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Vehicle/Track Interaction Test at Bennington, NH

Revision 1.0

Office of Research and
Development
Washington DC 20590

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NOTICE

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16. Abstract

This report describes the results of the Vehicle/Track Interaction tests conducted at Bennington, NH on August 28-31, 1982. The purpose of these tests was to determine the effects of well defined perturbations of track alignment, gage, and crosslevel on rail car response as a function of speed. The track included a 12-degree curve with high rail alignment and crosslevel variations, a tangent section with sinusoidal alignment variations of different amplitudes and wavelengths, and finally, a 6-degree curve with a section of sinusoid alignment variations and a section with high rail alignment variations. The report includes a description of the behavior of wheel rail forces, developed by a partially loaded 100-ton open hopper car and a 4-axle locomotive.

The data collected indicate that combinations of crosslevel and alignment variations on sharp curves may lead to wheel climb conditions. In addition, the tests show that, in the absence of crosslevel greater than 0.4" the rail forces resulting from these perturbations are essentially gage widening and do not significantly increase with speed in the 5 to 25 mph regime.

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PREFACE

This report describes the experimental investigation conducted at Bennington, NH on August 28-31, 1982 to define the vehicle response to certain well defined track geometry irregularities. This test is part of the Vehicle Track Interaction studies being conducted by Transportation Systems Center (TSC) under Improved Track Safety Research Program (RR-19). The results of these studies will be used in the development of performance based track safety specifications. This work is sponsored by the U.S. Department of Transportation, Federal Railroad Administration, Office of Research and Development, Track Safety Research Division. The American Railway Engineering Association (AREA) ad-hoc Committee on Performance Standards provided considerable guidance in the planning of these tests and in the interpretation of the results.

The authors would like to thank William O'Sullivan of the FRA Track Safety Research Division and members of the TSC staff for their guidance and support during the test period. In addition, individuals from Arthur D. Little Inc., Battelle Columbus Laboratories, ENSCO Inc, and The Analytic Sciences Corporation (TASC) were instrumental in the completion of the tests and in the writing of this report. Finally, the authors would like to acknowledge the extraordinary efforts of the Boston and Maine railroad and particularly John Love in the completion of these tests.

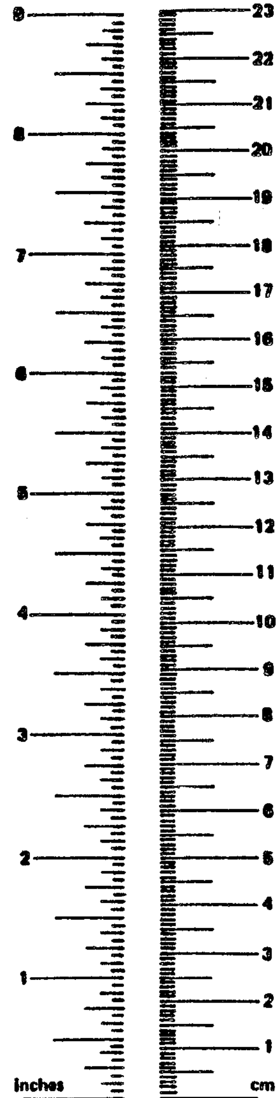
Revision 1.0 of this report contains changes and corrections made to the original text on pages 2-26, 3-2, 3-4, 3-5, 3-8, 3-10 through 3-16, 3-20, 3-24, 3-48, 4-1, and 4-2.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

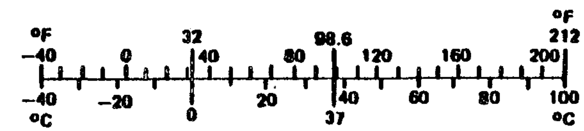
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF TABLES

EXECUTIVE SUMMARY

As part of the Track Safety Research Program sponsored by the Federal Railroad Administration (FRA), the Transportation Systems Center (TSC) is developing safety-related data on the interaction of rail vehicles and track structures. This work, conducted in cooperation with the American Railway Engineering Association (AREA) ad hoc committee on performance based track safety standards, has concentrated on the development of specifications in the areas of rail restraint, track lateral restraint, rail fatigue, and vehicle/track interaction. In the area of vehicle/track interaction, a series of tests[1,2,3] have been conducted to determine typical vehicle response to severe track irregularities. This report describes the objectives of the Bennington, NH tests conducted in August 1982 on the Boston and Maine railroad and the principal results of the data analysis.

The goal of these tests and of the analytical studies that have been conducted concurrently with the tests has been to define the limits of tolerable track geometry irregularities based on the response of a common vehicle type. These analytical studies, using the SIMCAR program[4], have concentrated on specific vehicles and specific derailment scenarios based on studies of the accident statistics of the American railroads and railroad operating experiences as communicated by AREA. Conditions of particular concern are harmonic roll generated from crosslevel variations, alignment variations, both on tangent track and in curves, and the combination of alignment and crosslevel.

For the low-speed curving studies, the loaded 100-ton open top hopper car, a typical coal car, was chosen because of its high wheel loads, its 39-foot truck center length matching the typical rail length, and its high center of gravity. The high center of gravity makes the car's response similar to the 100-ton covered hopper car. Previous tests[2,3] have studied harmonic roll and dynamic curving for this vehicle for speeds up to 25 mph and for curves up to 6 degrees. Analytic simulations[5] predicted that curves of 10 degrees or greater would require track geometry irregularities to be significantly smaller to ensure vehicle safety. The Bennington test was intended to collect data so that these predictions could be evaluated.

The major goal of the Bennington test was to provide vehicle response data during operation over known severe track geometry irregularities of different types to further understand the critical design characteristics of track as related to safety.

These test data were intended to evaluate the results of parametric studies in the areas of track alignment, curvature and high-rail alignment, and curvature with combinations of high-rail alignment and crosslevel.

These general goals resulted in the following two specific objectives:

1. To develop time history wheel and truck force data for a 100-ton, open top, hopper car and a 4-axle locomotive operating over known, severe track geometry irregularities including high-rail alignment, gage, and crosslevel on a curve of 12 degrees at speeds between 5 and 20 mph.
2. To develop time history wheel and truck force data for a 100-ton, open top, hopper car and a 4-axle locomotive in order to determine the dependence of wheel loads on speed (up to 30 mph) in a 6-degree curve and on a tangent track with sinusoidal alignment irregularities.

The track used for this test is located between the towns of Greenfield and Bennington, NH on a branch line of the Boston & Main railroad. This single track branch line carries less than 0.2 MGT per year. The track is unsignaled, and the Boston & Maine reports that a 10 mph speed limit is in effect throughout the area.

The test site, detailed in Figure ES-1, contains a 4-, 6-, and 12-degree curve and about a mile of tangent track which includes a bridge. The terrain was generally flat, although the tangent sections contained several slight grade fluctuations. (See Figure 2-3.) The primary test direction was south or from the 12-degree curve toward the 6-degree curve.

The test consist for the Bennington tests included a 4-axle GP-9 locomotive, the FRA T-7 data recording car, a gondola car, and a partially loaded open top hopper car. The FRA T-6 track geometry car was included in the consist to record the actual track geometry for each test section. It was not included in the consist during most of the test runs.

As shown by the shaded dots in the Bennington Test Summary diagram (Figure ES-2), the 3rd, 4th, 13th, and 14th axles were instrumented for this experiment. Also included in the diagram is the test matrix and a description of the sinusoid test zones.

Bennington data resolve five important issues relative to the analytical prediction of vehicle response.

1. The test data demonstrate that large lateral wheel rail forces, on the order of 20,000 pounds, are generated on small radius curves (about 500-foot radius or 12 degrees) at low speed (5 mph), and that these forces are relatively insensitive to speed. Peak lateral forces

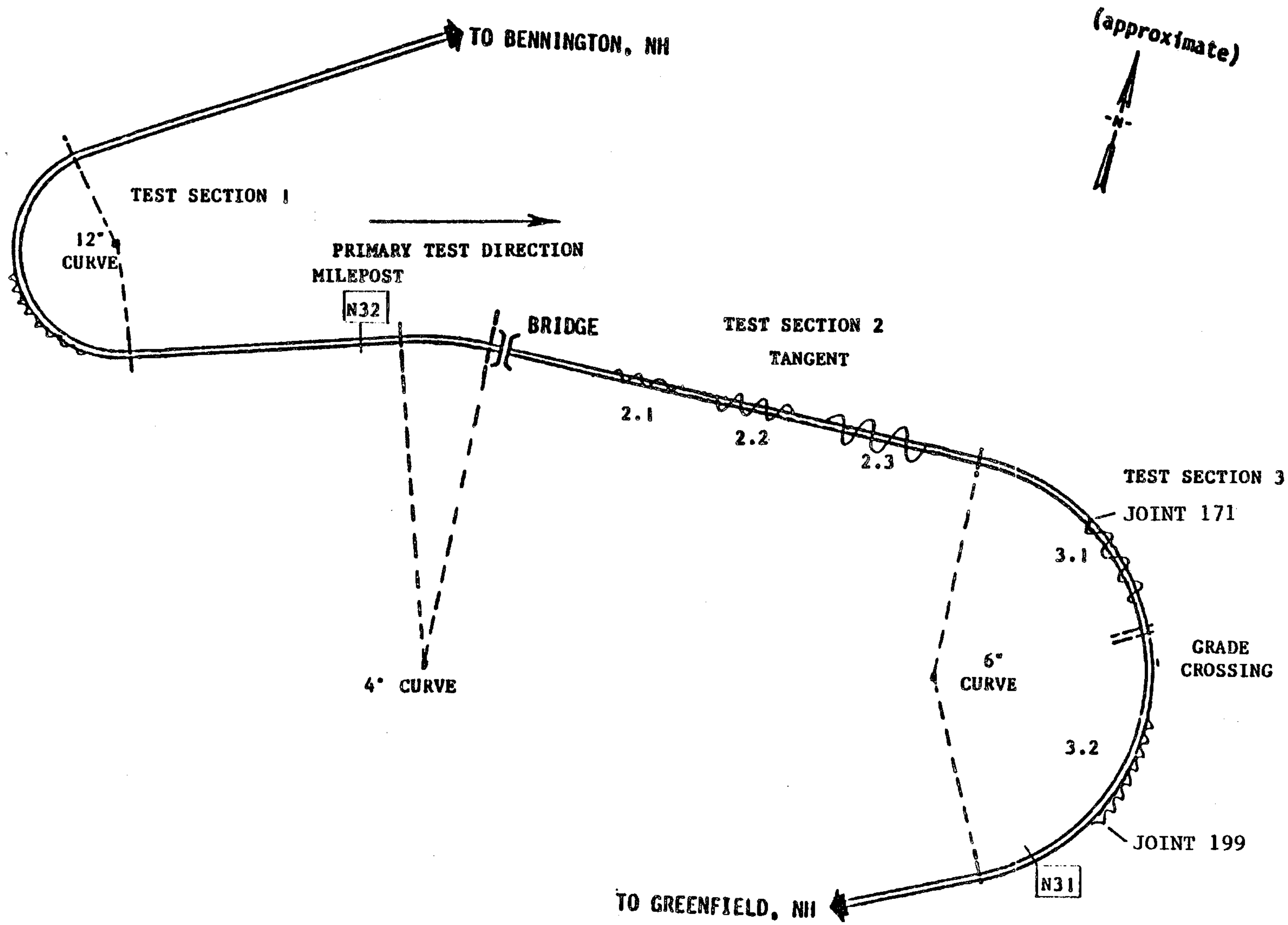
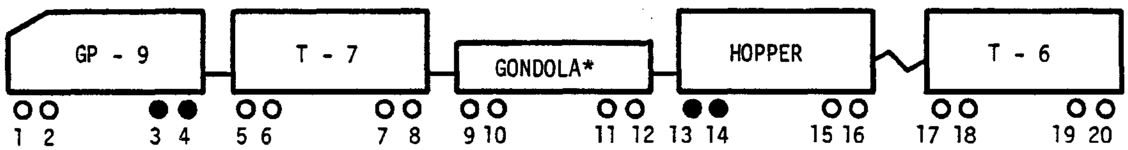


FIGURE ES-1. LAYOUT OF VTI TEST TRACK SITE

CONSIST



TEST MATRIX

TEST SERIES I: 12-DEGREE CURVE 1.25-inch OUTWARD ALIGNMENT CUSPS, HIGH RAIL, at 33-foot intervals, NO CROSSLEVEL 16 RUNS ON 8/28-29/82 SPEED RANGE 5-20 mph.

TEST SERIES II: TANGENT SINUSOIDS, 6-degree CURVE SINUSOID AND CUSPS 19 RUNS ON 8/30-31/82 SPEED RANGE 5-30 mph.

TEST SERIES III: 12-degree CURVE OUTWARD CUSPS WITH 0.75-inch CROSSLEVEL 6 RUNS ON 8/31/82 SPEED RANGE 5-14 mph.

SINUSOIDS:

39-foot 1.33-inch PEAK-TO-PEAK AMPLITUDE, 0.48-inch 62-foot MIDCHORD.

50-foot 1.25-inch PEAK-TO-PEAK AMPLITUDE, 1.08-inch 62-foot MIDCHORD.

90-foot 4.50-inch PEAK-TO-PEAK AMPLITUDE, 3.5-inch 62-foot MIDCHORD.

50-foot 6-degree 1-1/4 inch PEAK-TO-PEAK amplitude, 1.08-inch 62-foot MIDCHORD.

*A gondola car was used as a buffer; the low profile allowed observation of the open top hopper car from the T-7 data recording car.

FIGURE ES-2. BENNINGTON TEST SUMMARY

vary by only 5 kips (from 17 to 22 kips) over the speed range of 5 to 20 mph.

