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CANT DEFICIENCY TEST SAFETY MONITORING USING ACCELEROMETER MEASUREMENTS

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12 - Safety

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August 1989

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NOTICE

Technical Report Documentation Page

1. Report No. DOT-FRA/ORD-89/05	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle CANT DEFICIENCY TEST SAFETY MONITORING USING ACCELEROMETER MEASUREMENTS		5. Report Date August 1989
		6. Performing Organization Code 1750-503
7. Author(s) Patrick Boyd		8. Performing Organization Report No. DOT-FR-89-01
9. Performing Organization Name and Address ENSCO, INC Applied Technology and Engineering Division 5400 Port Royal Road Springfield, VA 22151		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DTFR53-86-C-00012
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Railroad Administration Office of Research and Development 400 Seventh St., SW, Washington, DC 20590		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The FRA has performed high cant deficiency curving tests on several passenger trains using instrumented wheels to measure wheel forces for comparison to derailment safety criteria. Data from these tests show that the vehicle overturning safety criterion which prevents wheel lift is the most restrictive for passenger vehicles operating on strong track. The measurement of side to side vertical load transfer was used to quantify overturning hazard.

This paper describes a way of using accelerometer measurements to estimate transient vertical load transfer. It is useful for monitoring curving safety when the cost of instrumented wheels is not justified. Its application to conventional and tilt coachs tested for high cant deficiency ride quality by Amtrak/CONEG is described.

17. Key Words Safety, Derailment Safety, Cant Deficiency, Wheel Forces, Lateral Acceleration, Instrumented Wheels	18. Distribution Statement This document is available to the public through the National Technical Information Service, Port Royal Road, Springfield, VA, 22151

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-72)

CANT DEFICIENCY TEST SAFETY MONITORING USING ACCELEROMETER MEASUREMENTS

BACKGROUND

The FRA[1] has performed high cant deficiency tests of derailment safety in which wheel force measurements were made using instrumented wheelsets. The peak and steady state vertical and lateral wheel forces were compared to safety criteria which set operating thresholds to prevent vehicle overturning, rail rollover, wheel climb and lateral track shift.

Amtrak and the Coalition of Northeastern Governors (CONEG) have been evaluating the ride quality of various passenger trains at increased cant deficiency above the FRA regulation limits, and it has been necessary to monitor derailment safety. Because of the cost of multiple instrumented wheelsets and the probability that operating cant deficiency would be limited by ride considerations rather than derailment risk, a method of estimating critical wheel forces using simple accelerometer measurements was used. This paper explains how accelerometer measurements were applied to monitor derailment safety during tests of three vehicles with great differences in suspension design. The Amcoach with modern conventional suspension, the Canadian LRC coach with an active tilt system and the Spanish Talgo coach with a pendular passive tilt system were tested.

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[1]Report No., DOT-FR-81-06, "High Cant Deficiency Testing of the LRC Train, the AEM-7 locomotive and the Amcoach," NTIS No.PB82213018

Report No. DOT-FR083-03, "High Cant Deficiency Testing of the F40PH locomotive and the Prototype Banking Amcoach," NTIS No. PB83219139

The previous tests with instrumented wheels attempted to define the absolute curving limits of several passenger coaches and locomotives from the viewpoint of derailment safety. Observations based on those tests suggested a simple method of estimating critical wheel forces. A key observation was that the unloading of the vertical wheel force at the low rail set the curving speed limit for every vehicle and every curve tested. The vehicle overturning safety criterion was more restrictive than the safety criteria against track panel shift, rail rollover or wheel climb when applied to passenger vehicles operating on the Northeast Corridor.

There were several reasons why the vertical wheel forces were more critical than the lateral wheel forces. The rail size and track strength are great and the curvature is gentle on the Northeast Corridor. Consequently the force limits for track panel shift and rail rollover are large while the lateral wheel forces produced by passenger vehicles are low because of their relatively light weight and their geometrically favorable two axle trucks (or steerable single axle bogies). However the soft suspensions and lateral compliance of passenger coaches promote vertical load transfer despite their lower centers of gravity. The vehicle overturning criterion also considers the possible vertical load transfer due to adverse high crosswinds. A crosswind allowance is subtracted from the total load transfer permitted to determine the load transfer threshold for test measurements or calculations. Since coaches have large surface areas, the cross wind allowance significantly restricts the dynamic load transfer threshold.

Another important observation was that the theoretical calculations of both steady state load transfer and steady state carbody lateral acceleration agreed well with experimental measurements and that a high degree of proportionality existed between these two well behaved measurements. Clearly the steady state carbody lateral acceleration measurement could be used to predict the steady state load transfer. The steady state curving force calculations for the Amcoach car in Table 1A provide an example. The side to side vertical load transfer, expressed in terms of vector intercept, increases with cant deficiency in an approximately linear fashion and so does the carbody lateral acceleration.

The easily measured lateral acceleration can be used to track the difficult to measure weight vector intercept once the proportionality factor has been established by computation or experiment. For example, both the calculations and measurements indicate that a steady state weight vector intercept of 10" would result during curving with approximately .15g lateral acceleration at the floor of the Amcoach.

The measurements in Table 1B exhibit the typical scatter of field measurements, but the smooth fit lines for the same data in figures 4 and 5 indicate good agreement with the calculated relationship between weight transfer and carbody lateral acceleration. Table 1A also provides insight into term vector intercept as a unit of load transfer. The load reduction ratio and the individual wheel loads are also given in the same table. The vector intercept is simply the offset of the axle balance point from the center of the axle. A symmetrically loaded car on level track would have equal wheel forces. It would be said to balance about the middle of the axle with a zero vector intercept. During curving at cant deficiency the vertical loads of the wheels must redistribute themselves to maintain equilibrium with the inertial curving force acting through the center of gravity. Suspension deflection, manifested as roll and lateral displacement of the body, superimposes another transfer of load from one wheel to the other. If all of the weight was transferred from one wheel to

TABLE 1A CALCULATED STEADY STATE CURVING PERFORMANCE OF AMCOACH

THE VEHICLE BEING MODELLED IS THE AMCOACH WITH THE CONSTANTS:

Ksub phi	Ksub L#1	Ksub L#2	TRUCK WT.	1/2 BODY WT.
7460	7500	20000	13710	44475

TRUCK C.G.	BODY C.G.	ROLL CNTR	LAT. COMP.	WT. OFFSET	K_sh
22.2	75.3	39.2	1.00;1.25	1.00	1000000

CANT DEF "s	VECTOR INTERCEPT "s	LOAD REDUCTION RATIO	H RAIL VERT LBS	L RAIL VERT LBS	TRUCK LAT LBS	LATERAL ACCEL g	CARBODY ROLL ANGLE DEGREES	CARBODY LATERAL "s
1	2.73	8%	15975	13311	976	0.02	0.30	0.10
2	3.98	13%	16613	12721	1957	0.04	0.60	0.20
3	5.23	17%	17253	12130	2942	0.07	0.90	0.30
4	6.48	21%	17893	11538	3932	0.09	1.21	0.40
5	7.72	25%	18534	10945	4929	0.11	1.52	0.50
6	8.97	29%	19176	10352	5934	0.13	1.82	0.60
7	10.21	33%	19819	9757	6946	0.15	2.14	0.71
8	11.45	37%	20464	9161	7966	0.18	2.45	0.81
9	12.68	41%	21110	8563	8996	0.20	2.77	0.92
10	13.91	45%	21751	7970	10036	0.22	3.09	1.01
11	15.09	49%	22374	7395	11087	0.24	3.41	1.05
12	16.28	53%	22998	6820	12149	0.26	3.74	1.09
13	17.46	57%	23623	6243	13223	0.29	4.07	1.13
14	18.64	61%	24249	5665	14310	0.31	4.40	1.17
15	19.81	65%	24877	5086	15410	0.33	4.74	1.21
16	20.99	69%	25503	4509	16525	0.36	5.08	1.25
17	22.13	73%	26116	3944	17654	0.38	5.43	1.25
18	23.27	77%	26730	3378	18798	0.40	5.78	1.25
19	24.41	81%	27345	2812	19959	0.42	6.14	1.25
20	25.54	85%	27961	2244	21135	0.45	6.50	1.25

TABLE 1B MEASURED STEADY STATE CURVING PERFORMANCE OF AMCOACH

CANT DEF "s	VECTOR INTERCEPT "s	CARBODY LAT ACC g's
2.8	4.0	.073
2.9	4.3	.071
3.6	5.9	088
4.0	6.3	.096
4.4	7.1	.110
4.6	6.9	.119
5.7	8.7	.143
6.4	9.4	.132
6.8	10.1	.144

the other, the balance point would move all the way to the contact point of the loaded wheel, resulting in a vector intercept of 30 inches. The load reduction ratio of the other wheel would be 100%, and it could lose contact with the rail.

The vehicle overturning safety criteria prevents this condition by limiting the steady state load reduction ratio to 60% and the peak load reduction to 80% including the load reduction due to the maximum unfavorable crosswind. The vector intercept is simply the load reduction ratio (expressed as a fraction) times 30 inches, neglecting the slight load increase due to the component of the lateral force perpendicular to superelevated track.

The steady state carbody lateral acceleration directly indicates the steady state vertical load transfer because the carbody lateral force and lateral displacement which cause the vertical load transfer are directly related to lateral acceleration at steady state. The one to one relationship between carbody lateral acceleration and vertical load transfer would deteriorate at high frequency because the accelerometer is sensitive to small body motions which may not directly influence vertical load transfer. However, the steady state relationship between vertical load transfer and carbody lateral acceleration is useful for estimating the peak load transfer from measurements of the peak lateral acceleration as long as the technique is confined to low frequency information. The vertical load transfer of large rail vehicles is a low frequency event which may be measured in a bandwidth of zero to 10 Hz. The ratio of vertical load transfer to car body lateral acceleration is actually a complex transfer function of frequency. But its value at 0 Hz, which may be determined accurately by a variety of means, is being used to estimate its value in the range of 0 to 10 Hz in order to estimate transient load transfer.

The assumption that the relationship between vertical load trasfer and lateral acceleration is relatively constant between 0 and 10 Hz can be tested using data from the 1980 test[1] of an Amcoach equiped with instrumented wheels. Table 2 gives the peak lateral body acceleration and peak vertical load transfer (in units of weight vector intercept) measured (with a 15 Hz bandwidth) at 64 curves between Boston and New Haven. It also gives the peak vector intercepts estimated from the peak lateral acceleration measurements and the steady state relationship between load transfer and lateral acceleration. The estimated peak intercepts are useful if they are accurate without underestimating critical (high) vector intercepts. The average estimated vector intercept was 9.75 inches versus the average instrumented wheel measurement of 9.24 inches indicating good accuracy. The last column is the amount the vector intercept measurement exceeds the estimate, and a negative number indicates a conservative error. The estimation error was more conservation at high vector intercepts. The accelerometer estimates of vertical load transfer obviously are not as accurate as direct force measurements, but the comparison of Table 2 shows that they are useful and appropriately conservative.

