RAILROAD PASSENGER
RIDE SAFETY

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16. Abstract

Safety requirements for high cant deficiency rail passenger service address the dangers of vehicle derailment, track damage and unreasonable risks to standing passengers of falling. Safety criteria concerning vehicle derailment and track damage have been well developed. Those applicable to passenger vehicle test data are discussed, and the vehicle overturning safety criterion is shown to be the most restrictive.

A literature search of ride criteria and research was conducted. The findings presented in this paper show that most criteria address ride comfort rather than ride safety. Ride comfort is viewed as an economic rather than safety issue. Objective experiments, described in the literature, relating the ability of test subjects to maintain equilibrium under various acceleration environments are described. Ride safety criteria are recommened which are based on the published experiments, recent vehicle acceleration measurements and railroad operating practices.

Appendix A, included in the April 1989 revision, places the proposed ride safety envelope in the context of the recent CONEG/AMTRAK train evaluation tests. The ride safety envelope would restrict conventional passenger cars to about 6 inches cant deficiency, but both the passive and active banking cars demonstrated adequate ride safety at over 8 inches cant deficiency.

17. Key Words
Safety, Ride Safety, Railroad Passenger Service, Lateral Acceleration, Jolt, Jerk, Cant Deficiency, Vehicle Over-Turning

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EXECUTIVE SUMMARY

Safety criteria to prevent derailment or track damage under high cant deficiency operations were gathered from world wide sources by the Battelle Memorial Institute[2]. The criteria were applied by ENSCO, Inc.[1] to wheel force measurements of several modern passenger rail vehicles taken during a high cant deficiency research program of the Federal Railroad Administration and Amtrak. The vehicle overturning criterion, which limits the unloading of the low rail wheel, was found to be the most restrictive of the vehicle safety criteria. The overturning safety criterion prohibits wheel unloading greater than 80% for transient peak occurrences and greater than 60% steady state. The maximum wheel unloading caused by crosswinds is to be included. Shown below is the typical wheel unloading break down for cant deficiency curving for a coach in accordance with the overturning criterion. Unloading is expressed as a percent of the static wheel load.

Maximum steady state wheel unloading	42%
Maximum crosswind* effect	18%
Maximum superimposed transient wheel unloading	20%
Minimum safety margin	20%

The maximum cant deficiency satisfying the steady state overturning criterion for a particular vehicle with a given maximum crosswind can be determined analytically from knowledge of the suspension characteristics, mass distribution and surface area.

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*Calculated in this example at 10 year mean occurrence level of 56 mph at Boston.

However, use of a cant deficiency limit based on steady state weight transfer assumes that there are no track perturbations capable of causing additional transient wheel unloading greater than 20%. The current practice is to find curves causing excessive transient wheel unloading experimentally by direct wheel force measurements or by less accurate accelerometer approximations. Problem curves would receive slow orders or extra maintenance.

The high cant deficiency testing performed in the past focused on derailment safety and safety against track panel movement. However, it is possible that curving accelerations could place standing or walking passengers at an unreasonable risk of falling within the operating limits of derailment safety. This paper contains a review of ride quality literature studied in an effort to separate the purely economic concerns of acceptable ride comfort from the safety concerns of unreasonable risk of falling. Most literature deals with only the former, but a transit car study by Hirshfield[10] in the 1930's provides objective experimental data relating the ability of test subjects on a movable platform to maintain equilibrium in an acceleration environment. Hirshfeld designed his experiment to study start-up acceleration rates and irregularities in acceleration of transit cars, but the results of his measurements of human response can also be applied to lateral acceleration and jolts at track perturbations. An important conclusions drawn from Hirshfeld's experiment is that smooth steady state lateral acceleration even at elevated levels is easier for passengers to cope with while walking than the likely acceleration jolts at track perturbations. The allowable jolts (peak-to-peak oscillations of acceleration) in present passenger service are great enough that most healthy, agile passengers would require a firm hand hold. A set of passenger ride <u>safety</u> criteria are recommended to prevent the degradation of ride <u>safety</u> in higher cant deficiency service. The ride <u>safety</u> criteria attempt to balance an increase in steady state lateral acceleration with a decrease in the jolt level to limit the risk to walking passengers.

The ride safety recommendations may be summarized as follows:

a) Steady state lateral accelerations up to .15g should not be considered hazardous unless accompanied by strong jolts.

b) Jolt, measured as a peak to peak excursion of lateral acceleration within a one second window, should be limited to .25g during steady state lateral accelerations up to .1 g. It should be further restricted for higher steady state lateral accelerations as indicated in figure 1.

c) The peak lateral acceleration should be limited to the value estimated as equivalent to the transient weight vector limit for overturning safety. The limit of peak lateral acceleration should be considered .3g unless justified by the especially favorable weight transfer characteristics of a particular vehicle. The lower speed as determined by recommendations b) or c) should be observed.

d) Since curving safety is dependent on the perturbations peculiar to each curve, a periodic acceleration measurement at full scheduled speed should be conducted on a route chosen for high cant deficiency operation. Bimonthly inspections for the first two months are recommended to create quickly a historical data base of four repetitions. Unless rapid changes are indicated by the historical database, monthly inspection intervals should be adapted and used to maintain the data base of track condition.

e) Cant deficiency increases rapidly with speed. Tighter controls on overspeed should be adopted for trains operating nearer the safety limit.

f) Convenient hand holds for walking passengers should be recognized as necessary for present conditions and receive more design attention in high cant deficiency vehicles.

RECOMMENDED RIDE SAFETY CRITERIA

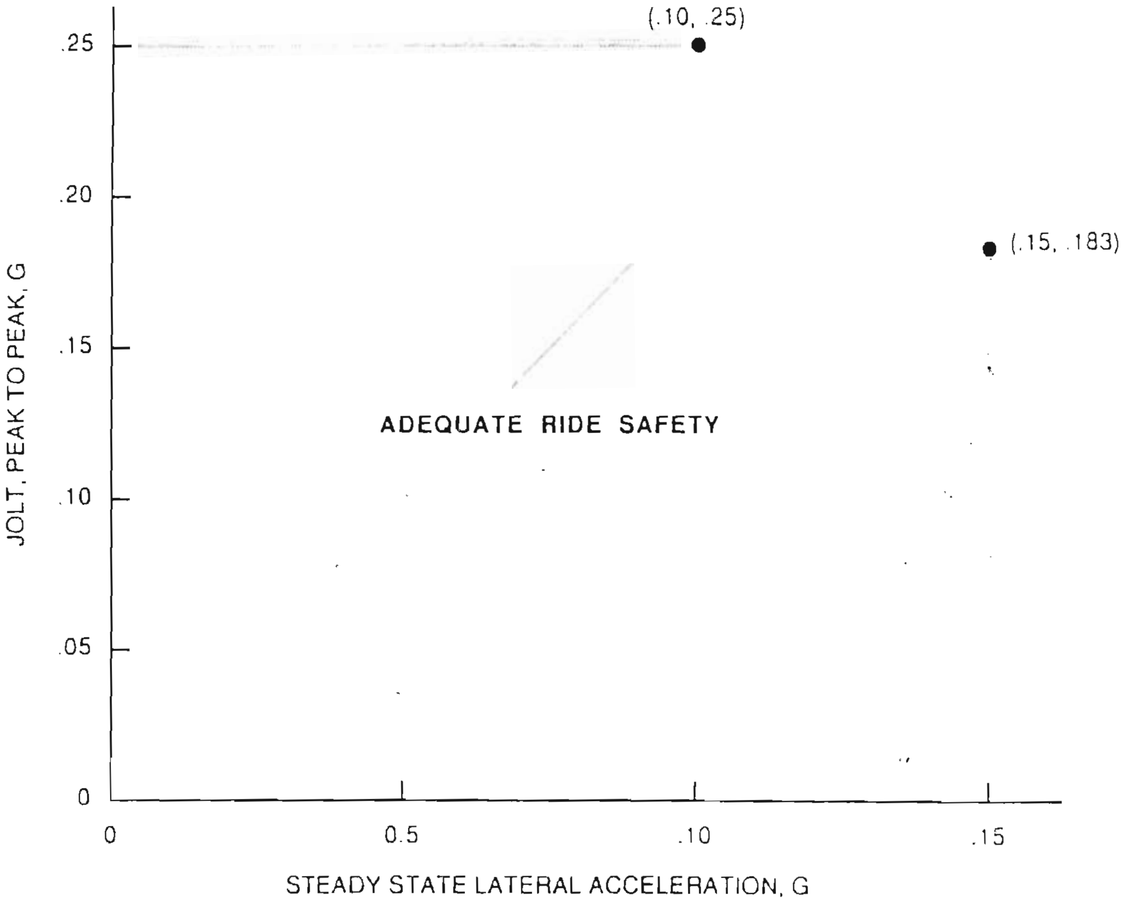


Figure 1

RAIL PASSENGERS RIDE SAFETY

A. Introduction

Recommended safety and comfort criteria used to evaluate the performance of high speed passenger trains is discussed in Reference 2, "Criteria for High Speed Curving of Rail Vehicles." This reference is an ASME paper published in 1979 by F. Dean and D. Ahlbeck of Battelle Columbus Laboratory. This paper is a condensed version of Reference 4 "Criteria for the Qualification of Rail Vehicles for High Speed Curving." Based on this report and other reference material, a set of safety criteria for use in the LRC high cant deficiency test was defined by Ensco, Inc. These safety criteria are described in Reference 1, "High Cant Deficiency Testing of the LRC Train, the AEM-7 Locomotive, and the Amcoach." The criteria are based on three derailment modes, avoidance of permanent track deformation and passenger comfort considerations. Derailment modes considered are:

* Wheel Climb
* Rail Rollover
* Vehicle Overturning

The avoidance of permanent track deformation (Track Panel Shift) is based on maximum allowable axle and truck lateral forces. The vehicle overturning criteria to limit vertical wheel unloading was found to be the most restrictive derailment safety limit on modern passenger equipment.

The passenger comfort considerations address the allowable acceleration levels imposed on the passenger riding in the vehicle. In some references, passenger comfort considerations are referred to as ride quality considerations. The passenger comfort considerations are usually based on the perceived comfort "feelings" of seated passengers.

The steady state and transient lateral accelerations are known to produce feelings of discomfort for seated passengers at certain levels, and at a high enough level would threaten the safety of standing or walking passengers. Acceleration levels high enough to cause walking passengers to lose balance may occur at cant deficiencies achievable by modern cars operating within the bounds of derailment safety. The determination of hazardous acceleration thresholds is difficult because human balance cannot be described mathematically in the same way as vehicle overturning. The variation between individuals is enormous and the presence of effective hand holds could be the dominant element in the ride safety records of railroads and transit systems.

The concept of cant deficiency and the derailment safety criteria are reviewed in this study. A literature review to identify the sources of existing ride quality criteria is presented. The ride quality information is analyzed to attempt to separate ride safety implications from mere comfort considerations. The objective of this study is to review the safety consequences of the ride quality considerations, to review the interrelationship among various criteria applied to high speed curving conditions, and to recommend a ride safety criteria.

B. Cant Deficiency

A section of curved track can be characterized by its degree of curvature and its cant or superelevation. Curvature is defined as the change in heading (measured in degrees) per 100 ft of cord length. Cant is usually measured in inches of height of the high rail above the low rail. The effective gage of the track (between wheel treads) is taken at 60 inches. The speed at which a train can traverse a curve and produce no net lateral force on the track is called the balanced speed. The balance speed is achieved when the centrifugal force of curving is balanced by the gravity force generated by cant. Figure 1 shows this situation. The net force on the track will be perpendicular to the track structure when:

$$M\ V_b^2/R \cos CA - M\ g \sin CA = 0$$

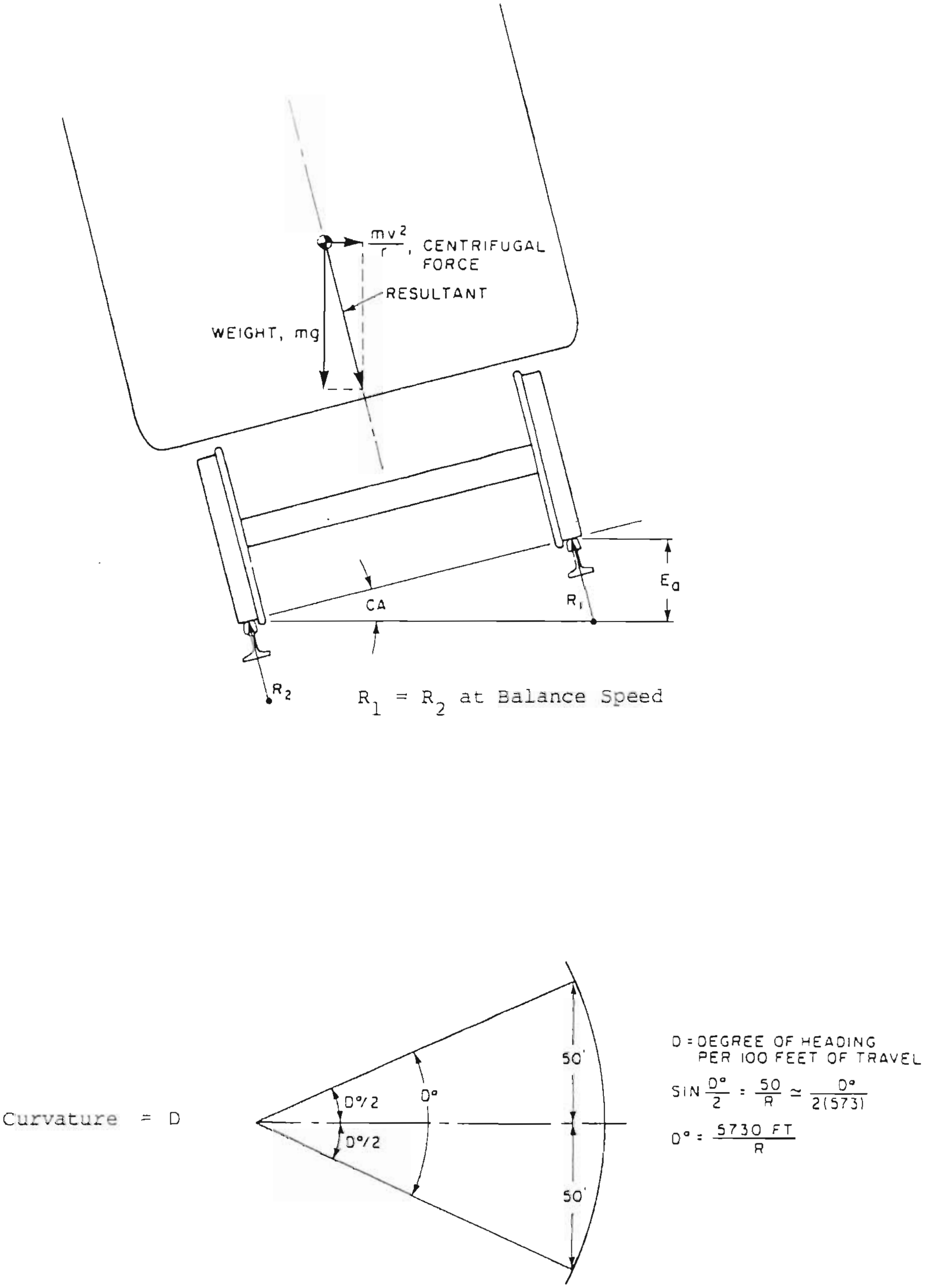
where M = mass of train (slugs)
V_b = balance speed of train (ft/sec)
R = radius of curve (ft)
= 5730/D
D = curvature (degrees per 100 ft)
g = acceleration of gravity (32.17 ft/sec^2)
CA = cant angle (radians)
= $E_a/60$
E_a = superelevation (in)

This expression can be solved for the balance speed to provide:

$$V_b^2 = R\ g \tan CA$$

For small angles, tan CA is approximately equal to CA when CA is measured in radians. Using this approximation, the balance speed is given by:

$$\begin{aligned} V_b^2 &= R\ g\ CA \\ &= (5730/D)\ (32.17)\ (E_a/60) \\ &= 3{,}072\ E_a/D \end{aligned}$$



$R_1 = R_2$ at Balance Speed

Curvature = D

Figure 1. Balance Speed Determination

This expression can be rewritten to provide the superelevation for balance speed

$$E_a = 0.0003255\ V_b^2\ D$$

$$= 0.0007000\ V_{bmph}^2\ D$$

where V_{bmph} = balance speed in miles per hour

The concept of cant deficiency is based on this formula: For a given train speed V and track curvature, the cant deficiency is defined by:

$$(E_a + E_u) = 0.00070\ V_{mph}^2\ D$$

where E_u = cant deficiency or required addition cant to produce balanced speed conditions

Cant deficiency increases rapidly when the speed increases above the balance speed. If a train was operating under a 3 inch cant deficiency limit, the speed limit on a 3 degree curve with 6 inches of superelevation would be 65.5 mph. A 10 mph overspeed would produce a cant deficiency of 6.0 inches or an increase of 100%.

Figure 2 shows the relationship between track curvature and curving speed for 5 levels of cant deficiency and a superelevation of 3 in. Figure 3 is a similar plot for 6 inches of superelevation.

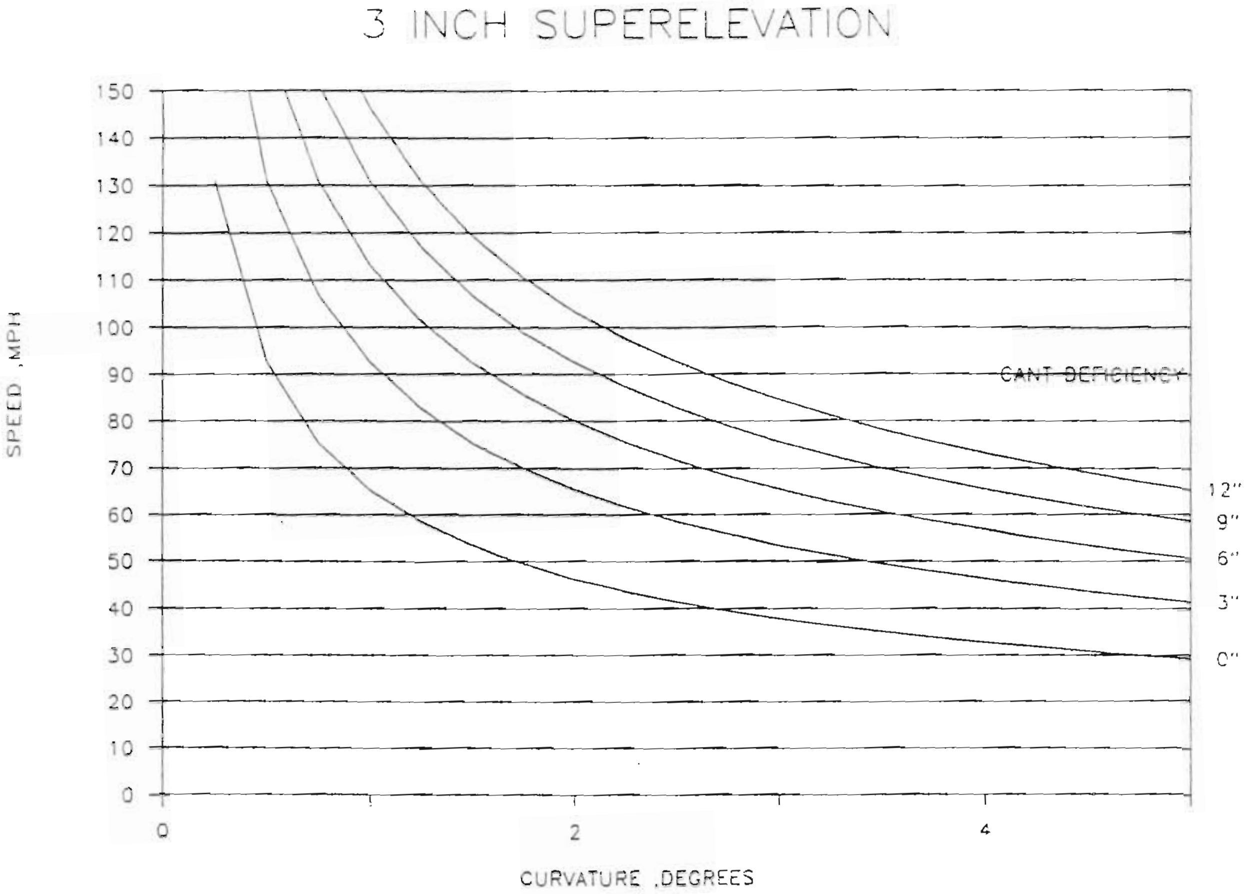


Figure 2. Relationship among curvature, speed and cant deficiency for a superelevation of 3 in

