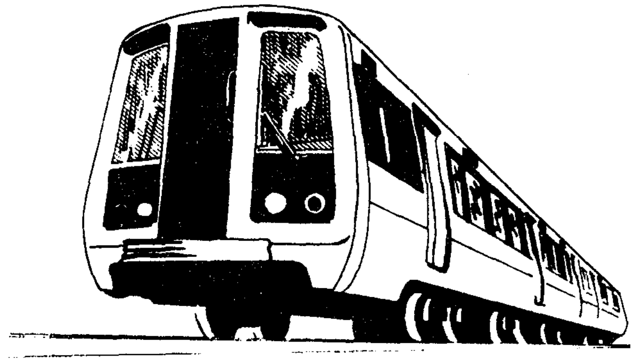
TECHNICAL NOTE

U.S. Department of Transportation

Urban Mass Transportation Administration



TRANSPORTATION TEST CENTER

TTC-010(UMTA-TN84) May 11, 1984

STATIC TRUCK CHARACTERIZATION OF THE TRI-COUNTY METROPOLITAN TRANSPORTATION AUTHORITY'S VEHICLE

by Nancy Blume
Association of American Railroads

INTRODUCTION

Twenty-six light rail vehicles were purchased from Bombardier, of Montreal, Quebec by the Tri-County Metropolitan Transportation Authority, of Portland, Oregon for transit service in the Portland Metropolitan area.

The six-axle, articulated light rail vehicles are equipped with a suspension system that will enable them to negotiate tight curves over routes in the downtown Portland area.

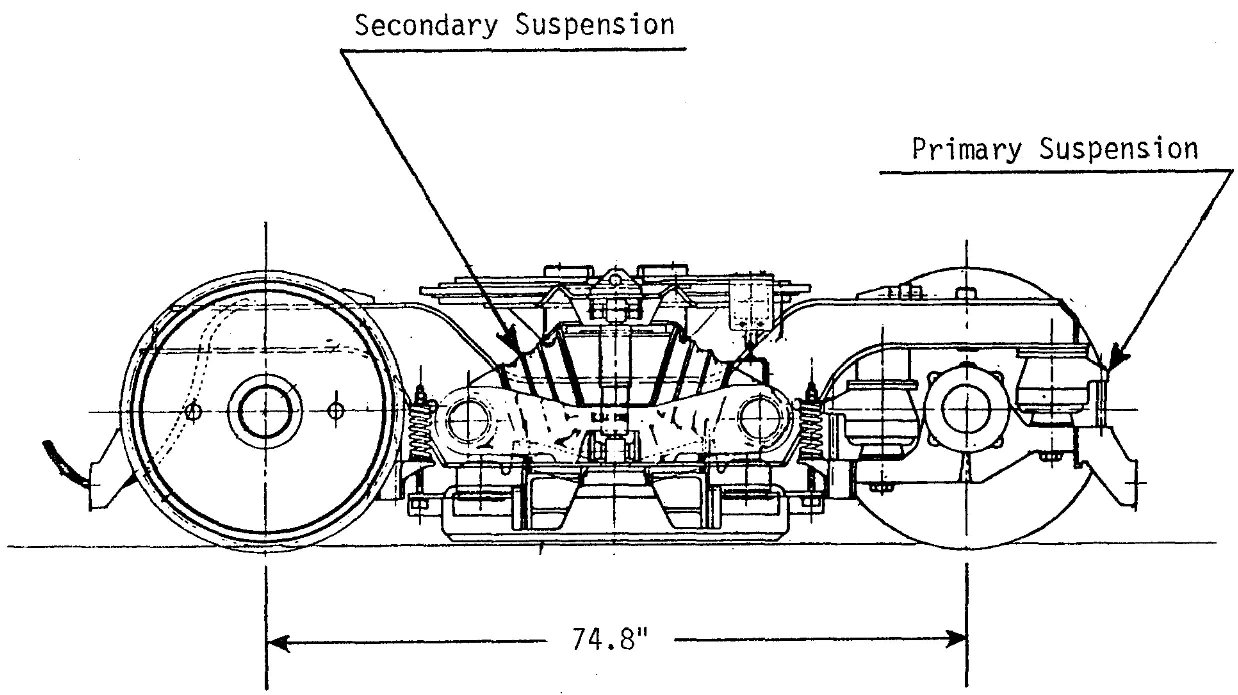
In support of the UMTA-sponsored Tri-Met Test Program at the Transportation Test Center (TTC) in Pueblo, Colorado, the TTC personnel performed tests on a prototype light rail Tri-Met vehicle in order to characterize its lateral, longitudinal, vertical, and rotational stiffness suspension parameters. The methodology and summary of the results of these tests are contained within this report.

1.0 OBJECTIVE

The objective of this series of special tests was to measure the static parameters of the suspension system of the Tri-Met vehicle's trucks while at AW0 weight (empty vehicle) plus approximately 1,350 pounds of testing instrumentation.

The articulated Tri-Met vehicle, designed and built by Bombardier Incorporated, has three trucks per car; two motor trucks, one on either end, and a trailer truck in the center position. The suspension systems of the three trucks are identical but the load distributions, braking and propulsion systems for the motor and trailer trucks differ.

Figure 1 (Bombardier Inc. #14 B 00 500 0) shows the primary suspension, which consists of eight rubber "donuts" per truck, and the secondary suspension, which is made up of four rubber chevrons per truck. A close-up view of the primary and secondary suspensions are shown in Figures 2 and 3 respectively.



Bombardier Incorporated
Drawing # 14 B 00 500 0

FIGURE 1. TRI-MET LIGHT RAIL VEHICLE SUSPENSION.

