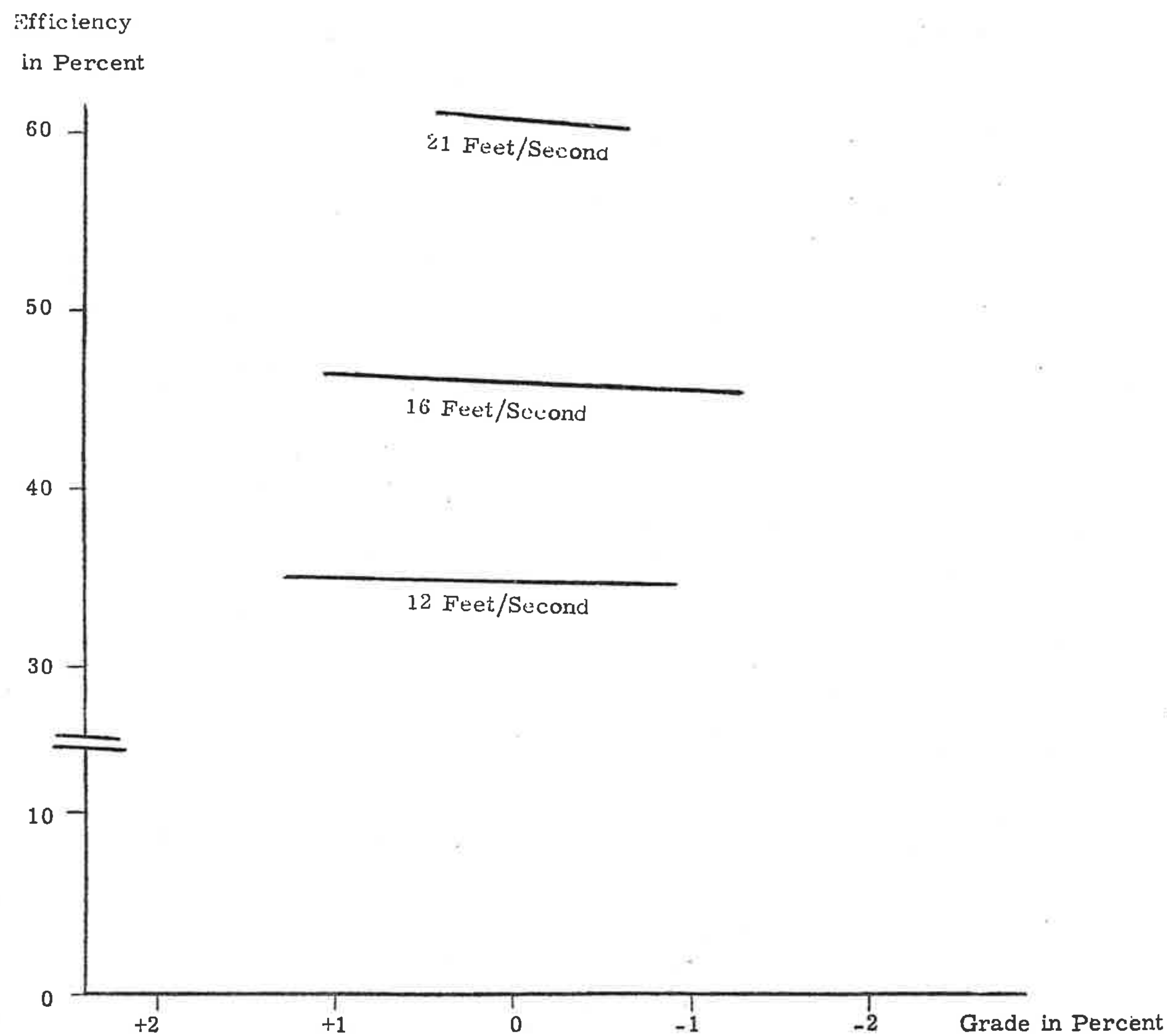


Figure 7-4. Cruise Efficiency Vs. Grade

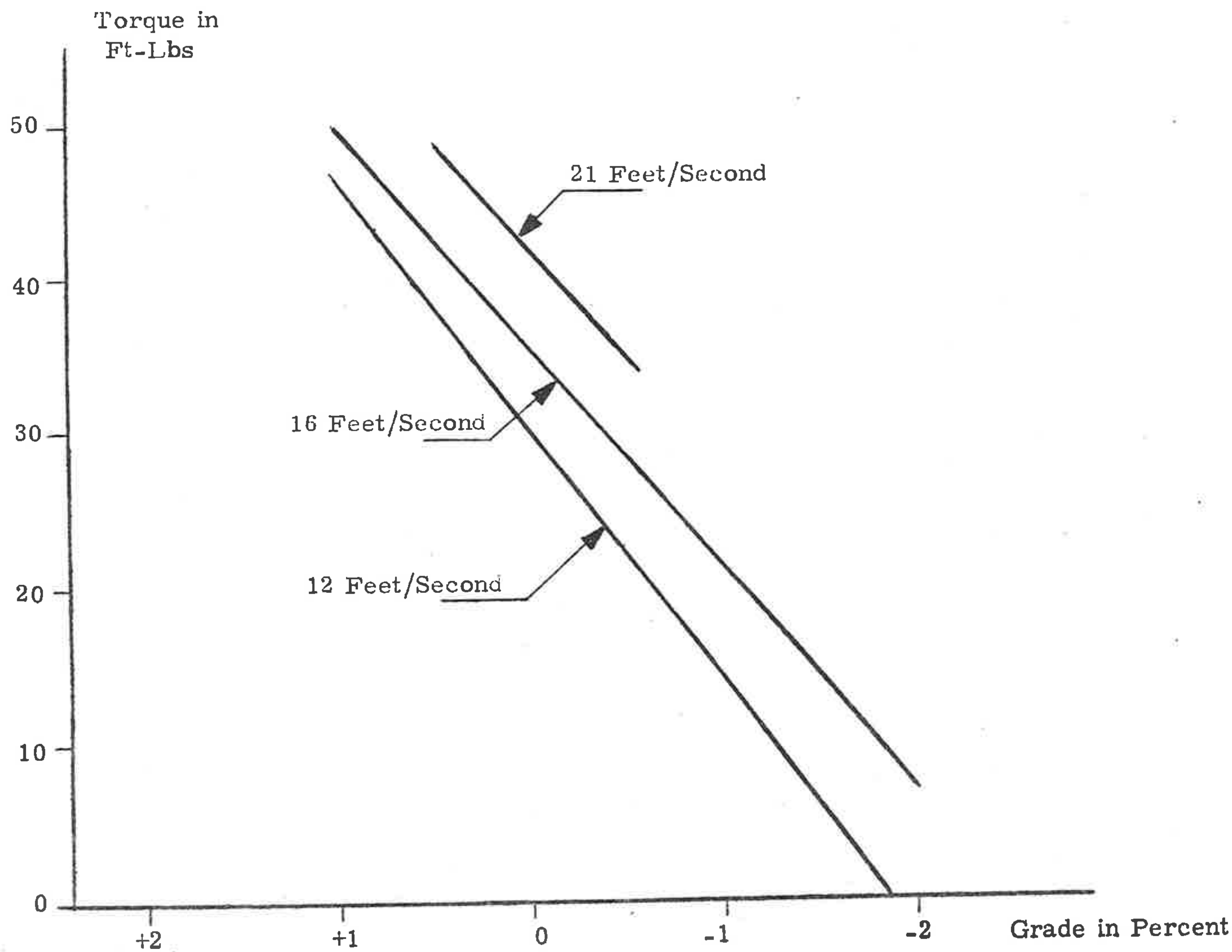


Figure 7-5. Drive Shaft Torque for Cruising Vs. Grade

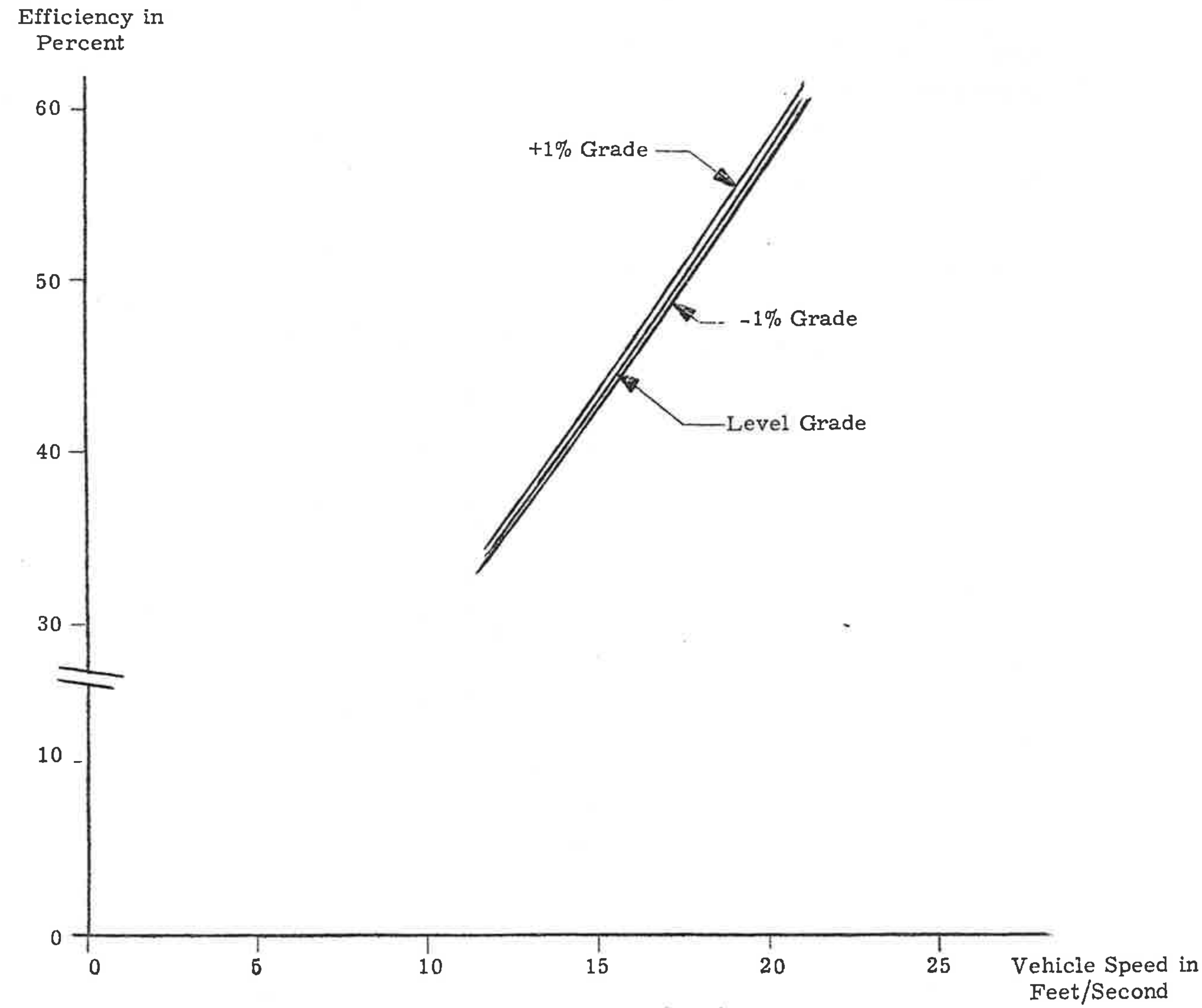


Figure 7-6. Cruise Efficiency Vs. Vehicle Speed

During the tests all accelerations were torque limited except when using manual control in the Speed 1 position. Charts have been prepared showing the performance of the variable speed eddy current clutch propulsion system during these torque limited accelerations.

The test data show that the drive shaft torque during torque limited conditions was very nearly independent of speed. The measured values of torque at different speeds are shown in Fig. 7.7.

Fig. 7.8 shows the measured values of acceleration under torque limited conditions as a function of grade.

During torque limited acceleration at a particular vehicle speed the motor operates with the slip speed necessary to produce the desired torque. The eddy current clutch operates at the same torque, with a slip speed equal to the difference in motor shaft speed and drive shaft speed. This means the operating conditions for the eddy current clutch propulsion system during torque limiting will be the same for a given vehicle speed even though the grade may differ.

In Figs. 7.9 and 7.10 the input power characteristics during torque limited acceleration is shown for two different grades.

The power required to accelerate is independant of the ultimate desired speed. This is shown in Fig. 7.11 for three different cruise speeds.

