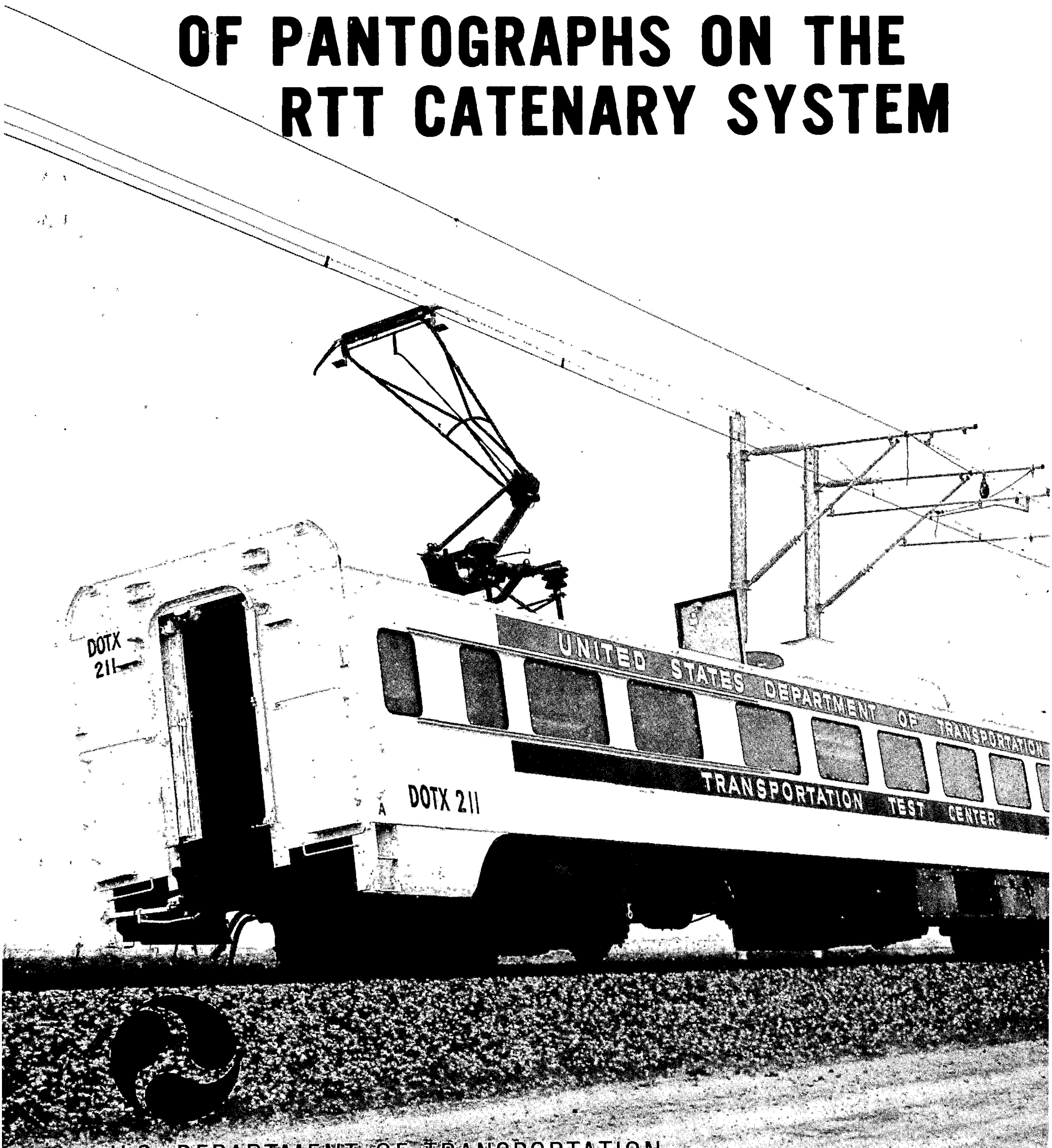
DEAD LINE TESTING OF PANTOGRAPHS ON THE RTT CATENARY SYSTEM



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NOTICE

NOTICE

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16. Abstract

The tests described in this report were carried out by the Transportation Test Center to verify the newly constructed overhead catenary system on the Railroad Test Track (RTT) and the pantographs to be used on it. The data produced included height and stagger measurements in support of the construction, also pantograph and catenary data up to speeds of 120 mi/h.

The experimental techniques consisted of running specially instrumented pantographs over the catenary which was isolated and grounded (dead line). The TTC pantograph test car DOTX 211 was used to carry the pantographs.

The results of these tests showed that instrumented pantograph techniques can successfully be employed in support of catenary construction. The results of the high speed pantograph tests showed that the new style 5 catenary proposed for the New Haven to Boston section of the Northeast Corridor has much improved performance over the existing catenary designs. It was also found that the dual stage Faiveley pantograph performed better than the single stage Faiveley.

It was concluded that the complete RTT catenary installation was suitable for operating speeds up to 120 mi/h.

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ACRONYMS

ACSR	Aluminum Conductor, Steel Reinforced
AEM-7	ASEA Electromotive-7000 (locomotive)
ALD	Automatic Location Detector
BICC	British Insulated Callander Construction
CCW	counterclockwise
CW	clockwise
FRA	Federal Railroad Administration
GE	General Electric
IECO	International Engineering Company
IRIG B	Inter Range Instrumentation Group B
LOC	Loss of Contact
NEC	Northeast Corridor
OCS	Overhead Catenary System
OIP	Office of Intercity Programs
OR&D	Office of Research and Development
PSD	Power Spectral Density
rms	root mean square
RTT	Railroad Test Track
SNCF	Societe Nationale des Chemins-de-fer Francais
TGV	Tres Grande Vitesse
TTC	Transportation Test Center

ABBREVIATIONS AND METRIC EQUIVALENTS

$^\circ$	(degree)	
%	(percent)	
$\therefore$	(therefore)	
d.c.	(direct current)	
Hz	(Hertz)	
ms	(milliseconds)	
V	(volts)	
mi	(miles)	= 1.6094 km
mi/h	(miles per hour)	= 1.6094 km/hr
',ft	(foot)	= .3048 m
",in	(inch)	= 2.54 cm
kip	(kilopounds)	= 453.59 kg
lbs	(pounds)	= .45359 kg
m	(meter)	= 3.281 ft

EXECUTIVE SUMMARY

INTRODUCTION

During fiscal year 1979 the Railroad Test Track (RTT) at the Transportation Test Center (TTC), Pueblo, Colorado, was electrified using an overhead catenary system. This project was funded by the Office of Intercity Programs (OIP) in support of the NEC improvement project. The OIP also funded the conversion of an AMTRAK passenger car to a pantograph test car and the design and manufacture of a dead line pantograph instrumentation system by ENSCO, Inc.

The purpose of the test car and instrumentation system was twofold:

- To measure the contact wire height above rail and contact wire stagger (lateral position with respect to the track centerline) of the newly constructed catenary.
- To evaluate the performance of the Faiveley single and dual stage pantographs on the styles 1, 3, and 5 catenary designs using dynamic measurements at speeds up to 120 mi/h. Included in the performance evaluation was the effect of pantograph collector shoe mass, the aerodynamic lift forces, and pantograph uplift force.

DESCRIPTION OF FACILITIES

The RTT and associated Balloon Loop (turning track) have been electrified. The RTT, which is approximately 13.5 mi in length, is equipped with three designs of compound (three conductor) catenary:

- Style 1--based on the existing catenary between Washington and New York.
- Style 3--based on the "hanging beam" catenary design between New York and New Haven.
- Style 5, 5X--based on the lightweight catenary proposed for the New Haven to Boston electrification.

The Balloon Track, which is 1.4 mi long, is equipped with a short span trolley wire (single conductor) catenary, designated style 5T. The 5T catenary is blended into the RTT style 5 catenary by a short length of simple catenary (two conductor) designated 5A.

One mile of the RTT has been designated a special test length in which two designs of catenary are available. The normal catenary installed in this length is the style 5X; however, this can be swung aside and replaced by a half-mile length each of the styles 1 and 3 designs. Transfer roller assemblies are provided for this purpose.

Items of particular interest in the RTT catenary installation included two phase breaks, one supplied by British Insulated Callander Construction (BICC), the other by Kupler (Pfisterer). The performance of the phase breaks, the Balloon Track turnout and section insulator, and overlaps were carefully evaluated.

Two pantographs were tested, namely, the Faiveley single and dual stage units; both were of single arm construction. A special pantograph collector shoe (head) was designed and manufactured by the TTC for the single stage pantograph to accommodate 47" of carbon collection width (across track).

Normally, the test train was composed of locomotive DOT 001, instrumentation car DOTX 208, and the TTC pantograph test car, DOTX 211. All vehicles in this consist were cleared for 120 mi/h operation.

The instrumentation was set up to measure:

- Contact force (force between pantograph head and contact wire),
- Contact wire stagger,
- Contact wire height,
- Head trajectory,
- Structure location,
- Loss of contact (LOC) between pantograph head and contact wire, and
- Train speed

Additionally, to support the aerodynamic lift force tests, instrumentation was used to measure the upward lift force and the train air speed.

DESCRIPTION OF TESTS

Before testing commenced, the catenary system was de-energized and grounded. This provided a safety ground for the pantograph-mounted transducer system, and a circuit for the low voltage d.c. loss of contact measuring systems.

Test operations depended on particular requirements. For example, catenary geometry measurements were carried out at a speed between 20 and 30 mi/h, whereas high speed performance tests and aerodynamic lift force tests were conducted under selected test sections of catenary at speeds between 30 and 120 mi/h.

All data channels were recorded on analog magnetic tape. Selected data channels also were displayed on strip charts for immediate quick-look analysis.

RESULTS AND DISCUSSION

From a methodology assessment of the height and stagger measurements, it was estimated that the height measurement error was ±2" absolute--in addition to uplift caused by pantograph pressure and the error on curves due to head (collector shoe) inclination geometry. A similar analysis of the stagger measurement indicated a ±1.25" error for the segmented head method, and ±1.0" for the force beam computed method.

The height and stagger measurements were compared with a modified construction specification:

- Contact wire height above rail: tangent track, 22'6" ± 2", curved track 22'10" ± 2", and

- Contact wire stagger nominal: ±1"

After initial post-construction adjustments, only one minor out-of-tolerance item remained, namely, the wire height at the Balloon Track turnout which was 6" below nominal wire height. However, two minor design errors are presently incorporated in the system:

- The 22'10" nominal wire height on curved track due to cross arm support bracket dimensional errors, and

- The 0.5" effective negative sag on curves due to pantograph head inclination.

The pantograph contact force and LOC data were analyzed to determine the performance of the overlaps and the balloon track turnout. In general, the performance of the pantographs over the overlaps and turnout were acceptable. However, the performance over the style 1/style 5 and style 3/style 5 overlaps showed increased contact force and loss of contact compared with the single catenary spans on either side. This was probably caused by the transition from a fixed terminated catenary (styles 1 and 3) to a fixed tension catenary (style 5).

The aerodynamic force measurements on the pantographs yielded the following:

- Single stage pantograph: 15 to 9 lbs positive lift at 100 mi/h, and

- Dual stage pantograph: 5 lbs positive lift at 100 mi/h.

The OIP catenary design specification (Task 16) limits the acceptable aerodynamic lift force to 5.5 lbs at 100 mi/h.

The pantograph current collection performance was assessed mainly on the basis of measured LOC. The percentage LOC was measured for designated test lengths using contact losses greater than 2 ms duration. LOC durations were also analyzed. To augment the LOC data, the contact force and head trajectory (collector shoe vertical displacement relative to the car body) measurements were analyzed.

Using 20 and 28 lb uplift pressures, with 1% LOC as the criterion for acceptable performance, each pantograph was assessed on the styles 1, 3, and 5 catenaries. In addition, the single stage pantograph was assessed on the basis of reduced head mass. As a result, the following conclusions are made.

CONCLUSIONS

The height and stagger measurements provided a useful contribution to the construction of the RTT catenary system. They enabled measurements to be taken and corrections assessed quickly and efficiently.

The dead line testing techniques can be used to assess the current collection performance of a pantograph on a given catenary design.

With experience, the probable effect of pantograph performance can be predicted from dead line measurements. However, only measurements made on the fully energized system can confirm the dead line predictions.

All RTT Catenary Systems were installed to an acceptable standard for long-term operation.

The current collection performance of the style 5 catenary, based on measured LOC, showed much improvement over styles 1 and 3 designs. The style 3 catenary appeared to be totally unacceptable for long term operation at speeds in excess of 90 mi/h with any combination of pantograph tested.

The results of dead line testing over phase breaks were inconclusive, due to incorrect installation of the BICC unit. However, the Kupler phase break appeared to give a satisfactory mechanical performance.

The single stage pantograph was only marginally acceptable for operation on the RTT catenary system at a speed of 120 mi/h with an uplift force of 28 lbs.

The dual stage pantograph gave acceptable performance at 120 mi/h on the styles 1 and 5 catenary systems, but not the style 3.

Both pantographs would benefit from a reduction in head mass. It is estimated that a head mass of approximately 20 lbs could be achieved by careful redesign of the head structure.

Dead line testing techniques require careful interpretation of the data when they are compared with empirical criteria derived from tests on dissimilar equipment.

To derive the best performance from the style 5 catenary, adjustments would be necessary to the wire height and midspan sag on the curved track sections.

The single stage pantograph develops large aerodynamic lift forces, particularly when running in the knuckle-trailing direction. This effectively reduces the LOC, but increases pantograph head and contact wire wear.

RECOMMENDATIONS

For a dedicated geometry measurement instrumentation system, the head force load cells should be designed on the basis of slow speed force levels in order to reduce the error in stagger measurement caused by load cell zero drift.

To make the RTT catenary system more representative of the NEC system, a graded wire and bridge arrangement should be installed, and one tension section of the RTT style 5 should be modified to represent the new ELECTRAK style 5 design planned for the New Haven to Boston electrification.

The styles 1 and 3 catenaries should be retained in the test length for the AEM-7 test; style 3 should provide useful data on wire erosion from high LOC levels.

One termination in the RTT style 1 and 3 catenaries should be allowed to float on the balance weights to provide better compatibility in the overlaps with style 5 catenary.

A redesign of the pantograph head should be undertaken to include a carbon strip width of 47" and to reduce the overall head mass to 20 lbs or less. Careful evaluation of the required load cases and aerodynamic lift characteristics should be included in the redesign.

The single stage pantograph should be restricted to a maximum operating speed of 100 mi/h on the RTT catenary systems.

The British Insulated Callander Construction (BICC) phase break installation should be corrected and the phase break re-evaluated.

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1.0 INTRODUCTION

1.1 BACKGROUND

During fiscal year 1979 an electrified overhead catenary system (OCS) and substation were installed on the Railroad Test Track (RTT) at the Transporation Test Center (TTC), Pueblo, Colorado. This project was funded by the Office of Intercity Programs (OIP) to provide a facility that could be used to evaluate components and vehicles under controlled conditions in support of the Northeast Corridor (NEC) improvement project. The OCS and substation were designed by the International Engineering Company (IECO), San Francisco, California, who subsequently supervised the site construction. The construction contract was administered by the Federal Highway Administration (FHWA).

Concurrent with the electrification construction, two additional projects were funded by the OIP. The first was the conversion of an AMTRAK passenger car to a pantograph test car (DOTX 211) at the TTC. The second was the design and manufacture of a dead line pantograph instrumentation system by ENSCO, Inc., Colorado Springs, Colorado, under a Federal Railroad Administration (FRA), Office of Research and Development (OR&D) contract.

The TTC prepared a test plan[1] which was approved and funded by the OIP. This plan included a series of dead line pantograph tests using the DOTX 211 and pantograph instrumentation system.

All aspects of the RTT electrification program were technically coordinated by the FRA OR&D, Office of Passenger Systems.

1.2 PURPOSE

The dead line tests were designed only to evaluate the existing pantographs specified by the OIP, not to develop pantographs. The tests were designed to satisfy three main objectives:

- To determine the constructional accuracy of the RTT catenary system;
- To evaluate the high speed performance of styles 1, 3, and 5 catenaries--in particular, the two phase breaks, overlaps, and turnouts; and
- To evaluate the relative current collection performance at speeds up to 120 mi/h of the Faiveley single and dual stage pantographs on the three catenary styles.

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[1] Transportation Test Center, RTT Electrification Test Plan, FY-1979, August 1978.

1.2.1 Catenary Geometry Measurements

Before high speed operations are carried out on a newly constructed catenary system it is usual to verify the construction quality. Following careful visual inspection, two measurement checks are normally undertaken. First, the height of the contact wire above rail and the stagger (lateral position) of the contact with respect to the track centerline are measured. This procedure is followed by a number of slow speed (10 to 30 mi/h) passes of a pantograph over the catenary to check for incorrect overlap profiles, registration arm settings, kinked contact wire, and any other obstructions to the smooth passage of the pantograph along the wire. In the past it has been the practice to measure height and stagger manually with a specially constructed height and stagger gage (a time consuming and costly method). To speed up the catenary construction at the TTC, the dead line instrumentation system was set up to measure height and stagger. This enabled the comparative height and stagger measurements and slow speed shakedown runs to be accomplished in one operation. This procedure accelerated the identification of construction errors and the checkout of later adjustments.

1.2.2 High Speed Catenary Performance Measurements

After successful completion of the low speed evaluation of the catenary system and the subsequent corrective adjustments, higher test vehicle speeds were run. The dead line instrumented pantograph was set up to measure dynamic performance (see paragraph 2.5.1). Test runs were made on the catenary system starting at a speed of 45 mi/h, increasing in 10 to 15 mi/h increments to 120 mi/h. The data were analyzed to determine whether the catenary gave a uniform performance over its length. Any irregularities in performance were investigated and corrected where necessary.

1.2.3 Pantograph Performance Assessments

Once final adjustments of the catenary system were complete, comparative pantograph performance studies could be made.

Two pantographs were tested:

- The Faiveley single stage 17MCP1A5, and
- The Faiveley dual stage AM-DS12.

Each pantograph was evaluated over three basic designs (styles) of catenary, styles 1, 3, and 5 (described in section 2.2.1). Both pantographs were evaluated over the BICC and Kupler phase breaks. Overlap and turnout performances were also assessed.

The effect of static uplift force (pan pressure) on pantograph current collection performance was investigated, as was the aerodynamic effect on pantograph behavior. As the pantograph travels through the air at speed, two major aerodynamic force components act on the pantograph mechanism. The first force to be considered is the lift force. This force tends to modify the pantograph uplift force. The aerodynamic uplift of each pantograph was determined as part of the dead line test program.

The second aerodynamic force acting on the pantograph which affects the performance is the drag force acting on the pantograph head. If the center of pressure of the head is significantly displaced from the head pivot centerline, offloading of one of the carbon shoes is likely to occur at high speed. Since this problem is usually overcome at the pantograph development stage, and as the testing at the TTC was not intended as a pantograph development program, no attempt was made to measure the drag force.

2.0 DESCRIPTION OF FACILITIES AND EQUIPMENT

2.1 TEST TRACK

The RTT is a loop of track forming the outer perimeter of the main test track complex at the TTC (figure 2-1). It is approximately 13.5 mi in length and is designed for a maximum speed of 125 mi/h over its entire length. A small turning loop, the Balloon Track, leads off the east side of the RTT; this enables test consists to be turned easily. For convenience of operation, the Balloon Track has been electrified as part of the RTT electrification. A location reference system is provided on the RTT; marker posts are positioned at 1,000-ft intervals around the track with the location number displayed (for example, R30). Throughout the remainder of this report the "R" station numbers will be used to reference locations on the RTT.

2.2 CATENARY

2.2.1 Catenary Designs

Five different catenary designs are used for the electrification of the RTT and the balloon track:

- Styles 5 and 5X, compound catenary,
- Style 1, compound catenary,
- Style 3, compound catenary,
- Style 5A, simple catenary, and
- Style 5T, trolley wire.

A summary of conductor sizes and tensions for each style is given in table 2-1; and a brief description of each is given in text below and in figure 2-2.

TABLE 2-1. CONDUCTOR DETAILS.

Catenary Type	Contact Wire	Auxiliary Wire	Messenger Wire	Return Wire
Style 5,5X	4/0 grooved	7/0.0833	19/0.0833	2/0 ACSR*
Style 1	336.MCM grooved	4/0 grooved	5/8" copper weld	2/0 ACSR
Style 3	4/0 grooved	4/0 grooved	5/8" steel 7/8" steel	2/0 ACSR
Style 5A	4/0 grooved	-	19/0.0833	2/0 ACSR
Style 5T	4/0 grooved	-	-	2/0 ACSR

* Aluminum Conductor, Steel Reinforced

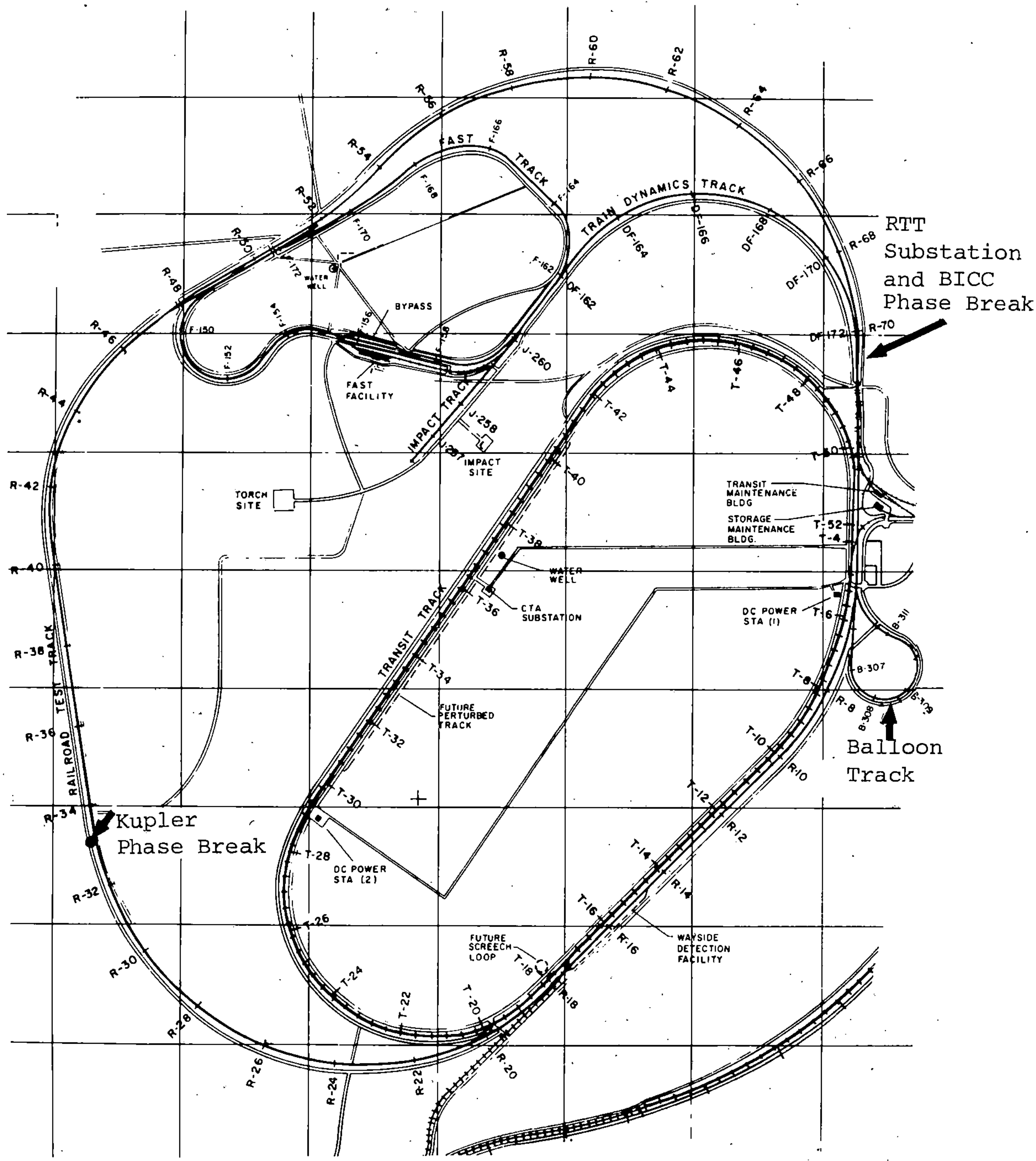
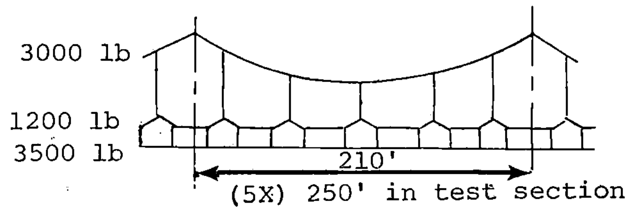
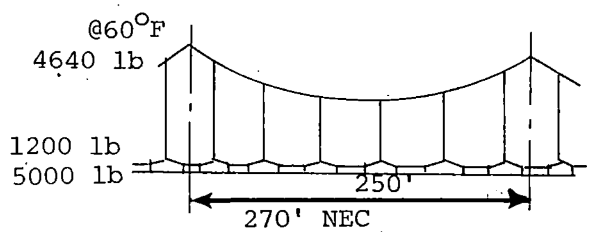


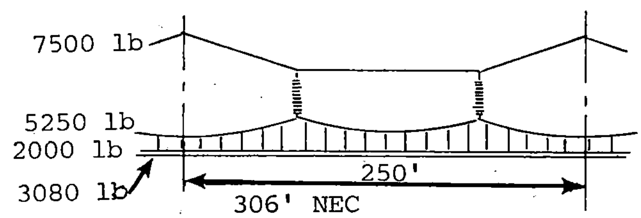
FIGURE 2-1. THE RAILROAD TEST TRACK.



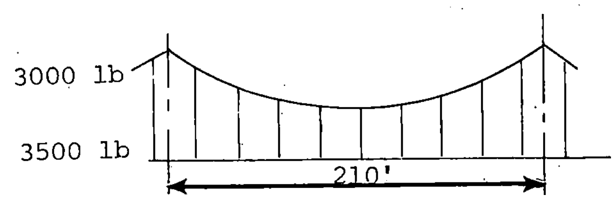
Compound Catenary, Style 5, (5X), proposed New Haven to Boston.



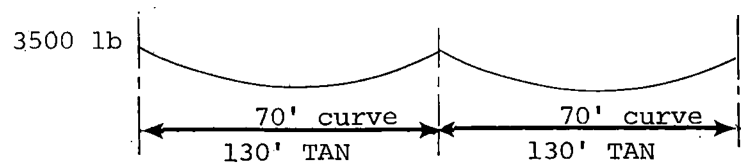
Compound Catenary, Style 1, in use Washington to New York.



Hanging Beam Catenary, Style 3, in use New York to New Haven.



Simple Catenary, Style 5.



Trolley, Style 5 T.

FIGURE 2-2. OVERHEAD CONTACT SYSTEMS.

a. Styles 5 and 5X. The style 5 catenary is a lightweight compound catenary design based on the proposed system for the new electrification between New Haven and Boston on the NEC[2].

The term "compound" refers to a 3-conductor design of catenary in which an intermediate conductor (auxiliary messenger) is suspended from the messenger wire by a system of hangers. The contact wire, in turn, is suspended from the auxiliary messenger by a second set of hangers. The resultant catenary has a substantially uniform compliance over the span length.

The Style 5 catenary on the RTT is supported and registered by a single pole and cantilever support structure (figure 2-3). The majority of the poles are galvanized steel broad flange beams; however, a short section between R56 and R59 has concrete poles for comparison. The maximum support spacing (span length) on the Style 5 catenary is 210 ft. The tension on the conductors is maintained by balance weights. Catenary terminated in this fashion is called "fixed tensioned equipment."

The style 5X catenary is identical to the Style 5 except that the maximum span length has been increased to 250 ft; it is installed on the test length on the west tangent.

b. Style 1. The style 1 catenary is a much heavier compound system, a design based on the existing catenary between Washington and New York on the NEC. The style 1 catenary uses much heavier conductors at much higher tensions than the style 5, and conductor tensions are variable because the termination of the conductors in the original design is fixed with no balance weights. However, the RTT system is equipped with balance weights, which can be fixed to simulate the original equipment termination or allowed to float in order to simulate the fixed tensions at different ambient temperatures.

c. Style 3. The style 3 catenary on the RTT is also representative of the existing NEC catenary design, which lies between New York and New Haven. Its hanging beam construction supports a compound catenary (similar to the Style 5) from a beam which is in turn supported by an across-track support wire. For the single track design at the TTC, the support wire is arranged longitudinally parallel to the track. Like the Style 1, the Style 3 is fixed-terminated, but balance weights are incorporated in the RTT system to simulate various ambient temperatures.

d. Style 5A. The style 5A catenary is a simple catenary design (figure 2-2) in which the contact (trolley) wire is suspended directly from the messenger by hangers. At the TTC, this equipment is used to blend the slow speed Balloon Track single trolley wire equipment into the high speed RTT style 5 equipment. The style 5A simple catenary is normally used for medium speed (30 to 90 mi/h) applications.

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2 Pehrson, Vernon W.; Shaw, Peter L., Suddards, A. Donald; and Willetts, Thomas A.; Northeast Corridor High Speed Rail Passenger Service Improvement Project; Task 16: Electrification Systems and Standards, December 1976.

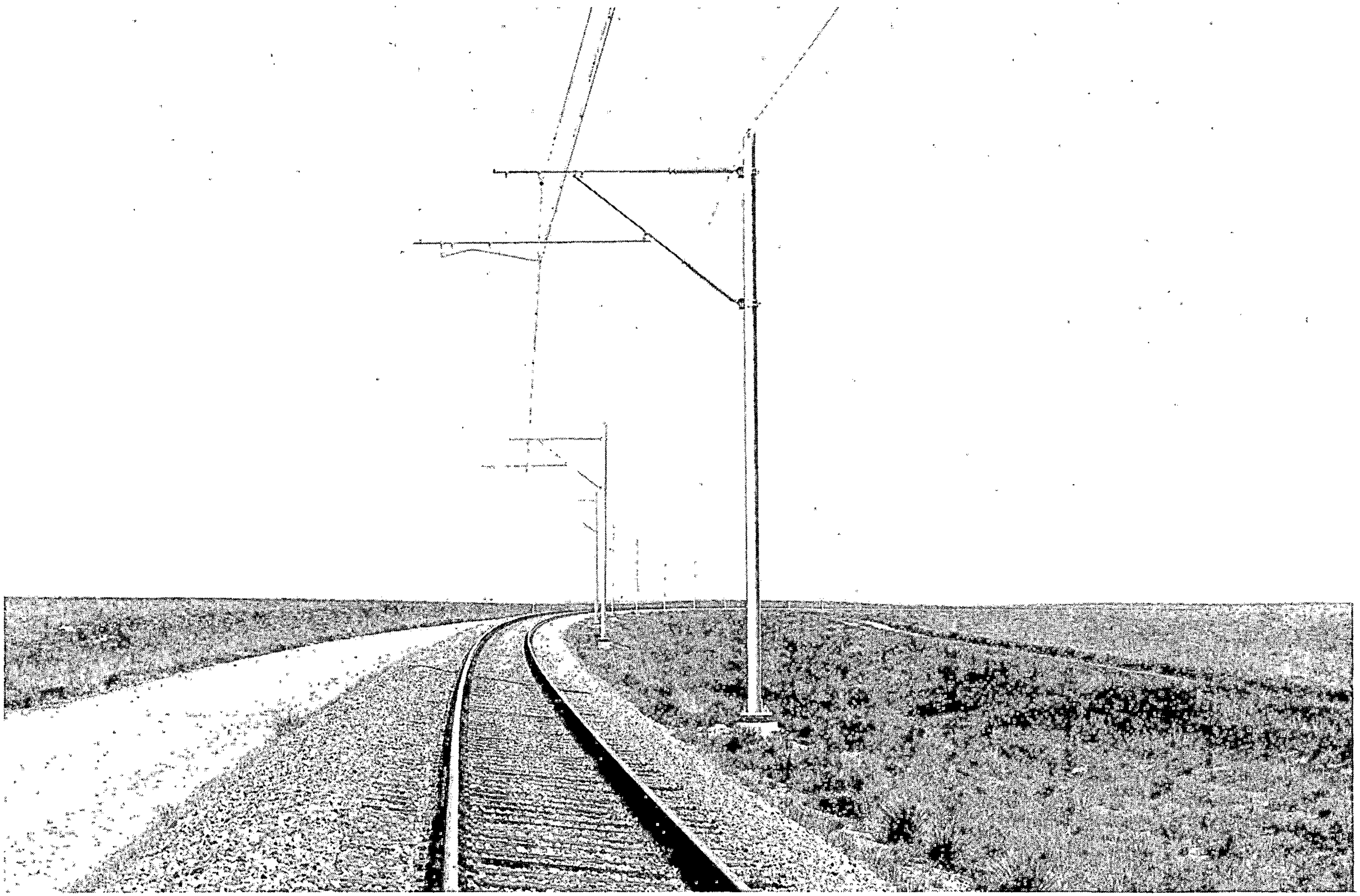


FIGURE 2-3. STYLE 5 CATENARY AND SUPPORT STRUCTURES.

e. Style 5T. The style 5T simple trolley wire is the most basic system employed for electrification. It is a single contact wire, directly supported by a pole and cantilever without the use of a messenger wire. It is designed for very low speed operation (less than 40 mi/h), and is used only on the Balloon Track.

2.2.2 Test Length

The major portion of the RTT, between stations R34 and R39, is equipped with the lightweight Style 5 catenary. However, the 1-mi section between R39 and R34 on the west tangent is set up as a special test length. Here the support structures are broad flange beam portal frames spanning the track and adjacent roadway (figure 2-4), spaced for 250-ft spans. Two sets of cantilevers are used, one hinged to the east side upright of the portal, the other on a transfer roller system on the bridge of the portal.

The east side cantilevers are used to support two half-tension sections of style 5X lightweight catenary. When not in use this equipment is stored flat aginst the east side portals (figure 2-4).

The cantilevers on the transfer system are used to support one half-tension section in the style 1 and style 3 catenary designs. The style 1 system is at the south end of the test length; the style 3 is at the north end. When not in use, this equipment is stored over the roadway. For the major portion of this test, styles 1 and 3 catenary systems were in use.