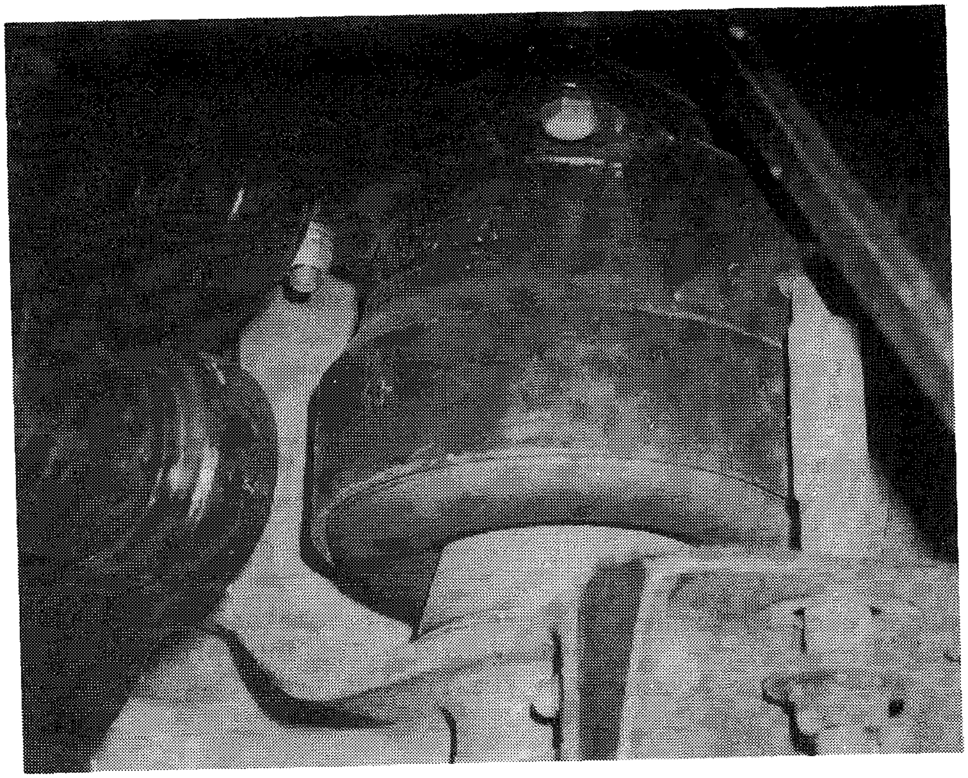


FIGURE 2. PRIMARY SUSPENSION DONUTS.

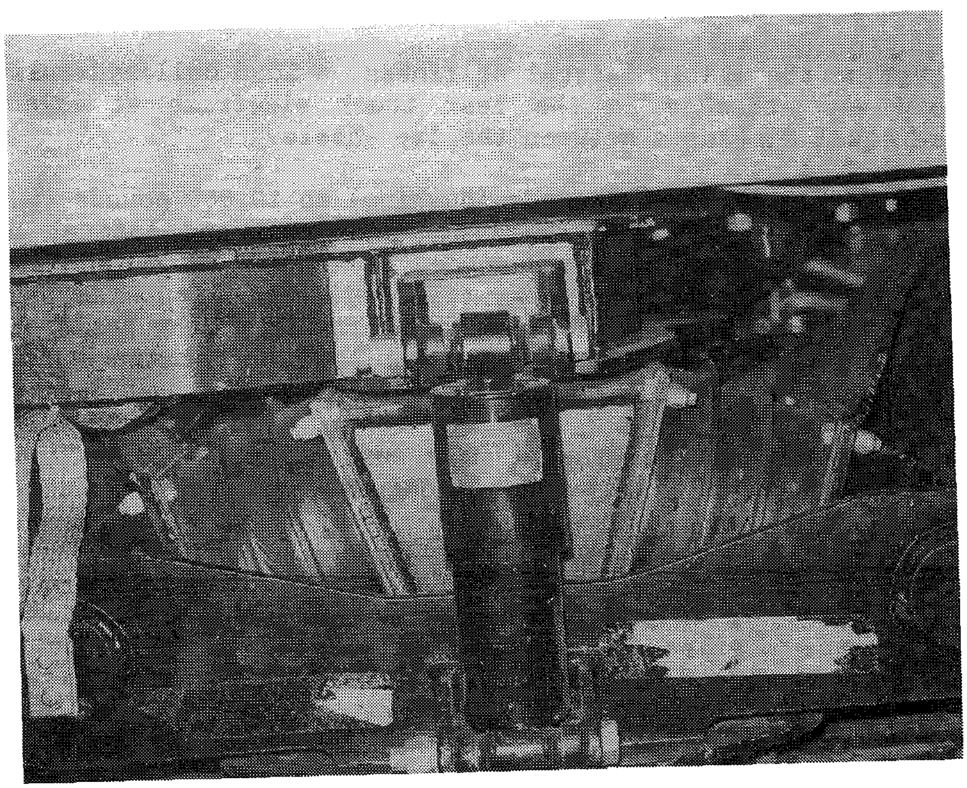


FIGURE 3. SECONDARY SUSPENSION CHEVRONS.

To quantify the truck static characteristics the following parameters were measured:

1.1 The lateral spring rate of the primary suspension and the apparent stiffness of the resilient wheel

1.2 The longitudinal spring rate of the primary suspension

1.3 The vertical spring rate of the primary and secondary suspensions

1.4 The truck rotational stiffness in terms of the break-away value of yaw torque between the carbody and a test truck

1.5 The axle alignment of the test truck wheelsets with respect to each other

2.0 METHODOLOGY

The methods used to measure the preceding parameters were standard Transportation Test Center Transit Vehicle Testing procedures that were slightly modified to accommodate the Tri-Met vehicle.

2.1 The Lateral Spring Rate

The lateral suspension of motor trucks and of the trailer truck are equal; therefore it was necessary to measure only one truck. The "A" end motor truck was used.

To determine the static lateral stiffness, a load cell/hydraulic cylinder assembly was attached to the test truck sideframe at axle level and located equal distances between the two wheels.