In the case of the recent Amtrak/CONEG Test, the steady state relationship between lateral acceleration and vertical load transfer was determined from previous instrumented wheelset measurements for the Amcoach and the LRC Coach. The manufacturer of the Talgo coach provided static lean measurements of body c.g. movement as a function of lateral force which were used to calculate its steady state relationship between lateral acceleration and vertical load transfer. The peak vertical load transfer of the Amtrak/CONEG test cars was estimated by applying this relationship to peak

TABLE 2 COMPARISON OF ACCELEROMETER ESTIMATIONS AND INSTRUMENTED WHEEL MEASUREMENTS OF AMCOACH TRANSIENT LOAD TRANSFER IN 1980 TEST

CURVE #	DIRECTION	1980 FRA TEST MEASUREMENTS PEAK LATERAL ACCELERATION (g's)	PEAK VECTOR INTERCEPT (inches)	ACCELEROMETER ESTIMATED PEAK VECTOR INTERCEPT (inches)	UNDERESTIMATION ERROR (inches)
51	WEST	0.126	8.4	8.6	-0.2
52	WEST	0.156	11.7	10.5	1.2
58	WEST	0.065	6.2	4.7	1.5
61	WEST	0.109	8.7	7.5	1.2
62	WEST	0.077	6.8	5.5	1.3
64	WEST	0.096	7.7	6.7	1.0
66	WEST	0.11	8.4	7.6	0.8
68	WEST	0.081	6.2	5.8	0.4
69	WEST	0.122	8.5	8.4	0.1
72	WEST	0.176	11.3	11.8	-0.5
74	WEST	0.104	7.4	7.2	0.2
75	WEST	0.074	6.4	5.3	1.1
75A	WEST	0.145	9.6	9.8	-0.2
78	WEST	0.06	2.9	4.4	-1.5
79	WEST	0.154	9.8	10.4	-0.6
80	WEST	0.053	4.6	4.0	0.6
83	WEST	0.103	7.7	7.2	0.5
84	WEST	0.153	10.8	10.3	0.5
85	WEST	0.228	14.6	15.1	-0.5
86	WEST	0.086	6.8	6.1	0.7
88	WEST	0.137	8.9	9.3	-0.4
101	WEST	0.139	8.6	9.4	-0.8
102	WEST	0.129	8.6	8.8	-0.2
103	WEST	0.134	8.4	9.1	-0.7
107	WEST	0.106	7.8	7.3	0.5
109	WEST	0.17	12.1	11.4	0.7
111	WEST	0.136	8.9	9.2	-0.3
112	WEST	0.189	12.4	12.6	-0.2
114	WEST	0.059	6.3	4.4	1.9
120	WEST	0.181	11.7	12.1	-0.4
122	WEST	0.121	8.6	8.3	0.3
123	WEST	0.053	5.2	4.0	1.2
127	WEST	0.164	11.4	11.0	0.4
134	WEST	0.191	12.4	12.7	-0.3
139	WEST	0.119	7.2	8.2	-1.0
142	WEST	0.114	8.1	7.9	0.2
141	EAST	0.188	11.4	12.6	-1.2
138	EAST	0.096	6.4	6.7	-0.3
136	EAST	0.139	9.1	9.4	-0.3
133	EAST	0.128	7.9	8.7	-0.8
131	EAST	0.162	7.7	10.9	-3.2
130	EAST	0.239	9.7	15.8	-6.1
128	EAST	0.159	10.6	10.7	-0.1
116	EAST	0.152	10.3	10.3	0.0
115	EAST	0.117	8.6	8.0	0.6
113	EAST	0.146	8.9	9.9	-1.0
110	EAST	0.19	12.2	12.7	-0.5
108	EAST	0.222	12.7	14.7	-2.0
106	EAST	0.192	10.7	12.8	-2.1
105	EAST	0.124	9	8.5	0.5
89	EAST	0.046	4.6	3.5	1.1
87	EAST	0.19	8.9	12.7	-3.8
82	EAST	0.127	9.3	8.7	0.6
81	EAST	0.226	13.7	15.0	-1.3
77	EAST	0.137	10	9.3	0.7
76	EAST	0.149	9.8	10.1	-0.3
73	EAST	0.22	12.2	14.6	-2.4
71	EAST	0.331	14.7	21.7	-7.0
70	EAST	0.24	12.6	15.9	-3.3
67	EAST	0.185	11.7	12.4	-0.7
65	EAST	0.201	11.1	13.4	-2.3
63	EAST	0.286	14.3	18.8	-4.5
53	EAST	0.147	8.1	9.9	-1.8
50	EAST	0.052	3.9	3.9	-0.0
OVERALL AVERAGES		0.14	9.24	9.75	-0.52

lateral acceleration measurements at each curve. Test safety monitoring was accomplished by comparing the vertical load transfer estimates to the thresholds set by the vehicle overturning safety criteria for each vehicle.

The previous wheel force tests of passenger vehicles, which included the Amcoach and LRC, and the computed estimates of track panel shift, rail rollover and wheel climb risk in Appendix A indicated that the vehicle overturning safety criterion was the most restrictive for the vehicles in questions. Therefore, the safety monitoring was focused on the vehicle overturning safety criterion.

Vehicle Overturning Safety Criterion

The overturning safety criteria applied by the Japanese National Railway were used. This method provides a means of safety evaluation (valid for unperturbed track) based on steady state lateral weight transfer measurements or computations. It also provides an alternate criterion for placing individual restrictions on perturbed curves based on transient weight transfer measurements.

The vehicle overturning safety criteria limits side to side weight transfer such that unloaded wheels retain at least 40% of the nominal static load under steady state conditions and 20% under adverse transients, including the effect of lateral wind forces. Weight vector intercept is the common indicator of vehicle overturning in American railroad literature. The overturning criteria may be stated in terms of vector intercept as follows:

Steady State Vector Intercept $\leq$ $18 - (.0306V^2SH_{cp}/W)$ inches

and

Transient Vector Intercept $\leq$ $24 - (.0306V^2SH_{cp}/W)$ inches where:

V is the anticipated lateral wind speed in mph

S is the lateral surface area of the vehicle in ft^2

H_{cp} is the height of the center of wind pressure in ft.

W is the unloaded weight of the vehicle in pounds.

The overturning criteria may be stated in term of the more direct wheel unloading ratio as follows:

Steady Wheel Unloading Ratio	$\leq$	$60\% - (.102V^2SH_{cp}/W)\%$

and

Transient Wheel Unloading Ratio	$\leq$	$80\% - (.102V^2SH_{cp}/W)\%$

Note that the maximum adverse load transfer due to unusual crosswinds has been subtracted from the safety thresholds so that they are very conservative for operation in normal weather.

Table 3 lists the physical constants of the various test vehicles and the resulting safety thresholds against overturning. The differences in the thresholds result from differences in crosswind susceptibility. The anticipated maximum crosswind of 56 mph on the Northeast Corridor can unload as much as 25% of the static load of a wheel on the light weight Talgo car, consuming almost half of the total 60% steady state unloading permitted by the safety criteria. Heavier vehicles are penalized less by the crosswind safety factor.

Effect of Accelerometer Mounting

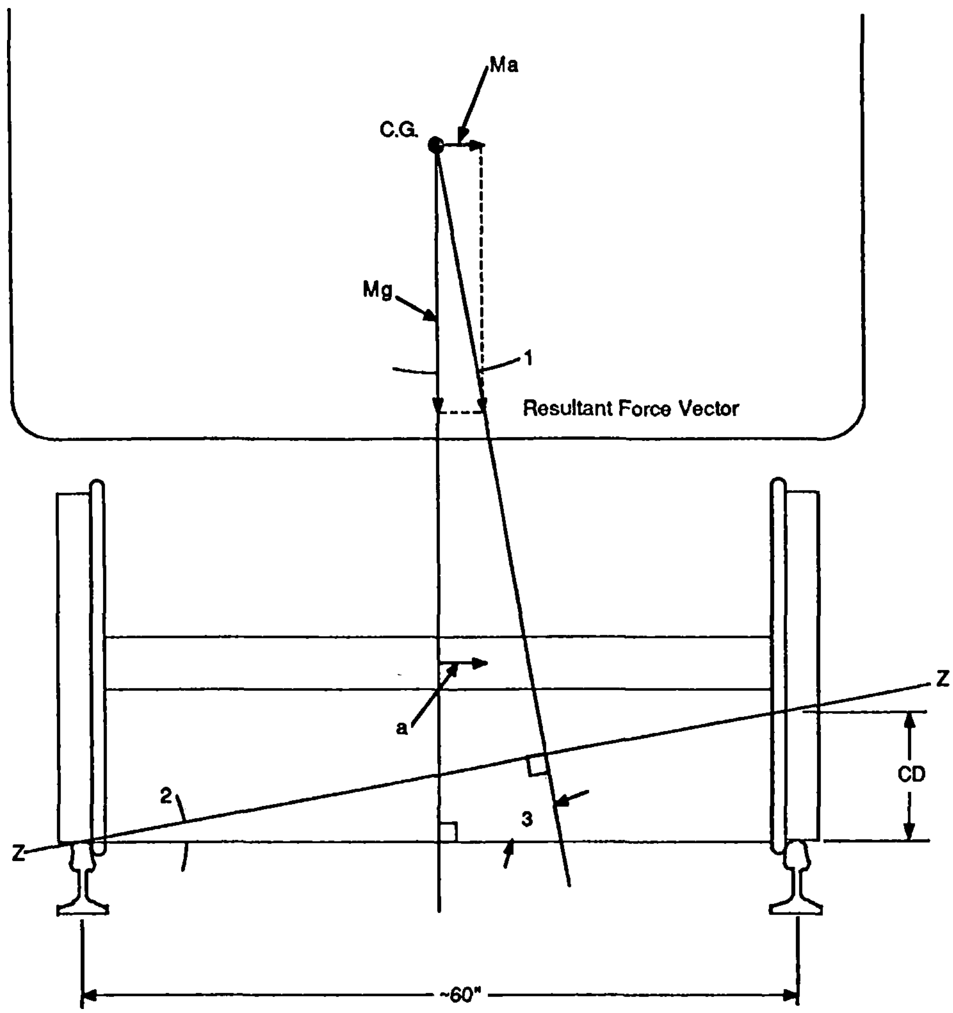
In order to monitor safety by the accelerometer method, the accelerometer readings equivalent to the load transfer