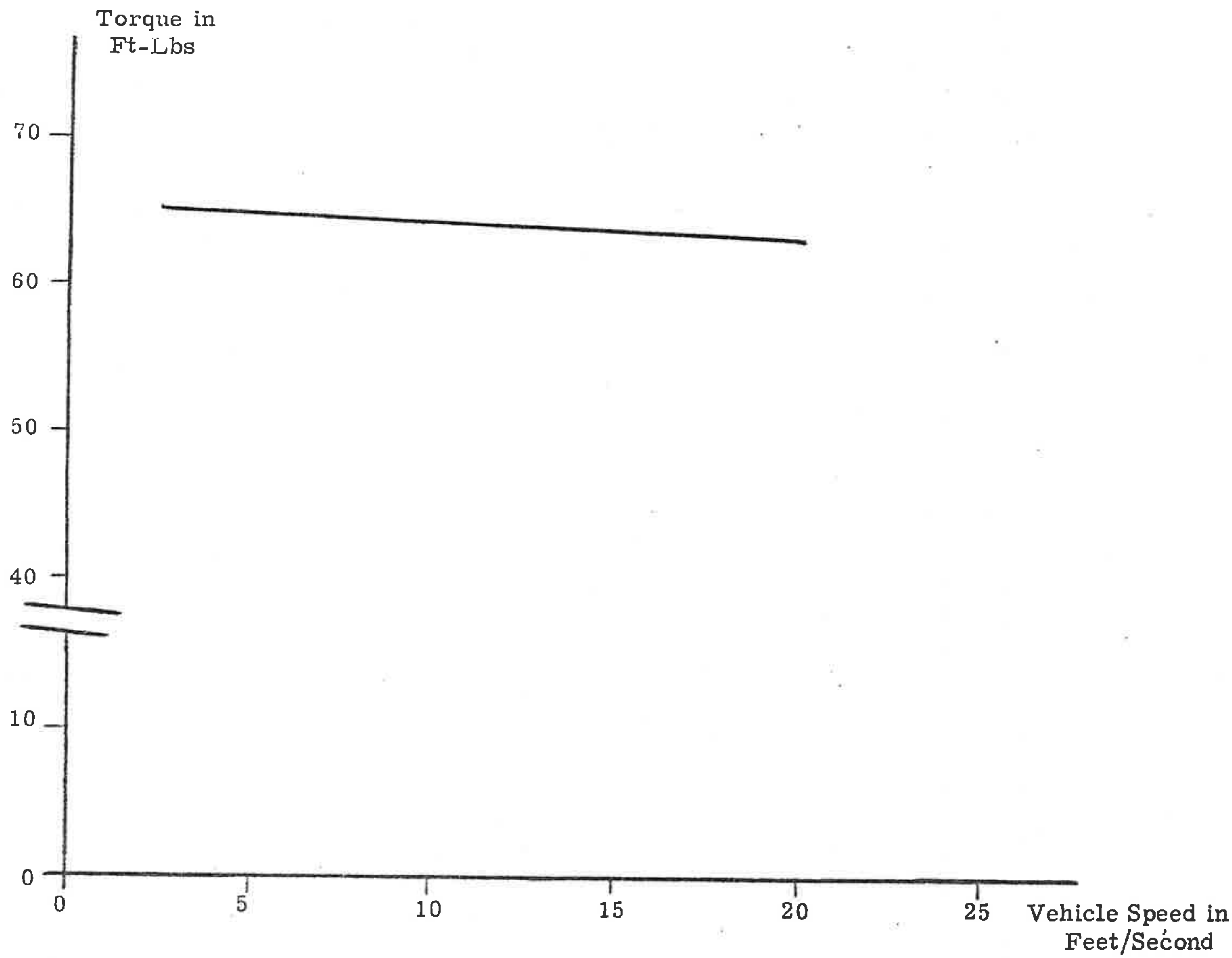


Figure 7-7. Drive Shaft Torque During Maximum Acceleration Vs. Grade

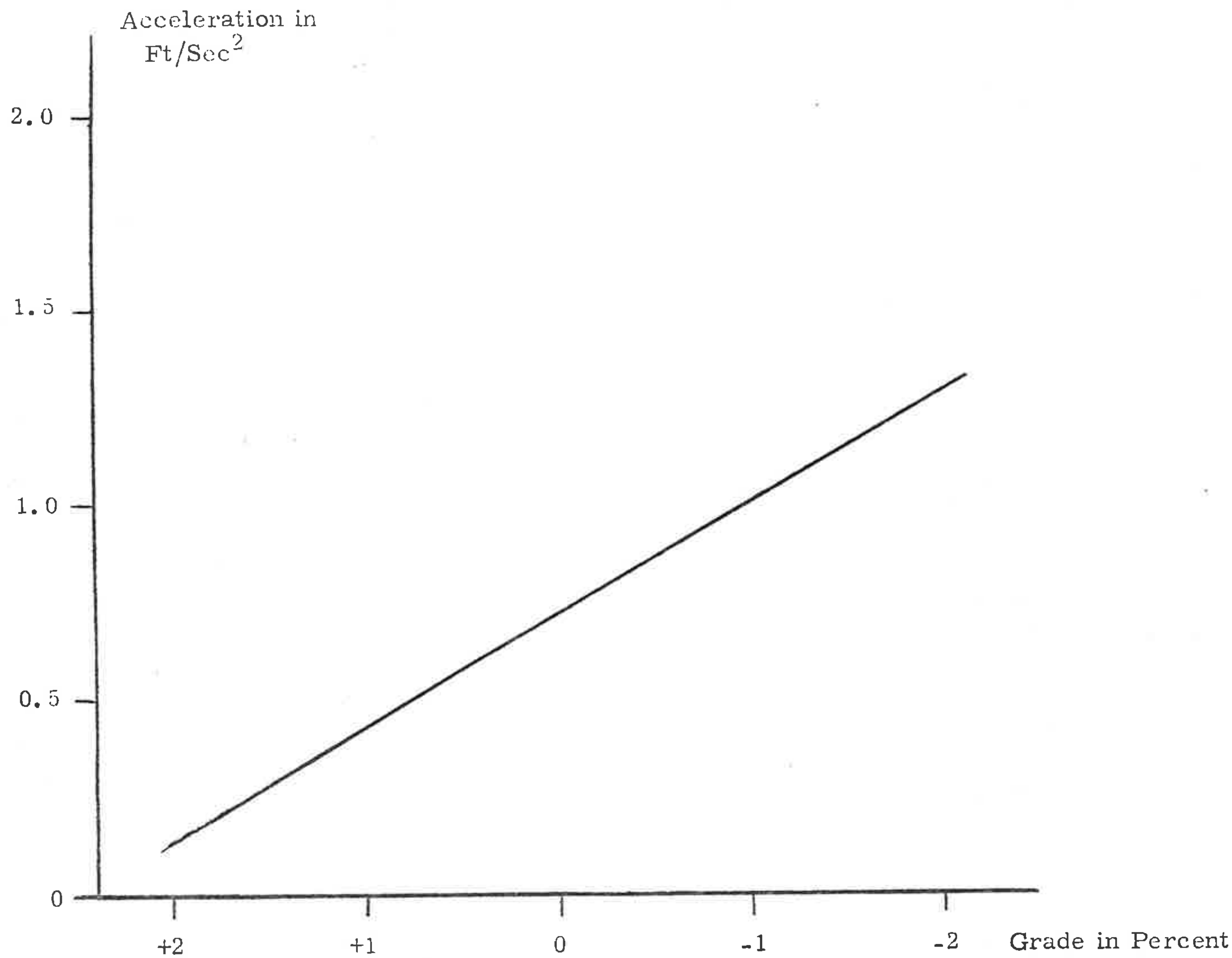


Figure 7-8. Maximum Acceleration Vs. Grade

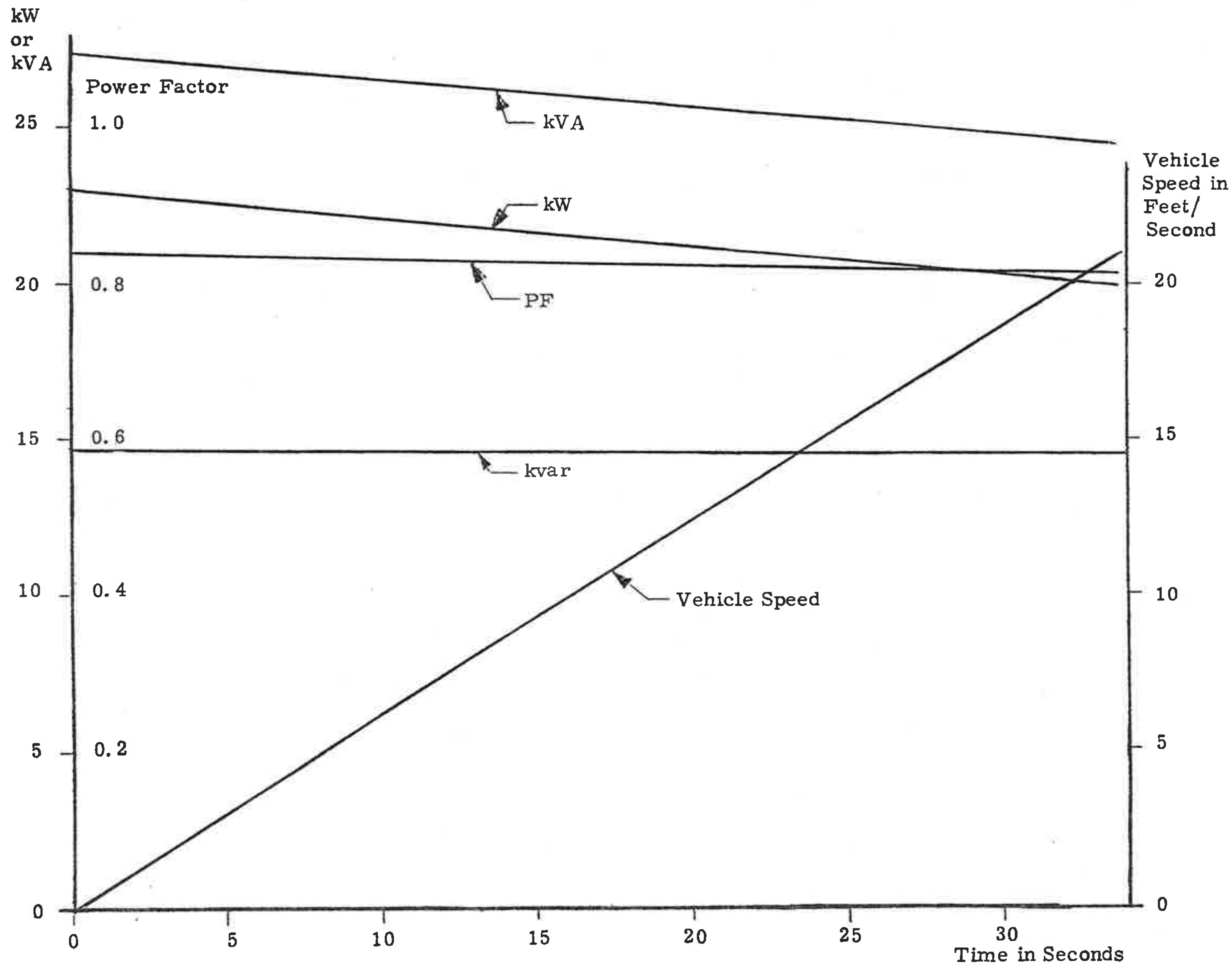


Figure 7-9. Input Power Characteristics During Acceleration on 0.38% Upgrade

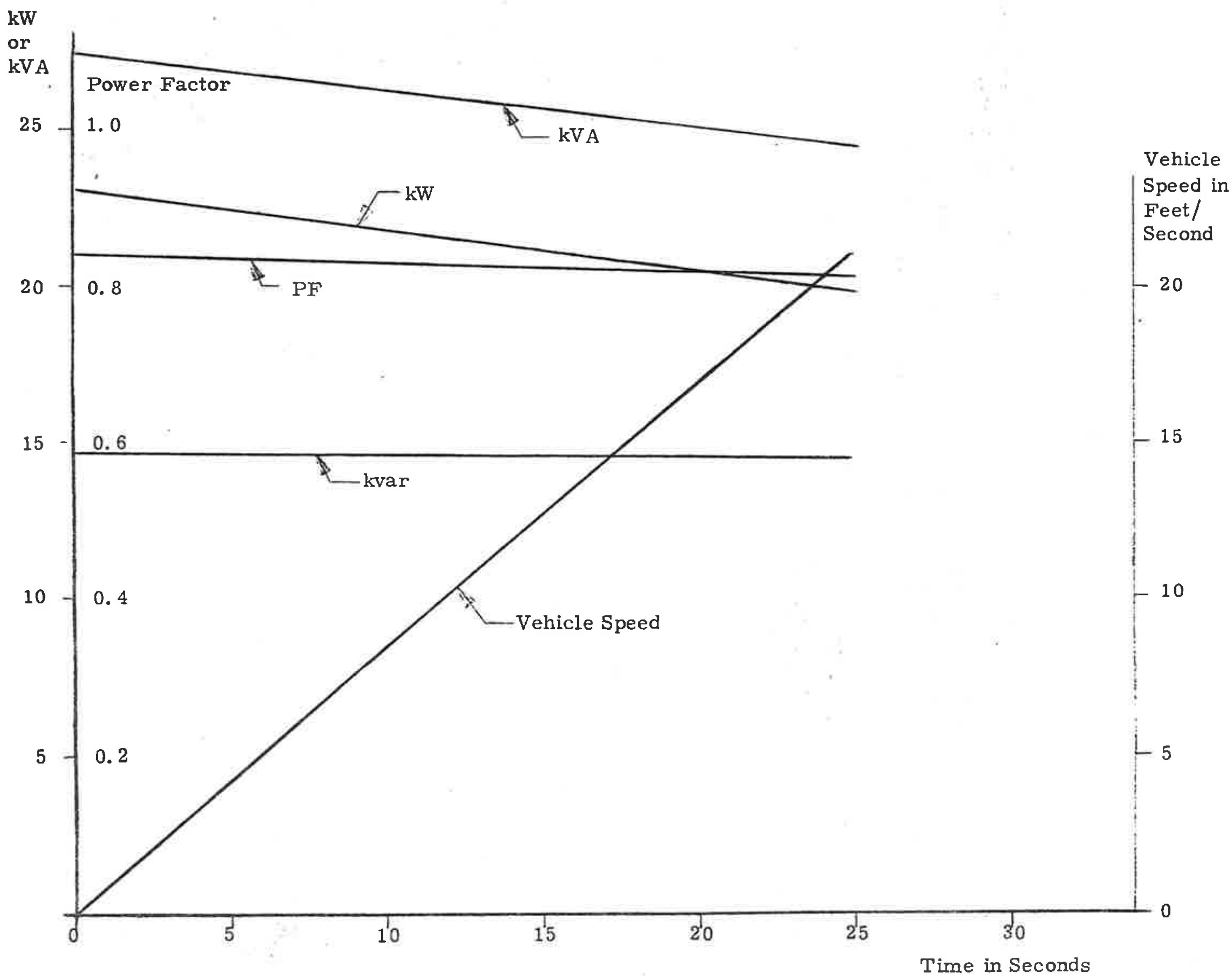


Figure 7-10. Input Power Characteristics During Acceleration on 0.38% Downgrade

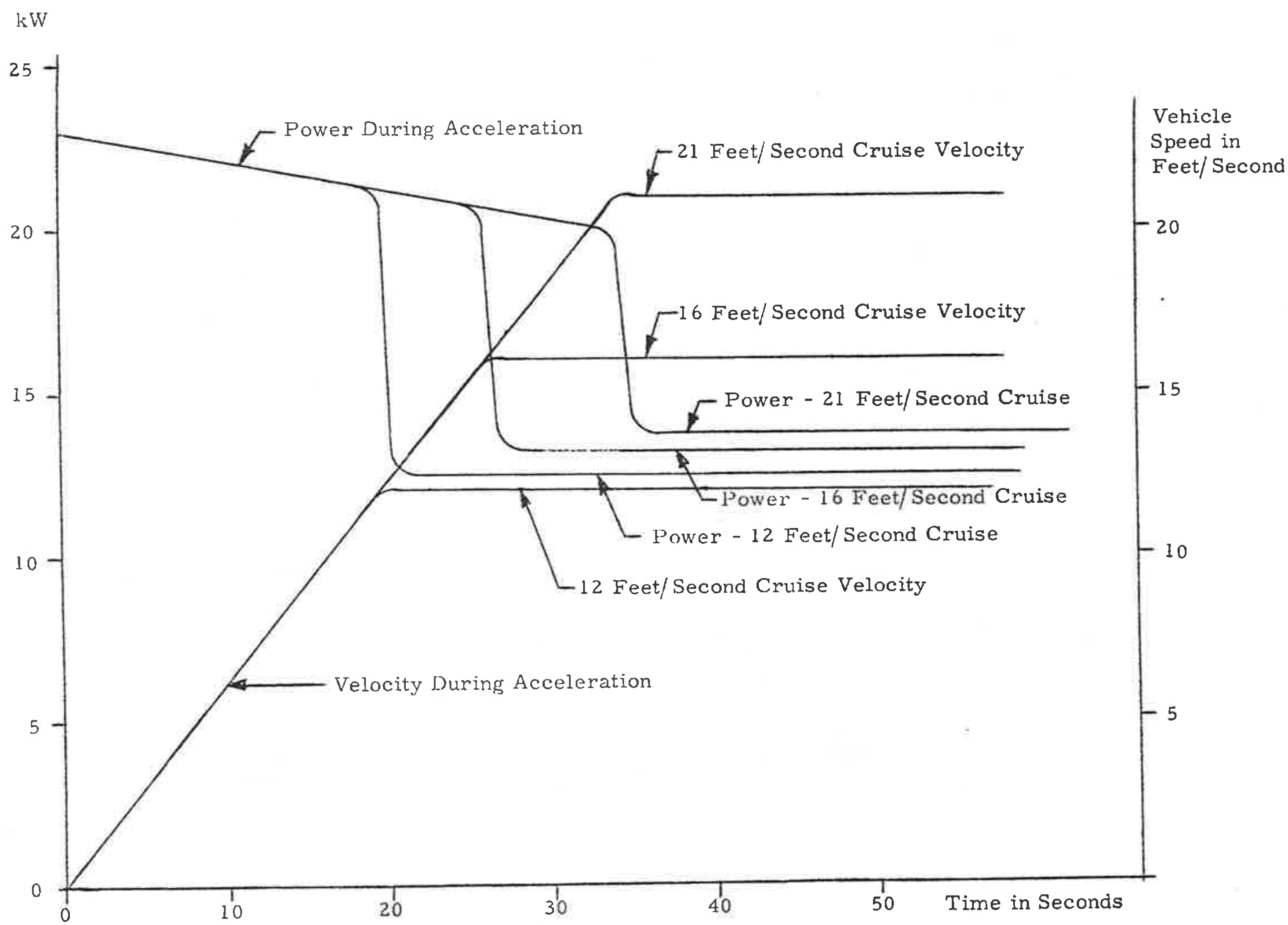


Figure 7-11. Power for Acceleration and Cruise on 0.38% Upgrade

7.4 Operation During Deceleration

The test data show that constant deceleration rates were achieved when stops were ordered. Fig. 7.12 shows performance during a typical stop. During the stop the motor draws only enough power to operate the fan. As indicated in the figure, the mechanical brakes were applied at a speed just under 4 fps.