A lateral force of -4,000 pounds (pushing) to 10,000 pounds (pulling) was applied to the center of the truck sideframe and lateral deflections relative to the ground were recorded at each 1,000 pounds increment in the following locations: at the top of the wheel outside of the resilient ring, at the bottom of the wheel outside of the resilient ring, in the middle of the wheel at the journal, and on the truck sideframe, 16 inches to either side of the load point.

The lateral stiffness of the primary suspension per truck is defined as the pounds of force to the truck sideframe per inch of wheel deflection measured at the wheel journal.

The apparent stiffness of the wheel is determined by dividing the lateral load per wheel by the difference in the deflection between the journal and the lower portion of the wheel outside of the resilient ring. Although this is not a true measure of the rubber ring stiffness, it does provide an indication of its significance.

Overall, the truck lateral stiffness can be computed from the applied truck load divided by the truck deflection minus the lower wheel deflection.

2.2 The Longitudinal Spring Rate of the Primary Suspension

The static longitudinal stiffness of the primary suspension was determined by placing the leading axle of the test truck on an air-bearing table and supporting the other axle at an equal height but on a non-moveable surface. A load cell/hydraulic cylinder was mounted longitudinally on each side of the truck between the truck frame and the floating axle.

Dial gauges were mounted to measure the longitudinal movement of each of the floating wheels relative to the truck sideframes. A pushing force of 0 to 6,500 pounds was applied and the displacements were recorded at increments of 500 pounds. When the load was relieved, displacements were noted every 1,000 pounds. The procedure was then repeated in a pulling mode, with forces ranging from 0 to 3,500 pounds.

The longitudinal stiffnesses of all three trucks are theoretically equal, so only the "A" end motor truck was measured.

Frictional force between the air table and the ground is negligible.

The static longitudinal stiffness of the primary suspension was then determined by averaging the pounds of force per inch of journal deflection on each side of the test axle. The push and pull mode results were compared and an overall longitudinal spring rate of the primary suspension defined.

Any rotational deflection between the center portion of the wheel and its rim beyond the resiliency was disregarded.

2.3 The Vertical Spring Rates of the Primary and of the Secondary Suspensions

The primary and secondary suspension vertical stiffnesses were measured on the "A" end motor truck and the primary suspension stiffness was measured on the trailer truck.

Dial gauge indicators were mounted between the truck sideframe and the ground to measure vertical displacement of the primary suspension and between the truck sideframe and the carbody to measure vertical displacement of the secondary suspension. See Figure 4.

A load cell and hydraulic cylinder were placed in the middle of the truck sideframe between the frame and the ground. See Figure 5. (Note: When the trailer truck was measured, the wheels were on a wood surface, therefore, vertical deflection between wheels and the ground was also measured.)

A load from 0 to 13,000 pounds was applied by the hydraulic cylinder to gradually relieve the suspension system of the vehicle weight. Vertical deflections at each 1,000 pound increment were recorded as the hydraulic load was increased and decreased.

The vertical suspension stiffnesses were then determined by the average force per deflection rate.

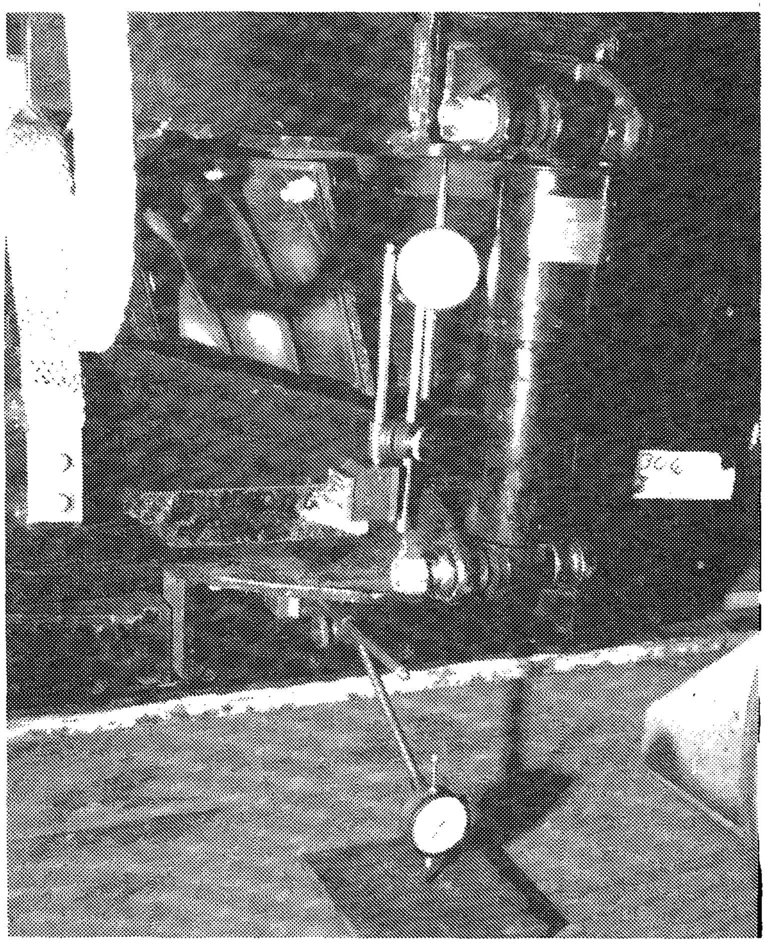


FIGURE 4. DIAL GAUGES MONITORING VERTICAL DEFLECTION OF PRIMARY AND SECONDARY SUSPENSION OF THE TEST MOTOR TRUCK.