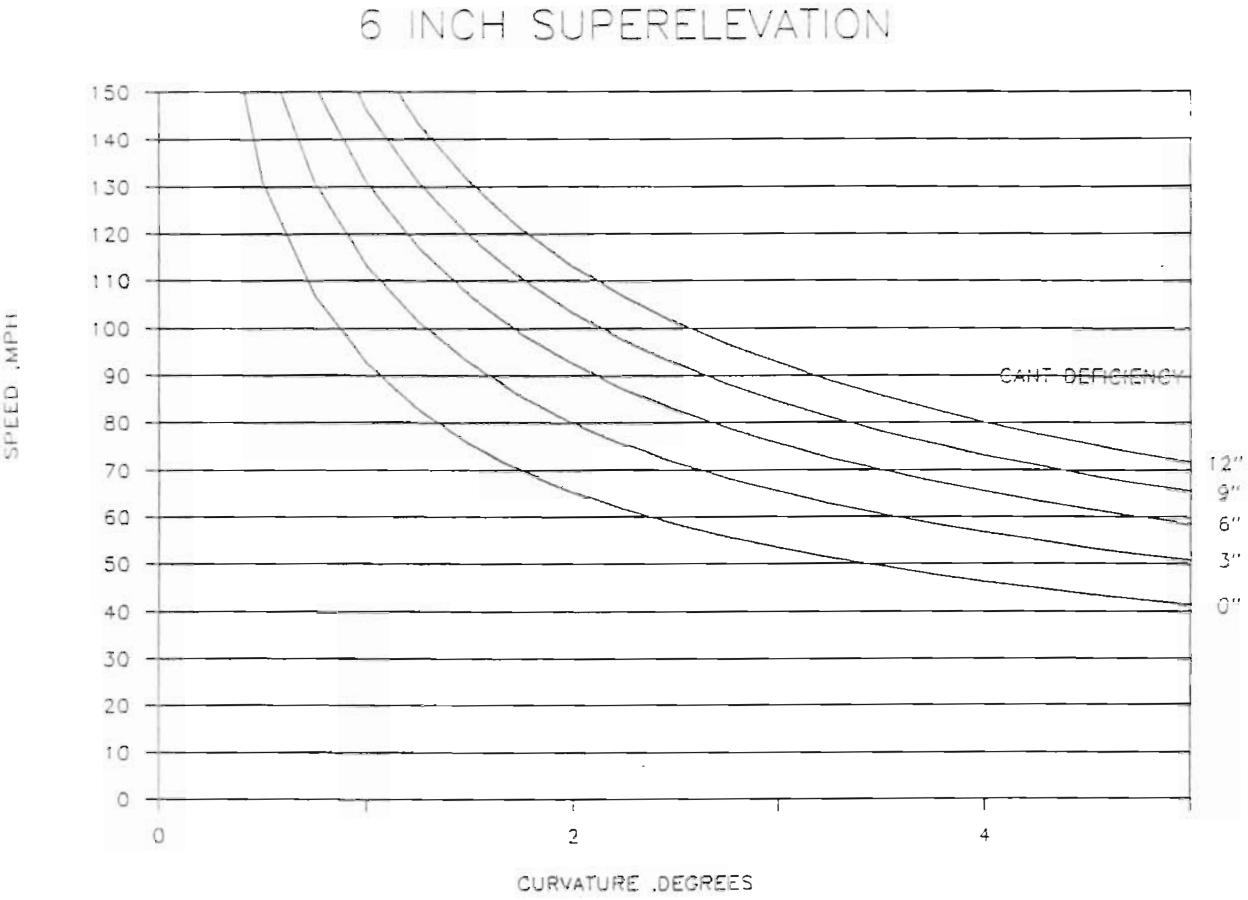


Figure 3. Relationship among curvature, speed and cant deficiency for a superelevation of 6 in.

Cant deficiency provides an indication of the steady state lateral force imposed on the track. The lateral steady state force imposed on the track is related to the cant deficiency by:

$$F_{lat} = W\ E_u/60$$

where F_{lat} = steady state lateral force generated the weight of the train W

C. High Speed Curving Safety Criteria

A comprehensive high speed curving safety criteria must consider both vehicle derailment avoidance and the safety and comfort of the passenger riding in the vehicle. A review of the elements of the existing high speed curving criteria are provided below to show the relationship between elements and the measurement requirements to apply the criteria.

1. Vehicle Overturning

An overturning type of derailment is addressed by two criteria. The first is a steady state criterion and the second is a transient criterion. The concept of the weight vector intercept (WVI) is used to quantify both criteria. The weight vector intercept is the distance from the center line of the track to the point where the resulting force acting on the vehicle crosses the line connecting the top of two rails. WVI is a traditional but awkward term to describe the wheel load reduction of the low rail wheel operating above balance speed. The definition of weight vector intercept is shown in figure 4. The distance from the vehicle vertical centerline to top of the rail head is defined as 30 inches. A weight vector intecept of zero indicates balance

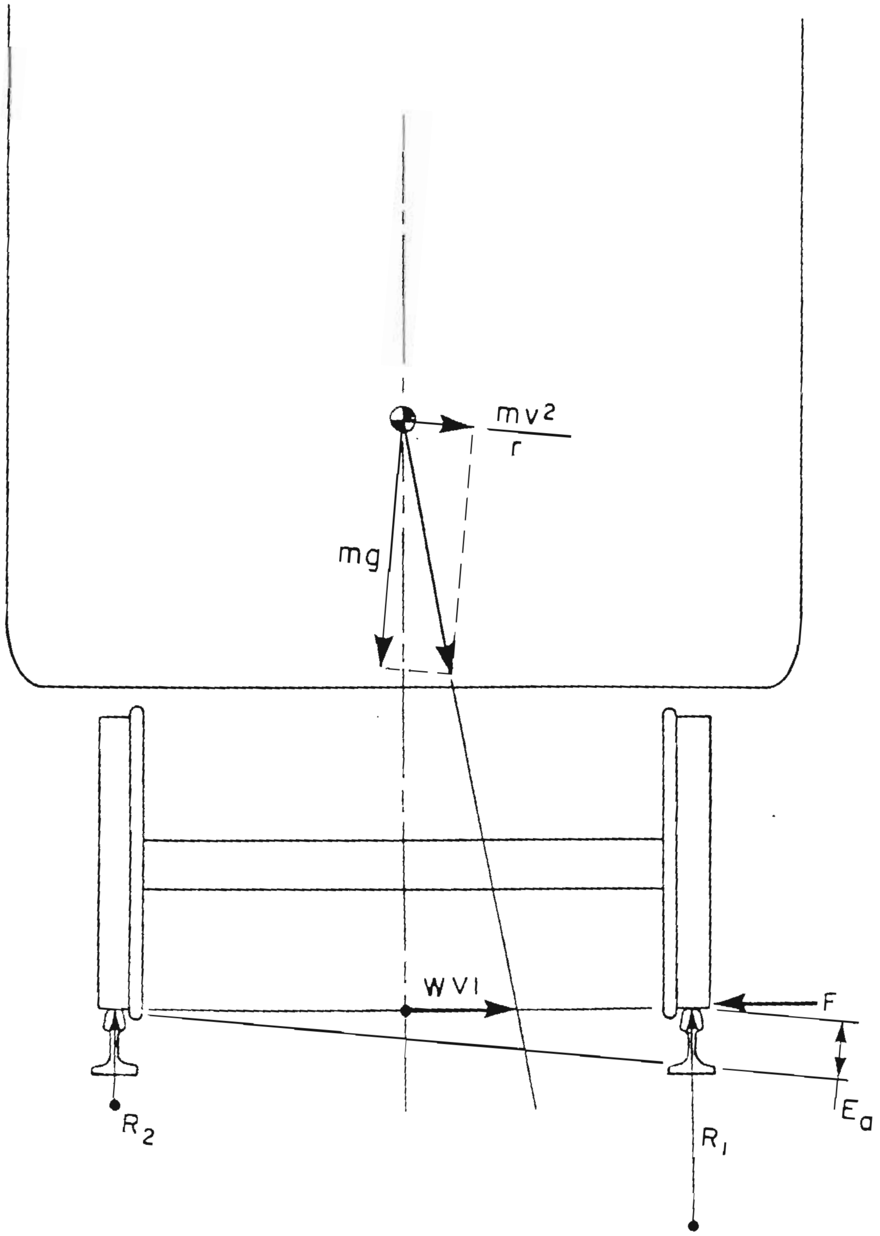


Figure 4. Weight Vector Intercept

speed; a weight vector intercept of 15 inches indicates a 50% reduction in the load on the low rail wheels. A weight vector intercept of 30 inches would mean that the low rail wheel forces would be zero and rollover would be impending. The weight vector intercept is calculated from the measured vertical wheel forces. The weight vector intercept is calculated for a truck from the formula given by:

$$\text{WVI} = 30\,\frac{(R_{lf} + R_{lr}) - (R_{rf} + R_{rr})}{(R_{lf} + R_{lr}) + (R_{rf} + R_{rr})}$$

where

R_{lf} = vertical force on left front wheel
R_{lr} = vertical force on left rear wheel
R_{rf} = vertical force on right front wheel
R_{rr} = vertical force on right rear wheel

The vehicle overturning criterion established in the LRC program allowed a maximum steady state wheel unloading of 60% and a maximum transient peak wheel unloading of 80%. Both of these figures include the maximum adverse effects of crosswinds. Under the worst case conditions assumed in the LRC program for coaches operating in the Northeast Corridor, the crosswind allowance by itself could equal a wheel unloading of almost 20%. In terms of WVI, the overturning criterion translates to 18 inches steady state and 24 inches peak. Test measurements in still air would indicate 12 to 13 inches steady state and 18 to 19 inches peak with a wind allowances of 5 to 6 inches.

The 18 inch steady state WVI allowance is divided into two parts. The first part is associated with effect of wind loading on the vehicle. To quantify this part, the force generated by the wind acting perpendicular to the vehicle is used. The formula for the wind force acting on one half of the carbody is given by:

$$F_W = (S/2) [m (F V)^2/2] C_d$$

where F_W = wind force acting on half carbody (lbs)

S = lateral surface area of the whole vehicle (ft^2)

m = air density (0.002378 $slugs/ft^3$)

V = wind speed (mph)

C_d = drag coefficient (assumed value 1)

F = gust factor (usually 1.0 to 1.3)

The value of the wind velocity used in this formula shows considerable variation in the literature. Table 1 summaries the values used in various references.

The minimum wind speed was used in LRC program but it appears to be very reasonable based on the vehicle operating under normal conditions. The other values in Table 1 appear overly restrictive.

Table 1. Design Wind Conditions

Source	Wind Speed MPH	Gust Factor	Wind Pressure (nominal) lb/ft^2	Wind Force Half Car (LRC Coach) lb
Dean and Ahlbeck	75	1.0	15	6,700
NECPO	85	1.1	22	10,500
LRC Report	56	1.0	8	3,700
British	75	1.0	15	6,700
German	69	1.0	12	5,700

The wind force is assumed to act an height H_{cp} above the rail height. The resulting weight vector intercept allowance for wind effects is given by:

$$WVI\ (wind) = 0.0153\ F^2\ V^2_{mph}\ S\ H_{cp}/W$$

where

WVI (wind) = weight vector intercept allowance for wind (inches for track center)
V_{mph} = wind speed (mph)
W = half weight of car body plus weight of truck (lb)
F = gust factor
S = lateral surface area of whole vehicle (ft^2)
H_{cp} = height of center of wind force (ft)

The second part of the allowable weight vector intercept is based on standard operating conditions with no wind. Field test measurements and vehicle simulations should be compared to this second component of the weight vector intercept specified in the overturning safety criterion. The overturning criterion may be summarized by an equation of wheel unloading descriptors in which the sum of the wind allowance plus the still air operating limit equals the incipient overturning condition minus the safety factor. In the case of the LRC coach in which the wind allowance is equivalent to 5.5 inches weight vector intercept, The steady state criterion would be described as follows:

Wind Allowance		Steady State Allowance		Critical WVI		Safety Allowance
5.5 inches WVI	+	12.5 inches WVI	=	30 inches WVI	-	12 inches WVI

The same expression in terms of wheel unloading ratio is:

$$18.3\% + 41.7\% = 100\% - 40\%$$

Tables 2 and 3 summarize the components of the steady state and transient vehicle overturning criteria for the various vehicles investigated in the LRC program report. The wheel unloading is presented in terms of weight vector intercept with the equivalent wheel unloading ratio in parenthesis. A much lower wind allowance is required by the locomotives because they are heavier than coaches and present a smaller surface area.

A major question is which of the two criteria will limit the high speed curving performance of a vehicle. The transient criterion may impose a lower limit than the steady state criterion on a curve by curve basis depending on track perturbations. This is not an easy question to answer even from test results. In a test, a curve is traversed at a given cant deficiency, and steady state and transient WVI levels are determined. If these values are below the limiting values, the cant deficiency at which the limits would be encountered has to be estimated. In the LRC testing, the steady state WVI was observed to be highly correlated to the cant deficiency. In addition, a simple mathematical model was developed to predict steady state WVI based on vehicle suspension and inertial properties. The transient WVI level showed a general level of correlation with cant deficiency, but some results differed significantly from the general trend. In most cases, these results could be attributed to special features in the curve such as switches, roadcrossings or undergrade bridges. Since test data for curves showing these characteristics were analyzed at only one cant deficiency the estimation of the limiting cant deficiency based on the transient overturning criteria was difficult.

The limiting factor on the vast majority of curves is based on the steady state criterion. Based on maximum allowable speed of 110 mph (New York-Boston Amtrak route), only three curves were found where the transient criteria was the limiting factor for

Table 2.

Components of Steady State Vehicle Overturning Criteria in Terms of Weight Vector Intercept (inches) and Wheel Unloading Ratio (%)

	Wind Allowance	+	Still Air Operating Limit	=	Incipient Rollover Condition	-	Safety Factor
LRC Coach	5.5 (18.3%)	+	12.5 (41.7%)	=	30 (100%)	-	12 (40%)
LRC locomotive	1.7 (5.7%)	+	16.3 (54.3%)	=	30 (100%)	-	12 (40%)
Amcoach	5.2 (17.3%)	+	12.8 (42.7%)	=	30 (100%)	-	12 (40%)
AEM-7	1.8 (6.0%)	+	16.2 (54.0%)	=	30 (100%)	-	12 (40%)

Table 3.

Components of Transient Vehicle Overturning Criteria in Terms of Weight Vector Intercept (inches) and Wheel Unloading Ratio (%)

	Wind Allowance	+	Still Air Operating Limit	=	Incipient Rollover Condition	-	Safety Factor
LRC Coach	5.5 (18.3%)	+	18.5 (61.7%)	=	30 (100%)	-	6 (20%)
LRC locomotive	1.7 (5.7%)	+	22.3 (74.3%)	=	30 (100%)	-	12 (20%)
Amcoach	5.2 (17.3%)	+	18.8 (62.7%)	=	30 (100%)	-	12 (20%)
AEM-7	1.8 (6.0%)	+	22.2 (74.0%)	=	30 (100%)	-	12 (20%)

the LRC train. On two of these curves, the transient weight vector actually exceeded the still air operating limit of 18.0 inches. On the third curve it was projected to be the limiting criteria. For the LRC locomotive, the speed was limited by the transient criteria on only three curves. In no case was the transient limit of 22.3 inches weight vector intercept exceeded during testing. In all cases tested, the Amcoach speed on a curve was limited by the steady state criteria based on the projection scheme used in the LRC report.

The AEM-7 was run over a different test zone than the rest of the vehicles because of the need for electrification. A 4.7 inch cant deficiency limit was projected on one curve with a rough switch which was tested at only 1.5 inches cant deficiency. The transient vehicle overturning criteria did not limit any other curve in the Washington-New York test zone below 7.4 inches cant deficiency. Table 4 presents the results from the LRC testing.

Table 4.

Cant Deficiency Limits
(Results of LRC Test Program)

	Steady State Limit	Transient Limit*
LRC Coach	9.3"	8.7"
LRC Locomotive	12.2"	10.6"
Amcoach	8.3"	> 8.3"
AEM-7	10.5"	4.7"

*Based on the single worst curve in the test zone.

An observation from the LRC testing is that when the transient WVI is the limiting factor a significant transient is usually observed in the lateral acceleration level. If a lateral acceleration always occurs when the transient overturning criterion is the limiting factor, a linkage between the transient overturning criterion and ride quality might be determined. This would be advantageous since it is much easier to measure lateral acceleration in a vehicle than to measure wheel/rail forces. The steady state overturning criterion can be applied based on track curvature, superelevation and vehicle characteristics, because steady state weight transfer can be mathematically predicted on perfect track. The extra safety factor included in the steady state criterion is meant to account for the effects of typical track perturbations. The few curves limited by the transient overturning criteria presumably contained perturbations more severely affecting peak wheel unloading.

2. Rail Rollover

A rail rollover type of derailment occurs when the outside rail is rotated with the head of the rail moving to the outside of the curve. The criteria to prevent rail rollover is based on the total truck forces on the high rail and is expressed in terms of the total lateral to vertical force ratio on the outside rail. The expression is given by:

$$\text{Peak truck L/V} < [0.5 + 2{,}300/P_W] \qquad \text{for } T > 50 \text{ msec}$$

$$\text{Peak truck L/V} < 0.133\,[0.5 + 2{,}300/P_W]\,T^{-0.728} \qquad \text{for } T < 50 \text{ msec}$$

where P_W = nominal vertical wheel load

Application of this criterion is based on knowing the magnitude of the wheel lateral and vertical forces. This usually means instrumented wheels must be used in testing. During the LRC program the maximum truck L/V ratio measurements were about half the limiting values. Modern passenger vehicles with two axle trucks were operated up to 15 inches cant deficiency in this program, and it was observed that the increased vertical load at high cant deficiency tended to balance the increased lateral forces.

3. Lateral Track Shift

The lateral track shift criterion is related to the prevention of permanent lateral movement of the ties relative to the ground. The criteria for track shift has two parts. The first part addresses the axle lateral force and the second part addresses the truck lateral force. The criteria for part 1 is based on limiting the lateral axle force to:

$$F_{max}(\text{axle}) = .61P + 5{,}800 - 0.00128\ S\ (F\ V)^2$$

where

F_{max} (axle) = maximum axle lateral force (lb)

P = nominal axle vertical force (lb)

S = lateral surface area of vehicle (ft^2

V = wind speed (mph)

F = gust factor

The criteria for part 2 is based on limiting the truck lateral force to:

$$F_{max}(\text{axle}) = 0.7N\ [.61P + 5{,}800 - 0.00128\ S\ (F\ V)^2]$$

where N = number of axles per truck

Table 5 shows limiting truck and axle loads.

Table 5.

Limits for Truck and Axle Loads (lb)
Set by Lateral Track Shift Safety Criteria

	Nominal Axle Load	Lateral Load Limit	
		Axle	Truck
LRC Coach	26,400	18,200	26,900
LRC Locomotive	62,700	41,300	58,900
Amcoach	26,100	18,600	27,300
AEM-7	49,500	34,000	48,400

The maximum lateral truck forces measured at the most severe curves during the LRC test program were less than 65% of the maximum set by the track shift safety criteria for the above vehicles.

4. Wheel Climb

The descriptor for wheel climb derailments is the wheel L/V ratio. The criterion is based on limiting the L/V ratio to:

$$L/V < 0.056\ T^{-0.927} \quad \text{for } T < 50 \text{ msec}$$

$$L/V < 0.90 \quad \text{for } T > 50 \text{ msec}$$

where

L = lateral force at wheel/rail interface
V = vertical force at wheel/rail interface
T = time duration above force level

The lateral forces generated by the wind are not included in this expression. The experience from the LRC program is that wheel L/V ratios of modern passenger vehicles remain below about 0.5 during high cant deficiency curving. Higher L/V ratios were measured at switches in high speed low cant deficiency curves.

5. Ride Comfort

The ride comfort or ride quality criteria limits the acceleration levels to which the passenger is exposed. For high speed curving, two criteria are used. Both are based on measuring the lateral acceleration at the floor level of the vehicle. Figure 5 shows a typical time history of the lateral acceleration for cant deficiency operation and very good track geometry conditions. The average level of lateral acceleration in the body of the curve is called the steady state lateral acceleration. The ride quality criteria from the Dean and Ahlbeck paper for steady state lateral acceleration is 0.1 g's. The average slope of the acceleration during the entry and exit spiral is called the spiral jerk. The units of spiral jerk are g's/sec. The ride quality criteria from the Dean and Ahlbeck report is 0.04 g/sec. Table 6 from the Dean and Ahlbeck paper show ride quality values specified used by various organizations.