7.5 Thermal Conditions

The fan in the propulsion system draws air through the motor, then exhausts it through the eddy current clutch. Temperature probes were located on the case of the propulsion system and in the exhaust air stream. An examination of the test data shows the air is very effective in providing cooling. Case temperature was always within 5° C of ambient. Exhaust air temperature changed very quickly as the losses in the propulsion system changed. Typical exhaust air temperature data is shown in Channel 1 of several recordings in Appendix B.

The temperature data show that sustained operation at low speed with high losses in the eddy current clutch produces the highest exhaust air temperature. The highest exhaust air temperature recorded was 76° C during Run 9 on July 25. This occurred at the top of the long upgrade on Tangent G after a sustained run at 12 fps. Ambient temperature that day started at 23° C and became 43° C near midday when Run 9 was made.

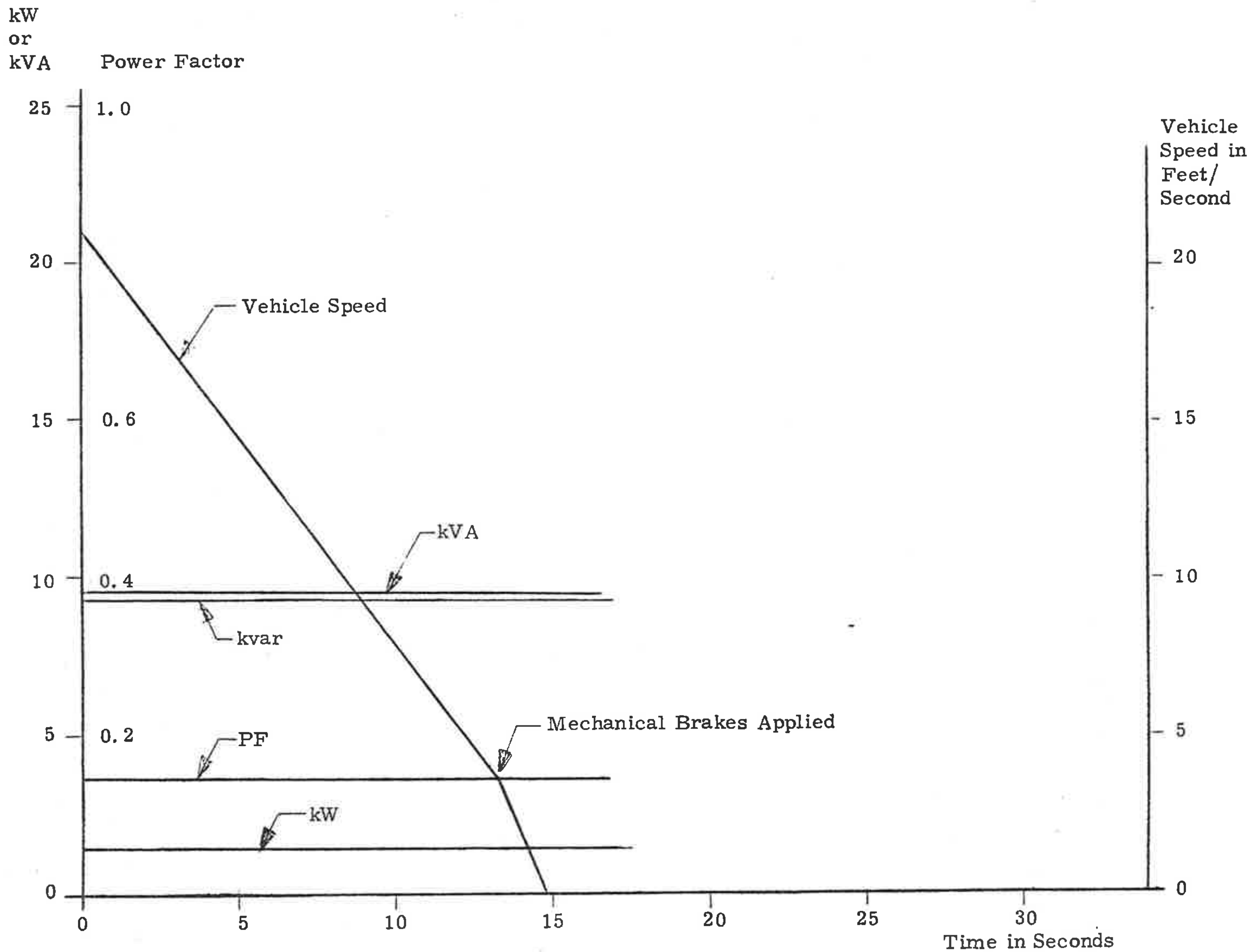


Figure 7-12. Input Power Characteristics During Deceleration

The effectiveness of the air in removing heat can be seen in the data where exhaust air temperature decreases at rates of over $1^{o}C$ per second after loads are removed.

7.6 Life Testing

A life test which would simulate the use of the variable speed eddy current clutch propulsion system in commercial operation of a vehicle was not planned. Records were kept during the preliminary tests, steady state and acceleration power tests and the thermal stability tests to determine whether there were parts subjected to overloads which could cause an unacceptable life expectancy.