2.2.3 Phase Breaks, Section Breaks, and Turnouts

Two designs of phase breaks are presently employed in the RTT catenary system. At the substation location (R70), a British Insulated Callander Construction (BICC) phase break is installed (figure 2-5). At the halfway point (R33), a Pfisterer (Kupler) phase break is used (figure 2-6). Both designs were evaluated during the test program.

Two other aspects of catenary design were also evaluated. The turnout from the Balloon Track onto the RTT was the first to be considered. It is important that the turnout give a smooth transition from the Balloon catenary onto the RTT without a resultant "hard spot" in the catenary itself.

The second feature to be tested was the section break in the Balloon Track equipment. The section break, designed by Ohio Brass Company, was not expected to give trouble because of low speed application.

2.3 PANTOGRAPHS

Two pantographs were evaluated as part of this test program. Both pantographs were of the Faiveley asymmetric (single arm) design, as described below.

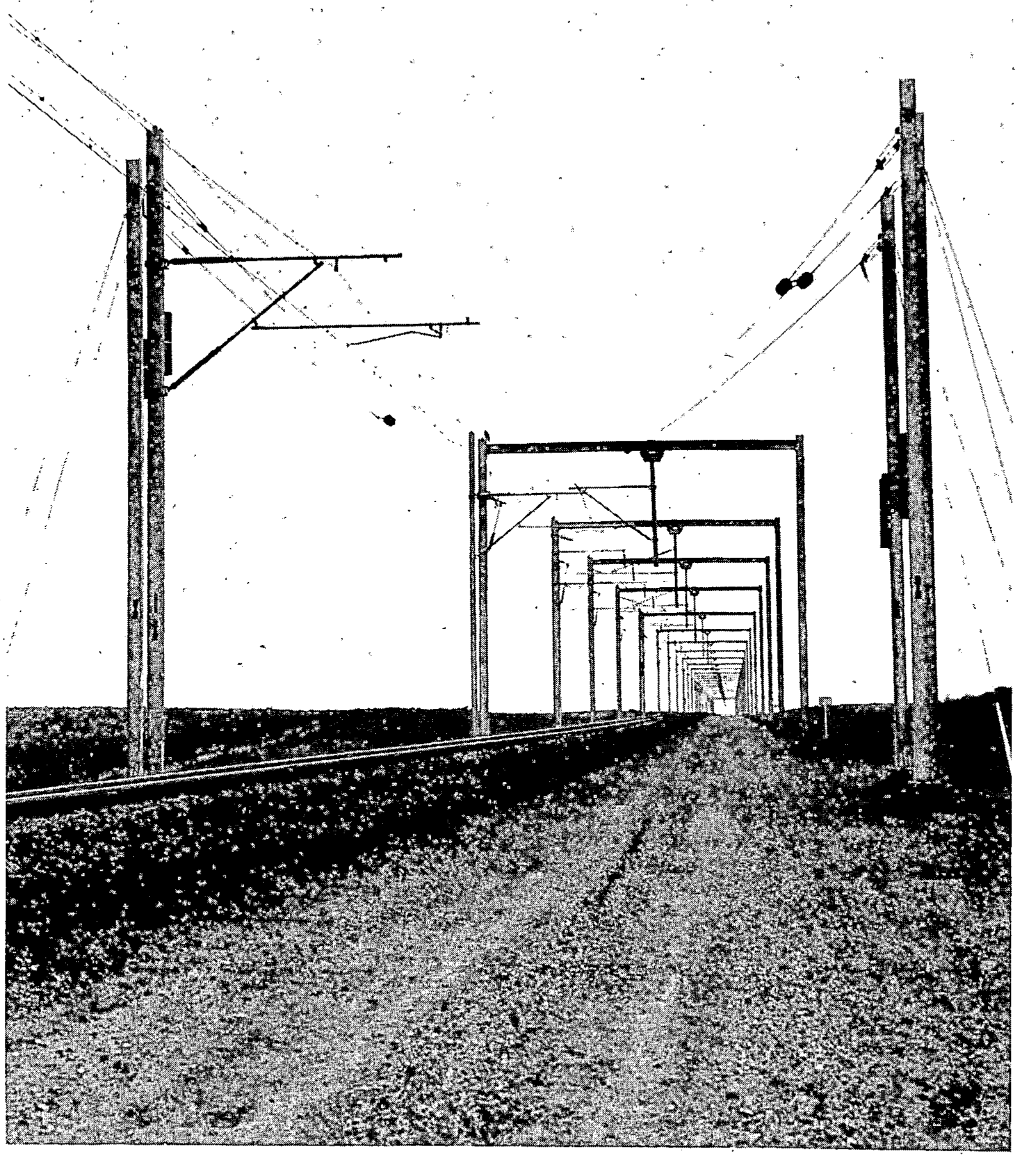


FIGURE 2-4. DESIGNATED ONE-MILE TEST LENGTH (USING PORTAL FRAMES).

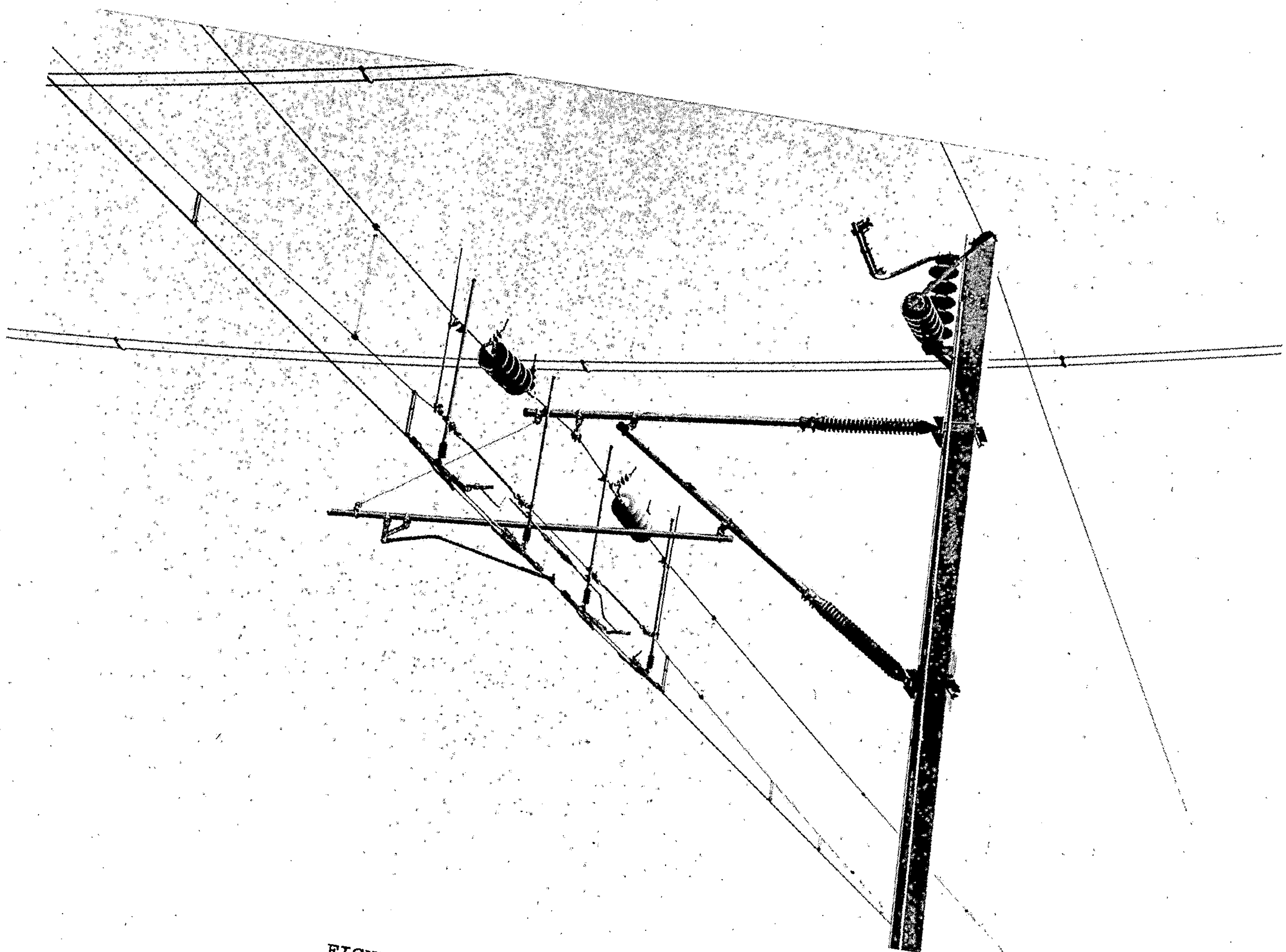


FIGURE 2-5. BICC PHASE BREAK.

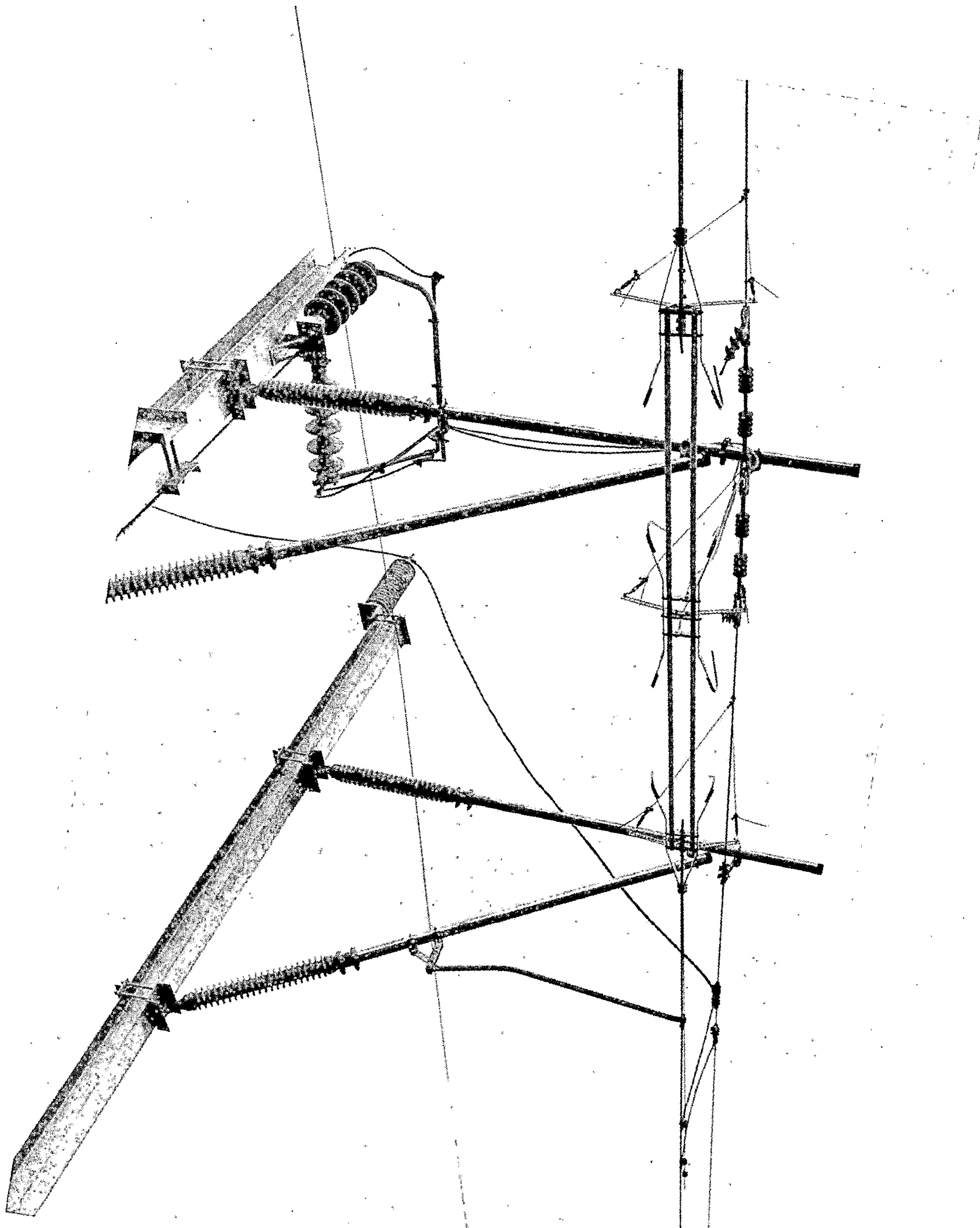


FIGURE 2-6. KUPLER PHASE BREAK.

2.3.1 GE/Faiveley Single Stage Pantograph

The single stage Faiveley pantograph was manufactured by General Electric (GE) under license to Faiveley. A number of different models were manufactured for various applications; the model (17MCP1A5) tested at the TTC is presently used on the GE-built Metroliners.

The 17MCP1A5 pantograph (figure 2-7) consists of a single articulated main frame with a total reach of 11 ft. A pair of coil springs acting over a cam arrangement exert the force required to raise the main frame and apply the necessary upward constant pressure on the contact wire (figure 2-8). The adjustment of the uplift force is achieved by altering the pretension in the springs. To lower the pantograph, air pressure is applied to a pneumatic cylinder. Pneumatically released mechanical latches are provided to secure the pantograph for long term storage.

The pantograph head is attached to the main frame through a spring plunger suspension system onto the ends of a transverse shaft, hereafter referred to as the "control bar." The control bar is attached to the upper frame by two transverse bearings which allow the bar to rotate about its centerline. Rotation of the bar is restrained by means of a rod attached to the pantograph knuckle (articulated joint). The geometry of this linkage is designed to keep the centerline of the head suspension plungers vertical regardless of pantograph height. To allow for longitudinal irregularities and grades in the contact wire, the head is allowed to pivot freely about a transverse centerline at the top of the head suspension system. The allowable angle of inclination of the head is $\pm$ 30^{o}.

2.3.2 Faiveley Dual Stage Pantograph

The Model DS12 dual stage pantograph (figure 2-9), tested at the TTC was one of two evaluation units purchased by AMTRAK directly from Faiveley. These units were manufactured in France and were identical to those used by Societe Nationale des Chemins-de-fer Francais (SNCF) on the Tres Grande Vitesse (TGV) locomotives. The maximum reach of the pantographs was 2.4 m. Production pantographs for the ASEA Electromotive-7000 (AEM-7) locomotive have a maximum reach of 3.2 m.

In principle, the mechanism of the dual stage pantograph is similar to the single stage. Again, the main stage consists of an articulated frame, with total upward travel of 2.2 m, which is raised by the two-spring and cam arrangement. The main stage geometry is designed to maintain a constant upward force (independent of position). A second lightweight articulated frame is mounted atop the main stage, on a fixed reference control bar and rod arrangement similar to that provided for the head suspension of the single stage pantograph. The second stage has a total travel of 0.4 m, but its mean operating position is controlled by the stiffness of its coil spring suspension. The head is attached to the top of the second stage through a spring plunger suspension system and control bar, similar to that used in the single stage pantograph. The second stage is designed to operate about its mean position with the static uplift force applied, and its operating position is adjusted by altering the length of the second stage coil spring assembly.

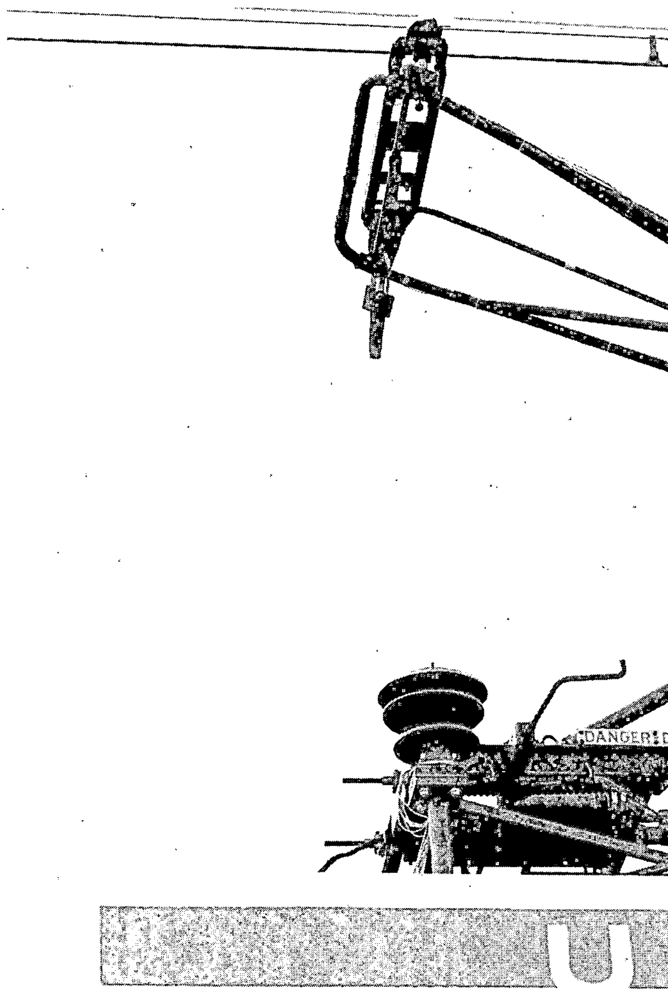
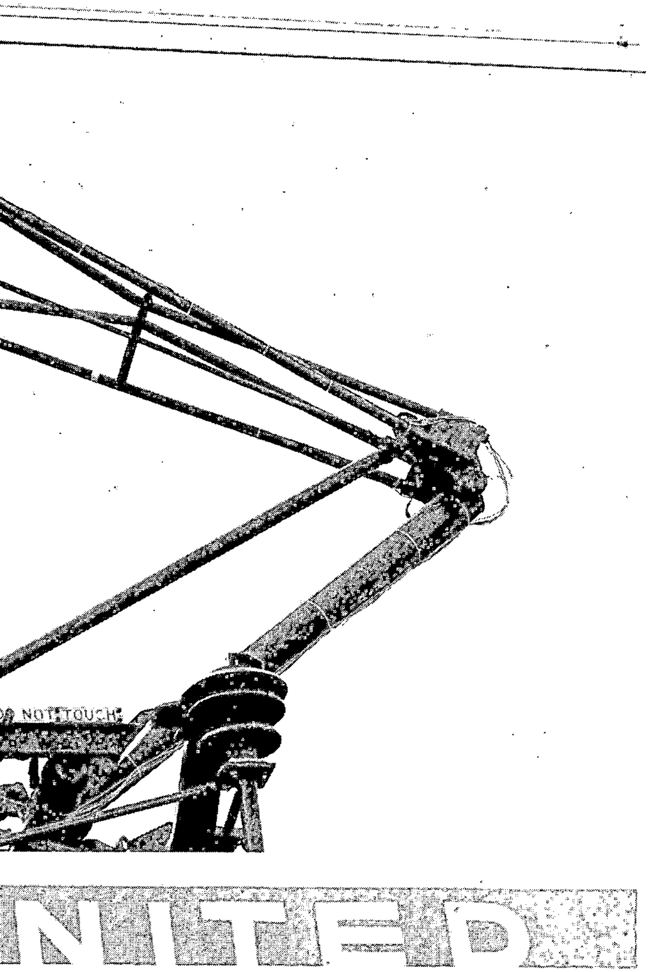


FIGURE 2-7. SIDE VIEW,



SINGLE STAGE PANTOGRAPH.

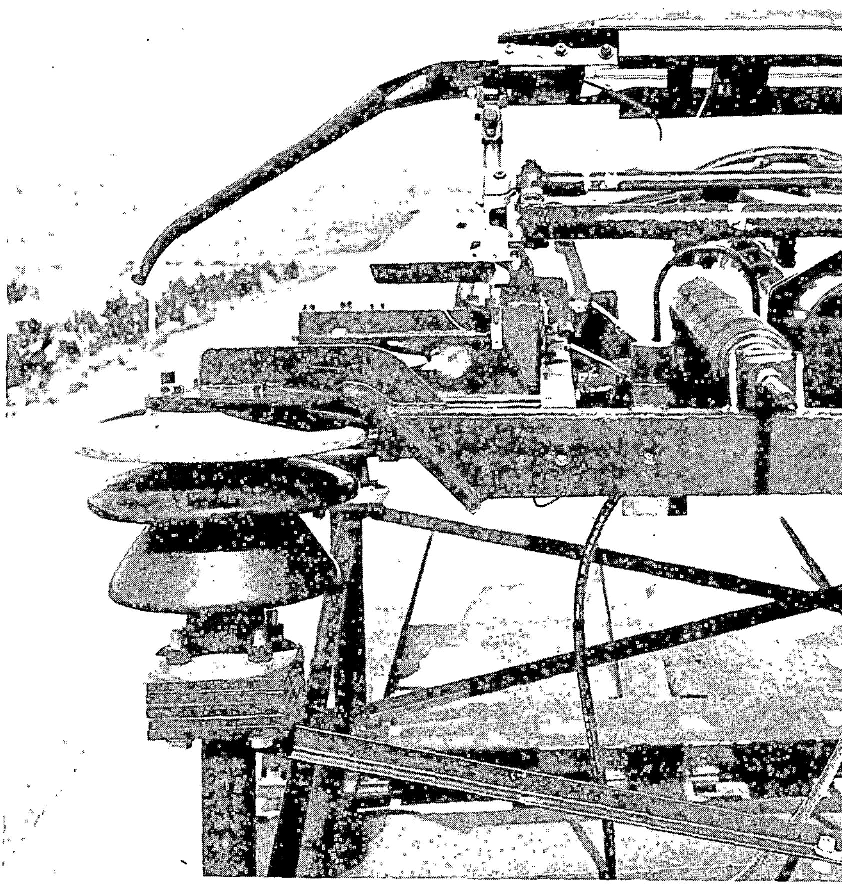
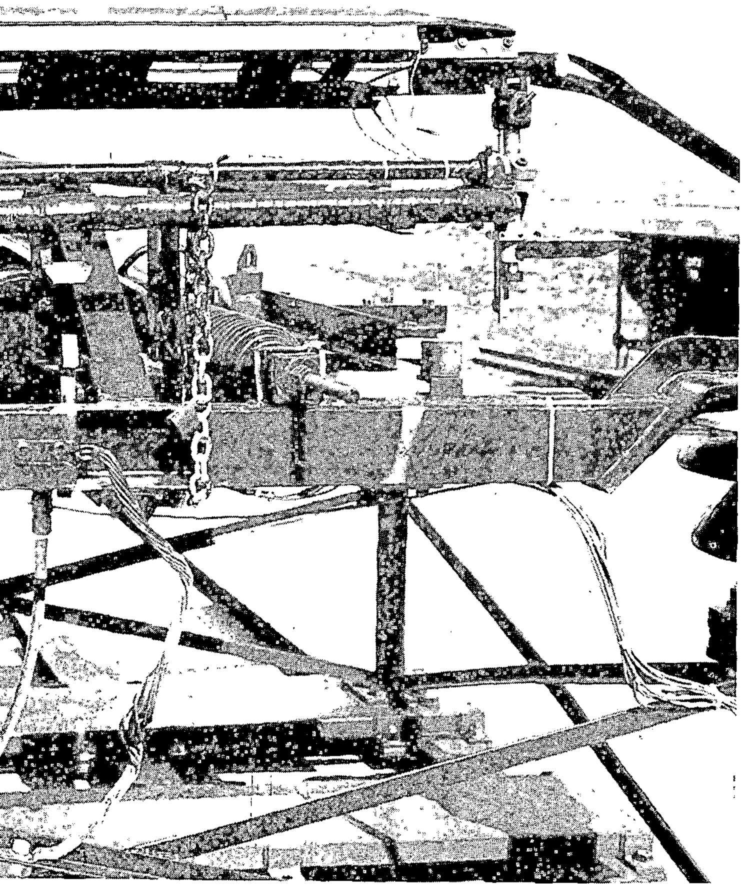


FIGURE 2-8. UPLIFT SPRINGS,



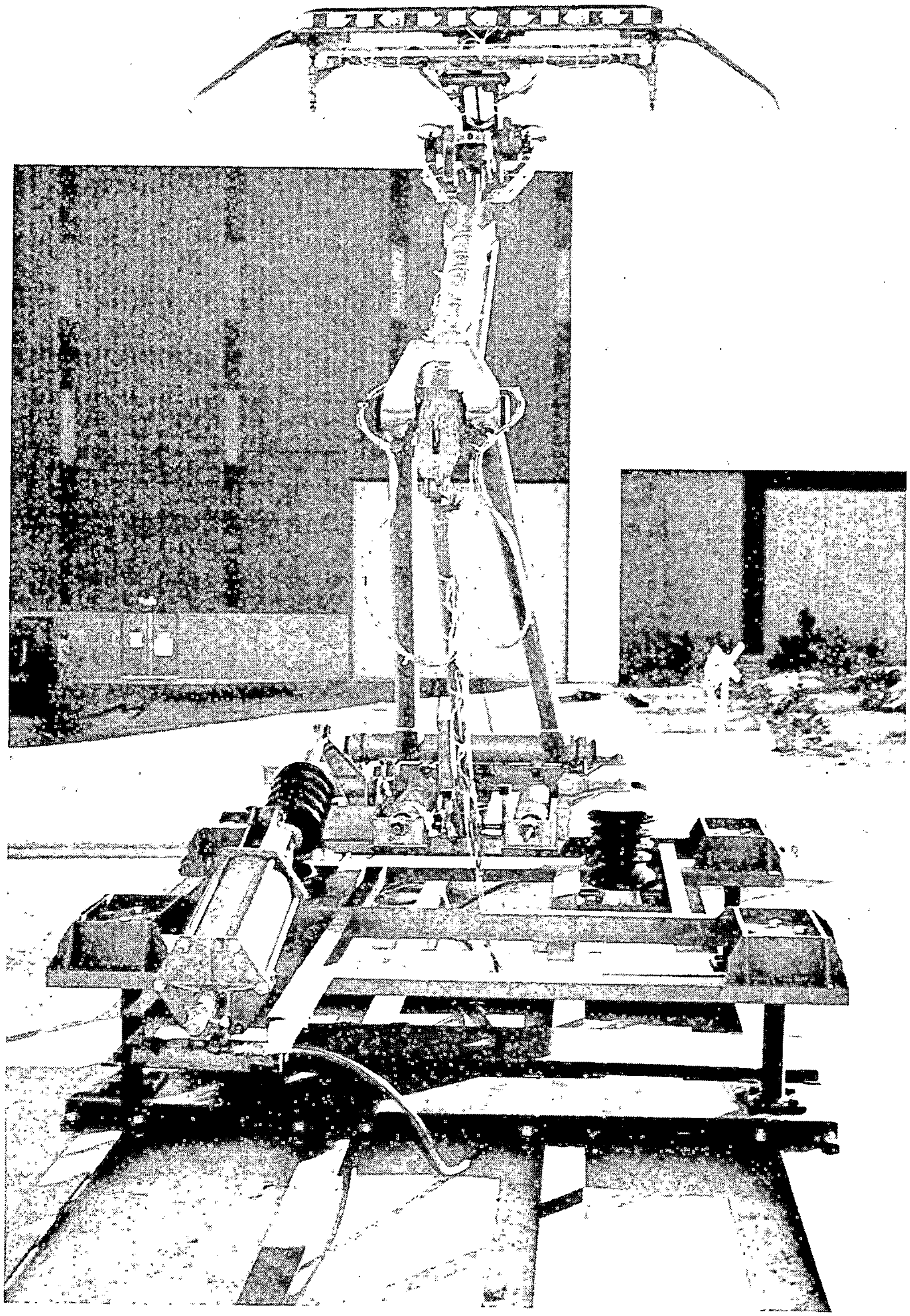


FIGURE 2-9. FRONT VIEW, DUAL STAGE PANTOGRAPH.

A high rate hydraulic shock absorber (damper) is fitted to the main stage to control its motion. This arrangement moves the main stage to accommodate the large contact wire height changes, and lets the second stage accommodate the smaller, higher frequency displacements.

2.3.3 Pantograph Head

The design specified for the RTT catenary[3] was based on the use of a pantograph head with a 52" across-track carbon contact surface (carbon width). The standard 3-strip AMTRAK pantograph head, which is fitted to the 17MCP1A5 pantograph, has two outer sections with a carbon width of only 35", and a center section with 24" of carbon. Use of this head on the RTT would have led to accelerated contact wire wear at the structures on the curves, i.e., the contact wire would have ridden on the steel strips at the end of the carbons.

During the test preparation, a modified center section (figure 2-10) for the AMTRAK head was designed and manufactured by the TTC. In the new design, one additional carbon section was added to each of the outer two strips, and the middle strip, which consisted of two carbon sections, was omitted. Thus the total number of carbon sections was the same for both heads, but the total width of carbon on the TTC head was 47", adequate for RTT operations.

In order to maintain the same strength and retain the same aerodynamic profile, the TTC head was manufactured from 2"x2"x1/8" square, hollow aluminum tubing. The modified carbon strips were mounted on the AMTRAK cast aluminum horn and pivot assemblies. The total assembly weighed 27 lbs, a weight saving of approximately 6 lbs. In order to simulate the original AMTRAK head in dynamic terms, the TTC head was ballasted with a steel weight.

The head fitted to the two stage pantograph had a 40" carbon width. It was decided that it was not worthwhile to change the head design for the limited number of operations planned with this pantograph. Careful evaluation of the maximum lateral displacements of the contact wire with respect to the head during this test would determine whether or not redesign would be necessary for further extensive testing of this unit.

2.4 TEST CONSIST

The test train (figure 2-11) consisted of a locomotive, the instrumentation car (DOTX 208), and the pantograph car (DOTX 211). The pantograph car was coupled with the pantograph on the trailing end. The observation windshield faced away from the direction of travel to ensure that any components falling from either the catenary or pantograph would not damage the windshield.

All high speed testing was carried out using locomotive DOT 001, and low speed testing used DOT 003 when speeds in excess of 95 mi/h were not

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[3] Federal Highways Administration, RFP, TTC Project 4 (8), Track Electrification, 1974.

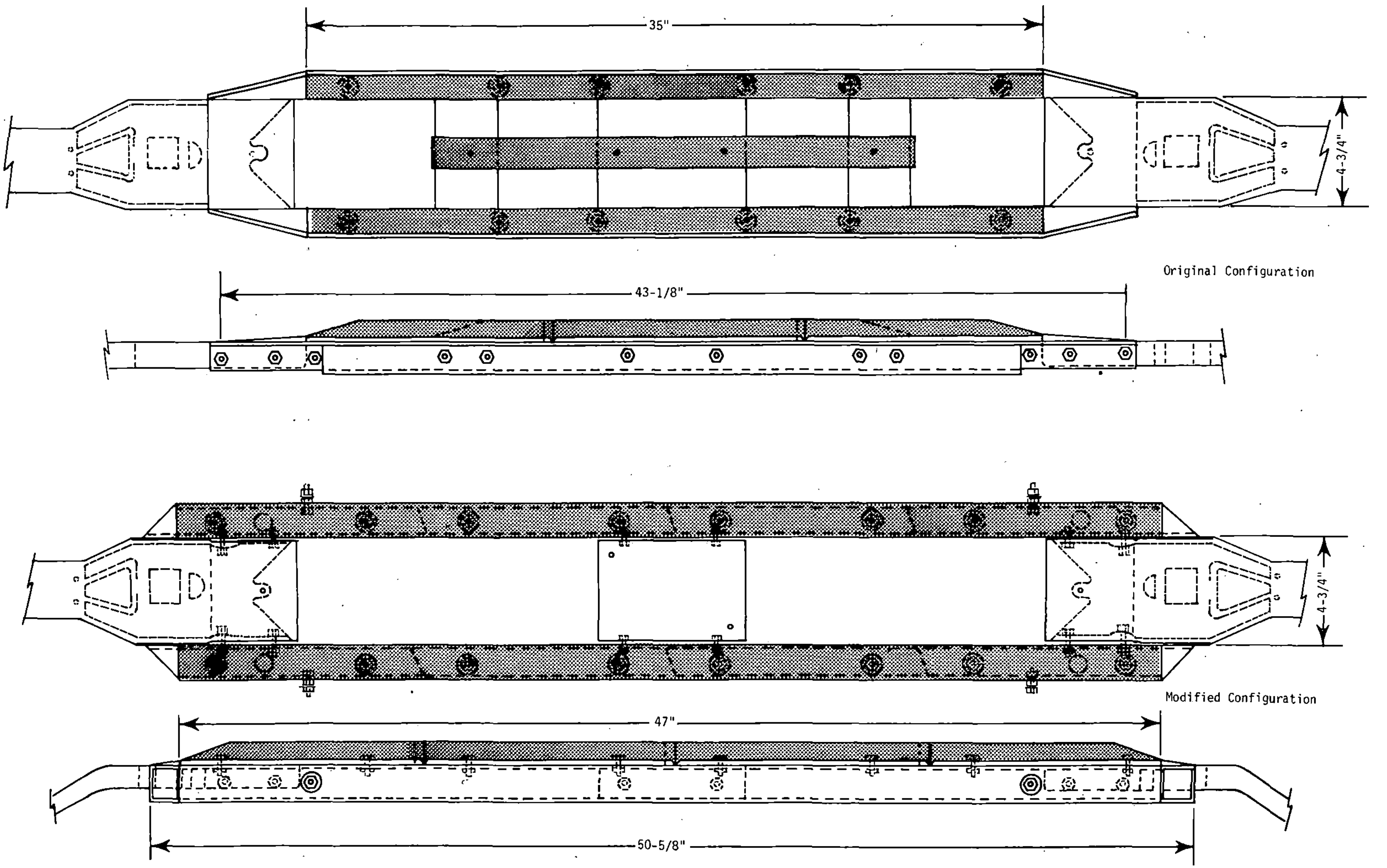


FIGURE 2-10. TTC MODIFIED PANTOGRAPH HEAD.