Table 6.

Ride Quality Parameters

Organization	Lateral Steady	Spiral Jerk State	Remark
BR	0.074	0.042	50% satisfied
AAR	0.100	0.030	50% satisfied
JNR	0.080	0.040	90% satisfied
OHSGT	0.080	0.030	
SNCF	0.150	0.100	
DB	0.066	-	Max. speed 124
	0.031	-	Max. speed 186

The LRC experience suggests that the relationship between cant deficiency and steady state lateral acceleration can be predicted from a simple mathematical model. The input parameters for the model can be determined from published vehicle geometric

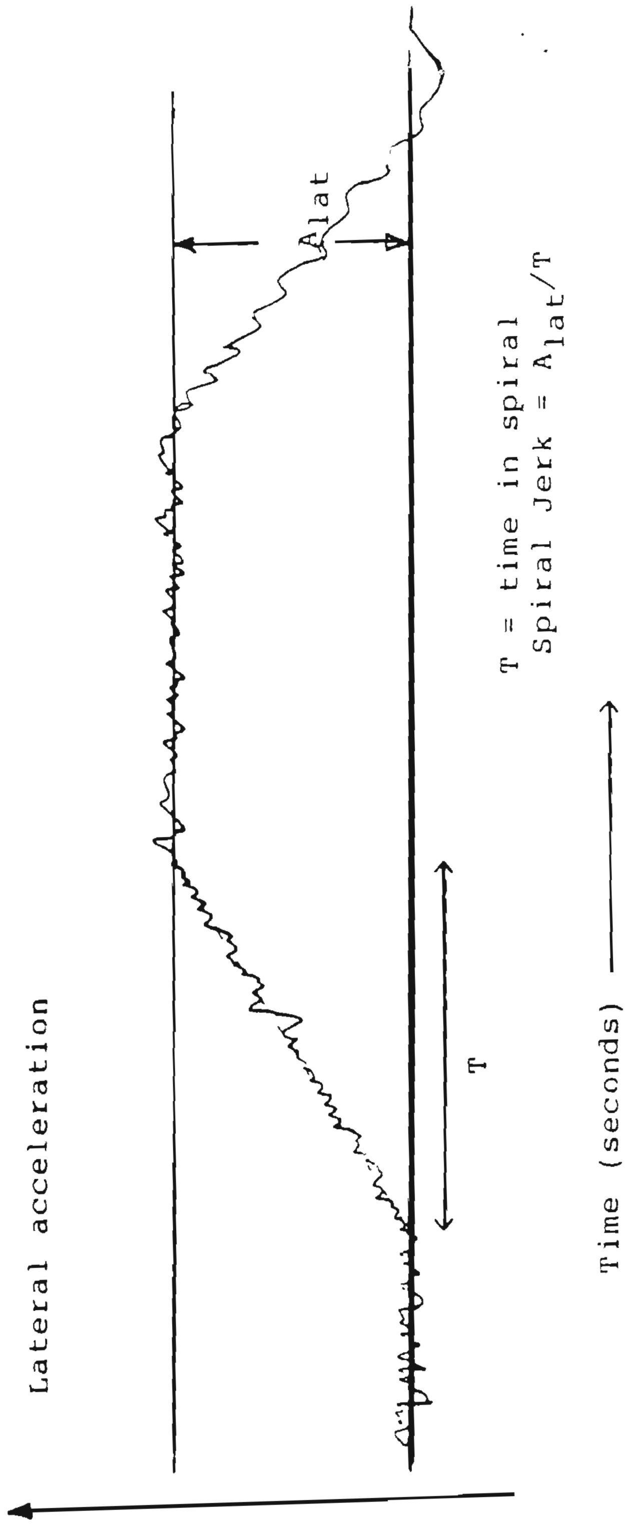


Figure 5. Lateral Acceleration Time
In Spiral and Curve Body

and suspension characteristics or calculated from suspension deflections during a static lean test. A static lean test is a test where the vehicle is parked on track with high superelevation and the movement of the suspension elements and carbody are measured.

Table 7 contrasts the vehicle overturning safety limits of several vehicles tested during the LRC Program to the cant deficiencies at which they reach the AAR ride comfort criterion of 0.1 g steady state lateral acceleration. As mentioned before the transient limit of the AEM-7 was at least 7.4 inches weight vector intercept at but one curve in the Washington-New York test zone. The locomotives are included in the table as examples of known vehicle behavior although they are not involved in the passenger ride safety issue. Clearly the 0.1 g steady state ride comfort criteria is much more restrictive than the derailment safety criteria for the non-banking equipment. Even at 0.15 g

Table 7.

Results of LRC Test Program
Cant Deficiency Limits for Vehicle Overturning

	Cant Deficiency Limits for Vehicle Overturning		Cant Deficiency	
	Steady State Limit (in)	Transient Limit (in)	at.1g** Steady State	at .15g Steady State
LRC Coach (banking)	9.3	8.7	9.5	12.0
LRC Coach (nonbanking)	9.3	8.7	4.0	6.0
LRC Locomotive	12.2	10.6	5.0	7.5
Amcoach	8.3	> 8.3	4.0	6.0
AEM-7	10.5	4.7	5.2	7.6

*Based on single worst curve in the test zone.
**AAR Ride Comfort Criterion

the steady state ride comfort criteria would remain more restrictive than the derailment safety criteria.

The relationship between ride comfort and ride safety must be made wisely. Reliance on steady state measurements emphasizes the advantage of tilt equipment. However, transient lateral accelerations imposed on passengers at track perturbations may be the greater hazard, and tilting does not reduce transient jolts. Track perturbations were also the reason why the transient vehicle overturning criterion set a lower cant deficiency limit than the steady state criterion at several curves in the cited test results.

D. Ride Comfort/Safety Research

Two studies conducted in the early 1950's, one by a joint committee of AREA[6] and AAR and one by the Track Committee of the Railway Executives of British Railways[16], established ride quality standards for rail vehicles.

1. British

The objective of this study was to establish limits (based on comfort and safety considerations) for:

- the maximum permissible cant
- the maximum rate (with respect to time) of gain and loss of cant
- the maximum permissible cant deficiency
- the maximum rate of gain and loss of cant deficiency
- the steepest permissible cant gradient

In a preliminary set of tests, the engineers were seated or standing, facing forward in a vehicle which accelerated at a constant rate. Initial runs were made with an electric train and

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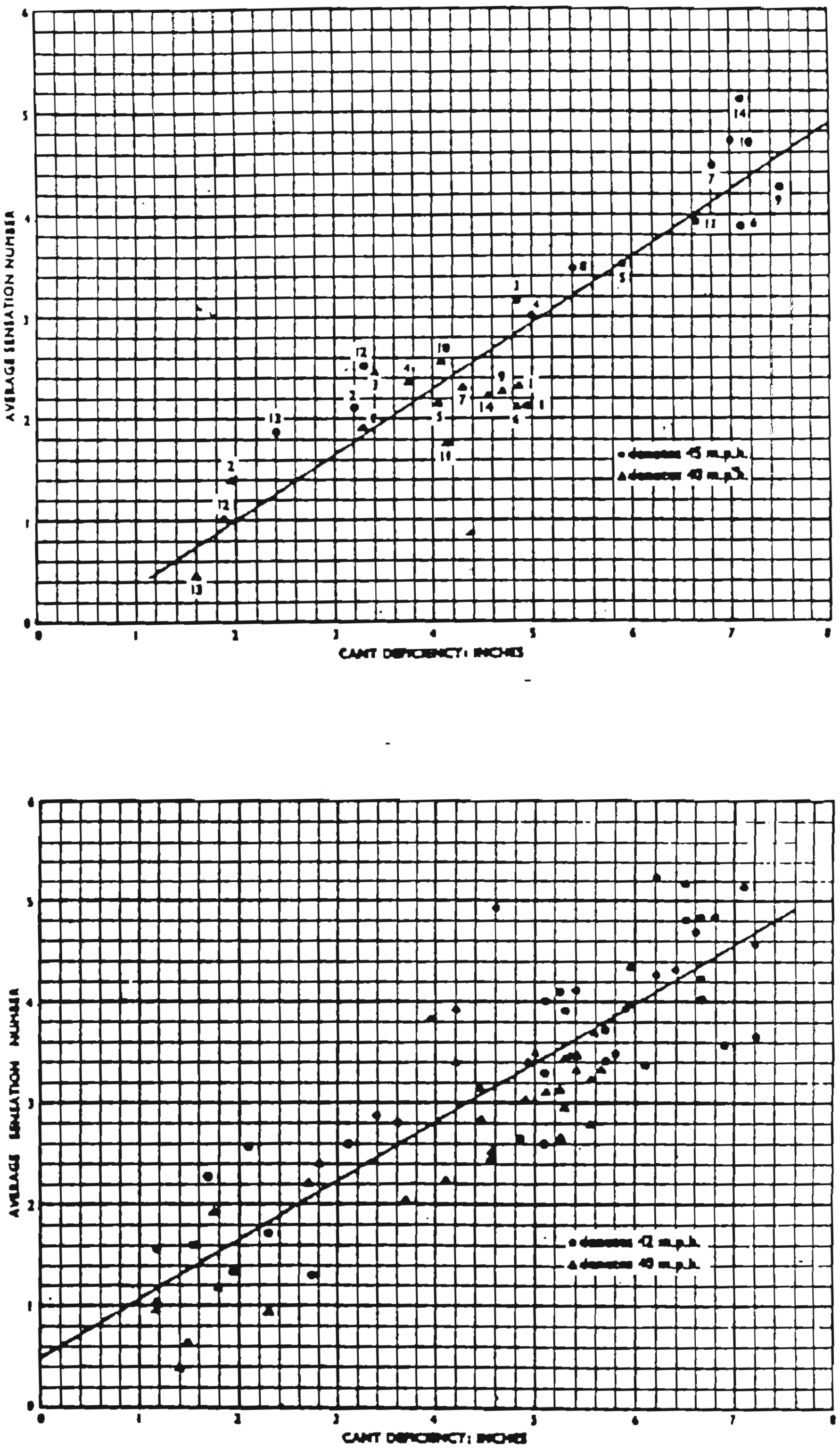


Figure 6. Ride Index versus Cant Deficiency for Two Groups of Curves

$$A_{lat}\ (g's) = (E_u/L)(\ 1 + DPG/57.3)$$

$$DPG = 1.8/[(6/60\ )]$$

$$DPG = 18 \text{ degrees per } g$$

where A_{lat} = lateral acceleration in g's at the carbody floor

E_u = cant deficiency measured in inches

L = track gage = 60 in

DPG = degrees of carbody roll per g of lateral load

For the vehicle used the relationship between cant deficiency and lateral acceleration measured in g's is given by:

$$A_{lat}\ (\ g's) = .022\ E_u\ (\ in)$$

The conclusions drawn from the cant deficiency test and the reasons for these conclusions are best expressed by quoting the report:

> Results "show that discomfort was not experienced until the deficiency in cant reached as much as 7 inches and, in this respect, the results of the trails in North Wales confirm very satisfactorily those obtained from the preliminary tests. It is recognized, however, that standing passengers would experience discomfort at deficiencies of less than 7 inches and that passengers who were trying to walk along corridors or through luggage vans would be unconvinced at even smaller cant deficiencies. It is also recognized that the curves for which a greater permissible cant deficiency would be most desirable were the sharper ones; in these cases a small increase in speed would increase appreciably the cant deficiency and the lateral thrust, and result in increased maintenance and shorter life of track. At the same time, the

> sensations of discomfort would be increased perhaps even more than cant deficiency. Consideration also had to be made of the ability of rail fasteners to withstand indefinitely the lateral thrusts which would be imposed on them when the fastest trains were running regularly at speeds associated with appreciable cant deficiencies, and the problem of maintaining good alignment. In the end, these two items influenced the Committee perhaps more than any other because, apart from a few abnormal cases where exceptional circumstances justify the frequent renewal of track, reasonably long life of the track is essential for reason of economy.
>
> The Track Committee therefore decided that 3.5 inches cant deficiency, corresponding to sensation No.2 (noticeable), was the maximum which should be tolerated in the design of curves in the more important and better maintained lines...

In turnouts, transitions cannot often be incorporated so that the entrance directly onto a circular curve imposes a sudden lateral thrust on the passenger, the vehicle and the truck. The Committee, therefore, felt that it was not desirable to exceed 2.5 inches cant deficiency in these cases.

In deciding on these figures, the Committee made allowance for drivers' errors in estimating their speeds where restrictions exist. "...The Committee also decided to make the permissible cant deficiency a function of cant. In the cases of the more important lines the maximum permitted deficiency decreased by a straight-line law from 3.5 inches at zero cant to 2 inches at 6 inches (maximum) cant..."

During the testing the ride was also evaluated based on the time rate of change of cant deficiency. The recommended limiting value was 2.25 inches per sec. Based on the relationship between cant deficiency and lateral acceleration, this is equal to 0.05 g/sec when the motion of the carbody is taken into consideration.

Table 9

Summary of Results

	Units	Limit	Desired
Cant	in	6.00	
Rate of gain/loss of cant	in/sec	2.25	
Cant deficiency (class A* and B)	in	3.50/2.0**	
Cant deficiency (class C and D)	in	2.50/1.0**	1.5
Rate of gain /loss of cant deficiency	in/sec	2.25	
Cant gradient	in/in	1 in 300	1 in 450
Steady state lateral acceleration	g's	0.08	
Spiral jerk	g's/sec	0.05	

*A is the highest quality track.

**The maximum cant deficiency was limited based on the amount of superelevation. For class A and B track, the permitted cant deficiency was decreased by a straight line law from 3.5 in at zero cant to 2.0 in at 6 in of cant deficiency and for class C and D from 2.5 in for zero cant to 1 in for 6 in of cant deficiency.

Table 10

AAR Ride Index

Definition	Ride Index	Lateral Acceleration
Not perceptible	0 to 1	0.00 to 0.04
Perceptible	1 to 2	0.04 to 0.11
Strongly Noticeable	2 to 3	0.11 to 0.19
Uncomfortable	3 to 4	> 0.19

2. AAR/AREA

The objectives of this study[6] were to:

- recommend permissible speeds on curves
- recommend the lengths of curves for passenger comfort
- establish clearance requirements on curves

Based on more than 30 observers, 300 curves and tests on two railroads, a relationship between the steady lateral acceleration on the floor of the carbody and a Ride Index was determined. A curve, called the Master Curve (see Figure 7) was established to define this relationship. The Ride Index is defined in Table 10.

The limiting level of lateral acceleration of 0.1 g's was selected based on the transition from the "perceptible" level to the "strongly noticeable" level with some consideration for scatter in the base data.

This program had the advantage of using 11 different vehicles in the test program. This clearly allowed the relationship between lateral acceleration and track cant deficiency to be investigated. Operating under a given level of cant deficiency, the carbody roll angle varied by a factor of 3 between the "best" to the "worst" car. Characterizing the test vehicles in terms of degrees per g (DPG), the vehicles showed a range from 48 to 18. Based on the 0.1 g limit on lateral acceleration, the limiting cant deficiency as a function of DPG is given by:

$$.1 = (E_u/60)[1+DPG/57.3]$$

$$E_u = 6/[1 + DPG/57.3]$$

For the vehicle with a DPG =48, the limiting cant deficiency is 3.2 in. For the vehicle with a DPG = 18, the limiting cant deficiency is 4.6 in. The level of DPG = 18 would appear to the practical lower limit on roll characteristics of a rail vehicle.

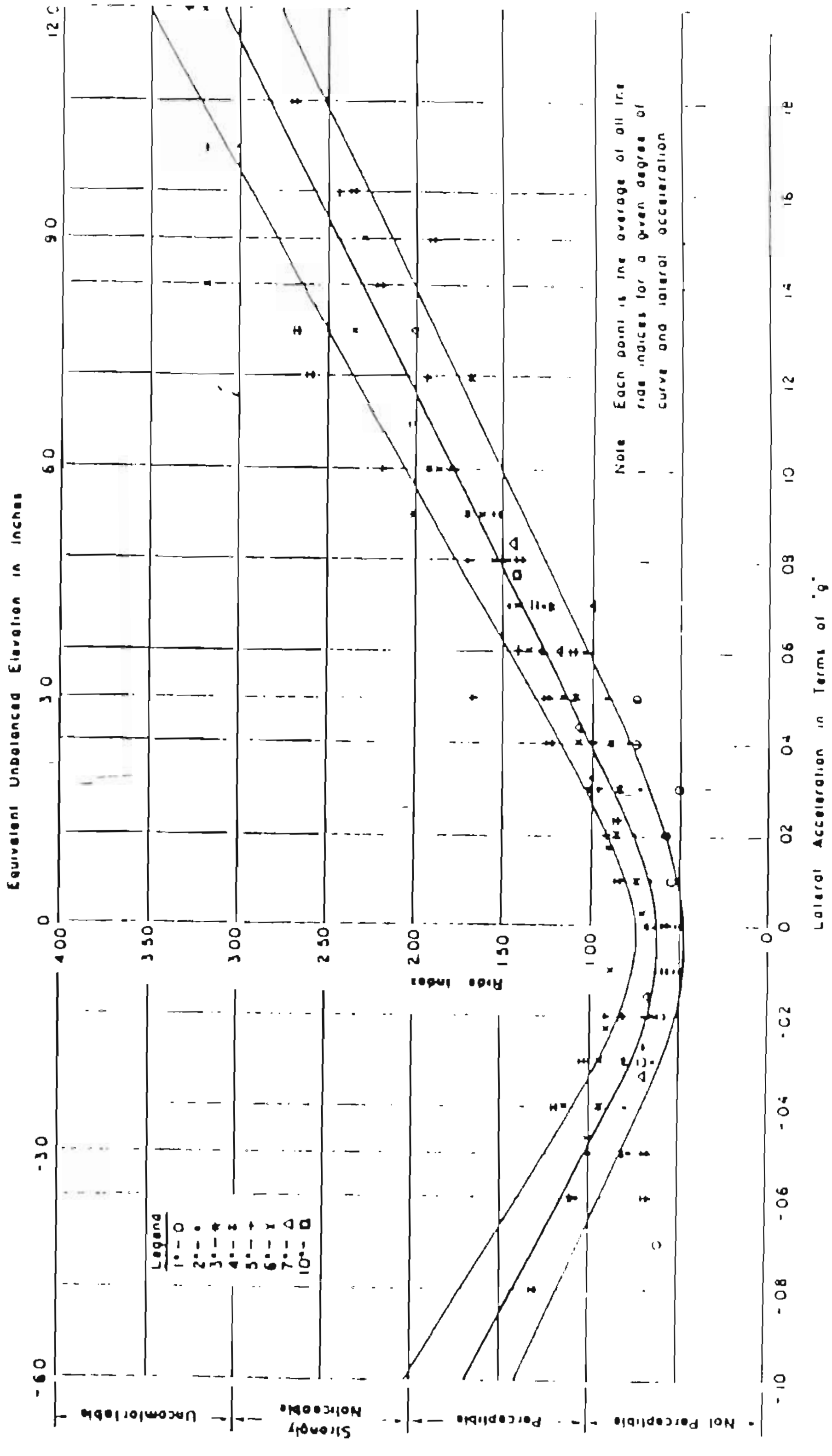


Figure 7. AAR Master Curve

The value of spiral jerk was based on the British work and set at a conservative 0.03 g/sec. Based on this limit, the minimum length of a spiral was established. The equation for the spiral length is given by

$$L_{min} = [A_{lat}/.03]\ V$$

where

L_{min} = minimum spiral length in feet
A_{lat} = steady state lateral acceleration in body of curve g's
V = vehicle speed in ft/sec

For a maximum lateral acceleration of 0.1 g's, this expression becomes:

$$L_{min} = 4.88\ V_{mph}$$

This is the expression for the minimum spiral length used by AAR since 1963. This expression is very sensitive to the allowable jerk level. A less restrictive value of 0.04 would reduce the spiral lengths by 25% and a value of 0.05 g's would result in 40% reduction.

3. Spiral Length

From the very early 1900's to 1965, AREA used a rule for the minimal spiral length give by:

$$L_{min} = 1.17\ E_a\ V_{mph}$$

This formula is based on limiting the rate of change of superelevation to 1.25 in/sec.

