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Effect of Track Twist on Vehicle Dynamic Performance

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16. Abstract

Results of tests conducted at the Transportation Technology Center (TTC), Pueblo, Colorado, indicate that vehicle response to track twist varies significantly with car type. Critical response variables include car body torsional stiffness, truck spacing, track alignment (tangent or curve), track geometry and wheel/rail friction coefficient. Test data collected during this project provides an experimental basis for investigation of performance-based track safety limits.

Track twist is defined as a variation in cross level between two points along the track. Excessive twist can cause truck center plate unloading on tangent track as indicated by wheel unloading, or wheel climb on curved-track as indicated by high wheel or axle L/V ratios. The limiting wheel unloading and L/V ratio criteria specified by the industry for new car acceptance (90 percent reduction of static vertical wheel force, 1.0 single wheel L/V ratio and 1.5 axle sum L/V ratio) were used as the guideline limits for this test.

Three vehicles were tested in an empty load condition — a 100-ton, 89-foot center beam flatcar, a 100-ton covered hopper car and a 70-ton tank car — over cross level and combined cross level/alignment perturbations on tangent, 7.5-degree curve, and 12-degree curve test zones.

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EXECUTIVE SUMMARY

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Three vehicles were tested in an empty load condition — a 100-ton, 89-foot center beam flatcar, a 100-ton covered hopper car and a 70-ton tank car — over cross level and combined cross level/alignment perturbations on tangent, 7.5-degree curve, and 12-degree curve test zones. Results of the testing are summarized as follows:

- The covered hopper car and the tank car negotiated a 2.5-inch change in cross level in 20 feet on tangent track at speeds up to 52 mph and 60 mph respectively without exceeding the wheel unloading or L/V ratio limits. In both cases, testing was stopped due to truck hunting. The flatcar experienced 90 percent wheel unloading at 48 mph over a 3-inch cross level deviation in the tangent zone. Adding a 1.75-inch misalignment to the tangent cross level deviation caused 90 percent wheel unloading of the covered hopper and tank car at speeds of 52 mph and 42 mph respectively, and a wheel L/V ratio above 1.0 at 35 mph under the flatcar.

- The covered hopper generated single wheel L/V ratios greater than 1.0 at less than 10 mph over a 2.5-inch cross level deviation in the 7.5- and 12-degree curve zones. The tank car operated to the maximum curve speed of 30 mph over the 2.5-inch cross level deviation in the 7.5-degree curve but exceeded 1.0 single wheel L/V ratio in the 12-degree curve at less than 10 mph. The flatcar operated up to 30 mph over a 3-inch cross level deviation in the 7.5-degree and 12-degree curves without producing L/V ratios greater than 1.0. All car types generated L/V ratios in excess of 1.0 at less than 10 mph over the cross level/1.75-inch alignment perturbation located in the 7.5-degree curve. The alignment perturbation was not added to the cross level perturbation in the 12-degree curve.

- Wheel/rail friction coefficient and use of locomotive sand significantly influenced the L/V ratios and wheel climb tendencies of all vehicles tested in the curved zones. The highest L/V ratios were measured when the coefficient of friction was 0.4 or higher and locomotive sand was applied.

The vehicles were characterized prior to the track tests to determine truck vertical spring stiffness, vertical snubber friction, and center plate breakout torque. Static jacking tests were also performed to measure vertical wheel load redistribution as the wheels on one side of a truck were raised to a maximum of 4 inches. Based on the relation of wheel unloading and cross level difference obtained from the static jacking test, the amplitudes of the cross level perturbations to be installed in the track tests were determined.

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1.0 INTRODUCTION

The Association of American Railroads (AAR) in conjunction with the Volpe National Transportation Systems Center (VNTSC), has investigated the effect of track twist on vehicle performance at the Transportation Technology Center (TTC), Pueblo, Colorado. The data contributes additional insight into how track twist affects the performance of car types on a variety of track sections. The project was jointly funded by the Federal Railroad Administration (FRA) and AAR as part of the Vehicle/Track Interaction Program.

1.1 BACKGROUND

Track twist is defined as a change in cross level between two points along the track. Track twist occurs by design (as superelevation is introduced) within transition curves or spirals. Twist also occurs as a defect in the track geometry. A redistribution of vertical wheel loading takes place when a vehicle travels over a change in cross level. Figure 1.1 illustrates the reaction of the car body and truck bolster to a change in cross level. The vertical load is shared by the edge of the center plate and the side bearings as the car body contacts the side bearings at the two diagonal corners. In an extreme twist condition, all the load may be transferred to the side bearing, in which case the center plate becomes unloaded and the wheels on the opposite side of the truck from the loaded side bearing also approach an unloaded condition. This condition may lead to a wheel climb derailment if a sufficient lateral force is present.

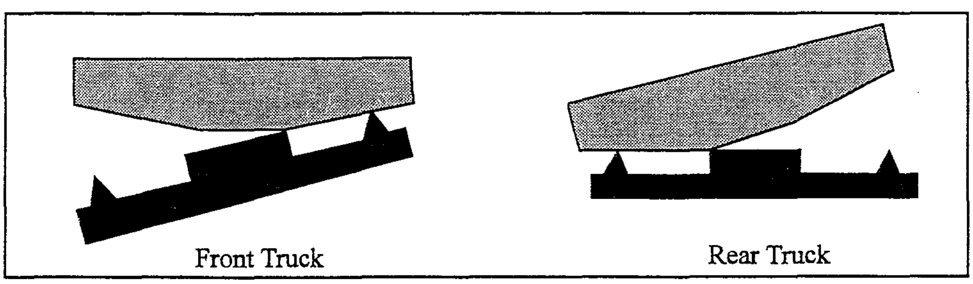

Figure 1.1 Reaction of Vehicle to Track Twist

VNTSC conducted static and quasi-static analysis of vehicle response to track twist to determine the maximum permissible twist deviation as a function of curvature[1]. An example of the relationship between vertical load redistribution and cross level difference produced by this analysis is shown in Figure 1.2. The quasi-static results indicated the maximum wheel unloading for a variety of car types to be in the range of 55 percent to 65 percent of the static wheel load. However, experimental quantification of vehicle dynamic response and the influence of speed on wheel unloading was necessary to adequately define the effects of track twist.

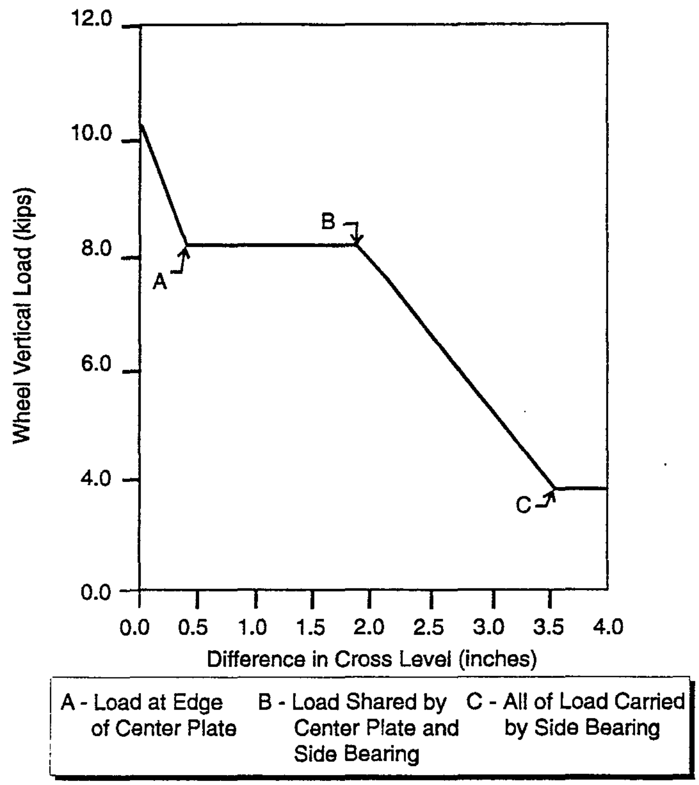

Figure 1.2 Relation of Wheel Load and Cross Level Difference

1.2 OBJECTIVE

The objective of the track tests was to measure the dynamic response, primarily wheel unloading and wheel climb tendencies, of specific freight cars to cross level and cross level/alignment deviations installed on tangent track and 7.5-degree and 12-degree curves.

1.3 TEST PROGRAM

The test program included a series of static and quasi-static characterization tests followed by a series of track tests performed on three freight cars. The static/quasi-static tests included truck suspension measurements to define the vertical spring stiffness and snubber friction band width, center plate breakout torque tests, and static jacking tests to measure the vertical wheel force redistribution and to make the qualitative comparison of torsional rigidity of three type of car bodies with the wheels at one corner of the car raised 4 inches. The static jacking test data was also used to determine the cross level perturbation amplitude to be installed during the track tests for each car. Truck characterizations test results are shown in Table 1. Other static/quasi-static test results are described in detail in a separate report[2].

Table 1. Vertical Characterization Results

Parameter	Truck	Value
Vertical Spring Stiffness without Snubbers, left	100 - B	25.7 kips/inch
Vertical Spring Stiffness without Snubbers, right	100 - B	26.4 kips/inch
Vertical Spring Damping with Snubbers, left	100 - B	5.7 kips
Vertical Spring Damping with Snubbers, right	100 - B	5.8 kips
Vertical Spring Stiffness without Snubbers, left	100 - A	25.6 kips/inch
Vertical Spring Stiffness without Snubbers, right	100 - A	25.4 kips/inch
Vertical Spring Damping with Snubbers, left	100 - A	5.5 kips
Vertical Spring Damping with Snubbers, right	100 - A	6.9 kips
Vertical Spring Stiffness without Snubbers, left	70 - B	31.0 kips/inch
Vertical Spring Stiffness without Snubbers, right	70 - B	30.0 kips/inch
Vertical Spring Damping with Snubbers, left	70 - B	5.5 kips
Vertical Spring Damping with Snubbers, right	70 - B	5.5 kips
Vertical Spring Stiffness without Snubbers, left	70 - A	31.0 kips/inch
Vertical Spring Stiffness without Snubbers, right	70 - A	30.0 kips/inch
Vertical Spring Damping with Snubbers, left	70 - A	5.5 kips
Vertical Spring Damping with Snubbers, right	70 - A	5.0 kips

* 100 - B (or A) indicates B (or A) -end of 100-ton ride control truck.
* 70 - B (or A) indicates B (or A) -end of 70-ton Barber truck.

Track tests were performed in the following test zones:

- Tangent track zone with cross level perturbation and combination cross level/alignment perturbation.

- 7.5-degree curve zone with cross level perturbation and combination cross level/alignment perturbation.

- 12-degree curve zone with cross level perturbation only.

- The bunched spiral and limiting spiral specified by AAR Chapter XI Service Worthiness Tests for New Freight Cars.

2.0 TEST VEHICLE AND TEST TRACK DESCRIPTION

2.1 TEST VEHICLE DESCRIPTION

Test vehicles included a 100-ton center-beam flatcar, a 100-ton covered hopper car, and a 70-ton tank car. This equipment, described in Table 2, represents a range of vehicle types (e.g. tank car shown in Figure 2.1) with different truck center spacings and empty weight. All vehicles were tested empty with the nominal side bearing clearances set at 0.25 inch before the tests.

Table 2. Description of Test Vehicles

Description	Truck Center Spacing	Empty Weight (lb)	Truck
Center-beam flatcar	59' 10"	64,000	100-ton ride control D-5 suspension
Covered hopper	40' 6"	61,800	100-ton ride control D-5 suspension
Tank car	29' 9"	56,400	Barber 70-ton D-3 suspension

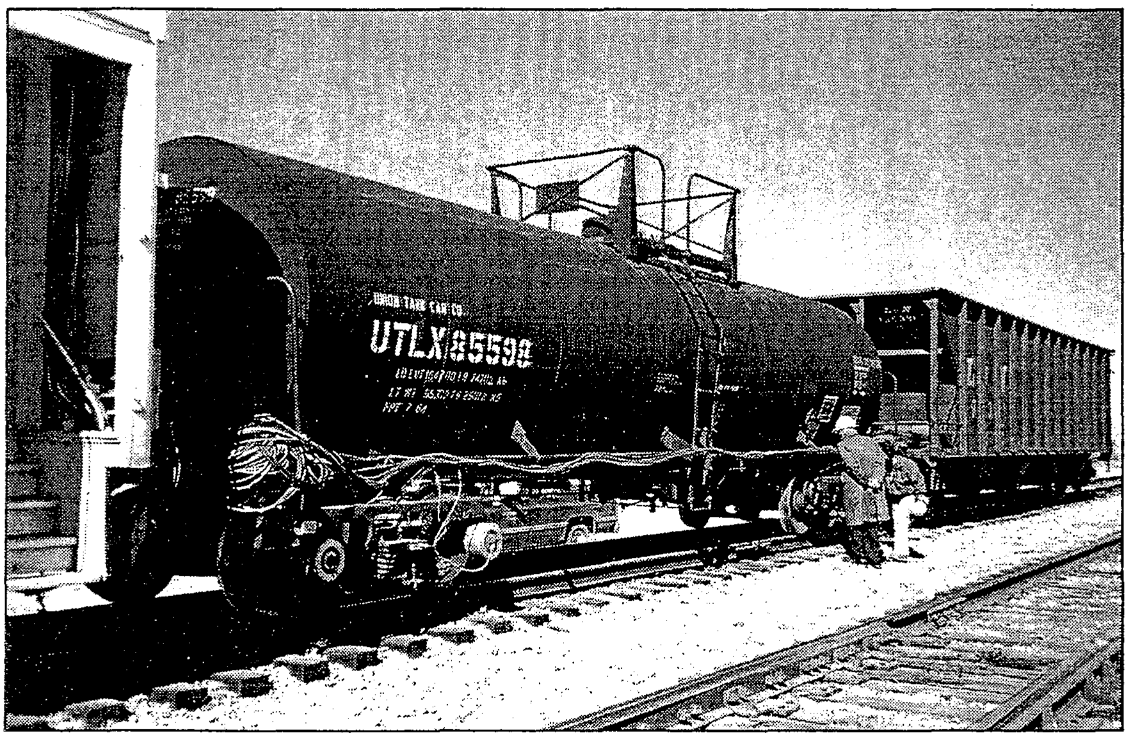

Figure 2.1 70-Ton Tank Car

2.2 TEST TRACK DESCRIPTION

Tangent track tests were conducted on the Railroad Test Track between section markers R-13 and R-14. Curved-track tests were conducted on the Wheel Rail Mechanism Loop. The cross level perturbations were installed on the left rail of the tangent zone and on the low rail of both 7.5- and 12-degree curves. Figure 2.2 shows the test zone locations.

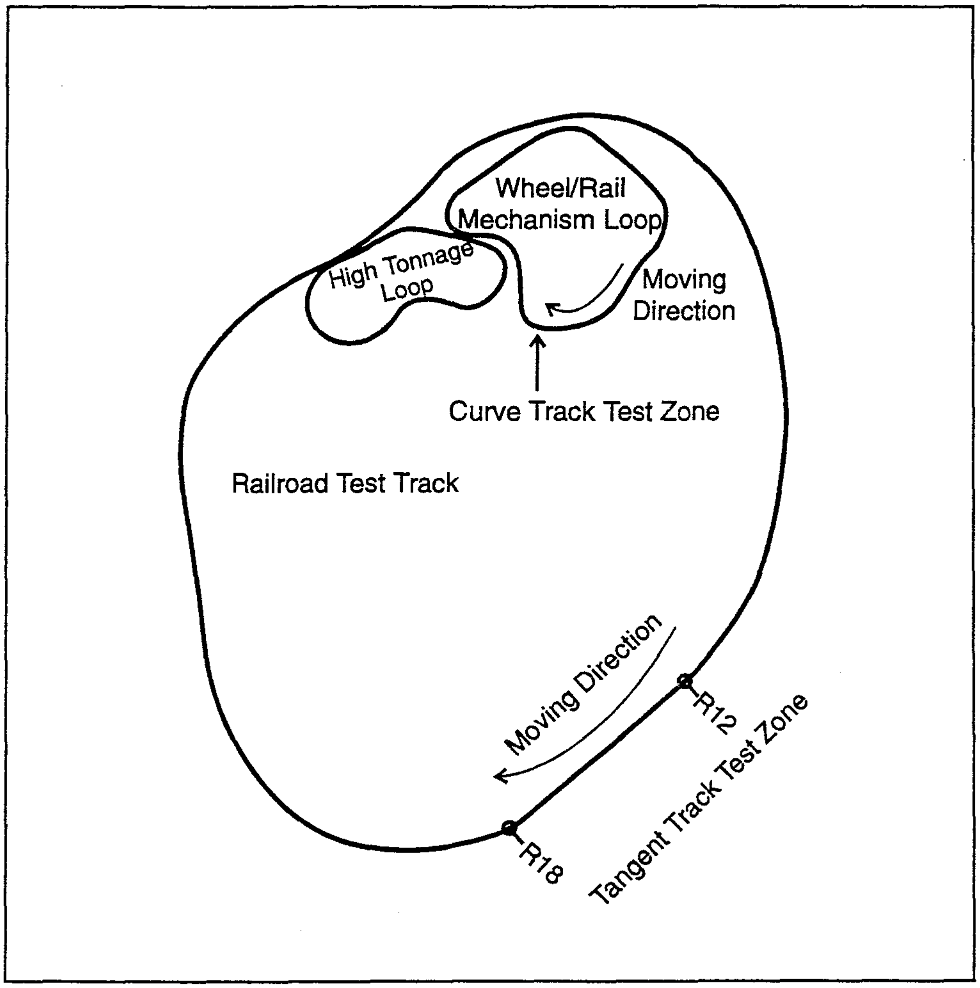

Figure 2.2 Location of Test Zones

Table 3 describes the amplitude of the cross level and alignment perturbations installed in each test zone and the design superelevation of the curve test zones. All cross level perturbations were at or within FRA Class 1 geometry deviations.

Table 3. Description of Test Zones

Vehicle Type	Track Alignment	Superelevation (inches)	Cross level Perturbation (inches)	Actual Cross level Difference (inches)	Alignment Perturbation (inches)
Flatcar	Tangent	0.0	3.0	3.0	1.75
	7.5-degree	3.0	3.0	0.0	1.75
	12-degree	5.0	3.0	2.0	0
Covered Hopper	Tangent	0.0	2.25	2.25	1.75
	7.5-degree	3.0	2.25	0.75	1.75
	12-degree	5.0	2.25	2.75	0
Tank Car	Tangent	0.0	2.5	2.5	1.75
	7.5-degree	3.0	2.5	0.5	1.75
	12-degree	5.0	2.5	2.5	0

The shape of the cross level perturbations is shown in Figure 2.3. Cross level perturbations were installed by placing wood and steel shims between the tie plate and tie as shown in Figure 2.3. The curve zone perturbations were located a sufficient distance from curve entry to allow the vehicle to approach steady-state before entering the perturbation. The alignment perturbation was installed by shifting the track panel with a track maintenance machine at the center of cross level perturbation, as shown in Figure 2.4. The track was misaligned to the left in the tangent zone and toward the outside of the curve in the curved zones.

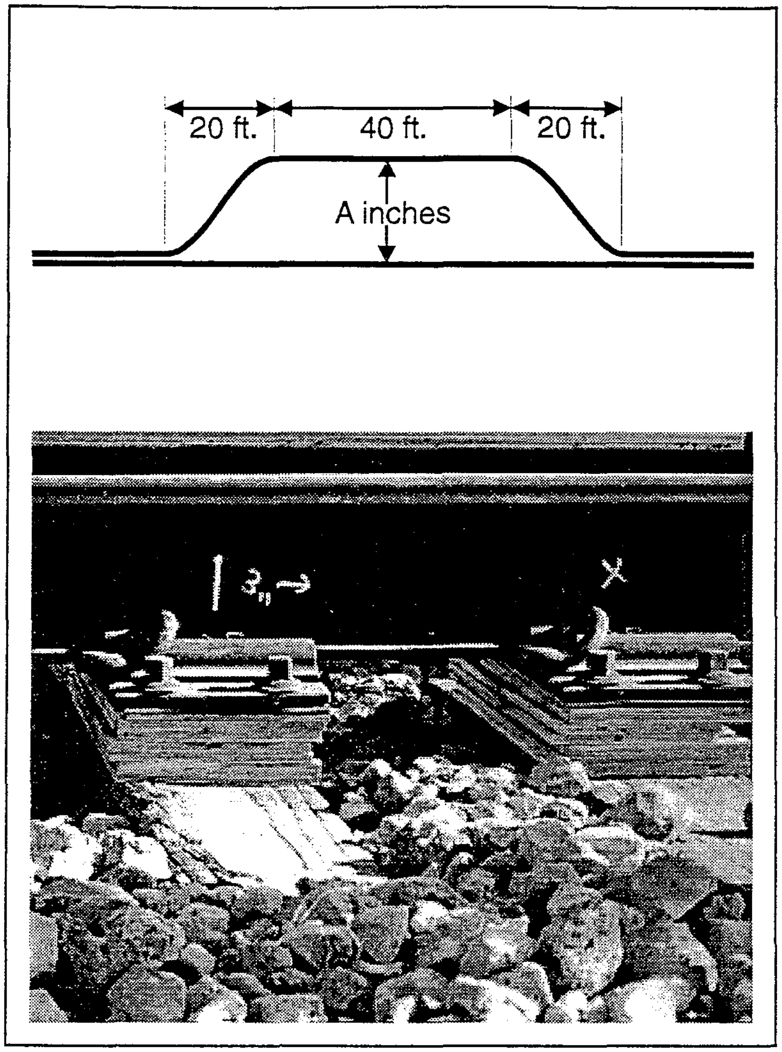

Figure 2.3 The Shape and Installation of the Cross Level Perturbation

Data was also taken in the bunched spiral and limiting spiral. The bunched spiral is the exit spiral of the 12-degree curve and has an effective change in cross level of 1.5 inches per 31 feet (5 inches over a 100-foot track segment). The limiting spiral is the entry spiral to a 10-degree curve and has an effective change in cross level of 1.75 inches per 31 feet (total cross level change of 5 inches over 88.75 feet). As shown in Figure 2.5, the curvature and superelevation change simultaneously in the limiting spiral while the change in superelevation is confined to the center 100 feet of the bunched spiral.

The track tests were conducted with the wheel/rail coefficient of friction above 0.4. Locomotive sand was applied when the coefficient of friction was below 0.4 as a means of increasing the friction coefficient.