2. The low-rail wheel forces show that coefficients of friction as large as 0.5 do exist on track. This allows the generation of large gage spreading forces on the order of 23 kips on the high rail and 15 kips on the low rail.

3. The Bennington test shows that lateral forces resulting from high-rail alignment variations do increase with curvature.

4. The test data from the 12-degree curve demonstrate that the combination of crosslevel and high-rail alignment variations results in high lateral to vertical (L/V) force ratios.

5. The wheel/rail forces measured in the three sinusoidal alignment sections on the tangent track test sections show that the vehicle response is sensitive to variations in wavelength while relatively insensitive to speed up to 30 mph. In addition, the results show that the 62-foot midchord offset method of specifying alignment variations does not produce a uniform measure of alignment variation severity.

1. INTRODUCTION

This report describes both the analytical and experimental investigation conducted at Bennington, NH on August 28-31, 1982. The primary goal of this investigation was to define the limits of tolerable track geometry irregularities based on the response of a common vehicle type.

The two conditions particularly addressed during the test are the harmonic roll and low speed dynamic curving responses of a freight car type. For harmonic roll, the 100-ton covered hopper car was found, statistically, to derail twice as often as any other generic car type due to crosslevel irregularities. For the low speed curving studies, the 100-ton open top hopper car, a typical coal car, was chosen because of its high wheel loads, its 39-foot truck center length matching the typical rail length, and its high center of gravity. The high center of gravity makes the car's response similar to the 100-ton covered hopper car, thus enlarging the population of the vehicle class studied. Previous tests[2,3] studied harmonic roll and dynamic curving for this vehicle for speeds up to 25 mph and for curves up to 6 degrees. Analytic simulations[5] predicted that curves of 10 degrees or greater would require track geometry irregularities to be significantly smaller to ensure vehicle safety. The Bennington test was intended to collect data so that these predictions could be evaluated.

Section 2 of this report outlines the test setup, which includes a description of the consist, the track site, and the test parameters. Section 3 is an analysis of the data collected during the test. The analysis discusses the effect of speed on sharp curves and the vehicle's response to curvature, crosslevel, and sinusoidal alignment variations as it traverses severely perturbed track.

The results and conclusions of the test data analysis are discussed in Section 4.

2. TEST DESCRIPTION

The test included an instrumented test consist operating over an instrumented track with well defined and maintained perturbations. Three test sections were prepared: Section 1 on a 12-degree curve, Section 2 on a tangent, and Section 3 on a 6-degree curve. Three distinct test series were conducted: Test Series I, with 16 runs between 5 and 20 mph, was conducted over Section 1; Test Series II, with 19 runs between 5 and 30 mph, was conducted over both Sections 2 and 3; and Test Series III, with 6 test runs between 5 and 14 mph, was conducted over Section 1. Crosslevel irregularties were superimposed on the perturbations in Section 1 prior to Test Series III. The test sequence is summarized below.

TEST SERIES	TEST SECTION	CURVATURE (degrees)	TRACK GEOMETRY	SPEED (mph)
I	1	12	High-Rail Misalignment	5-20
II	2	Tangent	Sinusoidal Alignment	5-30
II	3	6	High-Rail Misalignment	5-30
III	1	12	High-Rail Misalignment and Crosslevel	5-14

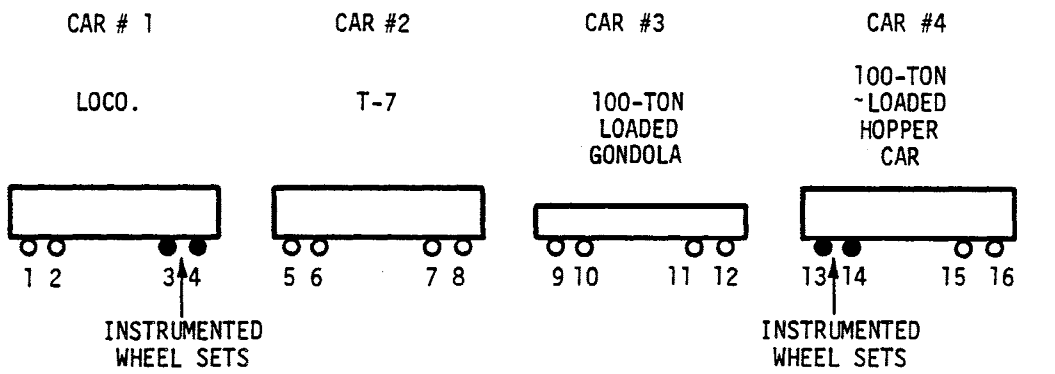
2.1 TEST CONSIST

The test consist included an instrumented 4-axle, GP-9 locomotive, the T-7 data recording car, a gondola, and an instrumented 100-ton partially loaded, open top, hopper car as shown in Figure 2-1. For some test runs, the T-6 track geometry measurement car was also included in the consist.

Both the 4-axle GP-9 locomotive and the 100-ton loaded hopper car were instrumented as indicated in Figure 2-1. The instrumented wheelsets for the locomotive were two of the wheelsets built for AMTRAK by the Swedish Railway first used during the perturbed track tests in 1978[6]. Each wheel had a standard 1/20 taper and a 40-inch diameter. The hopper car was equipped with the 70-ton wheelsets used in the Starr, Ohio V/TI test in 1980[7]. For the Bennington test, the 70-ton wheelsets were turned to a standard 1/20 taper and had a 33-inch diameter.

The onboard instrumentation included the instrumented force-measuring wheelsets and an inertial gyroscope system to measure the inertial roll angle of the hopper carbody. The gyroscope was mounted at the center of the hopper carbody at the "A" end, over the instrumented wheelsets.

A complete list of the onboard data collection channel assignments is given in Table 2-1. The range, units, and filter cut-off frequency for each channel are also shown in this table. Each channel was digitally sampled at 256 Hz and recorded on magnetic tape.



CAR	DESCRIPTION	INSTRUMENTATION
1	Locomotive GP-9	2 ASEA instrumented wheelsets (axles 3 and 4) ALD sensor
2	T-7 DATA RECORDING CAR	Speed, distance
3	Loaded Gondola	Buffer car
4	Loaded Hopper Car	70 ton instrumented wheelsets (axles 13 and 14) Carbody roll angle (Rate Gyro) Truck/carbody yaw angle Suspension vertical displacement Truck/carbody displacements ALD sensor Carbody accelerations, vertical and lateral Truck axle accelerations, vertical and lateral

FIGURE 2-1. TEST CONSIST

TABLE 2-1. ONBOARD DATA CHANNEL ASSIGNMENTS

CHN	MSR#	TYPE	LOCATION	SOURC	+1ØV RNG	UNITS	CTF FRQ
Ø	11VA	VERTICAL A	LOCO.AXL.#1 LFT.	1-1VA	1ØØ.Ø	KIPS	8Ø.Ø
1	11VB	VERTICAL B	LOCO.AXL.#1 LFT.	1-1VB	1ØØ.Ø	KIPS	8Ø.Ø
2	11LA	LATERAL	LOCO.AXL.#1 LFT.	1-1LA	1ØØ.Ø	KIPS	8Ø.Ø
3	NOOP				1.Ø		Ø.Ø
4	12VA	VERTICAL A	LOCO.AXL.#1 RHT.	1-2VA	1ØØ.Ø	KIPS	8Ø.Ø
5	12VB	VERTICAL B	LOCO.AXL.#1 RHT.	1-2VB	1ØØ.Ø	KIPS	8Ø.Ø
6	12LA	LATERAL	LOCO.AXL.#1 RHT.	1-2LA	1ØØ.Ø	KIPS	8Ø.Ø
7	NOOP				1.Ø		Ø.Ø
8	21VA	VERTICAL A	LOCO.AXL.#2 LFT.	2-1VA	1ØØ.Ø	KIPS	8Ø.Ø
9	21VB	VERTICAL B	LOCO.AXL.#2 LFT.	2-1VB	1ØØ.Ø	KIPS	8Ø.Ø
1Ø	21LA	LATERAL	LOCO.AXL.#2 LFT.	2-1LA	1ØØ.Ø	KIPS	8Ø.Ø
11	NOOP				1.Ø		Ø.Ø
12	22VA	VERTICAL A	LOCO.AXL.#2 RHT.	2-2VA	1ØØ.Ø	KIPS	8Ø.Ø
13	22VB	VERTICAL B	LOCO.AXL.#2 RHT.	2-2VB	1ØØ.Ø	KIPS	8Ø.Ø
14	22LA	LATERAL	LOCO.AXL.#2 RHT.	2-2LA	1ØØ.Ø	KIPS	8Ø.Ø
15	NOOP				1.Ø		Ø.Ø
16	31VA	VERTICAL A	HOP AXL.#1 LFT.	3-1VA	1ØØ.Ø	KIPS	8Ø.Ø
17	31VB	VERTICAL B	HOP AXL.#1 LFT.	3-1VB	1ØØ.Ø	KIPS	8Ø.Ø
18	31LA	LATERAL SINE	HOP AXL.#1 LFT.	3-1LA	5Ø.Ø	KIPS	8Ø.Ø
19	31LB	LATERAL COSINE	HOP AXL.#1 LFT.	3-1LB	5Ø.Ø	KIPS	8Ø.Ø
2Ø	32VA	VERT A	HOP AXL. #1 RHT	3-2VA	1ØØ.Ø	KIPS	8Ø.Ø
21	32VB	VERTICAL B	HOP AXL. #1 RHT	3-2VB	1ØØ.Ø	KIPS	8Ø.Ø
22	32LA	LATERAL SINE	HOP AXL. #1 RHT	3-2LA	5Ø.Ø	KIPS	8Ø.Ø
23	32LB	LATERAL COSINE	HOP AXL. #1 RHT	3-2LB	5Ø.Ø	KIPS	8Ø.Ø
24	41VA	VERTICAL A	HOP AXL. #2 LFT.	4-1VA	1ØØ.Ø	KIPS	8Ø.Ø
25	41VB	VERTICAL B	HOP AXL. #2 LFT.	4-1VB	1ØØ.Ø	KIPS	8Ø.Ø
26	41LA	LATERAL SINE	HOP AXL. #2 LFT.	4-1LA	5Ø.Ø	KIPS	8Ø.Ø
27	41LB	LATERAL COSINE	HOP AXL. #2 LFT.	4-1LB	5Ø.Ø	KIPS	8Ø.Ø
28	42VA	VERTICAL A	HOP AXL. #2 RHT.	4-2VA	1ØØ.Ø	KIPS	8Ø.Ø
29	42VB	VERTICAL B	HOP AXL. #2 RHT.	4-2VB	1ØØ.Ø	KIPS	8Ø.Ø
3Ø	42LA	LATERAL SINE	HOP AXL. #2 RHT.	4-2LA	5Ø.Ø	KIPS	8Ø.Ø
31	42LB	LATERAL COSINE	HOP AXL. #2 RHT.	4-2LB	5Ø.Ø	KIPS	8Ø.Ø
32	HCV1	CRBY VERT ACCEL	HOPPER MIDA END	ACCEL	5.Ø	G	1Ø.Ø
33	HCV2	CRBY VERT ACCEL	HOPPER LFTA END	ACCEL	5.Ø	G	1Ø.Ø
34	HCV3	CRBY VERT ACCEL	HOPPER MIDB END	ACCEL	5.Ø	G	1Ø.Ø
35	HCL1	CRBY LAT ACCEL	HOPPER MIDA END	ACCEL	5.Ø	G	1Ø.Ø
36	HCL2	CRBY LAT ACCEL	HOPPER MIDB END	ACCEL	5.Ø	G	1Ø.Ø
37	NOOP				1.Ø		Ø.Ø
38	NOOP				1.Ø		Ø.Ø
39	NOOP				1.Ø		Ø.Ø
4Ø	NOOP				1.Ø		Ø.Ø
41	NOOP				1.Ø		Ø.Ø
42	HTL1	TRK FRM LAT ACL	HOPPER AXL#1 LFT	ACCEL	3Ø.Ø	G	1Ø.Ø
43	HTL2	TRK FRM LAT ACL	HOPPER AXL#2 LFT	ACCEL	3Ø.Ø	G	1Ø.Ø
44	HTV1	TRK FRM VRT ACL	HOPPER AXL#1 LFT	ACCEL	3Ø.Ø	G	1Ø.Ø
45	HTV2	TRK FRM VRT ACL	HOPPER AXL#2 LFT	ACCEL	3Ø.Ø	G	1Ø.Ø
46	HTV3	TRK FRM VRT ACL	HOPPER AXL#1 RHT	ACCEL	3Ø.Ø	G	1Ø.Ø
47	HTV4	TRK FRM VRT ACL	HOPPER AXL#2 RHT	ACCEL	3Ø.Ø	G	1Ø.Ø
48	HTY1	A TRUCK YAW	HOPPER LFT A-END	STRING	5.Ø	INCH	1Ø.Ø
49	HSD1	SUSPENSION DISP.	HOPPER LFT A-END	STRING	5.Ø	INCH	1Ø.Ø
5Ø	HSD2	SUSPENSION DISP.	HOPPER RHT A-END	STRING	5.Ø	INCH	1Ø.Ø
51	HTC1	TRUCK-CRBY DISP	HOPPER LFT A-END	STRING	5.Ø	INCH	1Ø.Ø
52	HTC2	TRUCK-CRBY DISP	HOPPER RHT A-END	STRING	5.Ø	INCH	1Ø.Ø
53	LALD	MAG ALD RAW	LOCO LEFT A-END	ALD SNSR	1.Ø	EVNT	Ø.Ø
54	HALD	MAG ALD RAW	HOPPER LFT A-END	ALD SNSR	1.Ø	EVNT	Ø.Ø
55	HRA1	ROLL ANGLE	HOPPER CEN A-END	GYRO	2Ø.Ø	DEG	1Ø.Ø
56	LAZ	L ALD ZEROED	LOCO A-END	ALD SNSR	1.Ø	EVNT	8Ø.Ø
57	HAZ	H ALD ZEROED	HOPPER LEFT	ALD SNSR	1.Ø	EVNT	8Ø.Ø
58	TSPD	ANALOG SPD	T-7	TACH	1ØØ.Ø	MPH	2Ø.Ø
59	TCAL	1HZ, .2VPP SQ	T7	CAL BOX	1Ø.Ø	V	8Ø.Ø

2.2 TEST TRACK SITE

The track used for this test is located between the towns of Greenfield and Bennington, NH on a branch line of the Boston & Maine Railroad. This single track branch line carries less than 0.2 MGT per year. The track is unsignaled, and the Boston & Maine reports that a 10 mph speed limit is in effect throughout the area.