TABLE 3 VEHICLE OVERTURNING SAFETY CRITERIA APPLIED TO AMTRAK TEST VEHICLES

	Amcoach	LRC	TALGO
V, anticipated wind speed	56 mph	56 mph	56 mph
S. lateral surface area	762 ft^2	935 ft^2	396 ft^2
H_{cp}, center of pressure height	7.5 ft	6.5 ft	6.2 ft
W, unloaded weight	104,400 lb	105,500 lb	31,435 lb
Wind Allowance, Vector	5.2"	5.5"	7.5"
Wind Allowance, Unloading Ratio	17.3%	18.3%	25%
Steady State Criterion			
Vector intercept	12.8"	12.5"	10.5"
Unloading ratio	42.7%	41.7%	35%
Transient Criterion			
Vector	18.8"	18.5"	16.5"
Unloading ratio	62.7%	61.7%	55%

thresholds in table 3 must be determined. The accelerometer mounting location and the suspension roll characteristics of the vehicle will greatly influence the accelerometer reading at the point of critical wheel unloading. For this reason, the critical lateral acceleration thresholds of the Amcoach, LRC and Talgo varied greatly although the corresponding load transfer thresholds were similar. Steady state lateral acceleration measured in the plane of the rail heads (on any parallel plane) is the same for any vehicle at a given cant deficiency. Figure 1 proves that the lateral acceleration, in a plane parallel to the rail heads, equals the cant deficiency divided by the trend spacing (approx. 60 inches). The effect of the accelerometer mounting location is illustrated in figure 2 for a conventional vehicle. Typical suspension roll angles were assumed to provide a numerical example. At six inches cant deficiency, the formula in figure 1 indicates that .1g would be measured steady state at the axle of any vehicle. Another accelerometer mounted on the bolster would read .1175g for the same vertical load transfer because the assumed 1^{o} primary suspension roll angle would superimpose a gravitational offset. Likewise a body floor accelerometer would read .152g because of the gravitational offset superimposed by a cumulative 3^{o} roll angle.

The body acceleration provides the best correlation with transient load transfer because body forces cause most of the load transfer. The body acceleration measurements of the Amcoach and Talgo were suitable for estimating load transfer because they were functions of the inertial body forces. The LRC Coach is unlike the others because the body roll angle is altered by an active suspension stage in the secondary suspension. Its steady state carbody acceleration is independent of the body forces because the tilting action of the active suspension holds it near zero for a wide range of cant deficiencies. Therefore it provides no information about the steady state body forces causing load transfer. Similarly



M = body mass
a = lateral acceleration

Resultant force vector is perpendicular to line Z-Z
$\therefore$ CD is cant deficiency in inches

angle 1 + angle 3 = angle 2 + angle 3 = 90°
$\therefore$ angle 1 = angle 2

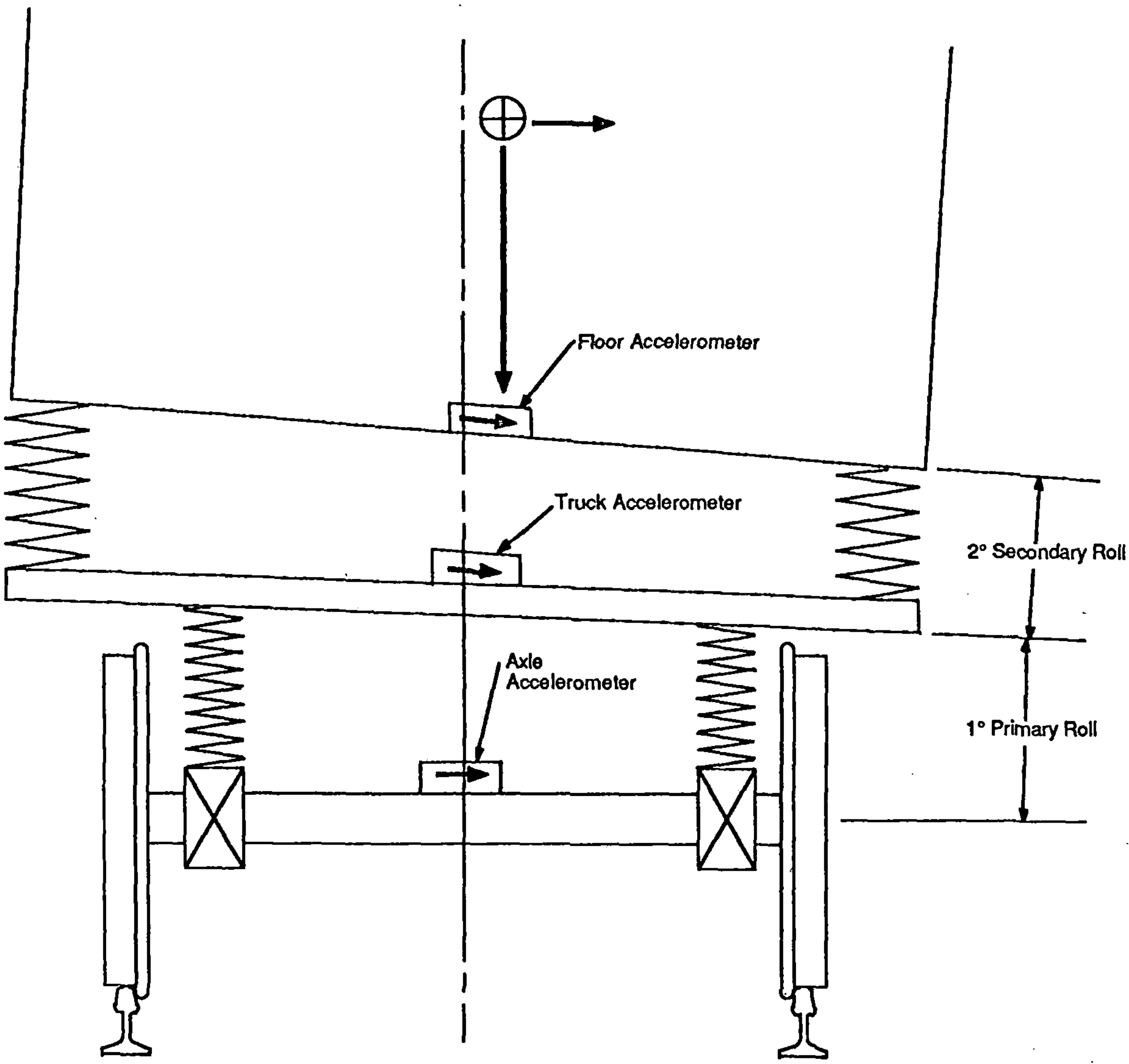
$$\text{Tan (angle 1)} = \frac{Ma}{Mg} = \frac{a}{g}$$

$$\text{Tan (angle 2)} = \frac{CD}{60}$$

$$\therefore \frac{a}{g} = \frac{CD}{60}$$

$\therefore$ The lateral acceleration in g's in the plane of the axle of any vehicle equals the cant deficiency divided by the tread spacing.

Figure 1: Axle Accelerometer Reads CD/60



Example @ 6" Cant Deficiency

$$\underline{\text{Axle Accelerometer}} = \frac{CD}{60} = .1g$$

Assume 1° primary roll

$$\therefore \underline{\text{Truck accelerometer}} = .1g + g \sin(1°) = \underline{.1175g}$$

Assume 2° secondary roll

$$\therefore \underline{\text{Floor accelerometer}} = .1g + g \sin(1° + 2°) = \underline{.152g}$$

∴ The critical value of an accelerometer used to estimate wheel forces depends on mounting locations

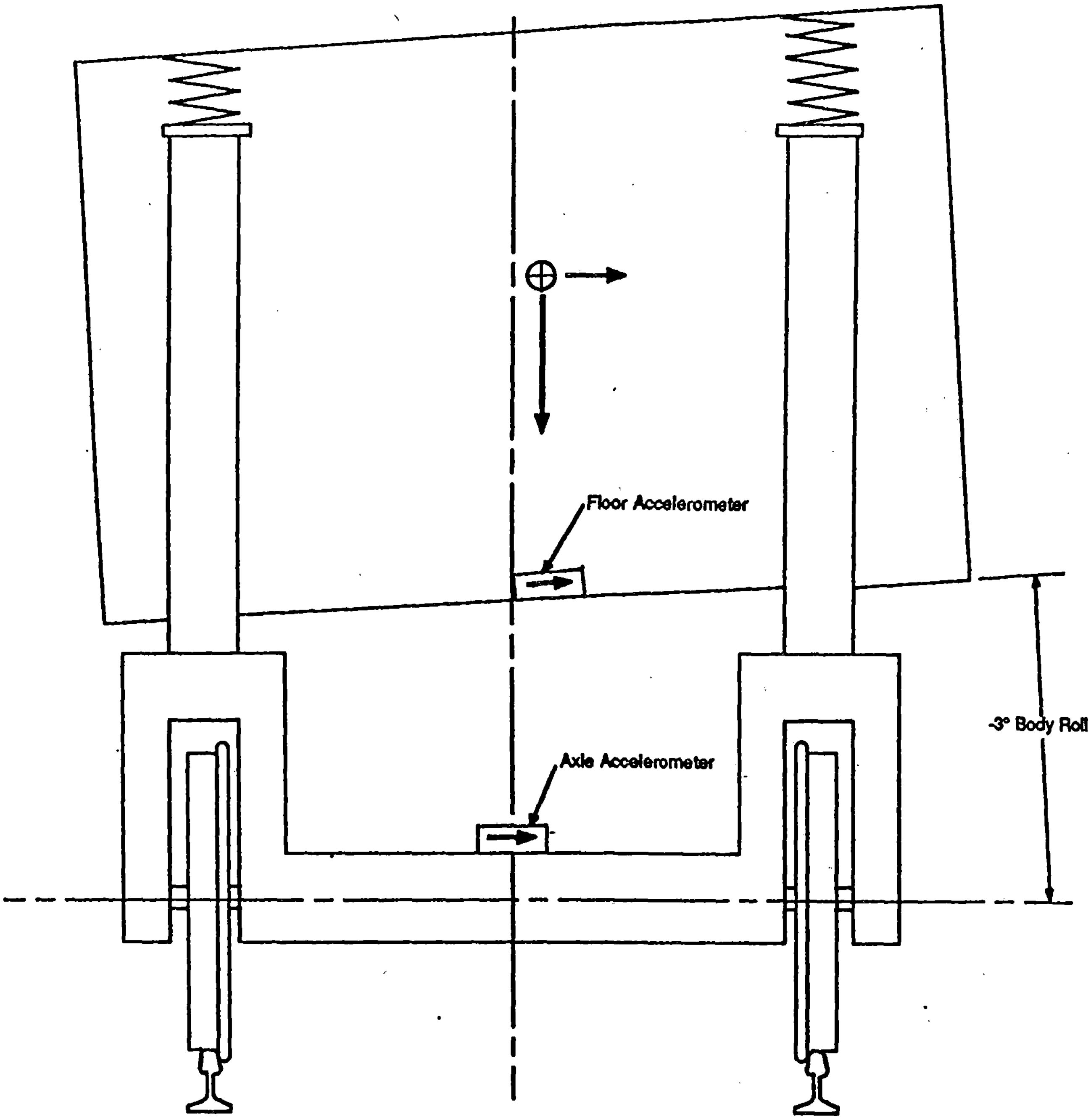
Figure 2: Effect of Accelerometer Mounting Location

the transient carbody lateral accelerations of the LRC coach are driven by the tilting motions as well as by transient body forces. Therefore an accelerometer analogous to the truck accelerometer in figure 2 provided the best measurement for estimating the load transfer of the LRC coach.