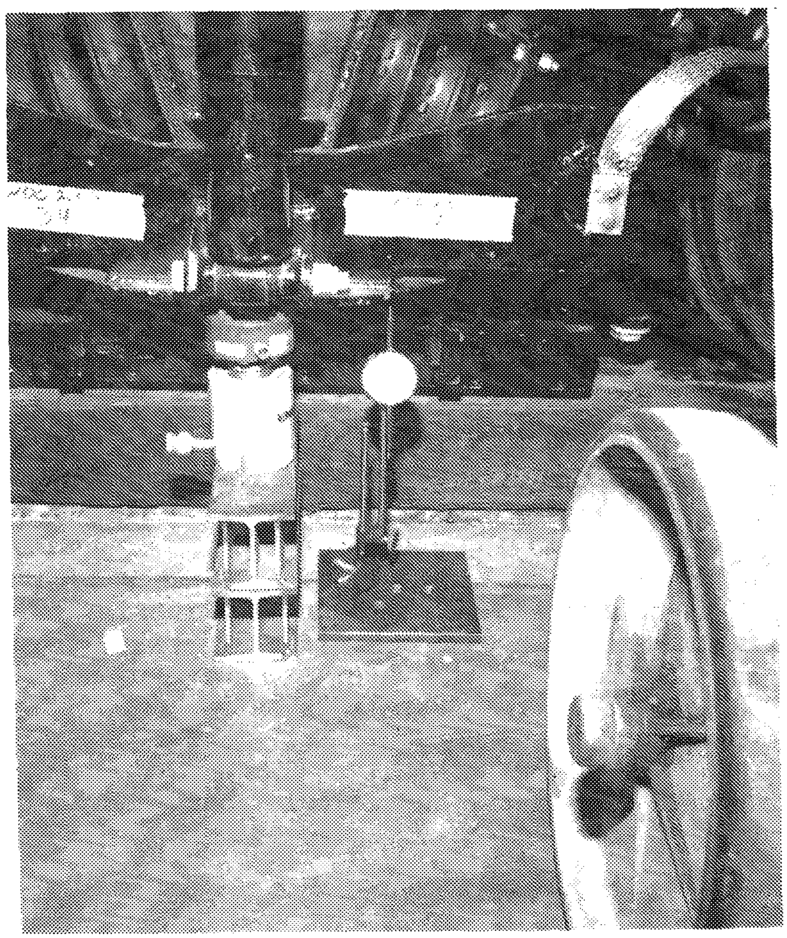


FIGURE 5. HYDRAULIC CYLINDER AND LOAD CELL SET-UP TO APPLY VERTICAL FORCES TO THE TRAILER TRUCK.

2.4 The Truck Rotational Stiffness

To determine the yaw break-away torque, both axles of the test truck were supported on a single air-bearing table such that the truck was allowed to yaw freely with respect to the ground. Equal and opposite lateral forces were applied to the diagonally opposite wheel axle journals while the magnitudes of the applied forces were measured with load cells. The set-up is shown in Figure 6.

The angular displacement of the truck relative to the carbody was measured with a string potentiometer. With the truck floating freely on the air-bearing table, rotational forces were slowly applied by one smooth stroke of the hydraulic pump.

The rotational stiffness was determined from the average maximum torque obtained before gross truck rotation occurred.

The frictional force between the air table and the ground is negligible.

This procedure was performed on the "A" end motor (powered) truck and on the trailer (non-powered) truck.

2.5 The Axle Alignment

The axle alignment of the test truck was measured with an optical transit. This test was performed on the motor truck only. The wheels of the truck were allowed to position in their "natural" alignment by floating each axle independently on separate air-bearing tables. Precision scales were positioned, parallel and level to each other, against the front face of each wheel on one side of the truck, 9 inches from the axle centerline. The scales were sighted through the transit and an optical line-of-sight was determined. From the four lateral distances measured between the outside faces of the wheels and the optical line-of-sight, the angular misalignment of the test truck axles with respect to one another was calculated.

Figure 7 shows the geometry and calculations used to determine θ_C, the axle alignment.

3.0 RESULTS

3.1 The Lateral Spring Rate

The lateral static stiffness of the primary suspension was determined from the change of applied lateral load divided by deflection of the wheel journal relative to the truck sideframe. The data is shown in Figure 8.

Figure 8 also shows that the transition from the push to the pull mode was smooth, indicating that there is no slack in the bearings. However, with a lateral load between 6,500 pounds and 8,000 pounds, there was a sudden jump of approximately 0.050 inches in the deflection. The cause of this is not known, but the test was repeated and the results were the same.