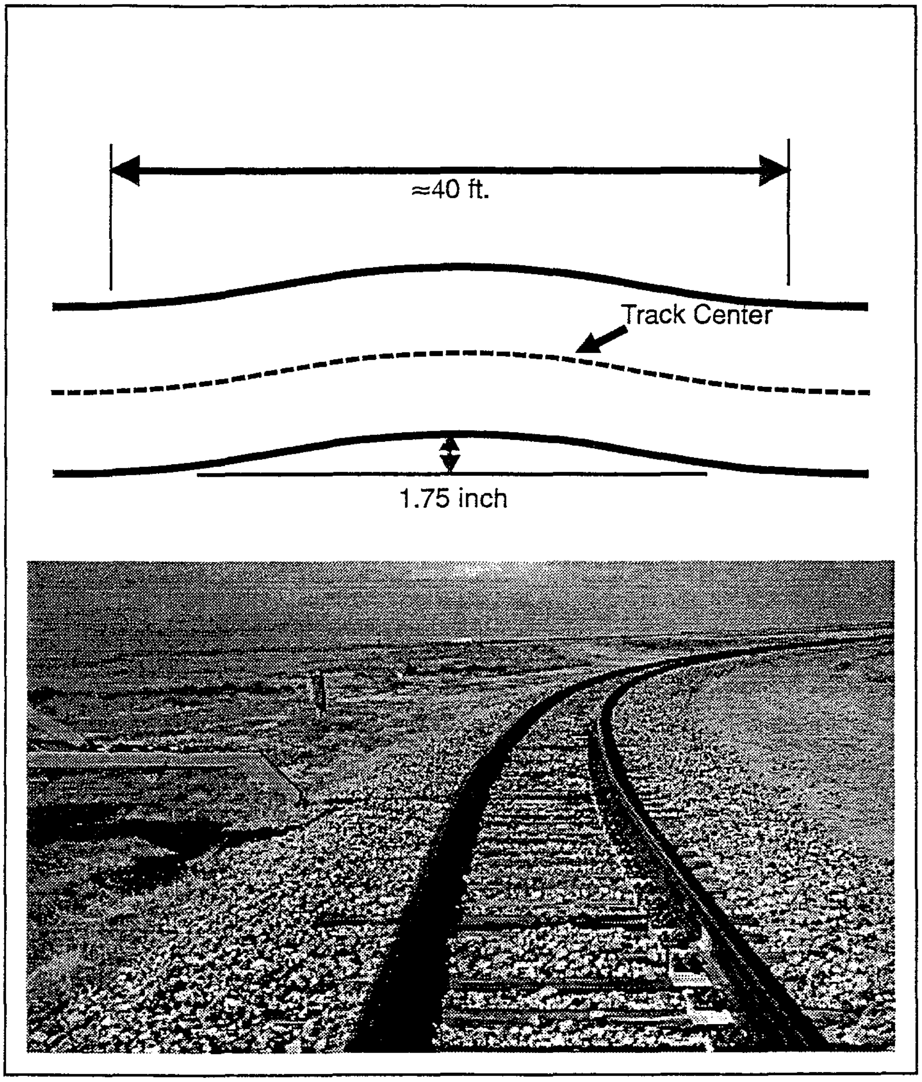

Figure 2.4 Alignment Perturbation

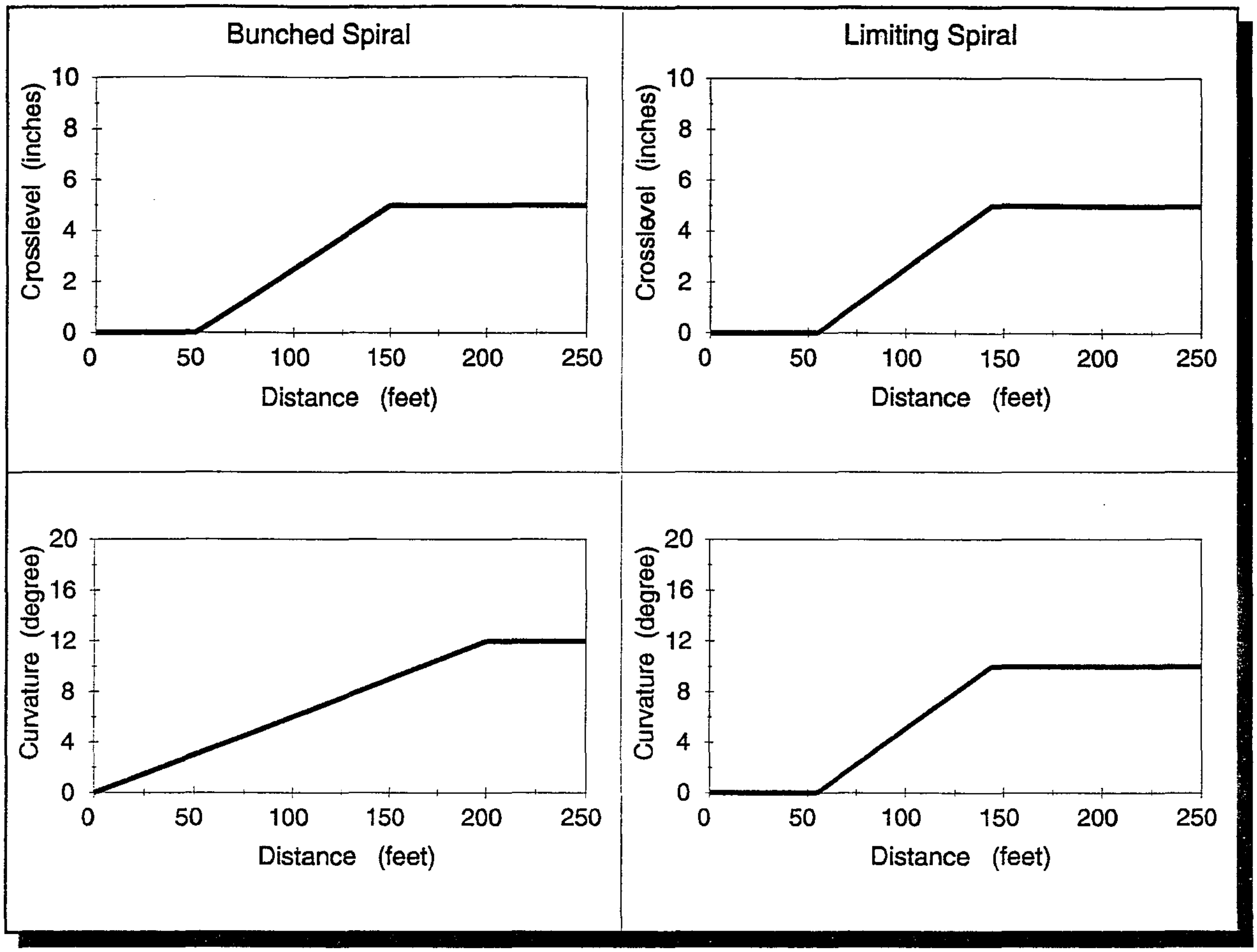

Figure 2.5 Bunched Spiral Track Segment and Limiting Spiral Track Segment

2.3 <u>TEST CONSIST</u>

Figure 2.6 shows the test train configuration. The consist included the DOTX 205 instrumentation car equipped with the data acquisition system, followed by the test car with the A-end leading and a buffer car. Instrumentation on the test car included instrumented wheel sets in the lead truck and displacement transducers to measure spring nest and car body to bolster displacements.

Figure 2.6 Test Train Configuration

3.0 RESULTS OF QUASI-STATIC JACKING TESTS AND GEOMETRIC CRITERION OF CENTER PLATE SEPARATION

Quasi-static jacking tests were conducted prior to the track test to obtain the response of the test cars to cross level difference and to determine the track test perturbation amplitude. The jacking test procedure is described in a separate report[2]. Results of the jacking tests, which provide static vehicle twist characters, are presented below along with the discussion of the wheel unloading mechanism due to the track twist.

3.1 RESULTS OF QUASI-STATIC JACKING TESTS

Figure 3.1 shows the percent of vertical wheel unloading for each car in the jacking tests. The unloading increased somewhat linearly with the height of the cross level difference for the flatcar, although a rate change is evident at 2.4 inches. About 57-percent wheel unloading was recorded at a cross level difference of 4 inches under the flatcar.

A critical cross level difference, between 2- and 2.25-inches, was found for the covered hopper and the tank car. A significant static wheel unloading, up to 57 percent for the covered hopper car and 68 percent for the tank car, occurred between a cross level difference of 2.0- and 2.6-inches. Above 2.6 inches, the static vertical forces remain almost constant, indicating the total vertical load was carried by the side bearing. Comparing to 57 percent and 68 percent wheel unloading for the covered hopper and the tank car at 2.6-inches cross level difference, there was only about 30 percent wheel unloading at the same cross level difference for the flatcar.

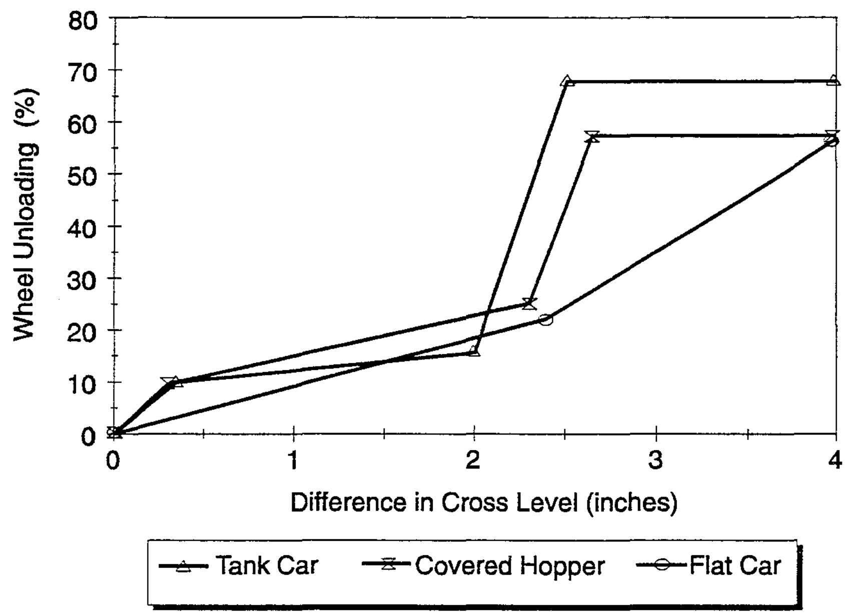

Figure 3.1 Relationship Between Static Wheel Unloading and Cross Level Difference

Wheel loading and unloading occurred in a diagonal pattern during the jacking tests. However, the force distribution was not diagonally symmetric. For example, if the left side of the B-end truck was raised, the maximum wheel unloading occurred at the left side of the A-end truck. Figure 3.2 shows the comparison of maximum wheel unloading at the diagonal corners (left side of A-end truck and right side of B-end truck) while the left side of the B-end truck was raised.

Figure 3.3 shows car body displacement relative to ground at the maximum wheel unloading corner during the jacking tests. When the wheels on the left side of the B-end truck were raised 4 inches (presented as Cross Level Difference in Figure 3.3), the left side car body at the A-end was raised 1 inch for the flatcar, 2.5 inches for the tank car and 2.65 inches for the covered hopper car. Although car body torsional stiffness was not quantitatively defined, a qualitative comparison can be made based on the displacement of the car body during the jacking tests. Results indicate that the center beam flatcar has less car body torsional rigidity than the covered hopper car or tank car.

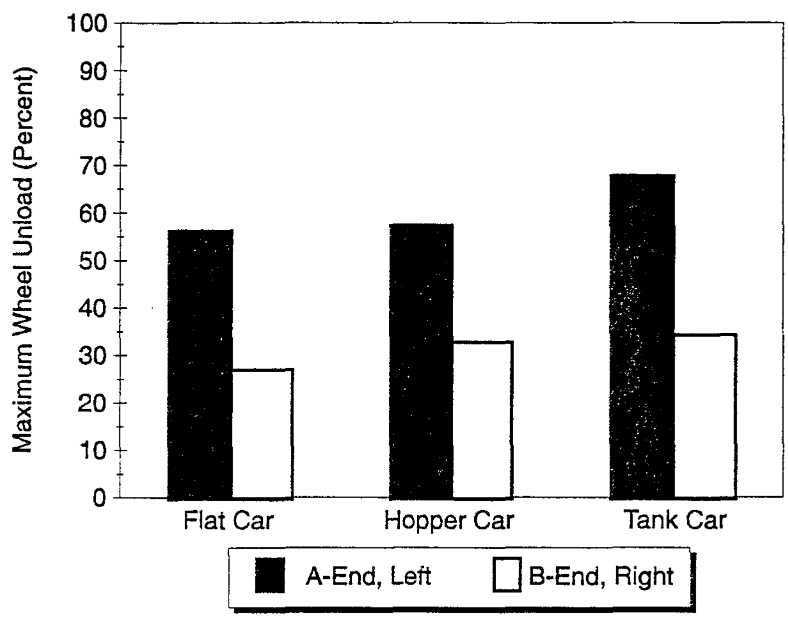

Figure 3.2 Comparison of Maximum Wheel Unloading at the Diagonal Corners

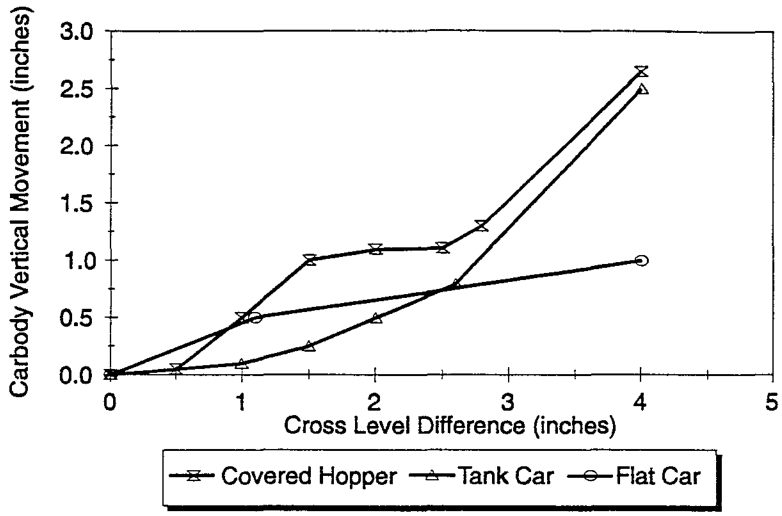

Figure 3.3 Torsional Displacement of Car Body

3.2 GEOMETRIC CRITERION OF CENTER PLATE SEPARATION

The geometric criterion of center plate separation discussed below determines when the center plate is completely separated from the truck bolster center bowl. Once separation is complete, the vertical load is carried only by the side bearing.

As illustrated in Figure 3.4, the car body rotation center is assumed at the edge of the center plate. The geometric criterion of center plate separation can be simply defined by Equation 3.1,

$$H > c_2 + c_1 \frac{D + d}{D - d} \tag{3.1}$$

where H is the side bearing to car body distance,

c_1 and c_2 are the initial settings of side bearing clearance,

D is the distance between the center of two side bearings, and

d is the dimension of the center plate.

If the side bearing clearances are the same before the vehicle is exposed to the cross level difference, then $c_1 = c_2 = c$, and Equation 3.1 can be written as:

$$H > \frac{2cD}{D - d} \qquad (3.2)$$

Because the relative motion was measured between the side bearing and the car body, the geometric criterion of center plate separation was not affected by the displacement of truck suspensions.

The dimensions and the initial side bearing clearances for three vehicles during the static jacking tests are listed in Table 3.1.

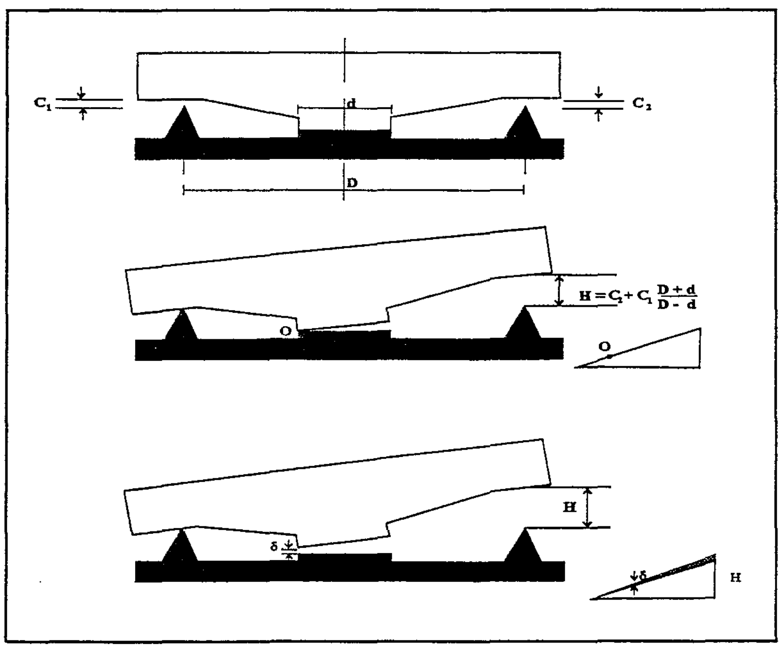

Figure 3.4 Center Plate Separation

Table 3.1 Dimensions and Initial Side Bearing Clearances

	Center Beam Flatcar	Covered Hopper Car	Tank Car
D (inch)	50	50	52
d (inch)	15	13	13
c_1 (inch)	0.25	0.25	0.25
c_2 (inch)	0.25	0.25	0.25

Using the parameters in Table 3.1, the geometric criteria for center plate separation for the three test vehicles can be computed using Equation 3.2 as follows:

$H > H_{HC} = 0.676$ inch — Covered Hopper

$H > H_{TC} = 0.667$ inch — Tank Car

$H > H_{FC} = 0.714$ inch — Center Beam Flatcar

Figure 3.5 shows the side bearing clearance relative to car body at the maximum wheel unloading corner. Side bearing to car body clearance is about 0.7 inch at 2.6-inches cross level difference for both the covered hopper and the tank car, which is higher than H_{HC} and H_{TC}. Notice that maximum wheel unloading occurred at 2.6-inches cross level difference for the covered hopper and 2.5 inches for the tank car. Above 2.6-inches cross level difference, the further separation of side bearing to car body had no influence to the wheel load. The maximum clearance between car body and side bearing was 0.69 inch at 4 inches cross level difference for the flatcar, which is lower than H_{FC}. Flatcar center plate separation did not occur during the jacking test as indicated also by the wheel unloading.

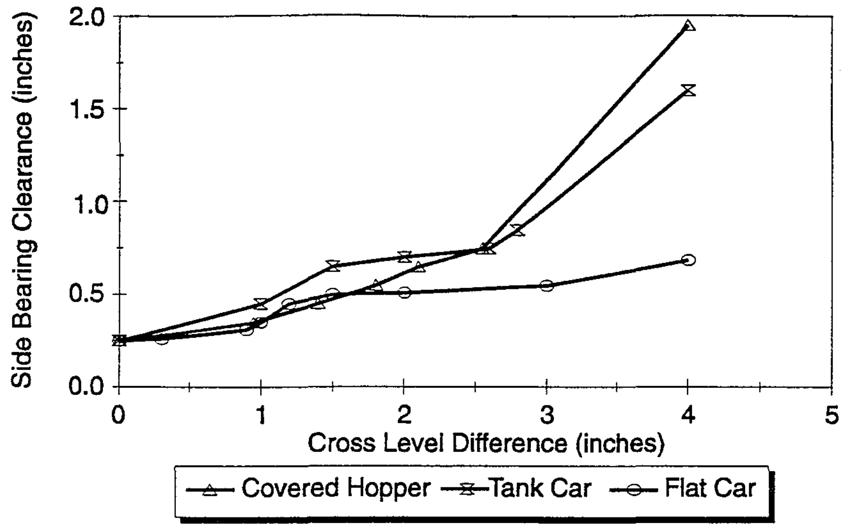

Figure 3.5 Relative Displacement Between Car Body and Side Bearing

Notice that a large percentage of vertical force was transferred from the center plate to the side bearing before the center plate fully separated, as shown in Figure 3.1. Hence, the criteria indicate the completion of the force transformation. Also note that the above criteria are based on two-dimensional analysis. The rotation center of the center plate is on its center line in the lateral direction. The validity of the two- dimensional assumption has been proven in the track test and is discussed in a later section.

4.0 TRACK TEST INSTRUMENTATION

4.1 INSTRUMENTED WHEEL SET

Two instrumented wheel sets with AAR-1B profiles were installed in the leading truck (A-end) of each test vehicle. The data collection sample rate was 200 samples per second and the filter frequency was 100 Hz for raw data collection and 15 Hz for data processing. Table 5 lists the instrumented wheel set measurement channels.

Table 5. Instrumented Wheel Set Measurements (Leading Truck)

Channel	Description and Location	Serial Number	Wheel Diameter (inch)
VA25	Vertical Wheel Force, Leading Axle Left	25	33
LA25	Lateral Wheel Force, Leading Axle Left	25	33
POA25	Contact Position, Leading Axle Left	25	33
LVA25	L/V Ratio, Leading Axle Left	25	33
VB25	Vertical Wheel Force, Leading Axle Right	25	33
LB25	Lateral Wheel Force, Leading Axle Right	25	33
POB25	Contact Position, Leading Axle Right	25	33
LVB25	L/V Ratio, Leading Axle Right	25	33
ASUM252	L/V Axle Sum, Leading Axle	25	33
VA26	Vertical Wheel Force, Trailing Axle Left	26	33
LA26	Lateral Wheel Force, Trailing Axle Left	26	33
POA26	Contact Position, Trailing Axle Left	26	33
LVA26	L/V Ratio, Trailing Axle Left	26	33
VB26	Vertical Wheel Force, Trailing Axle Right	26	33
LB26	Lateral Wheel Force, Trailing Axle Right	26	33
POB26	Contact Position, Trailing Axle Right	26	33
LVB26	L/V Ratio, Trailing Axle Right	26	33
ASUM262	L/V Axle Sum, Trailing Axle	26	33
VA28	Vertical Wheel Force, Leading Axle Left	28	36
LA28	Lateral Wheel Force, Leading Axle Left	28	36
POA28	Contact Position, Leading Axle Left	28	36
LVA28	L/V Ratio, Leading Axle Left	28	36
VB28	Vertical Wheel Force, Leading Axle Right	28	36
LB28	Lateral Wheel Force, Leading Axle Right	28	36
POB28	Contact Position, Leading Axle Right	28	36
LVB28	L/V Ratio, Leading Axle Right	28	36

Table 5. Instrumented Wheel Set Measurements (Leading Truck) continued

Channel	Description and Location	Serial Number	Wheel Diameter (inch)
ASUM282	L/V Axle Sum, Leading Axle	28	36
VA29	Vertical Wheel Force, Leading Axle Left	29	36
LA29	Lateral Wheel Force, Leading Axle Left	29	36
POA29	Contact Position, Leading Axle Left	29	36
LVA29	L/V Ratio, Leading Axle Left	29	36
VB29	Vertical Wheel Force, Leading Axle Right	29	36
LB29	Lateral Wheel Force, Leading Axle Right	29	36
POB29	Contact Position, Leading Axle Right	29	36
LVB29	L/V Ratio, Leading Axle Right	29	36
ASUM292	L/V Axle Sum, Trailing Axle	29	36

4.2 MEASUREMENTS OF DISPLACEMENT

Displacement measurements were taken to determine vertical suspension strokes, center plate separation and truck yaw angles. Table 6 lists displacement measurement locations and descriptions.