Figure 3 illustrates that the Talgo suspension operates like the primary suspension of a conventional car except that the spring roll center has been elevated above the body c.g.. The body roll angle is a function only of the body forces, but the roll direction is opposite that a conventional car because of the inverted relationship between the roll center and c.g. At the same assumed axle acceleration of .1g, the body floor acceleration of the Talgo with the assumed roll angle of -3° would be .048g. These examples which roughly approximate the Amcoach LRC and Talgo, indicate readings of .152g, .1175g (truck), and .048g respectively at the accelerometers used to estimate vertical load transfer although all of the vehicles were assumed to be operating at the same cant deficiency with similar load transfer. Consequently, the relationship between measured lateral acceleration and load transfer will reflect the effect of the mounting location of the accelerometer.

Amcoach Acceleration Monitoring Thresholds

As shown in table 3, the overturning safety criterion limits the Amcoach to 12.8 inches vector intercept (42.7% wheel unloading) steady state and 18.8 inches peak (62.7%). The acceleration monitoring thresholds are estimated to coincide with the overturning safety criterion limits. The relationship between weight vector intercept and carbody lateral acceleration can best be determined from previous field test measurements shown in figure 4 and 5 and also in table 1B. The lines marked 'avg' represent the steady state vector intercepts and lateral acceleration as functions of cant deficiency. (The other lines represent percentile levels



Example @ 6" cant deficiency

Axle accelerometer $= \frac{CD}{60} =$ .1g same as all other cars

Floor Accelerometer = .1g + g sin (-3°) = .048 g with the same absolute body roll as conventional car

Figure 3: Talgo Accelerometer Mounting Location

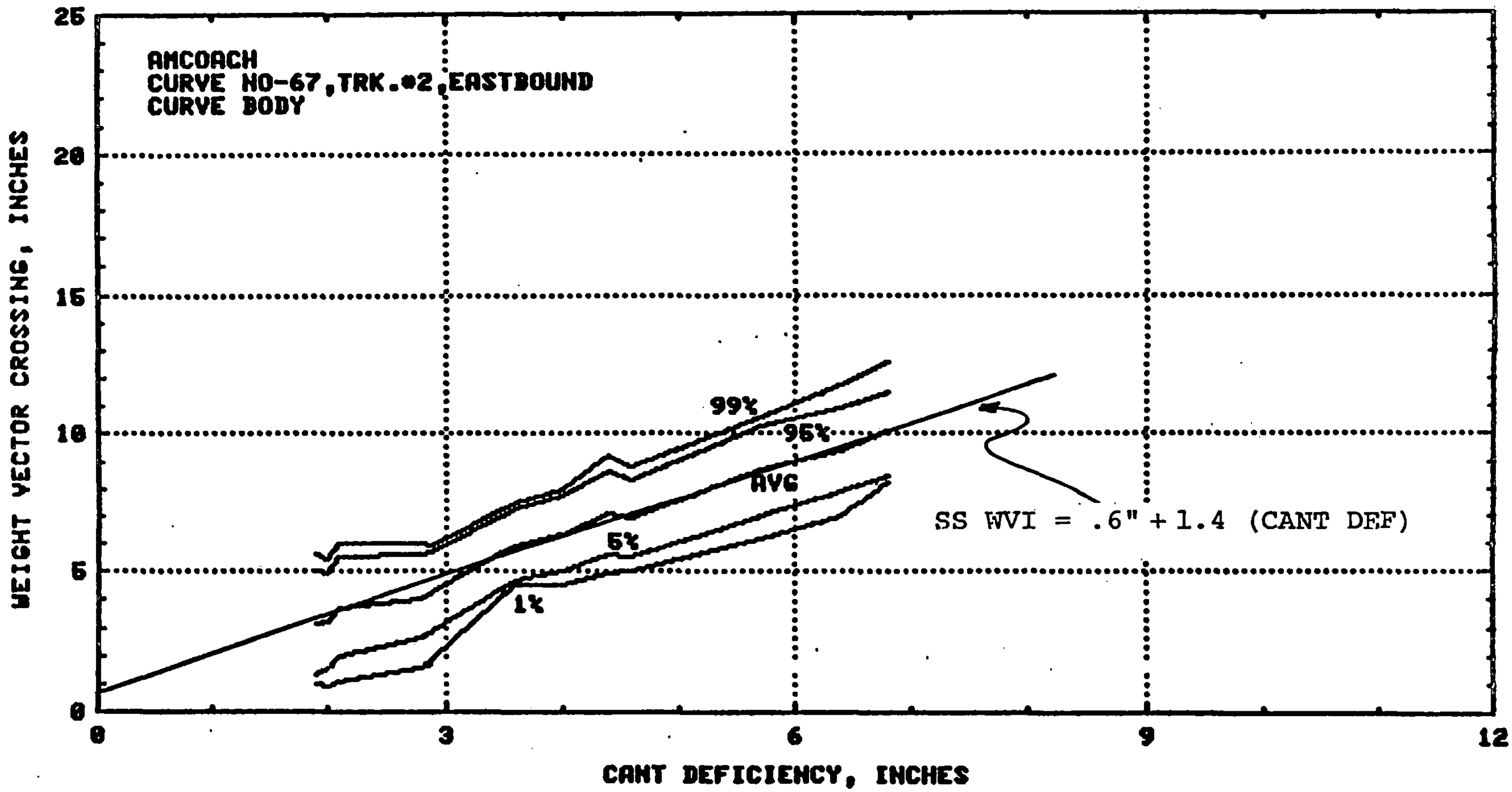


Figure 4 Measurements of Load Transfer versus Cant Deficiency for the Amcoach

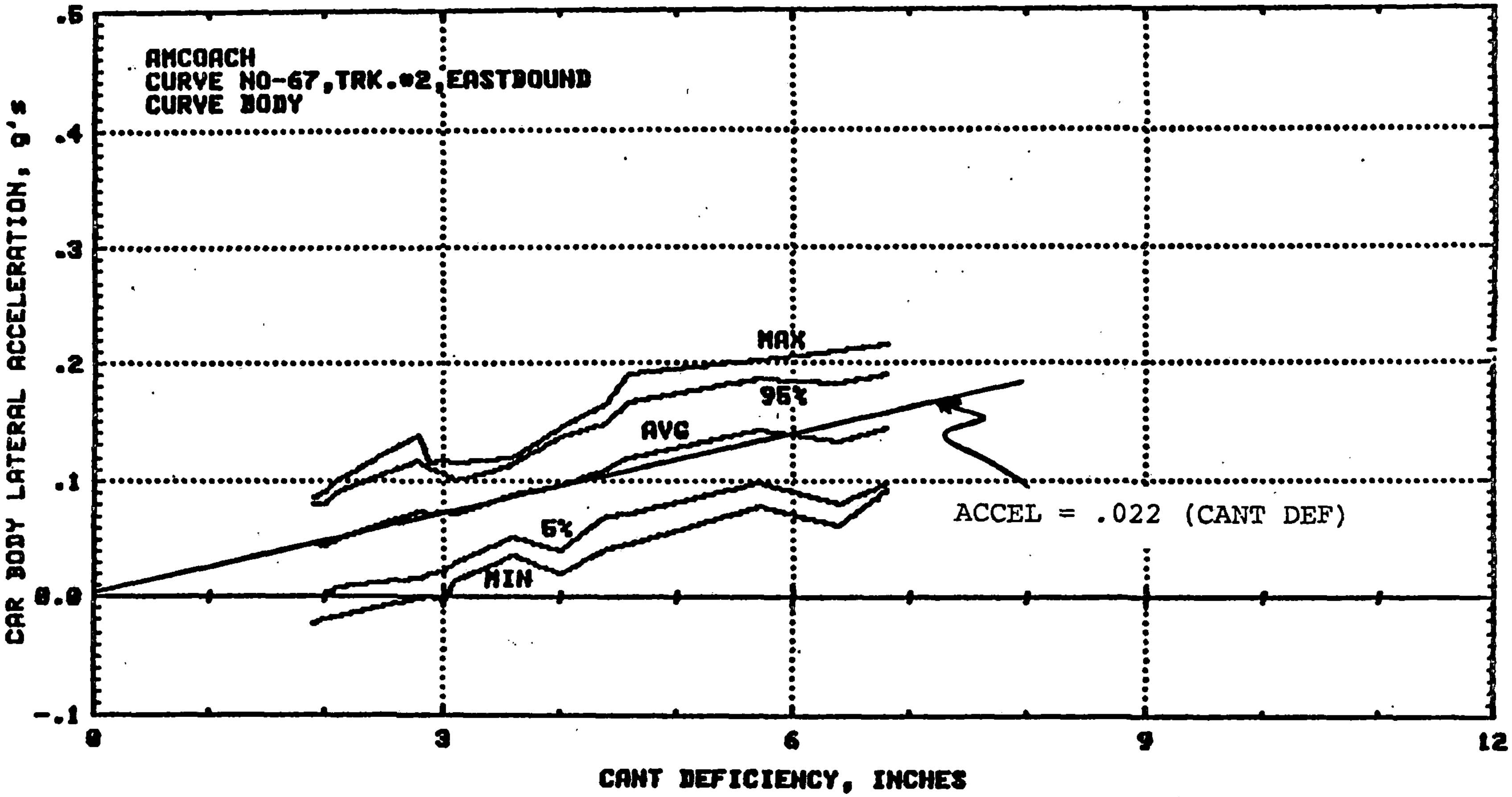


Figure 5. Measurements of Lateral Acceleration versus Cant Deficiency for the Amcoach

of the samples averaged to find the steady state). A straight line fitting the steady state experimental observations and the equation of the line are also given to relate both measurements to cant deficiency. Using these equations weight vector intercept can be related to carbody lateral acceleration as follows:

where:

Vector = steady state weight vector intercept in inches

A = steady state carbody lateral acceleration in g's

CD = can deficiency in inches

From figures 4 and 5,

$$\text{Vector} = .6 + 1.4\ (CD)$$

$$A = .022\ (CD)$$

$$\text{Vector} = .6 + 1.4\ (A/.022)$$

$$\text{Vector} = .6 + 63.6A$$

The final equation exactly relates steady state weight vector intercept to steady state carbody lateral acceleration within the accuracy of the experimental measurements, and it relates the peak weight vector intercept to the peak lateral acceleration within the frequency limitations which have been discussed.