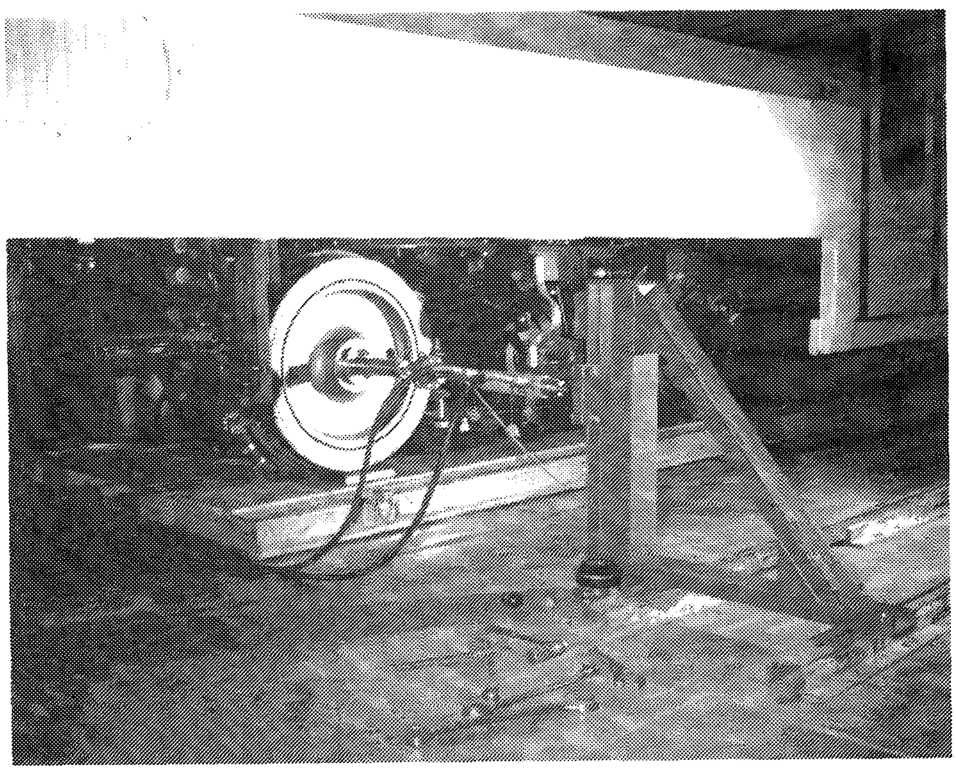
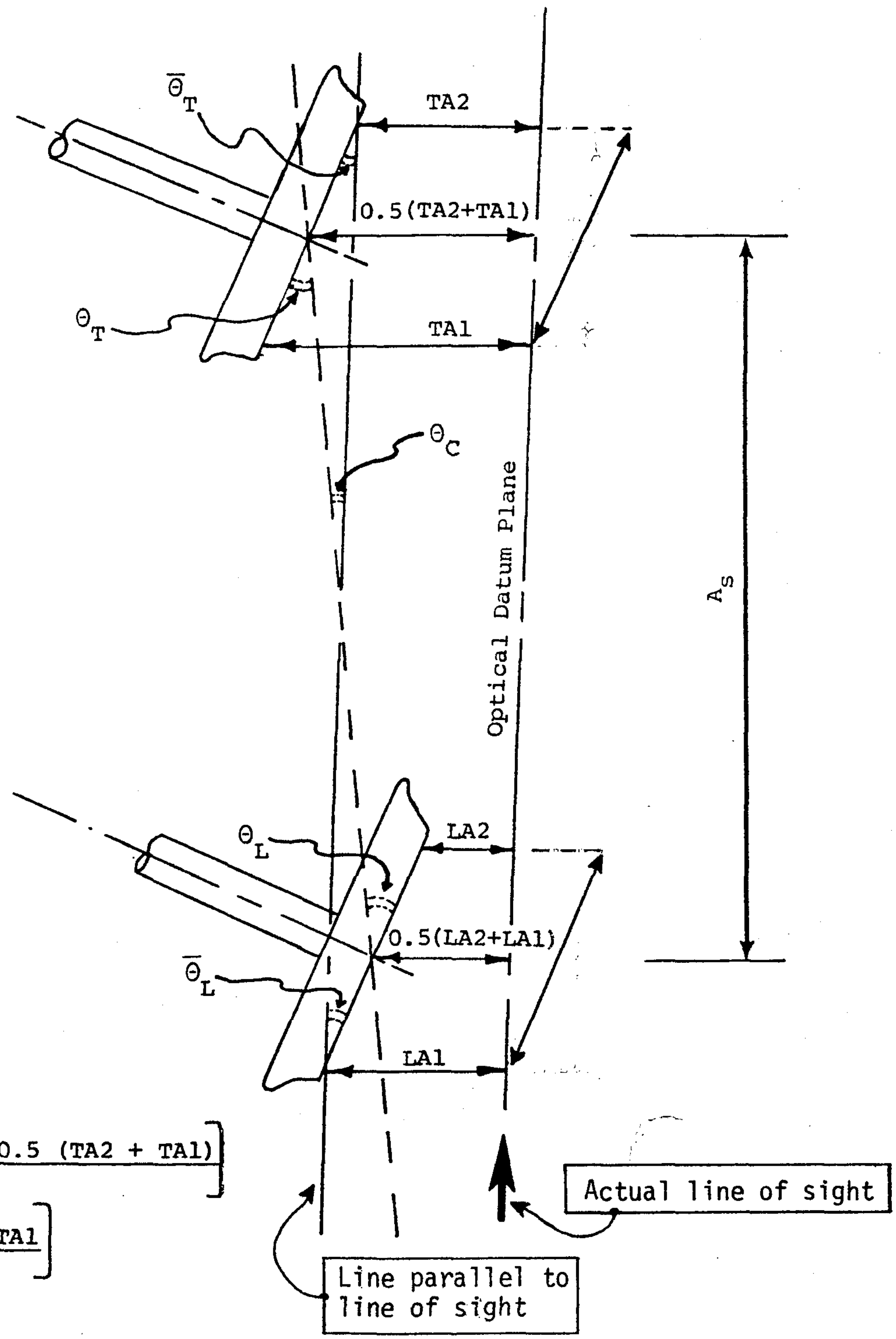


FIGURE 6. TRUCK ROTATIONAL STIFFNESS MEASUREMENT.



OBJECTIVE:

calculate Θ_T and Θ_L

$$\Theta_T = \overline{\Theta}_T - \Theta_C$$

$$\Theta_L = \overline{\Theta}_L - \Theta_C$$

Where:

$$\overline{\Theta}_T = \mathrm{Sin}^{-1} \left[\frac{(TA1 - TA2)}{TA3} \right]$$

$$\overline{\Theta}_L = \mathrm{Sin}^{-1} \left[\frac{(LA1 - LA2)}{LA3} \right]$$

$$\Theta_C = \mathrm{Sin}^{-1} \left[\frac{0.5\ (LA2 + LA1) - 0.5\ (TA2 + TA1)}{A_s} \right]$$

$$= \mathrm{Sin}^{-1} \left[\frac{LA2 + LA1 - TA2 - TA1}{2A_s} \right]$$

FIGURE 7. AXLE ALIGNMENT CALCULATION.