Table 6. Displacement Measurements

	Location and Description	Transducer Type	Sensitivity (inch / volt)
DZ1L	Vertical Displ., CB to Bolster, Leading Left	LVDT	0.1245
DZ1R	Vertical Displ., CB to Bolster, Leading Right	LVDT	0.1293
DZ3L	Vertical Displ., Spring Nest, Leading Left	String Pot	1.0649
DZ3R	Vertical Displ., Spring Nest, Leading Right	String Pot	1.0668
DX1L	Long. Displ., CB to Bolster, Leading Left	String Pot	0.9455
DX1R	Long. Displ., CB to Bolster, Leading Right	String Pot	1.6042
DZ2L	Vertical Displ., CB to Bolster, Trailing Left	LVDT	0.1231
DZ2R	Vertical Displ., CB to Bolster, Trailing Right	LVDT	0.1299
DZ4L	Vertical Displ., Spring Nest, Trailing Left	String Pot	1.0631
DZ4R	Vertical Displ., Spring Nest, Trailing Right	String Pot	1.0678
DX2L	Long. Displ., CB to Bolster, Trailing Left	String Pot	0.1231
DX2R	Long. Displ., CB to Bolster, Trailing Right	String Pot	0.1299
DZ5L	Vertical Displ., CB to Bolster, Leading Left	LVDT	0.1223
DZ5R	Vertical Displ., CB to Bolster, Leading Right	LVDT	0.2161
DZ6L	Vertical Displ., CB to Bolster, Trailing Left	LVDT	0.1299
DZ6R	Vertical Displ., CB to Bolster, Trail Right	LVDT	0.1234

* CB indicates the car body. The LVDT's were installed at the locations of side bearing for the track test of the flatcar and the covered hopper, and were installed at the edges of center plate for the track test of the tank car.

4.3 TEST ZONE INDICATORS

Each test zone was marked by five automatic location devices (ALDs) as shown in Figure 4.1. ALD 3 was located at the center of the perturbation and ALD's 2 and 4 located at the beginning and end of the perturbation. ALD's 1 and 5 were located about 100 feet from the ends of the perturbation. Data analysis, in most cases, was confined to the segment between ALD 1 and ALD 5. The configuration of ALDs on the curved-track is shown in Figure 4.2

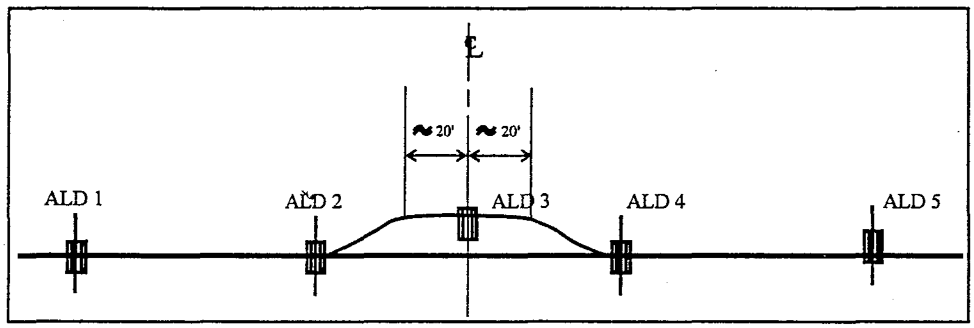

Figure 4.1 Test Zone Indicators

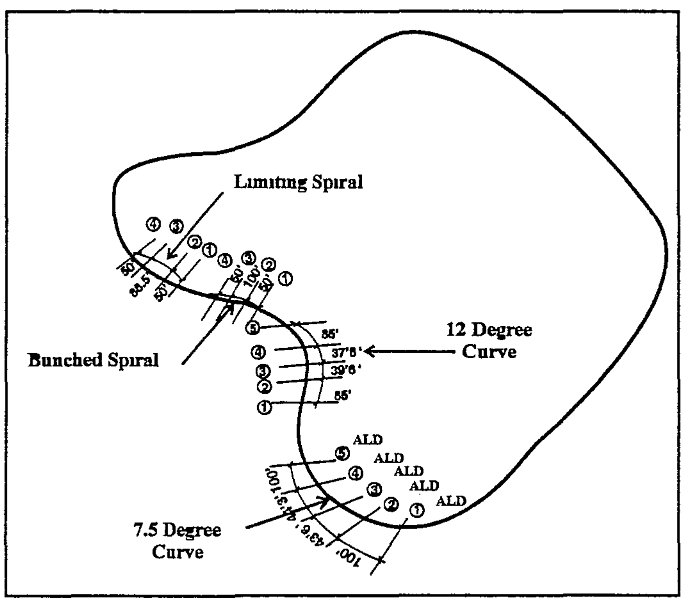

Figure 4.2 Configuration of ALDs on the Curved-track

5. 0 TEST OPERATING CRITERIA

Test operating criteria were formulated to meet test requirements and assure safe operating conditions. For each test, vehicle speed was increased incrementally with maximum speed determined by one of the following conditions:

- Incipient derailment condition, as indicated by instrumented wheel set data and/or visual observation of wheel unloading.
- Onset of truck hunting in the tangent zones.
- Maximum curve speed of 32 mph based on maximum unbalanced superelevation of 3 inches.

The AAR Chapter XI limits of single-wheel L/V ratios greater than 1.0, axle sum L/V ratios greater than 1.5 and wheel vertical unloading greater than 90-percent of static loading were used as safety guidelines during the test.

6.0 DEFINITION OF TEST PARAMETERS

Test results are presented as plots in which the selected output variables are shown as function of time or speed. Variables of primary interest are:

- Maximum wheel unloading as defined by the following formula:

$$Wheel\ Vertical\ Unloading\ (\%) = 100 - \frac{Min.\ Vertical\ Load}{Static\ Wheel\ Load} \times 100 \qquad (6.1)$$

- Maximum wheel lateral loads.
- Single wheel L/V ratios defined as the wheel lateral force divided by the same wheel vertical force at the same time instant.
- Axle sum L/V ratios defined as the sum of the absolute values of left and right wheel L/V ratios at the same time instance.

- Center plate separation determined by displacement measurements obtained at the side bearing or the edge of the center plate.

7.0 RESULTS OF TANGENT TRACK TESTS

The limiting conditions for testing on the perturbed tangent track were wheel unloading and onset of truck hunting. The tangent track test matrix is listed in Table 7.

Table 7. Tangent Track Test Matrix

Car Type	Perturbation Description	Test Speed Range (mph)	Number of Runs
Flatcar	Cross level 3 inches	5 - 45	14
Flatcar	Cross level 3 inches and Alignment 1.75 inches	5 - 36.5	15
Covered Hopper	Cross level 2.25 inches	5 - 65	27
Covered Hopper	Cross level 2.25 inches and Alignment 1.75 inches	5 - 55	22
Tank Car	Cross level 2.5 inches	5 - 55	16
Tank Car	Cross level 2.5 inches and Alignment 1.75 inches	5 - 43	10

Figure 7.1 shows a time history plot of the dynamic response of the covered hopper car operating over the 2.25-inch cross level perturbation with 1.75-inch alignment perturbation at 55 mph. The perturbation position is indicated by ALDs. Note that the left side bearing clearance (DZ1L) increased sharply when the same side wheel showed vertical unloading (VA28). The wheel L/V ratio (LVB28) gave the relationship between the vertical and lateral wheel force at the same instance on a single wheel.

Note that the maximum and minimum values for each measured parameter may not occur in the same time instance. For example, in Figure 7.1, the maximum lateral force (LB28) was not recorded at the same time the maximum L/V ratio (LVB28) occurred.

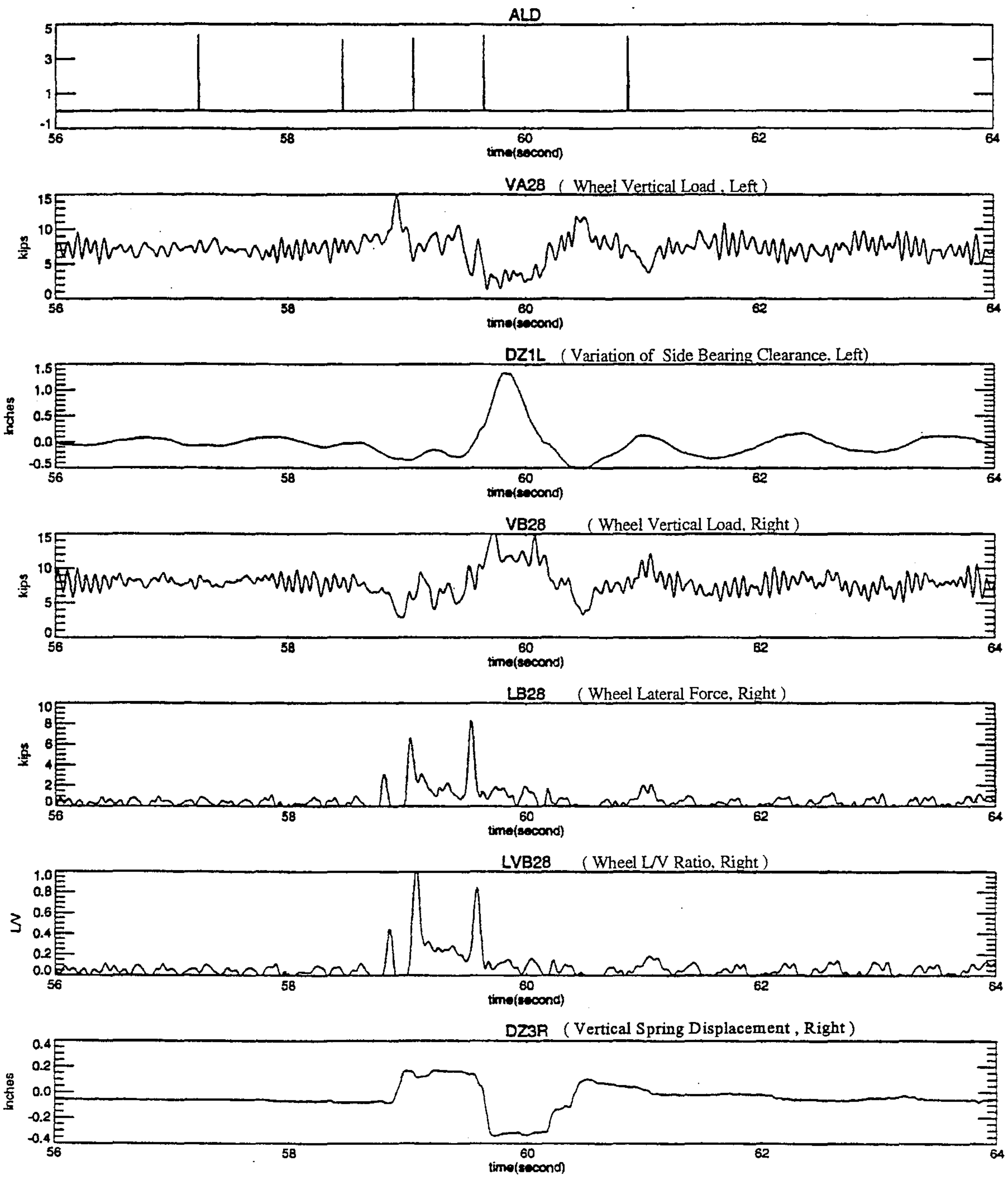

Figure 7.1 Vehicle Dynamic Response to Track Twist, Tangent Track, Covered Hopper

7.1 VEHICLE INSTABILITY

Tangent track test maximum speeds were often limited by instability of the test cars rather than wheel unloading or L/V ratios. Truck hunting was detectable at 47.5 mph for the covered hopper and was fully developed at 60 mph. The cross level perturbation tended to disrupt and dampen the hunting of the hopper car as shown in Figure 7.2. The perturbation had the opposite effect on the tank car, causing it to begin hunting at 52 mph as also shown in Figure 7.2.

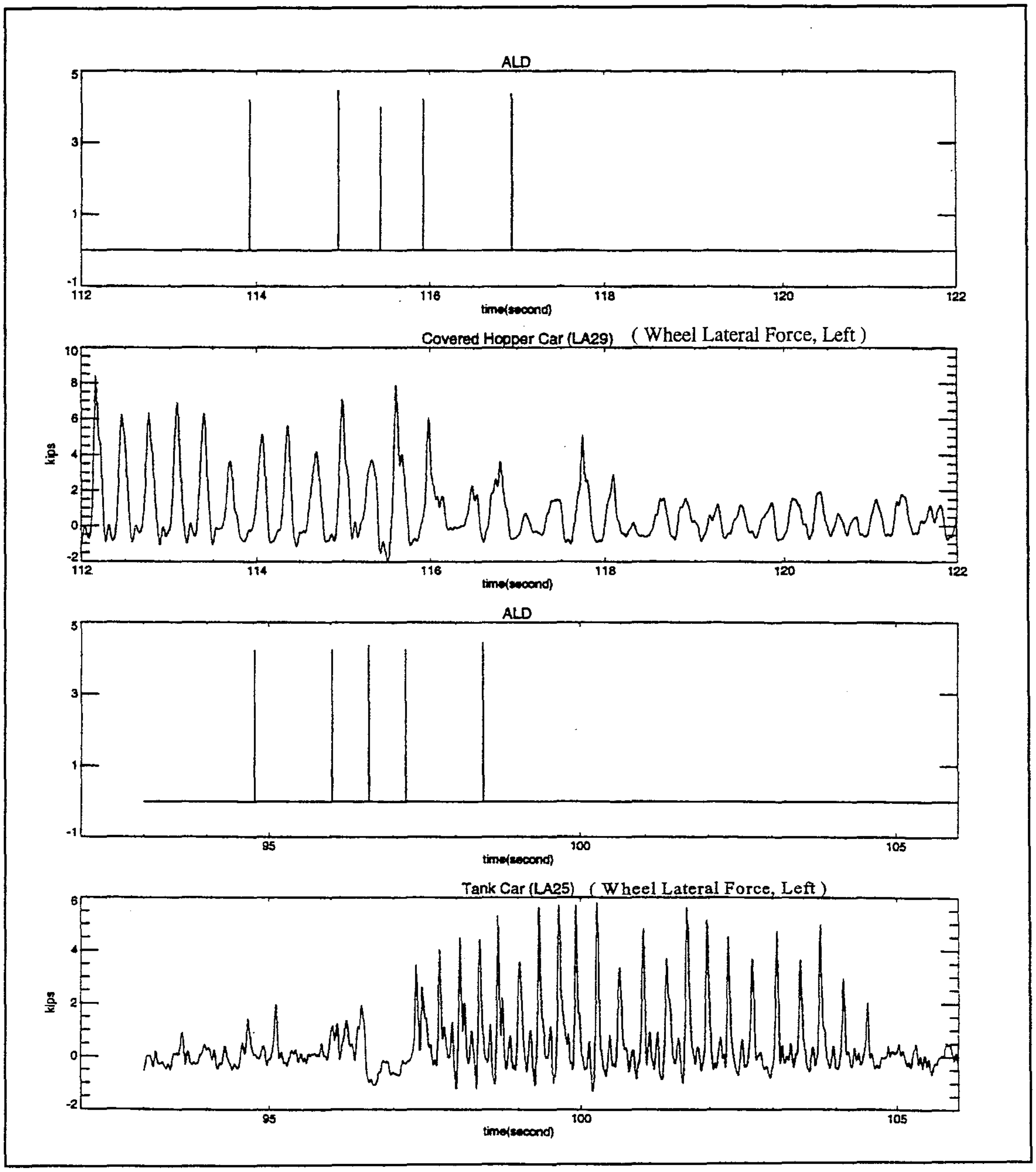

Figure 7.2 Effect of Track Perturbation to Vehicle Instability

7.2 WHEEL UNLOADING

Figure 7.3 presents vertical wheel load time histories for all three vehicles types over the tangent track cross level perturbation at 40 mph. The left wheel load of the leading axle is shown. Since the instrumented wheel sets were installed in the leading truck, peak wheel unloading was recorded when the trailing truck was at the top of the perturbation and the leading truck was outside of the perturbation zone. In contrast, the right wheel peak unloading occurred when the left wheel of the same axle was on top of the perturbation. This diagonal wheel unloading pattern agreed with the response measured during the quasi-static jacking tests.

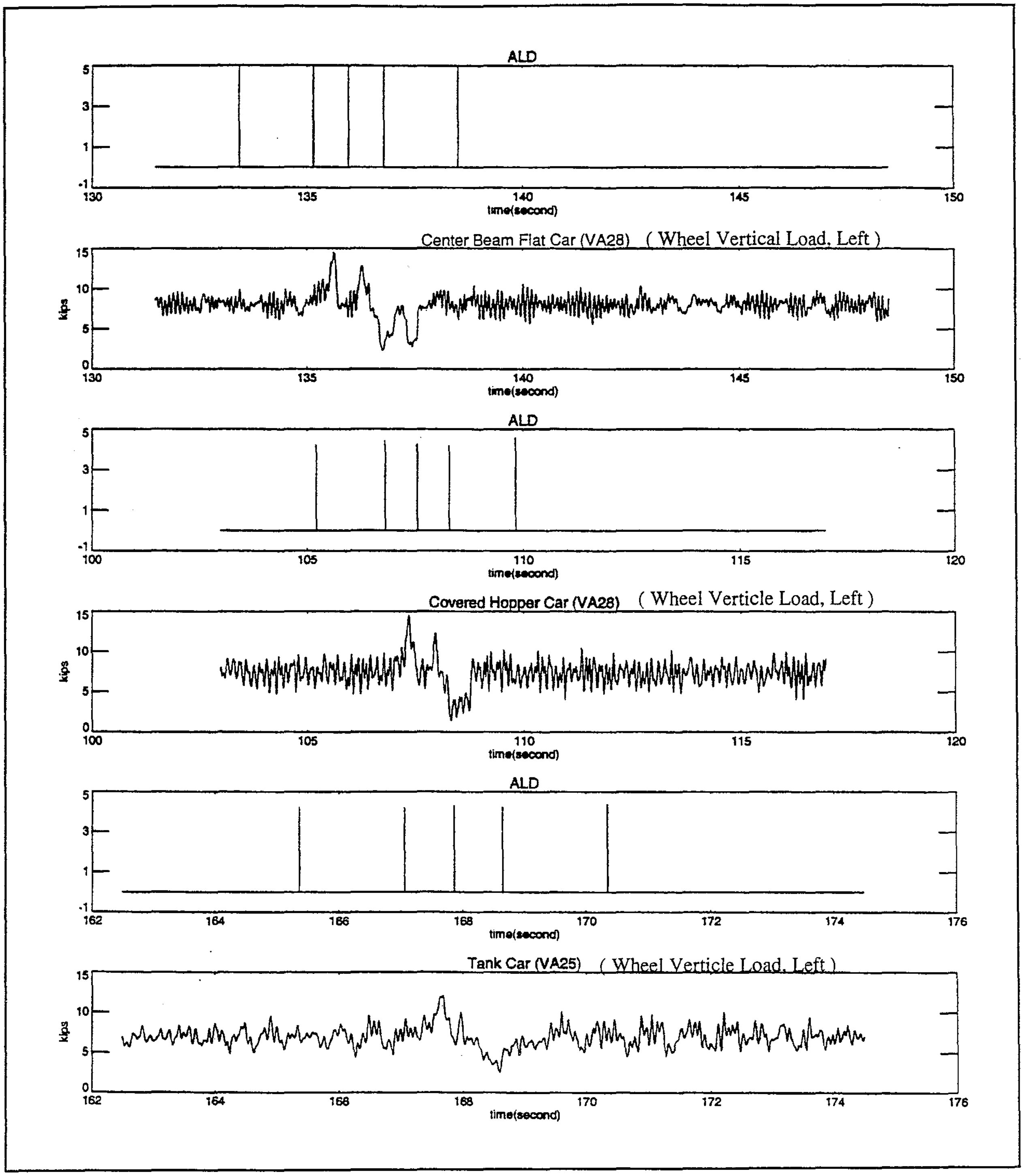

Figure 7.3 Wheel Vertical Load Variations over a Cross Level Perturbation

Figure 7.4 presents the maximum percentage of wheel unloading as a function of speed for the flatcar. The peak wheel unloading was below 60 percent at 5 mph compared to the static response of 50 percent at 3 inches of cross level difference. The peak unloading of the left wheels was relatively constant until 35 mph. The peak unloading then sharply increased with increasing speed. Peak unloading reached 88 percent at 46 mph. Ninety-percent wheel unloading could be expected at 48 mph and the test was halted. Wheel unloading of the flatcar was not significantly affected by adding the 1.75-inch alignment perturbation. The unloading of the right wheel increased with increasing speed as shown in Figure 7.5.