The carbody lateral acceleration monitoring thresholds are obtained by solving the last equation for acceleration at the steady state and peak vector intercept limits set by the overturning safety criterion. The steady state lateral acceleration coincident with the steady state overturning limit is computed as follows:

$$\text{SS Vector Limit} = 12.8 = .6 + 63.6A$$

$$A = \frac{12.2}{63.6} = .19g$$

A steady state carbody lateral acceleration of .19g is the safety monitoring threshold for steady state load transfer.

To monitor the transient overturning criteria:

$$\text{Peak Vector Limit} = 18.8 = .6 + 63.6A$$

$$A = \frac{18.2}{63.6} = .29g$$

A peak carbody lateral accelerometer of .29g is the safety monitoring level for peak load transfer.

LRC Coach Acceleration Monitoring Thresholds

As shown in table 3, the overturning safety criterion limits the LRC Coach to 12.5 inches vector intercept (41.7% wheel unloading) steady state and 18.8 inches peak (61.7%). Accelerometer readings which correspond to the critical vector intercepts uniquely are required for the indirect monitoring of load transfer.

Unfortunately a carbody mounted accelerometer on the LRC coach cannot supply readings which correspond to vector intercepts on a one to one basis because the action of the active tilt system alters the steady state and transient carbody acceleration. The purpose of the active tilt system is to eliminate the steady state entirely, and the body rotation dynamics required of the tilt system introduce transient accelerations which are independent of transient wheel load transfer.

The only suitable location for acceleration measurement was on the non-tilting part of the truck frame, but this choice also carried a drawback. The body accelerations of a conventional car correspond to the large lateral forces which cause vertical load transfer. Truck accelerations however can result from relatively small lateral forces which do not cause much load transfer. The secondary lateral suspension allows abrupt lateral movements of the truck at minor track perturbations where the large mass of body remains steady.

The steady state lateral acceleration measured at the truck can be used to indicate steady state load transfer without difficulty because the steady state motions of the truck and carbody occur in unison, but the transient lateral acceleration of the truck can be greater in frequency and amplitude than those of the massive carbody. In order to use the steady state relationship between lateral acceleration and vertical load transfer to predict transient peak load transfer, it was necessary to try to eliminate high frequency truck accelerations which did not involve significant body motion from the lower frequency accelerations which would be expected to occur in unison with the body mass.

The acceleration filter frequency was varied in order to achieve a transient truck acceleration signature similar to that of the Amcoach body accelerations and similar to the transient body accelerations of the LRC coach during periods of when the active suspension was not moving. The filter tuning of the truck acceleration signal was a subjective process which resulted in a choice of a 3 Hz corner frequency. The object was to preserve as much of the signal as possible to remain conservative while eliminating the measurement of truck movements which were obviously 'noise' with respect to vertical load transfer.

Estimating the vertical load transfer from truck accelerations probably overestimates the transient load transfer of the LRC coach in certain instances. The relationship between cant deficiency and steady state vertical load transfer of the LRC coach determined by previous experiments with instrumented wheels is shown in Figure 6 along with the following equation of a straight line fitted to the data.

Vector = 2.4" + 1.09 CD

The truck accelerometer reading as shown in Figure 2 is:

A = (CD/60)g + g sin(primary roll angle)

Appendix B computes the steady state primary roll angle of the LRC truck in terms of cant deficiency to show that:

A = .0195 CD
Vector = 2.4 = 1.09 CD
Vector = 2.4 + 55.9A

The last equation is the desired relationship between weight vector intercept and truck accelerometer reader. It represents exactly the steady state load transfer measurements and forms the basis for estimating transient load transfer.

The steady state lateral acceleration at the LRC truck coincident with the steady state vehicle overturing load transfer limit is computed as follows:

SS Vector Limit = 12.5 = 2.4 + 55.9A

$$A = \frac{10.1}{55.9} = .18g$$

A steady state truck lateral acceleration of .18g is the safety monitoring threshold for steady state load transfer of the LRC coach.

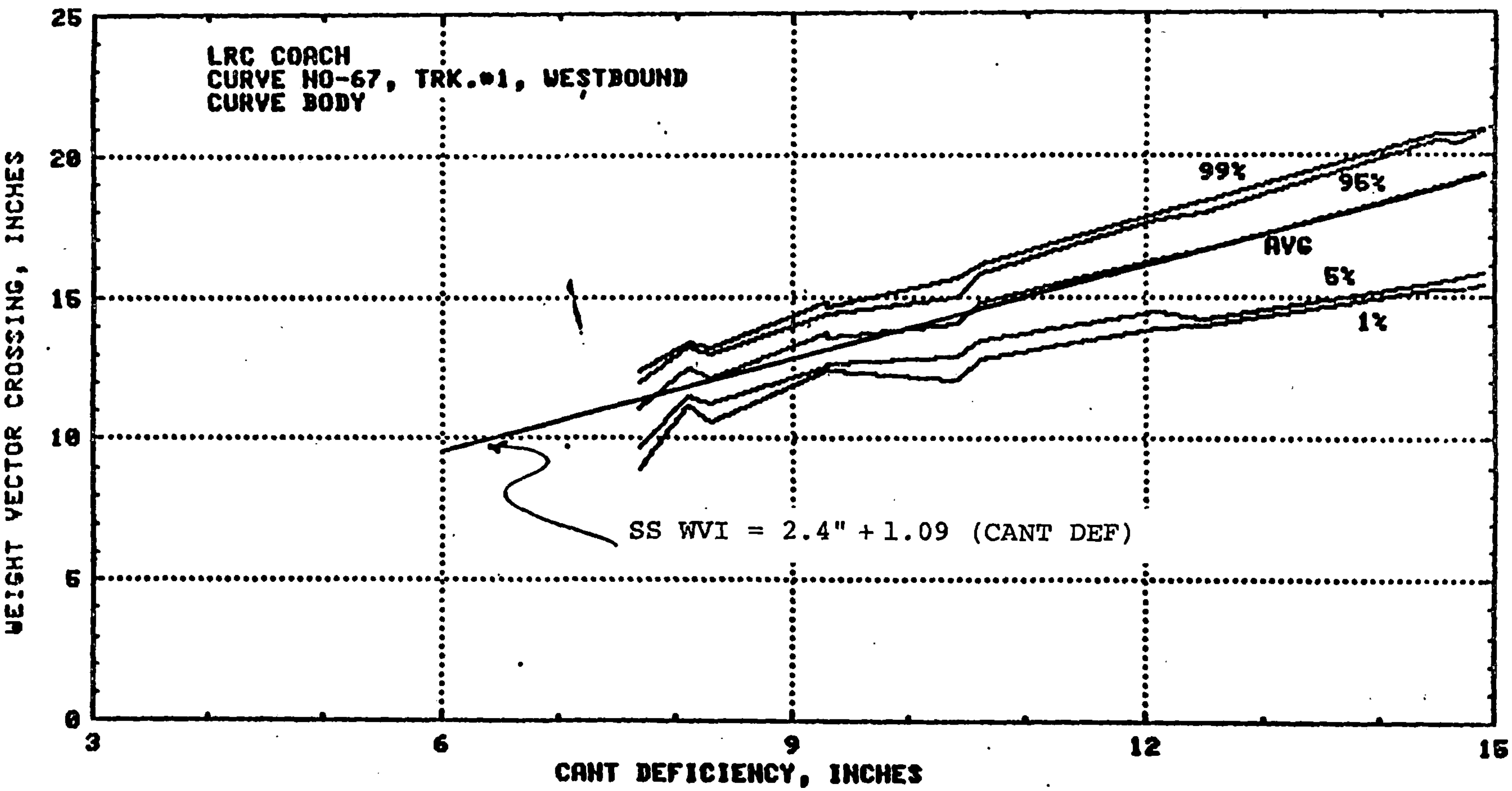


Figure 6 Measurements of Load Transfer versus Cant Deficiency for the LRC Coach

To monitor the transient overturning criteria:

$$\text{Peak Vector Limit} = 18.5 = 2.4 + 55.9A$$

$$A = \frac{16.1}{55.9} = .29g$$

A peak truck lateral acceleration of .29g is the safety monitoring level for transient load transfer of the LRC Coach.

TALGO Coach Acceleration Monitoring Levels

As shown in Table 3, the overturning safety criterion limits the TALGO Coach to 10.5" vector intercept (35% wheel unloading) steady state and 16.5" peak (55%). The suspension movements of the TALGO, like the conventional Amcoach, are driven by the inertial body forces, and the floor accelerometer readings can be used to indicate vertical load transfer. Unlike the conventional car the steady state lateral acceleration at the floor of the TALGO is less than at the axle because the gravitational offset due to the body roll opposes the lateral acceleration of curving as shown in the example Figure 3.

In the absence of prior instrumented wheel force measurements, the relationship between load transfer and carbody lateral acceleration of the TALGO was based on static lean measurements and computations provided by the manufacturer. Figure 7 plots the steady state weight vector intercept versus cant deficiency for the TALGO car. The steady state limit of 10.5" weight vector intercept is reached at 8.03 inches cant deficiency for a half loaded car.