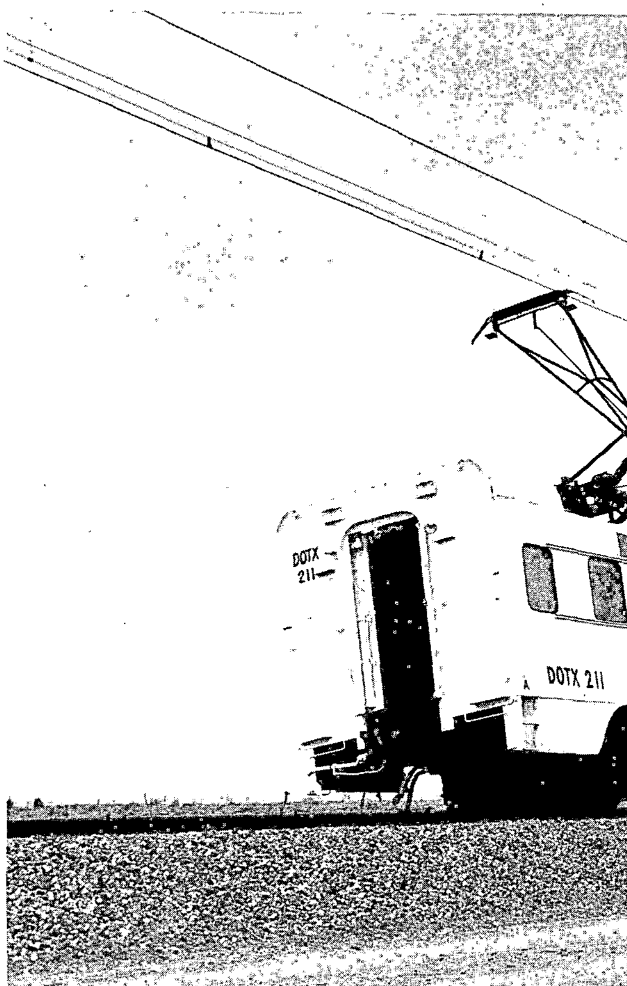
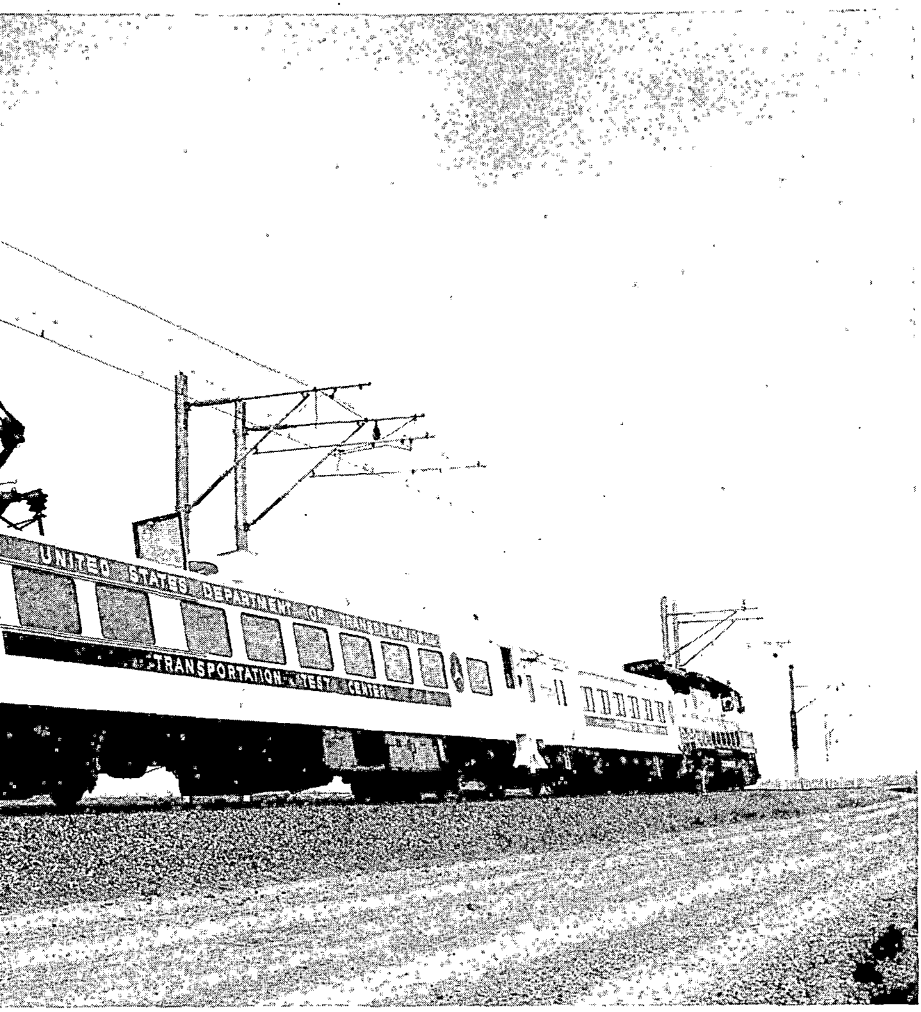


FIGURE 2-



11. TYPICAL TEST CONSIST.

required. Figure 2-11 shows the consist used in one of the earlier tests with DOT 003 as the locomotive.

2.5 INSTRUMENTATION

2.5.1 Dead Line Instrumentation System

The deadline instrumentation system[4] is outlined in appendix A. It can be used at slow speeds to measure the catenary geometry, or at high speeds, it can be used to assess the current collection performance of the pantograph. It can be set up to measure:

- Contact force,
- Contact wire stagger,
- Contact wire height,
- Head trajectory,
- Structure location, and
- Loss of contact (LOC).

The LOC data can be processed real-time to give an LOC percentage over a test zone selected manually, or remotely through the use of automatic location detectors (ALD) on the track.

2.5.2 Support Instrumentation and Recording Equipment

The standard instrumentation signal conditioning and recording system permanently installed in the DOTX 208 instrumentation car was used to support the dead line tests. Additional accelerometers were added to the pantograph top left and right hand corners of the upper frame to measure vertical, lateral, and torsional structural bending.

All acceleration, force, and displacement transducer signals were conditioned using signal conditoners and amplifiers filtered at a cutoff frequency of 30 Hz. Structure location and LOC signals were processed unfiltered. Dynamic signals required for the dead line instrumentation system processor were taken from the filter outputs, and the remainder were recorded directly. A block diagram of the instrumentation installation is presented in figure 2-12.

A number of data reference signals were added to the data flow. Position was referenced by the ALD's and the station markers. Site time, Inter Range Instrumentation Group B (IRIG B), was used as a recording reference. Train

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[4] ENSCO, Inc., User Manual for Pantograph Deadline Instrumentation, to be published.

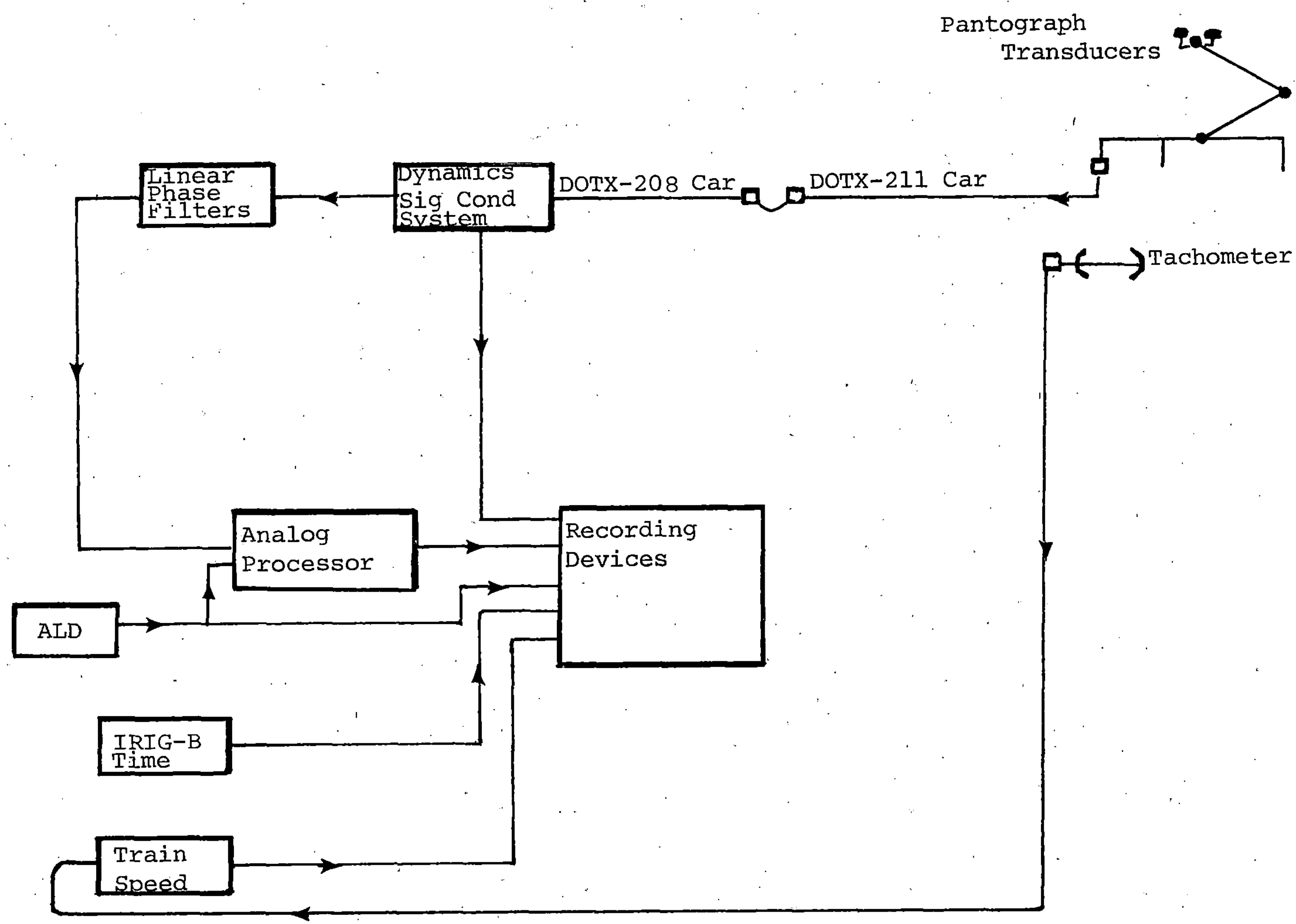

FIGURE 2-12. INSTRUMENTATION BLOCK DIAGRAM.

speed was recorded from an axle-mounted tachometer, and air speed was derived from an anemometer mounted on the roof of the DOTX 211 car. The anemometer was attached to the top of a sliding bar so that its height above roof line could be adjusted up to a 20-ft maximum height above the rail.

The data were recorded on a 14-channel analog tape recorder for post-test digitization. Selected channels of data were displayed on a strip chart recorder for real-time assessment of pantograph behavior.

The total aerodynamic lift force on the pantograph was measured with a load cell attached to the pantograph base frame. For stability, the pantograph head was then attached to the load cell by two lengths of lightweight chain, one to each of the outer carbon shoes. The lengths of the chain restraints could be adjusted to fix the head at any desired height above rail up to a maximum of 22 ft. Turnbuckles were used to adjust the inclination angle of the head.

Head suspension load cells were used to monitor the force between the head and frame by separating the head and frame lift components out of the total lift. For convenience, the pantograph uplift force was zero-balanced out of the transducer signals with the train stationary so that transducer outputs indicated aerodynamic lift force components directly when the consist was in motion.

2.5.3 Photographic and Video Support

Continuous video recording was used during the test runs to document unforeseen incidents such as pantograph failure or dewirement. Although no such incidents occurred, a selected number of tapes have been retained for reference.

High speed filming (100 frames/second) was used for visual analysis of pantograph behavior at phase breaks and overlaps. Still photography was used to document instrumentation transducer layout and to provide figures for reports.

3.0 DESCRIPTION OF TESTS

3.1 SCOPE

Since the instrumentation provided for this test was not set up to telemeter data across the high voltage barrier, all measurements were taken on a de-energized (dead) and grounded catenary. The grounding provided:

- A safety ground for pantograph-mounted transducers to guard against induced voltages on the catenary, and
- A circuit for the low voltage d.c. LOC measuring system (appendix A).

A maximum operating speed of 120 mi/h was imposed on these tests by the test consist, in particular the locomotive (DOT 001). This is not necessarily the design maximum performance limit of the catenary.

The assessment was made on the basis of constant height catenary only. No facilities were available to include the effects of graded wire or over-bridge arrangements in the assessment.

3.2 TEST OPERATIONS

Details of test operations were dependent on test requirements. For example, catenary geometry measurements required a different range of speeds and measured parameters from the high speed performance operations. Operations were in three categories; a typical operation from each is described below.

3.2.1 Geometry Measurements

The instrumentation was set up to monitor and record the following data:

- Contact force,
- Contact wire stagger,
- Contact wire height,
- Head trajectory (amplification of the measured contact wire height),
- Structure location,
- LOC,
- Train speed, and
- IRIG B time.

The pantograph was set up at the minimum practical uplift force to maintain a reliable contact with the catenary. For the single stage pantograph, the minimum contact force was 10 lbs, mainly from friction in the main frame mechanism.

Initial operations with the pantograph in contact with the catenary were undertaken with caution. Critical installations such as the Balloon Track turnout, phase breaks, the critical overlaps, and the Balloon Track section break were first negotiated at a speed of 5 mi/h in both directions. The test was then repeated at a speed of 10 mi/h. Analysis of strip chart data determined whether or not the critical installation in question gave satisfactory performance; i.e., that there were no sudden changes in pantograph head trajectory and no measurable impact forces.

Once satisfactory performance of the particular feature under review was established, the pantograph was run under the entire test section of catenary at a speed of 10 mi/h in both directions of travel. Data from the pantograph was recorded on a strip chart, and the strip charts were analyzed for contact wire height and stagger. Where the measured heights and staggers deviated from a normal pattern, these areas were identified for investigation and adjustment.

The pantograph uplift force was increased to 20 lbs, the nominal value specified by IECO in the RTT catenary design[3]. Test runs were then made under the catenary, first at 10 mi/h in one direction of travel, followed by 30 mi/h runs in both directions of travel.

Subsequent runs to verify any needed adjustments were made at a speed of 30 mi/h with a pantograph force of 20 lbs. For sections of catenary with no special features the 10-lb uplift force measurements were omitted to shorten the measurement process.

3.2.2 Aerodynamic Forces

Aerodynamic uplift forces on the pantograph were measured as part of the pantograph evaluation tests. The pantograph was mounted on the DOTX 211 car with the head restrained by a light chain, as described in section 2.5. Parameters measured were:

- Total aerodynamic uplift force (restraint load cell output),
- Head suspension force,
- Train speed relative to surrounding air (DOTX 211 anemometer output),
- Direction of air flow relative to train,
- Train speed (tachometer),

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[3] Op. cit.

- Structure location, and
- IRIG B time.

The instrumentation transducer signals were all zero-balanced with the train stationary, the pantograph raised but restrained by the chains, and the anemometer propeller clamped and alined with its axis of rotation parallel to the vehicle center line.

Test runs were then made around the RTT at nominal speeds of 70, 90, 100, 110, and 120 mi/h. Data were recorded over selected sections of the track on analog tape and strip charts for post-test analysis.

3.2.3 High Speed Pantograph and Catenary Performance Tests

The same data were used to assess the high speed performance of a pantograph and the catenary on which the pantograph was running, but data analysis for the two aspects of the test differed.

For the RTT high speed tests, the pantograph instrumentation was set up to measure:

- Frame vertical acceleration,
- Frame lateral acceleration,
- Head inertia (vertical),
- Head suspension force,
- Contact force,
- Main or first stage displacement,
- Second stage displacement,
- Head trajectory,
- LOC,
- Air speed,
- Structure marker,
- Train speed,
- ALD, and
- IRIG B time.

A number of combinations of head mass and uplift force, the two available variable pantograph parameters, and direction of travel (clockwise and counterclockwise--CW and CCW) were tested for each pantograph. These are detailed in the test matrix (section 3.4).

3.3 PRETEST CHECKOUT

Before each test operation, a thorough instrumentation checkout was conducted to ensure that the real-time computed data channels for contact force and trajectory were correctly scaled. For contact force measurements, a calibration weight was applied to the pantograph head to check the overall sensitivity of the force measuring system, and to check the static uplift force. The trajectory was checked by applying known displacements to the head and frame suspensions.

After satisfactory static checkout of the instrumentation system, the pantograph was run at a speed of 30 mi/h under the selected test section of the catenary. This run served as a track conditioning run (a TTC requirement), and as a dynamic checkout of the instrumentation system.

3.4 TEST MATRIX

Following the track conditioning run, the test run matrix was initiated (table 3-1). Test runs were made on the RTT at nominal speeds of 60, 70, 80, 90, 100, 105, 110, 115, and 120 mi/h. The data from the pantograph were recorded on analog magnetic tape, and critical performance assessment channels (e.g., contact force, LOC) were displayed on a strip chart recorder. All speed increments were usually achieved in successive laps of the RTT, but for some operations fewer speed increments were used.

3.5 DATA PROCESSING AND ANALYSIS

Two methods of analysis were applied to the recorded data: visual analysis of strip chart data, and computer analysis of selected data. For the geometry measurements and aerodynamic lift force measurements, it was considered more convenient to reduce the data from the strip chart rather than use computer techniques. This decision is discussed further in section 4. The data were processed by replaying the analog LOC data through the dead line instrumentation LOC processor five times. The rejection level was set at the upper limit of each time bin in succession, starting with 2 ms and ending with 50 ms. The percentage of LOC remaining after raising the rejection level was noted for the selected time slice. The 2 ms percentage was then used as the denominator to determine the relative percentage of contact loss in each time bin. This procedure permitted the comparison of ratios for a number of parameter changes, including speed and uplift. It should be noted that this comparison was made on the basis of time and not number; therefore, it could be related directly to information given in 4.4.1.a and b.

For the high speed catenary and pantograph data, a combination of strip chart analysis and computer analysis was used. Where computer analysis techniques were required, selected time slices of the analog tapes were low pass filtered and digitized. IRIG B time was used to reference the data, both for the digitization process and subsequent analysis.

TABLE 3-1. TEST MATRIX.

Oper. No.	Date	Purpose	Speeds (mi/h)	Test Zone (Sta. Nos.)	Direction of Test	Catenary Styles	Pantograph Type	Head Mass (lbs)	Uplift Force (lbs)	Analog Type RTT 7151-
1	7/13/70	Instrumentation checkout	10	R21 - R26	CW	5	17MCP1A5	33	20	001
2	7/16/79	Catenary performance	30-95	R21 - R32	CW	5	17MCP1A5	33	20	002
3	7/18/79	Catenary performance	30-95	R21 - R32	CW	5	17MCP1A5	33	20	003
4	7/19/79	Geometry measurement	10-30	R21 - R60	CW	5	17MCP1A5	33	20	004
5	7/27/79	Geometry measurements	10-45	R60 - R74	CW	5	17MCP1A5	33	10	005
6	8/02/79	Pantograph performance	30-120	R60 - R21	CW	5	17MCP1A5	33	20	006
7	8/13/79	Geometry measurements	5-20	RTT	CW	1,3,5	17MCP1A5	33	10	007
8	9/29/79	Pantograph performance	30-120	R60 - R48	CW	1,3,5	17MCP1A5	33	20	008
9	9/27/79	Geometry measurements	10-25	RTT & Balloon	CW & CCW	1,3,5	17MCP1A5	33	20	009
10	9/28/79	Pantograph performance	10-70	R69 - R22	CCW	1,3,5	17MCP1A5	33	20	010
11	10/02/79	Aero	70-120	R69 - R8	CCW	-	17MCP1A5	33	20	011
12	10/05/79	Pantograph performance	30-115	RTT	CW	1,3,5	17MCP1A5	33	20	012
13	10/12/79	Aero	30-120	R69 - R8	CCW	-	17MCP1A5	33	20	013
14	10/17/79	Pantograph performance	30-120	R69 - R22	CCW	1,3,5	17MCP1A5	33	20	014
15	10/19/79	Panto. perf. & Geo. measurement	30-120	RTT	CCW	1,3,5	17MCP1A5	33 29	28* 20	015
16	11/15/79	Panto. perf. & Aero	30-120	R69 - R8	CCW	1,3,5	17MCP1A5	33	20	016
17	12/07/79	Pantograph performance	30-120	R69 - R74	CCW	1,3,5	AM-DS12	33	20	017
18	12/12/79	Panto. perf. & Aero	30-120	R69 - R74	CCW	1,3,5	AM-DS12	30	20	018
19	12/20/79	Pantograph performance	3-120	R69 - R74	CCW	1,3,5	AM-DS12	30	20* 28	019

* Changed parameters midshift.

The TTC standard software for the Varian V76 and PDP 11/60 computers was used as the basic data reduction tool, although some minor additions were necessary. Specific details of the analysis techniques employed are:

Measurement	Analysis Technique
Contact force	Mean, root mean square (rms), and standard deviation
LOC	Modified histogram (exceedence count)
Frame acceleration	Summation, Power Spectral Densities (PSD)
Speed	Mean
Air speed	Mean

4.0 RESULTS AND DISCUSSION

4.1 CATENARY GEOMETRY MEASUREMENTS

4.1.1 Methodology Assessment

A careful assessment of the accuracy of the measuring technique was essential before the system could be used for reliable catenary geometry measurements. Since the instrumented pantograph used the car roof as a datum, the car dynamics inevitably affected the measurements. Thus contact wire height and contact wire stagger were separately evaluated.

a. Contact wire height. The contact wire height was measured using the main frame (first stage) displacement. For the slow speed geometry measurements, the head suspension was mechanically locked out and did not figure in the measurements.

The pantograph was located directly above one of the trucks, therefore, the dynamic effects of only one truck needed to be considered. The effects of carbody pitch were also substantially eliminated. Thus, truck and carbody errors were derived from two sources--carbody bounce and wheel diameter tolerance.

Next to be considered were errors due to the pantograph itself. Because the pantograph height varations were so large, direct measurement of the main frame displacement was impractical, and an indirect measurement was used (appendix A). The pantograph lockdown height was used as the measurement datum and the electrical output of the displacement transducer was calibrated against measured frame height above lockdown. Significant nonlinearities existed in this method of measurement.

Next to be considered was the effect of pantograph uplift. As the pantograph passed over the catenary, the uplift force tended to lift the contact wire, the wire lift being greater in midspan than at the support. One way to overcome this problem was to use the minimum uplift force required to maintain reliable contact with the catenary. However, the single stage pantograph unit tested at the TTC exhibited a vertical friction level of approximately ± 2 lbs. This, coupled with the natural nonlinearity in the uplift characteristic, limited the minimum permissible uplift to 10 lbs. Since the vertical stiffness of the supported catenary is in the order 10 to 20 lb/in, a contact wire lift of 0.5 to 1.0 in was experienced. It was decided to conduct the later geometry measurement with a standard uplift of 20 lbs, and treat the resultant measurements as loaded wire measurements. This was found to be acceptable from a constructional support/acceptance point of view. The accuracy assessment of the method was made on the basis of a loaded wire measurement.

The third pantograph-related problem occurred on the curved sections of track. As the car on which the pantograph was mounted negotiated a curve at slow speed, the roof of the vehicle became inclined at an angle equivalent to the angle of superelevation plus the quasistatic car roll angle. The pantograph head remained parallel to the car roof and was, therefore, inclined at the same angle.

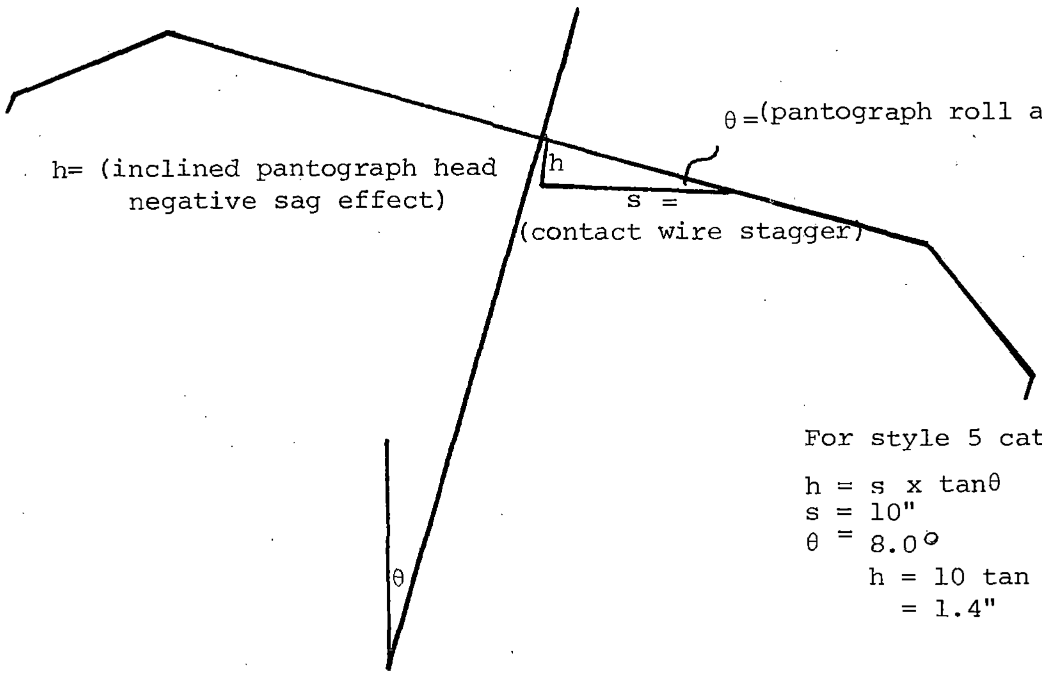
The wire movement with respect to the pantograph head as the car traveled the length of one span of catenary was as follows: at each of the support structures the contact wire was displaced laterally by a horizontal displacement equivalent to the wire stagger, while at midspan the contact wire was at the projected track centerline. The contact wire effectively moved a distance across the included pantograph head equivalent to the stagger. By simple geometry (figure 4-1) it can be shown that, for a 6° (6") superelevated track, a car roll of 2°, and a wire stagger of 10", an apparent wire height change of 1.4" is indicated by the pantograph frame. This effect cannot be considered a limitation on the measurement technique for two reasons. First, the standard height and stagger gage were subject to the same error. Second, the pantograph at speed was subjected to the same effect. Since the inclined pantograph head effect appeared to the pantograph as a reduction in contact wire presag, it must be overcome in the catenary design by increasing the contact wire presag on curves by an equivalent amount.

Thus, the limitation to be placed on desired wire height measurements can be summarized as follows: the absolute height accuracy is ± 2", accuracy for comparison measurements ± 0.75", and this method can be used for measuring the height of loaded wire (table 4-1).

TABLE 4-1. SUMMARY OF HEIGHT MEASUREMENTS.

Source	Estimated Error (in)	Cumulative Error (in)
Pantograph lockdown height	0.5	0.5
Carbody bounce	0.5	1.0
Wheel diameter tolerance	0.25	1.25
Calibration nonlinearity	0.75	2.0
Pantograph uplift (20 lbs)	1-2	-
Head inclination	1.4	-

b. Contact wire stagger. Two methods of stagger measurements were employed (appendix A), the segmented head and the force beam computed methods. The segmented head method has the advantage of employing a direct measurement technique but has the disadvantage of requiring a special head manufactured of copper. In addition, it does not allow LOC to be measured with the same head. The computed method, on the other hand, uses a standard head and therefore overcomes the segmented head disadvantages, but requires very careful setup.



For style 5 catenary and DOTX-211 Car

$h = s \times \tan\theta$

$s = 10"$

$\theta = 8.0°$

$h = 10 \tan 8.0$

$= 1.4"$

FIGURE 4-1. NEGATIVE SAG (HOG) DUE TO PANTOGRAPH HEAD INCLINATION.

Two major errors arose in the use of the instrumented pantograph for wire stagger measurements:

- Basic transducer error. Each of the stagger measurement methods was subject to transducer error. The segmented head derived its error from lack of resolution; it could measure only to the nearest segment and each segment was 1" wide, giving a maximum possible error of ±0.5". On the other hand, the computed stagger method derived its error from the computation; it relied on a very accurate zero balance of the transducers and amplifiers. However, with careful setup the computation error could be kept to within ±0.25".

- Carbody roll. Both methods of stagger measurements were subject to error due to carbody roll on superelevated track. The amount of rollover was dependent on the amount of superelevation and the speed at which the vehicle negotiated the curve. Measurements were made while the DOTX 211 car was stationary on a 6" superelevated curve on the RTT (appendix B). It was found that the carbody rolled through a $2^{\circ}15'$ angle about a center approximately 8" below rail level, giving an equivalent pantograph head lateral displacment of 10.75" at a height of 22'6". Since the roll is maximum at zero speed, zero at balance speed (V_B), and is inversely proportional to the square of the car speed (V), a correction (C) can be applied to the mean of the stagger data for curved track given by:

$$C = 10.75 \left[1 - \left(\frac{V}{V_B} \right)^2 \right]$$

This formula applies only to a pantograph head on the DOTX 211 car on a 6" superelevated curve at 22'6" above rail. On the RTT, all curves are identical in curvature, having the same balance speed (105 mi/h) and 6" nominal superelevation. For the curve spiral, the corrected mean was taken as a straight line drawn between the zero for the level tangent track and the corrected mean for the circular curve.

Based on the residual error after the curved track correction and the transducer error had been applied, the estimated maximum overall error for the segmented head was ±1.25", and for the computed method, ±1.0" (table 4-2).

TABLE 4-2. SUMMARY OF STAGGER MEASUREMENTS.

Source	Segmented Head Estimated Error (in)	Segmented Head Cumulative Error (in)	Computed Method Estimated Error (in)	Computed Method Cumulative Error (in)
Transducer error	±0.5	0.5	±0.25	0.25
* Car body roll	+0.75	1.25	+0.75	1.0
Total		+1.25		+1.0

*After correction factor is applied.

4.1.2 Interpretation of Catenary Geometry Measurements

a. Construction Limits. The original construction limits for the RTT catenary[3] were:

- Contact wire height above rail 22'6" ± 2"
- Contact wire stagger

  (Tangent track, 210 ft spans) 9" ±1"

  (Curved track, 210 ft spans) 10" ±0.5"

  (Tangent track, 250 ft spans) 6" ±1"

During construction it was found that differences in some components caused the actual wire height on curved track to be a nominal 22'10". To overcome these deficiencies it would have been necessary to lower the cantilever supports on each of the poles along the curved sections of track, approximately 75% of the RTT. In view of the impact such a major adjustment would have had on completion of the project, the contact wire height specification was modified to read:

- Contact wire height above rail

  Tangent track - 22'6" ± 2"

  Curved track - 22'10" ± 2"

- Contact wire stagger - Nominal = ± 1"

Catenary height and stagger, as measured with the instrumented pantograph, were judged on the basis of the revised specification.

b. Height and Stagger Measurements. Several examples of height and stagger measurements are given in figures 4-2 through 4-5. Figures 4-2, 4-3, and 4-4 are examples of tangent, spiral, and curved track, respectively, all of which were in tolerance. It was found that, with experience, it was possible to see where catenary sections were out of tolerance as the strip charts were being produced. These areas could then be identified by marking the strip charts for post-test analysis. An example of out-of-tolerance catenary is shown in figure 4-5.

This example, a stagger error near station R17, was identified as the specified stagger being displaced by one span on entry to a curve spiral. An error in wire height was also identified near station R52. Before and after the necessary adjustments were carried out, the construction contractor used a height and stagger gage to measure the two short catenary sections containing the errors in order to verify the instrumented pantograph measurement technique.

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[3] Op. cit.

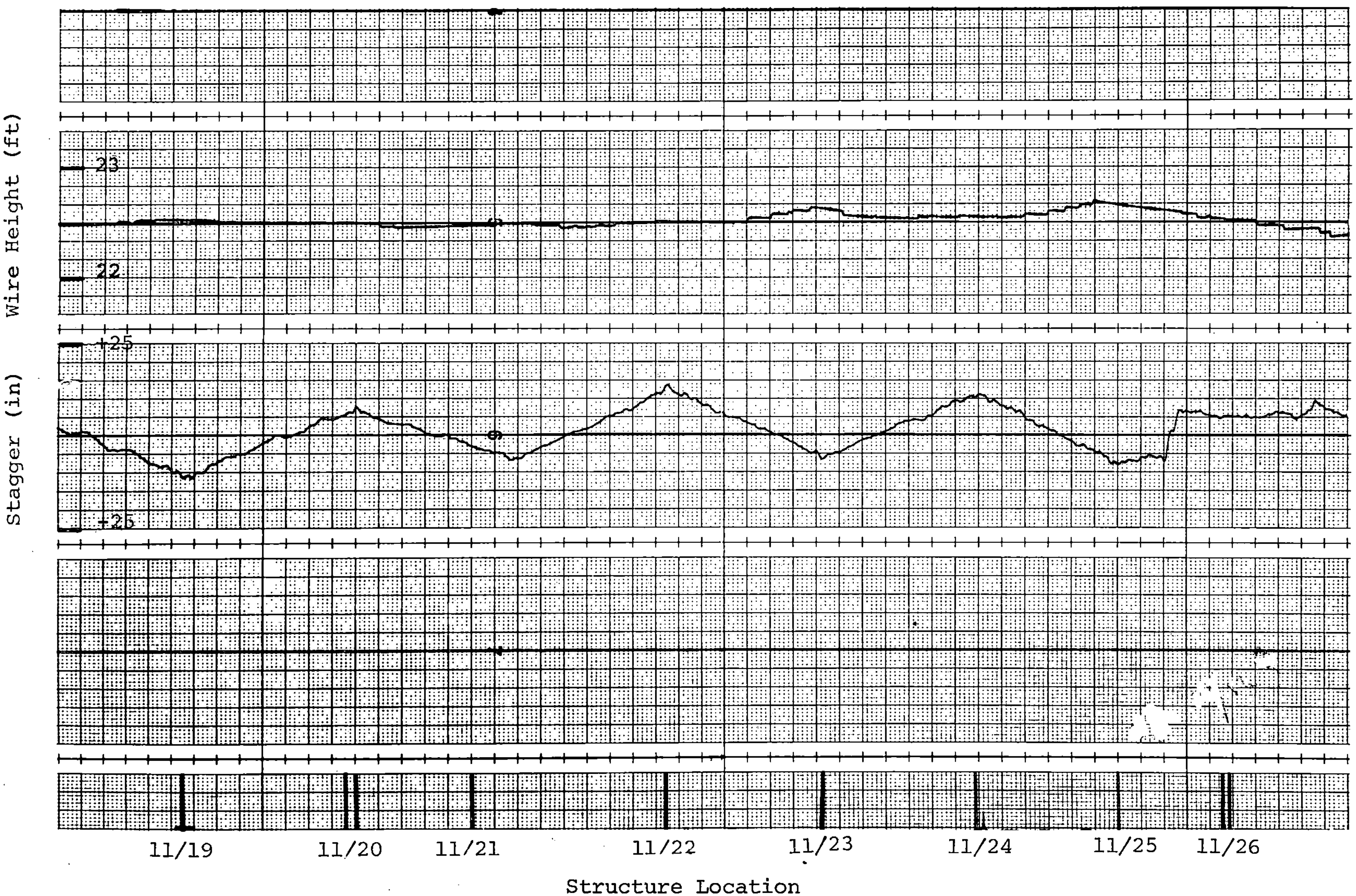

FIGURE 4-2. HEIGHT AND STAGGER MEASUREMENTS (TANGENT TRACK).