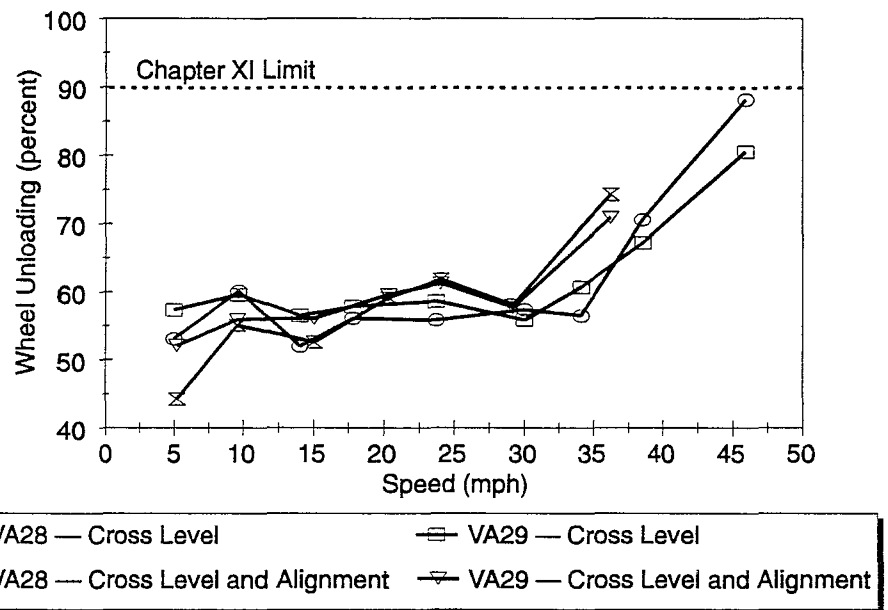

Figure 7.4 Vertical Wheel Unloading on Tangent Track, Left Wheels, Flatcar

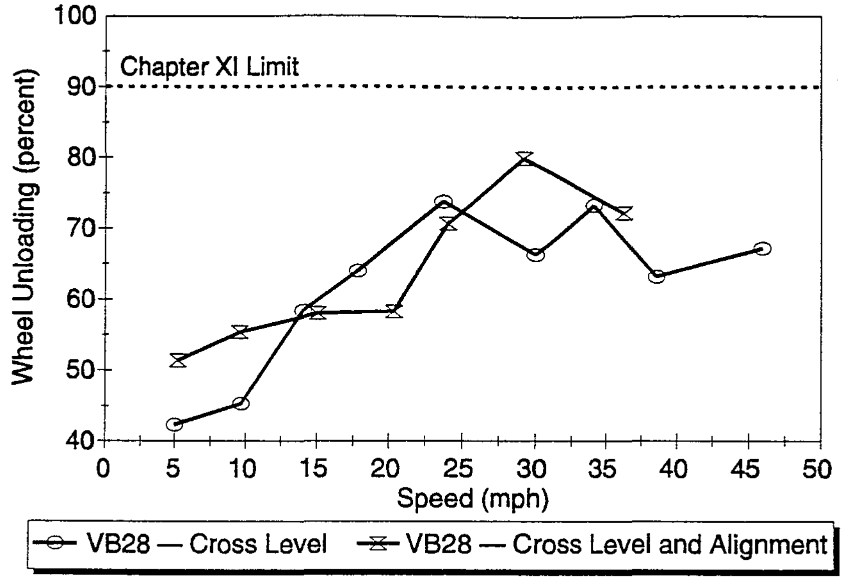

Figure 7.5 Vertical Wheel Unloading on Tangent Track, Right Wheels, Flatcar

Figure 7.6 presents the maximum percentage wheel unloading as a function of speed for the covered hopper car. The peak wheel unloading of left wheels was between 58 and 68 percent at 5 mph compared to the static response of 58 percent and increased with speed for both left and right wheels. At 38 mph, the left wheel of the leading axle reached 90 percent unloading over a 20-millisecond duration. After a decline of percentage wheel unloading between 38 and 50 mph, the maximum wheel unloading reached 88 percent at 65 mph. However, vehicle hunting was fully developed at this speed. Ninety-percent wheel unloading occurred at 24 mph after adding the 1.75-inch alignment perturbation and rose to 92 percent at 53 mph. A sharp increase in unloading of the right wheels occurred at approximately 25 mph. The unloading reached 82.5 percent at the hunting speed with cross level perturbation, and reached 82 percent at 32 mph with cross level and alignment, as shown in Figure 7.7.

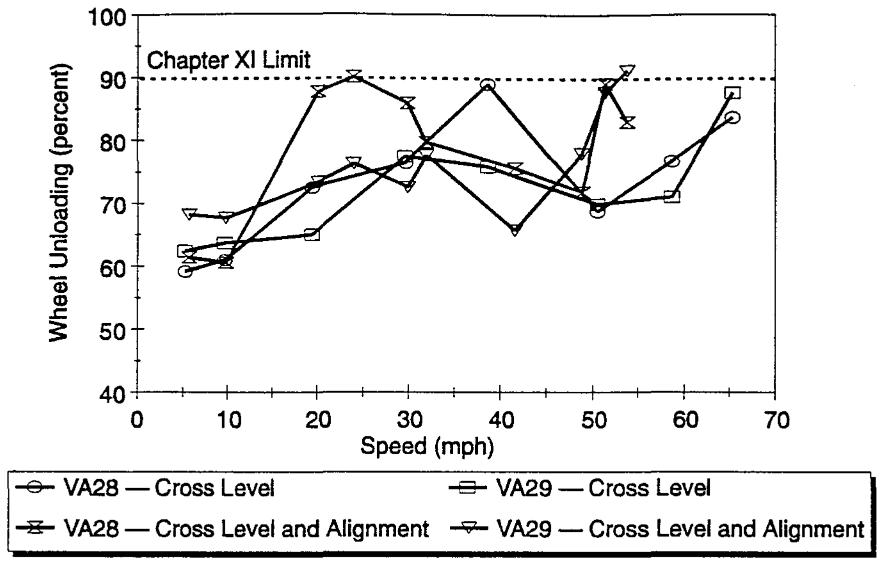

Figure 7.6 Vertical Wheel Unloading on Tangent Track, Left Wheels, Covered Hopper Car

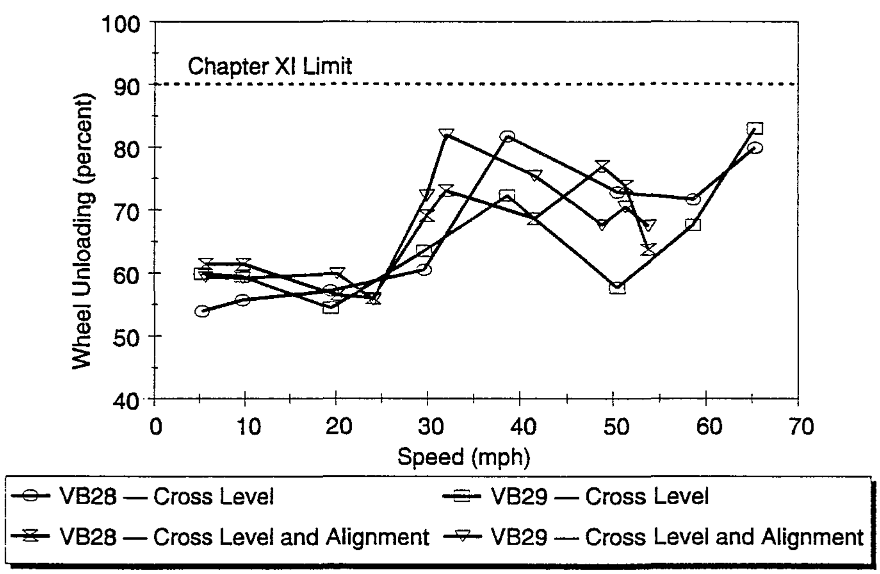

Figure 7.7 Vertical Wheel Unloading on Tangent Track, Right Wheels, Covered Hopper Car

Figure 7.8 presents the maximum wheel unloading percentage of left wheels as a function of speed for the tank car. The wheel unloading was between 45 and 65 percent at 5 mph, compared to the static response of 68 percent. A sharp rise in wheel unloading occurred between 30 and 35 mph. Adding the alignment perturbation significantly increased the percentage of unloading at the same speed levels with wheel unloading rising to 95 percent at 40 mph. Wheel unloading was below 75 percent for the tank car right wheels, as shown in Figure 7.9.

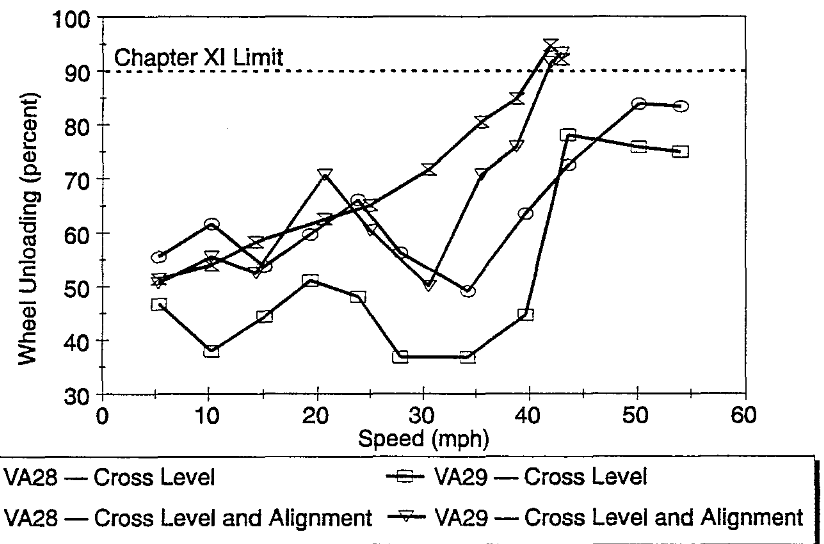

Figure 7.8 Vertical Wheel Unloading on Tangent Track, Left Wheels, Tank Car

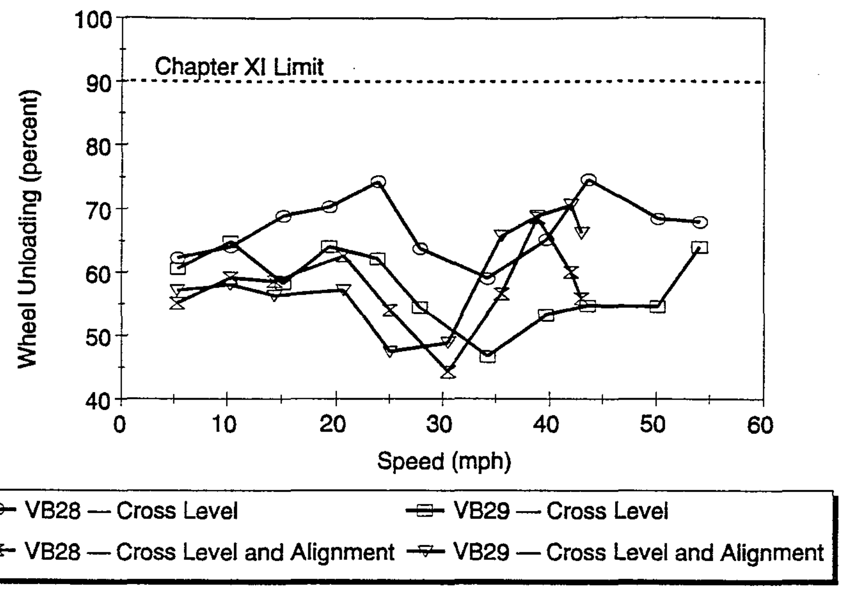

Figure 7.9 Vertical Wheel Unloading on Tangent Track, Right Wheels, Tank Car

7.3 WHEEL/RAIL LATERAL FORCE

Figure 7.10 shows a lateral force time history from the covered hopper car over the 2.25-inch cross level perturbation with 1.75-inch misalignment. Data is recorded from the right wheel of the lead axle at 35 mph. The peak lateral forces occurred when the left wheels in the same axle were at the top of the perturbation. At 35 mph, the vehicle was stable. The lateral force oscillation excited by the perturbation was not sustained. At higher speeds, as the truck hunting was initiated, the wheel set oscillation continued and resulted in repeated peak lateral forces. For a stable vehicle, the peak lateral forces at the right wheels were higher than the forces at the left wheels.

Figures 7.11, 7.12, and 7.13 show the maximum lateral forces of right wheels for three vehicles. With cross level perturbation only, the increased lateral force at the higher speed on the covered hopper and the tank car were caused by vehicle hunting. Adding the alignment perturbation (to the left) caused much higher lateral forces due to flange contact of the right wheels.

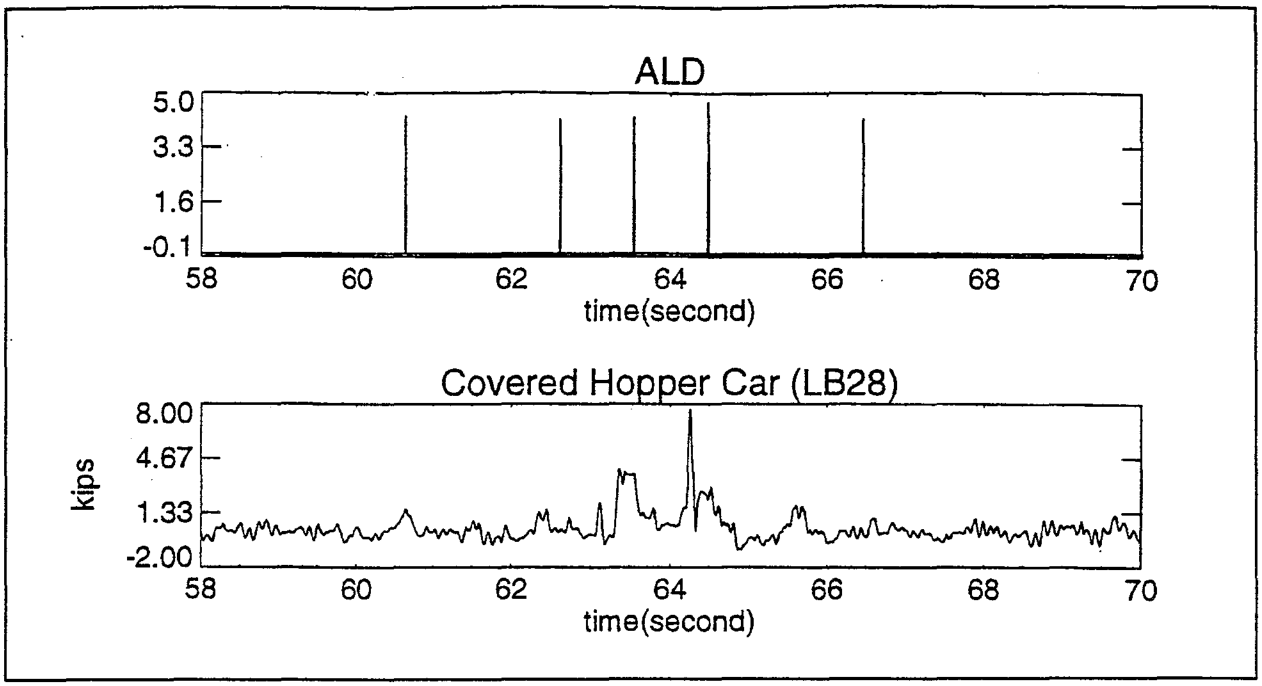

Figure 7.10 Wheel Lateral Force Variations over a Cross Level/Alignment Perturbation

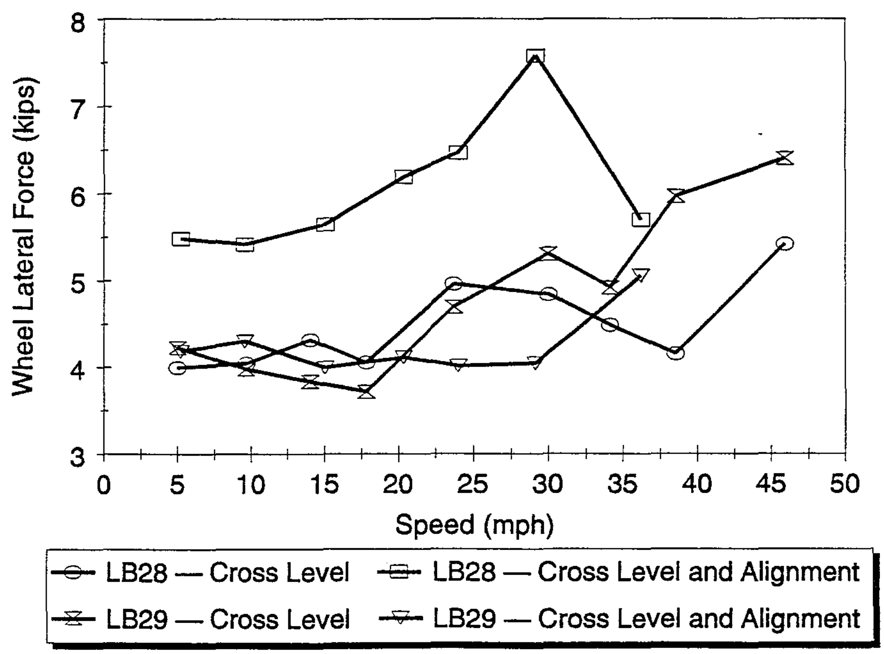

Figure 7.11 Wheel/Rail Lateral Force on Tangent Track, Right Wheels, Flatcar

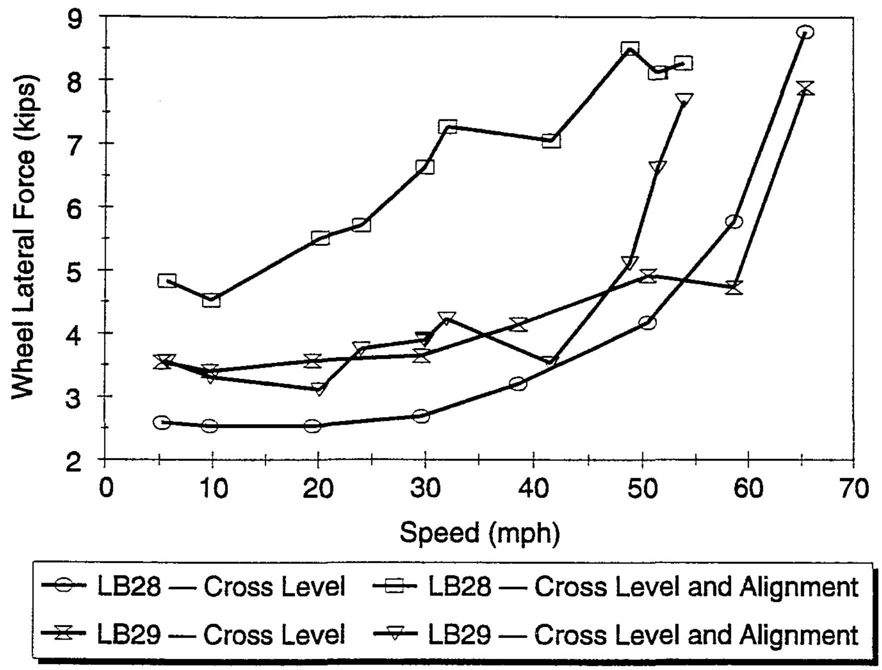

Figure 7.12 Wheel/Rail Lateral Force on Tangent Track, Right Wheels, Covered Hopper

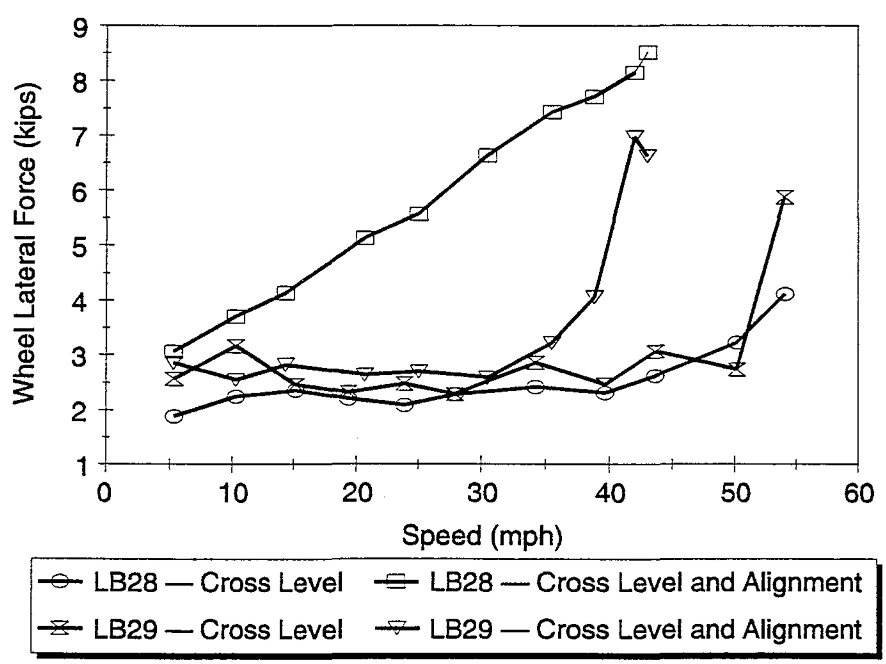

Figure 7.13 Wheel/Rail Lateral Force on Tangent Track, Right Wheels, Tank Car

7.4 WHEEL L/V RATIO

Figure 7.14 shows a sample wheel L/V ratio traced over a perturbation with 2.25-inches cross level difference and 1.75-inch alignment. The data recorded is from the right wheel of the lead axle of the covered hopper at 35 mph. Similar to the lateral force response, the peak of the L/V ratio was recorded in the perturbation zone. Notice that the peak L/V ratio and the peak lateral force were recorded on the right wheel of the leading truck when the left wheels of same axle were on the top of the perturbation. Then, as the vehicle moved forward, the maximum wheel unloading was recorded at the left wheel of leading truck when the leading truck was outside the perturbation zone, as shown in Figure 7.3.