The test site, detailed in Figure 2-2, contains a 4-, 6-, and 12-degree curve and about a mile of tangent track including a bridge. The terrain was generally flat, although the tangent sections contained several slight grade fluctuations. The primary test direction was south, or from the 12-degree curve toward the 6-degree curve.

The track structure in the test zone was in generally good condition for the traffic carried. Ties were predominantly sound. The rail was double spiked. While no tie plates were used on the tangents, tie plates were used throughout the curves. The rails were 33-foot lengths of 75 or 85 pound stock rolled in 1905-1908 and placed as relay rail in 1929. The B&M track charts for the test site are shown in Figure 2-3. The ballast was generally well compacted sand or sand and gravel. Prior to the test, much of the test site was lined and surfaced.

The locations of the three test sections are shown in Figure 2-2. The 12-degree curve was used for two of the three test series. For the first series, the section consisted of eight repeated high-rail alignment perturbations at 33-foot intervals. The low rail was aligned into as smooth a curve as construction practices allowed. The maximum gage at the high-rail joints was an intentional (see Figure 2-4) 57.75 inches and the minimum gage was 56.5 inches. For the third test series, 6 repeated cycles of crosslevel were superimposed on the alignment/gage perturbations of the 12-degree curve.

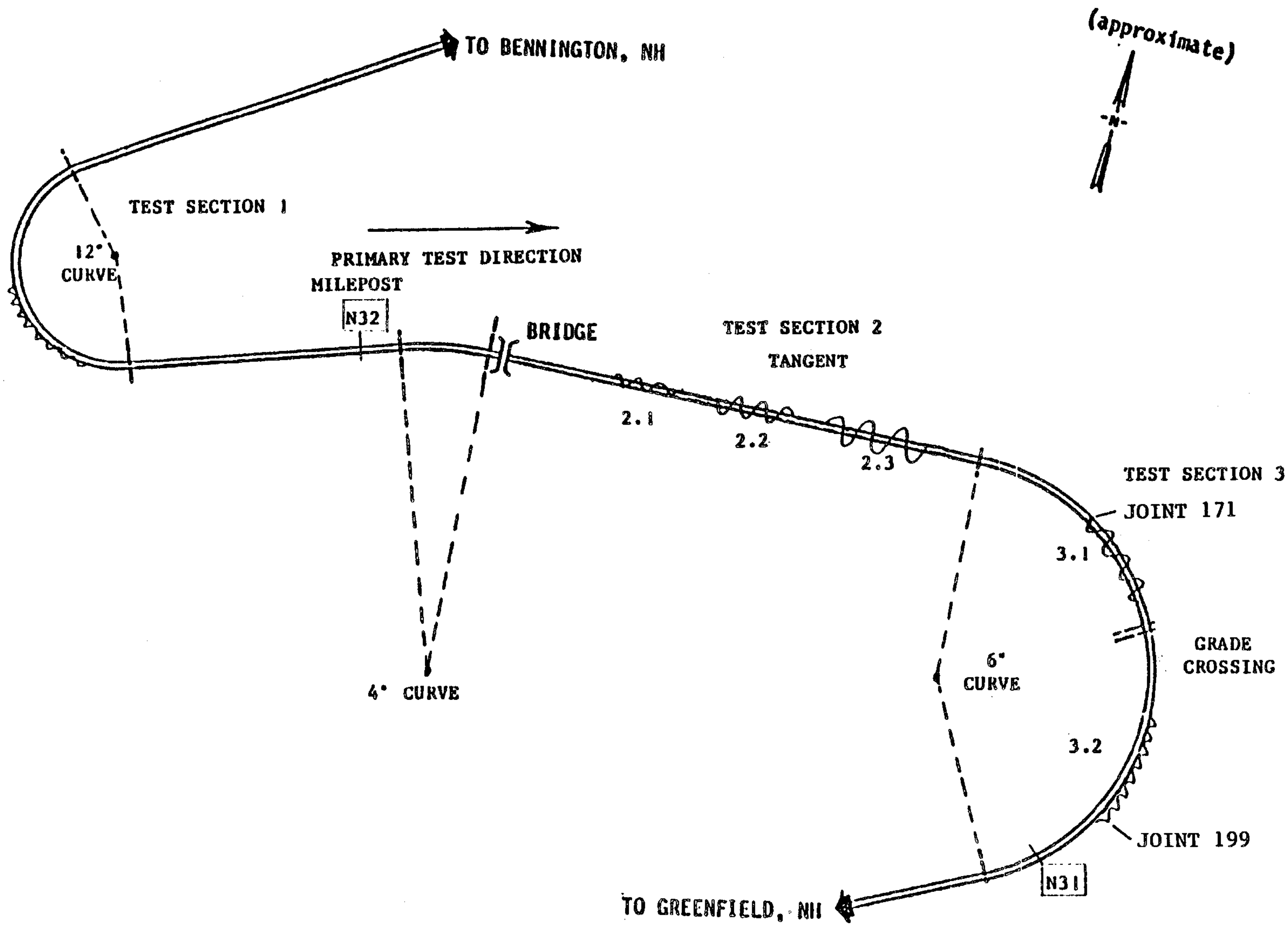


FIGURE 2-2. LAYOUT OF VTI TEST TRACK SITE

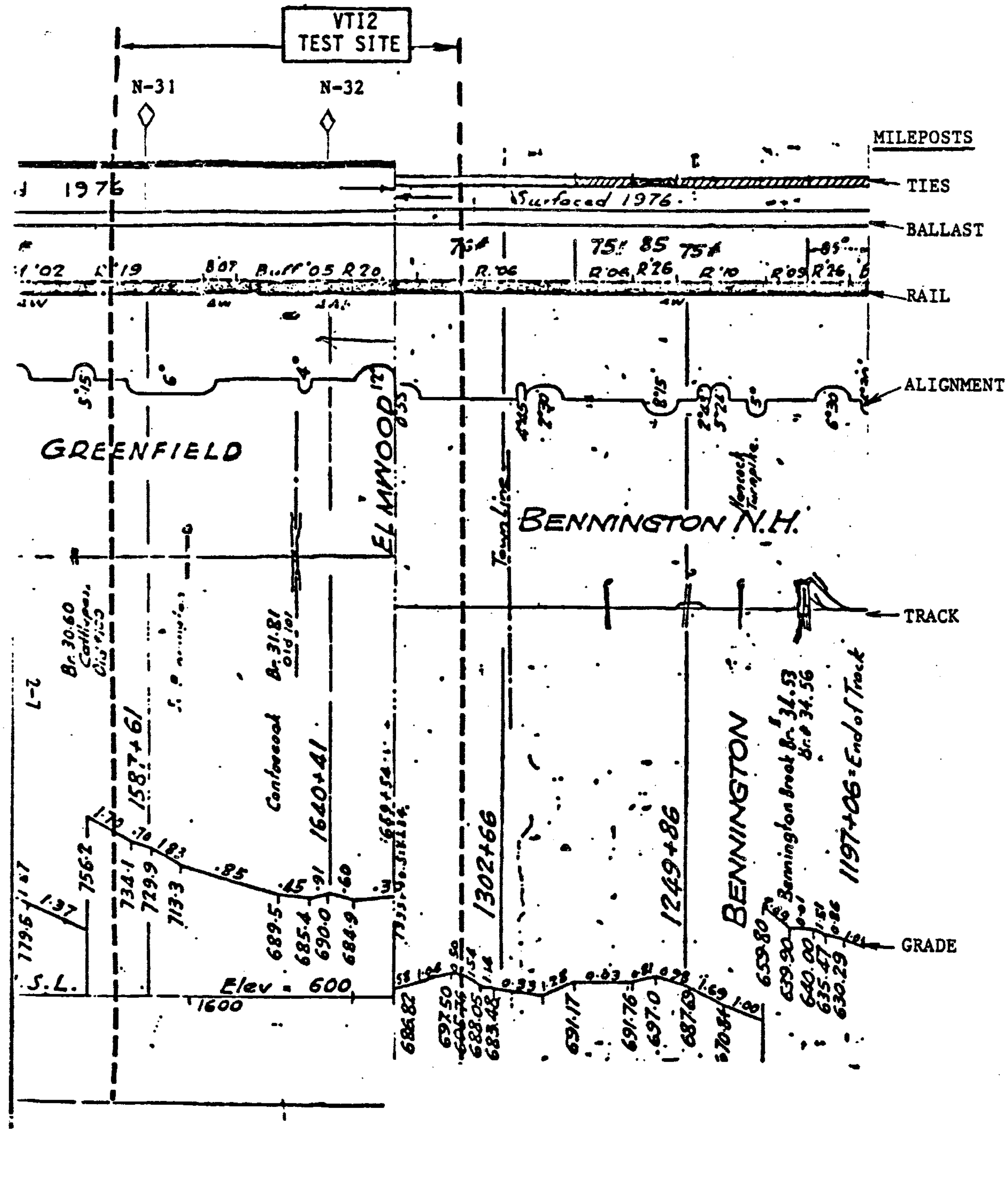


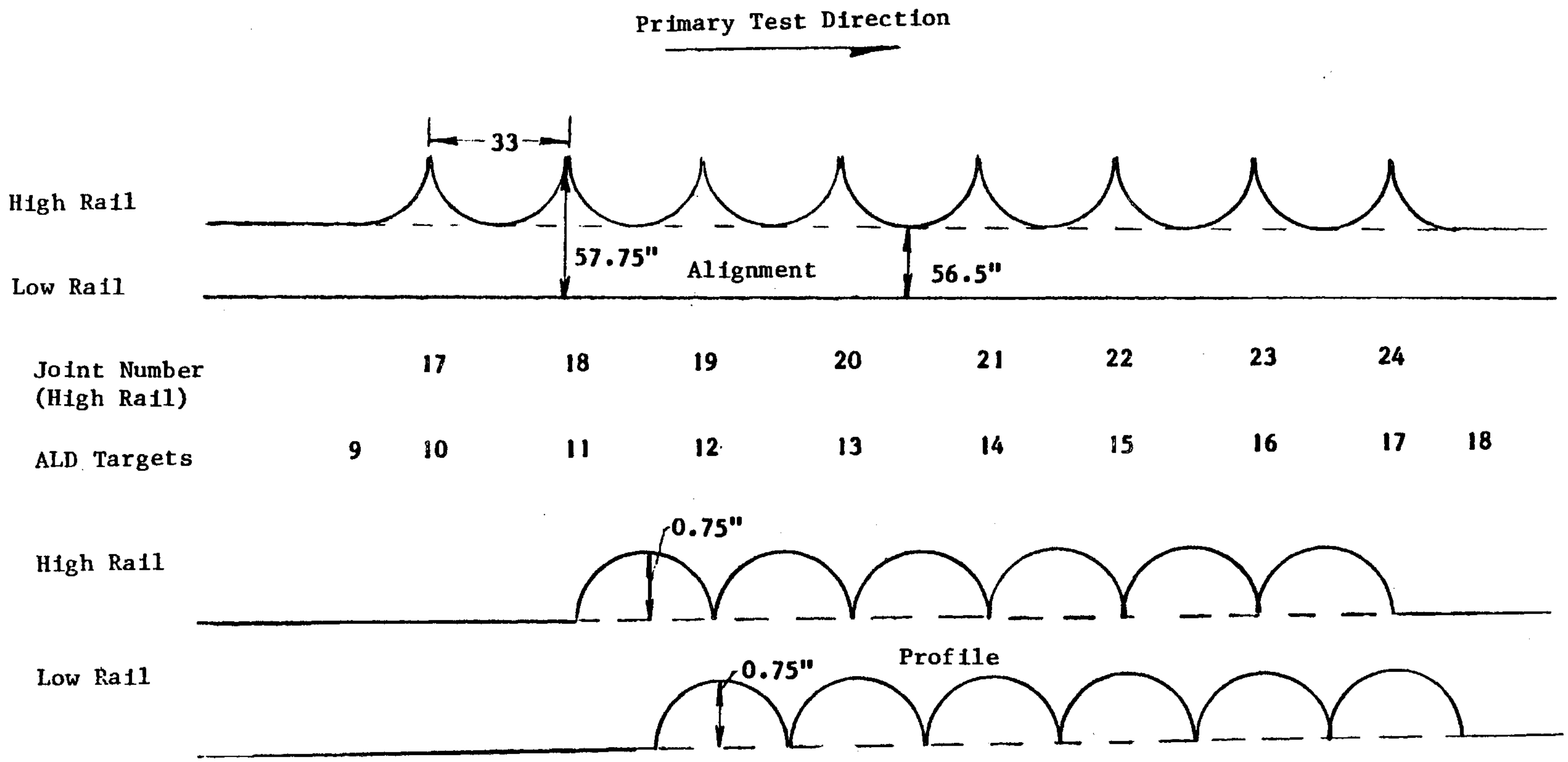
FIGURE 2-3. TRACK CHART OF TEST SITE

The second test series was conducted on the tangent and 6-degree curve test sections. The tangent zone has three test sections: 2.1, 2.2, and 2.3. These sections have pure sinusoidal alignment perturbations with different wavelengths and amplitudes. The wavelengths were 39 feet, 50 feet, and 90 feet, whereas the amplitudes (peak-to-peak) were 1.33 inches, 1.25 inches, and 4.5 inches, respectively. Analytic simulations predicted that these wavelengths and amplitudes would produce equally severe vehicle responses. The nominal gage in each section was 57 inches.