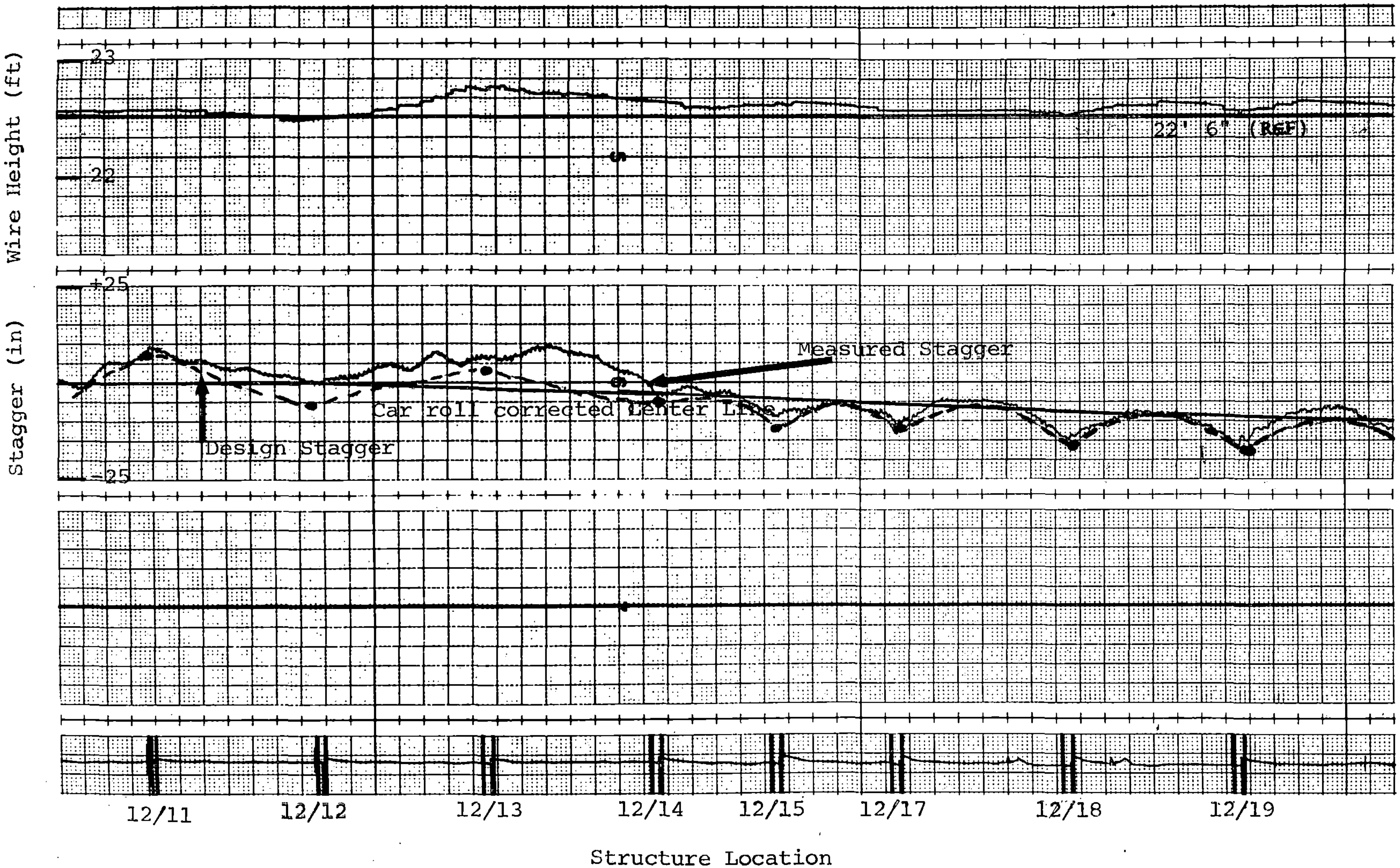

FIGURE 4-3. HEIGHT AND STAGGER MEASUREMENTS (SPIRAL TRACK).

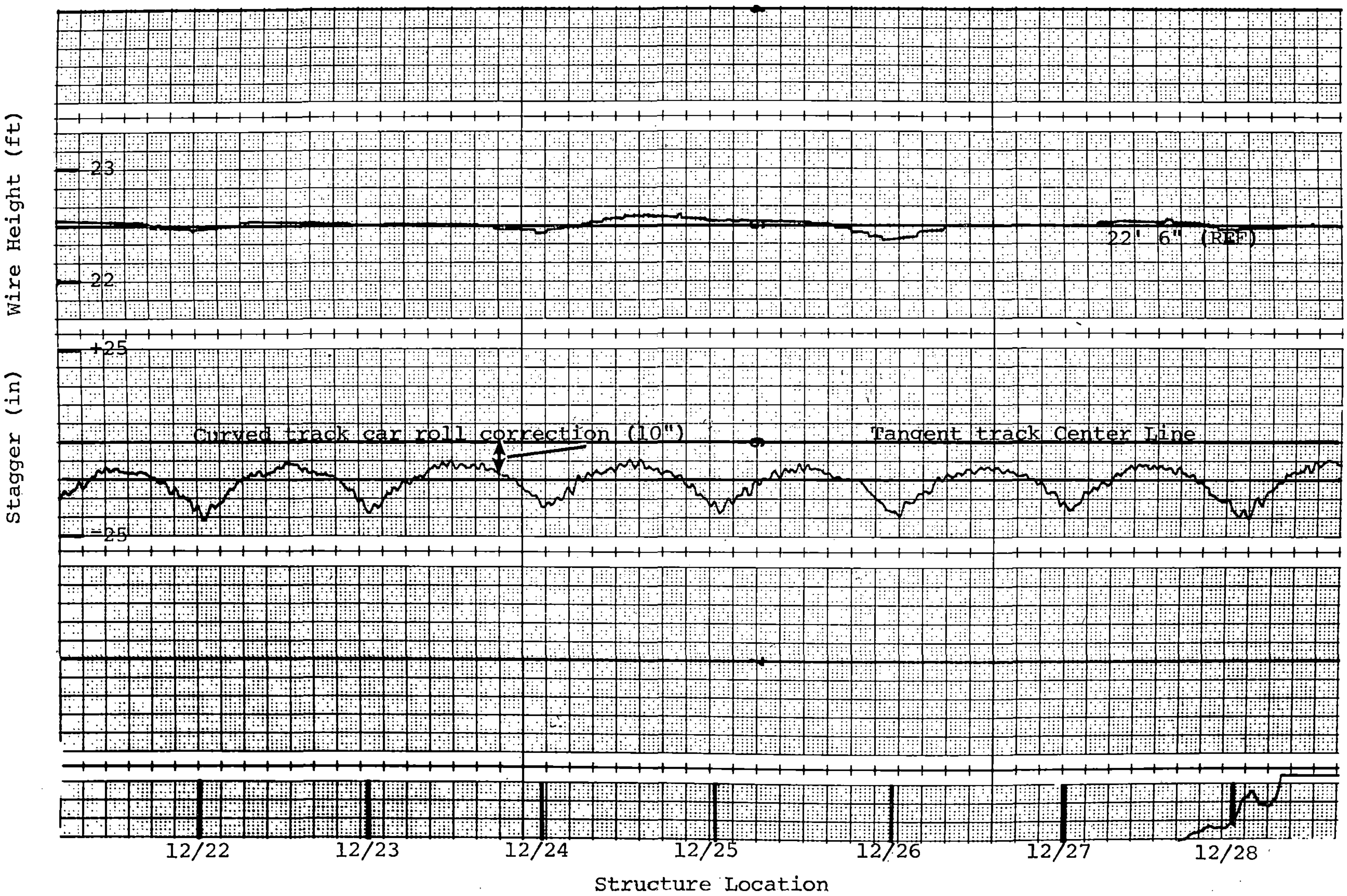

FIGURE 4-4. HEIGHT AND STAGGER MEASUREMENTS (CURVED TRACK).

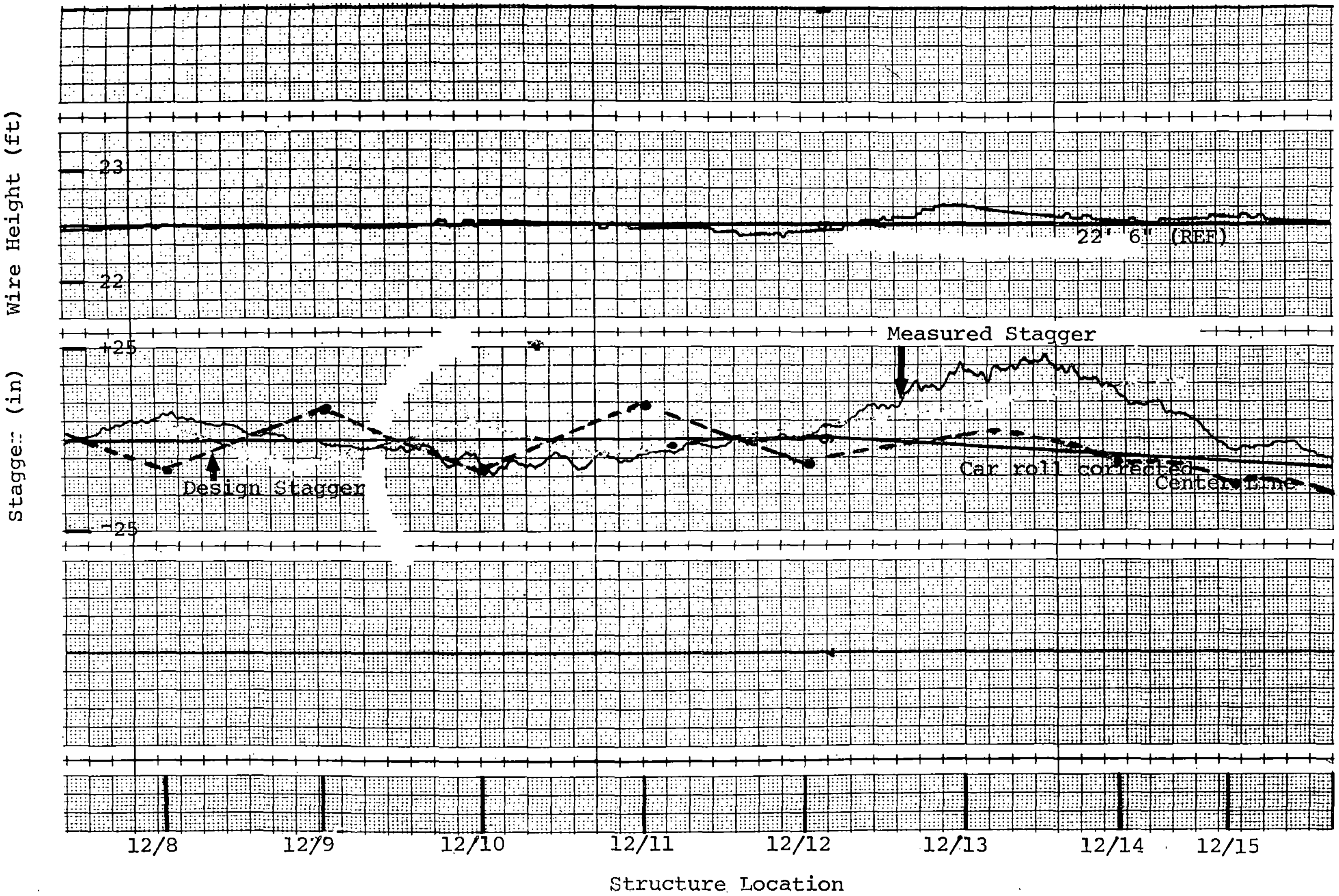

FIGURE 4-5. CONTACT WIRE STAGGER CONSTRUCTIONAL ERROR.
(SHOWN CORRECTED IN FIGURE 4-3).

included a design error in the out-of-running wire support arm in the overlaps, and a minor out-of-tolerance wire height at the balloon turnout.

These two errors, together with sag error on curves from pantograph head inclination, were the only major height and stagger errors to be identified in the newly constructed catenary. Other minor problems Balloon Track turnout. Since the necessary corrective measures would have involved major cantilever adjustments of both the RTT and Balloon Track catenaries, and as no appreciable high-speed performance degradation was anticipated (later confirmed by test), it was decided simply to note the error.

c. <u>Contact Force Measurements</u>. While the height and stagger measurements were considered to be the primary measurements, contact force data were also recorded. Information from these measurements included such things as minor obstacles caused by incorrectly installed hanger clips, equalizing and overlap jumpers hanging below the contact wire, and kinks in the contact wire.

The only examples of contact force-indicated faults were two instances of kinked contact wire, one in the Balloon Track trolley wire (figure 4-6), the other in the RTT contact wire near station R8. (It should be noted that this information cannot be derived from height and stagger measurements and requires the use of an instrumented pantograph.)

d. <u>Catenary Acceptance</u>. After completion of construction and corrective adjustments, a final set of geometry measurements was taken on the RTT and Balloon Track catenaries on October 19, 1979. The catenary system was accepted on the basis of these records. The data will be permanently retained at the TTC as the base record to which all future recordings will be compared. The record analog tape number is RTT7151-015.

4.2 CATENARY HIGH SPEED PERFORMANCE

The catenary has as much influence on the current collection performance of a pantograph as the pantograph itself. Before a pantograph can be assessed for maximum speed operation on a given catenary, it is important to ensure that the catenary is set up to its optimum condition. This is particularly true when the catenary system is newly installed, as was the RTT system during this test program.

Following the catenary geometry measurements and the subsequent adjustments, a speed upgrading of the catenary systems was conducted using the instrumented single stage pantograph to determine the suitability of the catenary system for 120 mi/h operation. Tests were carried out in both directions of travel, and the data analyzed to determine whether the pantograph performance was substantially uniform over each length of similar catenary. Visual analysis of the LOC data was used for this purpose and was supported, where necessary, by contact force and pantograph head trajectory data. The analysis was divided into five main areas, described below.

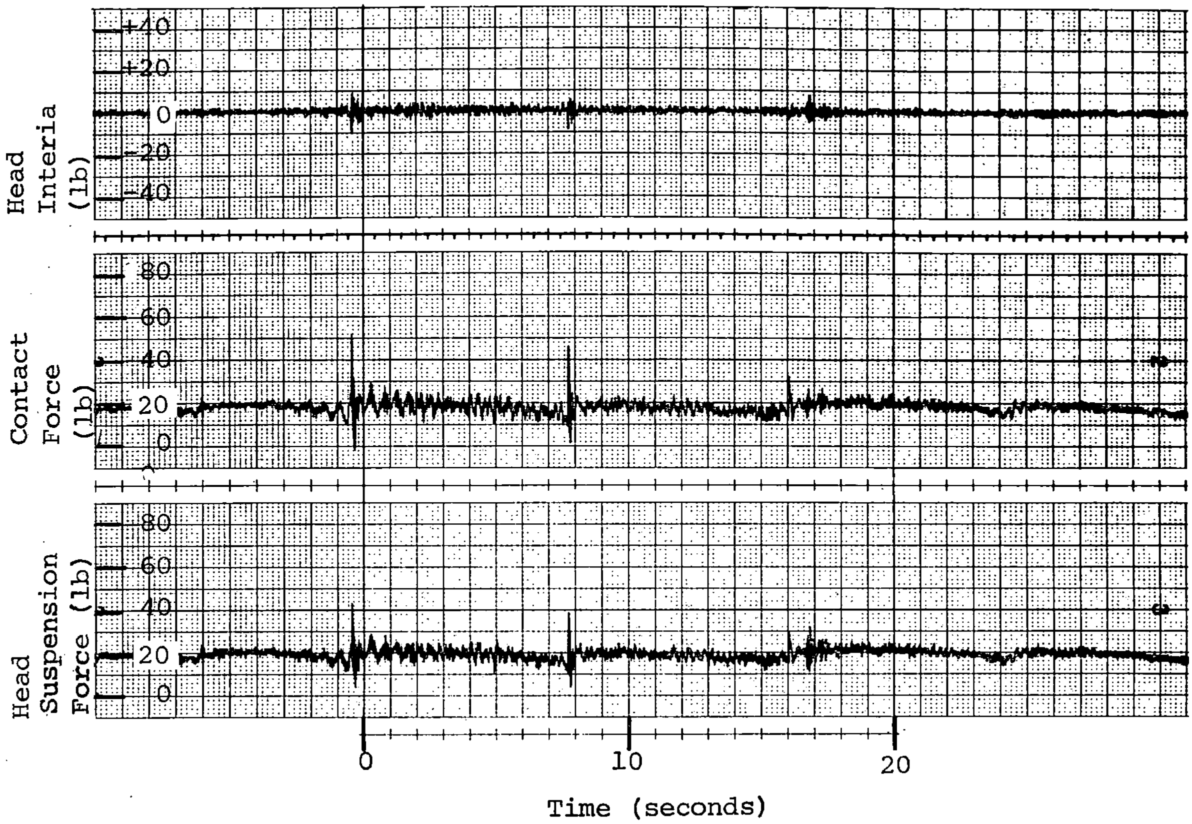

FIGURE 4-6. EXAMPLE OF CONTACT FORCE INDICATED ERRORS.

4.2.1 Style 5 Catenary

The style 5 catenary was subdivided into three parts:

- Style 5, 210-ft spans on tangent track,
- Style 5X, 250-ft spans on tangent track, and
- Style 5, 210-ft spans on curved track.

The records show that at a speed of 110 mi/h a regular pattern of contact loss developed on the 210 ft span style 5 catenary. This effect was more pronounced on curved track than tangent, probably due to the reduced contact wire presag on the curves. The registered contact losses appeared predominantly at the support structures. Figures 4-7 and 4-8 present examples of the LOC and contact force data.

Tests were run up to only 95 mi/h on the 250-ft span style 5X catenary system before it was replaced by the styles 1 and 3 catenary designs. This restriction was imposed because DOT 003 was substituted for DOT 001 for that period of testing. Only two sections of style 5 catenary showed nonuniform performance. These were at R8 (identified as small kinks in the contact wire) and R50 (caused by slight track irregularities at the track switches). Both sections of catenary were considered suitable for 120 mi/h operation based on the pantograph performance criteria described in paragraph 4.4.1.

4.2.2 Styles 1 and 3

Only one-half mile of each of the styles 1 and 3 catenary designs were available for evaluation; therefore, it was difficult to determine whether installation improvements were necessary. Both styles, particularly the style 3, showed significantly poorer performance than the style 5.

This statement is demonstrated by figure 4-9, which shows the transition from style 5 to style 3, and then to style 1. The RTT system was accepted as representative of the NEC counterparts and evaluated accordingly.

4.2.3 Overlaps

Without exception, the style 5 catenary overlaps showed no significant degradation in performance from the plain sections of style 5 catenary. However, the overlaps between the styles 5 and 3, the styles 1 and 3, and the styles 1 and 5, showed noticeably poorer performance (figure 4-9) than the basic catenary designs on either side of the overlap. This was caused by the difficulty in blending the different design styles, particularly the fixed tensioned style 5 and the fixed terminated styles 1 and 3. The suitability of these overlaps for 120 mi/h operation was marginal but acceptable for short term dead line testing. A decision on long term live line operation was deferred until a much fuller evaluation can be carried out.

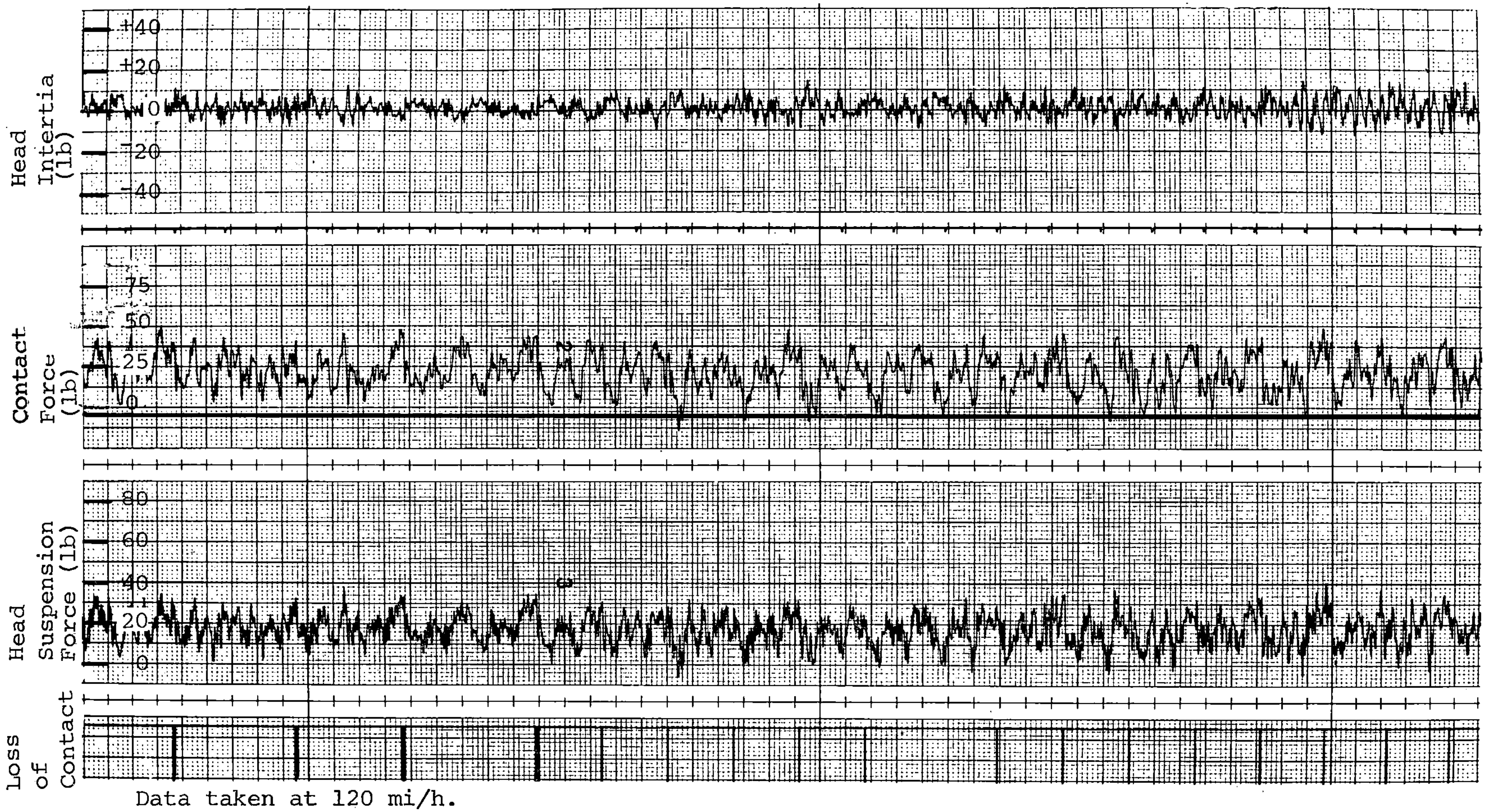

FIGURE 4-7. TYPICAL CONTACT FORCE AND LOC RECORD.

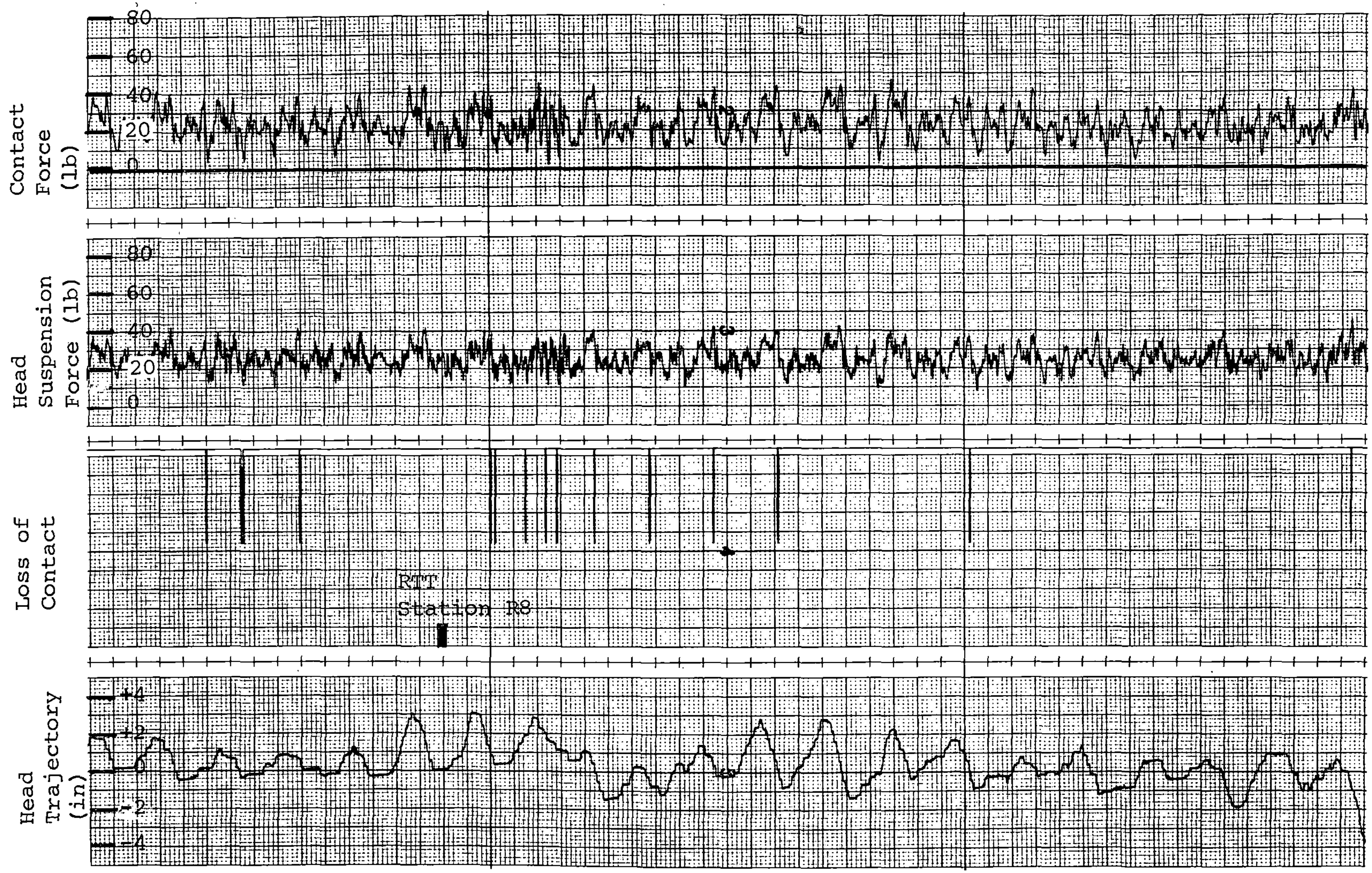

FIGURE 4-8. MEASURED LOSS OF CONTACT (STATION R8) DUE TO CONTACT WIRE KINKS.

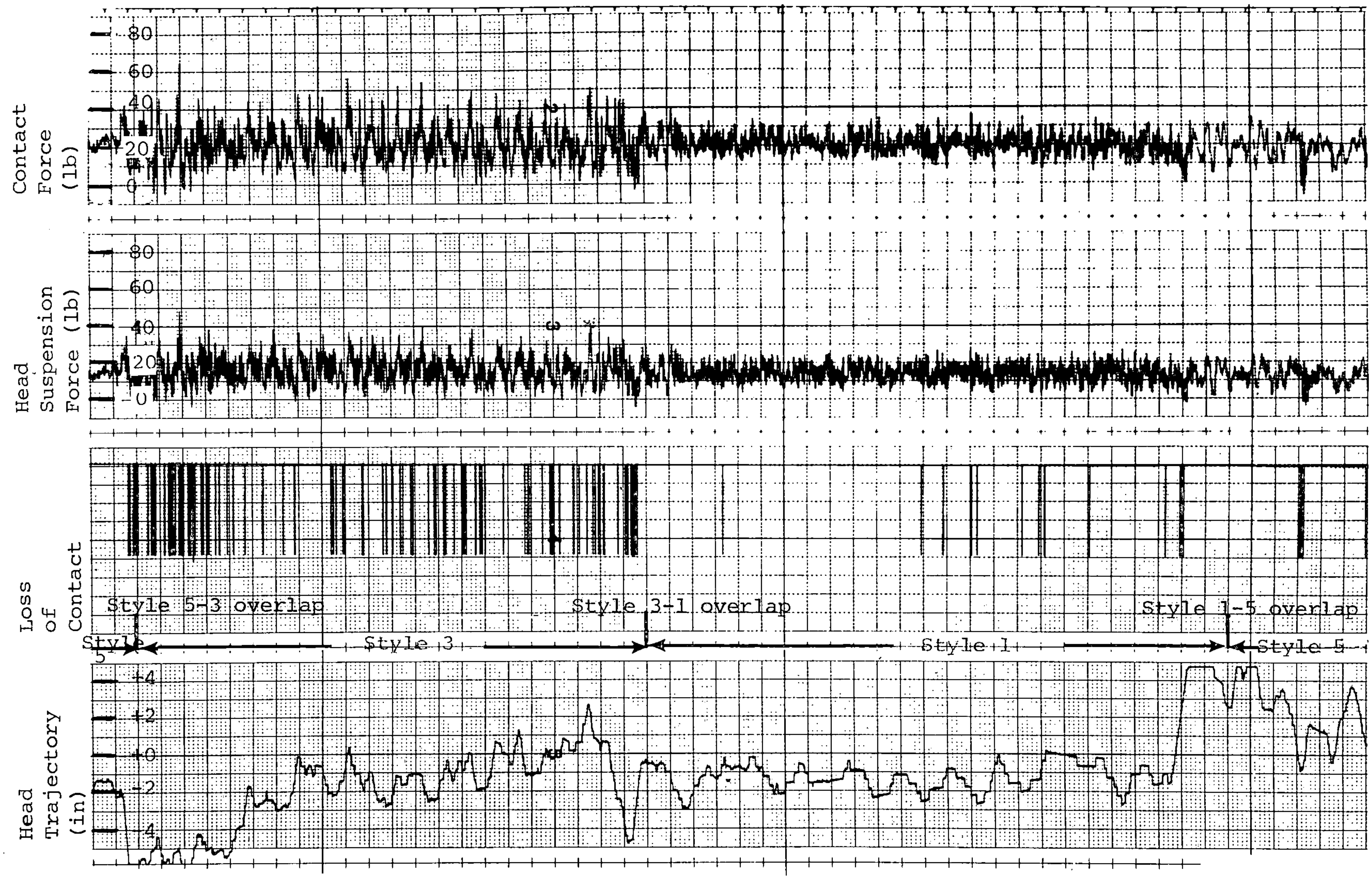

FIGURE 4-9. SEQUENCE OF OVERLAPS BETWEEN STYLES 5,3,1,5 CATENARY DESIGNS.

4.2.4 Turnouts

Only one turnout presently exists on the RTT, the junction between the balloon track and the RTT. Evaluation of this feature showed no significant increase in measured contact force despite the out-of-tolerance wire height at the turnout (figure 4-10).

4.2.5 Phase Breaks

Both phase breaks were installed in the catenary on a spiral, therefore the setup was difficult. (Ideally, phase breaks are installed in a section of catenary on tangent track.) During the increased speed runs, when approximately 120 passes were made over the BICC phase break and 80 over the Kupler phase break, the two phase break installations were carefully evaluated on the basis of the measured contact force.

Initially, the speed at which the measured contact force exceeded 125 lbs was set as the speed at which the test over the phase break would be terminated. Experience has shown[5] that measured contact force in excess of 125 lbs increases the chance of carbon chipping and corresponding phase break insulation and skid damage. Analysis of the data showed that the Kupler phase break generated a maximum force of 100 lbs in the speed range of 60 to 120 mi/h (see figure 4-11), while the BICC phase break generated forces exceeding the 125 pound limit over the same speed range (figure 4-12).

During the test program with the single stage pantograph, substantial carbon damage to the pantograph head was accumulated (figure 4-13). Detailed inspection of the BICC phase break showed corresponding damage to the skids. Analysis of the pantograph head trajectory at the phase break indicated that the contact wire on both sides of the phase break was incorrectly profiled. As a result, operation over the BICC phase break was suspended for the rest of the two stage pantograph tests until corrective measures could be taken. It should be noted that the fault was in the installation, and cannot be attributed to the phase break design. Post-test inspection of the Kupler phase break showed a slight bruising of one of the skids and a number of loose components.

4.3 AERODYNAMIC FORCES

4.3.1 Single Stage Pantograph

The aerodynamic lift forces were evaluated for a number of configurations of the single stage pantograph. First, it was aerodynamically tested with standard (AMTRAK) head heights of 22 and 19 ft above rail level. Although this head was not to be used for pantograph performance testing at the TTC, aerodynamic evaluation was necessary to provide a base comparison for the TTC

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5 British Rail R&D Division, "Pantograph and Catenary Evaluation Techniques," Unpublished Internal Memorandum, 1978.