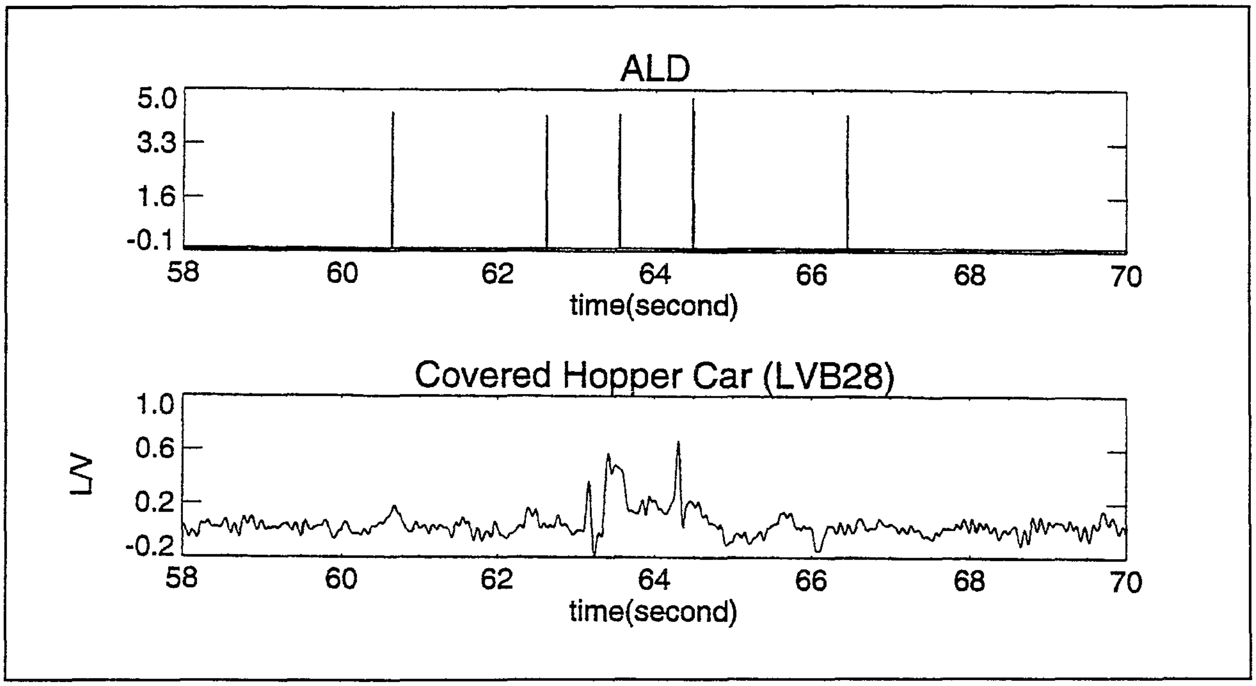

Figure 7.14 Wheel L/V Ratio Variations over a Cross Level/Alignment Perturbation

Figures 7.15, 7.16 and 7.17 show the peak values of wheel L/V ratios as a function of speed for the three vehicles. The flatcar L/V ratio was above 1.0 when speed exceeded 35 mph, in a 20- to 30-millisecond time duration. Similar to the lateral forces, the wheel L/V ratios recorded were much higher by adding the alignment perturbation. The ratio exceeded Chapter XI limits at low speed (below 10 mph) on the covered hopper and at higher speed (36 mph) on the flatcar.

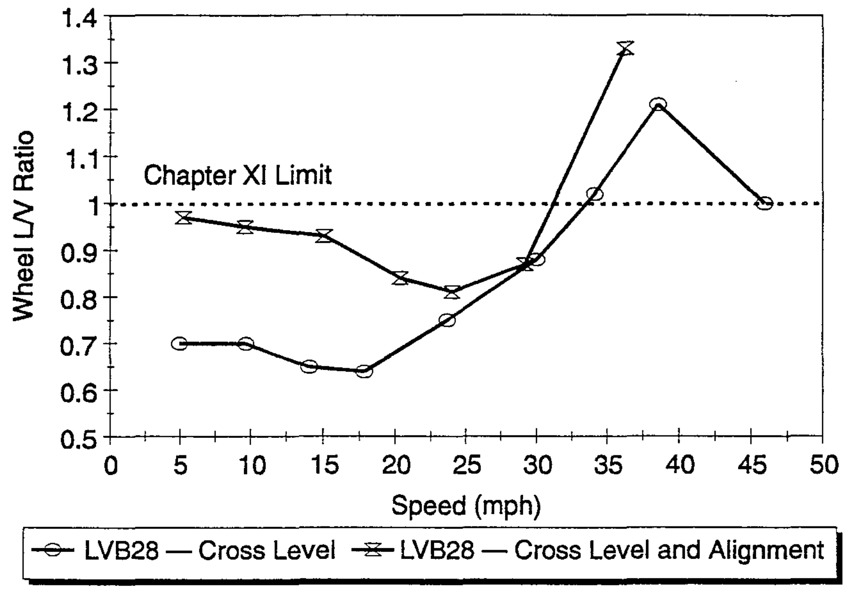

Figure 7.15 Wheel L/V Ratios on Tangent Track, Right Wheel of Leading Axle, Flatcar

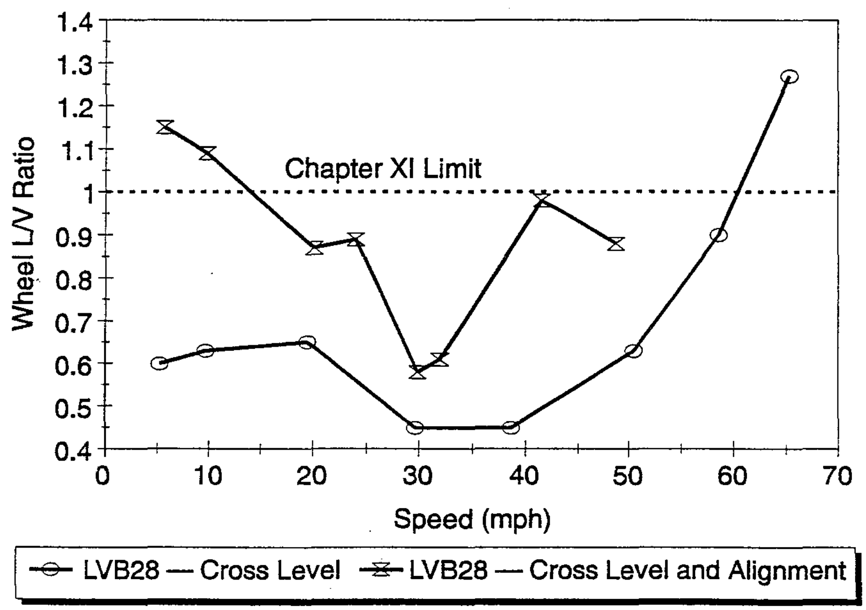

Figure 7.16 Wheel L/V Ratios on Tangent Track, Right Wheel of Leading Axle, Covered Hopper

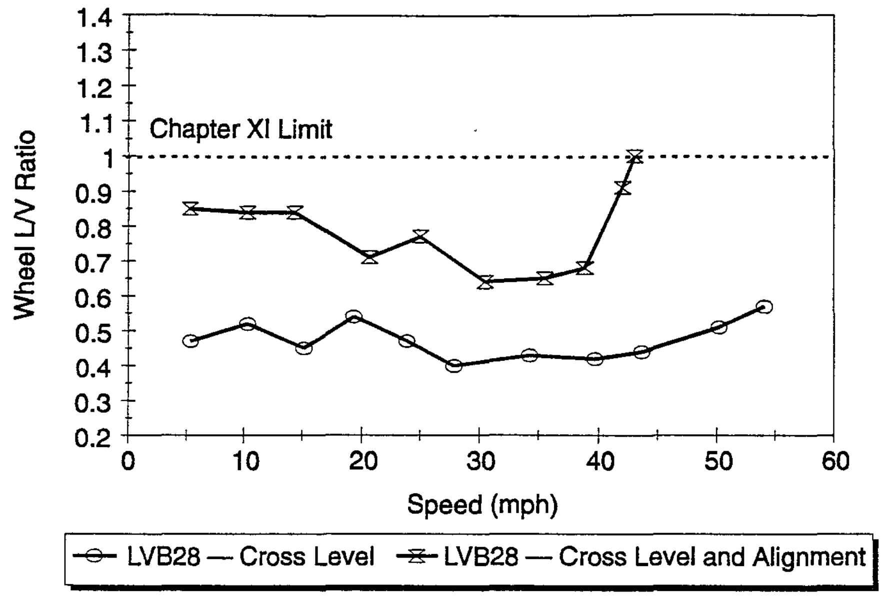

Figure 7.17 Wheel L/V Ratios on Tangent Track, Right Wheel of Leading Axle, Tank Car

7.5 AXLE SUM L/V RATIO

Figures 7.18 through 7.20 show the axle sum L/V ratios of the three vehicle types. Like the wheel L/V ratios, the axle sum L/V ratios were much higher when the alignment perturbation was added, especially at the lower speed. All values met the Chapter XI limit of 1.5, except at 35 mph for the flatcar.

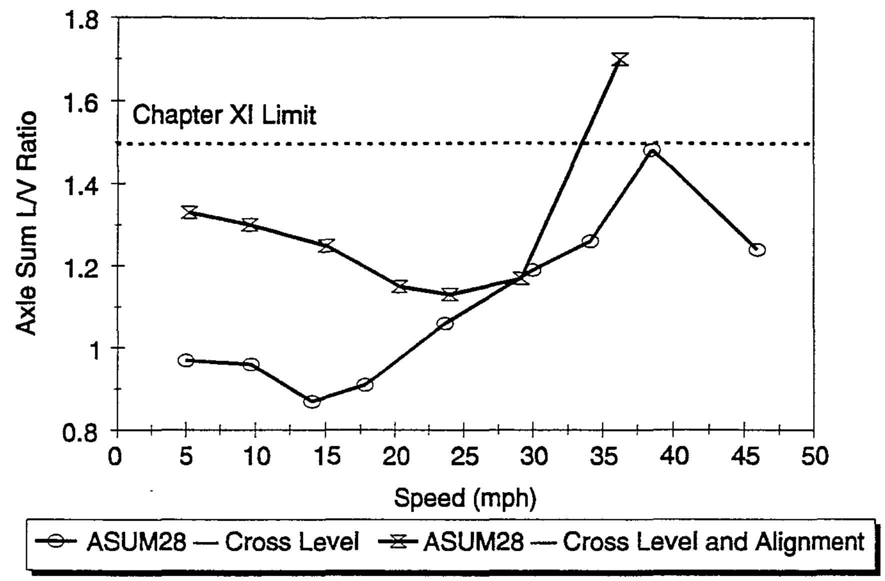

Figure 7.18 Axle Sum L/V Ratio on Tangent Track, Leading Axle, Flatcar

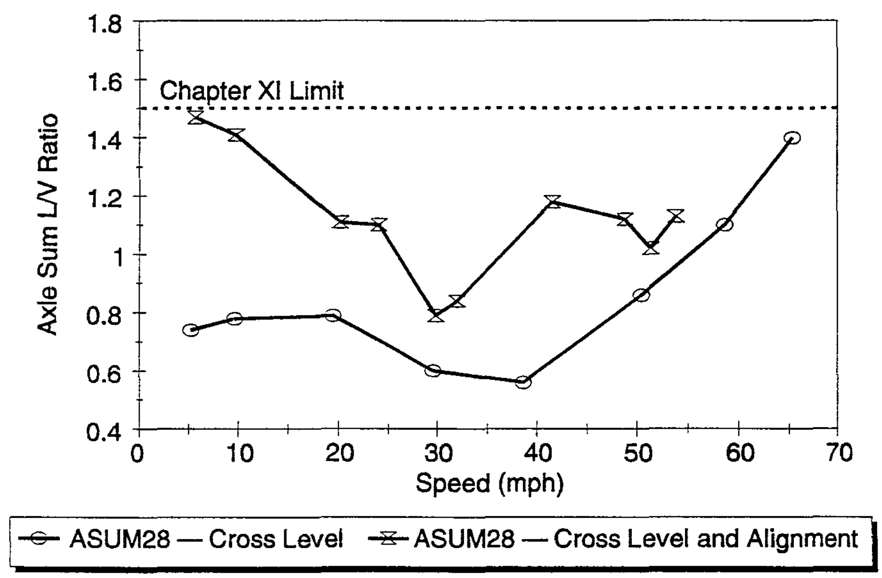

Figure 7.19 Axle Sum L/V Ratio on Tangent Track, Leading Axle, Covered Hopper

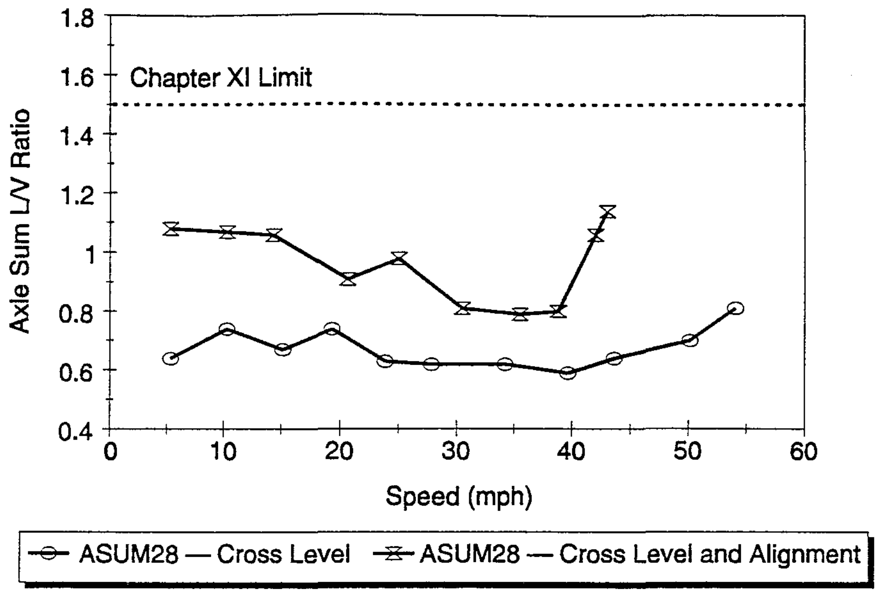

**Figure 7.20 Axle Sum L/V Ratio on Tangent Track,
Leading Axle, Tank Car**

7.6 CENTER PLATE SEPARATION

Analysis of center plate separation during the dynamic track test is more complex because of rail roughness disturbances and the differences in response of snubbers under dynamic loading situations.

Figure 7.21 shows the side bearing to car body displacement, spring nest displacement, and vertical wheel unloading of the leading truck of the covered hopper car as it passed over the 2.25- inch cross level and 1.75-inch alignment perturbation at 52 mph. A side bearing displacement of 1.35 inches was recorded at the unloading side of vehicle, and a 0.24-inch suspension compression was recorded on the right side with the same amount of extension recorded on the left side. Note that zero displacement was the 0.25-inch side bearing clearance. The center plate separation can be determined by Equation 3.2 as:

$$H = 1.35 + 0.25 = 1.6 \text{ inch} > H_{HC}$$

where $H_{HC} = 0.676$ inch

Since H is considerably larger than H_{HC}, the center plate was evidently fully separated from the truck center bowl. All loading at the lead truck was carried by the side bearing at the right side of the car.

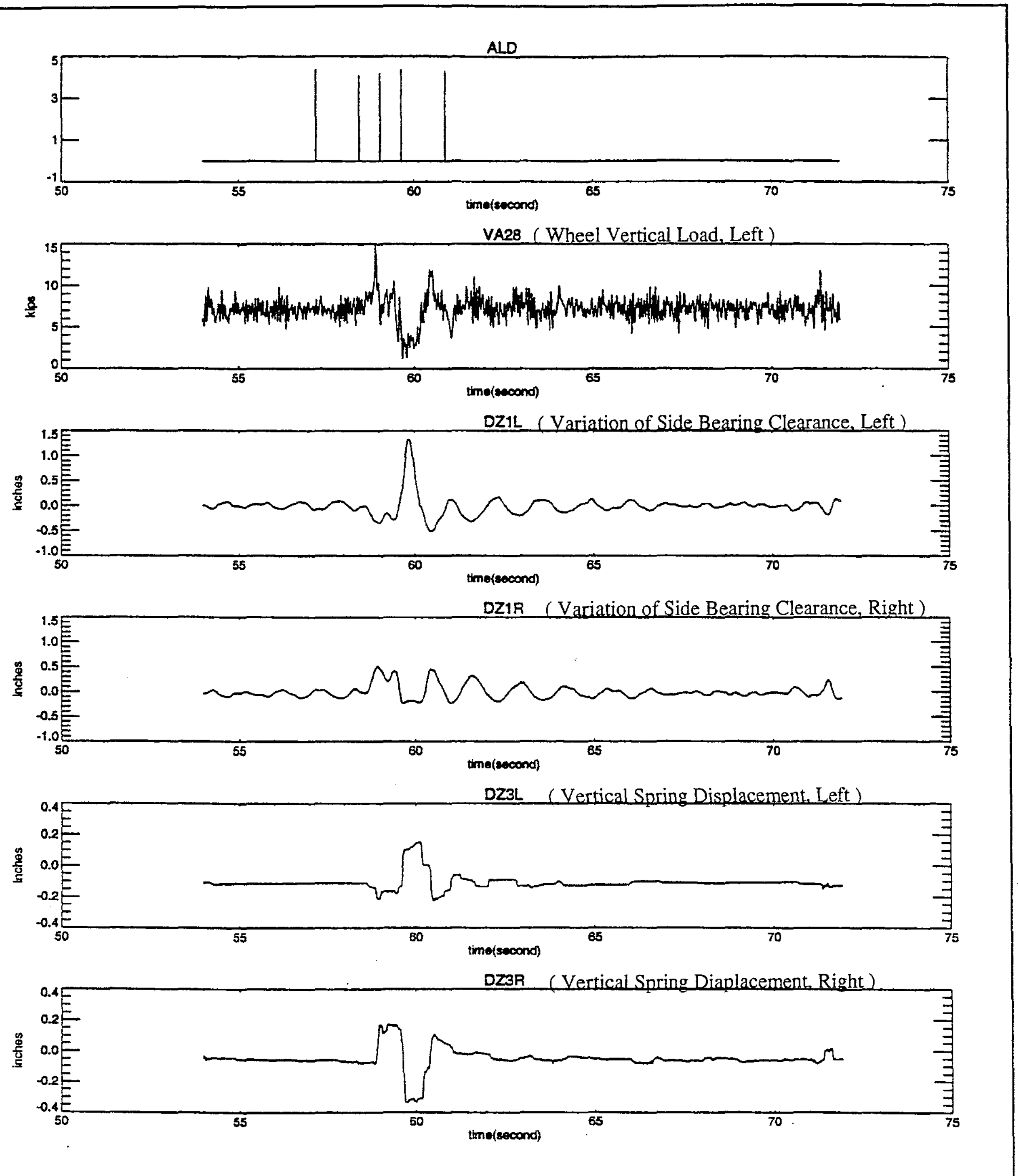

Figure 7.21 Example Displacement of Side Bearing Separation over a Cross Level Perturbation to Reflect the Center Plate Separation

Test results indicated that center plate separation was influenced by speed. Figures 7.22 and 7.23 present the car body to side bearing separation as a function of speed for the flatcar and the covered hopper car (SB indicates Side Bearing). The separation of the flatcar side bearing remained constant until the speed exceeded 35 mph with the cross level perturbation only and above 30 mph with both cross level and alignment perturbation, which had a good agreement with the wheel unloading (Figure 7.4). Above those speeds, the center plate full separation was certainly occurred according to the separation criterion. The separation sharply increased between 20 and 25 mph on the covered hopper.

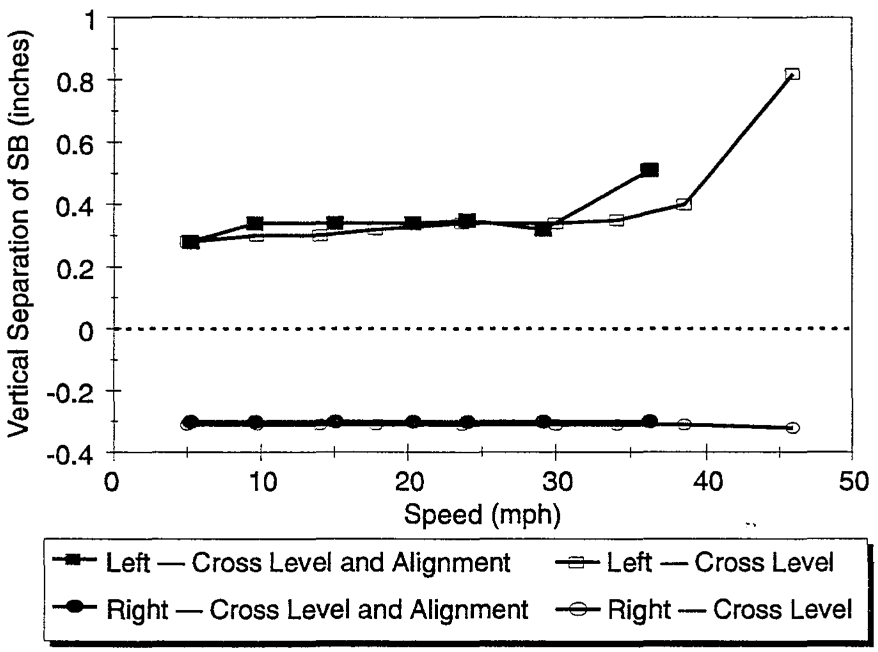

Figure 7.22 Center Plate Separation Indicated by Displacement of Side Bearing, Leading Truck of Flatcar

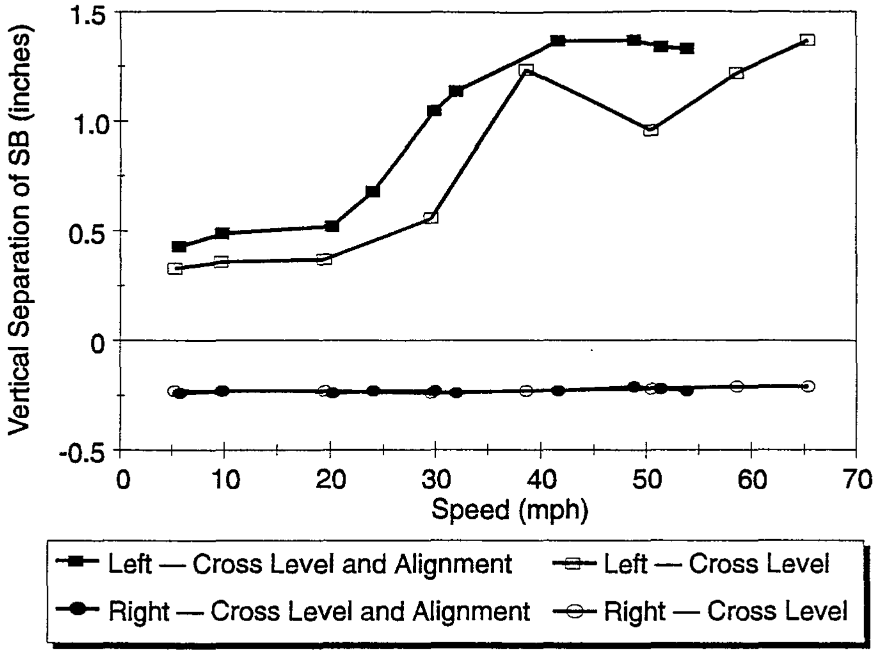

Figure 7.23 Center Plate Separation Indicated by Displacement of Side Bearing, Leading Truck of Covered Hopper

To more closely detect the center plate separation and to verify the two dimensional assumption in the analysis of rail vehicle center plate separation, four Linear Variable Differential Transformer's (LVDT's) were installed in the edges of each center plate of the tank car as shown in Figure 7.24. Because the measurements were taken directly at the edges of each center plate, the separation criterion can be defined using the following formula:

$$\delta_{TC} > \frac{2c_1 d}{D - d} \tag{7.1}$$

where δ_{TC} is the measurement taken at the edge of the unloading side (δ_2 in Figure 7.24) and other parameters are same as described in the Section 3.2.