In 1965, AREA adopted the formula:

$$L_{min} = 1.63\ E_u\ V_{mph}$$

This formula was based on a spiral jerk of 0.03 g/sec. The expression can be derived from:

$$T = L/V$$
$$A_{lat} = E_u\ (1 + DPG/57.3)/60$$

where T = time in spiral, sec

L = length of spiral, ft

V = vehicle speed, ft/sec

A_{lat} = lateral acceleration in body of curve, ft/sec^2

DPG = Degrees of roll per g of lateral loading

For jerk rate of 0.03 g's/sec, we have:

$$\begin{aligned} .03\ T &= A_{lat} \\ L &= V\ E_u\ [\ 1 + DPG/57.3]/(60 \times .03) \\ &= 0.814\ (V\ 60/88)\ E_u\ [\ 1 + DPG/57.3] \\ &= 0.814\ V_{mph}\ E_u\ [\ 1 + DPG/57.3] \end{aligned}$$

For a worst case vehicle DPG = 57.3 and the equation becomes:

$$L = 1.63\ V_{mph}\ E_u$$

For a modern coach with a DPG of about 20 degrees per g, this equation becomes:

$$\begin{aligned} L &= 0.814\ V_{mph}\ E_u\ [\ 1 + 20/57.3] \\ &= 1.34\ V_{mph}\ E_u \end{aligned}$$

This represents a 18% reduction in spiral length based on a modern coach.

If the allowable jerk was increased to point 0.04 g/sec, the equation would become

$$L = 1.00\ v_{mph}$$

This represents a 36% reduction in spiral length compared to the present AREA formula.

4. Transit Car Acceleration Experiments

A report entitled "Disturbing Effects of Horizontal Acceleration" was published in 1932 by the Electric Railway Presidents' Conference Committee. The author was C.F.Hirshfeld. The following paragraph was taken from the report:

> "Demand upon the part of the pubic for 'increased agility' in street cars undoubtedly arises through comparison with the performance of the modern automobile. If the public is to be fully satisfied with rail transportation, the car must at least approach the performance of the automobile in ability to hold its place in traffic, But, the automobile passenger is seated and in an ideal position to resist the forces of horizontal acceleration, while the street car must transport many passengers in a standing position in which they are much less capable of resisting these accelerating forces. The tolerance of standing passengers to such forces has become, therefore, a very vital factor in street car design and operation."

The study addressed the ability of the standing passenger to maintain equilibrium while standing in a cart which was accelerated along a track. The acceleration level of the cart could be closely controlled. The subjects were ask to stand in the center of the cart with their feet as shown in Figure 8. There was a switch put under the toe of the front foot and under the heel of the back foot. Motion of either foot was detected by the switch opening. Many types of acceleration time histories were used in the study. For the purpose of the present application, the acceleration time histories shown in Figure 9 was selected.

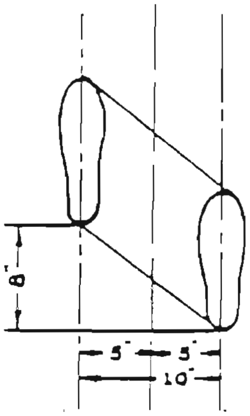
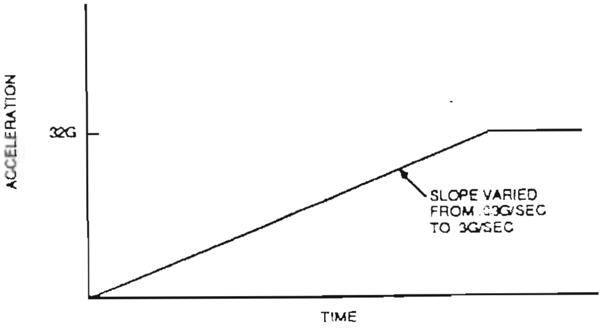
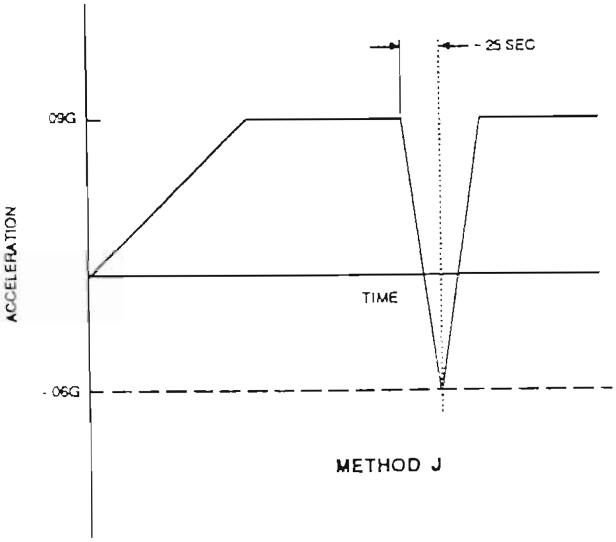


Figure 8. Standing Position in Hirshfeld Tests



METHOD A



METHOD J

Figure 9. Acceleration Time Histories in Hirshfeld Tests

The results of the tests for the starting method A (figure 9) are shown in Figure 10. This plot shows the percentage of passengers maintaining equilibrium as a function of the acceleration level attained. Two curves are plotted, one for a level of 0.046 g's/sec and one for 0.077 g's/sec.

Although these graphs were generated for passengers facing forward in a car accelerating on tangent track, they can also represent standing passengers facing the windows on the low rail side of a car curving above balance speed. Experiments describing the experience of passengers facing the opposite way indicated at 20% loss in equilibrium ability. The most common posture of passengers standing in a curving train is to be facing forward or backward which is analogous to facing the side in the experimental apparatus. Those experiments showing a 15% increase in ability to maintain equilibrium relative to the data shown in figure 10 without optimizing the foot positions. Experiments with passengers facing forward in the experimental apparatus holding onto straps or stanchions showed increased equilibrium abilities of 40% to 64%, and Hirshfeld speculated that even greater increases would have been likely had these passengers been facing the side of the experimental apparatus.

Hirshfeld designed these experiments to indicate the ability of passengers to maintain equilibrium under steady state acceleration, but he used a gradual increase in acceleration for the sake of experimental practicality. He reported similar results for experiments with acceleration increasing between 0.03 g/sec to .2g/sec. It is a coincidence that the entire range of likely spiral jerk rates is included in the lower end of the test arrange. It is significant that rates of change of acceleration in this range where not associated with loss of equilibrium. Only the absolute value of acceleration was considered to cause loss of equilibrium. Therefore, spiral jerk may not be important in determining ride safety.

Hirshfeld was also concerned with the effect of sudden spikes in acceleration caused by motor characteristics of contemporary transit cars. These acceleration spikes are

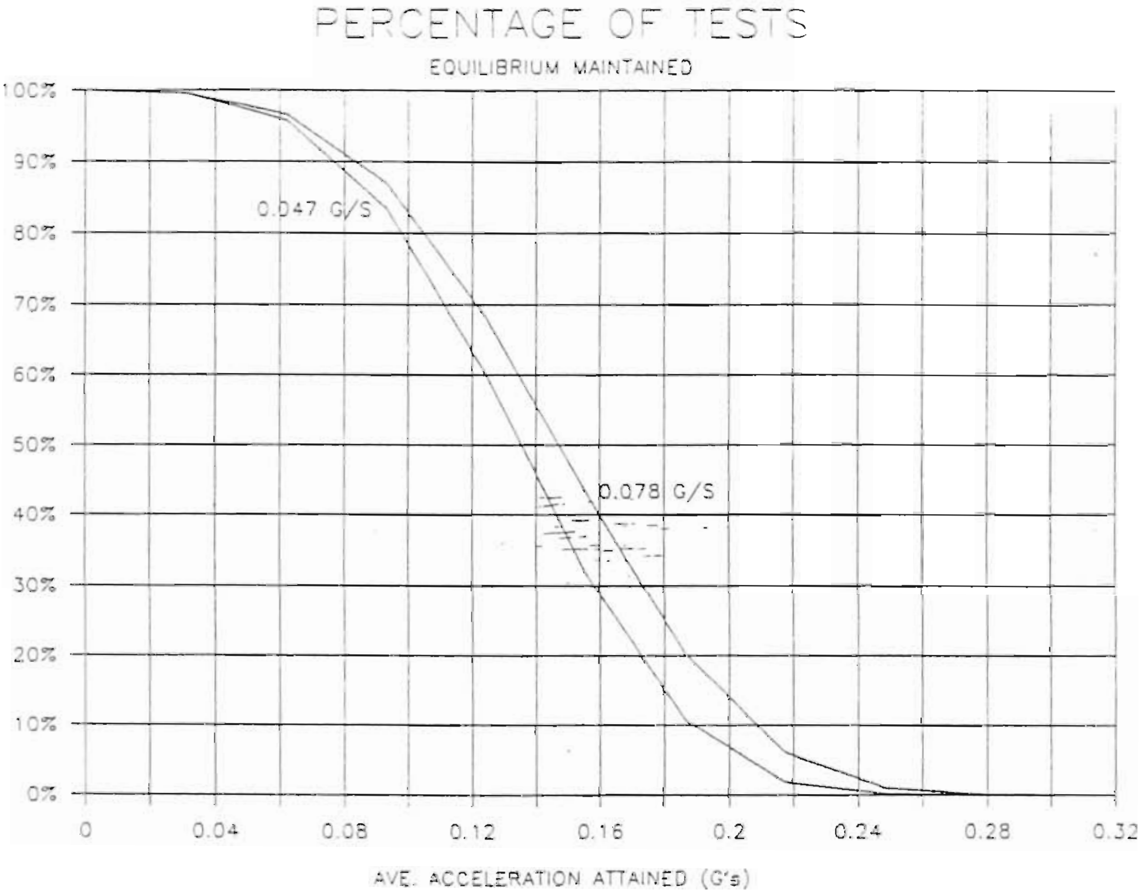


Figure 10. Results of Transit Car Experiments (Method A)

analogous to the lateral acceleration spikes at track perturbations in the case of curving. The passengers were facing the axis of the acceleration in Hirshfeld's experiments summarized in table 11. Presumably about a 15% improvement in equilibrium response would have occurred had the passengers been subjected to a lateral acceleration spike. The duration of the descending acceleration was about .25 sec, and many experimental subjects lost balance under quite small spikes. Hirshfeld indicates that equilibrium would not be lost as easily if the duration of the spike was shorter. He concludes that the key to using starting accelerations of .14g or better in transit cars is to reduce the spikes in the acceleration.

Table 11

Results of Method J Acceleration Tests
Results for Standing Passengers

Negative Acceleration Spikes, g's	Percentage of Tests in Which Equilibrium Maintained
.03 to .06	100
.06 to .09	50
.09 to .12	40
.12 to .14	20
.14 and more	0

5. Highway Design Approach

The design of highway curves presents a similar design problem to the design of curves for rail vehicles. The design procedure for horizontal alignment is defined in the text as "A Policy on Geometric Design of Highways and Streets." This is a publication of the American Association of State Highway and Transportation Officials (AASHTO). The model for the highway approach is shown in Figure 11. The side friction factor is related to the concept of cant deficiency. The maximum side friction allowed is a function of the design speed and has been

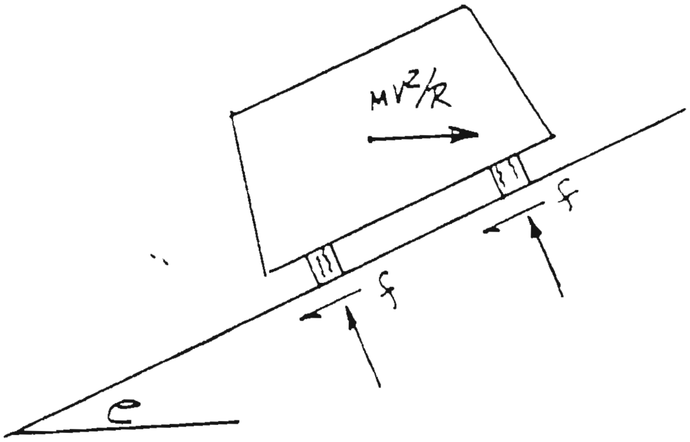


Figure 11. Side Friction Factor

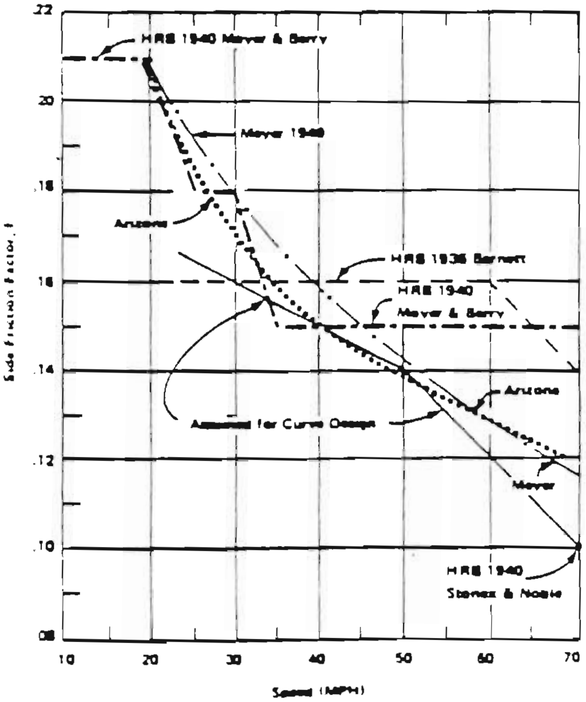


Figure 12. Side Friction Factor as a Function of Design Speed.

established based on driver feeling of discomfort due to lateral acceleration. Figure 12 shows the results of several studies to determine limiting values of side friction force. The first point to notice is that the allowable side friction force tends to decrease with increased speed. The curve marked "assumed for curve design" is used for the AASHTO design. The maximum design speed value shown is 70 mph, which corresponds to a level of .1 side friction factor. The side friction factor would be equal to the lateral acceleration measured in g's if an automobile did not roll during high speed curving. Including the roll of the vehicle, the estimated lateral acceleration corresponding to a side friction factor of .1 is 0.12 g's.

Highway agencies use a ball-bank indicator (see Figure 13) to check designs and to set safe speeds on curves. The ball-bank indicator consists of a curved sealed glass tube and steel ball. The ball rolls in the liquid filled tube which is marked in degrees. The ball-bank indicator measures the combined effects of carbody roll, centrifugal force and roadway superelevation. The ball-bank indicator reading and the amount of carbody roll are used to calculate the side friction factor.

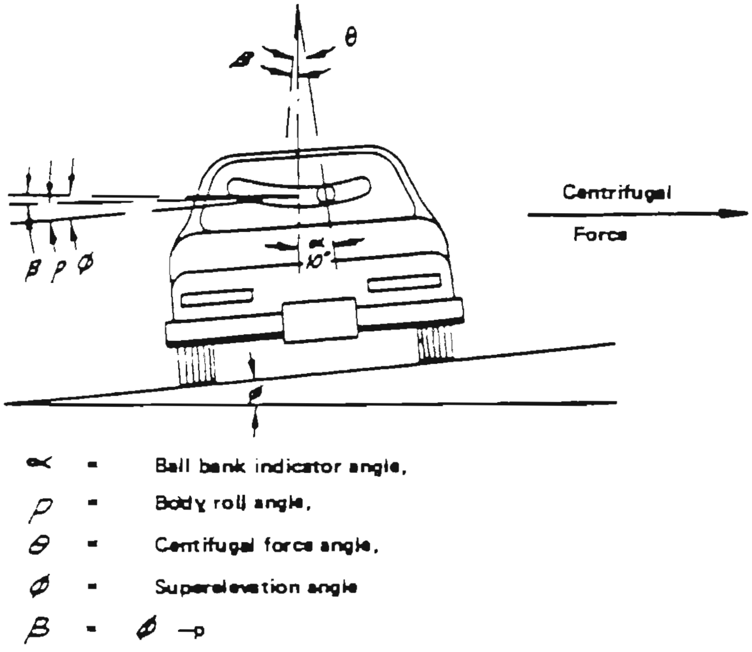


Figure 13. Ball-Bank Indicator.

Results of a series of experiments by Ritchie[18] are shown in Figure 14. In these experiments, drivers were allowed to determine their own limit of lateral acceleration.

E. Discussion of Ride Safety Criterion

A ride safety consideration should be based on providing an environment in which the passenger can move about the vehicle safely. A ride safety criteria must therefore take into consideration the ability of the passenger. Abilities of passengers are expected to vary greatly. The approach taken in this paper is based on an average "passenger" standing or walking. No special consideration is given for passengers with special difficulty maintaining their equilibrium. A passenger who has difficulty in maintaining equilibrium would be provided a safe environment by remaining in a seated position.

With the exception of the transit car experiments, the ride quality information available was developed in the context of ride comfort and perception and track maintenance. The perceptions of the cited automobile drivers also appear to be most influenced by the consequences of potential accidents since the acceptable lateral acceleration declines rapidly at highway speeds.

The ride safety issue should be kept distinct from the ride quality economic issues. Many passengers may prefer the ride quality of slower trains, and high cant deficiency curving may increase the costs of track maintenance. A legitimate ride safety requirement should protect the public from unconscionable risks. It should not casually prevent innovation in service by railroads even if some innovations are sure to be rejected by the public as poor tradeoffs between comfort and time saving.

Hirshfeld's transit car acceleration experiments offer an objective basis for considering ride safety criteria. He was concerned with longitudinal rather than lateral acceleration, and experiments with his subjects standing sideways correspond most

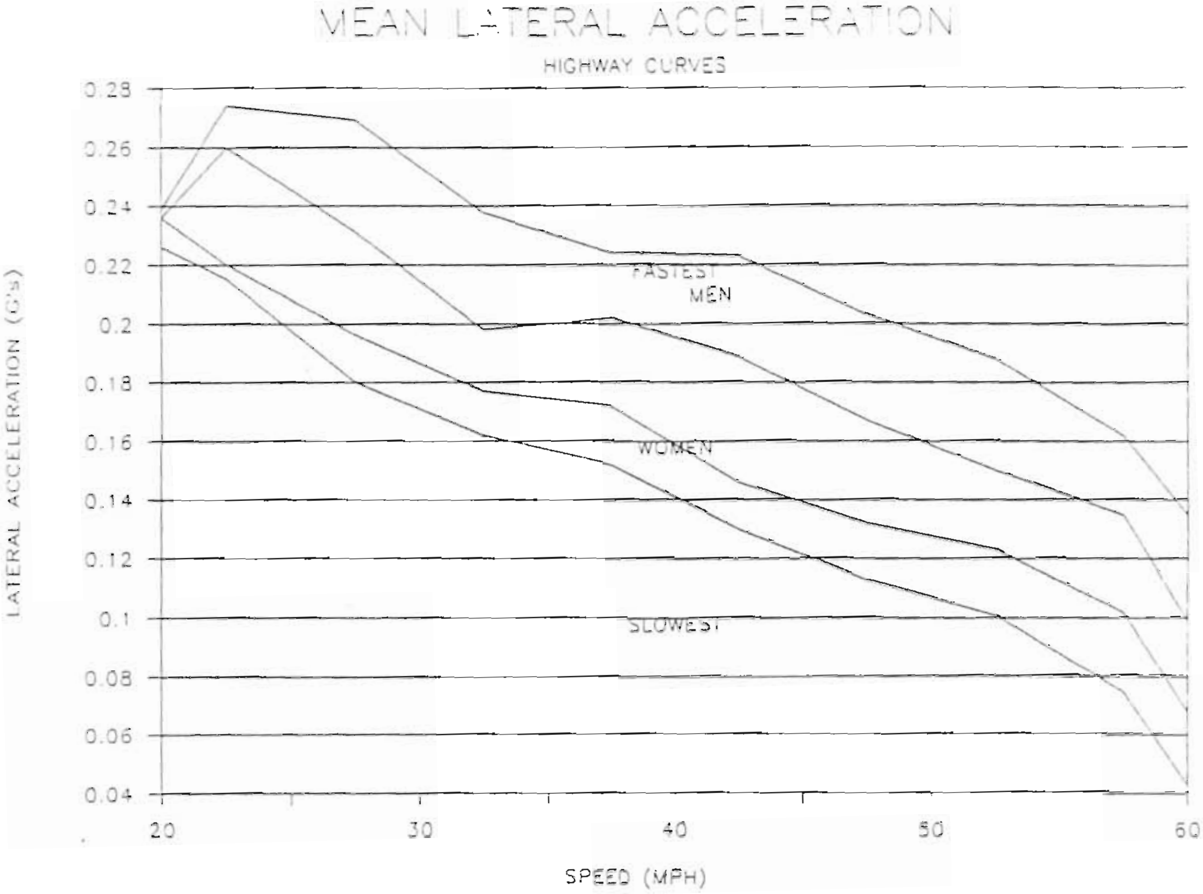


Figure 14. Results of Ritchie Experiment

closely with passengers passing through intercity cars in curves. His objective for determining loss of equilibrium was the subject's need to readjust the position of his feet. This is a vastly superior test criteria compared to asking subjects for a rating from 1 to 10, but it is very conservative in quantifying the danger of falling. The need to readjust foot position implies falling only in the case of a person whose agility is too impaired for normal movement, and the availability of a hand hold was shown to increase the ability to maintain standing equilibrium by about 50%.