Test Section 3, the 6-degree curve, had two sections. Test Section 3.1 had 50-foot wavelength sinusoidal alignment perturbations and Test Section 3.2 had high-rail alignment perturbations similar to those on the 12-degree curve.

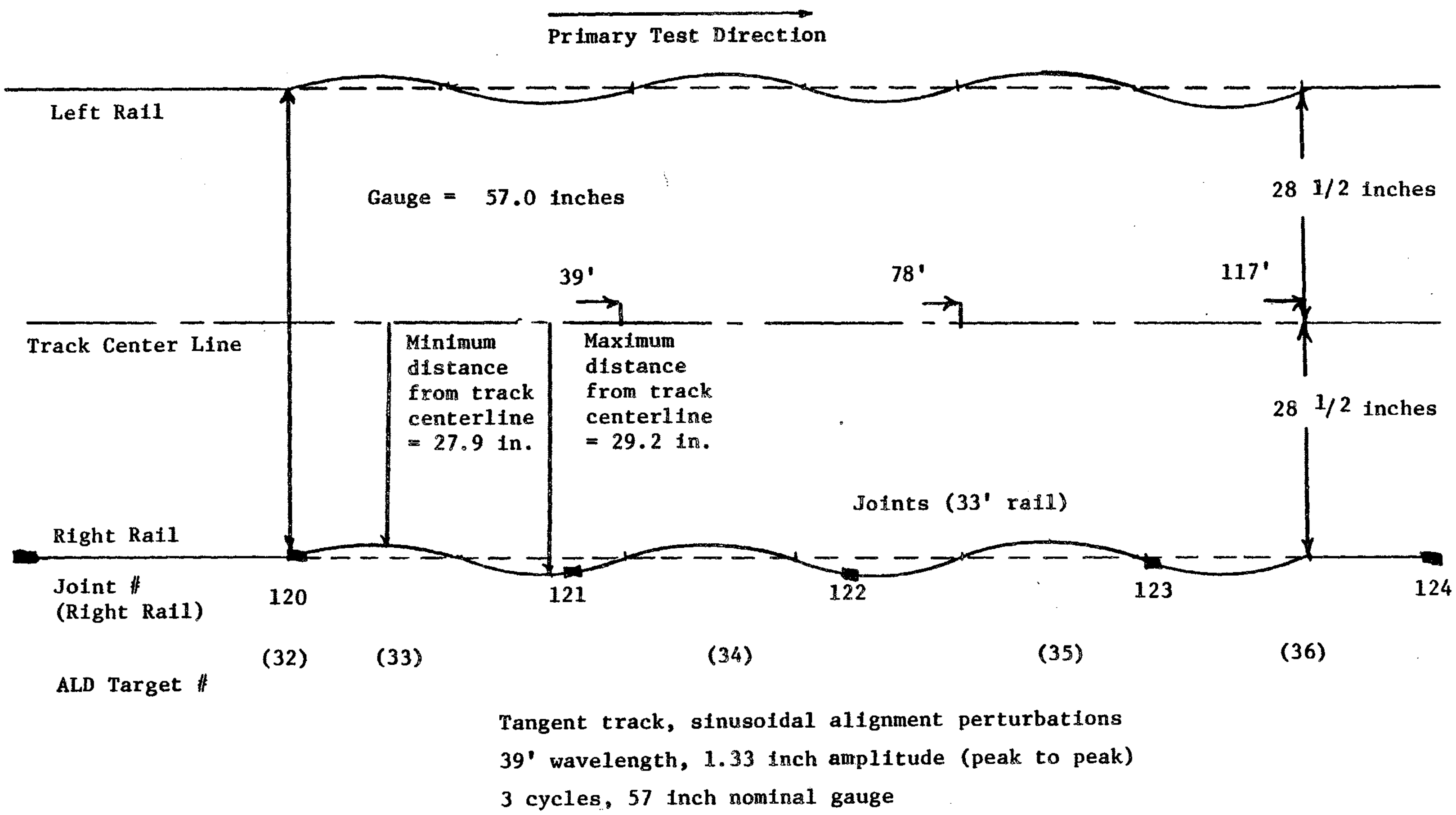
The details of the track geometry perturbations in each test section are provided in Figures 2-4 through 2-9. Each figure shows a schematic of the perturbations, appropriate wavelength and amplitude information, and joint locations. Also shown are the wayside locations of the automatic location detector (ALD) targets. ALD targets were used to accurately correlate the response of the test vehicles with specific locations on the test track.

The actual track geometry records for each test section, as measured with the T-6 car, are shown in Figures 2-10 through 2-15. Wheel forces and rail displacements were monitored at two wayside locations by rail-mounted transducers. The data from this instrumentation provided a comparison of all the wheels passing over the wayside sites. Locations of the wheel/rail load transducers in the wayside instrumentation arrays are shown in Figures 2-16 and 2-17. These arrays were installed on the last cycle of high-rail alignment perturbations on both the 6- and 12-degree curves. Lateral and vertical force transducers were installed on the high rail. The transducers were spaced approximately one truck wheel base length for the hopper car (every third crib)



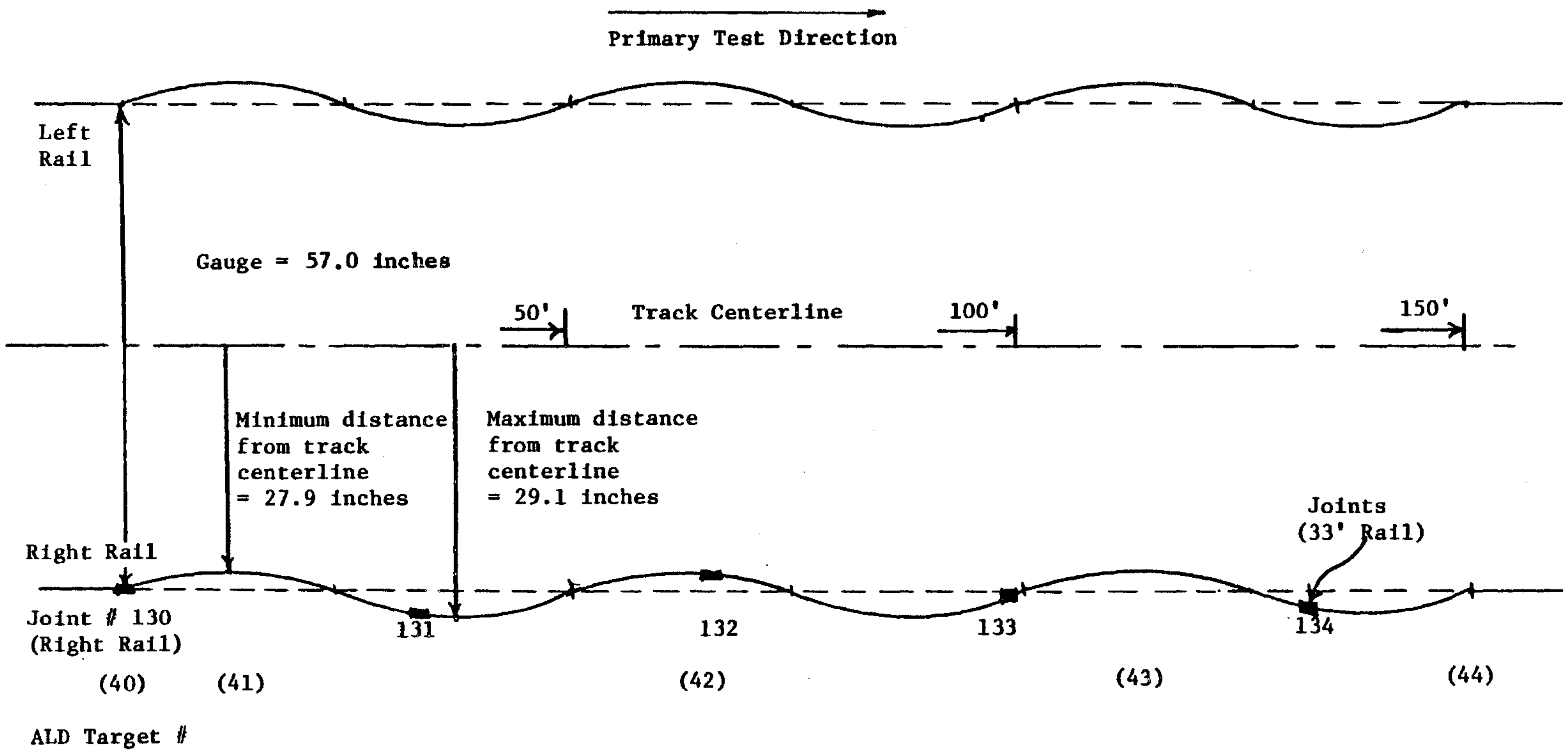
Cross Level Perturbation for Test Series III Only
12% Curve Track, Cusp Type Alignment-Gauge Perturbations
33' Wavelength, 8 Cycles, 1-1/4 Inch Cusp Amplitude
56-1/2 Inch Nominal Gauge

FIGURE 2-4. TRACK GEOMETRY PERTURBATION DETAILS OF TEST SECTION 1



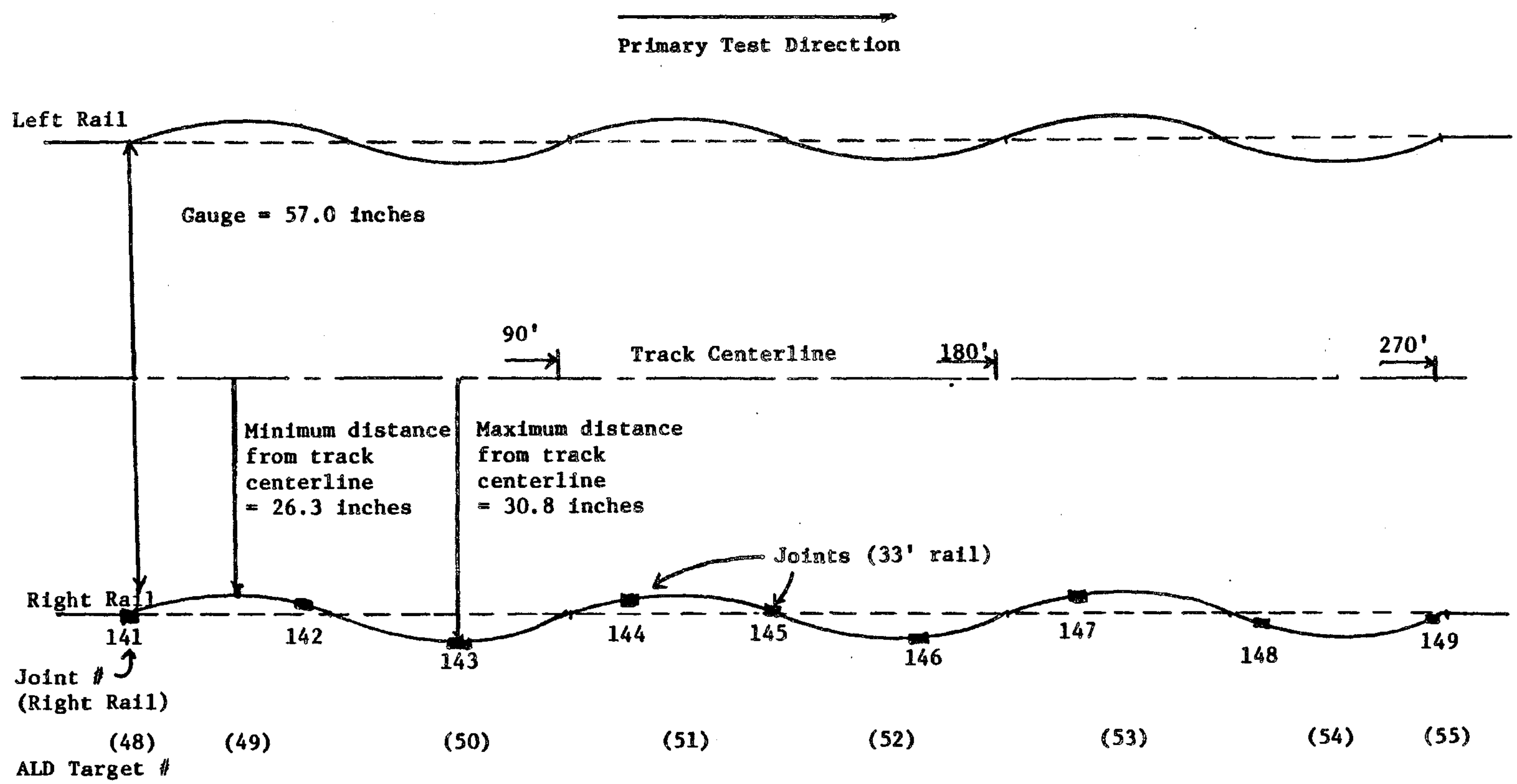
Tangent Track, Sinusoidal Alignment Perturbations
39-foot Wavelength, 1.33-inch Amplitude (peak-to-peak)
3 Cycles, 57-inch Nominal Gage.