Figures 8 and 9 show the dimensions and forces used by the manufacturer to compute weight vector intercept at 7.2 and 8.4 inches cant deficiency. The same information may be used to compute the steady state carbody lateral acceleration to

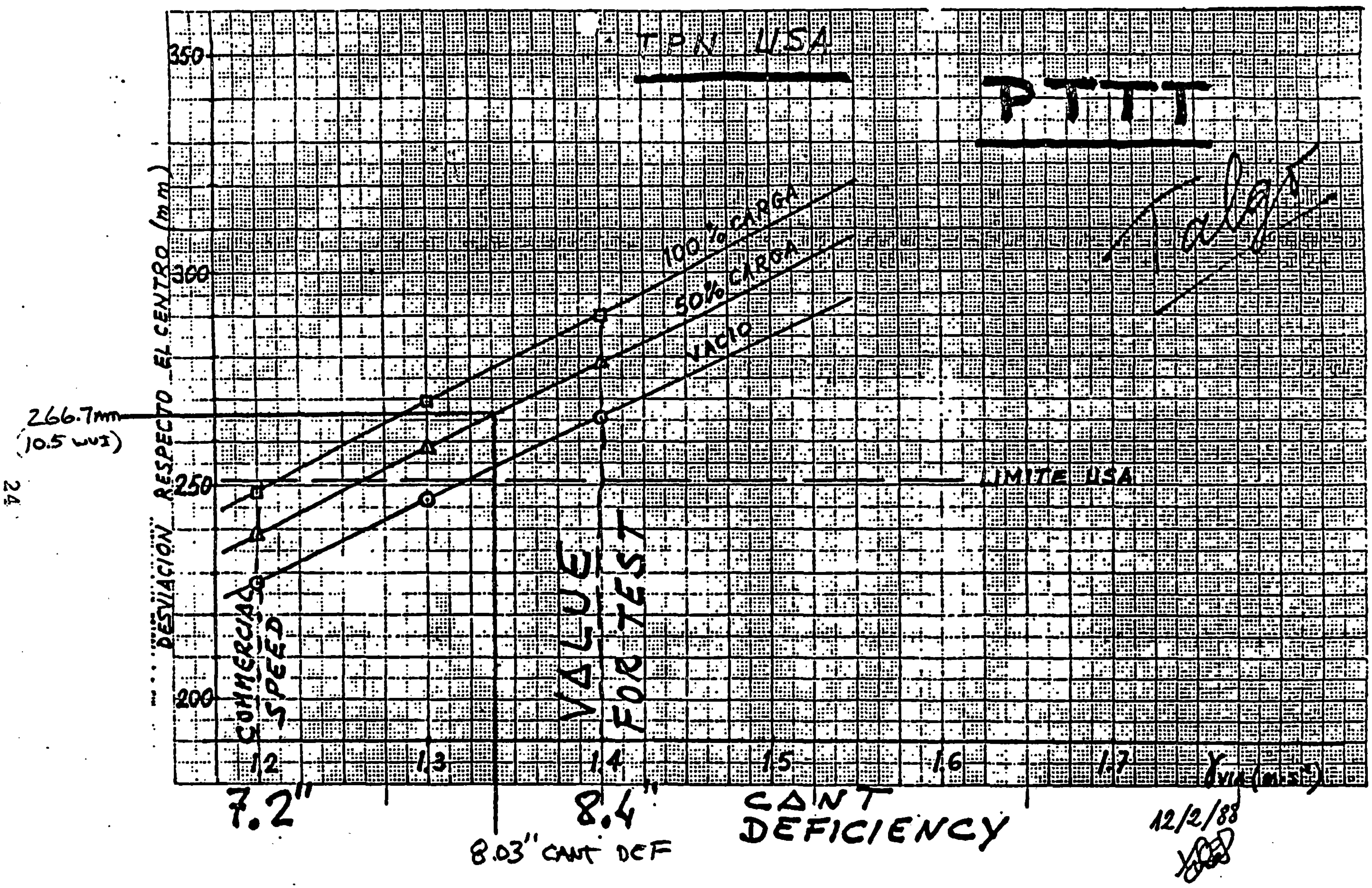
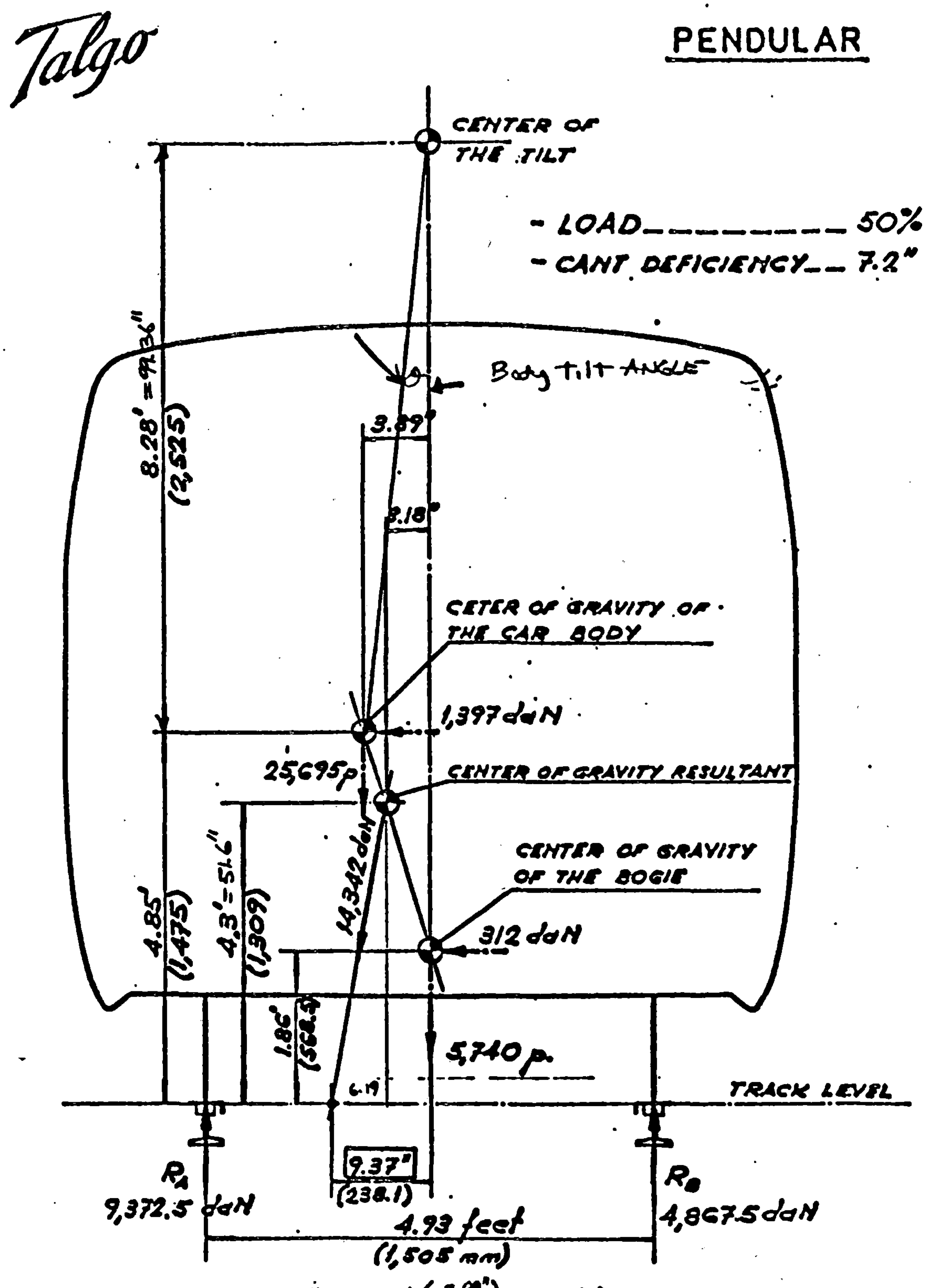


Figure 7 Computations of Load Transfer versus Cant Deficiency for the TALGO Car



Tilt angle at 7.2" $= \tan^{-1}\left(\frac{3.89"}{99.36"}\right) = 2.24°$

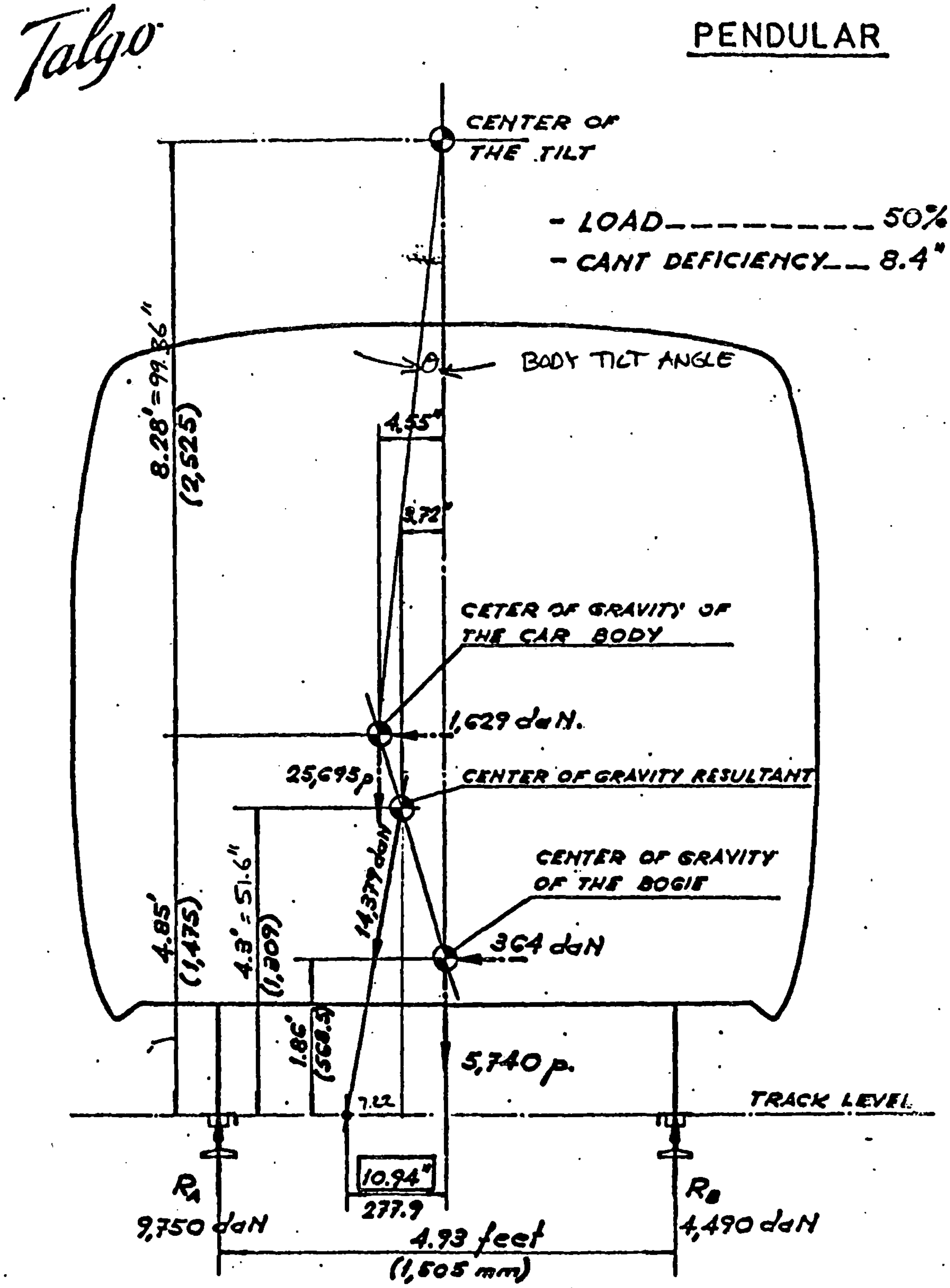
Lat accel at axle $= \frac{7.2}{60} = .12g$

Floor Accel $= .12g - g\sin(2.24°) = (.12 - .039)\,g$

Floor Accel at 7.2" cd. $= .0809\,g$

ANNEX 5

Figure 8. TALGO Car at 7.2" Cant Deficiency



Tilt angle at 8.4" = $\tan^{-1}\left(\frac{4.55''}{99.36''}\right) = 2.62°$

ANNEX G

Lat accel at axle = $\frac{8.4}{60}$ = .14g

Floor Accel = .14g − g sin(2.62°) = g(.14 − .457)

Floor Accel at 8.4" cd = .0942 g

Figure 9. TALGO Car at 8.4" Cant Deficiency

develop the relationship between weight transfer and lateral acceleration.