During the tests over 1200 separate runs of the vehicle were made. These runs required a total of 306 hours operation of the propulsion system. There were no component failures in the propulsion system. None of the components operated under stresses which would reduce life expectancy.

7.7 Ride Quality

The vehicle contained four speed select switches corresponding to speeds 6, 12, 16 and 21 ft/sec. During run 1, the speed of 6 ft/sec. was chosen and the following data were recorded:

(1) Linear Acceleration - X Axis	Channel 1
(2) Linear Acceleration - Y Axis	Channel 2
(3) Linear Acceleration - Z Axis	Channel 3
(4) Voice Annotation	Channel 4

During runs 2-4 similar data were recorded for speeds of 11, 16 and 22 ft/sec, respectively.

There were several different types of vehicle maneuvers (corresponding to guideway sections) including negotiation of left and right curves, S-curves, and climbing a 5% grade. It should be noted that the speed of 22 ft/sec was too rapid to permit the vehicle to negotiate the curves. The speed setting of 16 ft/sec was the only speed selected which could be maintained during all maneuvers throughout the run.

Test runs 5 through 8 employed vehicle speed of 6, 12, 16 and 21 ft/sec, respectively. During these runs angular acceleration data were recorded in the X, Y and Z axes on channels 1-3, followed by a voice annotation on channel 4.

The frequency range of the linear accelerometers was 0 to 500 cps and the frequency range of the angular accelerometers was 0 to 30 cps.

Frequency analysis was performed upon the linear acceleration data for the values 0 to 100 Hz. Results indicate that the linear X, Y and Z axes have highly dissimilar spectra, but all 3 axes show concurrent peaks at certain restricted frequencies (29-30 Hz and 59-60 Hz). The 29-30 Hz activity is always present - even when the vehicle is idling. Furthermore, the 29-30 Hz linear acceleration is largest in the Y-axis and increases with vehicle speed. From the graphs it becomes apparent that the type of maneuver is not a critical factor at speeds below 12 ft/sec; that is, the frequency spectrum does not vary as a function of vehicle maneuver at low speeds. As would be expected, the X-axis acceleration is influenced most by maneuvers. In addition, the lowest overall activity of the three axes appears in the X-axis, and X-axis activity practically disappears in the high frequencies. As evident from the graphs, there is very little activity (either high frequency or low frequency) in the X-axis at low speeds.

The spectral analyses of the Y- and Z-axis appear similar to one another; however, higher overall activity takes place in the Z-axis. There is very little low frequency activity in the X-axis.

Overall amplitude of the frequency curves increases as vehicle speed increases, however, frequency amplitudes of the Z-axis increase more rapidly with increases in speed than do the frequency amplitudes in the X and Y axes. X-axis activity, in contrast, shows little increase with speed, but does appear to show slight change as a function of type of vehicle maneuver.

From examination of the spectral analyses of the angular acceleration, it becomes apparent that most of the low frequency acceleration takes place in the X-axis (roll) - at least for lower speeds of 12 ft/sec or less. At these lower speeds the Y-axis (pitch) and the Z-axis (yaw) appear similar, both showing a low overall level of activity, but with similar peak acceleration occurring at 29-30 Hz and 59-60 Hz. At higher speeds (16 ft/sec and 22 ft/sec) the Y-axis and Z-axis show more activity, displaying especially high frequency amplitudes in the region of 20-30 Hz. Finally, angular acceleration frequencies do not change markedly as a function of vehicle maneuver.

For the linear data then, most of the low frequency acceleration takes place in the Y-axis, while for the angular data, most of the low frequency acceleration takes place in the Z-axis, while for the angular data, no frequencies were recorded above 30 Hz.

A second type of data analysis was performed in the acceleration data collected during test runs of the monorail vehicle. This work consisted of plotting graphs of acceleration values within certain frequency ranges (0 to 10, 10 to 20 and 20 to 30 Hz). These acceleration values were then continuously differentiated and a graph of the derivative or jerk was made for each of the acceleration frequency intervals (0 to 10, 10 to 20 and 20 to 30Hz), during various speeds and maneuvers of the vehicle. Graphs were plotted from analysis of both linear and angular acceleration data. These graphs showed clearly that as the frequency of acceleration increased, the values of jerk also increased. The overall amplitude and frequency of jerk was greatest in the Z-axis. In comparison, the amplitude and frequency of jerk present in the Y-axis was slightly less than that occurring in the Z-axis, and the frequency and amplitude of jerk present in the X-axis was much less than that occurring in either the Y- or Z-axis. In general, the higher speed of the vehicle, the more jerk is present in all axes.

Particular interest centers in the occurrence of jerk in the low frequency acceleration (0 to 10 Hz interval) since jerk occurring in these low frequency intervals has been found to be particularly annoying to human subjects and to markedly increase subjective ride discomfort. Analysis of low frequency (0-10 Hz) acceleration data revealed that very little jerk was present in the X-axis at acceleration frequencies of 0 to 10 Hz, and that most of the acceleration and jerk above 20 Hz is found in the Z-axis.

Further analysis was performed on recordings of linear acceleration in all 3 axes as the vehicle accelerated from a standing start up to a speed of 16 ft/sec. Similar to results discussed previously, the analysis showed that most of the acceleration components in the 0 to 10 Hz range are in the Z-axis, fewer are in the Y-axis, and very few are in the X-axis. Consequently, most of the jerk in the low frequency acceleration range 0 to 10 Hz takes place in the Z-axis. Acceleration takes place uniformly in the X-axis in the 10 to 20 Hz range. There are, however, few acceleration components in the X-axis above 20 Hz or below 10 Hz. Finally, the values for jerk increase roughly in proportion to increases in vehicle speed.

Further analysis was performed upon the angular acceleration data. Values of jerk were plotted as a function of angular acceleration. Values in the intervals 0 to 10, 10 to 20 and 20 to 30 Hz (Note: For the angular data no frequencies were recorded above 30 Hz) indicated that the amount and frequency of jerk increased as a function of increases in the frequency of angular acceleration. Jerk produced by 20 to 30 Hz acceleration is greater than that produced by 10 to 20 Hz acceleration, which, in turn, is greater that that produced by 0 to 10 Hz.

As the vehicle accelerates from a standing start, the angular acceleration increases steadily with increases in speed of the vehicle; and jerk increases steadily as a function of the amount and frequency of angular acceleration. Findings show that there are few components of angular acceleration in the X-axis for frequencies below 20 Hz. Most of the angular acceleration takes place in the Y- and Z-axes at acceleration frequencies above 10 Hz.

Angular acceleration and jerk were plotted for 2 conditions: one employing a constant vehicle speed of 6 ft/sec, and another employing a constant vehicle speed of 22 ft/sec. At a constant speed of 6 ft/sec, angular acceleration and jerk are greatest in the Y- and Z axes, with the Z axix displaying more activity than the Y-axis. Graphs were made of the angular acceleration occurring in the frequency bands 0 to 10 Hz, 10 to 20 Hz and 20 to 30 Hz. From these graphs it was evident that the amount of angular acceleration and, consequently, angular jerk, increased as a function of increasing frequency of acceleration. Similar to results from linear and acceleration, the amount and frequency of angular acceleration increased as a function of increases in vehicle speed.

8. Conclusions

The objectives of the Phase 2 test and evaluation program were successfully accomplished in that the test and evaluation program was completed, the data was gathered and analyzed, and the results from the analysis of the power, thermal and ride quality data has been presented. From the analysis of this data the following conclusions have been drawn:

The test data shows clearly that the eddy current clutch propulsion system will prove most attractive in applications of automatic people mover where the system's designer has optimized operation so that it operates at maximum speed most of the time.

The efficiency is a function of speed. It varies from slightly better than 60% at top speed to about 36% at half speed. The efficiency drops because the input power and output power do not decrease at the same rate. As the speed decreases the slip in the eddy current clutch increases resulting in more losses in the clutch and hence decreased efficiency. As the speed increases input power drops off to that required to maintain the desired cruise speed. The input power varies directly with the vehicle torque requirement. The thermal design of the eddy current clutch is dependant upon the peak torque demands which when occurring at low speeds results in high losses. During acceleration, minimum input power is required, it is that which is drawn during idle.

For cruise conditions, the real power requirements drop significantly with reduced speed, whereas the reactive power remains relatively constant. This results in very low power factor at low speeds. During acceleration the real power required is high compared to the reactive power resulting in a power factor greater than 0.8. During deceleration the real power required is much lower than the reactive power yielding a power factor of 0.14 from maximum speed to stop.

Grade also affects power factor. For positive grades, high real power is required resulting in high power factor, whereas for negative grades, low real power is required, hence low power factor. The data indicates that the reactive power requirements must be considered when specifying the power supply requirements for vehicles incorporating the eddy current clutch propulsion system, because it applies AC driver motors as primary power source.

The thermal tests that were conducted demonstrated that the internal cooling system was adequate to maintain safe operating temperatures, considering high ambient temperatures during the tests. There is constant air flow through the motor (clutch) brake assembly because the fins which draw the air through the assembly are mounted on the rotor of the motor, which always spins at slip speed, regardless of the drive output speed.

During the length of the test program approximately 300 hours of operation were logged. During this time no failure in the propulsion system occurred, and no degradation of performance was experienced.