Figure 7.25 shows the reaction of the LVDT's at the front and rear edges of the center plate (the negative values in the time history plots present the separation according to the instrumentation setting). Although the measurements were not identical at the two edges, the difference was not enough to significantly affect the two-dimensional analysis.

As illustrated in Figure 7.24, complete center plate separation could be detected from the same direction measurements at the left and right edges. Figure 7.26 shows center plate separation detected on the tank car with 2.5-inches of cross level perturbation at 54 mph. When the leading truck was on the top of the perturbation, the left wheel load increased and the right edge of the center plate rose to a maximum value of 0.15 inch while the left edge remained closed. By geometric computation, the side bearing at the right side was slightly touching the car body. The vertical load was carried primarily by the right edge of the center plate with some load transferred to the side bearing.

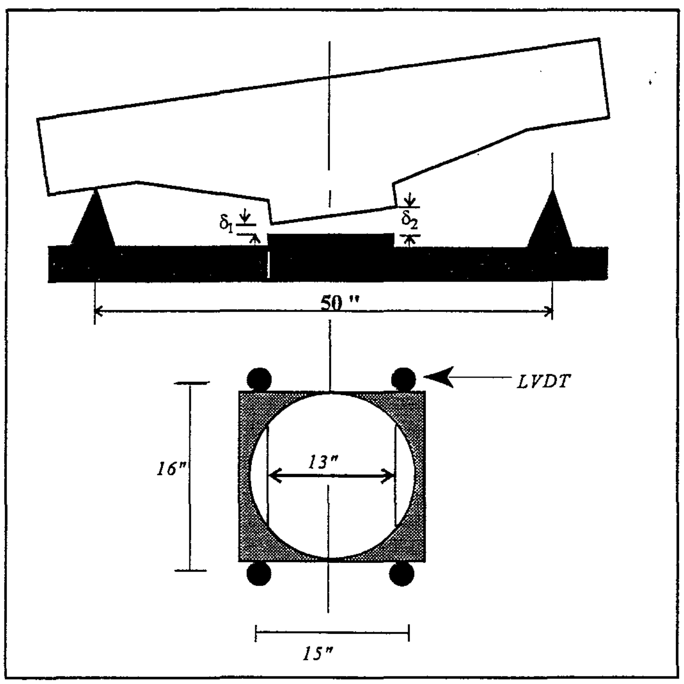

Figure 7.24 The Arrangement of LVDT to Directly Detect the Separation of Center Plate on Tank Car

When the trailing truck was run on the top of perturbation, the leading truck left wheel load decreased by about 85 percent of static load. The left edge of the center plate displacement was 0.3 inch while the right edge had risen to 0.05 inch. The rise of both the left and right edges of the center plate indicates the center plate was completely separated from the center bowl in that moment. Note that in the same moment, the left side suspension rose about 0.25 inch, while the right side compressed 0.1 inch.

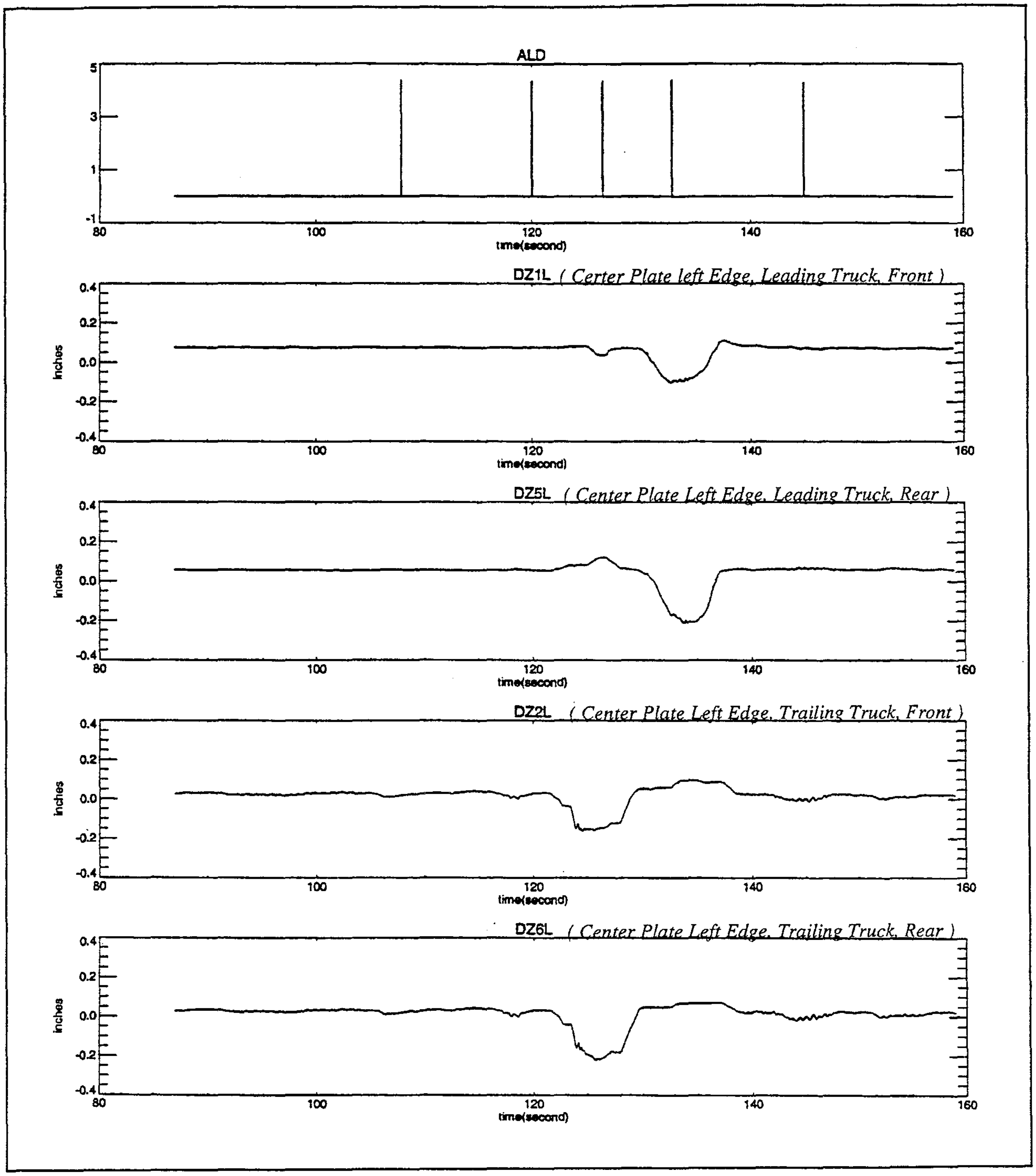

Figure 7.25 Comparison of Measurements at the Front and Rear Edges of Center Plate

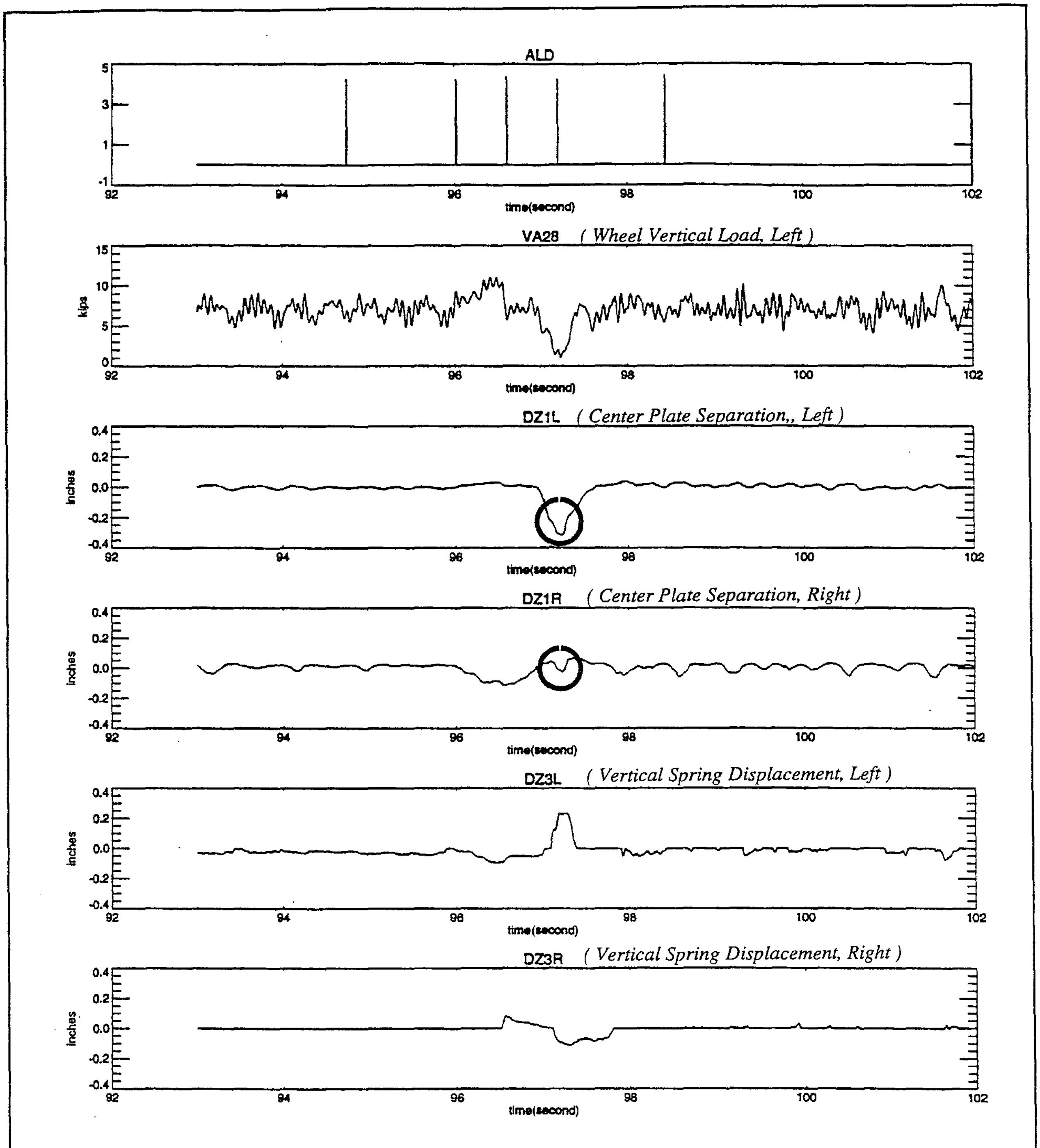

Figure 7.26 Example Center Plate Separation over a Cross Level Perturbation-Tank Car

Figure 7.27 presents the center plate separation as a function of speed for the tank car. If the side bearing clearance was 0.25 inch, by geometric computation, the center plate separated from the center bowl when the car body to bolster displacement at the unloading side of the center bowl was larger than 0.18 inch. With the cross level perturbation only, the displacement increased with speed exceeding 0.18 inch at about 35 mph. Displacement of 0.2 inch was recorded at all speeds over the cross level/alignment perturbation. A sharp increase occurred above 30 mph, which was in good agreement with the tank car wheel unloading.

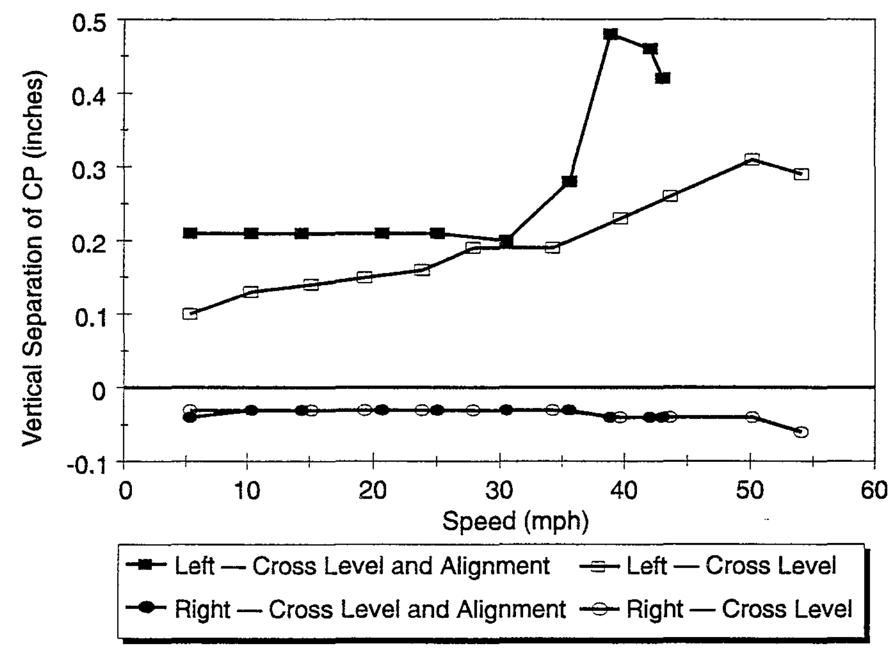

Figure 7.27 Center Plate Separation on Tangent Track, Leading Truck of Tank Car

Note that center plate separation criterion are sensitive to the initial settings of side bearing clearance. Also the small variations of the center plate separation measurements increase the difficulty to determine the starting stage of center plate fully unloading.

7.7 SUMMARY OF TANGENT TRACK TESTS

The critical track twist condition on tangent track is wheel unloading at higher speeds. Table 8 shows the maximum testing speeds achieved without exceeding Chapter XI limits.

Table 8. The Maximum Operating Speed Without Exceeding Chapter XI Limits on Tangent Track

	Center Beam Flatcar Speed (mph) (3" Cr)		Covered Hopper Speed (mph) (2.25" Cr)		Tank Car Speed (mph) (2.5" Cr)	
Chapter XI Limits	Unloading (90%)	L/V(W) (1.0)	Unloading (90%)	Hunting	Unloading (90%)	Hunting
Tangent, Cr	48	P	P	65	P	54
Tangent, Cr and Al	P	30	50*	N/A	40	N/A

* The L/V limit was exceeded below 15 mph.
L/V (W) is Chapter XI wheel L/V limit (1.0) and Unloading is Chapter XI wheel unloading limit (90 percent off static load).
P indicates the limit was not exceeded at stop speed.
Cr and Al are the cross level difference and alignment (1.75 inch).

Vehicle response was influenced by the operating speed. In all cases, the 90-percent wheel unloading occurred at speeds above 30 mph. Adding the alignment perturbation caused wheel unloading on the covered hopper and tank car, and caused a high L/V ratio on the center beam flatcar. Center plate unloading was detected at higher speeds for all three vehicles and was in good agreement with vehicle wheel unloading. As the hunting speed was reached, the cross level perturbation acted as a disturbance to initiate the hunting on the tank car, and to damp out the hunting on the coved hopper car. Peak wheel unloading was recorded at the left wheels of the leading truck while the trailing truck was in the perturbation zone. Peak wheel L/V ratios were recorded at the right wheels while the left wheels of the same axle were on the top of perturbation.

8.0 RESULTS OF CURVED-TRACK TESTS

As predicted, operating an empty vehicle on perturbed curved-track produced the conditions which can lead to flange climb derailment. Although derailment did not occur during the test, the excessive L/V ratios indicated the likely potential. Table 9 is the test matrix for the curved-track tests.

The cross level perturbation was installed in the low rail of the curves thereby reducing the superelevation at that point. The reduction in superelevation caused increased flange contact and the higher lateral forces on the high rail. At the same time, the vertical wheel load of the leading axle at the high rail was reduced as it ran on the top of the perturbation. Thus, the wheel L/V ratio was considerably higher on the perturbed curved-track compared to the rest of the curve.

Table 9. Curved-track Test Matrix

Car Type	Curve and Perturbation					Number of Runs
Flatcar	7.5-degree curve Cross level 3"	7.5-degree curve Cross level 3" and Alignment 1.75"	12-degree curve Cross level 3"	Bunched Spiral	Limiting Spiral	48
Speed	2 - 26 mph	2 - 30 mph	2 - 30 mph	2 - 23 mph	5-23 mph	
Covered Hopper	7.5-degree curve Cross level 2.5"	7.5-degree curve Cross level 2.5" and Alignment 1.75"	12-degree curve Cross level 2.25"	Bunched Spiral	Limiting Spiral	18
Speed	5 - 15 mph	5 - 10 mph	5 - 10 mph	5-10 mph	5-30 mph	
Tank Car	7.5-degree curve Cross level 2.5"	7.5-degree curve Cross level 2.5" and Alignment 1.75"	12-degree curve Cross level 2.25"	Bunched Spiral	Limiting Spiral	28
Speed	5 - 30 mph	5 - 15 mph	5 - 20 mph	5-25 mph	5-30 mph	

Figure 8.1 shows a time history plot of the dynamic response of the leading axle of the covered hopper car to the 2.25-inch cross level perturbation on the 12-degree curve. It is clear that the peak L/V ratio was due to the peak lateral force and wheel unloading occurring at about the same instant.

Flange climbing was observed and filmed at the high rail of the 12-degree zone for both the covered hopper and the tank car. During the climb, wheel/rail contact was at a very low position on wheel flange, sustaining about 15 to 20 percent of static vertical load and a high lateral force. Although derailment did not occur, flange climb tendency was evident.

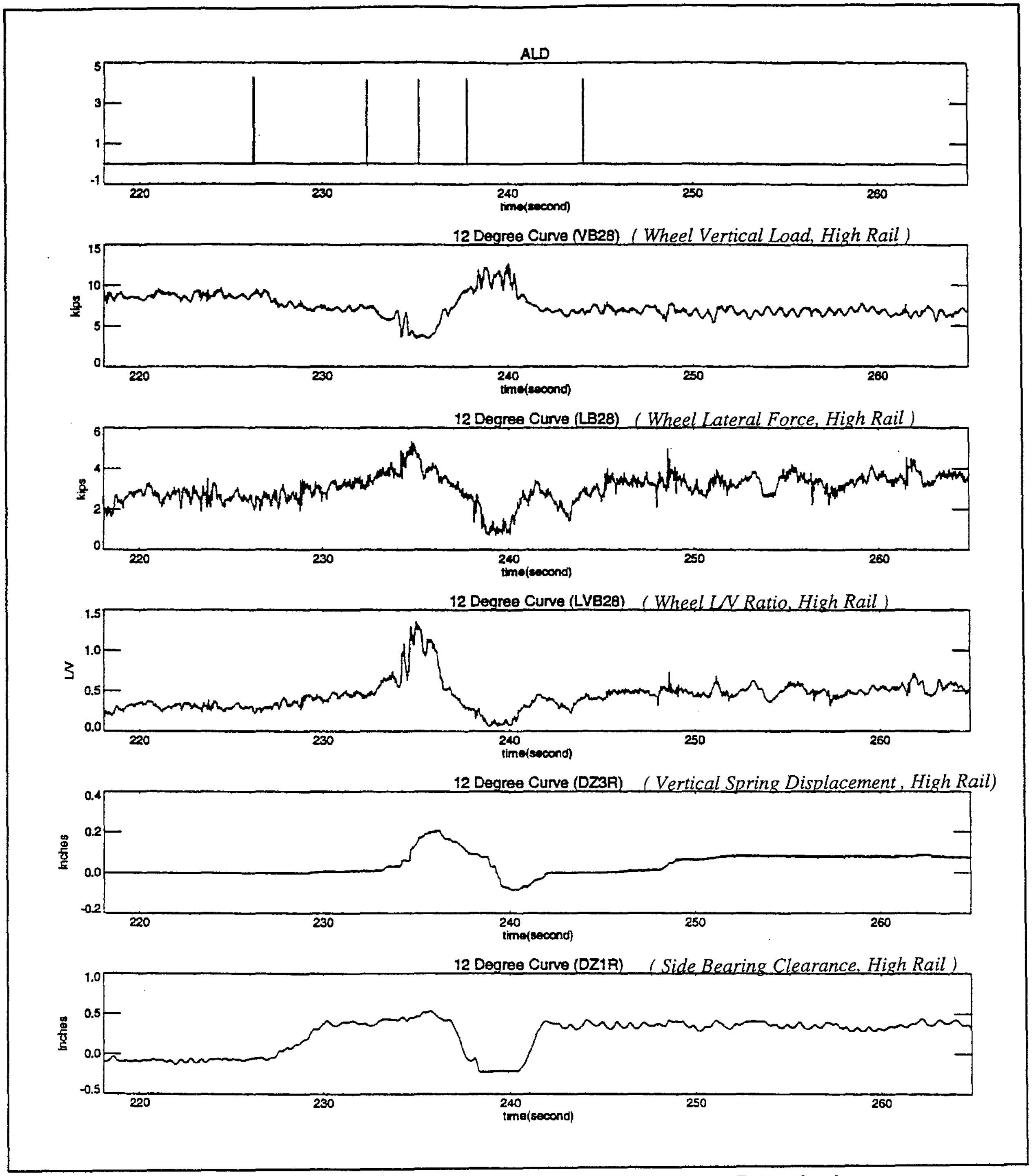

Figure 8.1 Dynamic Response to a 2.25-Inch Cross Level Perturbation on 12-Degree Curve, Covered Hopper

8.1 WHEEL L/V RATIO

Figure 8.2 shows the L/V ratios generated by the leading axle of the covered hopper at 10 mph over the curve test zones. The highest L/V ratios were recorded at the center of the perturbation zone. And compared to data on the undisturbed zone, curving performance was significantly affected by the perturbation.