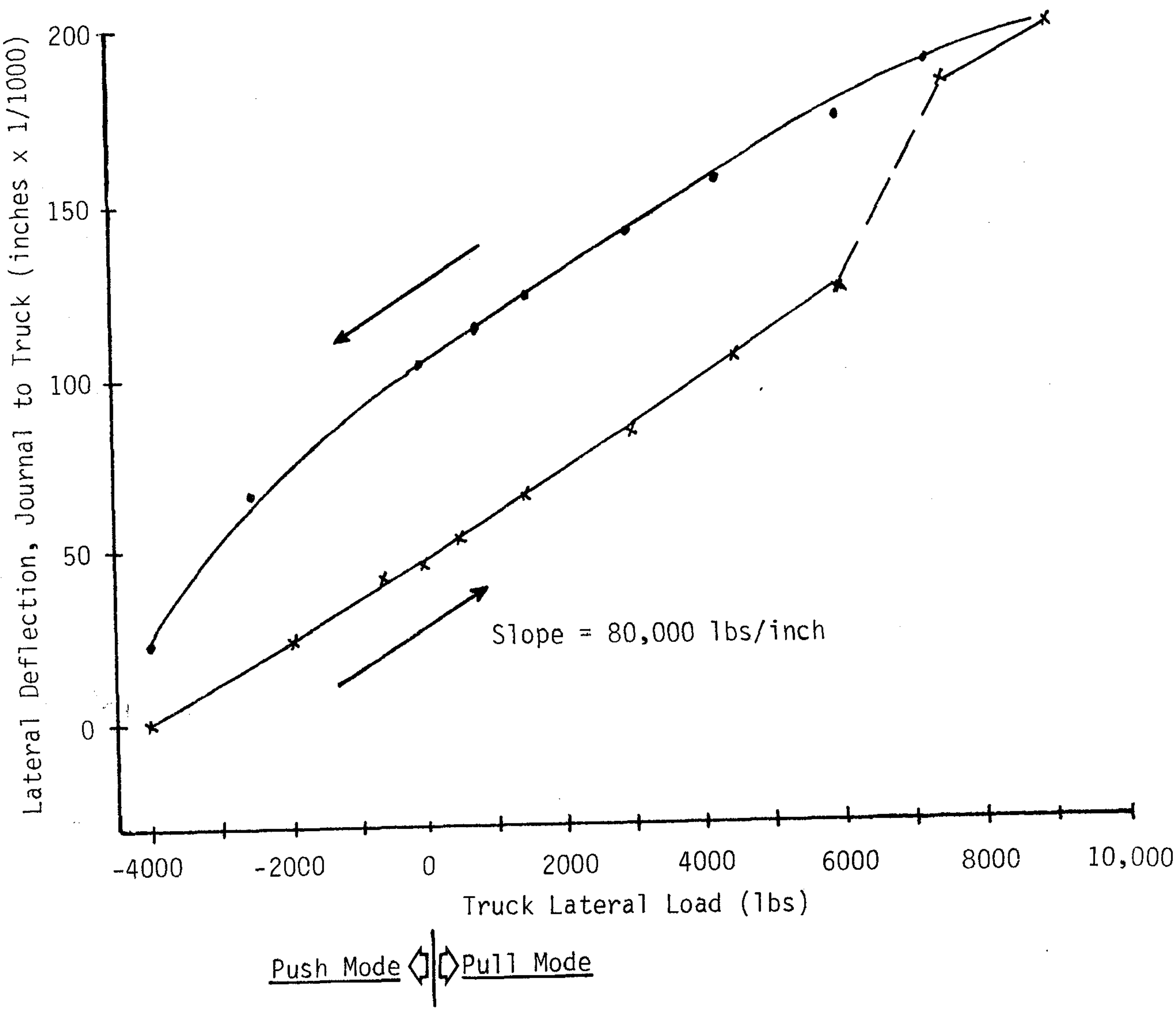


FIGURE 8. LATERAL SPRING RATE OF THE PRIMARY SUSPENSION.

If the unexplained lateral shift at approximately 7,000 pounds is ignored, the spring rate of the primary suspension is 80,000 pounds/inch for a wheel stiffness of 20,000 pounds/inch.

The apparent stiffness of the wheel was determined by dividing the lateral load per wheel (assume the wheel load equals one quarter of the truck load) by the difference between the wheel displacement at the axle and the displacement at the lower edge of the wheel outside of the resilient ring. The apparent wheel stiffness equals 60,000 pounds/inch.

The overall lateral spring rate of the system is the applied lateral load versus the difference between the truck sideframe deflecion and the deflection at the wheel/rail interface (the lower rim of the wheel outside of the resilient ring).

A plot of these data is shown in Figure 9. The overall truck stiffness is 60,000 pounds/inch for an overall wheel stiffness of 15,000 pounds/inch.

3.2 The Longitudinal Spring Rate of the Primary Suspension

The longitudinal stiffness of the primary suspension was measured both in the push and in the pull mode on each side of the vehicle. The following table shows the spring rate for each wheel in both modes.

TABLE 1. LONGITUDINAL SPRING RATES OF PRIMARY SUSPENSION.

	Side 1		Side 2	
Mode	Wheel Spring Rate	Correlation Coefficient	Wheel Spring Rate	Correlation Coefficient
Push	19,600 lbs/in	0.993	16,100 lbs/in	0.988
Pull	19,800 lbs/in	0.993	16,700 lbs/in	0.987

Averaging these values together yields an overall primary longitudinal wheel stiffness of 18,000 lbs/in with a standard deviation of 1,920 lbs/in. The average hysteresis of Side 1 was 0.020 inch and Side 2 was 0.030 inch.