FIGURE 2-5. TRACK GEOMETRY PERTURBATION DETAILS OF TEST SECTION 2.1



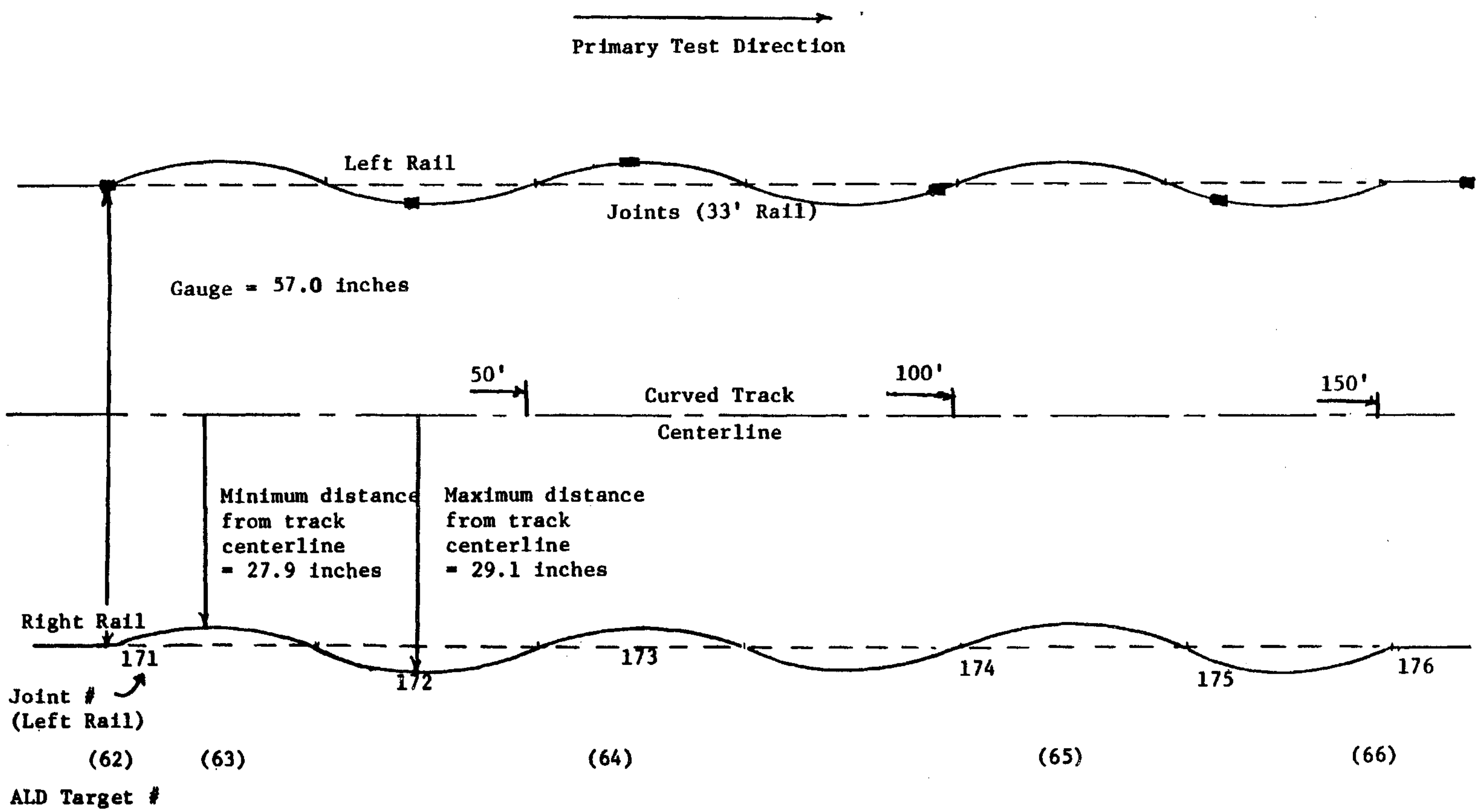
Tangent Track, Sinusoidal Alignment Perturbations
A 50-foot Wavelength, 1.25-inch Amplitude (peak-to-peak)
3 Cycles, 57-inch Nominal Gage.

FIGURE 2-6. TRACK GEOMETRY PERTURBATION DETAILS OF TEST SECTION 2.2



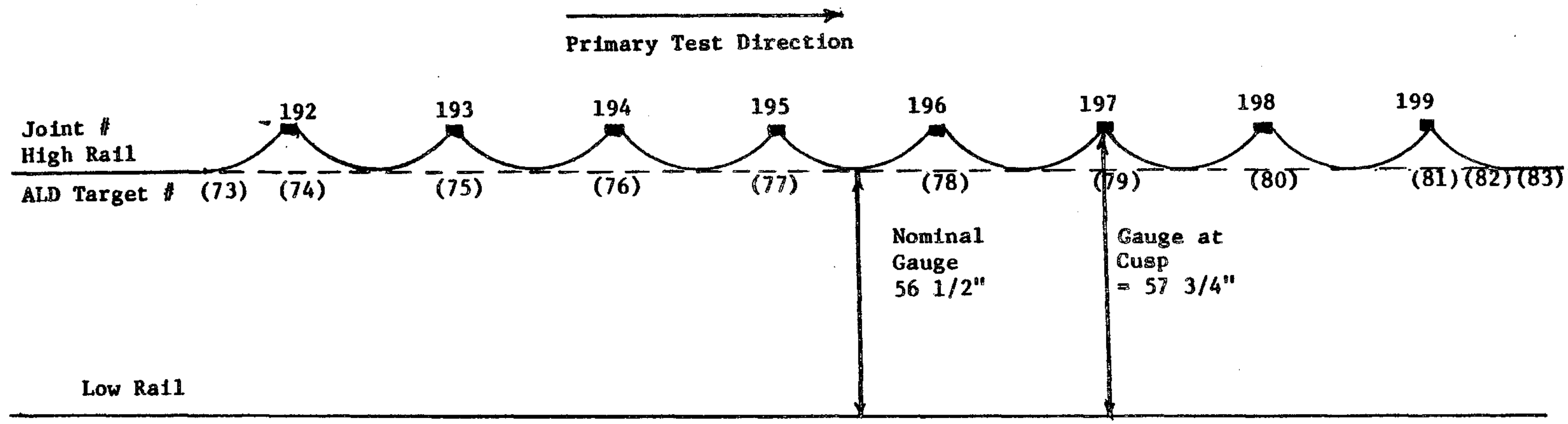
Tangent Track, Sinusoidal Alignment Perturbations
90-foot Wavelength, 4.5-inch Amplitude (peak-to-peak)
3 Cycles, 57-inch Nominal Gage.

FIGURE 2-7. TRACK GEOMETRY PERTURBATION DETAILS OF TEST SECTION 2.3



6-degree Curved Track, Sinusoidal Alignment Perturbations
50-foot Wavelength, 1.25-inch Amplitude (peak-to-peak)
3 Cycles, 57-inch Nominal Gage

FIGURE 2-8. TRACK GEOMETRY PERTURBATION DETAILS OF TEST SECTION 3.1



6-degree Track, Cusp Type Alignment-Gage Perturbations
33-foot Wavelength, 1.25-inch Cusp Amplitude, 8 Cycles
56.5-inch Nominal Gage