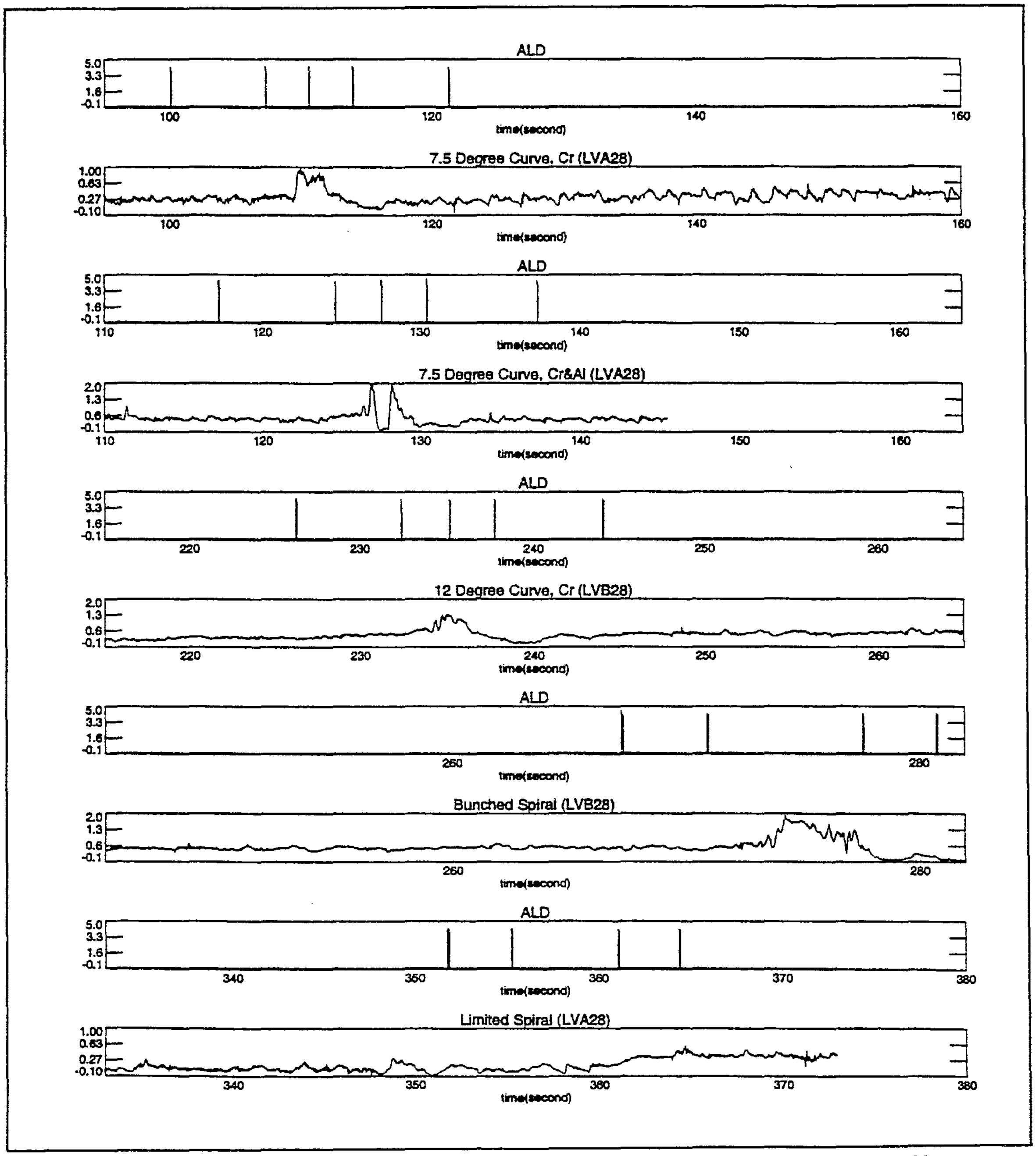

Figure 8.2 Wheel L/V Ratio Time History on Curved-track, High Rail, Covered Hopper

Figure 8.3 shows the peak wheel L/V ratios for the flatcar in all five curved-track test zones. Results indicate the flatcar can be operated up to 30 mph in all five curving test zones with peak wheel L/V ratios close to or slightly above 1.0. The dash lines in the plots for the 7.5-degree curve with cross level perturbation and the bunched spiral are predictions that if sand was not applied. In those two test series, sand was applied after 15 mph because a light snow started. The effect of sand on vehicle curve performance is discussed later.

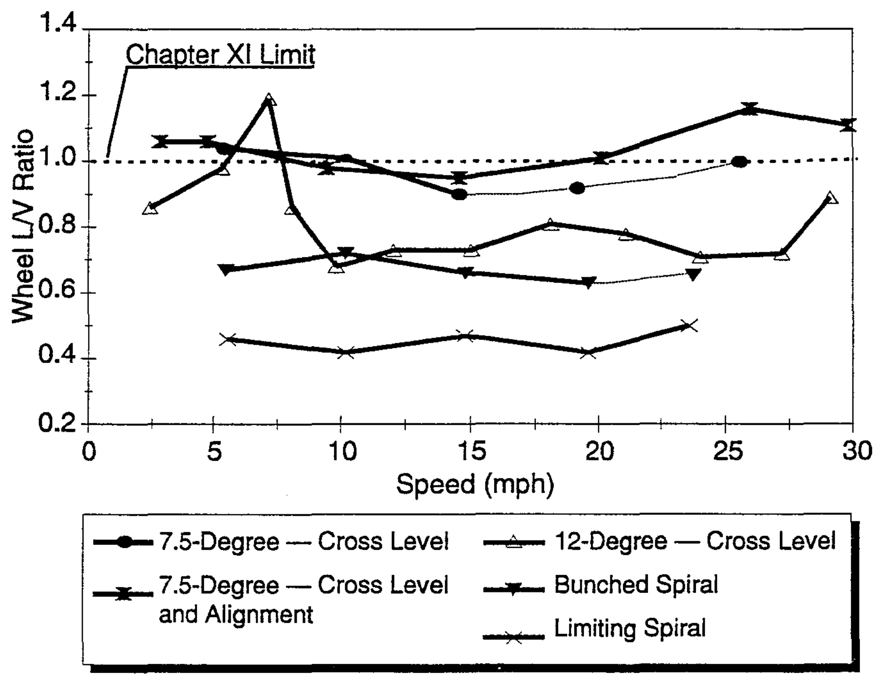

Figure 8.3 Maximum Wheel L/V Ratio on Curved-track, High Rail, Flatcar

Figure 8.4 shows the peak wheel L/V ratios recorded on the covered hopper in the five curve zones. Except for the limiting spiral, the wheel L/V ratios were all above 1.0. Ratios above 2.0 were recorded at the bunched spiral and at the 7.5-degree curve with cross level/alignment perturbation.

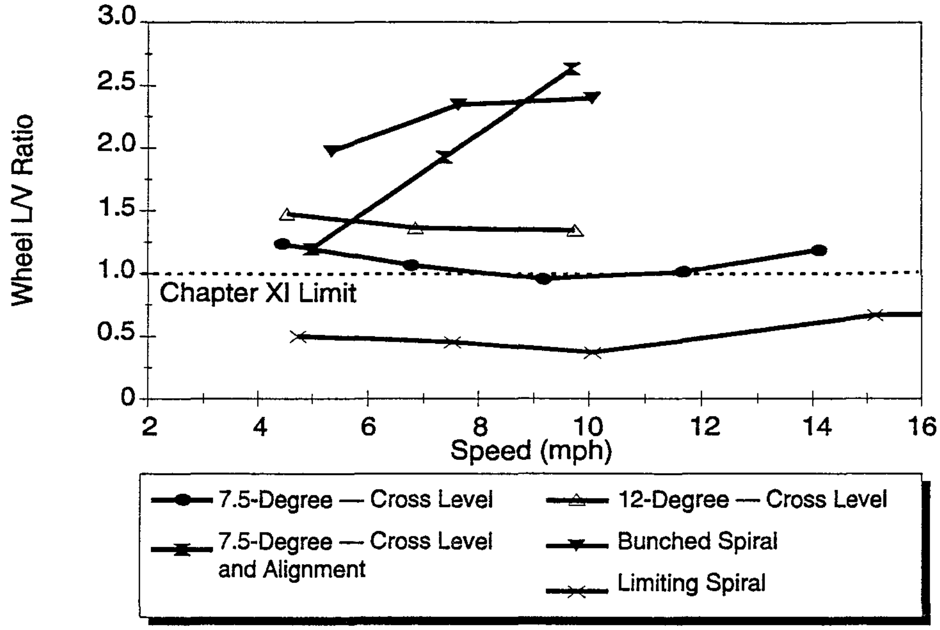

Figure 8.4 Maximum Wheel L/V Ratio on Curved-track, High Rail, Covered Hopper

Figure 8.5 shows the wheel L/V ratios recorded on the tank car without sanding the track. The values recorded at the 7.5-degree curve with cross level/alignment perturbation and the 12-degree curve, were above Chapter XI limits. The tank car was operated up to 30 mph on the 7.5-degree curve with cross level perturbation, the bunched spiral, and limiting spiral without exceeding Chapter XI limits.

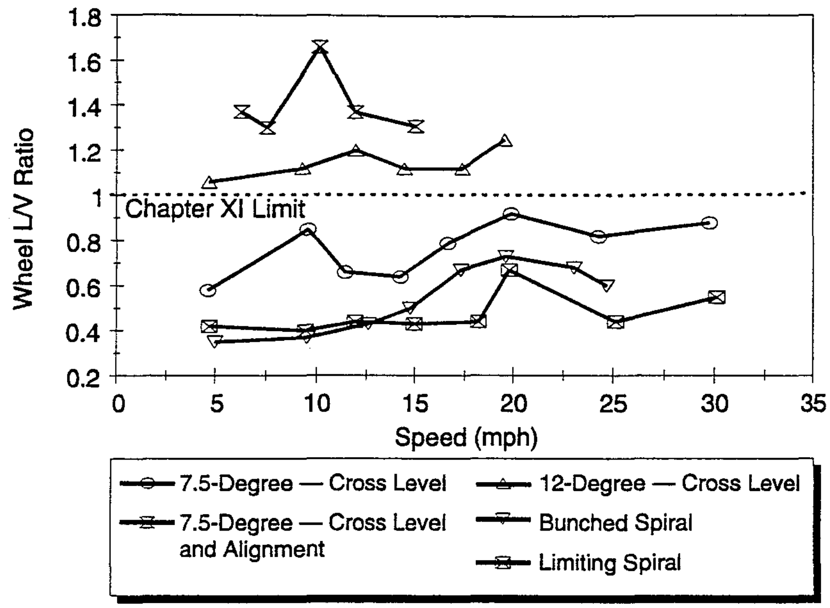

Figure 8.5 Maximum Wheel L/V Ratio on Curved-track, High Rail, Tank Car

8.2 AXLE SUM L/V RATIO

Figure 8.6 shows the flat car axle sum L/V ratios on the curved-track. As in Figure 8.2, the dash lines are the predictions that if sand was not applied. Except at 7 mph on the 12-degree curve, all axle sum L/V ratios are below the Chapter XI limit of 1.5.

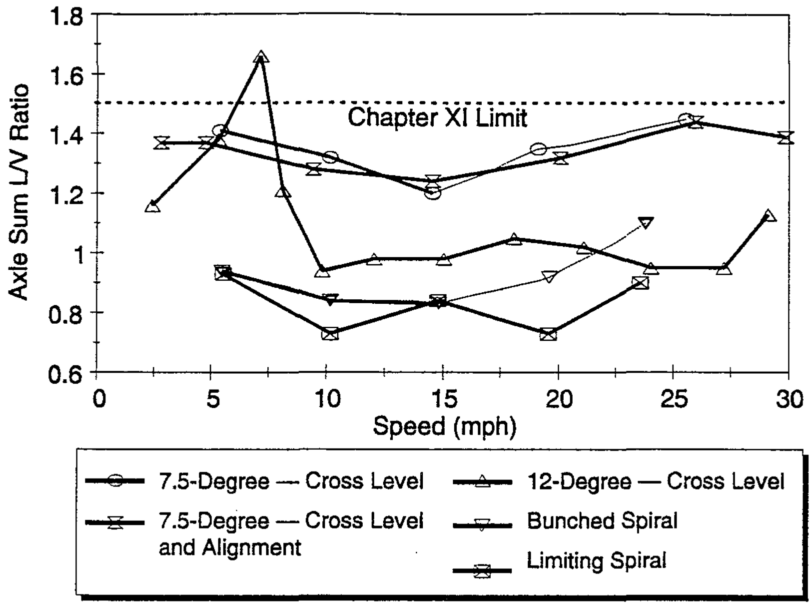

Figure 8.6 Maximum Axle Sum L/V Ratio on Curved-track, High Rail, Flatcar

The response of the covered hopper in the 7.5-degree curve with cross level perturbation is below the Chapter XI axle sum L/V ratio limit, as shown in Figure 8.7, but above the Chapter XI single wheel L/V ratio limit, as shown in Figure 8.4. A similar response was found on the tank car. While the tank car single wheel L/V ratio at the 12-degree curve is above the Chapter XI limit, the axle sum L/V ratio is below. For the tank car, only the response at the 7.5-degree curve with both cross level and alignment perturbation was above the Chapter XI limit as shown in Figure 8.8.

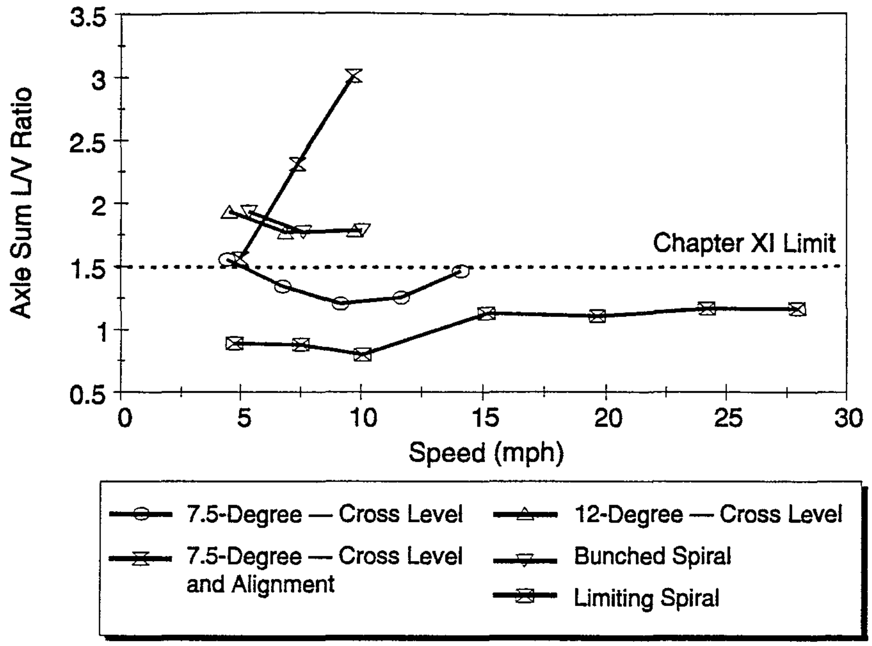

Figure 8.7 Maximum Axle Sum L/V Ratio on Curved-track, Covered Hopper Car

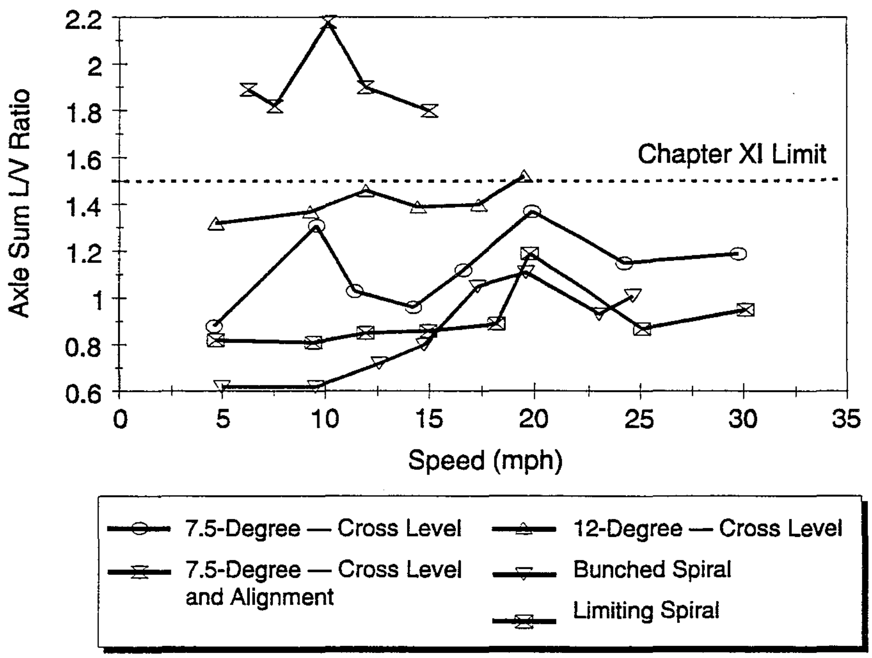

Figure 8.8 Maximum Axle Sum L/V Ratio on Curved-track High Rail, Tank Car

8.3 WHEEL/RAIL LATERAL FORCES

Lateral forces were highest for the outer wheel of the lead axle of each truck and increased with the addition of the alignment perturbation since the perturbation tended to further sharpen the existing curve. Figures 8.9, 8.10 and 8.11 show the combined lateral forces on one of the leading axle wheels which sustained the highest lateral force. The lateral forces were not affected significantly by speed for the flatcar and the tank car. However, the responses of the covered hopper on 7.5-degree curve with cross level and alignment perturbation and on the limiting spiral increased with the speed.

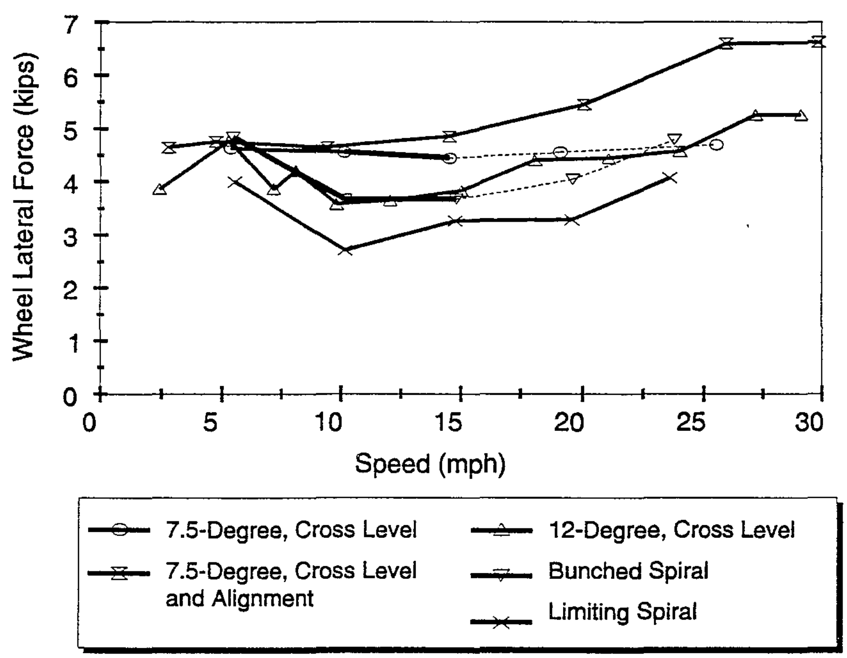

Figure 8.9 Maximum Wheel Lateral Forces, Flatcar

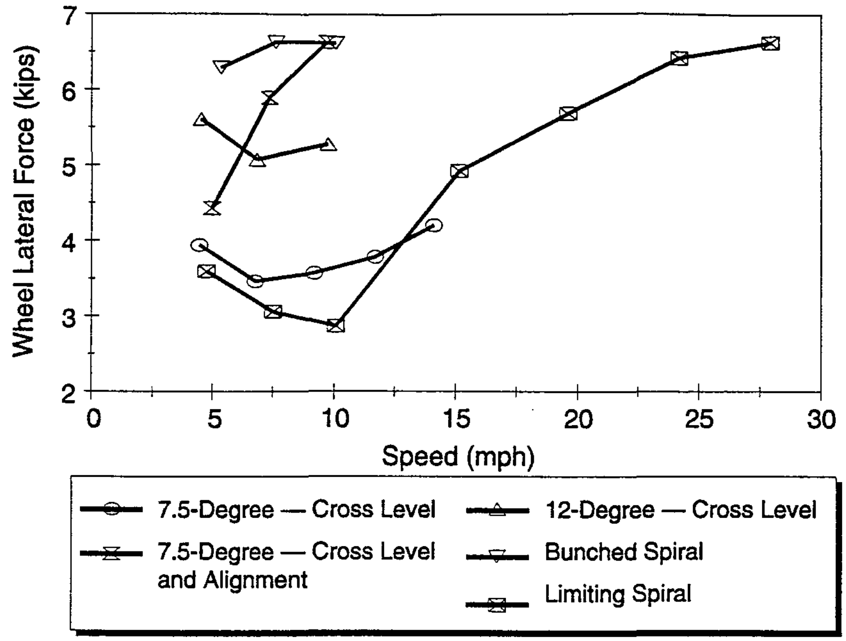

Figure 8.10 Maximum Wheel Lateral Forces on Curved-track, High Rail, Covered Hopper

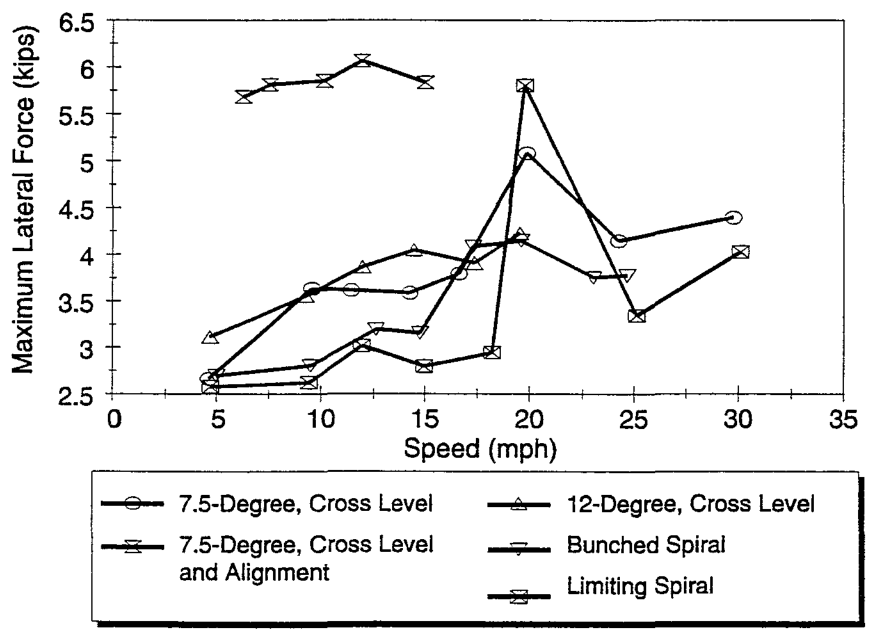

Figure 8.11 Maximum Wheel Lateral Forces on Curved-track, High Rail, Tank Car

8.4 WHEEL UNLOADING

Wheel unloading was not a critical situation for any of the vehicles operating on the curved-track. The maximum wheel unloading recorded was below 90 percent. However, the vertical load reduction recorded at the high wheel on the top of perturbation was the major cause of high L/V ratios. The maximum wheel unloading on the flatcar did not reveal a significant difference between different test zones, as shown in Figure 8.12. For the covered hopper and tank car, the maximum wheel unloading occurred on the 12-degree curve with 2.25-inch cross level perturbation, as shown in Figures 8.13 and 8.14. Wheel unloading also increased when the alignment deviation was added.