The typical person at risk of falling in an intercity coach is walking in the aisle. Since the act of walking can be viewed as a series of losses of equilibrium, it is reasonable to expect that the foot movements and balancing feats necessary to walk naturally fulfill some of the requirements for regaining equilibrium in the presence of quasi-static lateral accelerations.

Figure 10 indicates that about half of the standing subjects in the transit car experiments would require moving their feet to regain balance at .15g quasi-static lateral acceleration if they were facing the low rail windows. About 40% of standing passengers facing the aisle would require movement to regain equilibrium because of the better <u>lateral</u> stability of a standing person. If these people were walking, it is likely (but speculative) that they would not require any further movement to avoid falling even without recourse to hand holds. It would appear, then, that most people could walk a straight line along the center of a car, empty of seats and luggage railings, curving at six inches cant deficiency. Of course, casual train riding experience tells the reader that this scenario is ridiculous. Even a healthy agile person would want to walk near the wall to brace himself against the irregular jolts he expects at most curves. If the car were parked on six inches crosslevel (causing the same steady state lateral acceleration) he would not fear walking along the center although he would feel awkward; but he would not take the risk in a moving car.

The point of describing the empty car example is to suggest that even elevated smooth steady state lateral accelerations do not pose as great a risk to passenger safety as the jolts encountered in service now. A definition of jolt and a comparison between recent ride quality measurements of the (French-built) Amtrak RTG train and the Hirshfeld acceleration spike experiments will be introduced to make the same point more scientifically. The .15g steady state example level was chosen to include the operation of most coaches at around 6 inches cant deficiency. A ride safety requirement below that level would have the effect of requiring tilt equipment for meaningful increases in cant deficiency. But if the jolts are a greater safety concern than steady state acceleration, ride safety would not justify favoring tilt equipment at moderate levels of cant deficiency. If jolts are the issue, a jolt criterion should be presented directly. Tilt equipment has no inherent advantage in protecting passengers against jolt, and jolts have the potential to cause control difficulties in tilt equipment. However, at very high cant deficiency the lower steady state lateral acceleration provided by a tilt coach may be required to enable passengers to endure the additional jolts at perturbations.

On a very smooth curve, the lateral acceleration would build up slowly (at a spiral jerk rate of .03 g/sec to .05 g/sec under present ride quality standards) and remain constant in the body of the curve. The smooth increase warns the walking or standing passenger to assume a stable posture. An agile person would merely increase the distance between his feet slightly to improve balance and a feeble person would find adequate stability by using a hand hold. A ride safety requirement limiting steady state lateral acceleration below .15 g is not recommended in view of the ease of passengers in adjusting themselves, if necessary, to curving events of short duration. The most serious effect of elevated steady state lateral acceleration may be to make it more difficult for passengers to endure additional unexpected jolts, but a jolt criterion is the proper mechanism to address jolts.

The term 'jerk' is reserved to mean the low frequency (approx. 0.1 Hz) build up of acceleration in spirals, and it has been referred to in this study as spiral jerk to avoid ambiguity. The Hirshfeld experiments indicate that spiral jerk is not a ride safety issue for track designed to the conventional 3 inch cant deficiency rules even for trains running at higher cant deficiency. Hirshfeld considered accelerations increasing at greater than 0.1 g/sec to adequately represent steady states, and the responses of the human subjects were relatively invariant between .01 g/sec and .1 g/sec. No ride safety criterion is required for spiral jerk.

Hirshfeld measured the effect of "negative" acceleration spikes in his "method J" tests, and this paper attempts to apply his findings to spikes in lateral acceleration at curve perturbations. Spikes in the body of the curve are usually "positive" and result in about a 25% overshoot on the trailing edge. The increasing and decreasing slopes of lateral acceleration jolts have about the same time duration as the Hirshfeld experiments (figure 9), and they roughly approximate the mirror image of the Hirshfeld experiment. Spikes at the exit of curves are frequently more oscillatory and have a larger time duration. Tables 12 and 13 present the measurements of steady state and peak accelerations and acceleration spikes, occurring in the RTG power car running at between 3 to 6 inches cant deficiency between Boston, MA and New Haven, CT.

Hirshfeld referred to the acceleration spikes in his experiment as 'jerks', contributing to the ambiguity of that term. The term jolt has been adopted in this paper to mean higher frequency (approx. 2 Hz) perturbation "jerks." Tables 12 and 13 describe jolts encountered on a typical high speed passenger route in terms of a rate of change of acceleration with a time duration and also as a peak to peak measurement. Except for the occasional oscillatory acceleration trace at spirals, most of the acceleration spikes had durations between .2 and .3 sec. Hirshfeld noted that spikes with smaller time durations

Table 12

Lateral Acceleration in Westbound Curves, NEC Boston-New Haven Measured in RTG Train at 3 to 6 Inches Cant Deficiency

Westbound Curve No.	Lateral Acceleration g's Steady State	Lateral Acceleration g's Peak	Jolt Peak-Peak g's	Slope of Jolt g's/sec	Jolt Duration sec	Subjective Characterization
24	.13	.20	.14	.50	.20	Average
25	.14	.22	.19	1.00	.15	Average
26	.11	.28	.28	1.40	.20	Harsh
45	.07	.15	.18	.45	.40	Rough
46	.11	.18	.08	.40	.20	Smooth
50	.11	.25	.25	1.00	.25	Harsh
52*	.11	.38	.38	1.90	.20	Very Harsh
53	.08	.14	.10	.25	.40	Average
66	.13	.17	.10	.66	.15	Smooth
70	.12	.18	.10	.66	.15	Smooth
71	.11	.16	.10	.12	.80	Smooth
72	.14	.21	.17	.85	.20	Average
73	.12	.18	.09	.45	.20	Smooth
79	.15	.25	.19	1.30	.15	Rough
86	.14	.22	.26	.50	.50	Harsh Exit
88	.10	.18	.12	.60	.20	Average
90	.10	.16	.08	.28	.30	Very Smooth
100	.12	.16	.10	.40	.25	Very Smooth
101	.14	.26	.14	.70	.20	Rough
106	.12	.18	.10	.10	.10	Very Smooth
107	.10	.20	.10	1.00	.20	Rough
109	.08	.23	.21	1.40	.15	Harsh
110	.12	.19	.12	.60	.20	Smooth
111	.08	.14	.10	.40	.25	Average
113	.12	.20	.15	.30	.45	Average
115	.09	.16	.16	.30	.50	Average
120	.15	.25	.22	1.10	.20	Rough
126	.13	.24	.18	.90	.20	Rough
127	.11	.20	.14	.50	.30	Average
134	.12	.18	.11	.45	.25	Average
137	.13	.27	.28	1.40	.20	Harsh
141	.13	.16	.07	.35	.20	Very Smooth
142	.12	.18	.14	.35	.40	Rough

*Limited by estimated transient wheel unloading

Table 13

Lateral Acceleration in Eastbound Curves, NEC New Haven-Boston Measured on RTG Train at 3 to 6 Inches Cant Deficiency

Eastbound Curve No.	Lateral Acceleration g's Steady State	Lateral Acceleration g's Peak	Jolt Peak-Peak g's	Slope of Jolt g's/sec	Jolt Duration sec	Subjective Characterization
143	.14	.21	.13	.35	.40	Average
142	.12	.20	.26	.52	.50	Harsh
141	.12	.18	.12	.60	.20	Average
137*	.14	.34	.37	1.50	.25	Very Harsh
134	.14	.24	.20	.50	.40	Rough
127	.14	.24	.26	.52	.50	Rough
126	.12	.30	.24	1.20	.20	Harsh
122	.14	.30	.25	1.00	.20	Harsh
121	.12	.24	.20	1.00	.20	Rough
120	.15	.20	.10	.33	.30	Smooth
118*	.14	.38	.38	1.90	.20	Very Harsh
116	.12	.18	.18	.90	.20	Average
113	.12	.21	.18	.90	.20	Average
112	.12	.26	.26	1.30	.20	Harsh
111	.12	.20	.15	.60	.25	Average
110	.10	.18	.13	.52	.25	Average
109	.12	.22	.20	1.00	.20	Rough
108	.12	.18	.10	.50	.20	Smooth
107	.10	.18	.16	1.00	.15	Average
106	.11	.17	.13	.43	.30	Smooth
105*	.12	.38	.40	2.00	.20	Very Harsh
101	.14	.30	.29	.60	.50	Very Harsh
100	.10	.19	.13	.40	.25	Smooth
98	.14	.30	.25	1.25	.20	Harsh
75	.13	.22	.17	.85	.20	Average
71	.10	.28	.24	.98	.25	Rough
70	.14	.29	.30	1.50	.20	Harsh
68	.11	.20	.15	.50	.30	Average
67*	.13	.33	.32	1.10	.30	Harsh
66	.10	.14	.08	.41	.20	Smooth
64	.11	.17	.22	.44	.50	Average
63	.10	.30	.30	1.00	.30	Harsh
52*	.11	.54	.49	2.45	.20	Very Harsh
50	.11	.22	.22	.70	.30	Rough
46	.12	.16	.08	.40	.20	Very Smooth
37	.08	.12	.06	.30	.20	Very Smooth
28	.11	.18	.14	.94	.15	Average
26	.10	.16	.08	.40	.20	Very Smooth
24	.09	.15	.08	.20	.40	Very Smooth

*Limited by estimated transient wheel unloading.

than he used would cause less disturbance to passengers, but the results in table 10 were generated with a spike duration typical also of curving perturbations. It should also be assumed that a person facing the direction of the aisle would maintain equilibrium at about 15% greater accelerations than shown in table 10 because a person is more stable under lateral than longitudinal acceleration. The peak to peak measurement will be taken as the standard unit of jolt because it is the most convenient measurement, because it includes the effects of both rate and duration and because it allows a comparison with Hirshfeld's experimental results.

A subjective characterization of the acceleration traces of each curve is also given in tables 12 and 13. The subjective characterization generally relates to the degree of geometric perfection of the curve as experienced by the car. Very smooth curves contained no perturbations which disturbed the measured car while very harsh curves contained perturbations causing abrupt significant lateral motions of the carbody. Curves rated as average were typical of the route.

Allowing for the 15% advantage in taking lateral jolts, table 10 indicates that 80% of passengers would lose equilibrium at a 0.14g jolt and all the passengers would lose equilibrium at a 0.16g jolt. Jolts of this magnitude are considered only slightly above average for the RTG train at 3 to 6 inches cant deficiency. Even at lower cant deficiency they would not be unusual. The steady state accelerations in the same curves would cause fewer than 40% of the passengers to lose equilibrium. Two conclusions can be drawn: a) passengers already rely on hand holds to negotiate the aisles because of jolts and b) the jolts pose a greater hazard to ride safety than do steady state acceleration levels.

Amtrak's current ride quality inspections use peak to peak lateral acceleration measurements at 10 Hz (tables 11 and 12 are 12 Hz measurements) to detect track perturbations. Peak to Peak jolts of .25g are considered unacceptable. The Hirshfeld experiments indicate that even a passenger with a hand hold would experience difficulty maintaining equilibrium at jolts that severe. The .25g jolt level, superimposed on steady state lateral accelerations up to 0.1g, represents the most severe present ride safety condition, and it appears to reflect a boundary in ride safety that should be maintained despite increases in cant deficiency. In order to maintain the minimum present level of ride safety, which includes circumstances requiring standing passengers to maintain a firm hand hold, it is obvious that jolts should be limited as steady state lateral accelerations are increased. Since there are no objective test results which relate the additive effects of jolt and steady state lateral acceleration, a common sense rule will be proposed.

Combinations of steady lateral acceleration and jolt which result in the same peak will be assumed to have equivalent ride safety for the purpose of estimating appropriate jolt limits for curving at greater than .1g steady state lateral acceleration. In order to adjust the jolt level to maintain constant peak lateral accelerations while increasing the steady state lateral acceleration, the shape of a typical jolt acceleration pattern must be assumed. A typical jolt will be assumed (based on observations of test data) to have three-fourths of its peak-to-peak magnitude directed in the same sense as the steady state acceleration upon which it is superimposed. Figure 15 illustrates equivalent combinations of steady state accelerations and jolts. The resulting rule of thumb relating eqivalent combinations of steady state acceleration and jolt is:

$$\text{Steady State } 1 + 3/4\ (\text{jolt } 1) = \text{Steady State } 2 + 3/4\ (\text{jolt } 2)$$

In order to maintain steady state and jolt combinations equivalent to .25g jolts at .1g steady state, the rule indicates:

$$.1g + 3/4(.25g) = .288 = \text{Steady State} + 3/4 \text{ jolt}$$

EQUIVALENT COMBINATIONS OF STEADY STATE LATERAL ACCELERATION AND JOLT

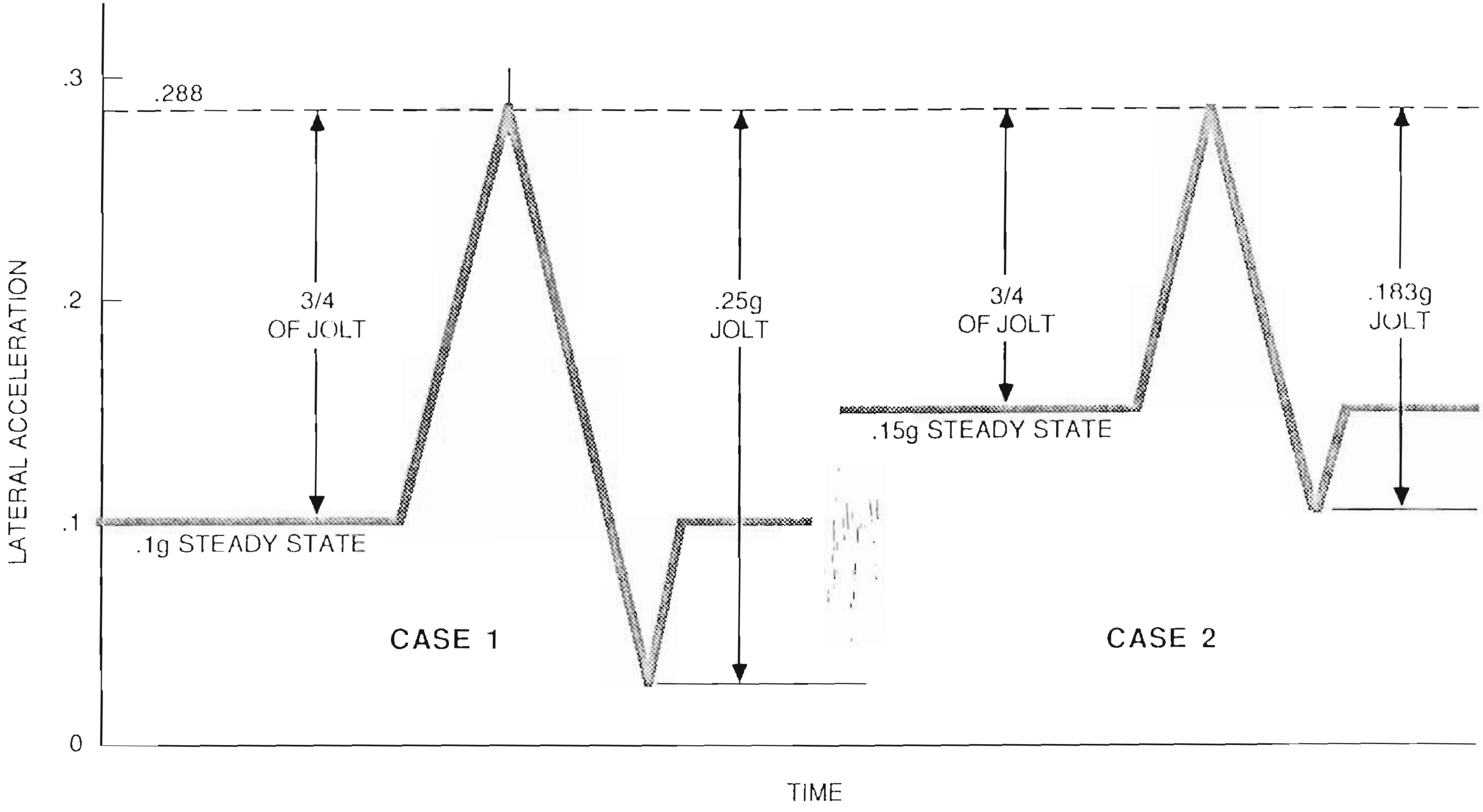


Figure 15

and the equivalent jolt at .15g steady state lateral acceleration is:

$$\text{Jolt} = 4/3\ (.288-.15) = .183\text{g}$$

Figure 16 presents a recommended ride <u>safety</u> criterion which balances jolt and steady state lateral acceleration to maintain today's minimum ride safety conditions while allowing for higher cant deficiencies. It uses the above rule of thumb equation to adjust jolt for higher lateral acceleration. The criterion would be used to evaluate 10 hz accelerometer data measured on the floor near the truck center pin. Steady state and jolt levels may be determined independently. The distribution of the jolt excursion about the steady state level in figure 15 was assumed to be typical in formulating a rule of thumb, but the criterion does not require the jolts to match this pattern. A separate criterion for peak acceleration is required because the extreme points of the jolt can vary with respect to the steady state level for actual measurements.