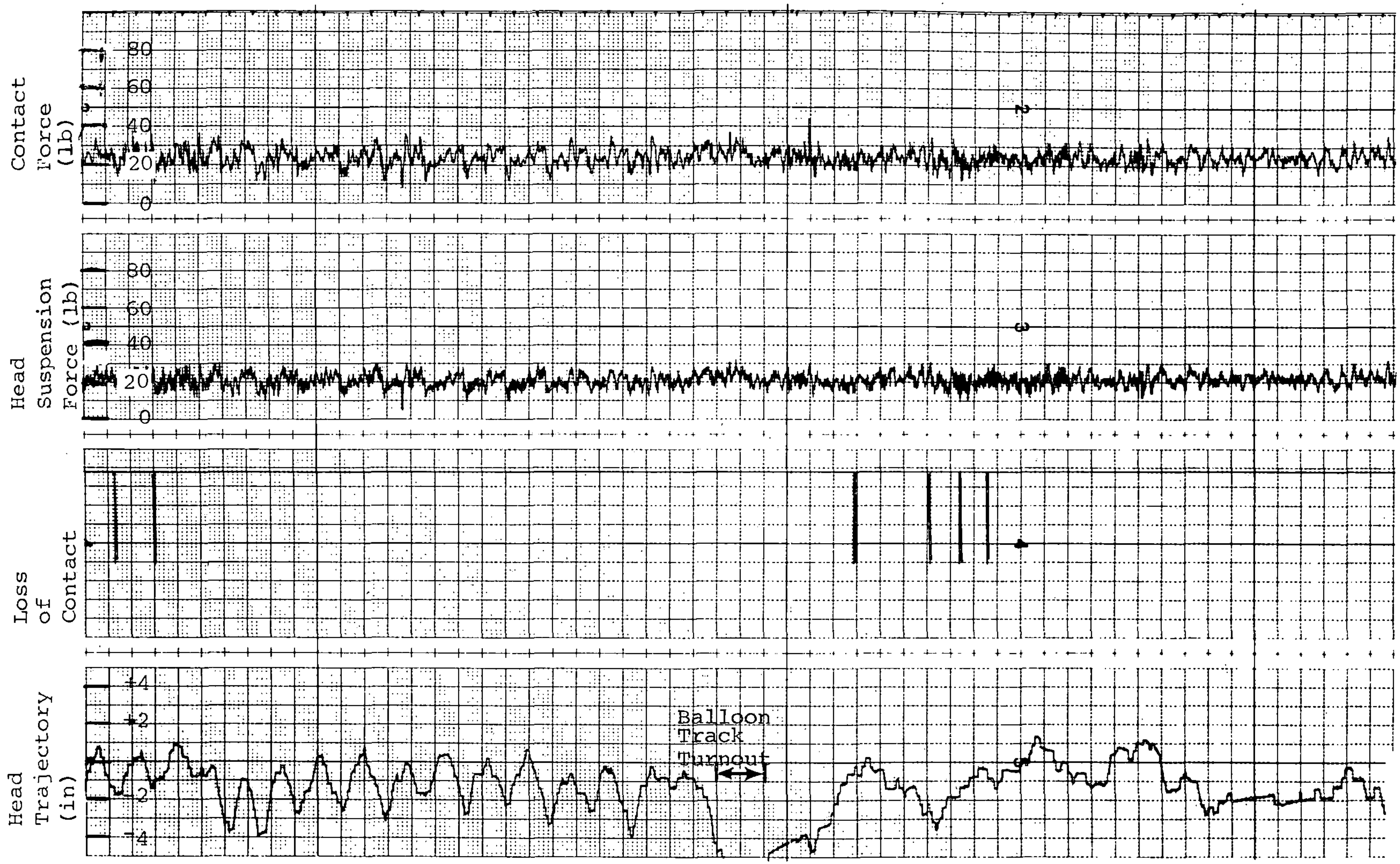

FIGURE 4-10. BALLOON TRACK TURNOUT PANTOGRAPH RESPONSE.

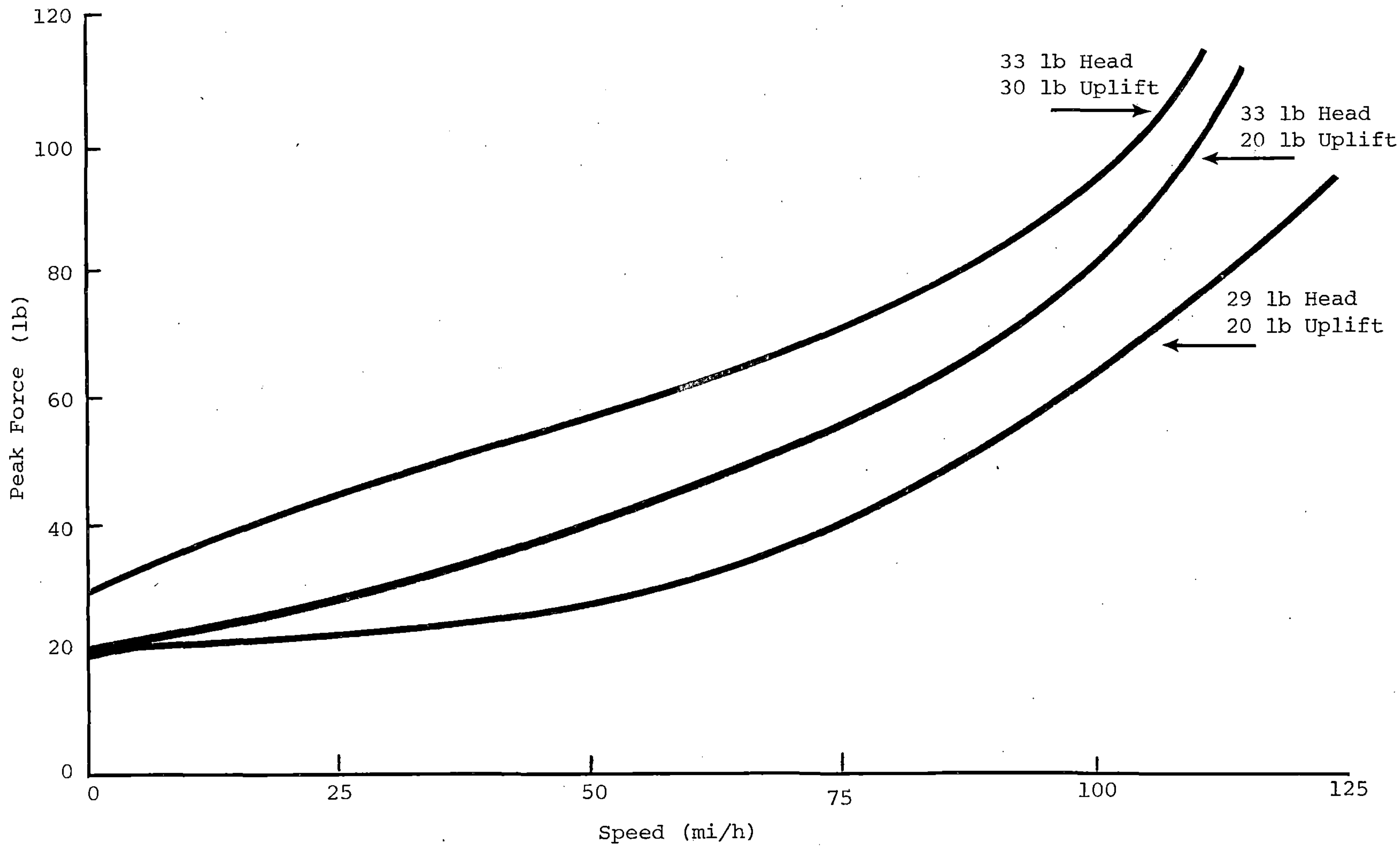

FIGURE 4-11. PEAK FORCE vs. SPEED BICC PHASE BREAK (CCW).

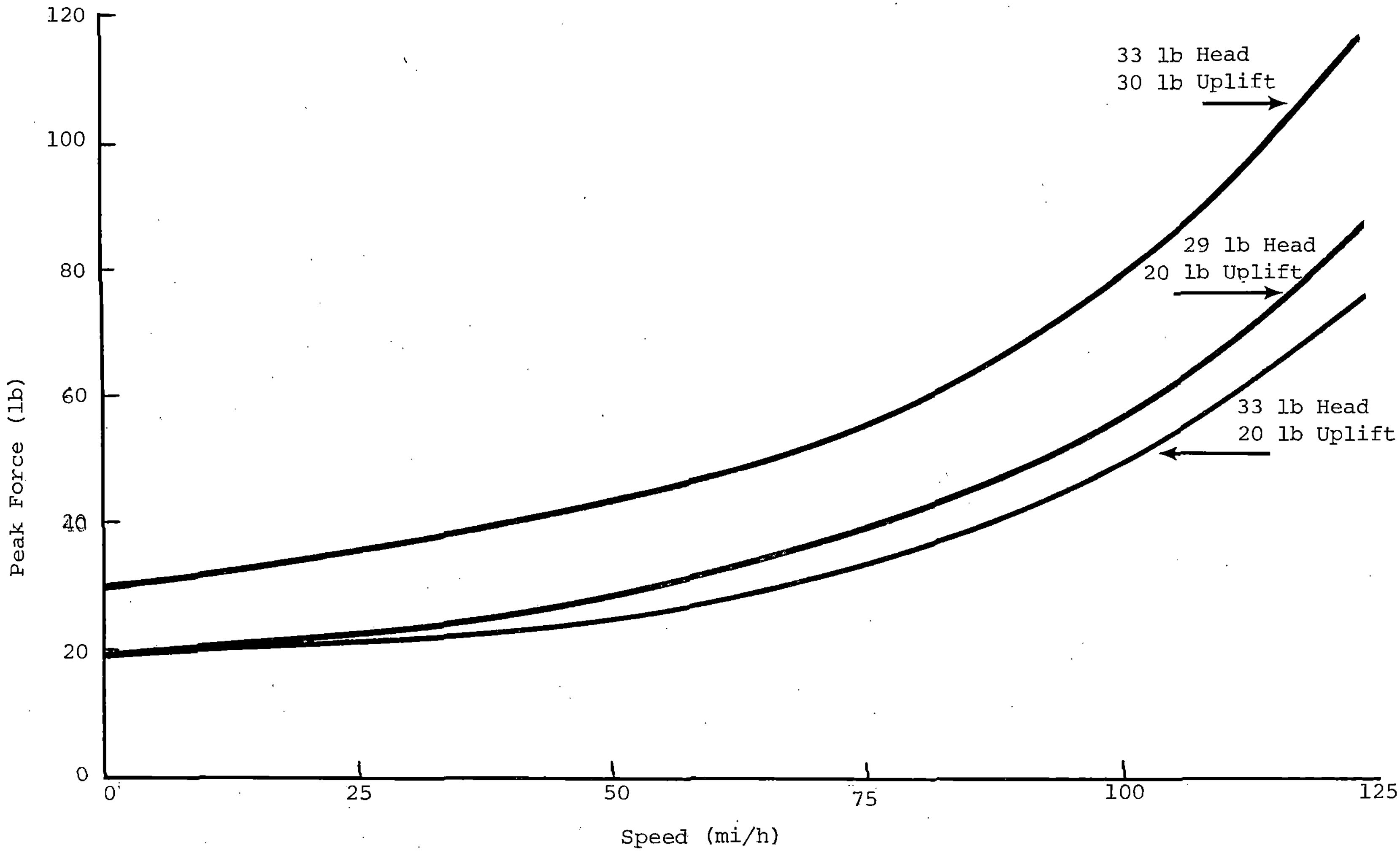

FIGURE 4-12. PEAK FORCE vs. SPEED KUPLER PHASE BREAK (CCW).

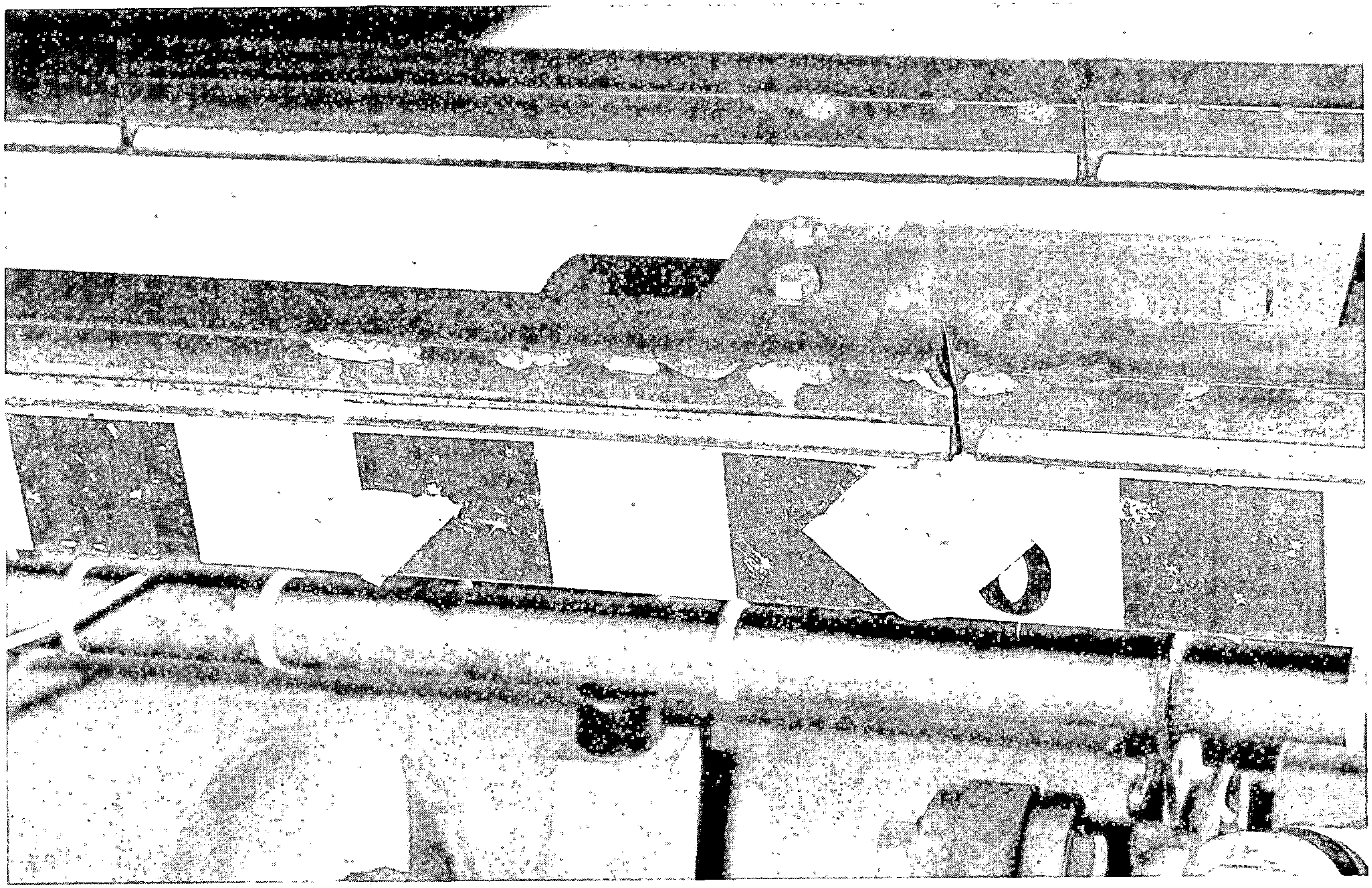

FIGURE 4-13. DAMAGED CARBON SEGMENTS ON PANTOGRAPH HEAD.

head. The TTC head was then mounted on the pantograph frame. This combination was then aerodynamically evaluated in both directions of travel with the head 22 ft above the rail level.

A series of summary plots are presented in figure 4-14. The results show that the pantograph developed a substantial aerodynamic lift force when compared with the limit recommended in Task 16.[2] In the knuckle-leading direction of travel, the measured frame lift force was 1 lb at 100 mi/h. In the knuckle-trailing direction of travel, the lift force increased to 6.8 lbs, but the head lift force remained at 12.8 lbs for the TTC head, the same as the knuckle-leading. Changing the height of the pantograph also affected the measured lift force of the AMTRAK head, reducing it from 19 to 15.5 lbs for a change in height from 22 to 19 ft. Reasons for the change cannot be clearly defined without more sophisticated testing procedures, but the most probable reason was the change in airflow pattern around the head due to the change in attitude of the frame. Also it is probable that the reduction in height brought the head down into the more turbulent flow caused by the locomotive cab and DOTX 211 car roof protrusions.

It should be noted that all data were referred to the relative airflow measured at the same height in the middle of the upper half of the pantograph main frame. In still wind conditions and with the TTC test consist, the measured relative airspeed was approximately 10-15% lower than the actual train speed. It is likely that for a pantograph mounted on the locomotive or near the front of a multiple-unit car, the same aerodynamic conditions would not apply.

A basic assumption was made that the lift forces obeyed an airspeed squared law, or in mathematical terms:

$$F_L = C_L \times v^2,$$

where:

F_L = aerodynamic lift force,

C_L = aerodynamic lift coefficient, and

v = relative airspeed.

A typical set of data, plotted on a logarithmic scale, is presented in figure 4-15. The data lie around a straight line with a slope of 2, indicating that the airspeed squared relationship holds. All data lie within a $\pm$15% band of the mean line, which is acceptable for the conditions under which this test was performed.

4.3.2 Dual Stage Pantograph

The aerodynamic lift forces on the dual stage pantograph were evaluated using the same techniques as for the single stage. A summary of test data is

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[2] Pehrson, V.W., et al., op cit.

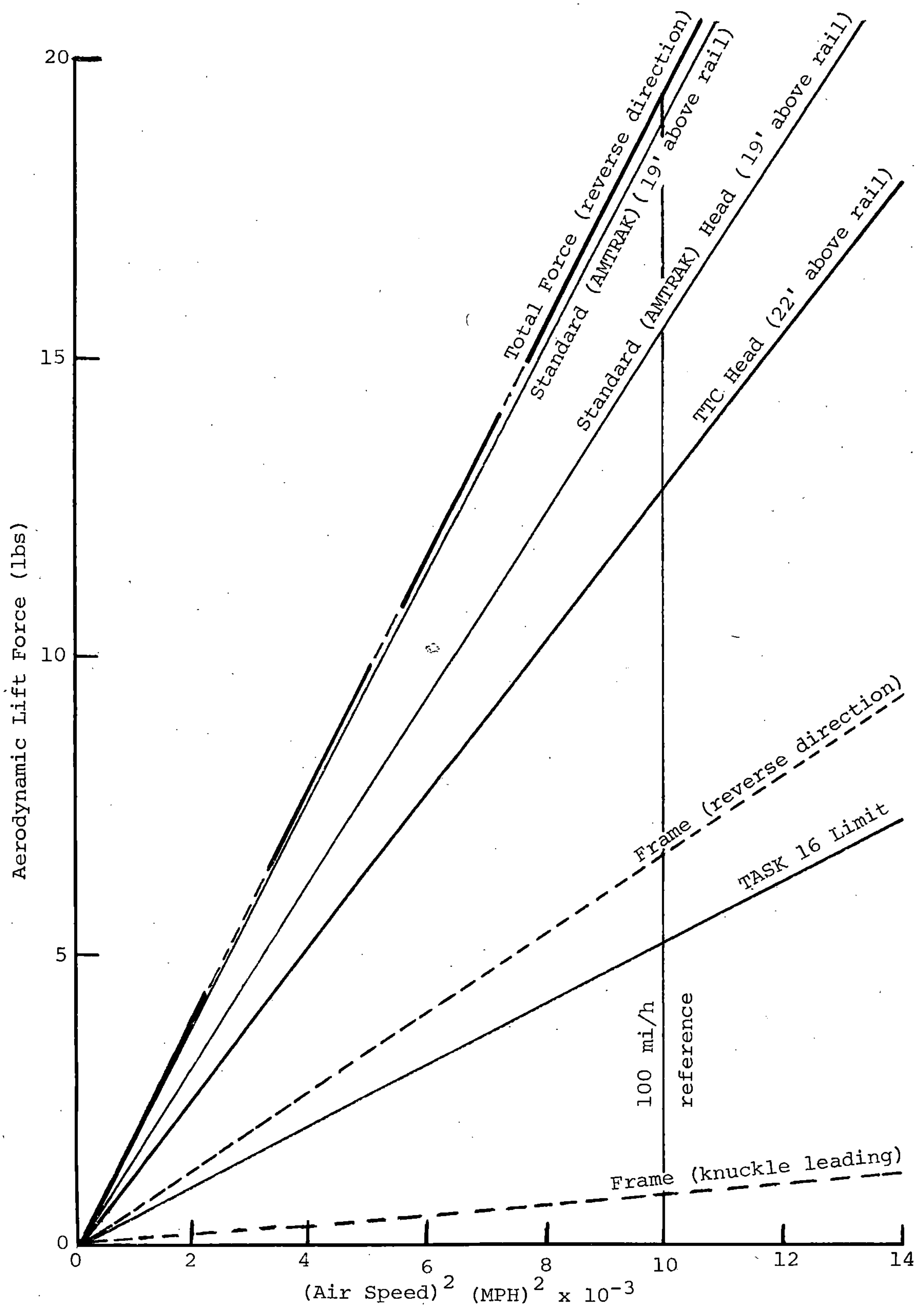

FIGURE 4-14. SINGLE STAGE PANTOGRAPH AERODYNAMIC LIFT FORCE SUMMARY.

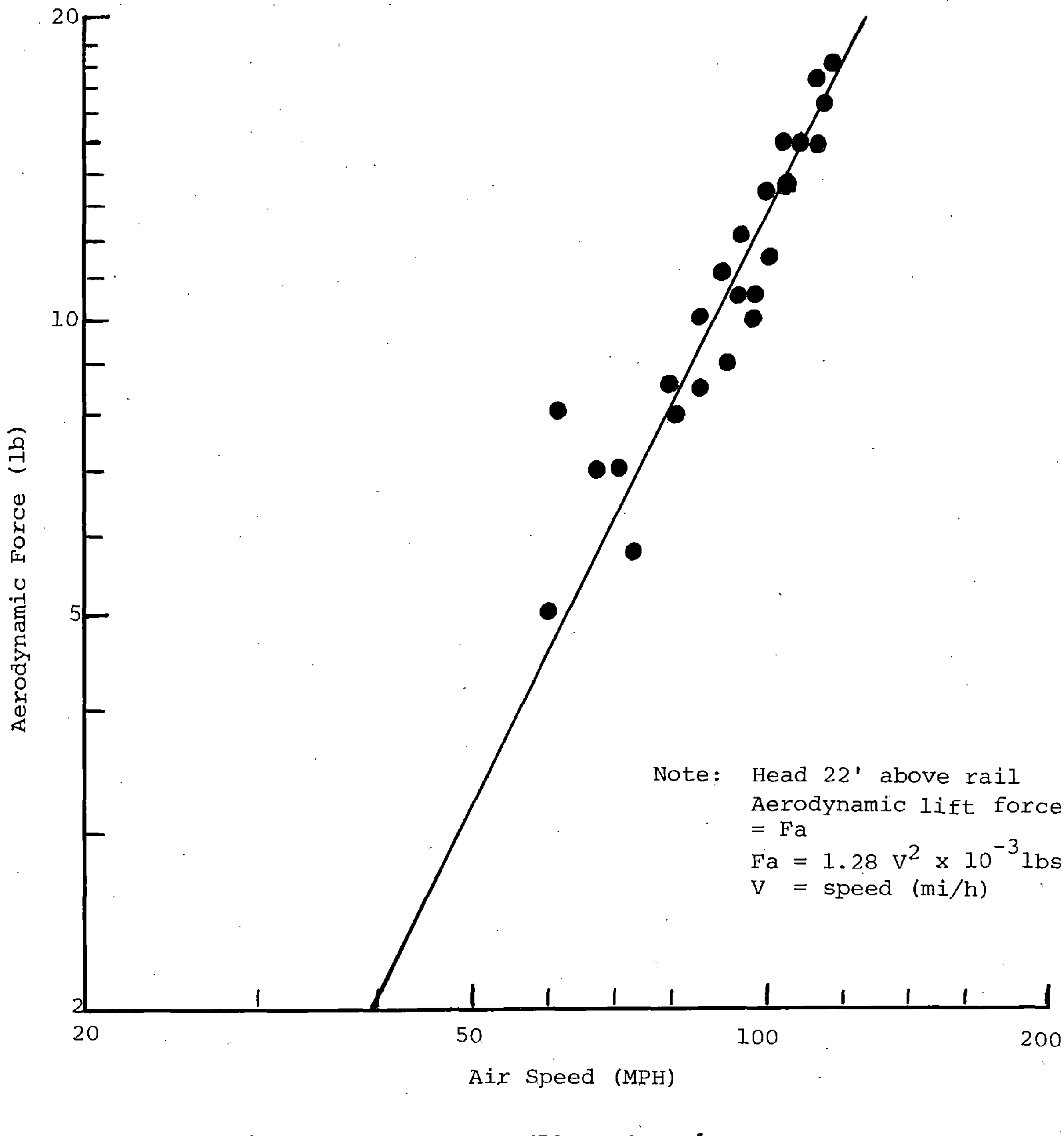

FIGURE 4-15. TYPICAL AERODYNAMIC LIFT FORCE PLOT SHOWING EXPERIMENTAL DATA SCATTER.

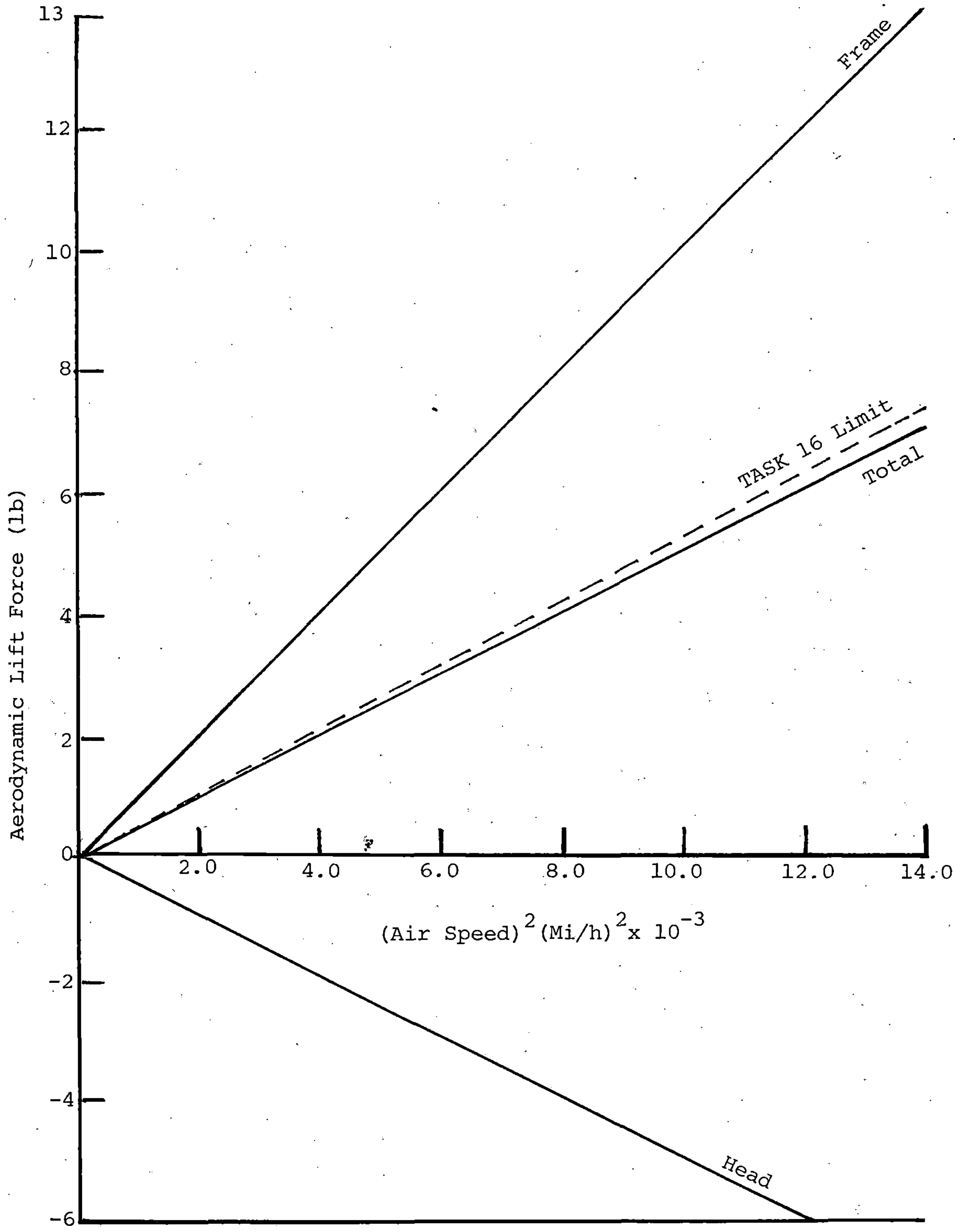

FIGURE 4-16. TWO STAGE PANTOGRAPH, KNUCKLE LEADING, HEAD 22 FT ABOVE RAIL.

presented in figure 4-16. The total lift force of 5.1 lbs at 100 mi/h is below the Task 16 limit. However, the total lift results from frame component of 10 lbs and a negative head component of 4.9 lbs.

Weather conditions during these tests were not ideal; gusting winds up to 20 mi/h produced substantial data scatter. Linear regression techniques were necessary to reduce the data. The estimated error for these data was ±20%.

4.4 PANTOGRAPH CURRENT COLLECTION PERFORMANCE ASSESSEMENT

4.4.1 Assessment Methods

The pantograph current collection performance is assessed mainly on the basis of the percentage of time the pantograph is not in contact with the trolley wire, generally referred to as the percentage LOC. However, percentage LOC alone is not sufficient to define an acceptable performance; the contact force and pantograph head displacements are also considered.

A clear definition of "acceptable performance" is not available. It would appear from the literature that the individual railroad administrations adopt their own criteria depending on the type of equipment and nature of their operation. For example, SNCF adopts a maximum permissable uplift of 8" at the support structure registration arms.[6] This works for the lightweight stitched simple catenary used by SNCF, but would be less applicable to the heavyweight style 1 catenary on the NEC.

An alternative method developed by British Rail makes the assessment on the basis of pantograph-measured data.[5] These measurements can be taken dead line, as described in this report, or alternatively may be taken on an energized catenary and pantograph by a live line telemetry system. Both methods are currently used by British Rail for pantograph/catenary development and catenary maintenance. In either case, the analysis techniques are identical. The British Rail techniques, together with additions offered herein, are used to define pantograph performance as determined on the RTT catenary systems. Details of the analysis methods are discussed below.

a. Percentage LOC. Experience has shown that LOC measurement by the low voltage d.c. method is unreliable for contact losses of less than 2 ms duration. Consequently, measurements were cut off at 2 ms on the 4/0 contact wire (5 ms on the British Rail half-scaled catenary, which has a stranded contact wire), and only losses of longer duration were counted. Empirically derived performance limits were based on the measurement threshold. This procedure is based on approximately 15 years of operational experience, and the limits are projected to give a 40-year average contact wire life. These limits can be summarized as follows:

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5 Op. cit.

6 Boissonnade, Pierre, "Catenary Design for High Speeds," Rail International, March 1975.

Measurement Threshold (ms)	Maximum Acceptable LOC (%)
0	2
2	1
5	0.5
150	0

As the table implies, any contact loss (other than a phase break) with a duration of more than 150 ms is unsatisfactory and should be eliminated. A measurement threshold of 2 ms was used for the RTT data, and the resulting LOC percentage was plotted against the measured train speed for comparison with the 1% limit.

b. LOC Duration Distribution. Percentage LOC alone could not be used to define the absolute current collection performance limits for a pantograph running under the RTT catenary. Only 0.5 mi (each) for the style 1 and style 3 catenaries was available for evaluation. This represented a maximum sample length of 15 seconds at 120 mi/h. Unless the particular length of RTT sample catenary was truly representative of a long length of that same equipment, the data might be grossly distorted. For example, one out-of-tolerance registration arm, giving a contact loss of 30 ms, would alone give a 0.2% LOC when included in the half-mile test length. The same feature in a 4-mi test length of the same catenary, the normal recommended sample length, would represent only 0.025% LOC, or 2.5% of the acceptable limit. To overcome this difficulty, the duration distribution was also plotted for the higher speed runs.

The duration distribution is also important in assessing the probable effects of the contact loss. Three basic regimes exist in a given LOC pattern, based on time duration.

Regime	Duration (ms)	Probable Effect
1	0 - 5	Electromagnetic interference
2	5 - 20	Electromagnetic interference, contact wire damage
3	above 20	As duration increases so do chances for power interruptions

Other than environmental effects, the short duration contact losses (less than 5 ms) have little effect.

The resultant separations between the contact wire and pantograph head are small enough that they draw only a small, low temperature electrical arc which can easily maintain the traction transformer primary current. Little or no pantograph or contact wire damage results.

The medium duration losses (5 to 20 ms) result in the greatest amount of contact wire and pantograph collector shoe damage. In general, the mechanical separations of pantograph and wire of this duration will still allow the electrical arc to be maintained while carrying the full traction transformer primary current, but the temperature of the arc will be sufficient to cause erosion damage on both pantograph and contact wire.

Interruption in the locomotive power occurs when the arc between the separated pantograph head and contact wire is extinguished. The ease with which the arc is extinguished is dependent on the distance between the pantograph head and the contact wire, the train speed, the pantograph current, and the phase angle between current and voltage (power factor). In general, contact losses greater than 20 ms in duration could result in sufficient separation to allow the forward train speed to blow out the arc, resulting in pantograph sparking and measurable power interruption.

Thus the time duration distribution of the measured LOC can be used to predict the type of potential problems likely to occur with a given pantograph and plays an important part in pantograph assessment.

c. Contact Force. Measured contact force is another important parameter advocated by British Rail to assess pantograph performance. The force data are filtered at a cutoff frequency of 30 Hz, and the performance factor, defined as:

$$PF = \frac{M - 3 \times \sigma}{M} ,$$

is calculated, where M is the mean force (including static uplift and aerodynamic lift), and σ is the standard deviation of the dynamic component of the force signal about the mean, M. The quantity PF is then plotted against the forward speed of the pantograph; the recommended maximum operational speed is defined as the speed at which PF=0. In physical terms, the contact force is a random process with a Gaussian distribution, and sets the limit when 0.13% of the force samples fall below the zero force datum, that is, when contact is lost between pantograph and contact wire. Moreover, it also imposes a limit on the positive force components of the contact force, those likely to cause impact damage to the pantograph carbon collector shoes and catenary support structure registration arms.