3.3 The Vertical Spring Rate of the Primary and Secondary Suspension of a Motor Truck and the Primary Suspension Only of the Trailer Truck

Table 2 shows the results from the vertical spring rate characterization tests. It states the average spring rates per wheel, the number of times the test was repeated, and the standard deviation of the rates. All individual test results had a correlation coefficient of 0.985 or greater. The hysteresis levels for the primary and secondary suspensions were approximately 0.025 inch each. No difference was seen between one side of the vehicle and the other.

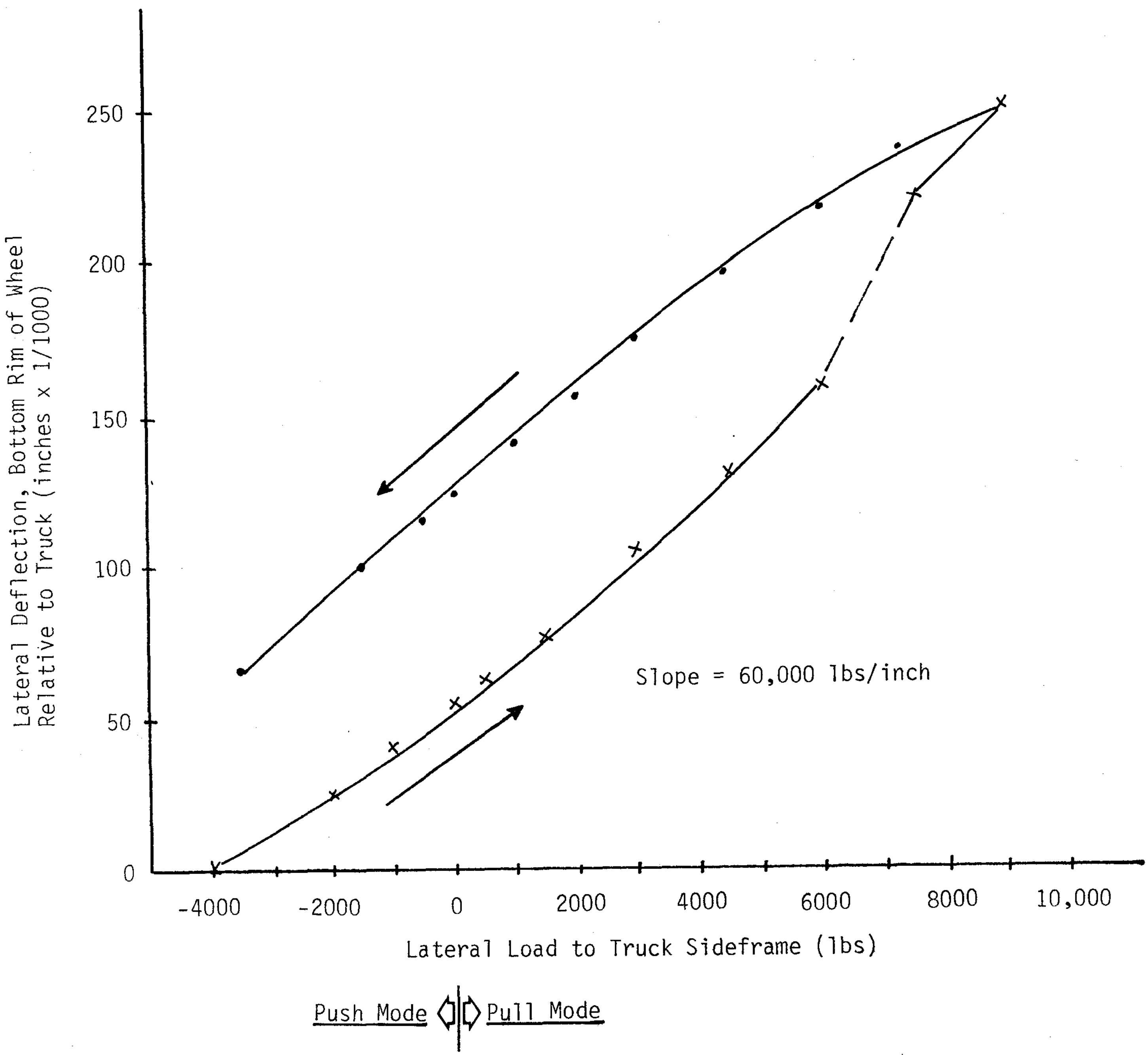


FIGURE 9. OVERALL TRUCK LATERAL SPRING RATE.

TABLE 2.

Suspension	Wheel Vertical Spring Rate	n	σ
Primary, Motor Truck	6,700 lbs/in	2	919 lbs/in
Primary, Trailer Truck	3,880 lbs/in	4	112 lbs/in
Secondary, Motor Truck	2,750 lbs/in	2	56.6 lbs/in

3.4 Truck Rotational Stiffness

The average rotational stiffnesses, the sample size, and the standard deviations of the data are as follows:

Truck	Break-Away Torque	n	Standard Deviation
Motor Truck	2,120 ft-lbs	10	291 ft-lbs
Trailer Truck	2,360 ft-lbs	4	166 ft-lbs

There is no statistically significant difference between the rotational stiffness of the motor truck and the trailer truck, therefore the values may be averaged together yielding a mean breakaway torque of 2,200 ft-lbs.

3.5 Axle Alignment

The average misalignment angle of one axle relative to the other on a motor truck is 1.5040 milliradians or 0.0862° with the standard deviation, $\sigma = 0.5764$ milliradians or 0.0330°, sample size $n = 4$.