During the ride quality test of the RTG train an effort was made to use accelerometer data to estimate lateral load transfer for comparison to the vehicle overturning criteria. A simple steady state curving model (refernce 1) was used to determine the steady state relationship between weight vector intercept from peak lateral acceleration. The same relationship was used to estimate the peak weight vector intercept from peak lateral accelerations. The relationship is not exact because of certain dynamic effects including the mechanical filtering of the car suspension, but it was hoped that the estimate would err on the conservative side. Tables 11 and 12 show that several curves were marked for speed restrictions from a six inch cant deficiency schedule because the transient WVI limit of 18.6 inches (for that particular car) was estimated to be equivalent to .33g peak lateral acceleration. As mentioned earlier in this

RECOMMENDED RIDE SAFETY CRITERIA

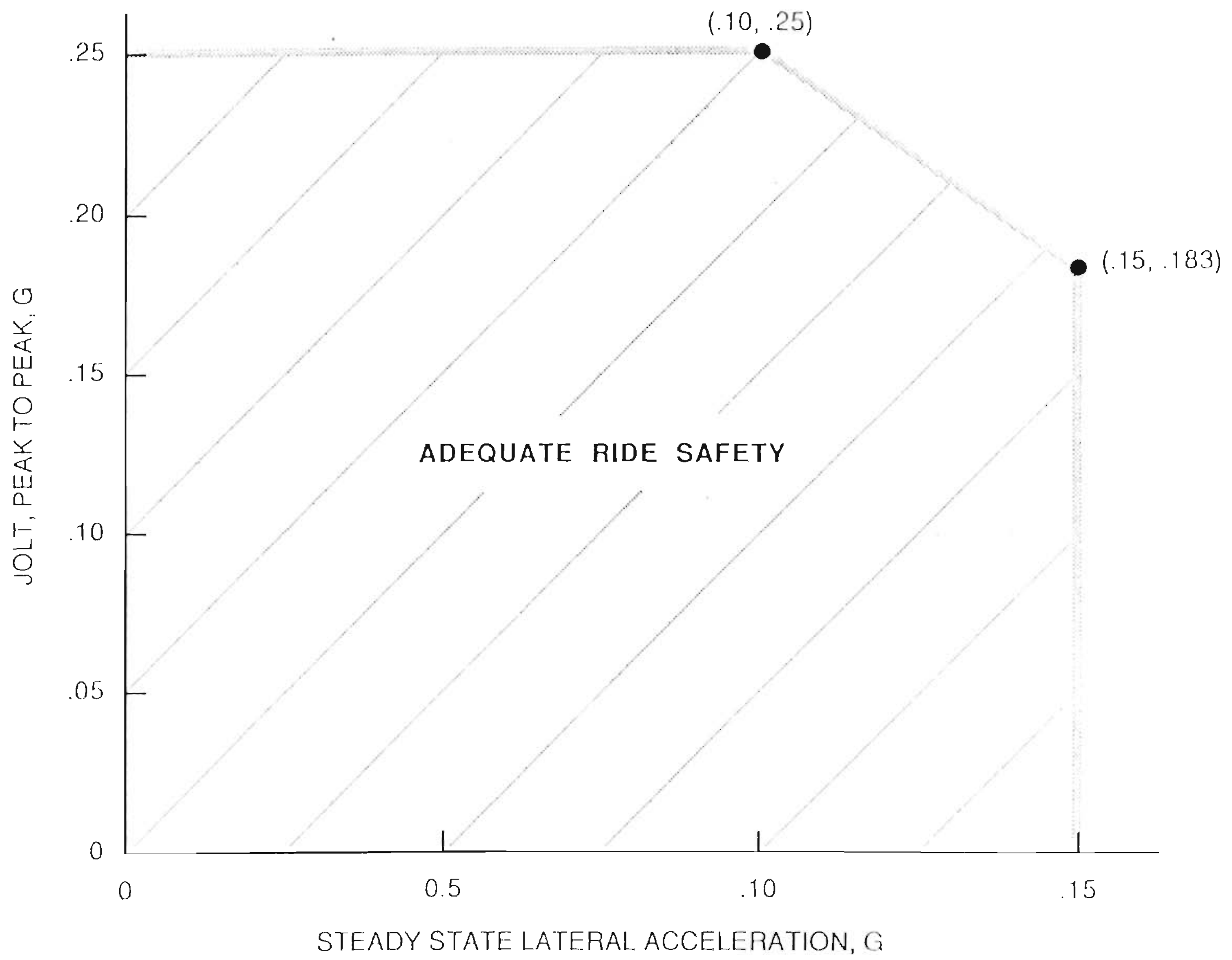


Figure 16

paper a .15g steady state lateral acceleration limit (allowing at least six inches cant deficiency) was more restrictive for all of the non-banking vehicles during the LRC test when the WVI was actually measured with instrumented wheels in the same test zone as the RTG test. Since the estimated peak weight vector intercepts for the RTG were higher than the actual measured WVI's for similar vehicles tested in the past on the same route we can conclude that either the estimation method errs on the conservative side or the test zone has deteriorated substantially since 1980. The first conclusion is more likely since the trend has been toward track improvement in the past decade.

The ride <u>safety</u> recommendations may be summarized as follows:

a) Steady state lateral accelerations up to .15g should not be considered hazardous unless accompanied by strong jolts.

b) No ride safety restriction on spiral jerk is required because track design considerations are more restrictive than human factors, assuming that a spiral jerk rate of .1g/sec greatly exceeds practical track layout limits.

c) Jolt, measured as a peak to peak excursion of lateral acceleration within a one second window, should be limited to .25g during steady state lateral accelerations up to .1 g. It should be further restricted for higher steady state lateral accelerations as indicated in figure 16.

d) The peak lateral acceleration should be limited to the value estimated as equivalent to the transient weight vector limit for overturning safety. The limit of peak lateral acceleration should be considered .3g unless the characteristics of the particular vehicle justify a higher acceleration equivalence estimate of the critical transient WVI. The lower speed as determined by recommendations c) or d) should be observed.

e) Since curving safety is dependent on the perturbations particular to each curve, a periodic acceleration measurement at full scheduled speed should be conducted on a route chosen for high cant deficiency operation. Bimonthly inspections for the first two months are recommended to quickly create a historical database of four repetitions. Unless rapid changes are indicated by the historical database, monthly inspection intervals should be adapted and used to maintain the database of track condition.

f) Cant deficiency increases rapidly with speed. Tighter controls on overspeed should be adopted for trains operating nearer the safety limit.

g) Convenient hand holds for walking passengers should be recognized as necessary for present conditions and receive more design attention in high cant deficiency vehicles.

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APPENDIX A

Discussion of Relevant Data from CONEG/AMTRAK Passenger Train Evaluation.

The passenger ride safety recommendations made in the main body of the report were based foremost on the authors' interpretation of laboratory experiments measuring human responses to various types of floor accelerations, which had been performed for the transit car community fifty years ago. Other less directly applicable information in the transportation ride quality literature and the personal observations of the authors, who have ridden many vehicles equipped with floor accelerometers during vehicle dynamics testing, were also considered in forming the proposed ride safety envelope in figure 16. Railroad passenger ride safety was viewed as acceptable as long as a normal healthy passenger could be expected to walk the aisle without unreasonable risk of falling while using handholds or seat backs for bracing.

The principal influences on ride safety in curves are the steady state lateral acceleration and the random acceleration spikes frequently encountered. The term jolt has been defined in this paper to represent the random acceleration spikes. It is defined as the maximum peak to peak acceleration span within a 1 second interval when the acceleration signal has been filtered at 10Hz with a 4 pole low pass filter. The ride safety envelope is a device to combine the effects of the predictable steady state lateral acceleration due to curving above the balance speed with the random jolts due to track irregularities and other vehicle/ track interactions. At the time the ride safety envelope was proposed, there was very little information available to relate it to the performance of contemporary vehicles. There was no organized body of data with which to test the indicated ride safety envelope against the floor accelerations typical of today's rail travel. And there was no way to estimate quantitatively the impact of increased operating cant deficiency on ride safety. In the spring and fall of 1988 Amtrak[1] performed evaluation tests of several conventional and tilting trains in response to the Coalition of Northeast Governors (CONEG). This appendix has been added to the original paper to provide a valuable context of acceleration measurements directly related to the consideration of ride safety. The steady state lateral accelerations and jolts were measured over a wide range of cant deficiency at many curves between Boston and New Haven. In addition the Federal Railroad Administration[2] (FRA) conducted passenger ride evaluations during selected test runs. Subjective discomfort ratings by a group of 60 to 80 passengers were collected at the same curves for which accelerometer measurements were recorded.

The data at thirty-three curves in the Boston-New Haven test zone was chosen as the best representation of the comparative ride comfort performance of the five test trains. The curves were situated so that cant deficiencies over six inches were usually attainable within the acceleration, braking and speed capabilities of all the test trains. The sample was composed of about equal numbers of smooth, rough and intermediate curves based on the jolt measurements. Regression lines relating steady state lateral acceleration to cant deficiency and jolt to cant deficiency were computed for each curve. Combinations of steady state lateral acceleration and jolt were taken from the regression lines at exact cant deficiencies of 2,4,6 and

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[1] CONEG/AMTRAK Evaluation of Tilt and Turbo Technologies, January 1989, Amtrak report to CONEG (Coalition of Northeastern Governors)

[2] Passenger Evaluation of Tilt and Turbo Train Ride, February 1989, FRA report to CONEG.

8 inches. The regression line data was used in the Amtrak report so that the various trains could be compared at exactly the same cant deficiency although the test cant deficiencies varied somewhat between comparative tests.

Figures A1 through A5 are taken from the cited Amtrak Report. Figure A1 compares the combined steady state and jolt acceleration performance of the Amcoach to the proposed ride safety envelope. The accelerations from the regression lines at exact cant deficiencies of 2,4,6 and 8 inches are shown for the 33 principal test curves. The Amcoach had floor accelerations below the threshold for every curve at 2 inches cant deficiency and for all but one curve at 4 inches cant deficiency. This is a significant observation which suggests that the current ride of Amcoach passengers satisfies the ride safety envelope. The observation is reinforced by noting that test curve population included a higher percentage (36%) of rough curves than would be expected on a usual route. The rough curves frequently include special features such as grade crossings, bridges and switches which cause track geometry maintenance difficulties. Figure A1 also indicates that the Amcoach satisfies the proposed ride safety envelope at almost 90% of the curves while operating at 6 inches cant deficiency. Clearly a conventional coach such as the Amcoach can be expected to provide adequate ride safety at 6 inches cant deficiency at most curves. Extra maintenance at isolated trouble spots or speed restrictions would be required on a small percentage of the curves. At eight inches cant deficiency, however, the accelerations at most curves fall outside the proposed ride safety envelope.

Figure A2 shows similar data for the RTL Turbo Coach. It has conventional non-tilting suspension, but it is a gas turbine powered locomotive with coach accommodations and an idler truck in its rear half. Its ride accelerations also

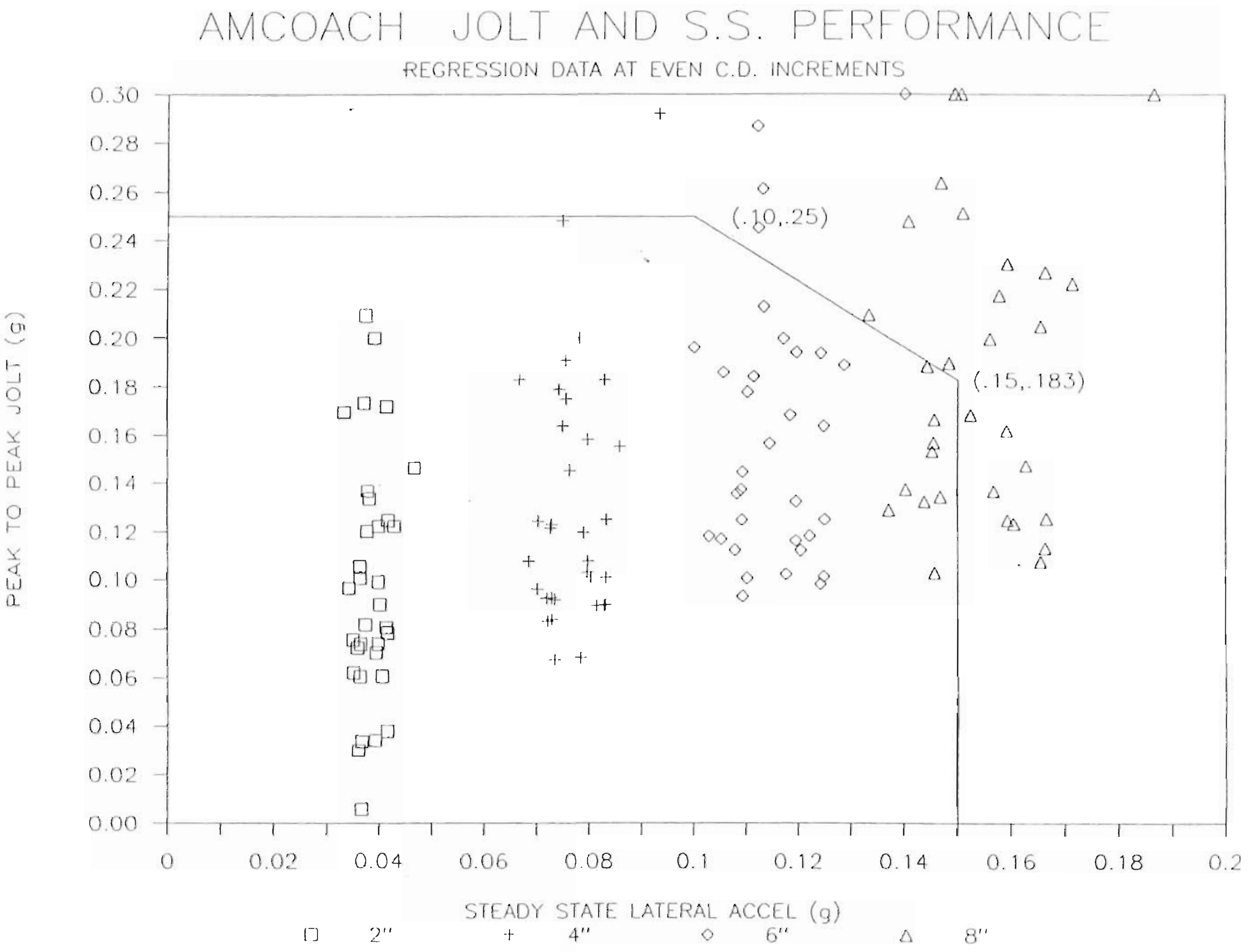

AMCOACH JOLT AND S.S. PERFORMANCE
REGRESSION DATA AT EVEN C.D. INCREMENTS
PEAK TO PEAK JOLT (g)
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
STEADY STATE LATERAL ACCEL (g)
(.10,.25)
(.15,.183)
□ 2″
+ 4″
◇ 6″
△ 8″

Figure A1

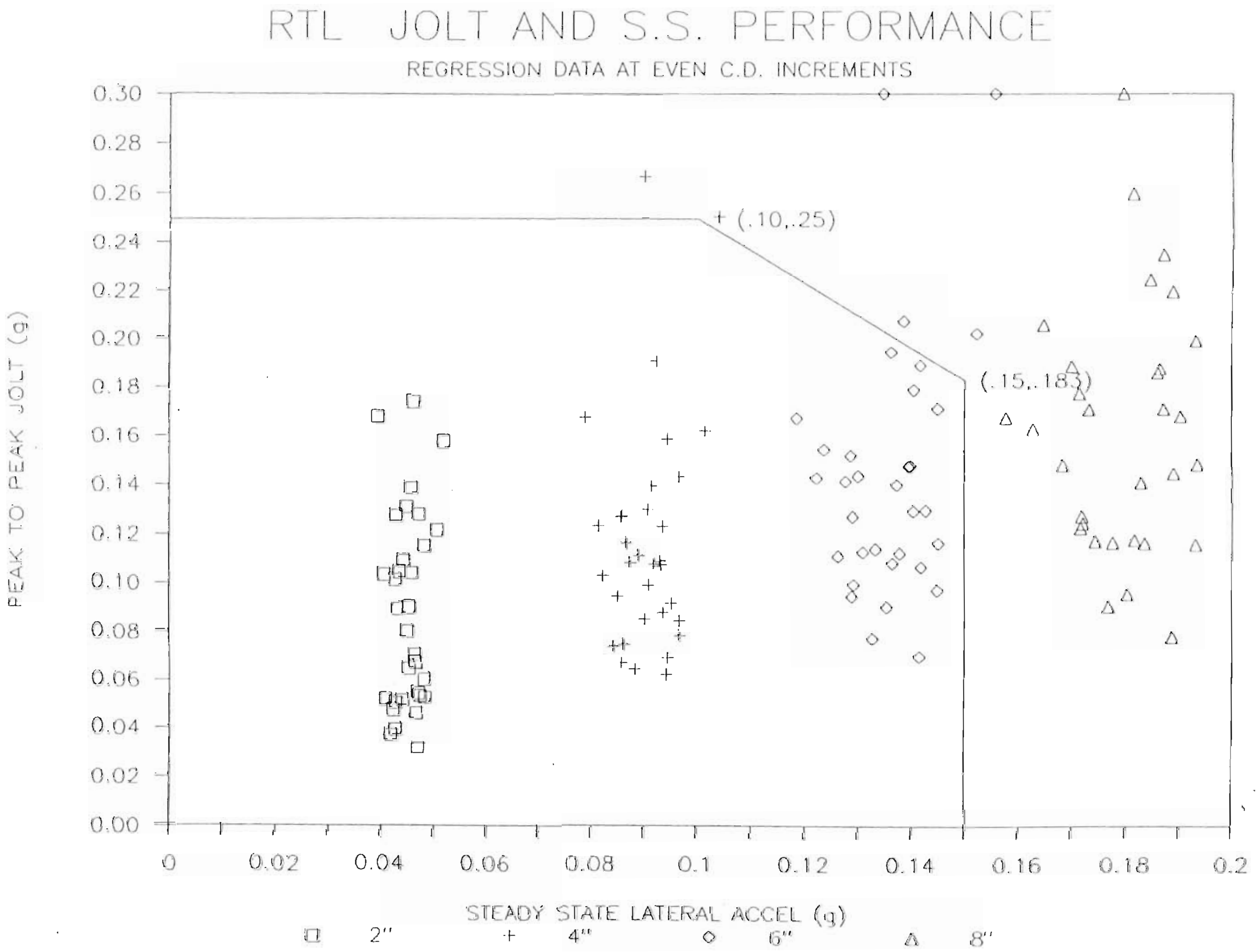

RTL JOLT AND S.S. PERFORMANCE
REGRESSION DATA AT EVEN C.D. INCREMENTS
PEAK TO PEAK JOLT (g)
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
(.10,.25)
(.15,.183)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
STEADY STATE LATERAL ACCEL (g)
□ 2"
+ 4"
◇ 6"
△ 8"

Figure A2

fall within the envelope for operation up to six inches cant deficiency at almost 90% of the sample of test curves. Operation at eight inches cant deficiency would be expected to always produce accelerations outside the hypothetical limit.

The measurements of the Amcoach and RTL Turbo Coach demonstrate that non-tilt equipment can satisfy the proposed ride safety limits for routine curving at 6 inches cant deficiency, but some conventional cars would not satisfy these limits. The RTG Turbo Coach is similar to the RTL Turbo Coach previously discussed. However, figure A3 shows that it experiences higher jolt accelerations at the same curves. It exceeded the hypothetical ride safety limits at about 40% of the sample of test curves at 6 inches cant deficiency, but its performance at 4 inches cant deficiency was comparable to the other conventional test vehicles. Since the RTG is so closely related to the RTL in design, it is unclear how much of the difference was vehicle specific.

Two types of tilt coaches were also tested during the CONEG/AMTRAK evaluation. The Talgo Coach used a pendular suspension in which conventional air springs supported the car body near the ceiling rather than near the floor. Having the body roll center above the center of gravity caused the body to sway in curves in a direction opposite to that of a conventional car. The body roll achieved in this way reduces the steady state lateral accelerations but does not eliminate it. The LRC Coach uses an active suspension to roll the body to a greater degree to eliminate steady state lateral acceleration, but the active suspension produces transitional states of higher lateral acceleration when it recognized the beginning and end of a curve. Figure A4 shows that the passive tilt Talgo Coach reduces the steady state lateral acceleration at eight inches cant deficiency to well below the boundary of the proposed ride