APPENDIX A

TEST EQUIPMENT SPECIFICATIONS

Brief specifications for the instruments used in the tests are given below. More complete data is available from the manufacturers.

Torque Sensor

Lebow Associates, Inc.
Model 1604-2K

Capacity	-	125 lb/ft
Maximum Speed	-	15,000 RPM
Rotary Inertia	-	1.6 lb/in^2
Weight	-	18 lbs
Non-Linearity	-	± 0.1% of full scale
Sensor	-	Four arm bonded strain gage
Tachometer	-	60 pulses per revolution

Strain Gage Conditioner - Amplifier Module

Daytronic Corporation
Model 878-A

Provides 3 kHz excitation to the torque sensor and incorporates carrier amplifier circuitry employing synchronous demodulation.

Frequency-to-Voltage Converter

Daytronic Corporation
Model 840

Accepts variable frequency input pulses and provides an output voltage dependent on frequency of pulses but independent of pulse shape and pulse amplitude.

Temperature Sensors

Yellow Springs Instrument Co.

Type YSI-705 Air Temperature

Temperature range - 30° C to +100° C (-22° F to + 212° F)

Time Constant - 06 seconds

Type YSI-709 Attachable surface temperature

Characteristics as above

Thermistor Conditioner - Amplifier Module

Daytronic Corporation

Model 815

Input	- "A", "B", or "A-B"
Measuring range	- -30° C to +100° C
Output	- Standard 1 or 10 volt signal

Current Transformers

Westinghouse

Type EX1

Ampere range - Primary, 100 amps
Secondary, 5 amps

Potential Transformers

Westinghouse

Type EMP

Primary, 480 V

Secondary, 120 V

Watt Transducer

Trans Data Inc.

Model 20WS 101

For measuring power in a 3-phase, 3-wire system.

2 potential inputs each nominally 120 V.

2 current inputs each nominally 5 A.

1000 watts full scale produces 1 ma dc output into 0 to 10 kΩ.

Response time < 200 ms.

Var Transducer

Trans Data Inc.

Model 20VS 101

For measuring vars in a 3-phase, 3-wire system.

2 potential inputs each nominally 120 V.

2 current inputs each nominally 5 A.

Phase shifting self contained.

1000 vars full scale produces 1 ma dc output into 0 to 10 kΩ.

Response time < 200 ms.

Voltage Transducer

Trans Data Inc.

Model PS101

For measuring voltage.

Input 150 V full scale produces 1 ma dc output into 0 to 10 kΩ.

Response time < 400 ms.

Current Transducer

Trans Data Inc.

Model 10CS 101

For measuring current.

Input 5 A full scale produces 1 ma dc output 0 to 10 kΩ.

Response time < 100 ms.

Calibrated Amplifier Modules

Daytronic Corporation

Model 863

For scaling voltages from sampling resistors.

Gain 0.01 to 11.00 with output of ± 1 V.

Recorder

Brush Instruments Div., Gould Inc.

Model 260

Provides for recording 6 channels of data plus a channel with 1 s time ticks.

Chart speeds 1 mm/s and 5 mm/s.

Recorder

Consolidated Electrodynamics Corp.

Type S-124

Provides for recording 6 channels of data on photographically sensitive chart paper.

Ride Quality Meter

DOT-Transportation Systems Center

Ride Quality Package

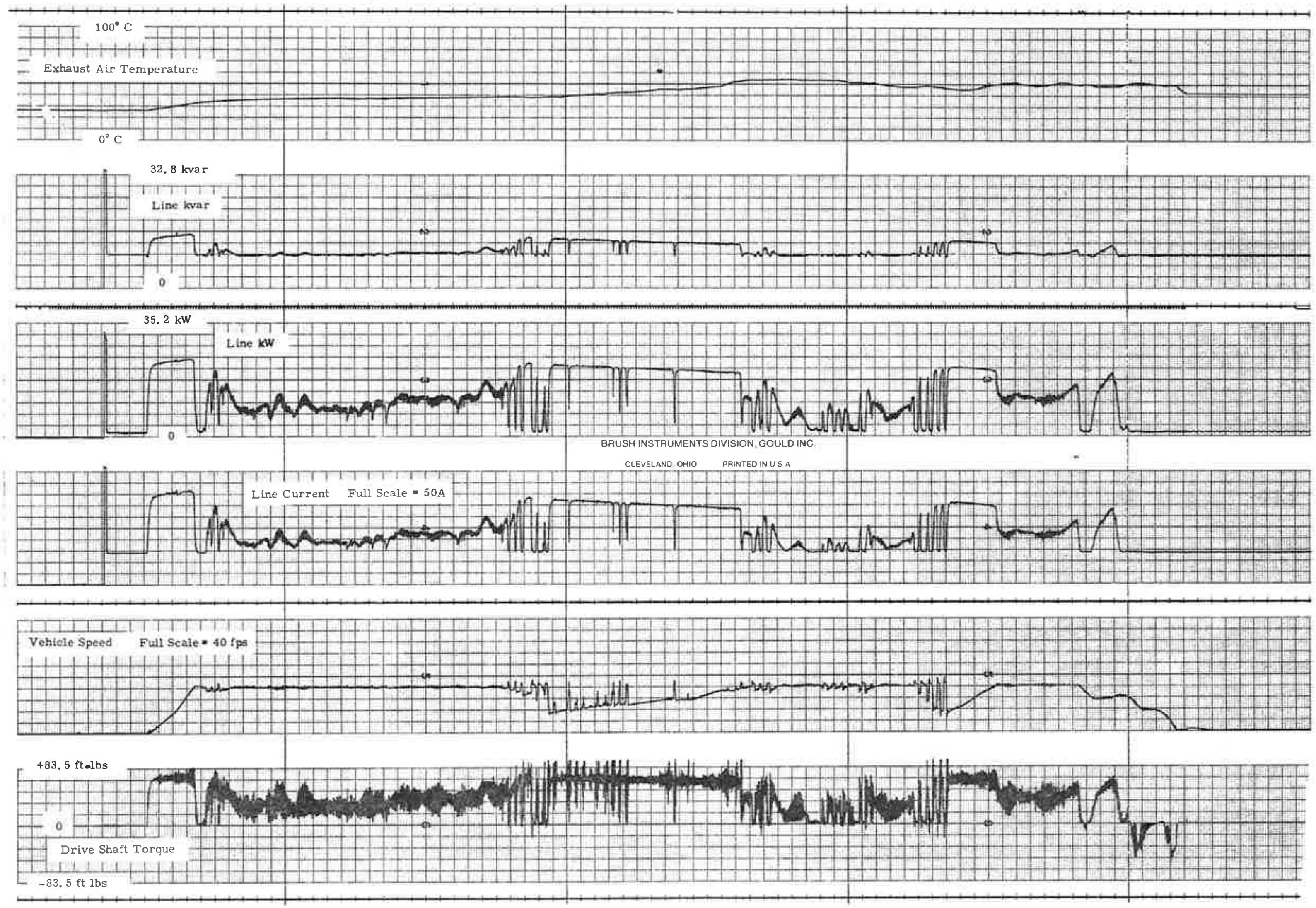
Provides sensors for detecting linear accelerations on three axes and angular accelerations around these axes, with a recorder to preserve the data for spectral and amplitude analyses.