Two operational speed limitation criteria have now been fixed, one based on directly measured LOC, the other based on LOC statistically predicted from measured contact force data. Ideally, both methods should agree, but experiments have shown that a pessimistic estimate is usually derived from the contact force method, indicating a slight positive bias on the force. In general, a 10% agreement in limiting speed between the two methods is considered acceptable.

d. RMS Pantograph Head Trajectory. The pantograph head trajectory is defined as the vertical displacement of the pantograph head with respect to the car roof. Since the prime objective is to maintain contact between the pantograph head mass and contact wire, it follows that large amplitude displacements of the pantograph head represent corresponding changes in contact force due to head inertia. The pantograph head trajectory can be used as an analysis tool to isolate low frequency components of the dynamic behavior of the pantograph in order to investigate the effects of such things as catenary presag and wire height changes. As an example, to demonstrate the effect of contact wire sag, the rms trajectory was plotted against speed for a section of curved track and a section of tangent track.

e. Frame Structural Vibrations (Flutter). In the design of a pantograph frame, a compromise must be reached between frame mass and structural rigidity. Low rigidity can result in structural vibration problems (flutter), which lead to fatigue failure, dewirement, and bad current collection performance. The vibrations can be induced either aerodynamically or by dynamic coupling between the coincidental pantograph speed over a spatial feature in the catenary (such as the hanger spacing) and the structural mode resonant frequency. These problems can be investigated by plotting PSD functions of data recorded from accelerometers suitably mounted on the pantograph frame. Analysis over a range of operating speeds identifies potential problems.

4.4.2 Current Collection Performance of the Single Stage Pantograph

The current collection performance assessment techniques, having been established, can now be applied to data collected for the single stage pantograph on the RTT catenary systems. Each catenary style will be considered in turn, followed by observations on frame vibrations.

a. Style 1 Catenary. The LOC and contact force data for the style 1 catenary are presented in figure 4-17. Four pantograph parameter cases are included; these are:

- 33-lb head, 20-lb uplift force;
- 33-lb head, 28-lb uplift force;
- 29-lb head, 20-lb uplift force; and
- 33-lb head, 20-lb uplift force (reversed pantograph).

On the basis of LOC data, the standard single stage pantograph running on level tangent style 1 catenary exceeds the 1% LOC criterion at 90 mi/h, when a nominal uplift force of 20 pounds was used. Significant improvements were obtained either by increasing the nominal uplift to 28 lbs and retaining the standard mass head, or by reducing the head mass by 4 to 29 lbs and maintaining the 20-lb uplift. In both cases, the speed at which the 1% LOC level was exceeded was increased to the 105/110 mi/h range. As expected, the reversed pantograph LOC data showed good agreement with the 20-lb uplift data at the lower test speeds, but they deviated towards the higher uplift force data at higher speeds. This deviation was caused by an increase in effective uplift force from the additional frame aerodynamic uplift force generated in the reverse direction of running.

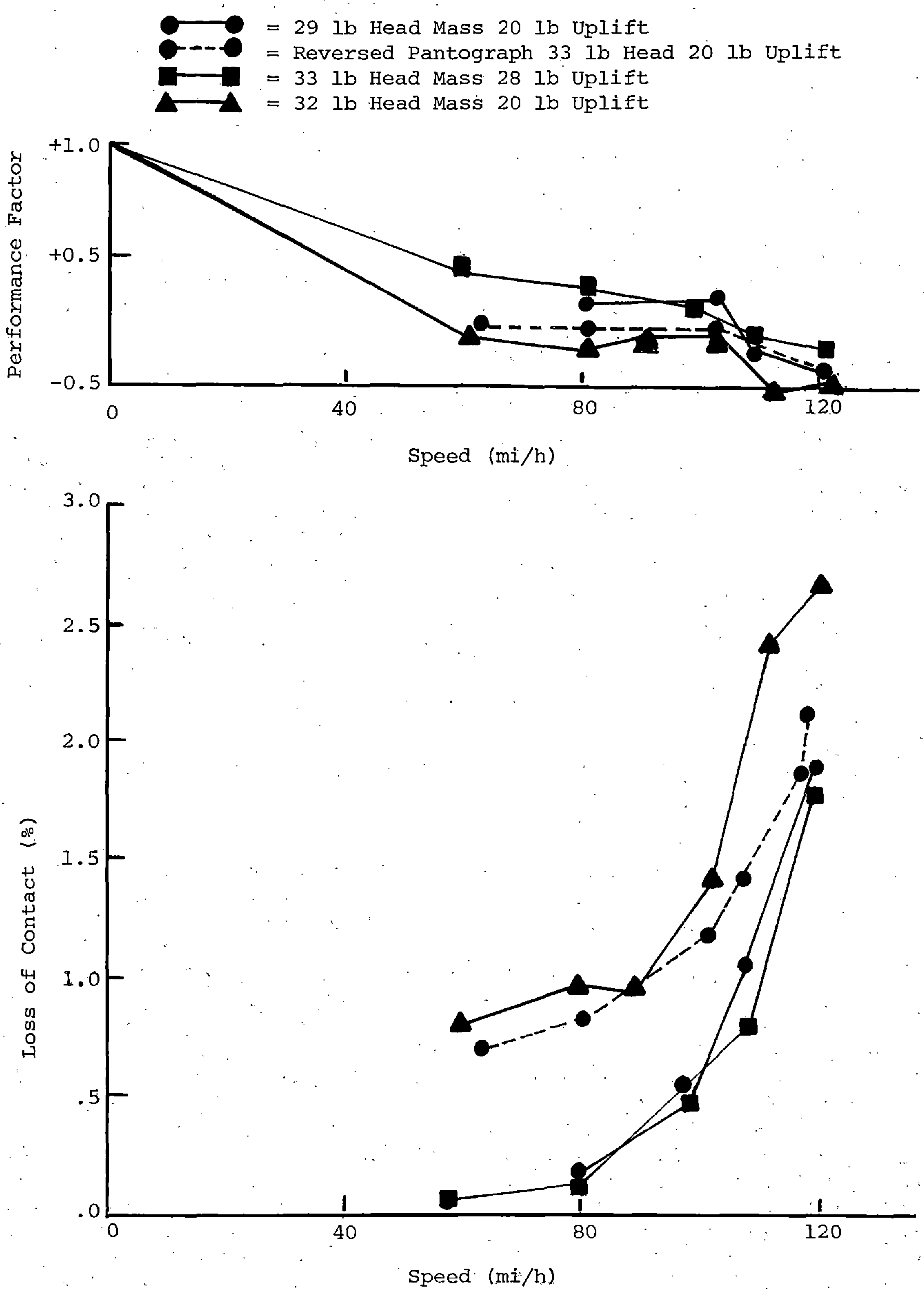

FIGURE 4-17. CONTACT FORCE AND LOSS OF CONTACT DATA FOR THE SINGLE STAGE PANTOGRAPH ON STYLE 1 CATENARY.

A representative sample of the LOC data was analyzed for time duration distribution and the results presented in table 4-3. The time duration limits used were 2 to 5 ms, 5 to 10 ms, 10 to 20 ms, 20 to 50 ms, and over 50 ms.

No significant trends were noted when comparing the effect of pantograph parameter changes. However, there were no measured contact losses exceeding 20 ms on the style 1 catenary. The time duration relative percentages per time bin were averaged for comparison with the other catenary styles. This procedure showed, for each of the catenary styles tested, that 45% ($\pm$1%) of the total time the pantograph lost contact was in the 2 to 5 ms range. Longer losses accounted for the remaining 55% of the time. This observation serves, in part, to substantiate that the alternative acceptance criteria of 1% at 2 ms or 0.5% at 5 ms (postulated in paragraph 4.4.1.a) are equivalent.

When plotted, statistically determined contact force data (figure 4-17) did not give good agreement with the LOC data for acceptable operating speed. In this case, contact force data gave an optimistic assessment of performance when compared to the LOC data, but this finding was contrary to previous experience at British Rail, and reasons for the discrepancy were sought. Closer examination of the two sets of graphs in figure 4-17 showed identical trends in the LOC and contact force data as a result of pantograph parameter changes.

Three aspects of the contact force measurement discrepancy were considered:

- Basic transducer error (drift),
- Frequency content of the signal, and
- Force distribution about the mean.

The basic transducer error, caused mainly by temperature drift, was quickly rejected as contributing to the discrepancy for two main reasons. First, the temperature stability of the transducer and signal conditioning system was found to be well within 1% variation over the duration of the runs. Second, the opposite effect was noted on the style 5 catenary although it was tested as part of the same test run series.

As a result of the requirement to filter the contact force signal at 30 Hz (to avoid the fundamental bending frequency of the pantograph head),* the frequency content of the LOC data extended over a much wider bandwidth than did the contact force data. The frequency components of the contact force above the 30 Hz cutoff frequency contributed significantly to the LOC pattern, but were not reflected in the contact force performance factor. An attempt was made to use PSD plots of the contact force to extrapolate the frequency content above the 30 Hz cutoff frequency by extending the 20 to 30 Hz frequency band trend, but the results were inconclusive. The filtering was identified as contributing, but could not be quantified.

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* See appendix A.

TABLE 4-3. LOC DURATION DATA.

Style 1 — Time Duration (ms) (Speeds of between 110-120)

	2-5 (% LOC TOTAL LOC)	5-10 (% LOC TOTAL LOC)	10-20 (% LOC TOTAL LOC)	20-50 (% LOC TOTAL LOC)	50+ (% LOC TOTAL LOC)
	42	39	19	0	0
	57	31	12	0	0
	29	47	24	0	0
	52	16	32	0	0
	51	35	14	0	0
Mean	46	34	20	0	0

Style 3 — Time Duration (ms) (Speeds of between 110-120)

	2-5 (% LOC TOTAL LOC)	5-10 (% LOC TOTAL LOC)	10-20 (% LOC TOTAL LOC)	20-50 (% LOC TOTAL LOC)	50 (% LOC TOTAL LOC)
	46	34	18	2	0
	37	35	16	12	0
	51	25	15	9	0
	48	35	13	4	0
	42	35	16	7	0
	40	31	16	19	0
	42	32	19	7	0
Mean	44	32	16	8	0

Style 5 — Time Duration (ms) (120 mi/h only)

	2-5 (% LOC TOTAL LOC)	5-10 (% LOC TOTAL LOC)	10-20 (% LOC TOTAL LOC)	20 (% LOC TOTAL LOC)	
	58	42	0	0	(33 lb head, 30 lb uplift
	48	52	0	0	(29 lb head, 20 lb uplift
	36	57	7	0	(33 lb head, 20 lb uplift
Mean	48	50	2		

Note

1. The figures contained in the tables refer to the percentages of the total measured loss of contact.

Detailed analysis of contact force data showed that the style 1 catenary exhibited a slight bias towards the positive forces. Figure 4-18 shows a section of the relevant contact force time history on which the data mean, static uplift force, and aerodynamic lift component have been identified. Also included is the friction band of the pantograph main frame mechanism. Comparison of the data mean and mean uplift demonstrates the small positive bias of the data, which is well within the uplift uncertainty due to friction in the main frame.

b. Style 3 Catenary. Figure 4-19 presents LOC and contact force data for the single stage pantograph on the Style 3 catenary. The same pantograph configuration parameters are included.

The measured LOC indicates a significantly poorer performance than the style 1 catenary with 1% LOC occurring at approximately 45 mi/h at the 20 lb uplift setting, and at approximately 60 mi/h for the 28 lb uplift case. Again, the reduced mass pantograph head provided the same improvement as increasing the uplift force. At speeds above 100 mi/h, LOC in excess of 5% was recorded regardless of pantograph parameters. That level of contact loss is defined by Task 16 as being unsatisfactory for long term use.[2]

The loss of contact duration data for the style 3 catenary is presented in table 4-3. Again, a number of typical speeds were analyzed for the pantograph parameter changes and, as before, no significant trends were apparent in conflict with the overall distribution of the style 1 data. A significant percentage of the contact loss measured on the style 3 catenary was contained in the 20 to 50 ms time band where power interruptions (LOC) was likely. No losses in excess of 50 ms were recorded.

The contact force-derived performance factor shows much closer agreement with LOC data than was apparent in the style 1 catenary analysis. The large negative performance factors at speeds above 100 mi/h indicate large positive forces between the pantograph head and contact wire.

c. Style 5 Catenary. The single stage pantograph performance data are presented in figure 4-20. Identical pantograph configuration parameter cases are included. The overall current collection performance of the style 5 catenary as indicated by percentage LOC shows much improvement over both the style 1 and style 3 catenaries. No pantograph configuration was found to exceeded the 1% LOC criterion.

The LOC distribution data are presented in table 4-3. Only those cases at a nominal speed of 120 mi/h were considered. A definite trend in the LOC pattern emerged to verify that a lower uplift force and a higher head mass tended to produce contact losses of longer duration, an expected result.

The contact force was analyzed to produce the performance factor, which is plotted against speed in figure 4-20. When the data mean was

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2 Op. cit.

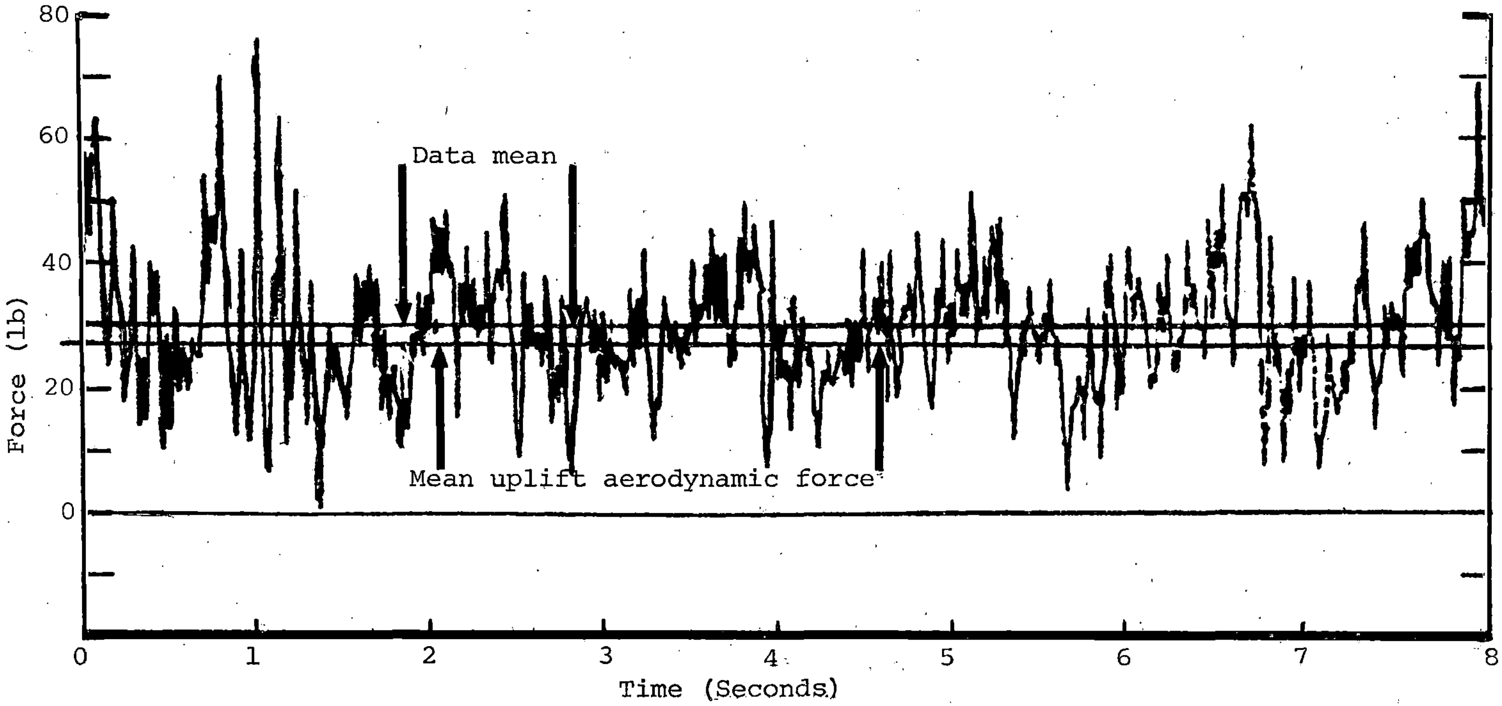


FIGURE 4-18. SECTION OF CONTACT FORCE TIME HISTORY.

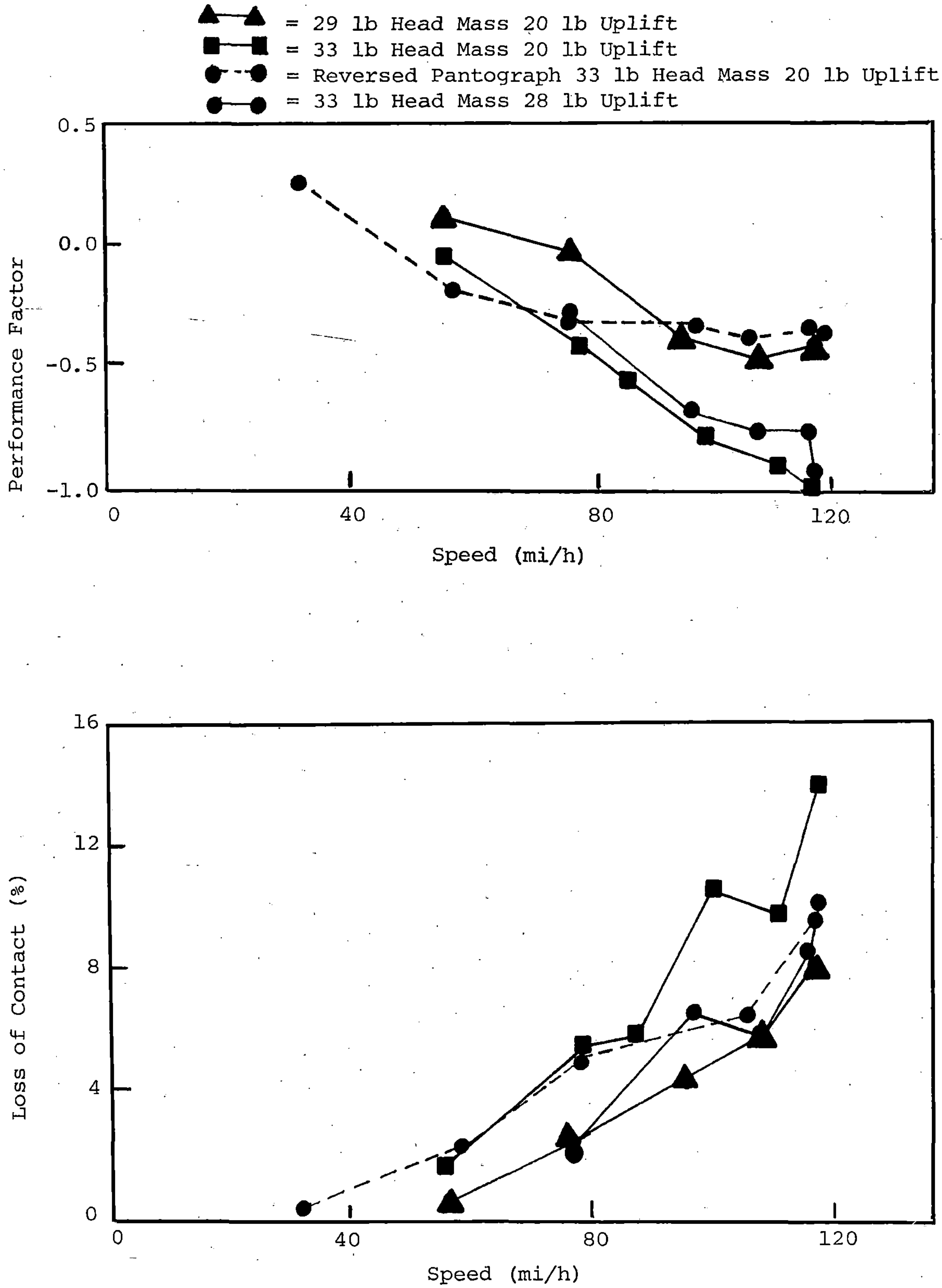


FIGURE 4-19. CONTACT FORCE AND LOC DATA FOR THE SINGLE STAGE PANTOGRAPH ON STYLE 3 CATENARY.

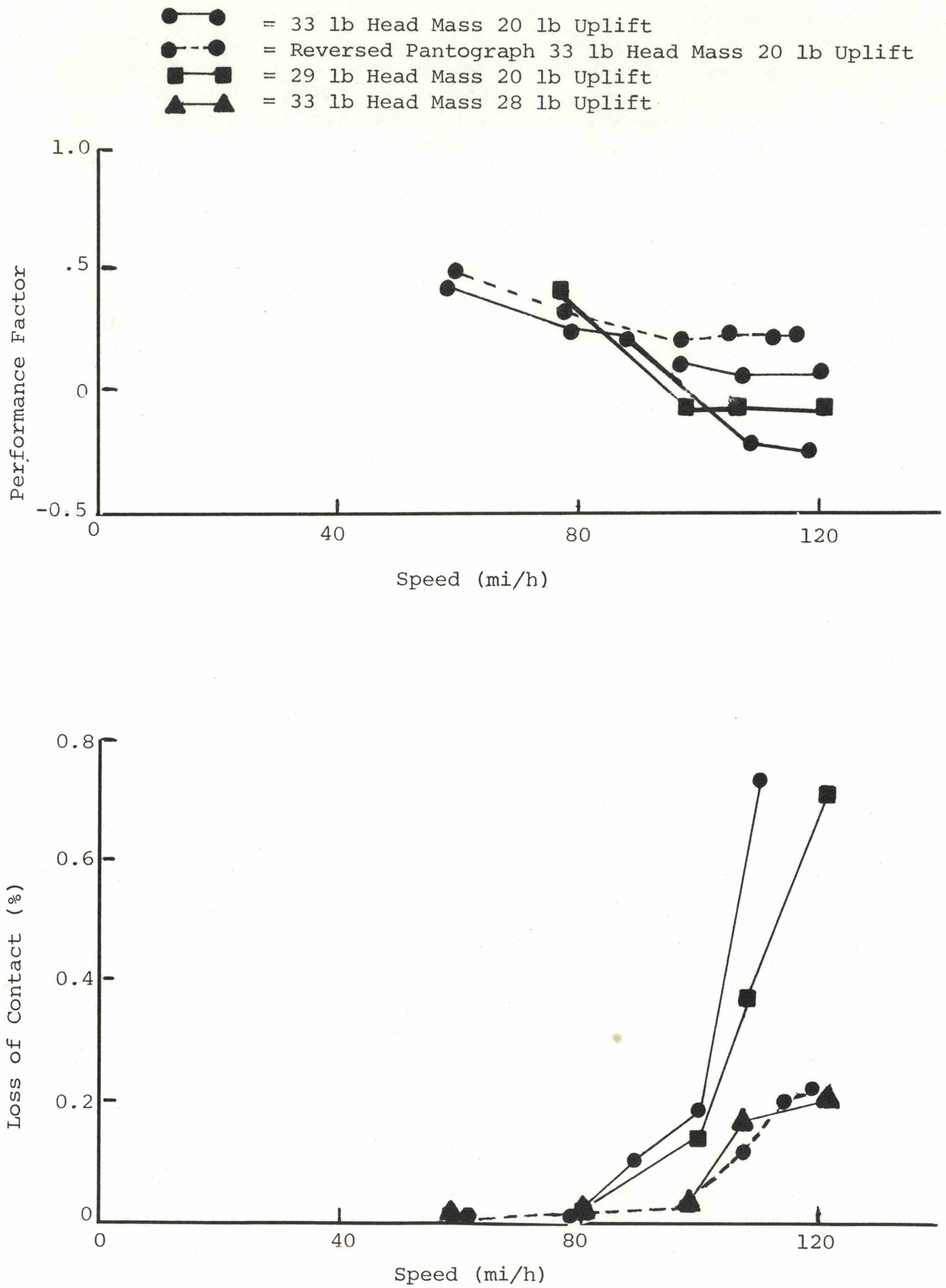


FIGURE 4-20. CONTACT FORCE AND LOSS OF CONTACT DATA, STYLE 5 CATENARY.

used in the performance factor calculation, a 25% difference was indicated in speed at which criteria levels were reached. Unlike the style 1 catenary, the contact force method gave a pessimistic result in comparison with the LOC method. A significant negative bias was apparent in contact force data when the calculated data mean was compared with the static uplift force. The most likely cause suggested for this phenomenum is the combination of a pantograph with a high friction level and a frame damper with an asymmetric characteristic running on a hogged (negative sag) contact wire. The effective hog in the contact wire is described in paragraph 4.1.1.a.

To demonstrate the effect of the difference in contact wire sag on the curved and tangent style 5 catenary, a typical length of each was taken and the standard deviation of the head trajectory and contact force were plotted against speed (see figure 4-21). An increase of approximately 50% in head trajectory and approximately 25% in contact force standard deviations on the curves resulted, indicating that the effective reduction of contact wire sag on curves had an adverse effect on current collection performance. A typical head trajectory time history for curved and tangent track is presented in figure 4-22.

d. Frame Vibrations. The torsional, lateral, and vertical vibration modes are presented in PSD form in figures 4-23, 4-24, and 4-25, respectively. No significant vibrational problems were apparent from the test data; however, the major fundamental bending frequencies were identified as follows:

- Upper frame torsion - 5.3 Hz,
- Upper frame vertical bending - 4.9 Hz, and
- Upper frame lateral bending - 3.5 Hz.

4.4.3 Current Collection Performance of the Dual Stage Pantograph

a. Pantograph Reach and Wire Height. The dual stage pantograph was supplied to the TTC complete with a base frame adapter unit designed for mounting the pantograph on an Improved Metroliner. Initially, the pantograph was mounted on the DOTX 211 car with a lockdown height of 14'9" when fitted with the standard AMTRAK head. The effective lockdown height of the pantograph fitted with the Faiveley head was reduced to 14'7" because of differences in head mounting details. Performance during subsequent testing of the pantograph at this height was totally unacceptable, and the tests were temporarily abandoned. Since tests with an identical unit, mounted on an NEC Metroliner, were proceeding without difficulty, the cause of the problems at the TTC were pursued.

The uplift characteristic of the pantograph (force vs. height) was plotted for the pantograph starting at the prevailing lockdown height of 14'7" and covering the total travel of the pantograph. To accomplish this, the aerodynamic uplift force measuring system was used to measure static uplift force, and a measuring tape was used to measure pantograph head height above a fixed reference point on the car roof. The head

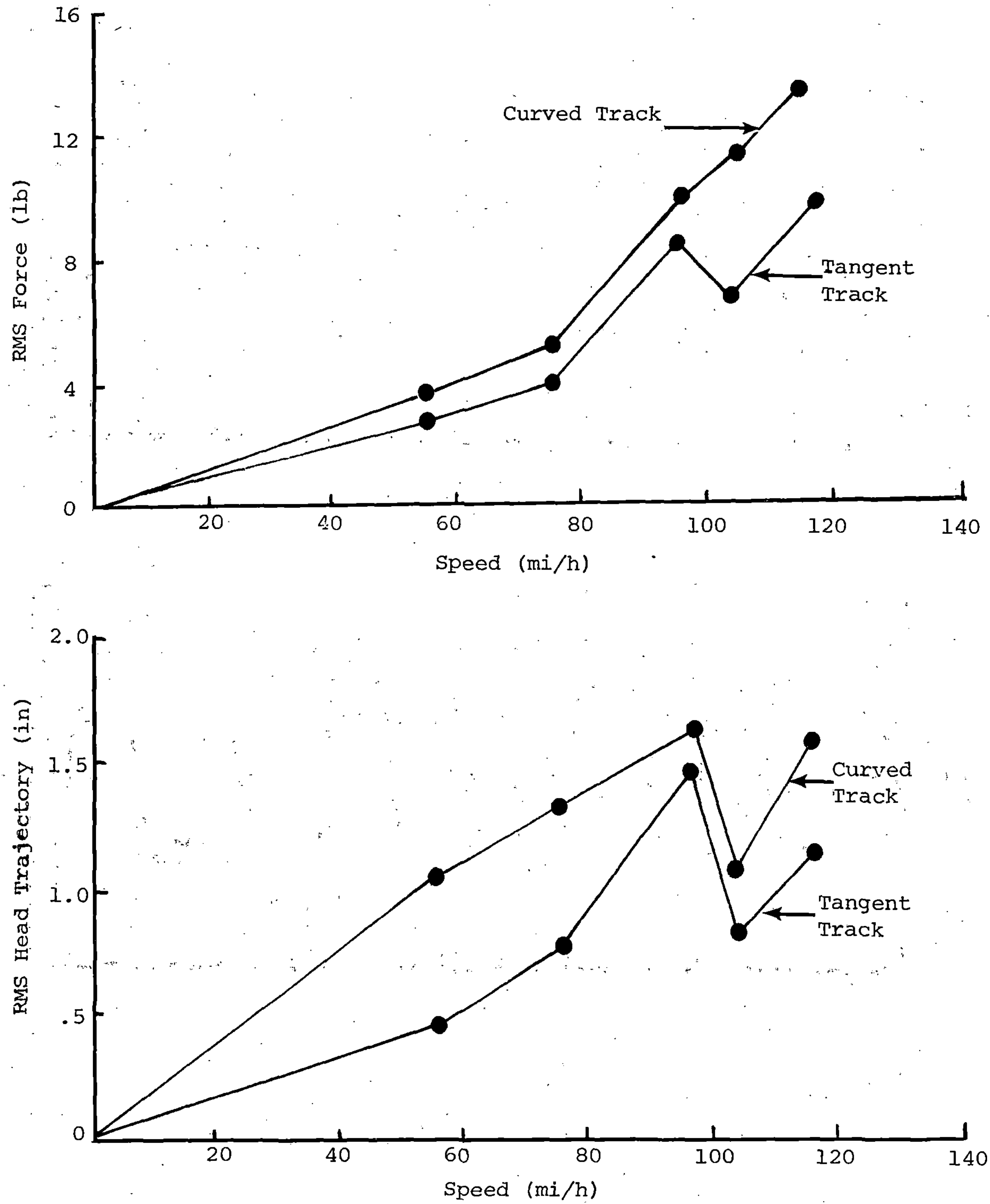
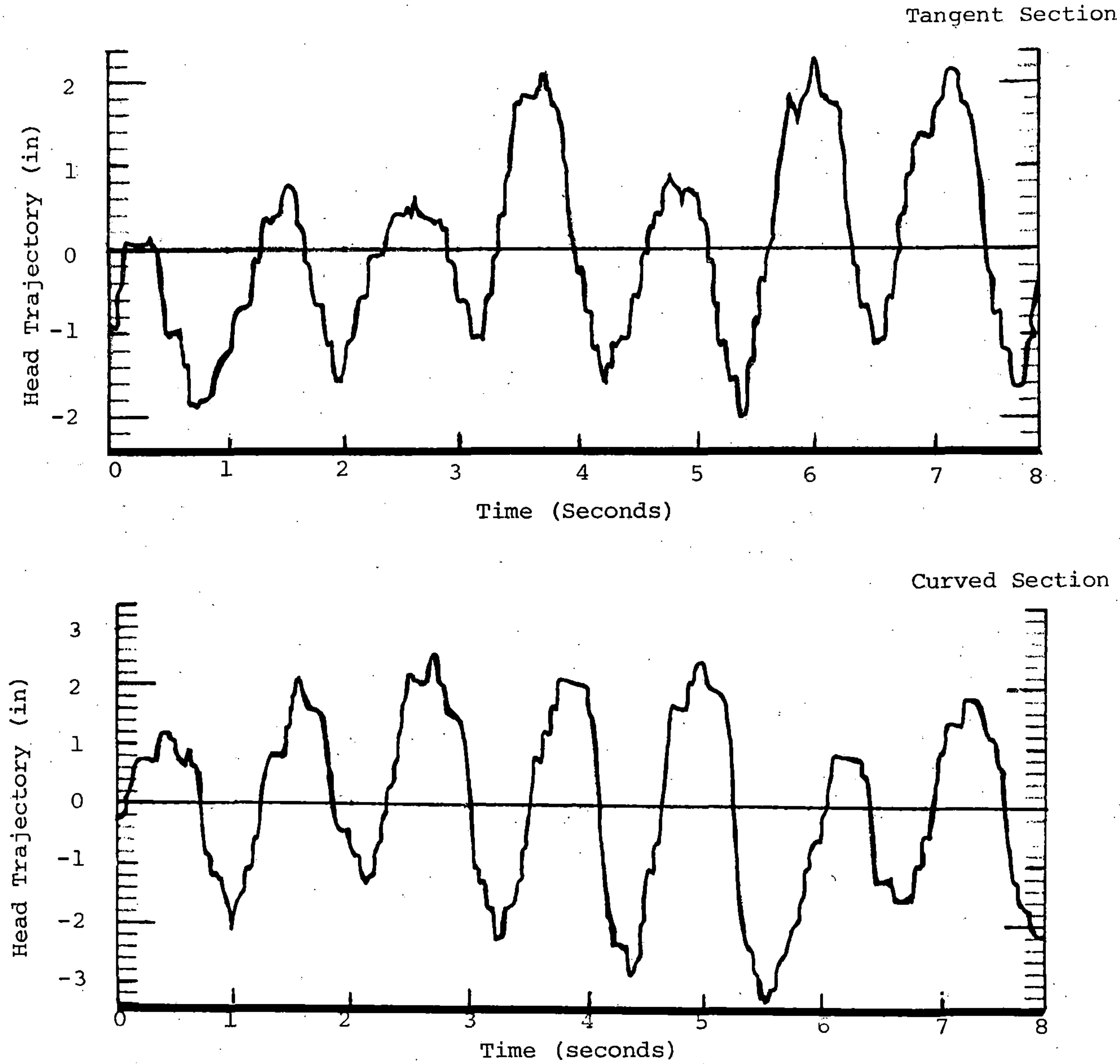


FIGURE 4-21. RMS CONTACT FORCE AND HEAD TRAJECTORY PLOTTED AGAINST SPEED, FOR CURVED AND TANGENT STYLE 5 CATENARY.



NOTE: Data recorded on unequal scales.

FIGURE 4-22. COMPARISON OF HEAD TRAJECTORY LEVELS FOR CURVED AND TANGENT STYLE 5 CATENARY.