FIGURE 2-9. TRACK GEOMETRY PERTURBATION DETAILS OF TEST SECTION 3.2

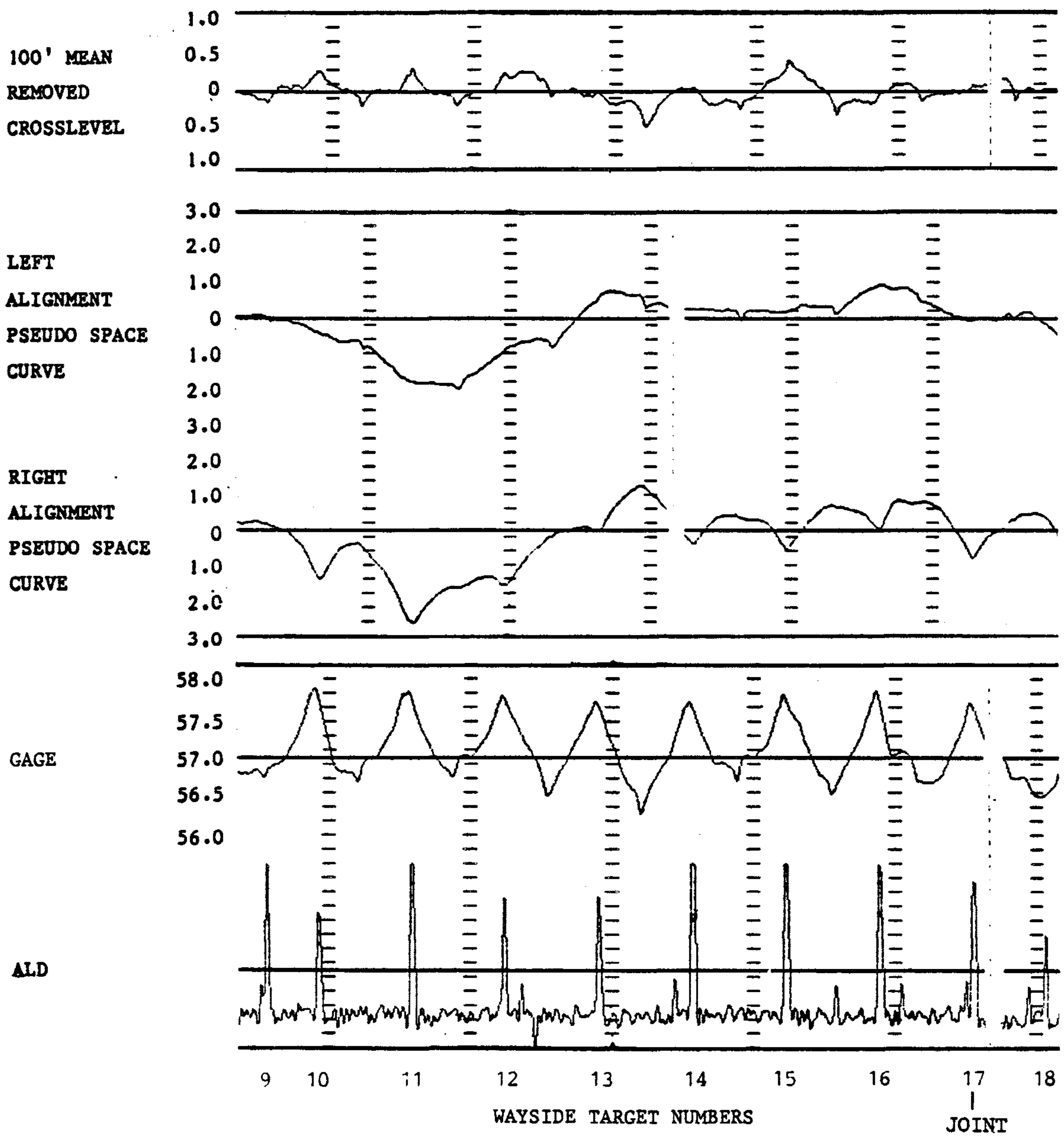


FIGURE 2-10. SECTION 1: T-6 SURVEY ON 8/28/82

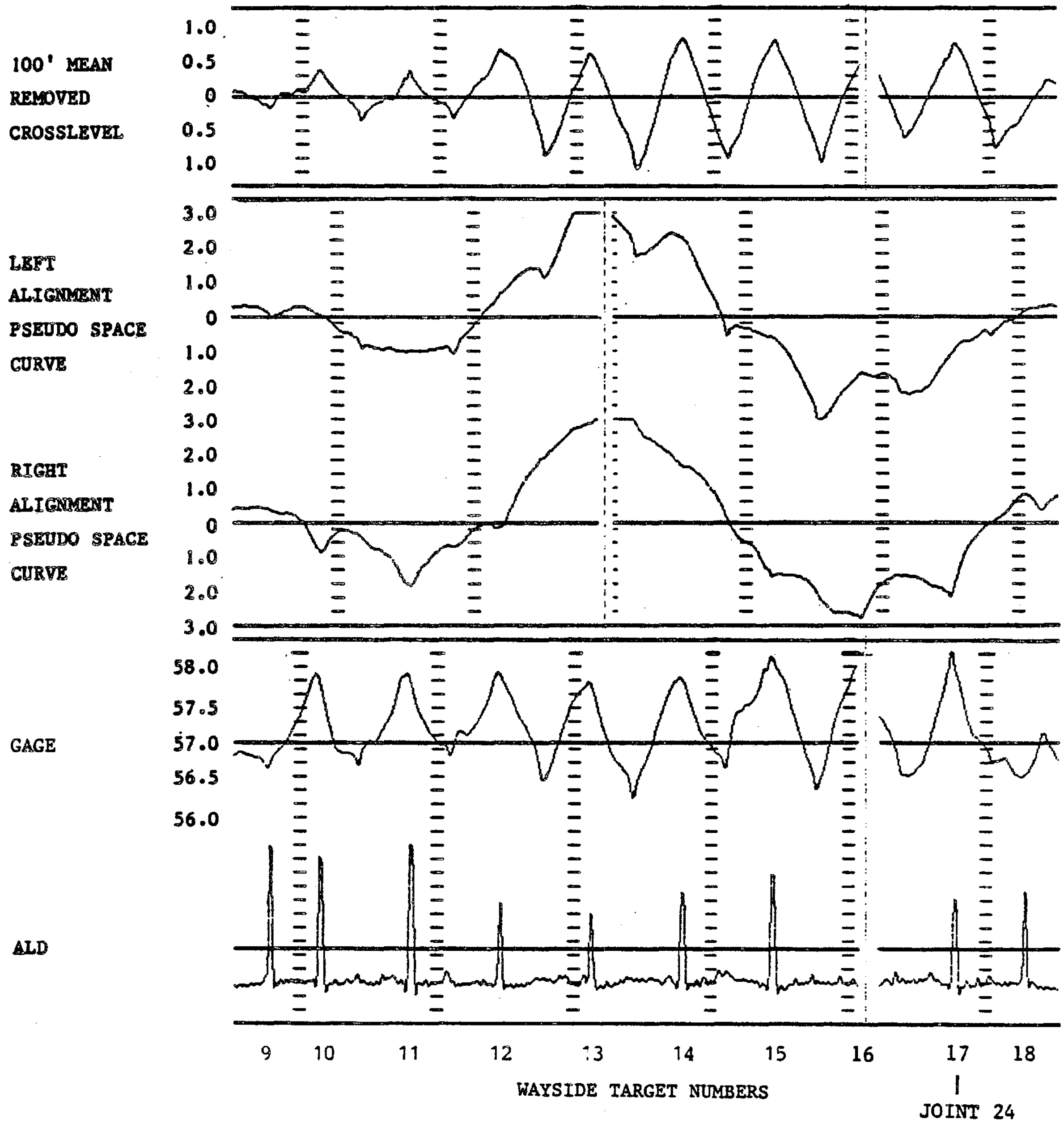
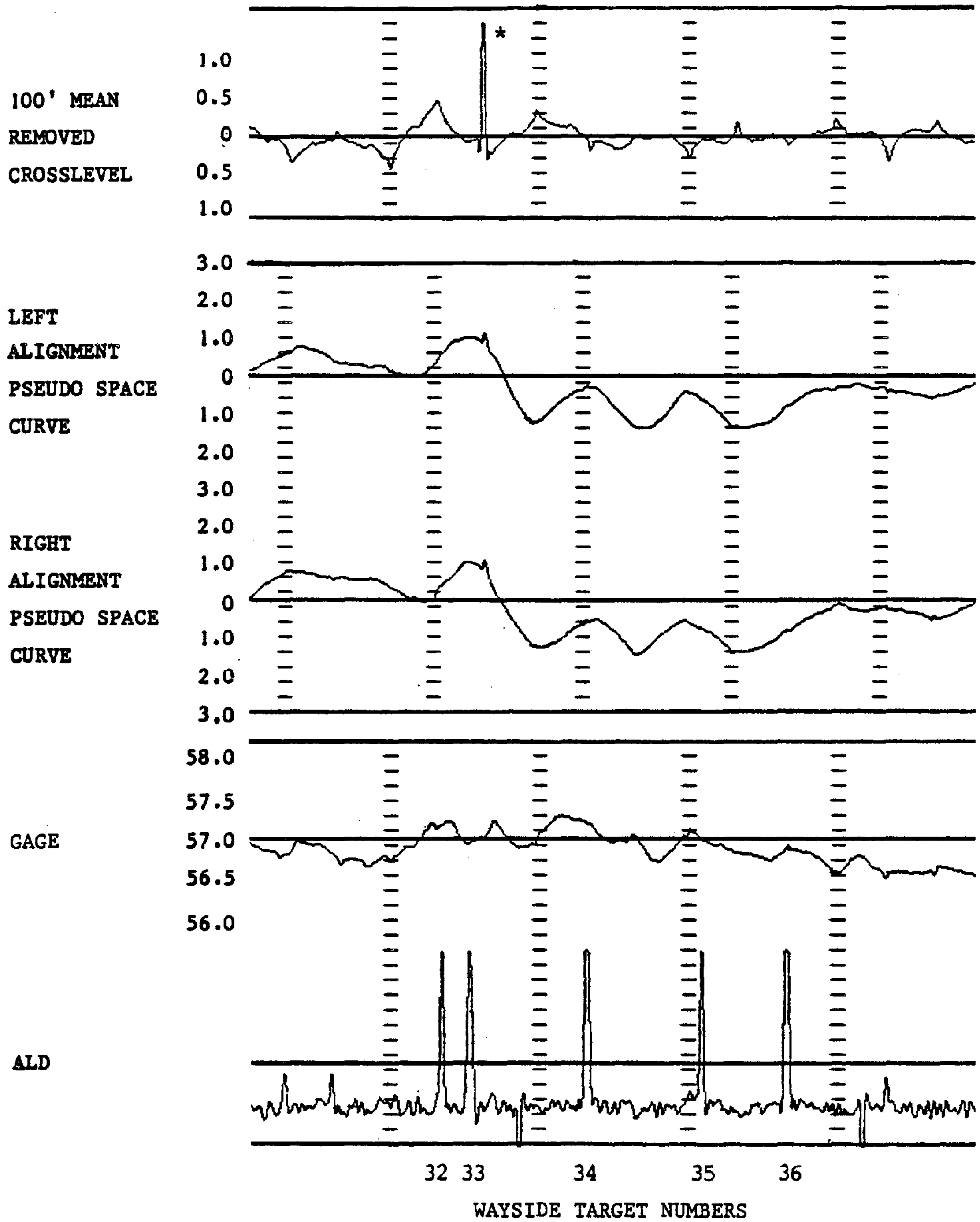


FIGURE 2-10 (CONCLUDED). SECTION 1: T-6 SURVEY OF 9/01/82



*Spurious electronic noise.