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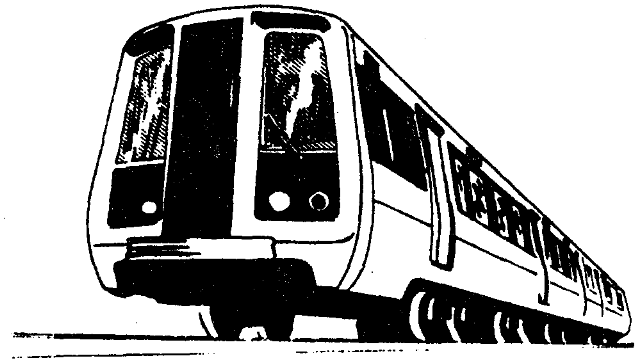


TRANSPORTATION TEST CENTER

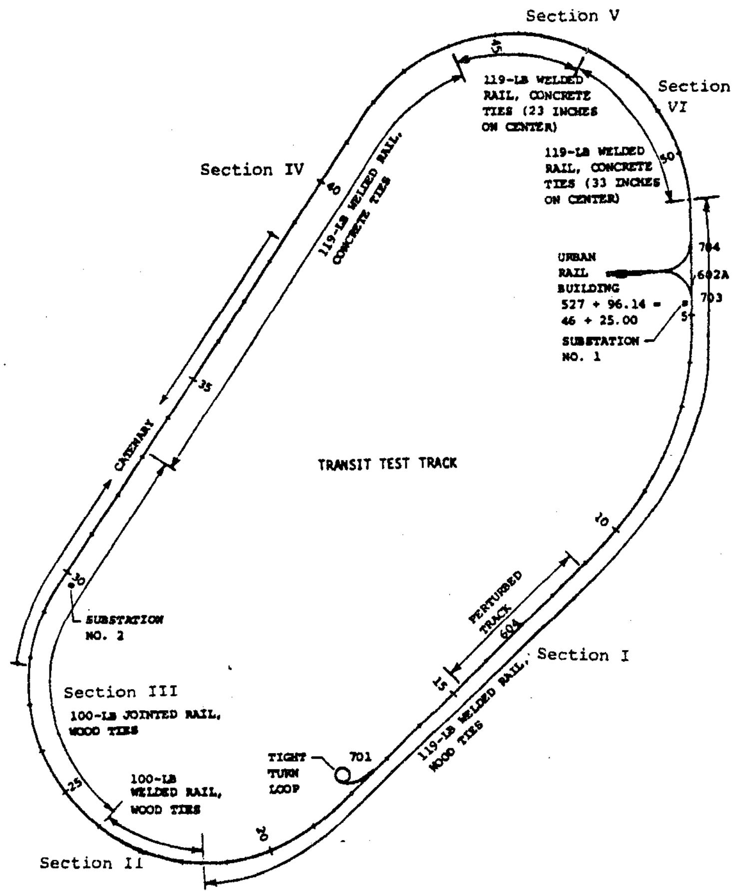
Test and evaluation activities of the Urban Mass Transportation Administration (UMTA) are coordinated through The Office of Technical Assistance in Washington, D.C., and are conducted by The UMTA Program Office at the Transportation Test Center (TTC) in Pueblo, Colorado.

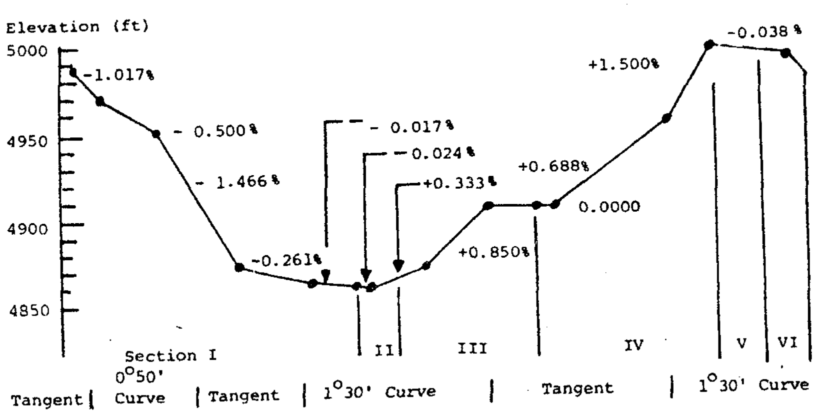
The urban rail transit test facilities at the TTC provide for test and evaluation of urban rail vehicles, subsystems, track, and structural components in an environment that is both safe and free from the scheduling constraints imposed by revenue service operations.

The Transit Test Track (TTT) is a 9.1 mile oval (see next page) designated for sustained 80 mi/h vehicle operation with the exception of the perturbed track section, which is subject to a speed limit based on ride quality test requirements and safety considerations. Power is provided either by a conventional third rail or a section of overhead catenary cable; the third rail was constructed to New York City Transit Authority specifications.

The rectifier station voltage can be varied infinitely from 400 to 1,200 V.d.c. with a current limit of 11,000 A. The stations each feed from one bus to all of the TTT and are designed to operate in several alternate modes, including computer control. Voltage can be controlled at a constant level at the substation, or at the position of the vehicle and held within the above constraints to a constant value at the vehicle regardless of demand or voltage drop through the rails. In alternate modes of operation the test vehicle can be subjected to a voltage profile or a voltage step such as might occur in revenue service at the transition between one substation and another.

The Test Center's technical support capabilities include test management, engineering instrumentation, calibration and electronic repair, photo-optical instrumentation, and data processing. In addition, TTC has the capability to assist users in developing test plans and requirements, and preparing reports.





NOTES:

Track Curvature:

Sta.	to Sta.	Degree of Curve
55.3	10.3	0° 50"
18.9	29.4	1° 30"
41.8	50.8	1° 30"

Elevation:

Minimum - 4863 ft at Station 22.0.
Maximum - 5003 ft at Station 46.0.

Curve Superelevation:

1° 30' curves are superelevated a maximum of 4.5". The maximum superelevation on the 0° 50' curve is 2".

Tight Turn Loop

150 ft radius.
119 lb AREA Head Hardened running rail.
85 lb ASCE restraining rail installed as per Massachusetts Bay Transit Authority specifications.