RTG JOLT AND S.S. PERFORMANCE

REGRESSION DATA AT EVEN C.D. INCREMENTS

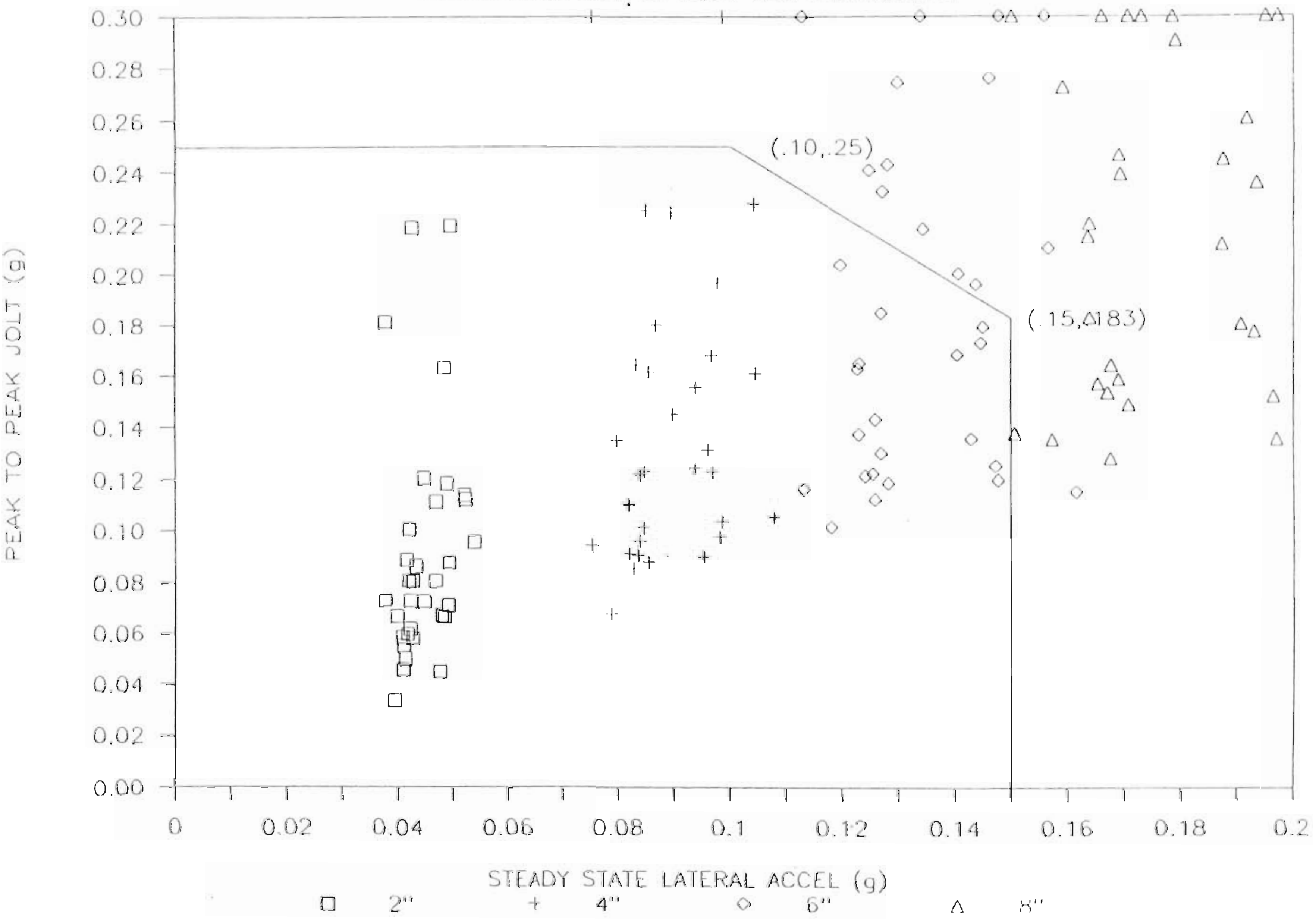


Figure A3

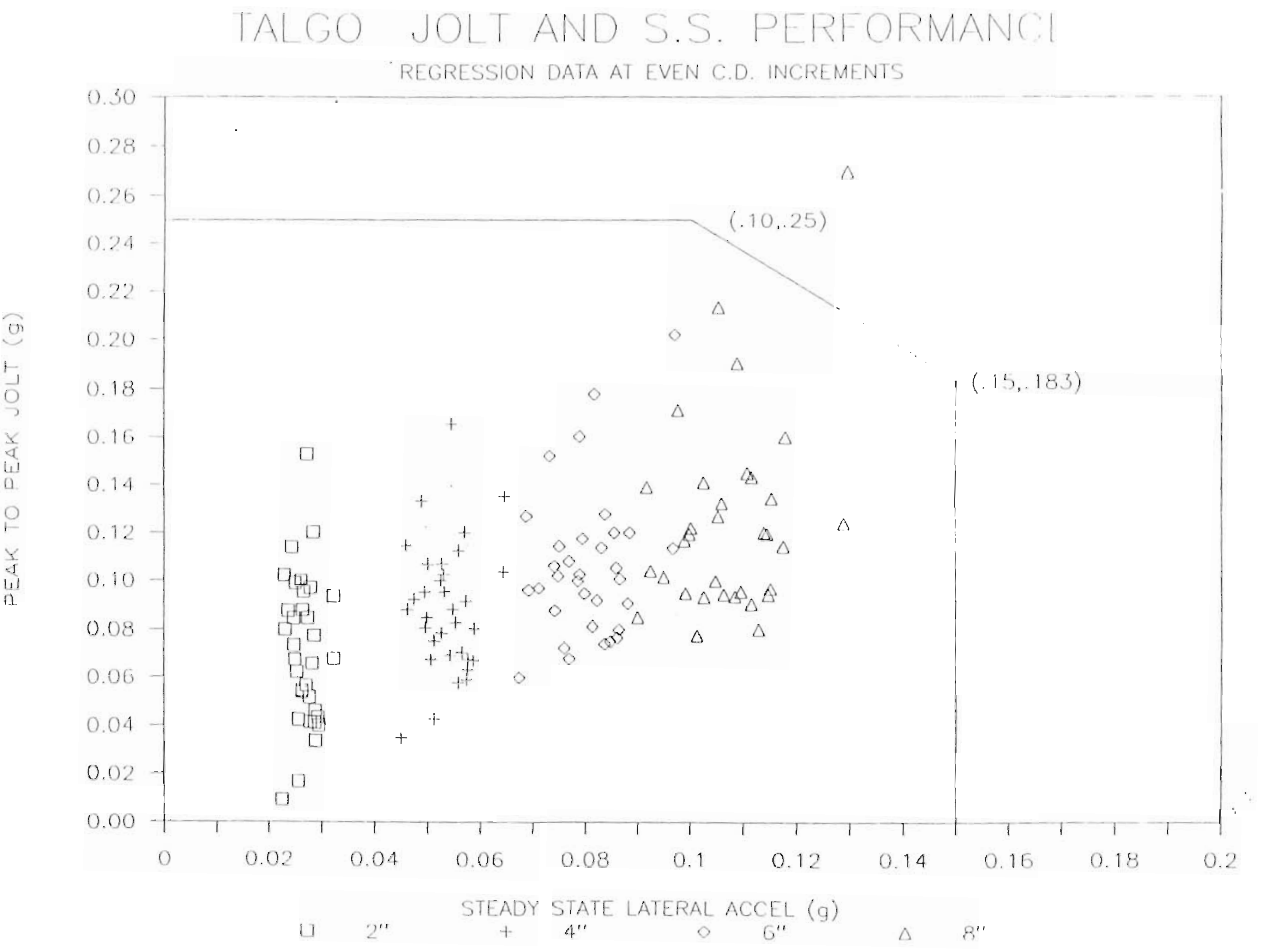

TALGO JOLT AND S.S. PERFORMANC
REGRESSION DATA AT EVEN C.D. INCREMENTS
PEAK TO PEAK JOLT (g)
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
(.10,.25)
(.15,.183)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
STEADY STATE LATERAL ACCEL (g)
□ 2''
+ 4''
◇ 6''
△ 8''

Figure A4

safety envelope. Its jolt measurements were also below the ride safety threshold for 97% of the sample curves at 8 inches cant deficiency.

The steady state and jolt acceleration data for the LRC Coach is shown in figure A5. The data points do not fall in distinct cant deficiency clusters because the active tilt system acts to eliminate the steady state lateral acceleration throughout the test cant deficiency range. Since the steady state lateral acceleration was kept very low by the tilt system, a high jolt acceleration is the only way an LRC acceleration measurement can fall outside the proposed ride safety envelope. The entry and exit transition accelerations are not described by the ride safety envelope unless they appear as the dominant jolt. The jolt measurements of the LRC were within the envelope for 94% of the sample curves at 8 inches cant deficiency. Both tilt vehicles were able to maintain floor accelerations within the proposed ride safety envelope efficiently enough for travel at 8 inches cant deficiency. Indeed, both tilt vehicles would probably exhibit adequate ride safety at cant deficiencies high enough to produce wheel lift. Good conventional vehicles would probably be cant deficiency limited by the proposed ride safety envelope rather than by wheel lift or other derailment hazards. Conventional vehicles would be expected to provide adequate ride safety up to six inches cant deficiency on curves without significant perturbations. However the ride safety envelope may impose a lower cant deficiency limit even for some modern conventional vehicles.

The passenger ride evaluations performed by FRA during the CONEG/AMTRAK testing were graded in terms of a discomfort index. The index represents the percentage of passengers experiencing discomfort with extra weighting for reports of intense discomfort. Most the evaluations were from seated

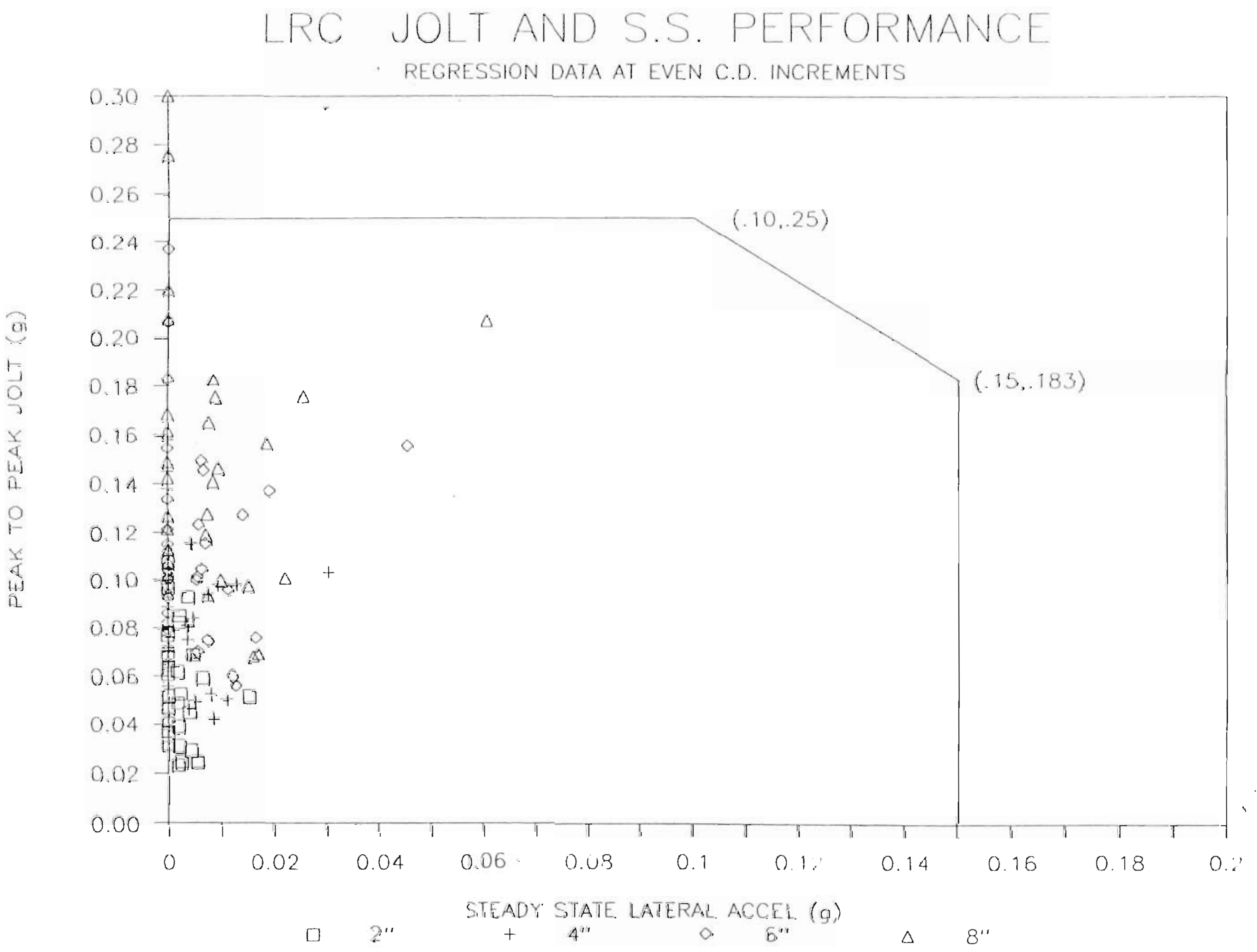

LRC JOLT AND S.S. PERFORMANCE
REGRESSION DATA AT EVEN C.D. INCREMENTS
PEAK TO PEAK JOLT (g)
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
(.10,.25)
(.15,.183)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
STEADY STATE LATERAL ACCEL (g)
□ 2"
+ 4"
◇ 6"
△ 8"

Figure A5

passengers but there were standing passengers during part of the test. The report does not separate the response of standing and seated passengers.

It would be expected that the same floor accelerations predicted to cause walking passengers to loose balance would be reported as occasions of discomfort by seated passengers. The FRA report shows that there is a general correspondence between a discomfort index of 15% and the predicted ride safety bounds, but on a curve by curve basis the correlation is tenuous. Figures A6 and A7 are taken from cited FRA report. Figure 6A shows that the discomfort index increases directly with steady state lateral acceleration even when the jolts are low. When higher jolts occur along with a given steady state lateral acceleration the discomfort index increases. The relative increase in the discomfort index due to jolts appears to greater at higher levels of steady state lateral acceleration. This trend is consistent with the clipped upper right corner of the proposed ride safety envelope, but it could also occur if the average high jolt (greater than .10g) coincident with steady state lateral accelerations of .11g and greater is considerably greater than the high level jolts coincident with lower steady state lateral accelerations. The discomfort index reached about 15% at steady state lateral accelerations over .11g accompanied by higher level jolts and at steady state lateral accelerations over .15g with low jolts. These conditions correspond to two of the boundaries of the proposed ride safety envelope.

The discomfort index appears to less sensitive to jolts than the proposed ride safety envelope. The FRA paper includes the following linear regression equation relating the discomfort index to the steady state and jolt acceleration measurements:

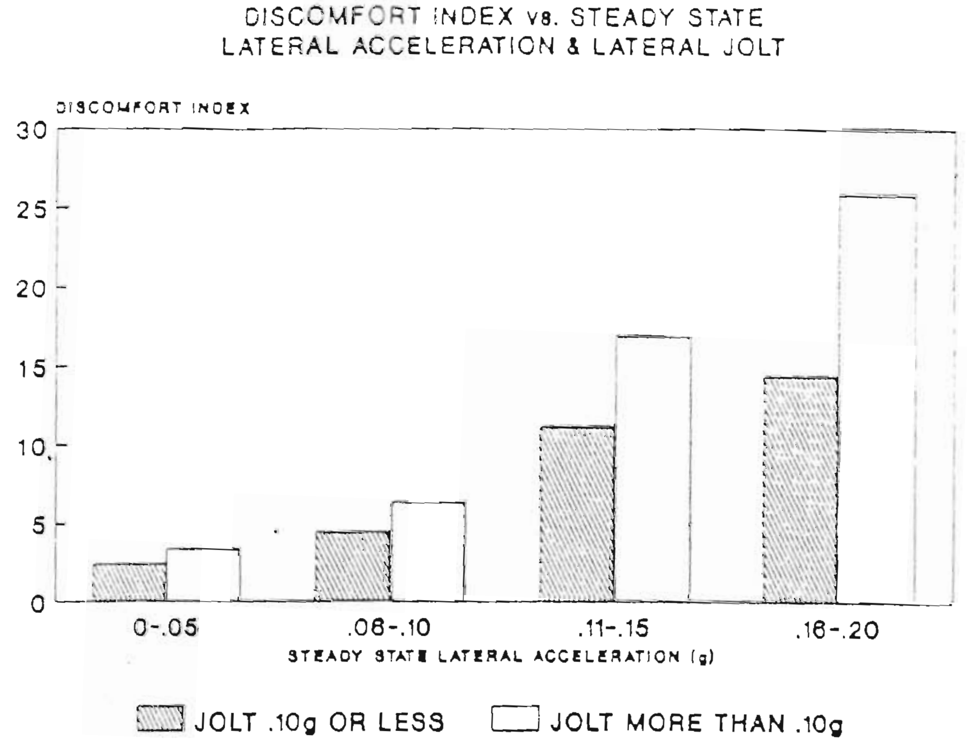
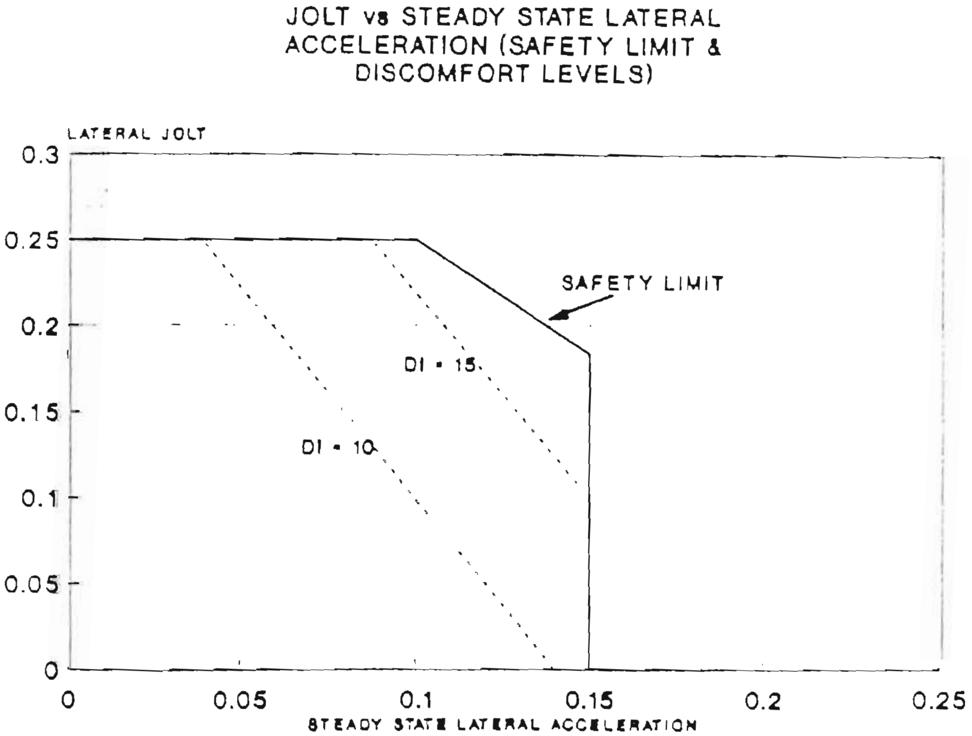


Figure A6



DI = DISCOMFORT INDEX
SAFETY LIMIT PROPOSED BY OWINGS & BOYD

Figure A7

$$DI = -5 + 104(s) + 44(j)$$

where: s is steady state lateral acceleration in g's
j is jolt in g's.

The steady state lateral acceleration has the greater influence on the discomfort index while the proposed ride safety envelope was based on the premise that high jolts are the primary cause of walking passengers loosing balance. The lower sensitivity of the discomfort index to jolts may reflect the differing perceptions of seated versus standing passengers.

Figure A7 superimposes the 10% and 15% lines of constant discomfort index, computed from the above equation, on the proposed ride safety envelope. Discomfort index values over 15% are associated with high cant deficiency ride environments near the ride safety limit. Tables A1 through A5 combine the Amtrak data at exact cant deficiencies plotted in Figures A1 through A5 with the Discomfort Index reported by the CONEG passengers at each curve and the actual cant deficiency and acceleration measurements during the passenger test. The "rough" and "smooth" curves are grouped to study the effect of jolts on the Discomfort Index. The average jolt was substantially higher at the rough curve group for each train. The discomfort index was also higher but not by the margin suggested by the jolt levels. A near doubling of the average Amcoach jolt increased the discomfort index from 7.83% to 10.97% as shown in Table A1. The passengers of the other cars also reported only a moderate sensitivity to jolt.

The cant deficiencies and discomfort indexes varied enormously within the groups, diminishing the utility of averaging. The actual passenger runs forced occasional slow orders and other variations from uniform cant deficiency.

There was no way to normalize and adjust the subjective discomfort reports to their equivalents at exact cant deficiencies. The passenger discomfort responses also appeared to depend on factors that were not measured by the accelerometers. Referring to Table A1, the instruments recorded a much larger jolt at curve 98 compared to curve 81 while the steady state lateral acceleration was the same. A satisfying increase in discomfort index from 6.7% to 16.7% resulted. But curve 125 produced acceleration measurements similar to curve 81 while the passengers reported a spectacular 36.7% discomfort index. The instruments were not in the same car as the passengers (to avoid foot traffic over the sensors and cables) but the occasional great discrepancies between measurements and human response, seen in each test car, appear to supercede such second order effects.

The discomfort of seated passengers bears only a general similarity to the risk of falling for walking passengers according to the risk criteria hypothesized in this paper. Certainly increases in steady state lateral acceleration and jolt diminish both comfort and ride safety. The discomfort ratings of the various vehicles were in qualitative agreement with the position of their floor acceleration measurements within the ride safety envelope. Both tilt vehicles had vastly superior discomfort ratings even though they were tested as slightly higher cant deficiencies than the conventional cars. But ride safety and ride comfort are not as similar as they appear at first glance.