FIGURE 2-11. SECTION 2.1: T-6 SURVEY ON 8/28/82

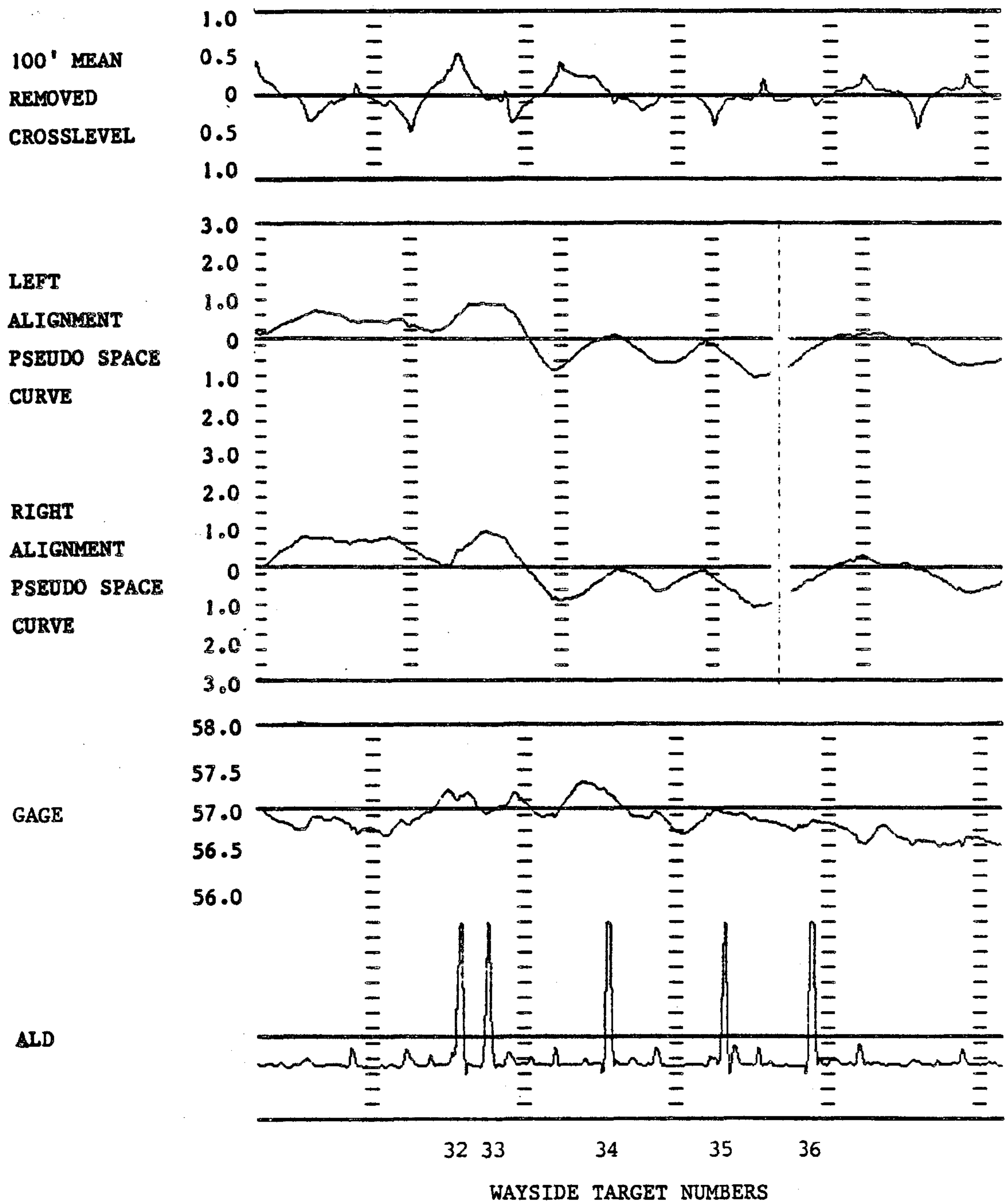


FIGURE 2-11 (CONCLUDED). SECTION 2.1: T-6 SURVEY ON 9/01/82

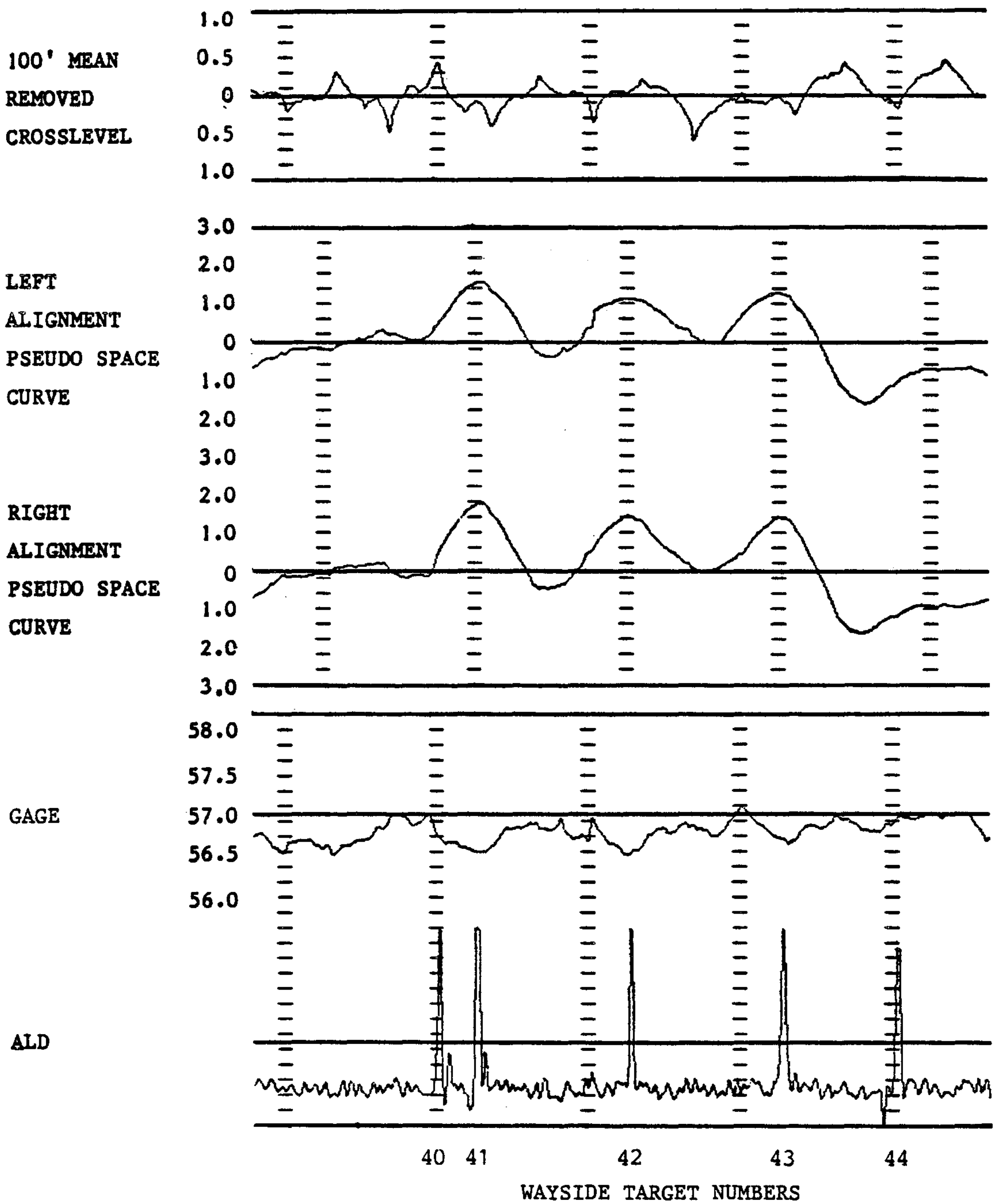


FIGURE 2-12. SECTION 2.2: T-6 SURVEY ON 8/28/82

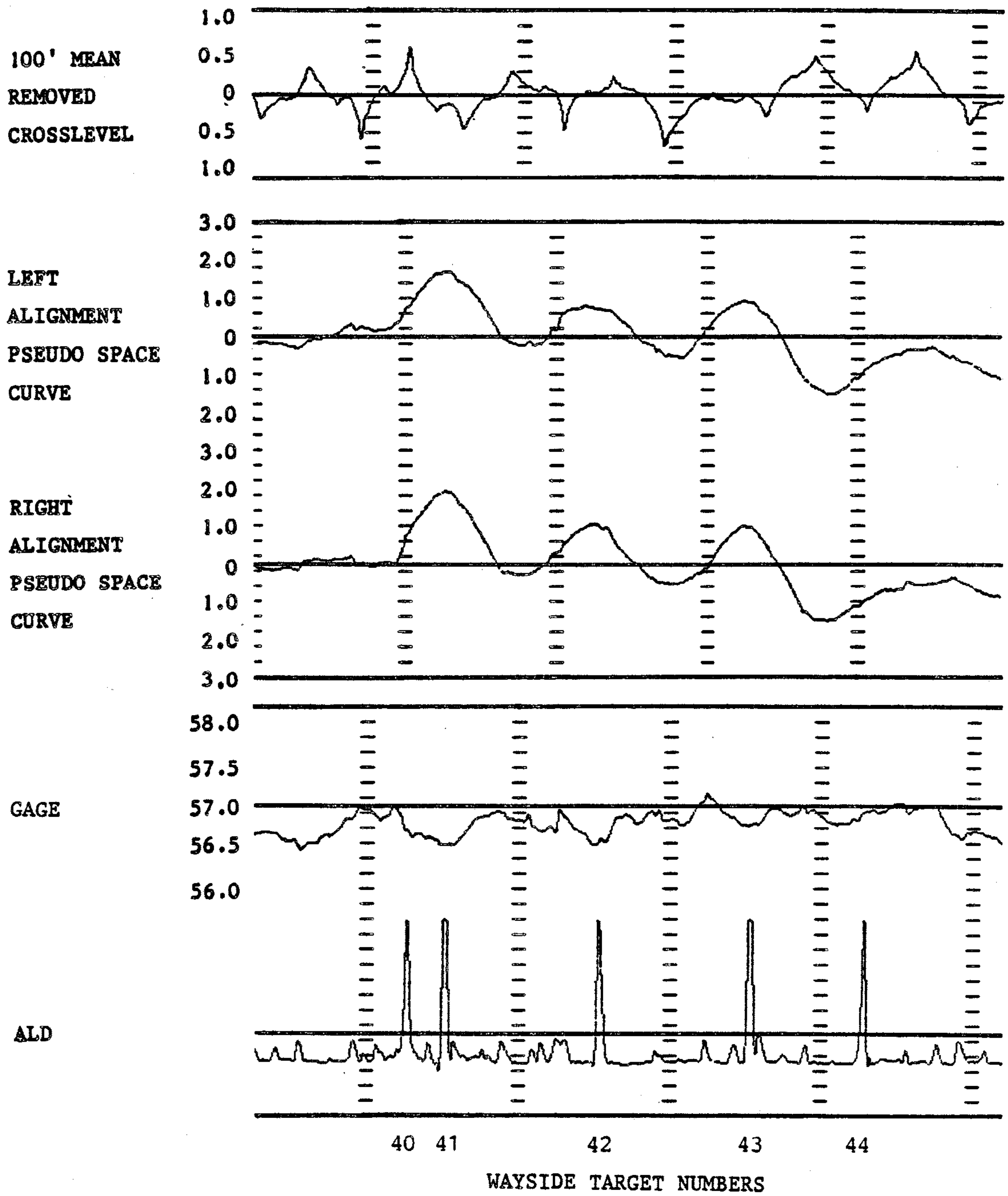


FIGURE 2-12 (CONCLUDED). SECTION 2.2: T-6 SURVEY ON 9/01/82

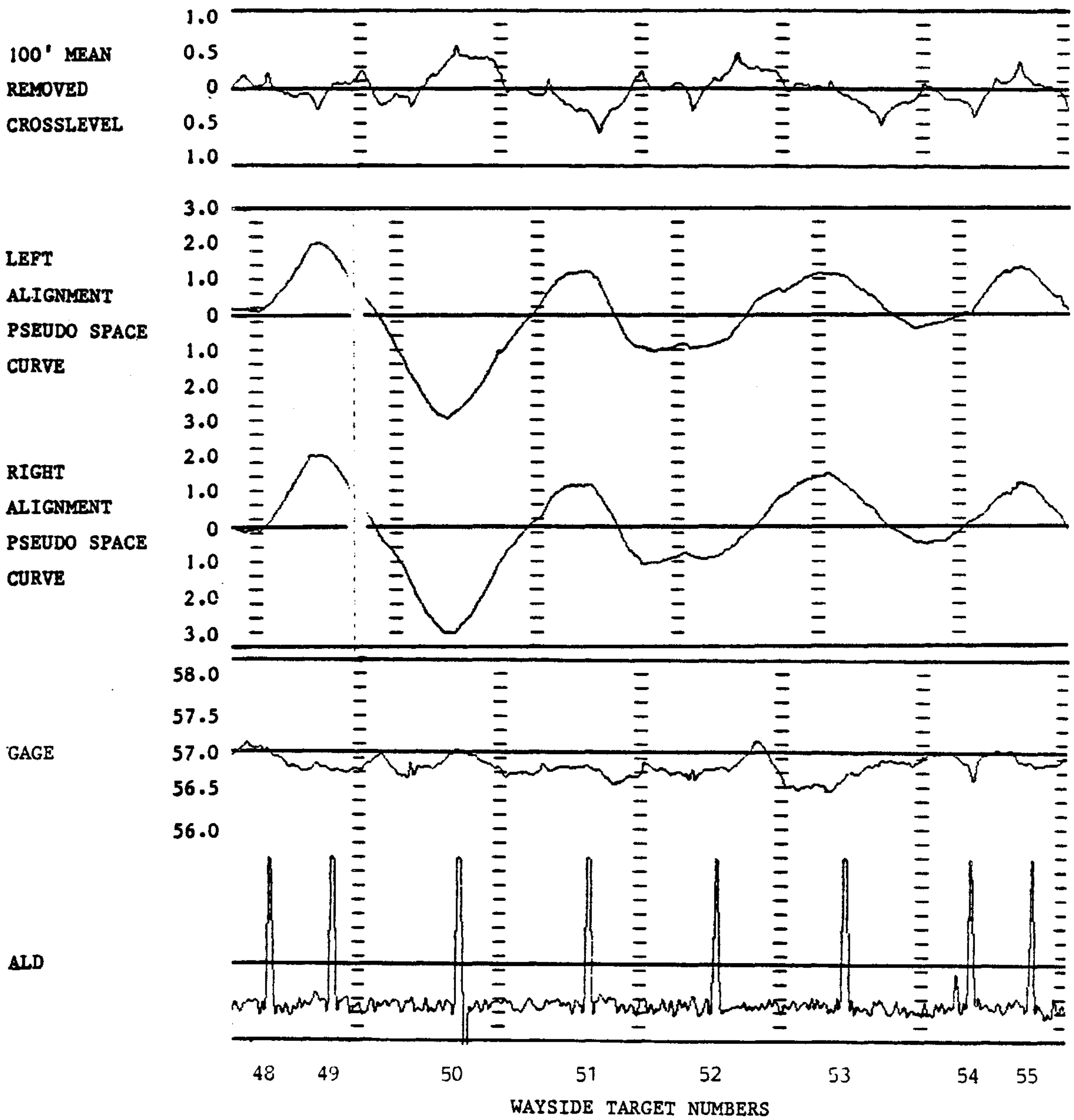


FIGURE 2-13. SECTION 2.3: T-6 SURVEY ON 8/28/82