Figure 8 shows that the body c.g. swings 3.89 inches to the left relative to the outline of the stationary position of the body while curving at 7.2 inches cant deficiency. Since the center of tilt is 99.36 inches above the c.g., the body has rotated clockwise by an angle Θ .

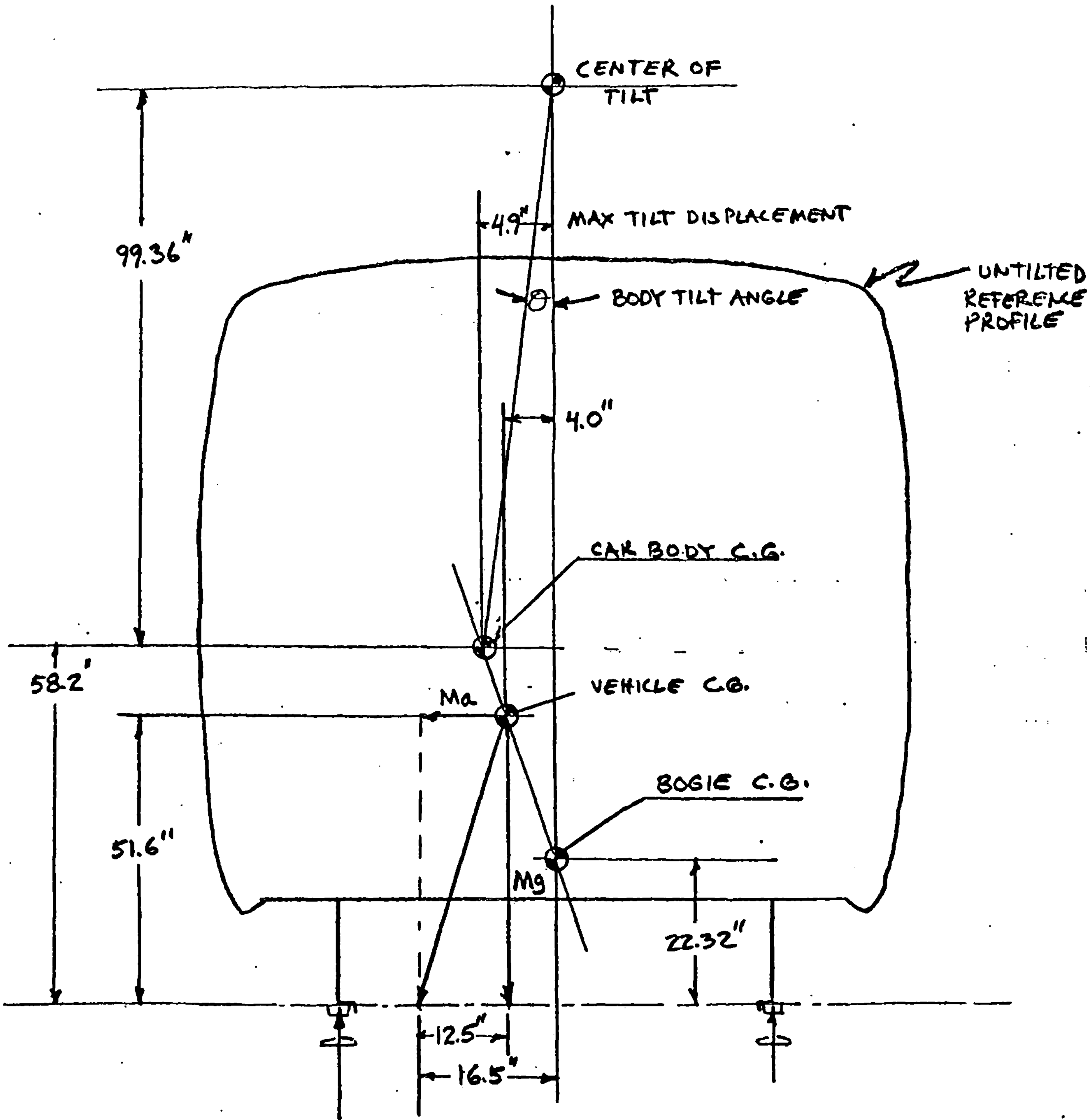
$$\text{Where } \Theta = \text{Tan}^{-1} \frac{3.89}{99.36} = 2.24^{\circ}$$

The lateral acceleration at the axle is CD/60 = .12g at CD = 7.2 inches, and the lateral acceleration at the floor of the carbody is:

$$A = (7.2/60)g - g \sin(2.24^{\circ}) = .0809 \text{ g}$$

at 7.2 inches cant deficiency because the gravitational offset of the TALGO floor rotation opposes the lateral acceleration at the axle. A similar computation at 8.4 inches cant deficiency yields .0942 g's measured a the floor. Interpolation between the manufactures analyses at 7.2 and 8.4 inches cant deficiency yields an expected carbody lateral acceleration of .091 g's at 8.03 inches cant deficiency, coinciding with the steady state overturning safety criterion of 10.5 inches weight vector intercept.

The relationship between load transfer and carbody lateral acceleration at 10.5 inches vector intercept cannot be projected to 16.5 inches vector intercept because the body tilting motion will reach its stops before the greater load transfer occurs. Figure 10 shows the computation of steady state floor acceleration at 16.5 steady state vector intercept. As with the other cars, it is assumed that the transient load transfer frequency is low enough that the



By similar triangles

$$\frac{Ma}{Mg} = \frac{12.5}{51.6} \rightarrow a = .242g$$

$$\text{Tilt angle} = \tan^{-1}\left(\frac{4.9}{99.36}\right) = 2.82^\circ$$

$$\therefore \text{Floor Acceleration} = .242g - g\sin(2.82^\circ) = \underline{.193g}$$

Figure 10 TALGO Carbody Lateral Acceleration at 16.5" Vector Intercept relationship between peak load transfer and peak lateral acceleration may be approximated by their steady state relationship. The carbody c.g. is limited to 4.9" movement from the bogie centerline. The maximum tilt angle is:

$$\text{Tilt angle} = \tan^{-1}\left(\frac{4.90}{99.36}\right) = 2.82^{\circ}$$

The resultant of the gravitational and inertial forces at the vehicle c.g. (displaced 4") intersects the plane of the rail heads at 16.5" from the center. Since the forces form a similar triangle to the dimensions in Figure 10.

$$\frac{Ma}{Mg} = \frac{12.5}{51.6}$$

$$a = \left(\frac{12.5g}{51.6}\right) = .242\ g$$

The lateral acceleration of the TALGO car in the plane of the rail heads is $(.242g - g\sin(2.82^{\circ})) = .193\ g$.

A peak carbody lateral acceleration of .193g would coincide with the transient load transfer limit of 16.5" vector intercept set for the TALGO car by the overturning safety criterion.

APPENDIX A

Relative Risk of Wheel Climb, Rail Rollover, and Track Panel Shift.

The vehicle overturning safety criteria is more restrictive for passenger vehicles operating on strong track than the safety criteria regarding wheel climb, rail rollover and track panel shift. The vehicle overturning safety criteria limits wheel unloading so that a 20% margin of safety against wheel lift remains even under the combined transient load transfer of high cant deficient curving and unfavorable high crosswind. It may be argued that the overturning criteria is too conservative because momentary wheel lift would probably not result in derailment, but the only sensible policy is to make sure that all the wheels are firmly on the rails at all times.

The wheel climb safety criterion requires that wheel L/V ratios remain below 0.9. The rail rollover criterion limits the truck side L/V ratio to 0.5 + (2300 lb/wheel load). The track panel shift limits the axle lateral force to .61(axle vertical force) + 5800 lb - (wind allowance). Table A-1 summarizes the safety criteria for the Amcoach, LRC coach and Talgo coach taking into consideration the wheel loads and surface areas of the vehicles.

Also given in Table A-1 are the L/V ratios and lateral forces projected to coincide with the limiting value of peak wheel unloading. If the cars are operated within the limits of overturning safety, the peak wheel L/V, peak truck side L/V and peak axle lateral load remain well below their safety criteria limits. The L/V ratios and lateral truck force coincident with critical vertical load transfer wear projected from steady state computations listed in Tables A-2 to A-4. It is assumed in the projection that ratio of truck lateral force to vertical load transfer remains similar for steady

TABLE A-1 COMPARISON OF DERAILMENT SAFETY CRITERIA SHOWING THAT THE OVERTURNING SAFETY LIMIT IS THE MOST RESTRICTIVE FOR THE TEST COACHES

		Amcoach		LRC Coach		Talgo Coach	
Hazard	Safety Measurement	Limit	Projected* @ Overturning Safety Limit	Limit	Projected* @ Overturning Safety Limit	Limit	Projected* @ Overturning Safety Limit
Overturning	Peak Wheel Unloading	63%	63%	62%	62%	55%	55%
Wheel Climb	Peak Wheel L/V	.90	.60	.90	.66	.90	.34
Rail	Peak Truck Side L/V	.68	.30	.67	.33	.79	.34
Track Panel Shift	Peak Axle Lateral Load	18,700lb	14,860lb	18,150lb	15,935lb	13,800lb	8,527lb

*Lateral Forces and L/V ratios well below the safety limits are projected to coinside with the limiting value of vertical load transfer based on steady state computations. The worst case assumption that the entire truck lateral force is borne by only one wheel has been applied to the Amcoach and LRC coach. The Talgo coach has single axle trucks.