APPENDIX B

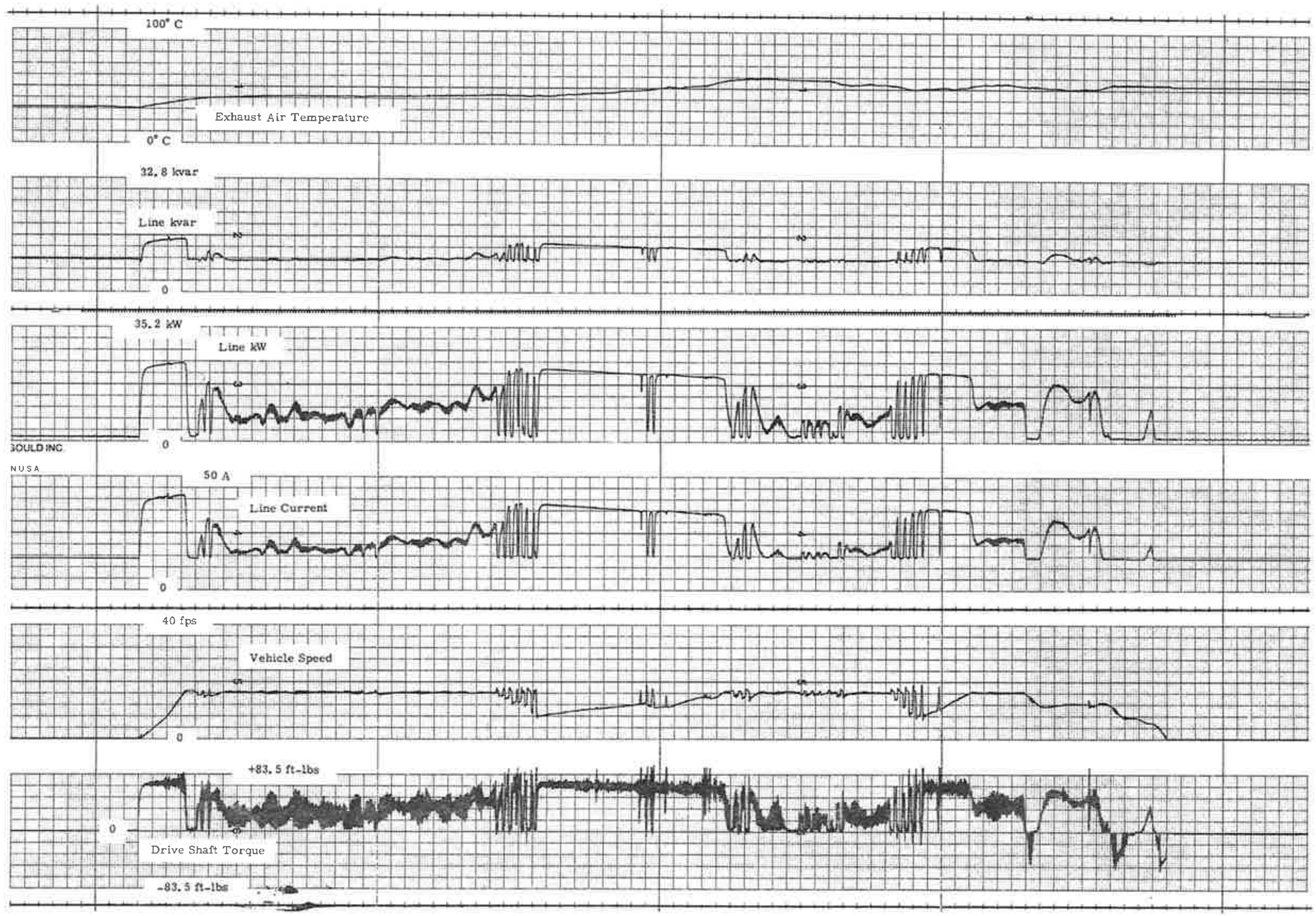
TYPICAL TEST DATA

This appendix includes copies of some typical recordings taken during the power and propulsion system tests on July 25, 1973 and the temperature stability test on July 26, 1973.

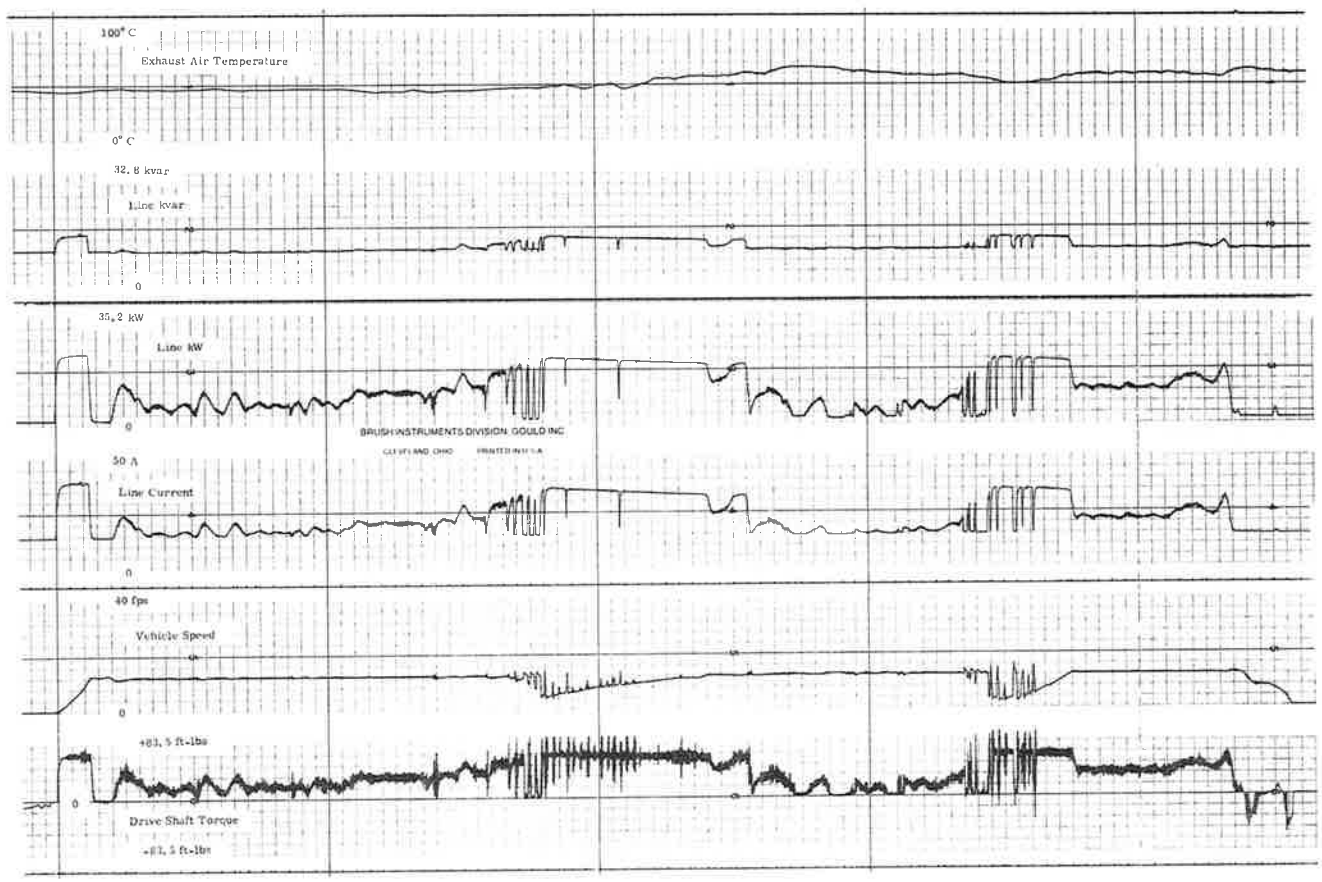
List of Charts



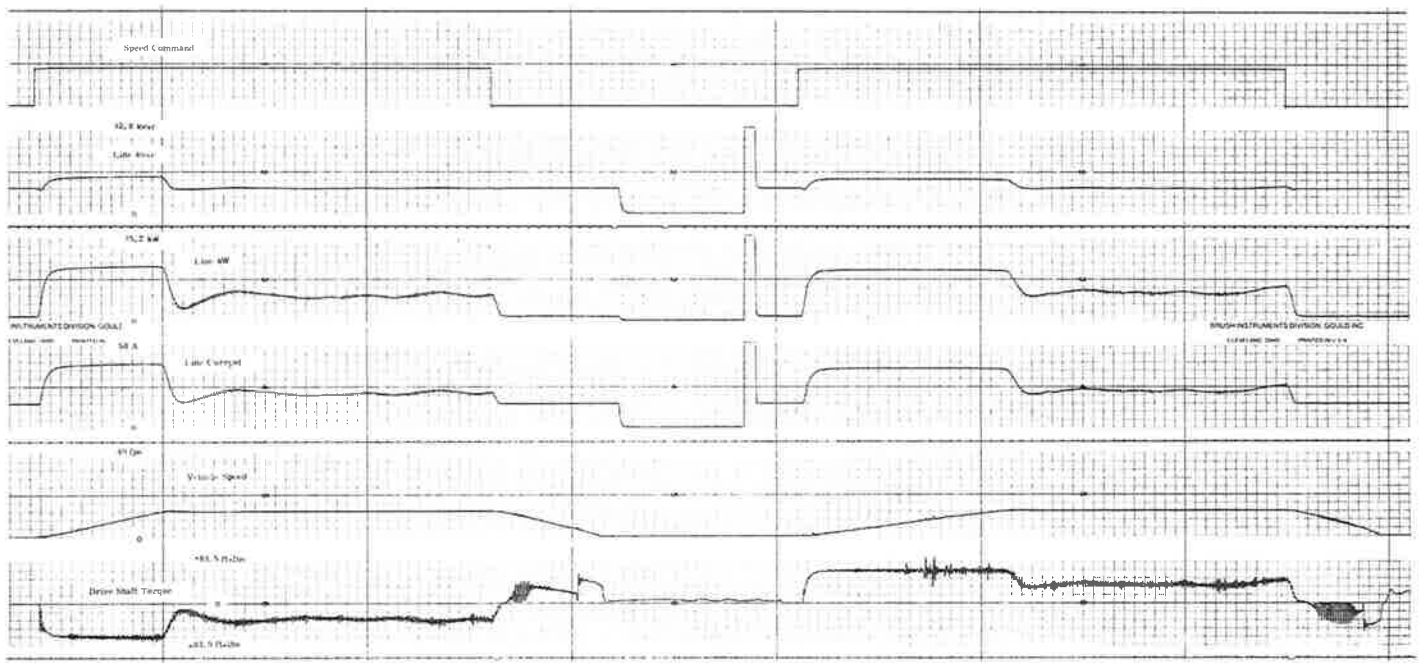
Run 1. 16 fps with 900 lbs Vehicle Weight