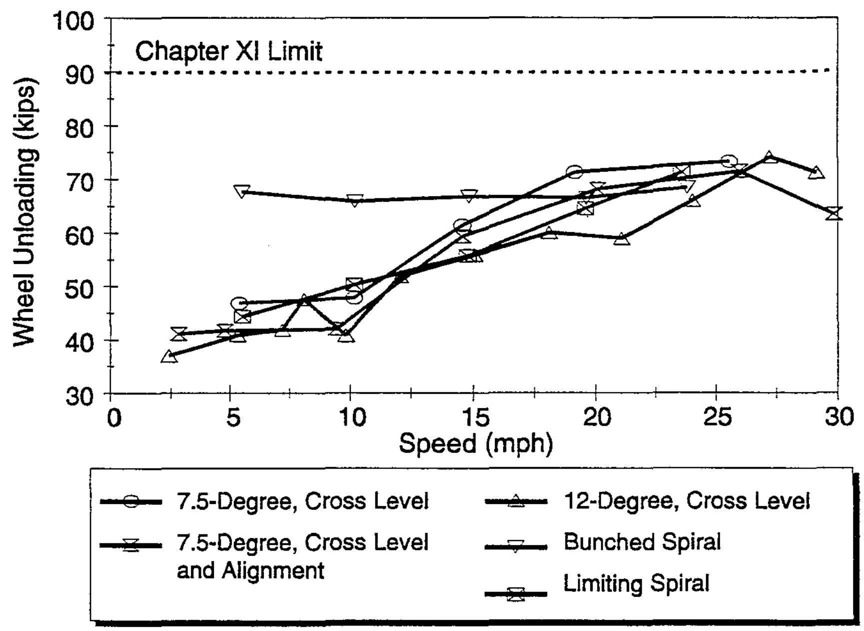

Figure 8.12 Maximum Wheel Unloading on Curved-track, High Rail, Flatcar

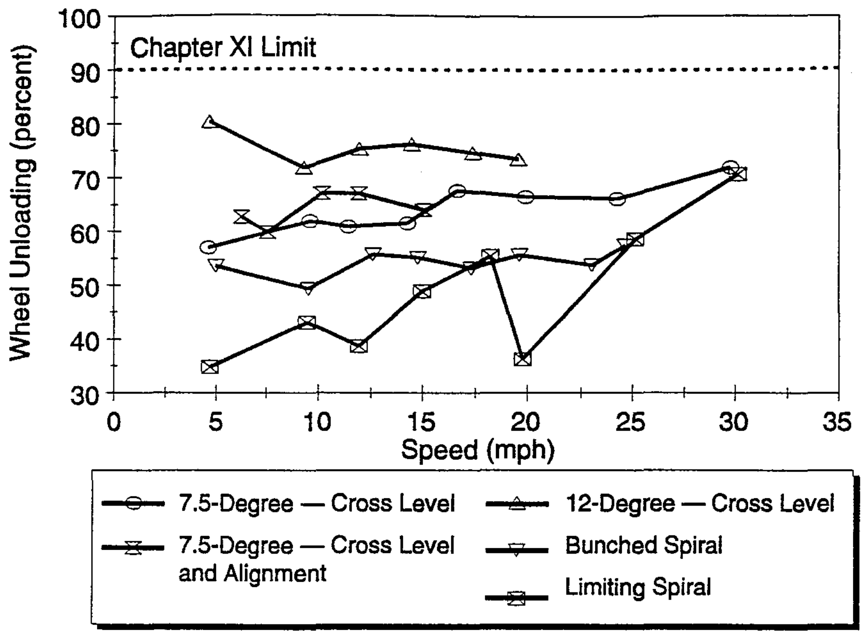

Figure 8.13 Maximum Wheel Unloading on Curved-track, High Rail, Covered Hopper

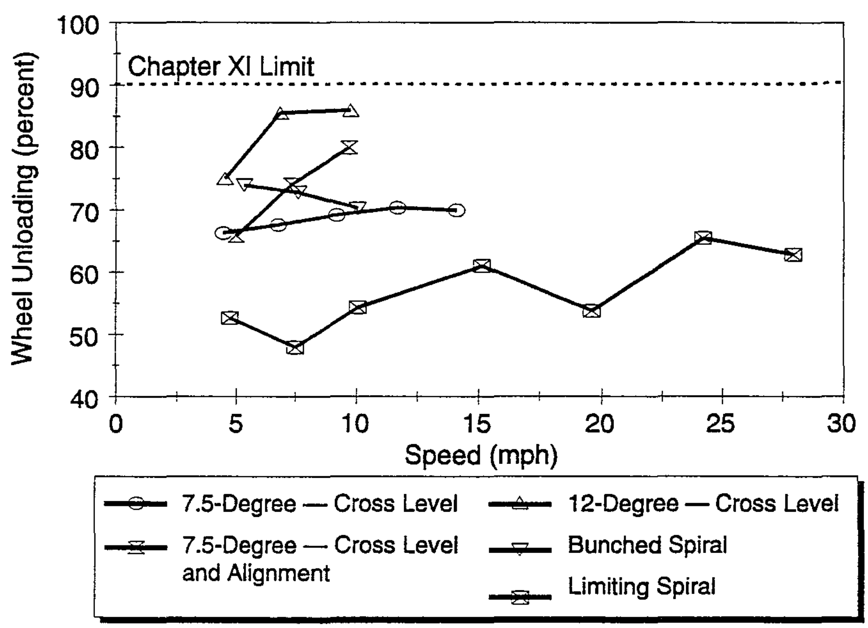

Figure 8.14 Maximum Wheel Unloading on Curved-track, High Rail, Tank Car

8.5 EFFECT OF SAND AND ICE TO VEHICLE CURVE PERFORMANCE

Sand was applied before the first series of flatcar tests on the 7.5-degree test zone to increase the coefficient of friction from 0.2 to above 0.4. Only three test runs were conducted at 2, 5 and 7 mph respectively. The single wheel L/V ratios recorded at the cross level perturbation in these three runs were between 1.31 and 1.54 while ratios on the unperturbed 7.5-degree track were between 0.5 and 0.6.

Sand was not applied before the second series of tests on the 7.5-degree curve since the coefficient of friction read above 0.4 before the test. In this case, the wheel L/V ratios were between 0.9 and 1.05 below 15 mph. A light snow started after 15 mph, and to maintain the coefficient of friction above 0.4, sand was applied for the 20 mph run. The L/V ratio sharply increased and reached 1.35 at 26 mph. The speculation can be made that without application of sand on a dry rail, the test speed might have been able to reach 30 mph.

Similar responses were observed for the covered hopper car. On the 7.5-degree curve, with the cross level perturbation, single wheel L/V ratios were extremely high, between 1.9 and 2.1, at 5 mph to 9.5 mph when sand was applied. Without sanding the track, the wheel L/V ratios were generally above 1.0 but did not exceed 1.2 below 14 mph in the same 7.5-degree curve zone.

A test, with sand consistently applied, was conducted on the tank car at the 7.5-degree curve with cross level perturbation, to further ascertain the sand's effect. Figure 8.15 shows the comparison. Without sand, the L/V ratios were below Chapter XI limit. As sand was applied, the L/V ratios rose sharply as speed increased, reaching 2.2 at 15 mph. Using sand and having the same level of friction coefficient reading from the tribometer, the mechanism of wheel/rail contact appears to be different from steel-steel contact. The wheel set steering ability was considerably reduced with the application of sand.

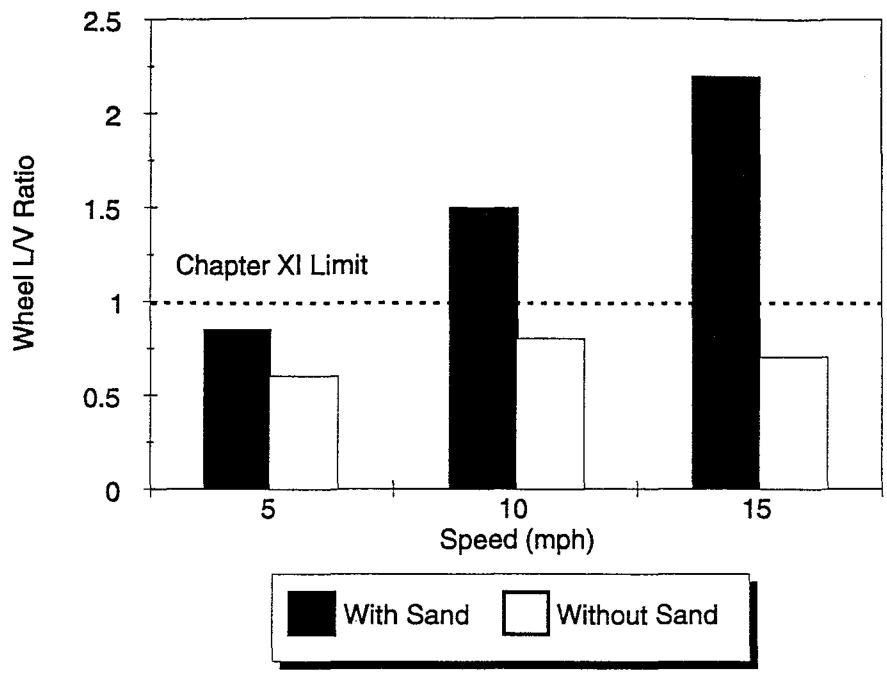

Figure 8.15 Effect of Applying Sand on Curved-track

Contaminants on the track surface have a significant effect on vehicle performance on curved-track by affecting wheel set steering behavior. The morning of the covered hopper test, the top of the track was icy due to the previous day's snow. The initial coefficient of friction measurement was 0.1. The test data was observed, but not collected during the first run over the icy track at 5 mph. Wheel L/V values were below 1.0 in all test zones. After the icy layer was broken by the vehicle running over the unsanded track, the coefficient rose above 0.4, and the wheel L/V ratios were sharply increased above 1.2 in most of the test zones at 5 mph (Figure 8.4).

In most cases, even the rail top friction coefficient was above 0.4 without sand. The friction coefficient of the rail gage was in the range of 0.2 to 0.3. With sand applied, the maximum coefficient obtained at rail gage was 0.37. This phenomena may be explained by the rail top being cleaned relatively easier by wheel/rail contact. However, the rail gage could only be cleaned when flange contact occurred.

8.6 SUMMARY OF CURVED-TRACK TESTS

Operating an empty vehicle on perturbed curved-track may lead to wheel climb. The L/V ratios obtained were considerably higher than the Chapter XI limit of 1.0 and sustained hundreds-milliseconds in some circumstances.

On the perturbed curved-track, the maximum operating speed without exceeding the Chapter XI limits varied, depending on the vehicle type. Table 8.2 shows the maximum operating speeds without exceeding Chapter XI wheel L/V limit or the axle sum L/V limit.

Table 10. The Maximum Operating Speed Without Exceeding Chapter XI Limits on Curved-track

	Center Beam Flatcar (3" Cr)		Covered Hopper (2.25" - 2.5" Cr)		Tank Car (2.25" - 2.5" Cr)	
Chapter XI Limits	L/V (W) (1.0)	L/V (A) (1.5)	L/V (W) (1.0)	L/V (A) (1.5)	L/V (W) (1.0)	L/V (A) (1.5)
7.5-degree, Cr	25*	30	5(E)	15*	30	30
7.5-degree, Cr & Al	5(E)	30	5(E)	5(E)	5(E)	5(E)
12-degree, Cr	30*	30*	5(E)	5(E)	5(E)	17
Bunched Spiral	30	30	5(E)	5(E)	30	30
Limiting Spiral	30	30	30	30	30	30

* only one point exceed the limit at low speed.
L/V (W) and L/V (A) are Chapter XI wheel L/V limit (1.0) and Chapter XI axle sum L/V limit (1.5).
E indicates the Chapter XI limit was exceeded.

Even with 3 inches of cross level perturbation, the flatcar still showed good performance on the perturbed curved-track because of less car body torsional stiffness. With the same level of car body torsional stiffness, the tank car showed better curve performance than the covered hopper due to the shorter truck spacing. Except in the limiting spiral, the covered hopper failed in all curve zones according to the Chapter XI wheel L/V limit.

When sand was applied, the wheel L/V ratios increased considerably. This phenomenon may be caused by the reduced steering ability of the wheel set.

9.0 CONCLUSIONS

Test results indicate that responses of different type of vehicles to track twist are varied. The major parameters affecting performance are car body torsional stiffness, truck spacing, track alignment (tangent or curve) track geometry, and wheel/rail friction coefficient. Only one initial side bearing clearance of 0.25 inch was tested.

The percentage of wheel unloading under dynamic operation is higher than static situations. Compared with a maximum 68 percent wheel unloading in the quasi-static test, the maximum wheel unloading can be over 90 percent in the track test.

9.1 TANGENT TRACK TEST

1. Without exceeding Chapter XI limits, the empty flatcar was be operated up to 45 mph with 3 inches of cross level perturbation. The empty covered hopper car and tank car was operated up to the hunting speed, which is 60 mph for the hopper car and 52 mph for the tank car, with 2.25 to 2.5 inches of cross level perturbation. Above 45 mph, 90-percent wheel unloading was observed for the flatcar.

2. Adding the alignment perturbation caused 90-percent wheel unloading on the covered hopper and tank car at 52 mph and 42 mph, respectively, and caused wheel L/V ratio above 1.0 at 35 mph on the flatcar.

3. The vehicle response was influenced by the operating speed. Each instance of 90-percent wheel unloading occurred above 30 mph.

4. Center plate unloading was measured above 30 mph for the flatcar and tank car and above 20 mph for the covered hopper.

5. As the hunting speed was reached, the cross level perturbation acted as a disturbance to initiate the hunting on the tank car, or deteriorate the hunting on the covered hopper.

6. The peak wheel unloading was recorded at the left wheels of the leading truck while the trailing truck was in the perturbation zone. The peak wheel L/V ratios were recorded at the right wheels, while the left wheels of same axle were on the top of perturbation.

9.2 CURVED-TRACK TEST

1. For the empty vehicle operating on the perturbed curved-track, the critical conditions were wheel L/V ratios above 1.0 or axle sum L/V ratios above 1.5. Flange climbing was observed and filmed in the 12-degree zone for both the covered hopper and the tank car.

2. The flat car and the tank car were operated above 25 mph without exceeding Chapter XI limits on the 7.5-degree curve with cross level perturbation only. The covered hopper car exceeded the single wheel Chapter XI L/V ratio limit below 10 mph.

3. All three vehicles exceeded the Chapter XI single wheel L/V ratio limit below 10 mph on the 7.5-degree curve with the cross level/alignment perturbation.

4. Except at 7 mph, the flatcar was operated to 30 mph without exceeding Chapter XI limits on the 12-degree curve with cross level perturbation only. The covered hopper and the tank exceeded the Chapter XI single wheel L/V ratio limit below 10 mph on the 12-degree curve.

5. The flatcar and the tank were operated to 30 mph without exceeding the Chapter XI limits over the Bunched Spiral. The covered hopper exceeded the Chapter XI single wheel L/V ratio limit at less than 10 mph over the bunched spiral.

6. All three vehicles were operated to 30 mph without exceeding Chapter XI limits in the limiting spiral.

7. In the curved-track test speed range (2 to 30 mph), the vehicle response was not affected significantly by the operating speed.

8. The wheel L/V ratio increased considerably when sand was applied. This may be caused by the reduced steering ability due to the high friction generated by the sand.

9. Even with 3 inches of cross level perturbation, the flatcar still showed good performance on the perturbed curved-track because of less torsional car body stiffness. With the same level of car body torsional stiffness, the tank showed better curve performance than the covered hopper due to the shorter truck spacing.

10.0 DISCUSSION

1. The maximum permissible track twist has not been defined completely. The track tests were conducted only on one level of perturbation for each track condition. Further investigation on different levels of perturbation should be conducted by more field tests or model simulations.

2. On the tangent track, all three test vehicles were operated at a considerably higher speed on 2.25 to 3 inches of cross level perturbation, than specified for Class 1 track. But the same perturbation levels installed in the curved-track appeared to be too severe in several cases, especially for the covered hopper car. Therefore, consideration should be given to the safety limit of track twist separately for tangent track and curved-track.

3. Vertical wheel unloading was caused by the center plate separation. However, the center plate separation is difficult to measure accurately because of the small variations. The permissible track

twist tolerance may have to be determined based on the wheel vertical load, which is a more feasible measurement.

4. The criterion established by well-known French theorist Nadal, formed as Equation 10.1 and plotted in Figure 10.1, relates the wheel L/V ratio to the wheel/rail contact angle and contact coefficient of friction. Derailment did not occur, even under a considerably high wheel L/V ratio with several seconds duration on the curved-track, perhaps because of the low friction coefficient (below 0.3) at the gage face. When flange contacts, the contact angle can be up to 75 degrees for the AAR1B profiles corresponding to the L/V limit above 1.5. Consistently, test results show that the Chapter XI axle sum L/V limit is less conservative.

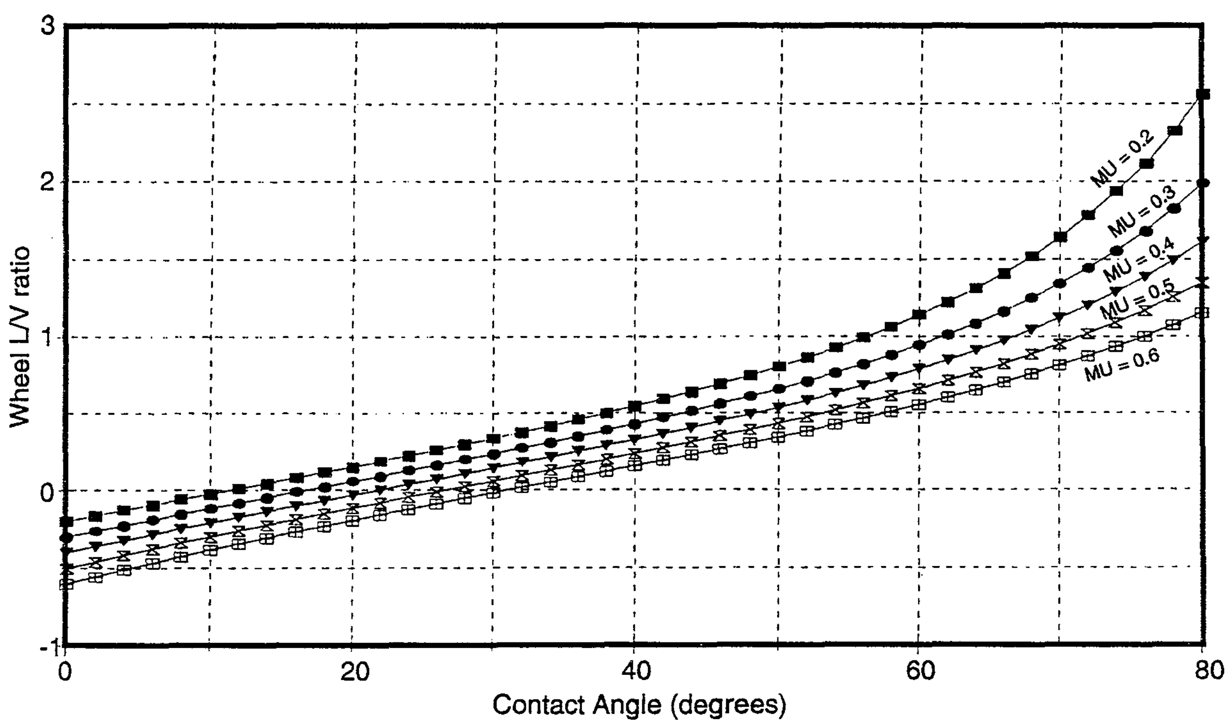

Figure 10.1 Nadal's Limit

The Nadal criterion:

$$\frac{L}{V} = \frac{\tan(\eta) - \mu}{1 + \mu\tan(\eta)} \qquad (10.1)$$

where η is the contact angle between the wheel and rail relative to a horizontal reference.

5. Although the same range of friction coefficient as the dry steel-steel contact was measured by the tribometer, the sand caused different contact mechanisms between wheel and rail. Sand appeared to reduce the steering ability of the wheel set which produced high lateral wheel forces.

6. An investigation on the effect of track twist on loaded vehicles has not been conducted. Although the wheel unloading may not be the critical situation for loaded vehicles, the dynamic factor may limit the permissible cross level difference since the suspension springs may be dynamically impacted to their solid height by the effect of the track twist.

REFERENCES

[1] D. Tyrell, H. Weinstock, R. Greif, "Wheel Unloading of Rail Vehicles Due to Track Twist," DOT-FRA-ORD-85/14, February 1986.

[2] H. Wu, D. Read, "Results of Static and Quasi-Static Tests for Track Twist Investigation," unpublished.