TABLE A-2. STEADY STATE CURVING COMPUTATIONS FOR THE AMCOACH

THE VEHICLE BEING MODELLED IS THE AMCOACH WITH THE CONSTANTS:

Ksub phi	Ksub L#1	Ksub L#2	TRUCK WT.	1/2 BODY WT.
7460	7500	20000	13710	44475

TRUCK C.G.	BODY C.G.	ROLL CNTR	LAT. COMP.	WT. OFFSET	K_sh
22.2	75.3	39.2	1.00;1.25	1.00	1000000

CANT DEF "S	VECTOR INTERCEPT "S	LOAD REDUCTION RATIO	H RAIL VERT LBS	L RAIL VERT LBS	TRUCK LAT LBS	LATERAL ACCEL g	CARBODY ROLL ANGLE DEGREES	CARBODY LATERAL "S
1	2.73	8%	15975	13311	976	0.02	0.30	0.10
2	3.98	13%	16613	12721	1957	0.04	0.60	0.20
3	5.23	17%	17253	12130	2942	0.07	0.90	0.30
4	6.48	21%	17893	11538	3932	0.09	1.21	0.40
5	7.72	25%	18534	10945	4929	0.11	1.52	0.50
6	8.97	29%	19176	10352	5934	0.13	1.82	0.60
7	10.21	33%	19819	9757	6946	0.15	2.14	0.71
8	11.45	37%	20464	9161	7966	0.18	2.45	0.81
9	12.68	41%	21110	8563	8996	0.20	2.77	0.92
10	13.91	45%	21751	7970	10036	0.22	3.09	1.01
11	15.09	49%	22374	7395	11087	0.24	3.41	1.05
12	16.28	53%	22998	6820	12149	0.26	3.74	1.09
13	17.46	57%	23623	6243	13223	0.29	4.07	1.13
14	18.64	61%	24249	5665	14310	0.31	4.40	1.17
15	19.81	65%	24877	5086	15410	0.33	4.74	1.21
16	20.99	69%	25503	4509	16525	0.36	5.08	1.25
17	22.13	73%	26116	3944	17654	0.38	5.43	1.25
18	23.27	77%	26730	3378	18798	0.40	5.78	1.25
19	24.41	81%	27345	2812	19959	0.42	6.14	1.25
20	25.54	85%	27961	2244	21135	0.45	6.50	1.25

TABLE A-3. STEADY STATE CURVING COMPUTATIONS FOR THE LRC COACH

THE VEHICLE BEING MODELLED IS THE LRC COACH WITH THE CONSTANTS:

Ksub phi	Ksub L#1	Ksub L#2	TRUCK WT.	1/2 BODY WT.
4370	1420	6400	17000	41750

TRUCK C.G.	BODY C.G.	ROLL CNTR	LAT. COMP.	WT. OFFSET	K_sh
18.5	65.5	29.1	1.82;2.38	0.50	1000000

CANT DEF "S	VECTOR INTERCEPT "S	LOAD REDUCTION RATIO	H RAIL VERT LBS	L RAIL VERT LBS	TRUCK LAT LBS	TRUCK ACCEL g	TRUCK ROLL ANGLE DEGREES	CARBODY LATERAL "S
1	2.40	7%	15970	13601	986	0.02	0.16	0.49
2	3.83	12%	16699	12920	1976	0.04	0.33	0.99
3	5.25	17%	17430	12238	2970	0.06	0.49	1.49
4	6.58	21%	18118	11599	3971	0.08	0.65	1.86
5	7.73	25%	18716	11049	4977	0.10	0.82	1.97
6	8.87	29%	19315	10499	5991	0.12	0.98	2.08
7	10.01	32%	19916	9947	7013	0.14	1.14	2.19
8	11.16	36%	20518	9394	8043	0.16	1.30	2.31
9	12.27	40%	21106	8855	9083	0.18	1.47	2.38
10	13.32	43%	21669	8340	10133	0.20	1.63	2.38
11	14.38	47%	22234	7825	11194	0.21	1.79	2.38
12	15.44	50%	22799	7308	12267	0.23	1.96	2.38
13	16.49	54%	23366	6791	13351	0.25	2.12	2.38
14	17.54	57%	23933	6272	14449	0.27	2.28	2.38
15	18.59	61%	24502	5752	15560	0.29	2.45	2.38
16	19.64	64%	25071	5232	16685	0.31	2.61	2.38
17	20.69	68%	25641	4711	17825	0.33	2.77	2.38
18	21.73	71%	26212	4188	18981	0.35	2.93	2.38
19	22.78	75%	26784	3665	20152	0.37	3.10	2.38
20	23.82	79%	27357	3141	21341	0.39	3.26	2.38

TABLE A-4. STEADY STATE CURVING COMPUTATIONS FOR THE TALGO COACH

THE VEHICLE BEING MODELLED IS THE TALGO COACH WITH THE CONSTANTS:

Ksub phi	Ksub L#1	Ksub L#2	TRUCK WT.	BODY WT.
11334	100000	100000	5740	25695

TRUCK C.G.	BODY C.G.	ROLL CNTR	LAT. COMP.	WT. OFFSET	K_sh
22.4	58.2	157.6	0.00;0.00	0.00	1000000

CANT DEF "S	VECTOR INTERCEPT "S	LOAD REDUCTION RATIO	H RAIL VERT LBS	L RAIL VERT LBS	TRUCK LAT LBS	LATERAL ACCEL g	CARBODY ROLL ANGLE DEGREES	CARBODY LATERAL "S
1	1.28	4%	16496	15148	527	0.01	-0.32	0.55
2	2.57	8%	17208	14488	1057	0.02	-0.63	1.10
3	3.87	12%	17923	13826	1589	0.03	-0.95	1.65
4	5.17	16%	18639	13161	2125	0.04	-1.27	2.20
5	6.47	21%	19359	12494	2663	0.05	-1.59	2.76
6	7.76	25%	20081	11824	3206	0.07	-1.92	3.33
7	9.06	29%	20806	11151	3752	0.08	-2.24	3.89
8	10.37	33%	21535	10475	4304	0.09	-2.57	4.46
9	11.56	37%	22206	9856	4860	0.10	-2.91	4.90
10	12.39	40%	22687	9427	5422	0.11	-3.24	4.90
11	13.22	43%	23169	8998	5990	0.12	-3.58	4.90
12	14.05	45%	23652	8567	6563	0.13	-3.93	4.90
13	14.87	48%	24136	8135	7144	0.14	-4.27	4.90
14	15.70	51%	24620	7703	7731	0.15	-4.62	4.90
15	16.53	54%	25106	7269	8326	0.16	-4.98	4.90
16	17.35	57%	25594	6834	8928	0.17	-5.34	4.90
17	18.18	59%	26082	6398	9538	0.18	-5.71	4.90
18	19.01	62%	26572	5960	10156	0.19	-6.08	4.90
19	19.83	65%	27064	5521	10783	0.20	-6.45	4.90
20	20.66	68%	27558	5079	11419	0.21	-6.83	4.90

state and peak measurements. This assumption is reasonable because the lateral force causes the vertical load transfer. A very conservative assumption that one wheel bears the entire lateral truck force was made to give worst case projections of the peak wheel L/V and peak axle lateral load.

The computed projections in Table A-1 are supported by direct wheel force measurements taken during the previously cited FRA Tests[1] in 1980 and 1982. Table A-5 lists the passenger coaches and locomotives tested and their derailment safety criteria limits. The Amcoach and LRC coach were among the test vehicles. Table A-6 gives the maximum cant deficiency set by the overturning safety criteria for each vehicle. It also gives the highest measurement of peak wheel L/V, peak truck side L/V, and peak truck lateral force expected at the worst case curves in the Northeast Corridor test zone for each test vehicle based on measurements with instrumented wheels. The L/V ratios and lateral forces are well below their critical levels at the overturning safety limit for all the vehicles. The measured L/V ratios and truck lateral forces for the Amcoach and LRC coach were in agreement with the computed projections in Table A-1. It is clear that the overturning safety criterion is the most restrictive for passenger vehicles operating on the Northeast Corridor.

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[1]Report No., DOT-FR-81-06, "High Cant Deficiency Testing of the LRC Train, the AEM-7 locomotive and the Amcoach," NTIS No.PB82213018

Report No. DOT-FR083-03, "High Cant Deficiency Testing of the F40PH locomotive and the Prototype Banking Amcoach," NTIS No. PB83219139

TABLE A-5

SUMMARY OF SAFETY CRITERIA LIMITS FOR SPECIFIC TEST VEHICLES
(USED IN 1980 AND 1982 FRA TESTS)

		Maximum Permissible Test Measurement					
Derailment Mechanism	Measurement	F40PH Locomotive	Banking Amcoach	Standard Amcoach	AEM-7 Locomotive	LRC Locomotive	LRC Coach
Vehicle Overturning	Steady State Weight Vector Intercept	15.7 in (52.5%)	12.8 in (42.7%)	12.8 in (42.7%)	16.2 in. (54.0%)	16.3 in (54.3%)	12.5 in (41.7%)
	Transient Weight Vector Intercept	21.7 in (72.5%)	18.8 in (62.7%)	18.8 in (62.7%)	22.2 in (74.0%)	22.3 in (74.3%)	18.5 in (61.7%)
	Crosswind Allowance	7.5%	17.3%	17.3%	6.0%	5.7%	18.3%
Wheel Climb	Transient Wheel (L/V) $T \geq 50$ ms	0.9	0.9	0.9	0.9	0.9	0.9
Rail Rollover	Transient Truck Side (L/V) $T \geq 50$ ms	0.57	0.65	0.65	0.59	0.57	0.65
Track Panel Shift	Transient Lateral Axle Force	41,900 lb	18,700 lb	18,700 lb	34,000 lb	41,300 lb	18,200 lb
	Transient Lateral Truck Force	59,800 lb	27,300 lb	27,300 lb	48,400 lb	58,900 lb	26,900 lb

TABLE A-6

SUMMARY OF TEST RESULTS
(FOR 1980 AND 1982 FRA TESTS WITH INSTRUMENTED WHEELS)

	F40PH Locomotive	Banking Amcoach (Worst case)	Standard Amcoach	AEM-7 Locomotive	LRC Locomotive	LRC Coach
Recomended General Cant Deficiency Limit	9 in	8 in (non-banking)	8 in.	10 in.	12 in.	9 in.
Cant Deficiency Limit Set by Steady State Overturning Criterion	9.5 in.	8.3 in.* (non-banking)	8.3 in.	10.5 in	12.2 in.	9.3 in
Lowest Cant Deficiency Limit Set by Transient Overturning Criterion at a curve without a special feature**	9.1 in.	8.6 in.* (non-banking)	8.5 in.	8.5 in.	10.6 in.	8.7 in
Lowest Cant Deficiency Limit Set by Transient Overturning Criterion at any Test Curve	6.3 in.	7.2 in.* (non-banking)	8.5 in	4.7 in	10.6 in	6.8 in
Estimated Maximums at General Cant Deficiency Limit						
Transient Wheel (L/V) Ratio***	.45	.64 (banking)	.60	.75	.60	.60
Transient Truck Side (L/V)**** Ratio	.36	.45 (banking)	.40	.50	.40	.40
Transient Lateral Truck Force	41,000 lb	18,000 lb (both)	18,000 lb	32,000 lb	33,000 lb	15,000 lb
Steady State Lateral Acceleration	.19g	0.10 (banking 0.18 (non-banking)	0.15g	0.18g	0.25g	0.09g

*Including allowance for typical static load asymmetry, see Section 6.6.
**Switches, undergrade bridges or grade crossings in curves are special features.
***Safety criterion in .9.
****Safety criterion is .57 to .65, see Table 1-1.