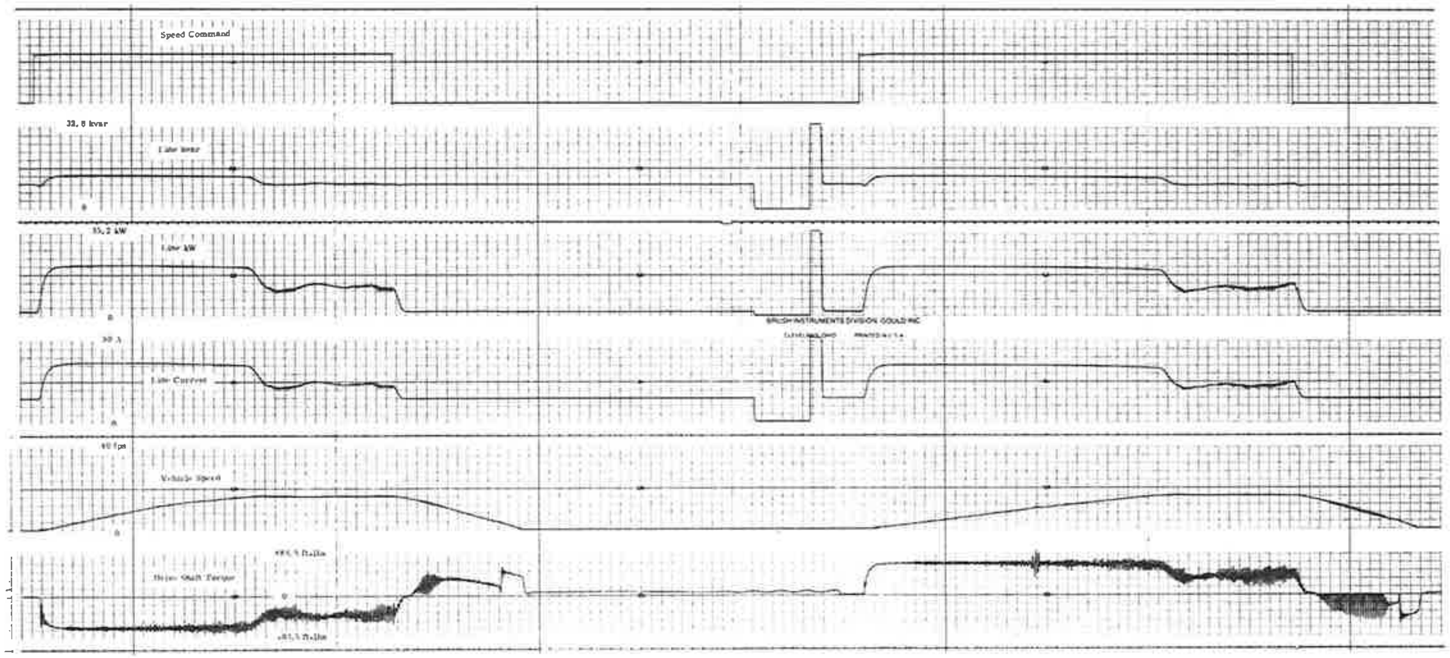
Run 3. 16 fps with 9500 lbs Vehicle Weight



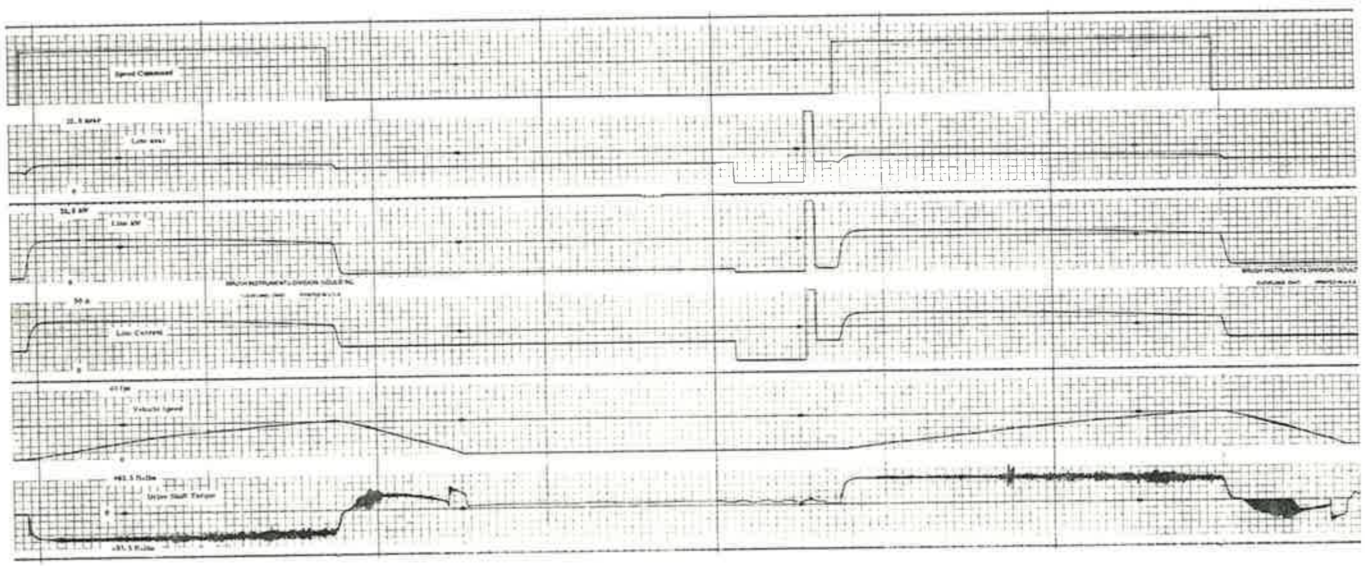
Run 5. 12 fps with 9000 lbs Vehicle Weight



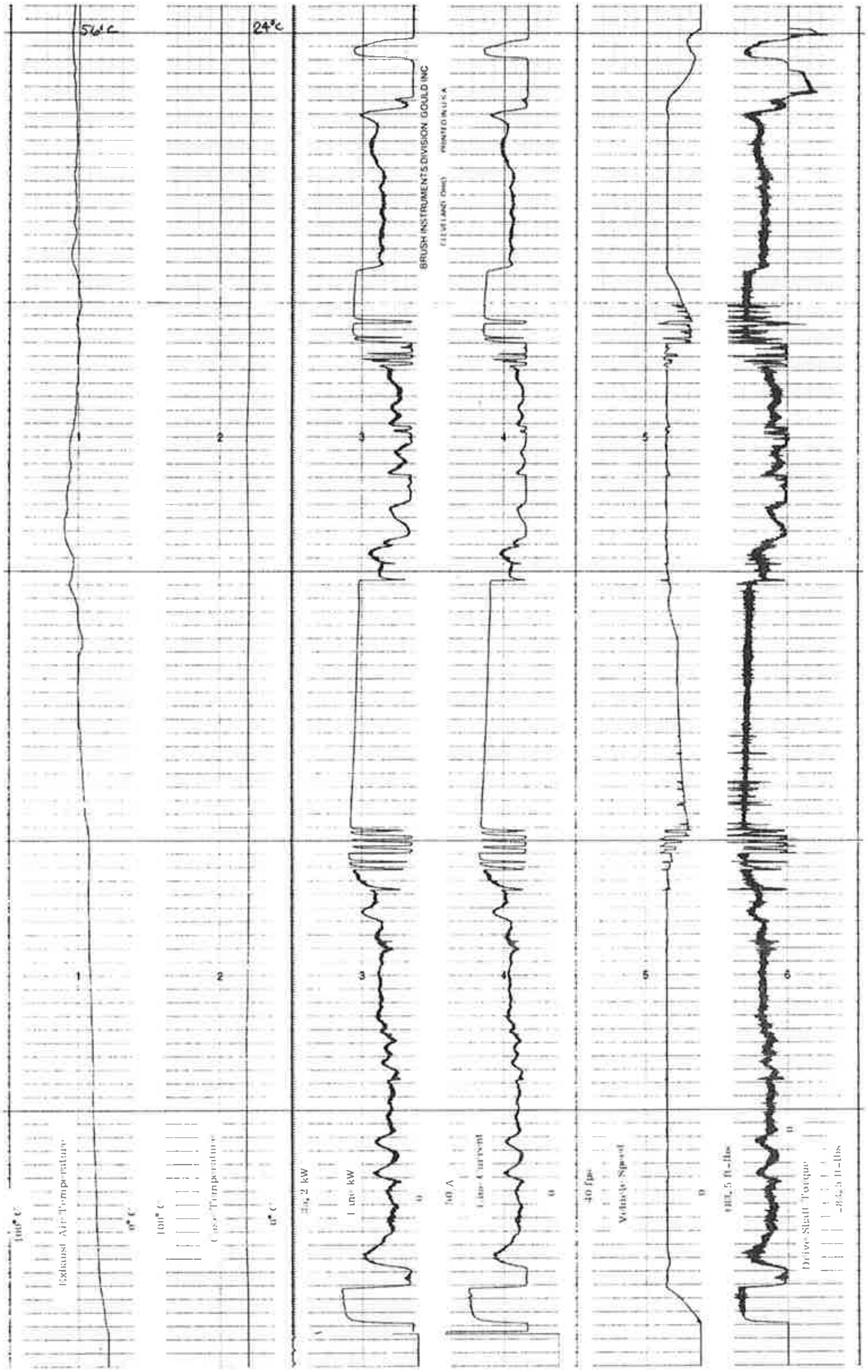
Run 15. Acceleration and Deceleration on Upgrade and Downgrade (12 fps)



Run 15. Acceleration and Deceleration on Upgrade and Downgrade (16 fps)



Run 15. Acceleration and Decleration on Upgrade and Downgrade (21 fps)



Temperature Stability Test

APPENDIX C

REPORT OF INVENTIONS

A diligent review of the work performed under this contract has revealed no new innovation, discovery, improvement or invention.