TABLE A1 COMPARISON OF ACCELERATION MEASUREMENTS TO DISCOMFORT INDEX FOR AMCOACH

	REGRESSION TREND LINES								PASSENGER RUN DATA						
	SS LAT ACCELERATION				PEAK TO PEAK JOLT (1 SEC)										
CURVE NUMBER	2" CD	4" CD	6" CD	8" CD	2" CD	4" CD	6" CD	8" CD	DISCOMFORT INDEX %	TEST SPEED (MPH)	CANT DEF (IN.)	SS LATERAL ACCEL (G)	P - P JOLT (1 SEC) (G)	PEAK LATERAL ACCEL (G)	ABS P - P (G)
12 ROUGH CURVES															
52	0.047	0.093	0.140	0.187	0.146	0.292	0.438	0.584	13.3	100	3.42	0.08	0.26	0.22	0.28
62	0.033	0.067	0.100	0.133	0.169	0.183	0.196	0.210	6.7	83	4.16	0.07	0.19	0.15	0.19
81	0.043	0.086	0.129	0.171	0.122	0.156	0.189	0.222	6.7	63	5.78	0.12	0.20	0.22	0.30
98	0.038	0.075	0.113	0.151	0.120	0.191	0.261	0.332	16.7	65	6.42	0.12	0.30	0.30	0.35
103	0.035	0.070	0.106	0.141	0.062	0.124	0.186	0.248	11.7	73	5.55	0.10	0.18	0.20	0.23
116	0.039	0.079	0.118	0.158	0.070	0.120	0.169	0.218	5.0	60	5.32	0.10	0.06	0.15	0.20
122	0.037	0.073	0.110	0.147	0.006	0.092	0.178	0.264	5.0	87	5.71	0.10	0.15	0.16	0.20
125	0.039	0.078	0.117	0.156	0.200	0.200	0.200	0.200	36.7	102	6.39	0.12	0.20	0.22	0.28
126	0.038	0.076	0.114	0.152	0.133	0.145	0.157	0.169	6.7	87	6.17	0.11	0.15	0.18	0.20
137	0.038	0.075	0.113	0.151	0.137	0.175	0.213	0.251	13.3	91	6.46	0.12	0.22	0.22	0.30
145	0.037	0.075	0.112	0.150	0.209	0.248	0.287	0.326	6.7	80	5.33	0.09	0.28	0.22	0.28
146	0.037	0.075	0.112	0.150	0.082	0.164	0.245	0.327	3.3	72	5.20	0.09	0.19	0.21	0.30
AVERAGES	0.038	0.077	0.115	0.154	0.121	0.174	0.227	0.279	10.972	80.667	5.494	0.102	0.198	0.204	0.259
10 SMOOTH CURVES															
61	0.036	0.072	0.108	0.144	0.030	0.083	0.136	0.189	5.0	90	4.95	0.07	0.10	0.14	0.20
66	0.042	0.083	0.125	0.166	0.078	0.090	0.101	0.113	10.0	86	4.83	0.09	0.10	0.14	0.14
70	0.036	0.073	0.109	0.146	0.061	0.093	0.125	0.157	10.0	85	5.98	0.10	0.10	0.15	0.20
72	0.037	0.073	0.110	0.147	0.034	0.067	0.101	0.134	11.7	84	5.63	0.10	0.12	0.16	0.20
79	0.034	0.069	0.103	0.137	0.096	0.107	0.118	0.129	5.0	68	5.60	0.09	0.10	0.17	0.20
88	0.040	0.080	0.119	0.159	0.099	0.108	0.116	0.125	5.0	60	3.67	0.07	0.10	0.12	0.16
100	0.041	0.083	0.124	0.165	0.081	0.089	0.098	0.107	5.0	70	4.56	0.10	0.10	0.12	0.16
118	0.036	0.073	0.109	0.146	0.101	0.123	0.145	0.167	11.7	83	5.05	0.08	0.16	0.14	0.16
120	0.035	0.070	0.105	0.140	0.075	0.096	0.117	0.138	1.7	74	5.45	0.08	0.10	0.11	0.19
134	0.036	0.072	0.108	0.144	0.072	0.092	0.112	0.132	13.3	80	5.62	0.09	0.11	0.14	0.18
AVERAGES	0.034	0.068	0.102	0.136	0.066	0.086	0.106	0.126	7.121	70.909	4.668	0.079	0.099	0.126	0.163

TABLE A2 COMPARISON OF ACCELERATION MEASUREMENTS TO DISCOMFORT INDEX FOR RTL

CURVE NUMBER	REGRESSION TREND LINES								PASSENGER RUN DATA						
	SS LAT ACCELERATION				PEAK TO PEAK JOLT (1 SEC)				DISCOMFORT INDEX %	TEST SPEED (MPH)	CANT DEF (IN.)	SS LATERAL ACCEL (G)	P - P JOLT (1 SEC) (G)	PEAK LATERAL ACCEL (G)	ABS P - P (G)
	2" CD	4" CD	6" CD	8" CD	2" CD	4" CD	6" CD	8" CD							
12 ROUGH CURVES															
52	0.052	0.104	0.156	0.208	0.157	0.251	0.344	0.437	4.3	98	3.09	0.10	0.14	0.15	0.18
62	0.045	0.091	0.136	0.181	0.065	0.130	0.195	0.260	37.0	101	6.74	0.16	0.21	0.27	0.32
81	0.048	0.097	0.145	0.193	0.115	0.143	0.171	0.199	20.7	62	5.43	0.14	0.16	0.22	0.26
98	0.046	0.091	0.137	0.183	0.139	0.139	0.140	0.141	4.3	55	3.13	0.08	0.13	0.16	0.19
103	0.047	0.094	0.140	0.187	0.067	0.123	0.179	0.235	34.8	78	7.15	0.17	0.24	0.34	0.38
116	0.051	0.101	0.152	0.203	0.122	0.162	0.202	0.243	12.0	63	6.23	0.17	0.20	0.25	0.27
122	0.039	0.079	0.118	0.158	0.167	0.167	0.167	0.167	7.6	94	7.50	0.15	0.18	0.29	0.35
125	0.045	0.090	0.135	0.180	0.131	0.267	0.403	0.540	1.1	86	3.29	0.08	0.25	0.23	0.28
126	0.047	0.094	0.142	0.189	0.128	0.159	0.189	0.220	27.2	88	6.44	0.16	0.20	0.30	0.33
137	0.043	0.086	0.129	0.171	0.101	0.127	0.152	0.177	7.6	89	5.93	0.14	0.15	0.20	0.28
145	0.041	0.082	0.124	0.165	0.052	0.103	0.155	0.206	2.2	78	4.83	0.10	0.13	0.18	0.24
146	0.047	0.094	0.140	0.187	0.046	0.088	0.129	0.171	9.8	78	7.17	0.18	0.16	0.28	0.32
AVERAGES	0.046	0.092	0.138	0.184	0.107	0.155	0.202	0.250	14.040	80.833	5.578	0.136	0.179	0.239	0.283
10 SMOOTH CURVES															
61	0.047	0.093	0.140	0.186	0.071	0.109	0.148	0.186	47.8	97	6.71	0.16	0.15	0.23	0.31
66	0.048	0.097	0.145	0.193	0.053	0.085	0.116	0.148	9.8	93	6.37	0.16	0.12	0.22	0.16
70	0.045	0.091	0.136	0.182	0.090	0.099	0.108	0.118	23.9	89	7.09	0.16	0.11	0.19	0.26
72	0.042	0.084	0.126	0.168	0.037	0.074	0.111	0.148	15.2	88	6.58	0.15	0.08	0.18	0.21
79	0.047	0.094	0.141	0.189	0.054	0.062	0.070	0.078	16.3	74	7.45	0.18	0.08	0.21	0.25
88	0.044	0.088	0.133	0.177	0.051	0.064	0.077	0.090	9.8	68	6.25	0.15	0.08	0.19	0.21
100	0.048	0.097	0.145	0.193	0.060	0.079	0.097	0.116	10.9	72	5.16	0.12	0.08	0.16	0.21
118	0.044	0.087	0.131	0.174	0.104	0.109	0.113	0.117	2.2	82	4.81	0.11	0.11	0.14	0.20
120	0.043	0.086	0.129	0.172	0.050	0.075	0.100	0.124	4.3	78	6.57	0.14	0.12	0.22	0.26
134	0.043	0.086	0.129	0.172	0.127	0.127	0.127	0.127	0.0	81	5.88	0.14	0.14	0.18	0.23
AVERAGES	0.045	0.090	0.136	0.181	0.070	0.088	0.107	0.125	14.022	82.200	6.287	0.147	0.107	0.192	0.230

TABLE A3 COMPARISON OF ACCELERATION MEASUREMENTS TO DISCOMFORT INDEX FOR RTG

	REGRESSION TREND LINES								PASSENGER RUN DATA						
	SS LAT ACCELERATION				PEAK TO PEAK JOLT (1 SEC)				DISCOMFORT INDEX %	TEST SPEED (MPH)	CANT DEF (IN.)	SS LATERAL ACCEL (G)	P - P JOLT (1 SEC) (G)	PEAK LATERAL ACCEL (G)	ABS P - P (G)
CURVE NUMBER	2" CD	4" CD	6" CD	8" CD	2" CD	4" CD	6" CD	8" CD							
12 ROUGH CURVES															
52	0.049	0.099	0.148	0.197	0.219	0.439	0.658	0.878	3.8	89	1.70	0.06	0.16	0.12	0.16
62	0.042	0.083	0.125	0.166	0.089	0.165	0.241	0.317	32.7	96	5.71	0.14	0.26	0.29	0.33
81	0.049	0.098	0.146	0.195	0.118	0.197	0.276	0.355	21.2	62	5.43	0.12	0.24	0.30	0.35
98	0.045	0.089	0.134	0.178	0.120	0.225	0.329	0.433	26.9	58	4.06	0.12	0.27	0.32	0.36
103	0.040	0.080	0.119	0.159	0.067	0.135	0.204	0.273	34.6	74	5.86	0.13	0.22	0.26	0.32
116	0.047	0.094	0.141	0.187	0.111	0.156	0.201	0.245	13.5	64	6.54	0.13	0.20	0.23	0.28
122	0.042	0.085	0.127	0.169	0.062	0.123	0.185	0.247	40.4	95	7.77	0.19	0.28	0.34	0.36
125	0.038	0.075	0.113	0.150	0.182	0.363	0.545	0.726	0.0	81	2.43	0.05	0.22	0.22	0.08
126	0.052	0.104	0.156	0.208	0.114	0.228	0.342	0.456	5.8	80	4.34	0.10	0.18	0.22	0.25
137	0.043	0.087	0.130	0.173	0.087	0.181	0.274	0.368	26.9	92	6.73	0.15	0.32	0.32	0.42
145	0.045	0.090	0.134	0.179	0.073	0.145	0.218	0.291	1.9	74	3.85	0.10	0.16	0.16	0.22
146	0.041	0.082	0.123	0.164	0.055	0.110	0.165	0.220	3.8	72	5.20	0.12	0.18	0.25	0.28
AVERAGES	0.044	0.089	0.133	0.177	0.108	0.206	0.303	0.401	17.628	78.083	4.970	0.118	0.224	0.253	0.284
10 SMOOTH CURVES															
61	0.043	0.085	0.128	0.171	0.058	0.088	0.119	0.149	38.5	94	5.94	0.14	0.13	0.22	0.27
66	0.042	0.085	0.127	0.169	0.073	0.102	0.130	0.159	19.2	96	7.06	0.17	0.17	0.22	0.24
70	0.048	0.095	0.143	0.191	0.045	0.090	0.136	0.181	28.8	90	7.38	0.15	0.16	0.23	0.29
72	0.039	0.079	0.118	0.157	0.034	0.068	0.102	0.136	11.5	89	6.83	0.14	0.12	0.22	0.24
79	0.042	0.084	0.126	0.168	0.081	0.096	0.112	0.128	3.8	71	6.51	0.15	0.13	0.22	0.26
88	0.042	0.084	0.125	0.167	0.060	0.091	0.122	0.154	1.9	69	6.60	0.15	0.14	0.23	0.26
100	0.054	0.108	0.162	0.215	0.096	0.106	0.115	0.125	25.0	76	6.40	0.16	0.12	0.22	0.26
118	0.042	0.084	0.126	0.168	0.101	0.122	0.143	0.164	15.4	90	6.86	0.14	0.14	0.22	0.26
120	0.041	0.082	0.123	0.164	0.046	0.092	0.137	0.183	13.5	80	7.15	0.15	0.18	0.29	0.35
134	0.041	0.083	0.124	0.165	0.050	0.086	0.121	0.157	15.4	85	6.98	0.16	0.14	0.22	0.25
AVERAGES	0.043	0.087	0.130	0.173	0.064	0.094	0.124	0.154	17.308	84.000	6.769	0.151	0.143	0.229	0.268

TABLE A4 COMPARISON OF ACCELERATION MEASUREMENTS TO DISCOMFORT INDEX FOR TALGO

CURVE NUMBER	REGRESSION TREND LINES: SS LAT ACCELERATION 2" CD	4" CD	6" CD	8" CD	PEAK TO PEAK JOLT (1 SEC) 2" CD	4" CD	6" CD	8" CD	PASSENGER RUN DATA: DISCOMFORT INDEX %	TEST SPEED (MPH)	CANT DEF (IN.)	SS LATERAL ACCEL (G)	P - P JOLT (1 SEC) (G)	PEAK LATERAL ACCEL (G)	ABS P - P (G)
12 ROUGH CURVES															
52	0.032	0.065	0.097	0.129	0.067	0.135	0.202	0.270	6.3	97	2.93	0.03	0.16	0.10	0.16
62	0.025	0.050	0.075	0.100	0.099	0.107	0.114	0.122	20.6	102	6.95	0.08	0.12	0.13	0.19
81	0.029	0.057	0.086	0.114	0.077	0.091	0.105	0.119	12.7	66	6.87	0.10	0.13	0.15	0.21
98	0.029	0.059	0.088	0.118	0.040	0.080	0.120	0.160	4.8	76	3.66	0.05	0.08	0.06	0.12
103	0.023	0.046	0.069	0.092	0.102	0.114	0.127	0.139	0.0	75	6.18	0.06	0.10	0.10	0.14
116	0.028	0.055	0.083	0.111	0.051	0.083	0.114	0.145	1.6	50	2.61	0.04	0.06	0.12	0.14
122	0.026	0.052	0.079	0.105	0.100	0.100	0.100	0.100	0.0	89	3.20	0.04	0.08	0.09	0.13
125	0.027	0.054	0.082	0.109	0.153	0.165	0.178	0.190	11.1	102	6.39	0.08	0.20	0.22	0.32
126	0.028	0.056	0.084	0.112	0.097	0.112	0.128	0.143	0.0	86	5.90	0.07	0.12	0.14	0.19
137	0.025	0.050	0.075	0.100	0.067	0.085	0.102	0.119	3.2	94	7.28	0.08	0.10	0.15	0.23
145	0.026	0.053	0.079	0.106	0.088	0.103	0.117	0.132	1.6	86	6.94	0.07	0.09	0.12	0.20
146	0.025	0.049	0.074	0.099	0.084	0.095	0.106	0.117	0.0	68	3.98	0.04	0.06	0.10	0.18
AVERAGES	0.027	0.046	0.081	0.108	0.086	0.106	0.126	0.146	5.159	82.583	5.240	0.062	0.108	0.123	0.184
10 SMOOTH CURVES															
61	0.024	0.049	0.073	0.098	0.114	0.133	0.152	0.171	17.5	98	6.97	0.08	0.16	0.14	0.24
66	0.029	0.059	0.088	0.117	0.043	0.067	0.091	0.114	4.8	94	6.59	0.09	0.10	0.12	0.12
70	0.027	0.054	0.081	0.108	0.057	0.069	0.081	0.094	4.8	90	7.38	0.09	0.10	0.13	0.22
72	0.026	0.051	0.077	0.103	0.017	0.042	0.068	0.093	0.0	88	6.58	0.07	0.06	0.10	0.18
79	0.022	0.045	0.067	0.090	0.009	0.035	0.060	0.085	4.8	72	6.82	0.07	0.08	0.12	0.20
88	0.026	0.051	0.077	0.102	0.042	0.075	0.108	0.141	0.0	64	4.92	0.07	0.08	0.11	0.19
100	0.029	0.058	0.086	0.115	0.046	0.063	0.080	0.097	1.6	73	2.92	0.04	0.05	0.06	0.10
118	0.027	0.053	0.080	0.106	0.096	0.095	0.095	0.094	0.0	68	1.67	0.02	0.11	0.06	0.12
120	0.029	0.057	0.086	0.115	0.041	0.059	0.077	0.094	0.0	70	4.39	0.07	0.06	0.10	0.15
134	0.028	0.056	0.085	0.113	0.066	0.070	0.075	0.080	0.0	85	6.98	0.09	0.08	0.12	0.20
AVERAGES	0.027	0.053	0.080	0.107	0.053	0.071	0.089	0.106	3.333	80.200	5.523	0.069	0.088	0.106	0.172

TABLE A5 COMPARISON OF ACCELERATION MEASUREMENTS TO DISCOMFORT INDEX FOR LRC

	REGRESSION TREND LINES								PASSENGER RUN DATA						
	SS LAT ACCELERATION				PEAK TO PEAK JOLT (1 SEC)										
CURVE NUMBER	2" CD	4" CD	6" CD	8" CD	2" CD	4" CD	6" CD	8" CD	DISCOMFORT INDEX %	TEST SPEED (MPH)	CANT DEF (IN.)	SS LATERAL ACCEL (G)	P - P JOLT (1 SEC) (G)	PEAK LATERAL ACCEL (G)	ABS P - P (G)
12 ROUGH CURVES															
52	0.000	0.000	0.000	0.000	0.069	0.138	0.207	0.276	0.0	100	3.42	0.00	0.12	0.1	0.18
62	0.000	0.000	0.000	0.000	0.036	0.071	0.107	0.142	7.4	100	6.53	0.00	0.10	0.09	0.21
81	0.004	0.007	0.011	0.015	0.093	0.094	0.096	0.098	0.0	63	5.78	0.00	0.08	0.08	0.18
98	0.002	0.004	0.006	0.008	0.082	0.116	0.149	0.183	2.5	63	5.72	0.00	0.18	0.22	0.28
103	0.002	0.004	0.007	0.009	0.085	0.115	0.145	0.176	4.9	80	7.82	0.01	0.19	0.19	0.37
116	0.005	0.009	0.014	0.019	0.069	0.098	0.127	0.157	0.0	64	6.54	0.00	0.12	0.16	0.26
122	0.000	0.000	0.000	0.000	0.037	0.067	0.097	0.127	2.5	96	8.04	0.00	0.12	0.16	0.29
125	0.000	0.000	0.000	0.000	0.079	0.158	0.237	0.316	9.9	98	5.56	0.00	0.28	0.27	0.48
126	0.000	0.000	0.000	0.000	0.061	0.081	0.101	0.121	1.2	83	5.10	0.00	0.12	0.09	0.20
137	0.002	0.004	0.005	0.007	0.062	0.081	0.100	0.119	0.0	98	8.41	0.00	0.14	0.16	0.28
145	0.000	0.000	0.000	0.000	0.047	0.101	0.155	0.208	0.0	78	4.83	0.00	0.12	0.1	0.22
146	0.000	0.000	0.000	0.000	0.107	0.145	0.183	0.220	1.2	77	6.83	0.00	0.24	0.24	0.36
AVERAGES	0.001	0.002	0.004	0.005	0.069	0.105	0.142	0.179	2.469	83.333	6.216	0.001	0.151	0.155	0.276
10 SMOOTH CURVES															
61	0.002	0.004	0.006	0.008	0.039	0.081	0.123	0.165	9.9	101	7.77	0.00	0.17	0.19	0.35
66	0.005	0.011	0.016	0.022	0.025	0.051	0.076	0.101	0.0	96	7.06	0.02	0.10	0.09	0.16
70	0.002	0.005	0.007	0.010	0.025	0.050	0.075	0.100	2.5	88	6.81	0.00	0.10	0.11	0.24
72	0.000	0.000	0.000	0.000	0.068	0.077	0.086	0.095	0.0	90	7.08	0.03	0.10	0.08	0.17
79	0.004	0.008	0.013	0.017	0.030	0.043	0.056	0.069	0.0	73	7.13	0.00	0.06	0.08	0.15
88	0.004	0.008	0.012	0.016	0.045	0.053	0.060	0.068	0.0	70	6.95	0.00	0.08	0.11	0.20
100	0.000	0.000	0.000	0.000	0.052	0.072	0.093	0.113	4.9	82	8.39	0.00	0.16	0.2	0.30
118	0.000	0.000	0.000	0.000	0.097	0.101	0.104	0.108	1.2	93	7.68	0.00	0.12	0.15	0.27
120	0.000	0.000	0.000	0.000	0.037	0.060	0.082	0.104	1.2	80	7.15	0.00	0.10	0.15	0.26
134	0.002	0.004	0.006	0.007	0.023	0.047	0.070	0.094	3.7	86	7.26	0.00	0.08	0.15	0.23
AVERAGES	0.002	0.004	0.006	0.008	0.044	0.063	0.083	0.102	2.346	85.900	7.327	0.005	0.107	0.131	0.233