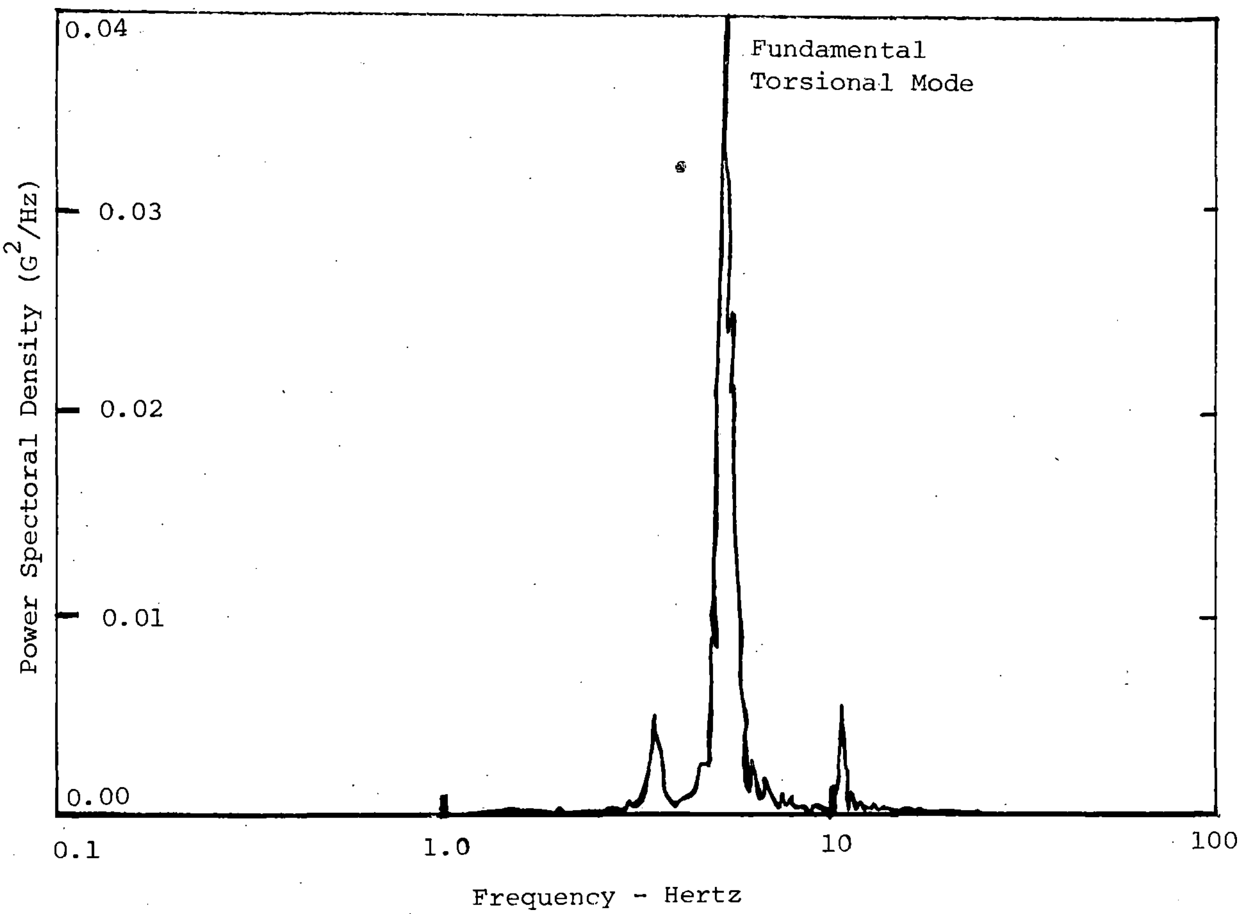


FIGURE 4-23. UPPER FRAME TORSION (95 mi/h).

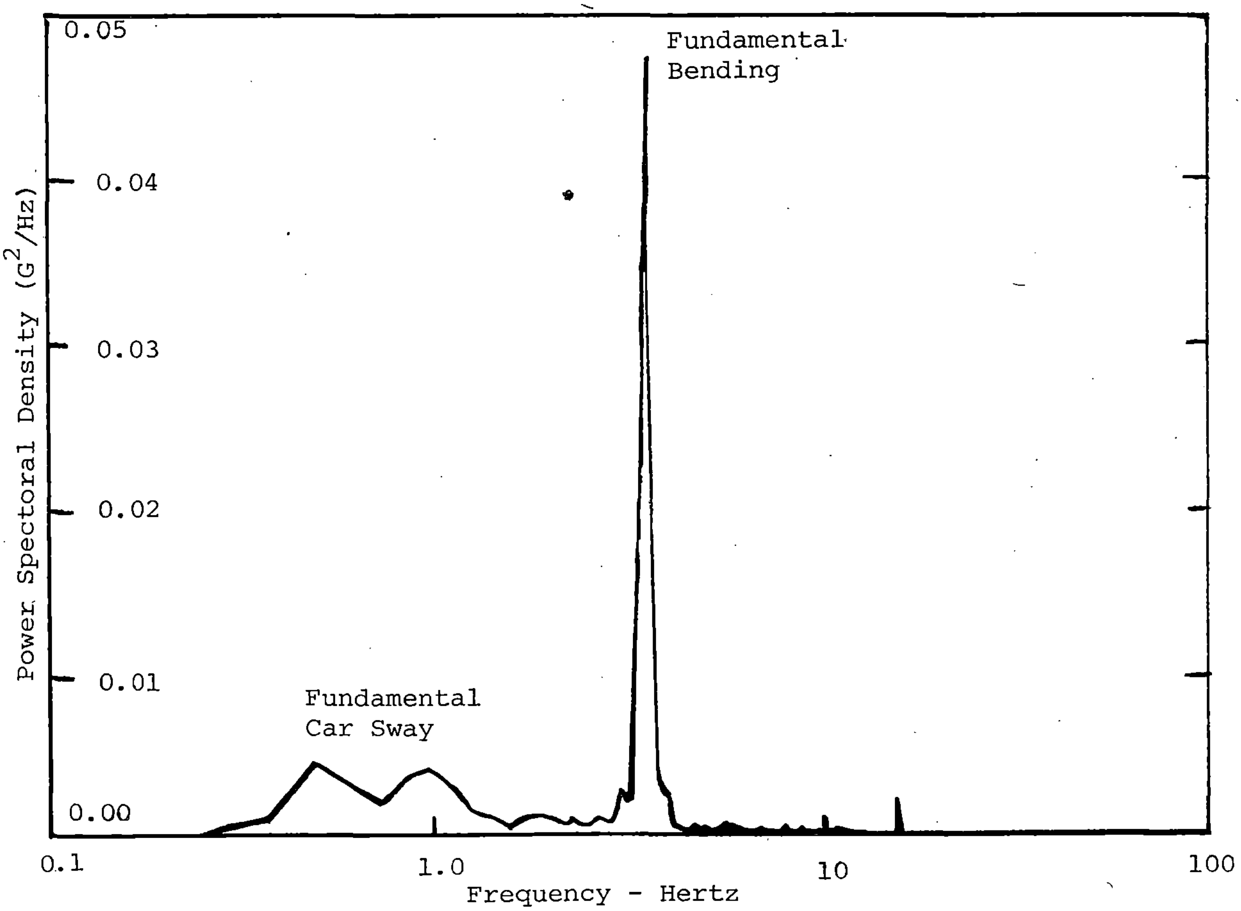


FIGURE 4-24. FRAME LATERAL BENDING (95 mi/h).

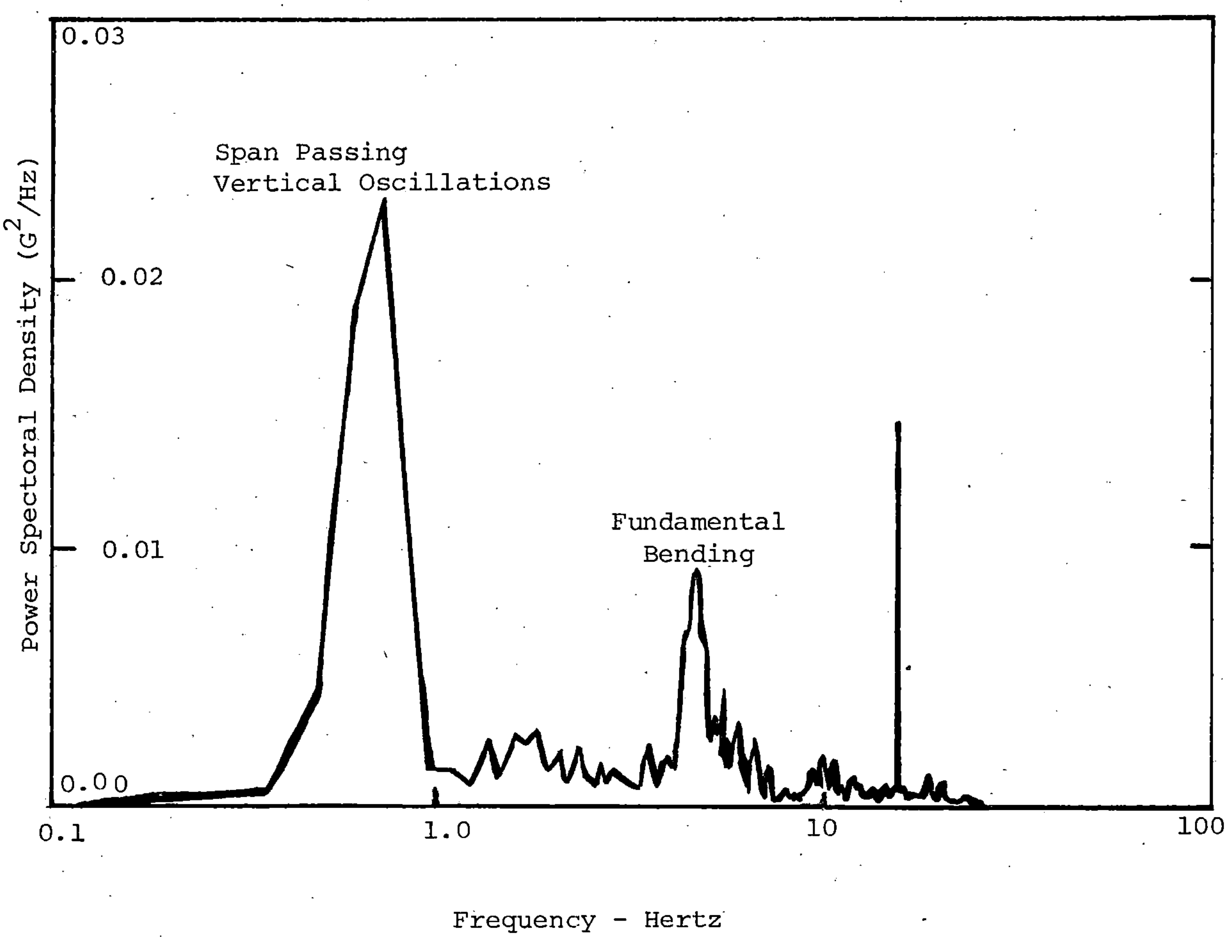


FIGURE 4-25. UPPER FRAME VERTICAL BENDING (95 mi/h).

height was incremented by adjusting the length of the restraint chains. The results are presented in figure 4-26. The RTT contact wire uplifted heights were superimposed on the pantograph characteristic.

The pantograph, which had been designed with a total reach of 2.4 m for use on the SNCF, was already in the nonlinear region of its characteristic. It was found that, due to a combination of increased static wire height on the curves of 22'10" above rail, slightly reduced lockdown height on the DOTX 211 car (14'7" instead of 14'8") and increased uplift of the catenary, the effective static uplift was reduced by as much as 40%; dynamic displacement further aggravated the problem. The pantograph was remounted on the DOTX 211 car at a lockdown height of 16 ft in order to better represent the AEM-7 two stage pantograph designed with a 3.2 m reach. A shortened test program was repeated.

b. <u>Current Collection Performance Test Results</u>. The pantograph was tested over the styles 1, 3, and 5 catenary designs at two static uplift force settings; 20 and 28 lbs. Only the LOC data were used to assess the current collection performance.

The percentage LOC was determined for the same test lengths of catenary used for the single stage pantograph assessment. The results are shown in figure 4-27 and 4-28 together with the data for the single stage pantograph.

The dual stage pantograph shows significantly improved performance over the single stage on all three styles of catenary and at both 20 and 28 lb uplift force.

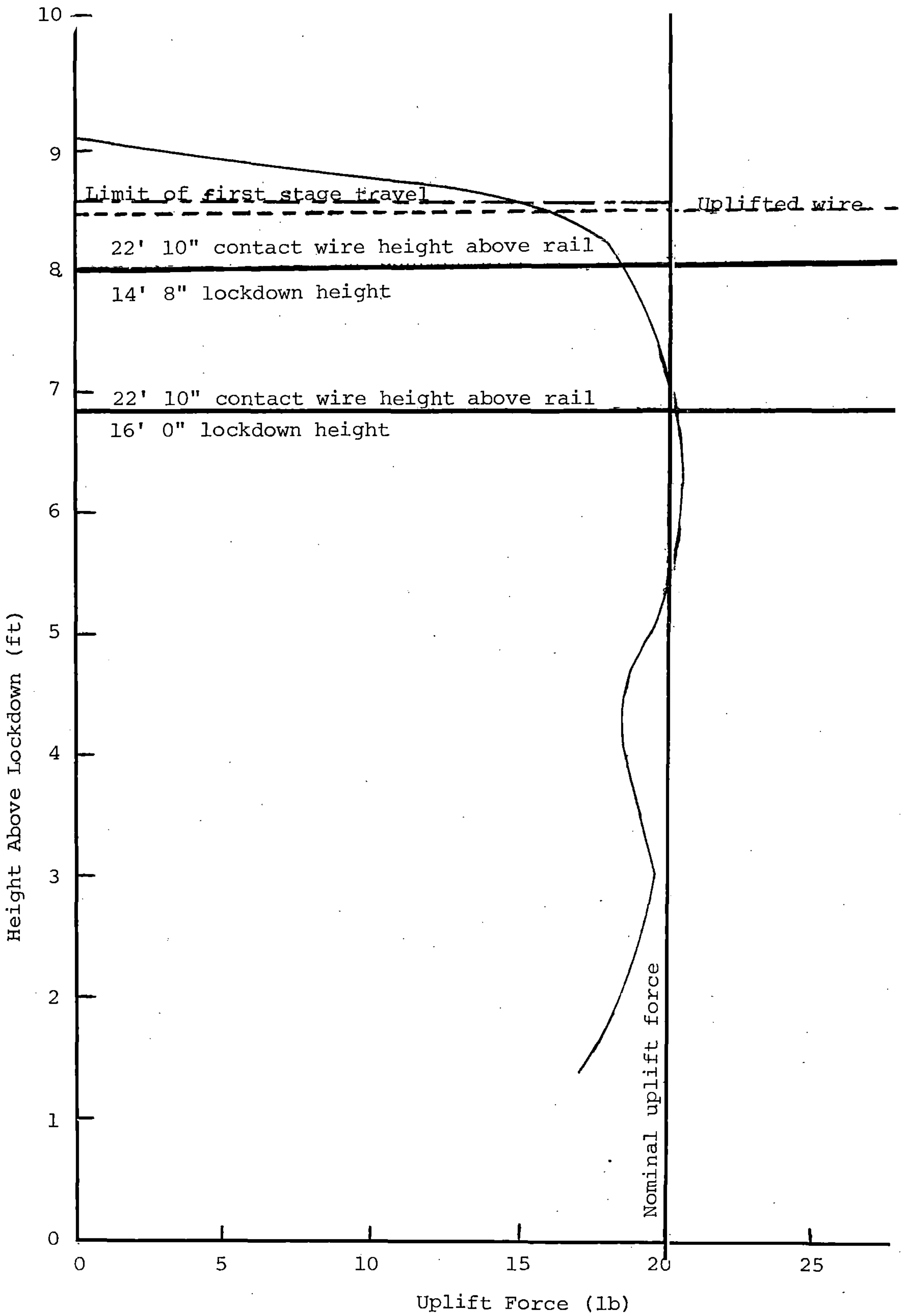


FIGURE 4-26. UPLIFT CHARACTERISTIC, DUAL STAGE PANTOGRAPH.

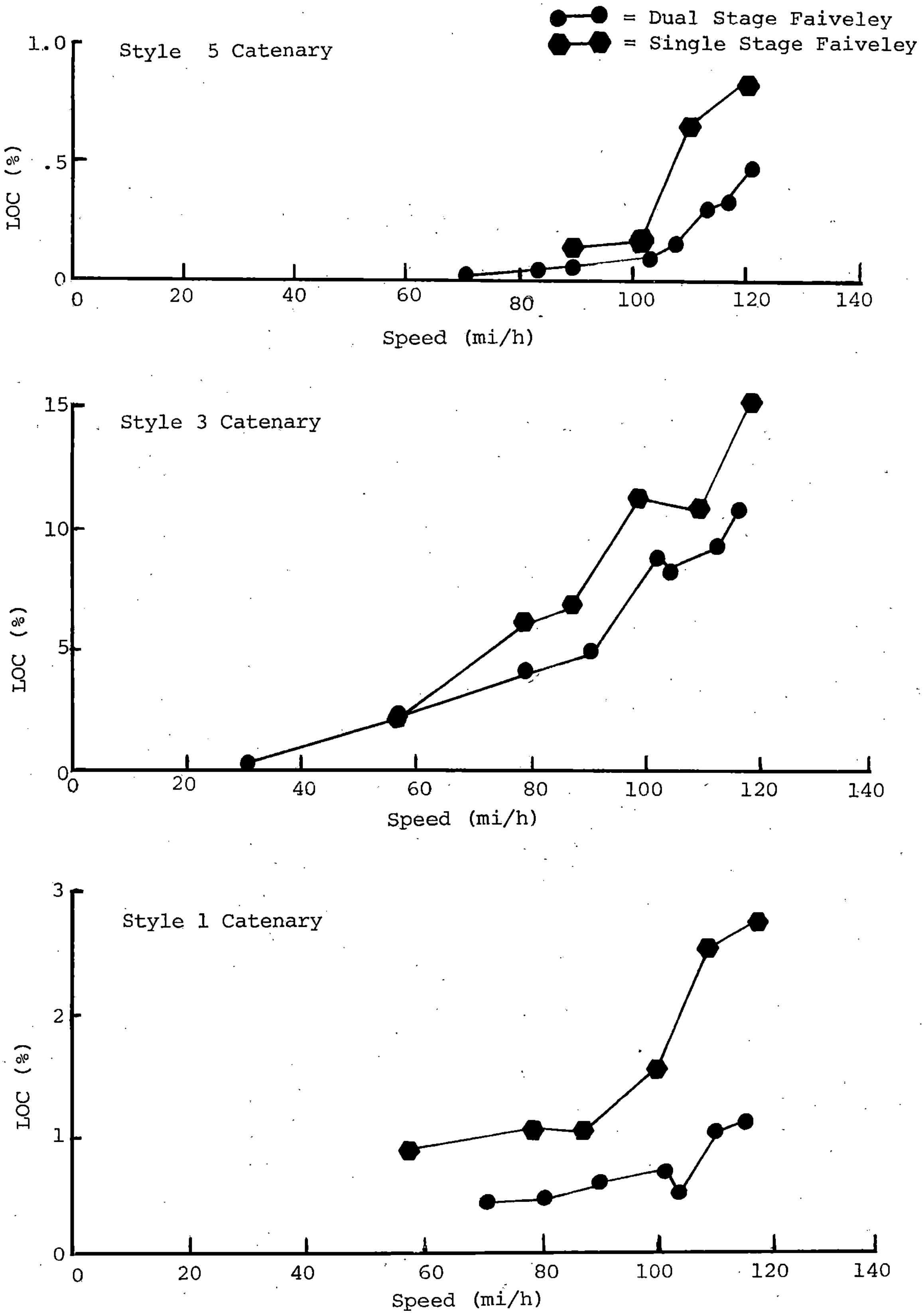


FIGURE 4-27. TWO STAGE PANTOGRAPH LOC DATA, 20 LB UPLIFT.

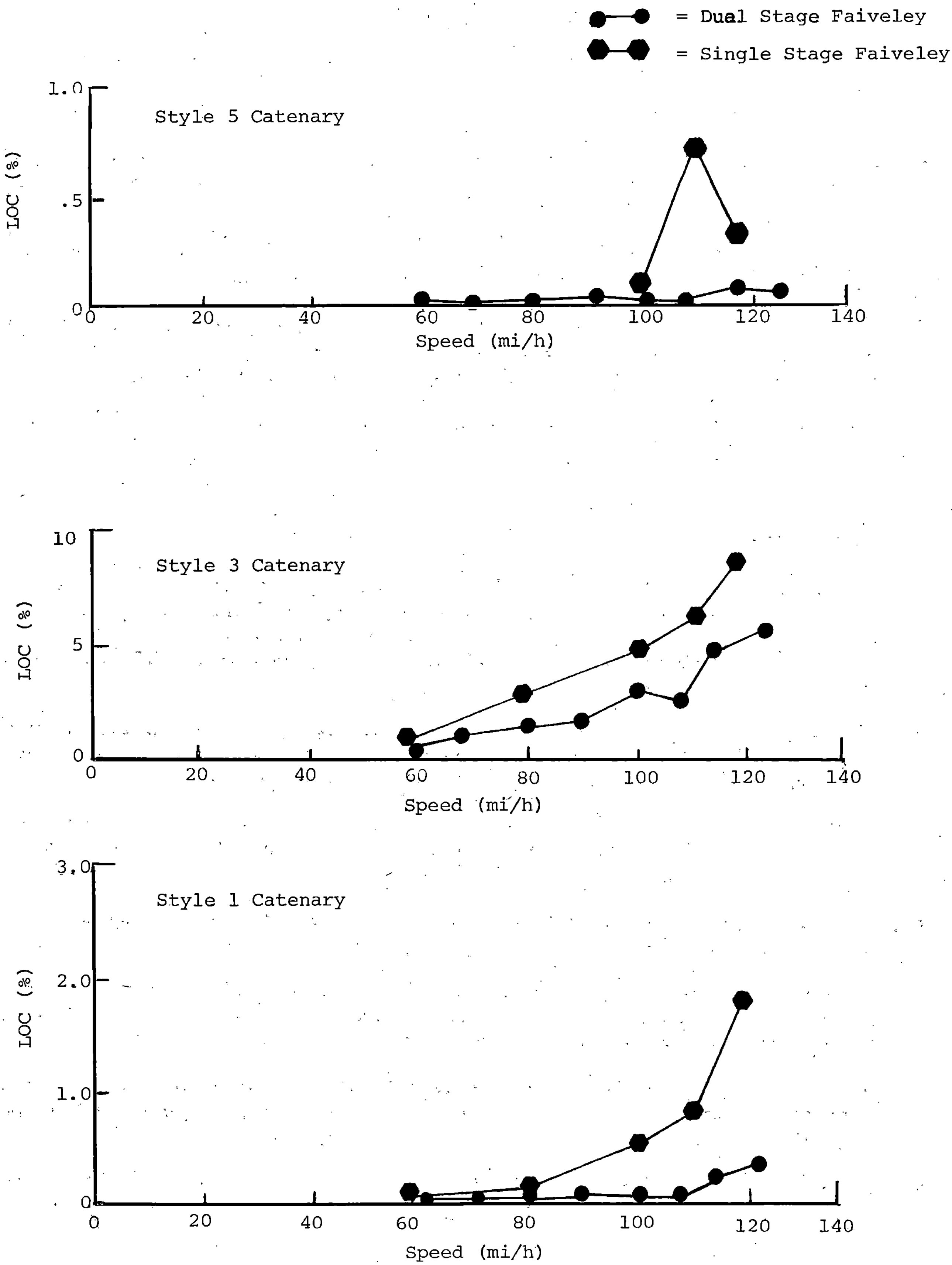


FIGURE 4-28. TWO STAGE PANTOGRAPH LOC DATA, 28 LB UPLIFT.

5.0 CONCLUSIONS

5.1 GENERAL

- The height and stagger measurements provided a useful contribution to the construction of the RTT catenary system. They enabled measurements to be taken and corrections assessed quickly and efficiently.
- The dead line testing techniques can be used to assess the current collection performance of a pantograph on a given catenary design.
- With experience, the probable effect of pantograph performance can be predicted from dead line measurements. However, only measurements made on the fully energized system can confirm the dead line predictions.
- All RTT Catenary Systems are installed to an acceptable standard for long term operation.

5.2 SPECIFIC

- The current collection performance of the style 5 catenary, based on measured LOC, shows much improvement over styles 1 and 3 designs. The style 3 catenary appears to be totally unacceptable for long term operation at speed in excess of 90 mi/h with any combination of pantograph tested.
- The results of dead line testing over phase breaks were inconclusive, due to incorrect installation of the BICC unit. However, the Kupler phase break appears to give a satisfactory mechanical performance.
- The single stage pantograph is only marginally acceptable for operation on the RTT catenary system at a speed of 120 mi/h with an uplift force of 28 lbs.
- The dual stage pantograph gives acceptable performance at 120 mi/h on the style 1 and 5 catenary systems but not the Style 3.
- Both pantographs would benefit from a reduction in head mass. It is estimated that a head mass of approximately 20 lbs could be achieved by careful redesign of the head structure.
- Dead line test techniques require careful interpretation of the data when performing comparisons with empirical criteria derived from tests on dissimilar equipment.
- To derive the best performance from the style 5 catenary, it would be necessary to adjust the wire height and midspan sag on the curved track sections.

- The single stage pantograph develops large aerodynamic lift forces, particularly when running in the knuckle-trailing direction. This effectively reduces the LOC, but increases pantograph head and contact wire wear.

6.0 RECOMMENDATIONS

6.1 MEASUREMENT/ANALYSIS CHANGES

- For a dedicated geometry measurement instrumentation system, the head force load cells should be designed on the basis of slow speed force levels to reduce the error in stagger measurement caused by load cell zero drift.

6.2 CATENARY

- To make the RTT catenary system more representative of the NEC system, a graded wire and bridge arrangement should be installed, and one tension section of the RTT style 5 should be modified to represent the new ELECTRAK style 5 design planned for the New Haven to Boston electrification.
- The style 1 and 3 catenaries should be retained in the test length for the AEM-7 test. The style 3 should provide useful data on wire erosion due to high LOC levels.
- One termination in the RTT style 1 and 3 catenaries should be allowed to float on the balance weights to provide better compatibility in the overlaps with style 5 catenary.

6.3 PANTOGRAPHS

- A redesign of the pantograph head should be undertaken to include a carbon strip width of .47" and to reduce the overall head mass to 20 lb or less. Careful evaluation of the required load cases and aerodynamic lift characteristics should be included in the redesign.
- The single stage pantograph should be restricted to a maximum operating speed of 100 mi/h on the RTT catenary systems.
- A more complete evaluation of the dual stage pantograph has been undertaken on the RTT system and a report is in progress.
- The BICC phase break installation has been corrected and the unit removed from the line.

7.0 REFERENCES

1. Transportation Test Center, RTT Electrification Test Plan, FY-1979, August 1978.

2. Pehrson, Vernon W.; Shaw, Peter L.; Suddards, A. Daniels; and Willetts, Thomas A.; Northeast Corridor High Speed Rail Passenger Service Improvement Project; Task 16: Electrification Systems and Standards, December 1976.

3. Federal Highways Administration, RFP, TTC Project 4(8), Track Electrification, 1974.

4. ENSCO Inc., User Manual for Pantograph Deadline Instrumentation, to be published.

5. British Rail R&D Division, "Pantograph and Catenary Evaluation Techniques," Unpublished Internal Memorandum, 1978.

6. Boissonnade, Pierre, "Catenary Design for High Speeds," Rail International, March 1975.

APPENDIX A

1.0 DEAD LINE INSTRUMENTATION SYSTEM

The dead line instrumentation system was designed and built by ENSCO, Inc., Colorado Springs, Colorado, under contact to the Federal Railroad Administration, Office of Research and Development, specifically for use at the Transportation Test Center. The design was based on similar equipment developed by British Rail. A full description and user manual has been produced by ENSCO for the system.* A brief functional description of the system and measurement parameters follows.

The system is restricted to applications where the pantograph is running on a dead and grounded catenary. It is designed to provide data for two main purposes:

- Slow speed catenary geometry measurements (height and stagger), and
- High speed pantograph current collection performance assessment.

To accomplish this a number of parameters are measured.

1.1 CONTACT FORCE

Since the contact point between the pantograph head and catenary trolley wire changes its lateral position over the full width of the pantograph head, it is impossible to measure contact force directly, although many attempts have been made to do so. The best results so far have been achieved by computing the contact force from its three major components:

- The head suspension reaction force,
- The head rigid body vertical inertia, and
- The head aerodynamic lift.

The head suspension reaction force is measured by summing the output from load cells fitted between the two head attachment pivots and the head suspension units. Alternatively, a suitable structural member in the head may be strain gaged and calibrated. A typical installation is shown in figure A-1.

The head rigid body inertia in the vertical direction is measured by two accelerometers mounted vertically on the pantograph head in such a way that, when the signals are averaged, the roll and pitch motions of the head are

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* ENSCO, Inc., User Manual for Pantograph Deadline Instrumentation, to be published.

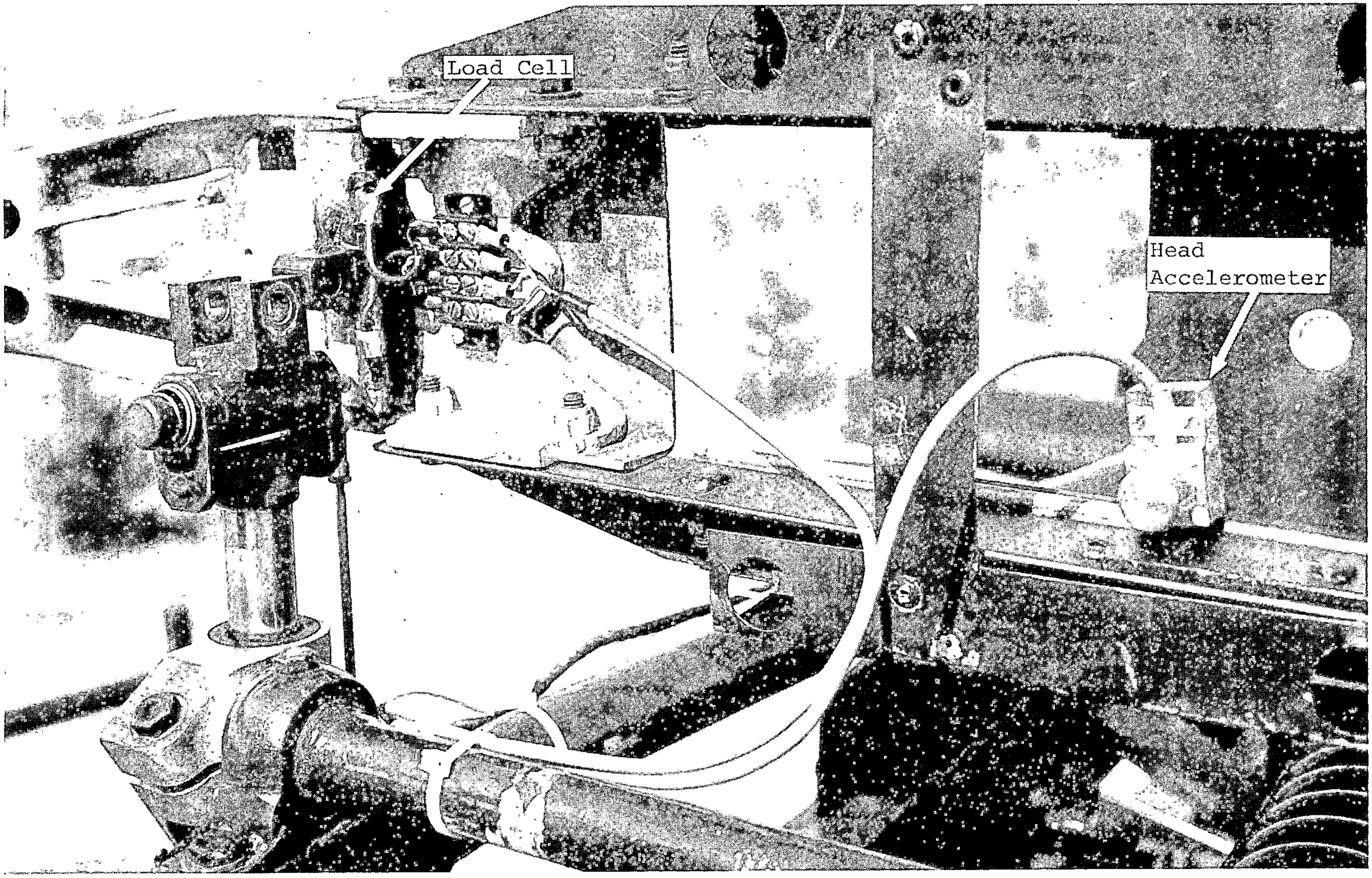


FIGURE A-1. HEAD SUSPENSION FORCE LOAD CELL AND HEAD ACCELEROMETER.

substantially eliminated from the measurements. The derived vertical acceleration is then multiplied by the effective head mass to produce the head inertia. In simple head arrangements like those on the Faiveley single and dual stage pantographs, the head mass is determined from the head weight. This measurement determines the frequency cutoff of the contact force computation since head flexibility invalidates the head inertia measurement. To overcome this, the head accelerometer signals must be filtered at a cutoff frequency which is 10% below the head fundamental bending frequency. The head suspension force signals must be filtered in an identical fashion to phase match the two component signals.

The aerodynamic lift component is provided by measuring the average relative air speed at the pantograph and multiplying its square by a head lift coefficient determined by separate experiment.

As part of the instrumentation, ENSCO produced an analog processor to compute the contact force from the above components, expressed in mathematical terms as:

$$F_c = F_s + Ma + Kv^2 \tag{1A}$$

where:

F_c = contact force,

F_s = total head static suspension force,

M = head dynamic mass,

a = calculated vertical acceleration,

K = head aerodynamic lift coefficient, and

v = average relative air speed at the pantograph.

1.2 CONTACT WIRE STAGGER

Contact wire stagger, defined as the lateral position of the contact wire relative to the track perpendicular centerline, can be measured by two alternative methods:

- Segmented pantograph head. The special two-strip head was manufactured of copper bar; one copper contact strip is continuous, the other is segmented in 1" units separated by insulation similar to a d.c. motor commutator. Each segment is jointed electrically to its neighbor by a resistor with the result that the segmented strip behaves as a stepped coil of a displacement transducer. The wiper is provided by the contact wire bridging the gap between the continuous strip and the segmented strip. Electrical resistance changes with the lateral position of the wire. A photograph of a segmented head is presented in figure A-2; the electrical circuit is shown in figure A-3.

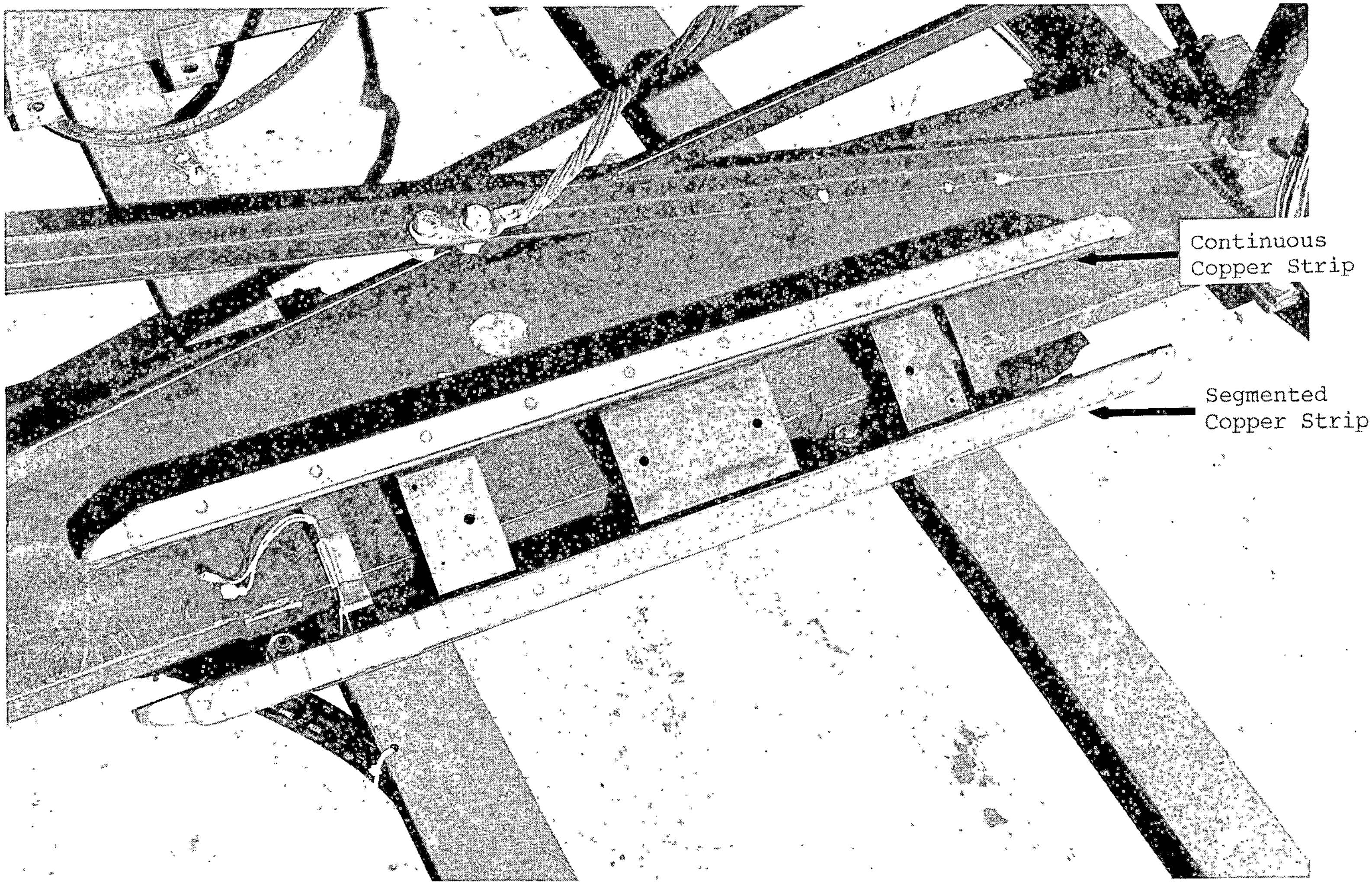


FIGURE A-2. SEGMENTED STAGGER HEAD CENTER SECTION
(SHOWN WITHOUT THE HORNS).

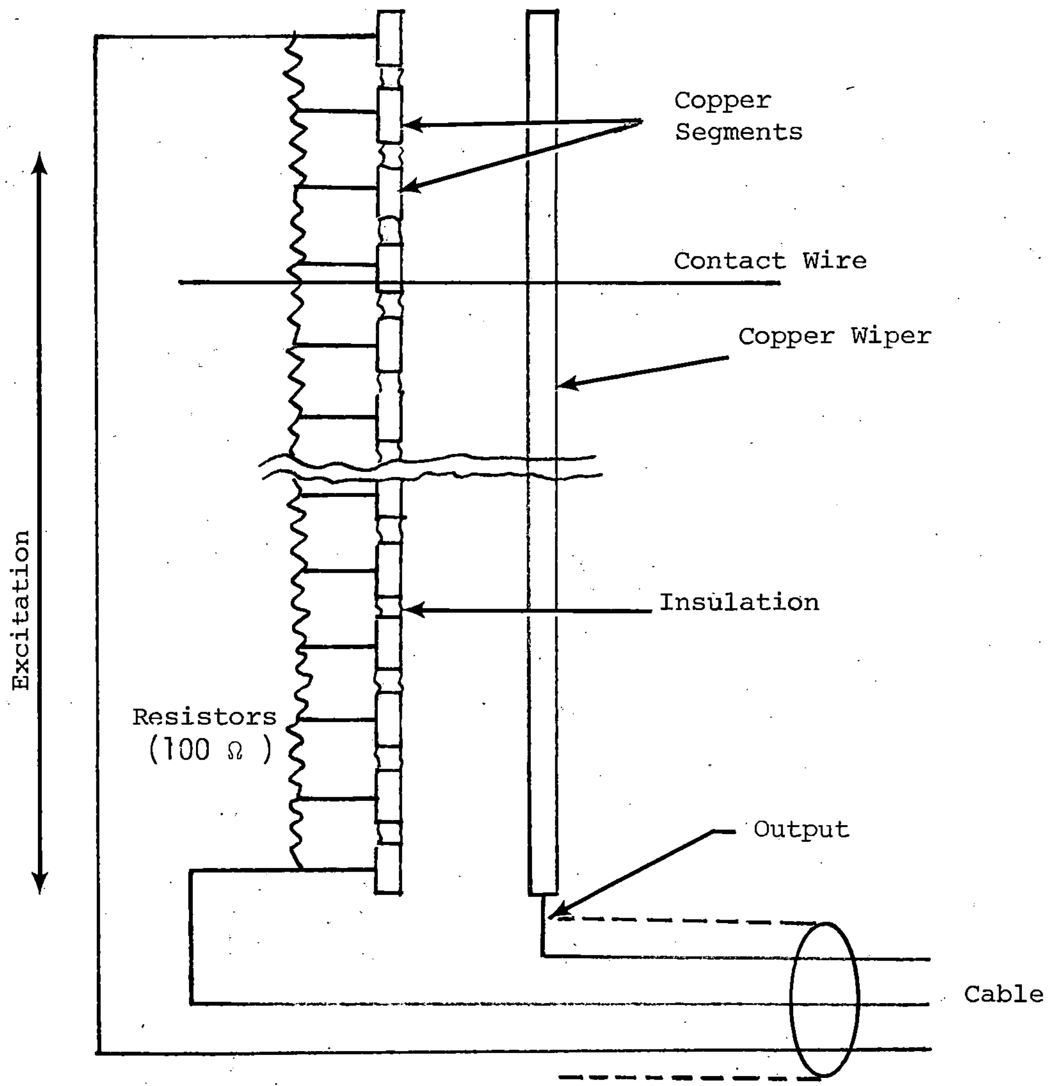


FIGURE A-3. SEGMENTED PANTOGRAPH HEAD (ELECTRICAL CIRCUIT).

- Computer Stagger. The output of the two head suspension force measurements are processed to compute the wire position on the head by moments. The mathematical relationship used for the computation is:

$$S = 1 - \left[\frac{2F_1}{F_1 + F_2} \right] x \frac{d}{2}$$

where:

S = wire stagger from head center line,

F_1, F_2 = left and right head suspension force components, and

d = distance between head suspension force load cells.

This method relies heavily on the lack of zero drift in head force transducer signals, and on the absence of large dynamic signals imposed on F_1 and F_2. Since both stagger methods are restricted to speeds where car body roll dynamics are negligible, this minimizes the vertical dynamic components of the force signals. Experience has shown that reliable stagger measurements can be obtained up to a speed of 50 mi/h, although 30 mi/h has been adopted for future RTT measurements.

1.3 CONTACT WIRE HEIGHT

The contact wire height above the pantograph lockdown is measured by means of a displacement transducer (string pot) applied to the main frame mechanism. For slow speed geometry measurements, the upper stage and head suspensions are mechanically locked out so that all pantograph vertical movement is restricted to the main stage. To reference the height to rail level, the measured data are added to the lockdown height above rail.

Direct measurement of the main stage displacement is difficult because of the travel. An indirect method of measurement was employed for the single and dual stage pantographs in which the string of a string pot was wrapped round the main pivot tube of the first stage mechanism. As the pantograph extended, the string wound onto the tube displacing the string relative to the string pot body which was attached to ground. The electrical output was calibrated against pantograph height above lockdown. The arrangement is diagramed in figure A-4 and a photograph of the single stage arrangement is shown in figure A-5. This technique provides a coarse measurement of wire height above rail, but insufficient resolution is available to determine inspan wire height changes. These are determined from the head trajectory measurement.

1.4 HEAD TRAJECTORY

The head trajectory maps displacement of the pantograph head relative to the average running height of the pantograph, allowing details of the pantograph head displacement (below a wavelength equivalent to approximately 2

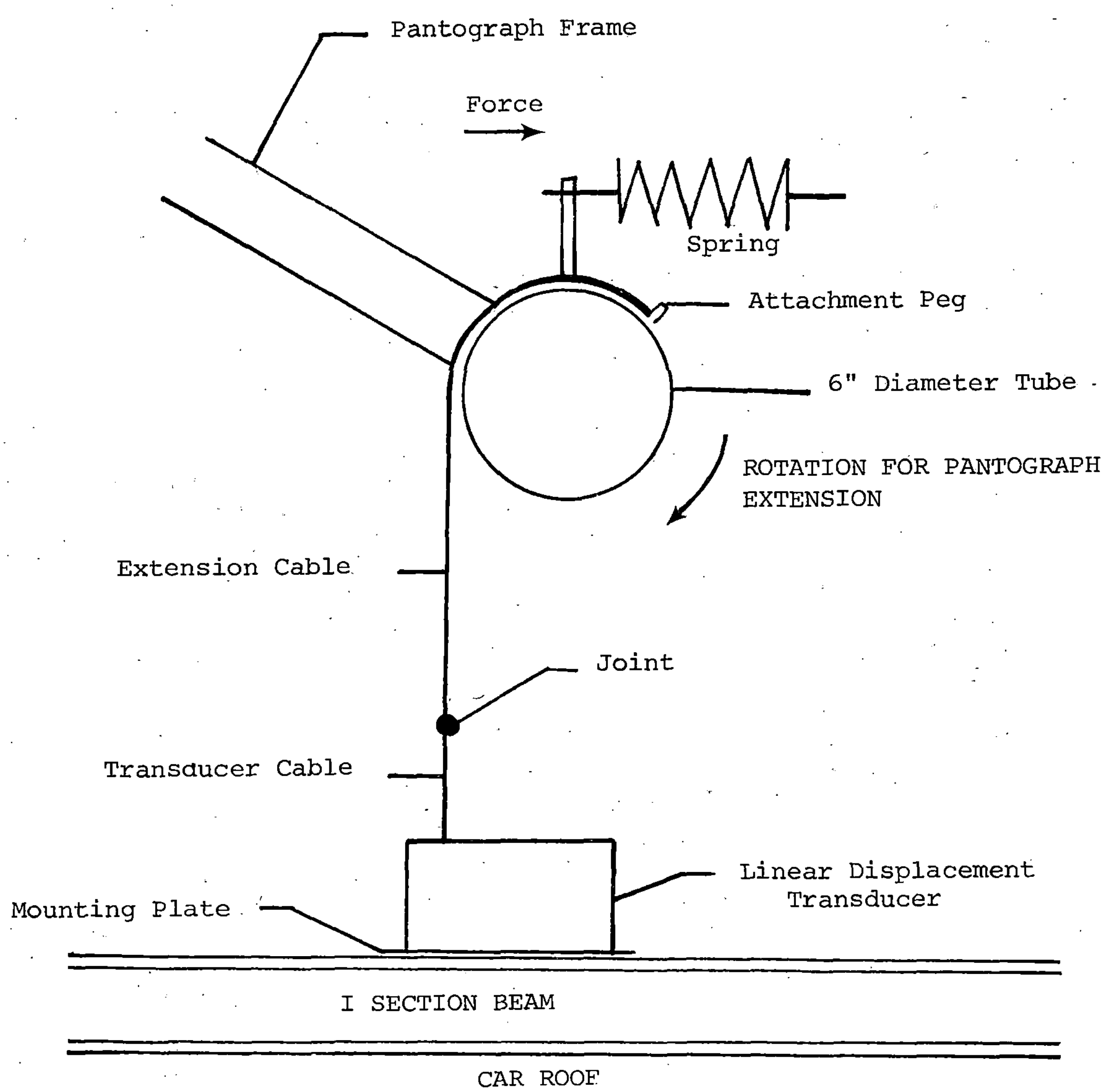


FIGURE A-4. PANTOGRAPH VERTICAL DISPLACEMENT MEASUREMENT SYSTEM.

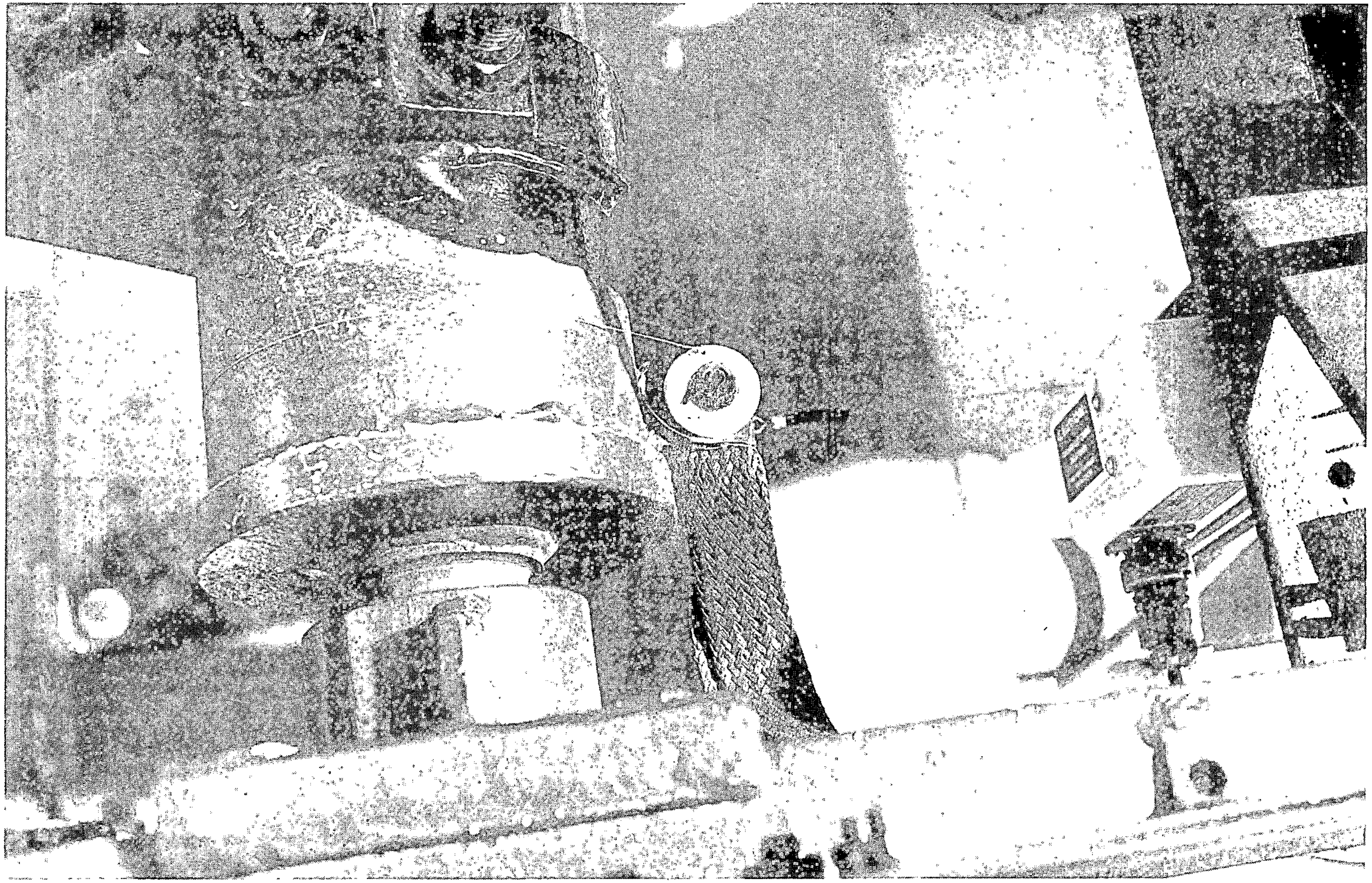


FIGURE A-5. MAIN FRAME DISPLACEMENT MEASUREMENT METHOD.

spans at 30 mi/h) to be enlarged for ease of analysis.

The pantograph head trajectory is computed from three components:

- The dynamic component of the main frame displacement,
- The second stage displacement (dual stage pantograph only), and
- The head suspension mean displacement.

The dynamic component of the main frame displacement is extracted by passing the relevant signal through a high pass filter set at 0.1 Hz. The resultant signal is then amplified to provide an output sensitivity of 6" = 1.4 V.

The second stage suspension displacement of the two stage pantograph is measured by a method identical to that employed for the main stage displacement. A reduced range string pot can be used with an output sensitivity set up to 6" = 1.4 V.

The head suspension mean displacement is measured by averaging the output of two displacement transducers connected across the head suspension units (figure A-6). Initially, linear displacement potentiometers were used, but these were later replaced by linear variable displacement transformers. For computation, the output sensitivity was made compatible with the main stage and second stage displacements.

For geometry measurements, the second stage and head suspension are fixed; therefore, the head trajectory becomes an amplified output of the main frame displacement.

1.5 STRUCTURE LOCATION

To provide a positional reference for the data, the catenary support structures are superimposed on the data by means of an optical sensor. During daylight, the unit is set up to detect the cantilever support arms against the background sky (not the sun-cast shadow as commonly believed). At night, the unit is set up to detect the reflection of a light beam off the underside of the cantilever support arms. In both cases, the output consists of a 1 V electrical pulse that can be recorded as a data channel.

1.6 LOSS OF CONTACT

Loss of contact between the pantograph head and the contact wire is detected by monitoring the voltage drop across a resistor in a circuit that includes a d.c. voltage source, the resistor, the insulated pantograph, the grounded catenary, the running rails, and the car underframe (figure A-7). When the pantograph is touching the contact wire, the circuit is completed, current flows, and a detectable voltage drop across the resistor results. When the pantograph loses contact, the current flow ceases, and the voltage across the resistor goes to zero.

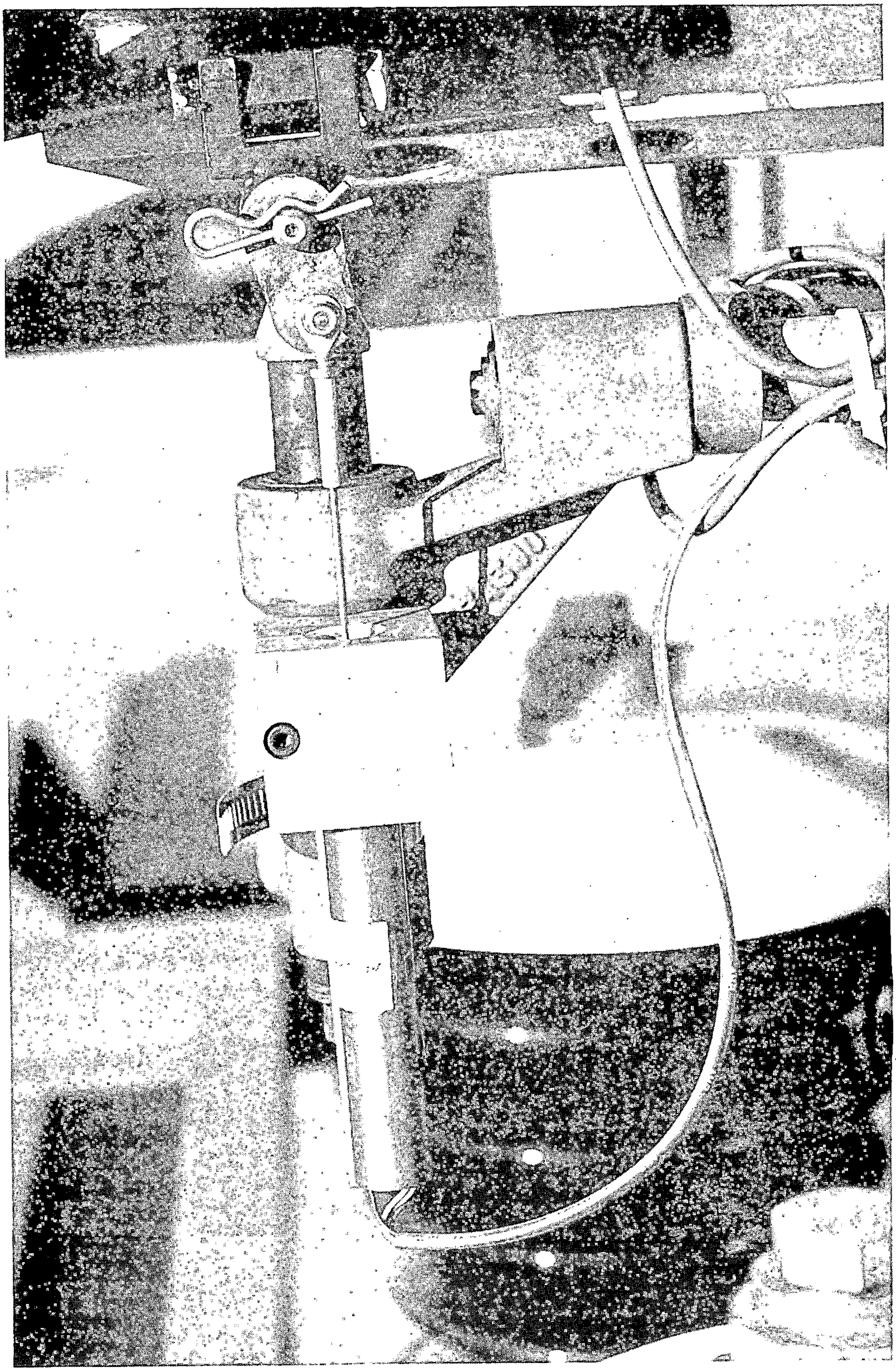


FIGURE A-6. HEAD DISPLACEMENT MEASUREMENT SYSTEM.

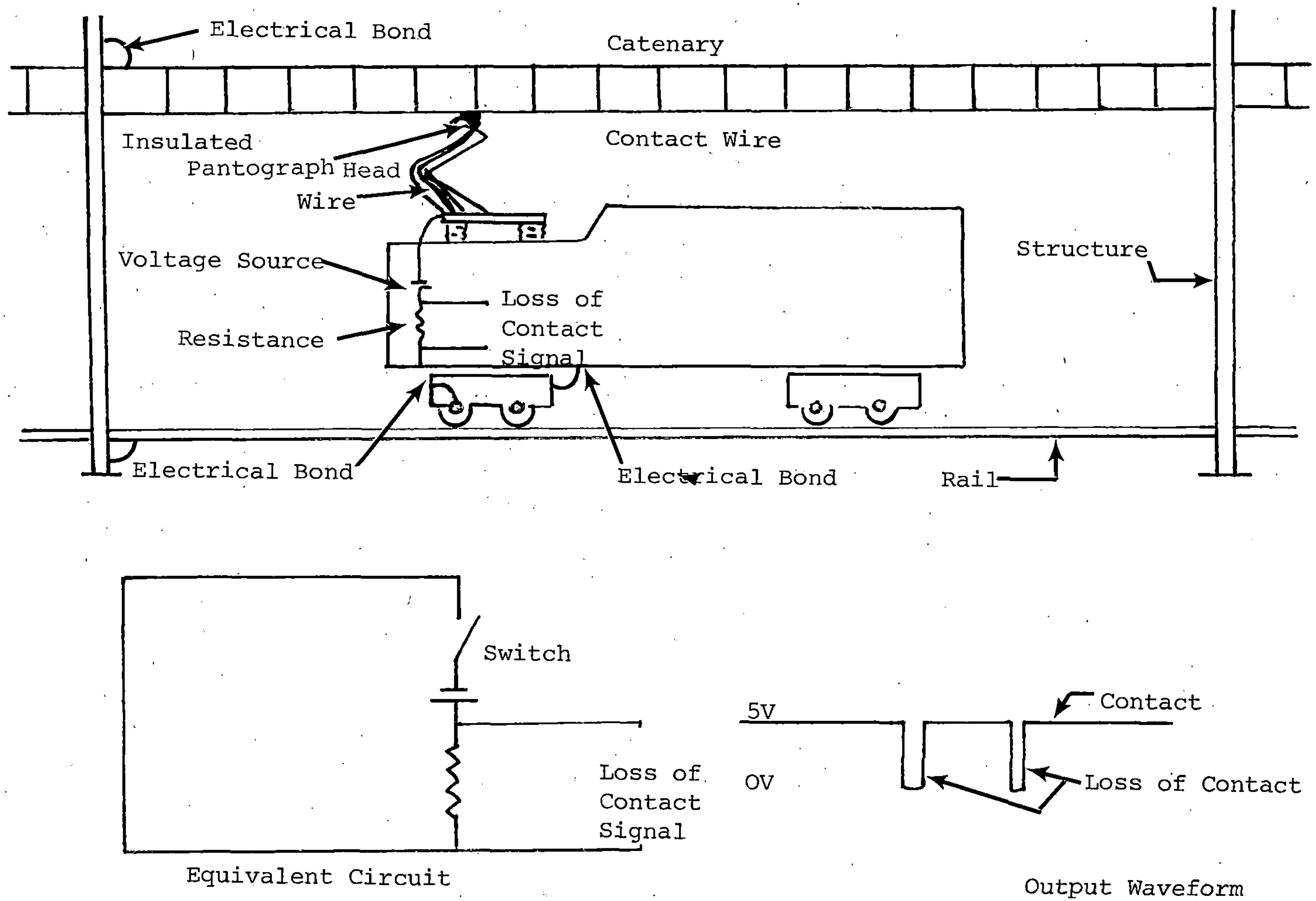


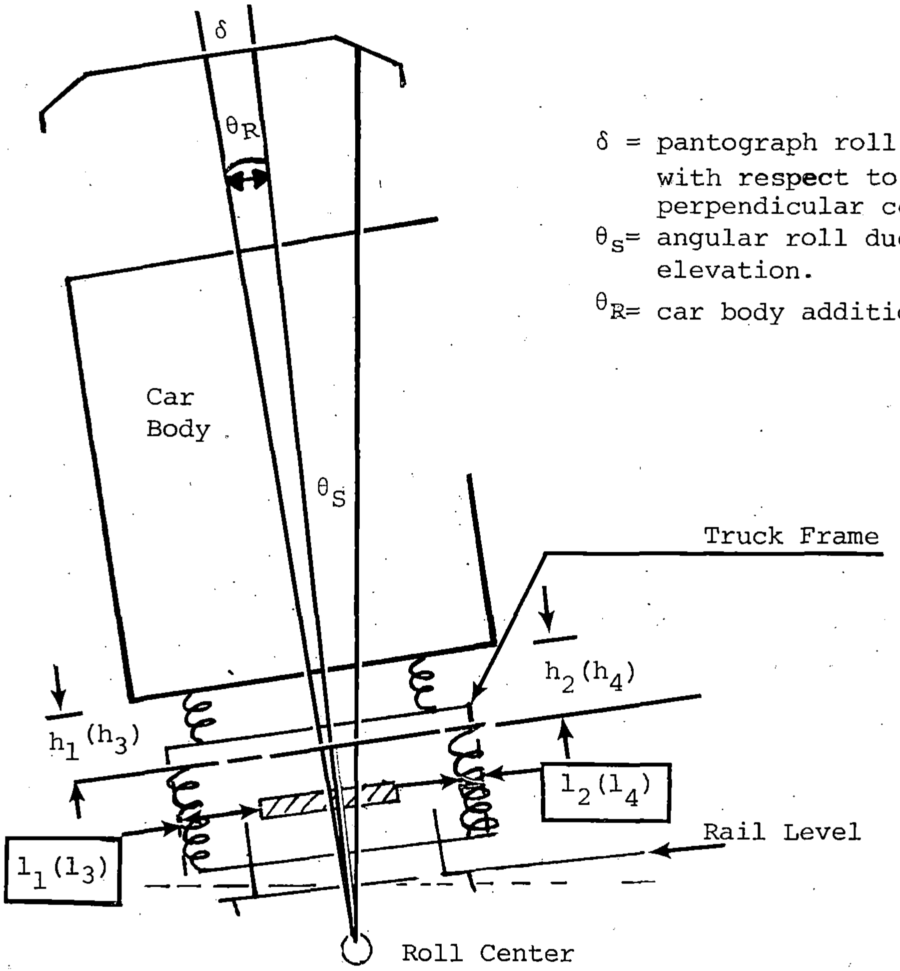
FIGURE A-7. DEAD LINE LOSS OF CONTACT MEASUREMENT.

The loss of contact signal is conditioned before being recorded, and contact losses below a selectable time duration can be ignored. The time duration threshold can be set between 0 and 99 ms; a minimum of 2 ms has been chosen for RTT data.

Selected lengths of loss of contact data can be processed real-time to produce percentage loss of contact. Provision is made to control the data block manually or by track-mounted automatic location detectors.

APPENDIX B

ANALYSIS OF THE DOT 211 CARBODY ROLL ON CURVES



δ = pantograph roll displacement with respect to the perpendicular center line.

θ_S = angular roll due to track super-elevation.

θ_R = car body additional roll angle.

Definition of Measurements:

h_1 = A-end left side truck frame to body height,

h_2 = A-end right side truck frame to body height,

h_3 = B-end left side truck frame to body height,

h_4 = B-end right side truck frame to body height,

l_1 = A-end left side truck frame to bolster lateral dimension,

l_2 = A-end right side truck frame to bolster lateral dimension,

l_3 = B-end left side truck frame to bolster lateral dimension,

l_4 = B-end right side truck frame to bolster lateral dimension, and

θ_T = Carbody total roll angle.

Measurements:

1. Car on level track

h_1 = 8-1/4" h_2 = 8-1/2" h_3 = 9" h_4 = 8-11/16"

l_1 = 5" l_2 = 5-5/8" l_3 = 5-1/4" l_4 = 5-3/8"

$\theta_T = 0^\circ$

2. Car on superelevated track

h_1 = 7-1/4" h_2 = 9-11/16" h_3 = 8" h_4 = 9-7/8"

l_1 = 4-3/8" l_2 = 6-3/8" l_3 = 4-1/8" l_4 = 6-1/8"

$\theta_T = 8.6^\circ$

Bolster height above rail = 12".
Distance between vertical measurement centers = 82"

Calculations:

1. Position of center of body lower sway

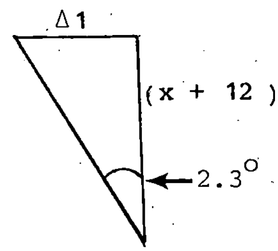
Angle of superelevation, $\theta_5 = \frac{6.25}{56.5} = 6.3^\circ$

$\therefore \theta_R = \theta_T - \theta_S = 2.3^\circ$

Lower sway center distance, x, from top of rail is calculated from the bolster lateral deflection by:

$$x + 12 = \frac{\Delta 1_{av}}{\tan 2.3} \qquad \Delta 1_{av} = \sum_{n=1}^{n=4} \frac{\Delta 1_{ln}}{n} - 3$$

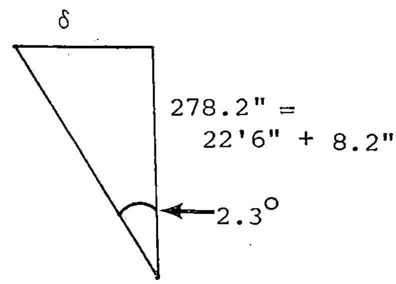
$$= 0.8125"$$



$$x + 12 = \frac{0.625}{\tan 2.3} = 15.6"$$

x = 3.6" (below rail)

2. <u>Pantograph throwover at 22' 6" above rail</u>



$$\delta = 273.6 \tan 2.3^{\circ} = 11.0"$$

(this is for 6 1/4" superelevation)

$$\delta 6" = 11.0 \times \frac{6}{6.25} = 10.5"$$

3. <u>Ratio of primary to secondary roll stiffnesses</u>

To calculate the ratio of the primary and secondary roll stiffnesses, the change in vertical height between bolster (carbody) and truck frame is used. The angle Θ_{BF} between carbody and truck frame is given by the equation:

$$\tan \Theta_{BF} = \left[\frac{1}{4} \sum_{n=1}^{n=4} \left| \Delta h_n \right| \right] d/2$$

where:

$|\Delta h_n|$ = modulus of the change in the truck frame to carbody height at position n, and

d = across track distance between vertical measurement centers.

From data table (page B.2):

$$\frac{1}{4} \sum_{n=1}^{n=4} \Delta h_n = \frac{1}{4} \left\{ (8.25 - 7.25) + (9.69 - 8.5) + (9.0 - 8.0) + (9.875 - 8.69) \right\}$$

$$= 1.09"$$

d = 82",

$$\therefore \quad \Theta_{BF} = \tan^{-1} \left[1.09 \div 82/2 \right] = \tan^{-1} \left[\frac{1.09}{41} \right]$$

$$= 1.52^{\circ}$$

Angle between truck frame and superelevated rail, Θ_{RF}

$$= \Theta_R - \Theta_{BF} = 2.3^{\circ} - 1.52^{\circ} = 0.78^{\circ}$$

The roll stiffness is inversely proportional to the roll angle.

$$\therefore \frac{\text{Primary roll stiffness}}{\text{Secondary roll stiffness}} = \frac{1.52}{0.78} = 1.95$$

This relationship was calculated to enable planning corrective modifications for the car suspension, should these have been necessary. However, no modifications are planned at this stage.