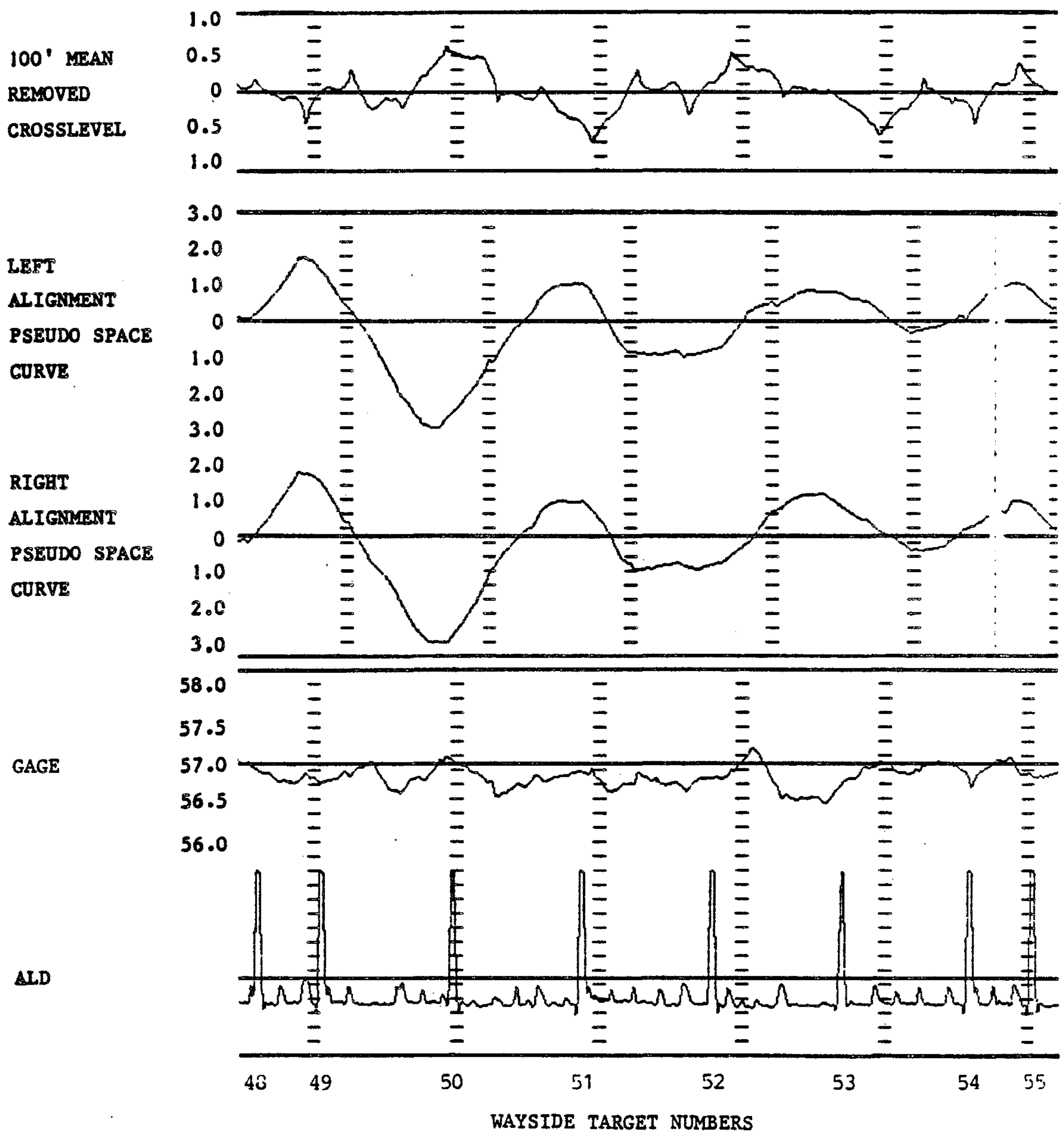


FIGURE 2-13 (CONCLUDED). SECTION 2.3: T-6 SURVEY ON 9/01/82

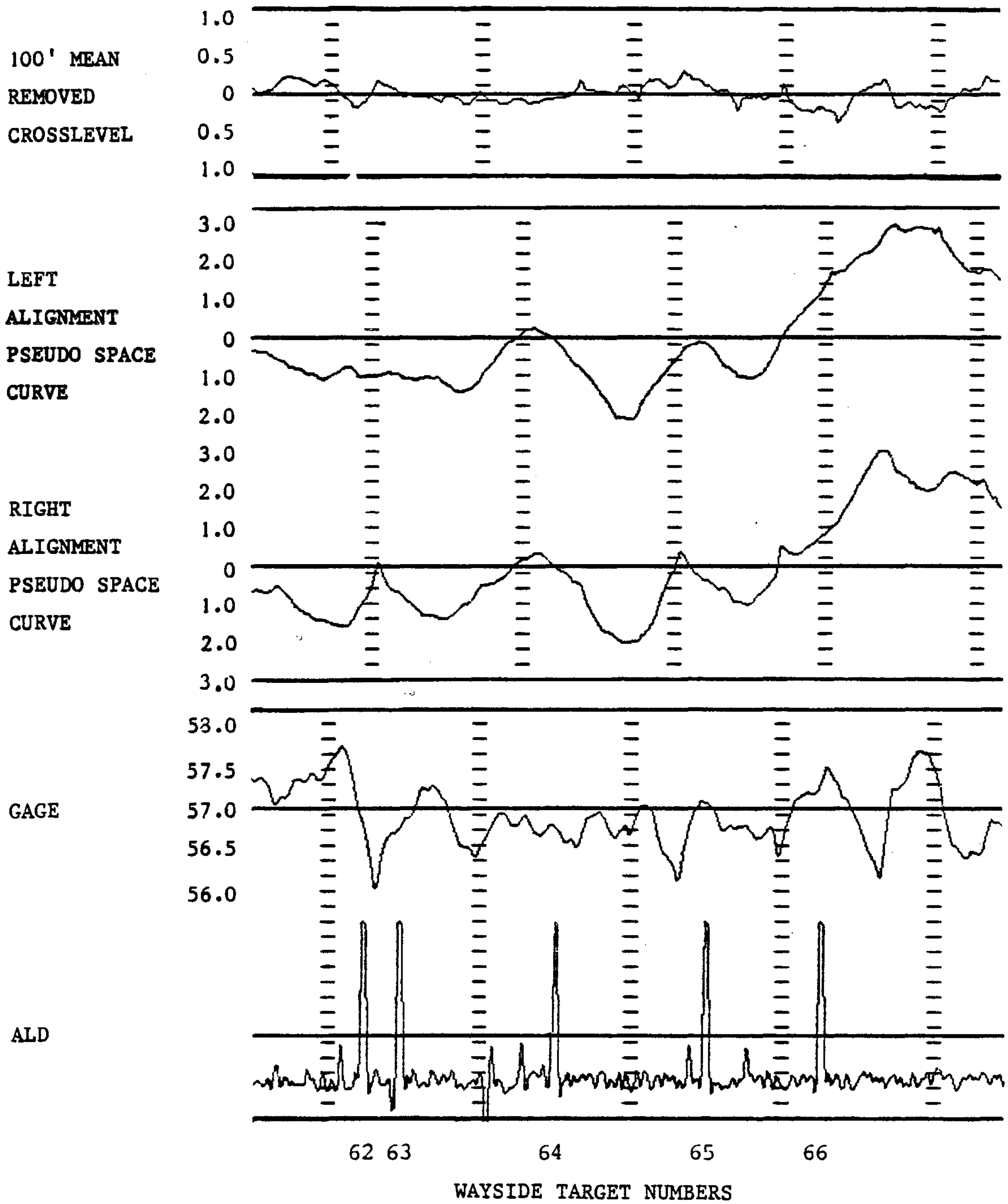


FIGURE 2-14. SECTION 3.1: T-6 SURVEY ON 8/28/82

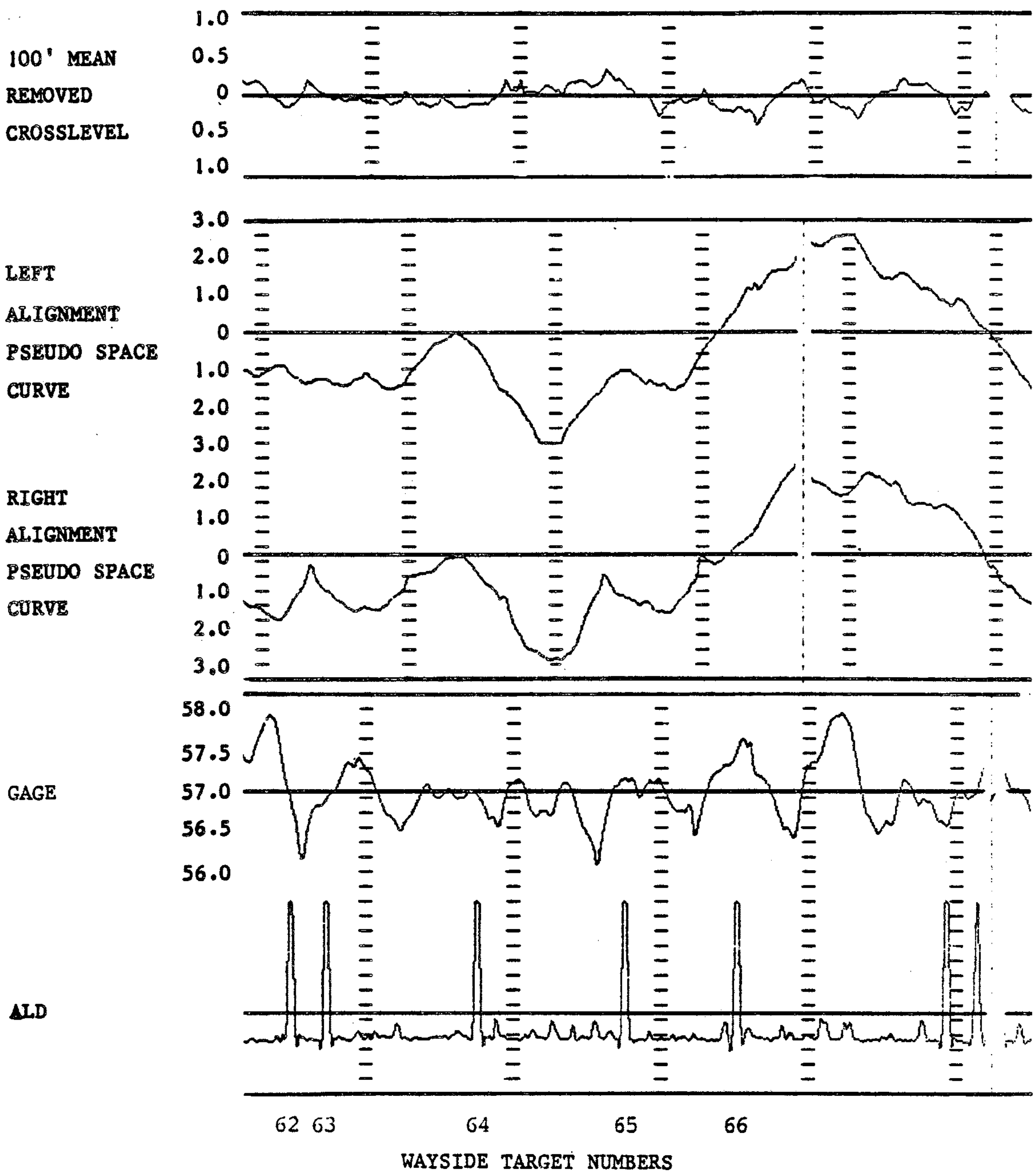


FIGURE 2-14 (CONCLUDED). SECTION 3.1: T-6 SURVEY ON 9/01/82

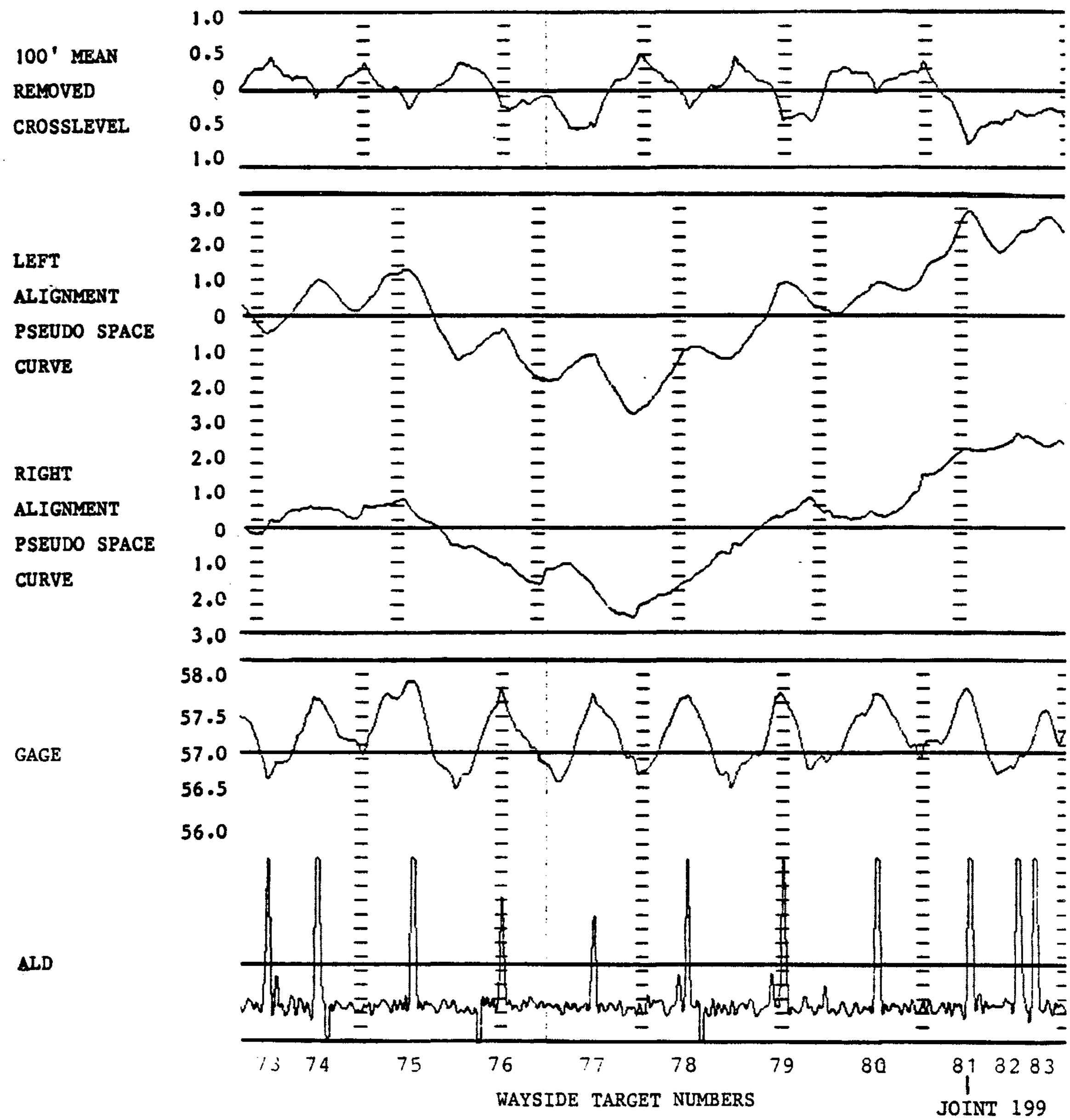


FIGURE 2-15. SECTION 3.2: T-6 SURVEY ON 8/28/82

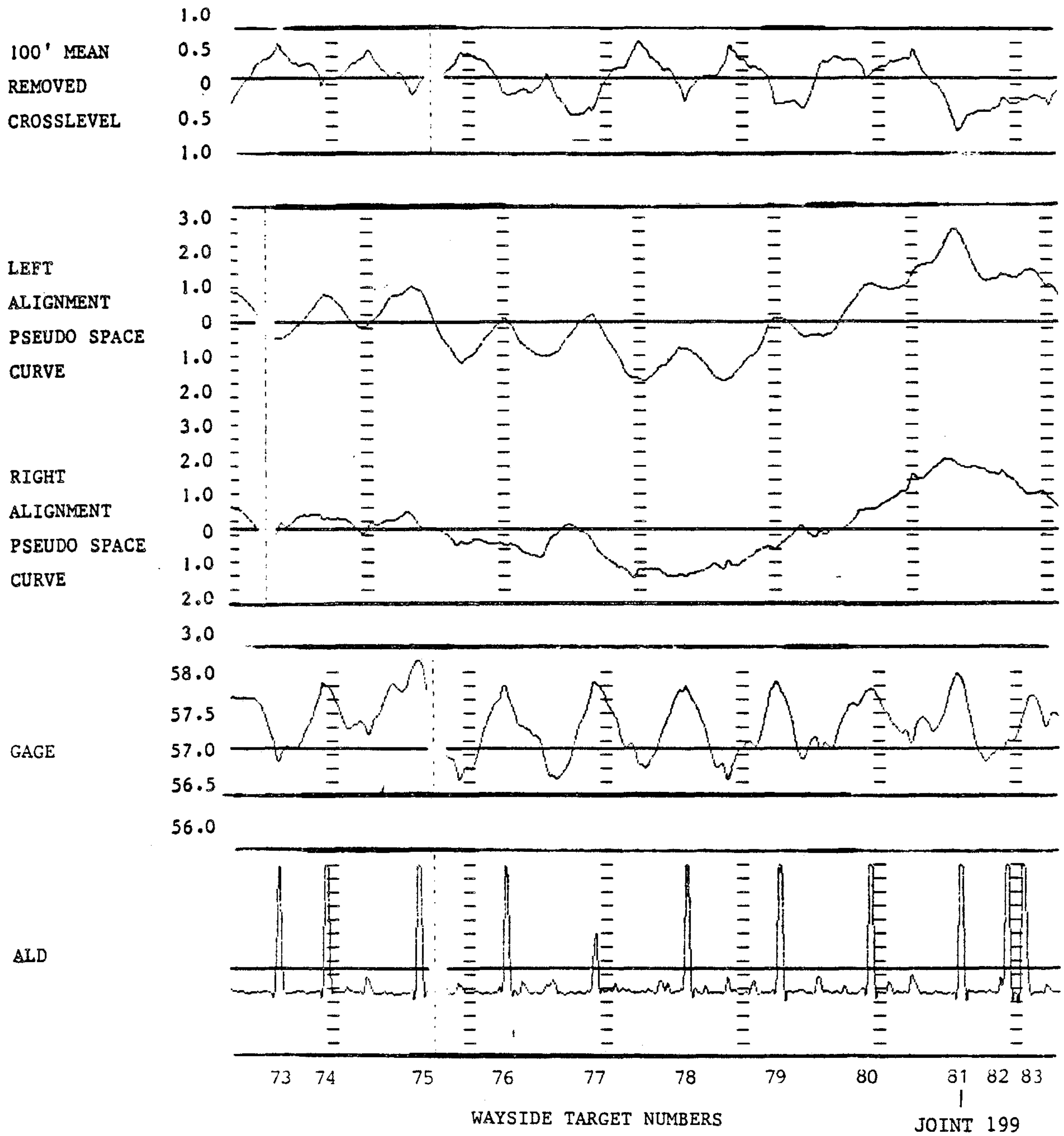
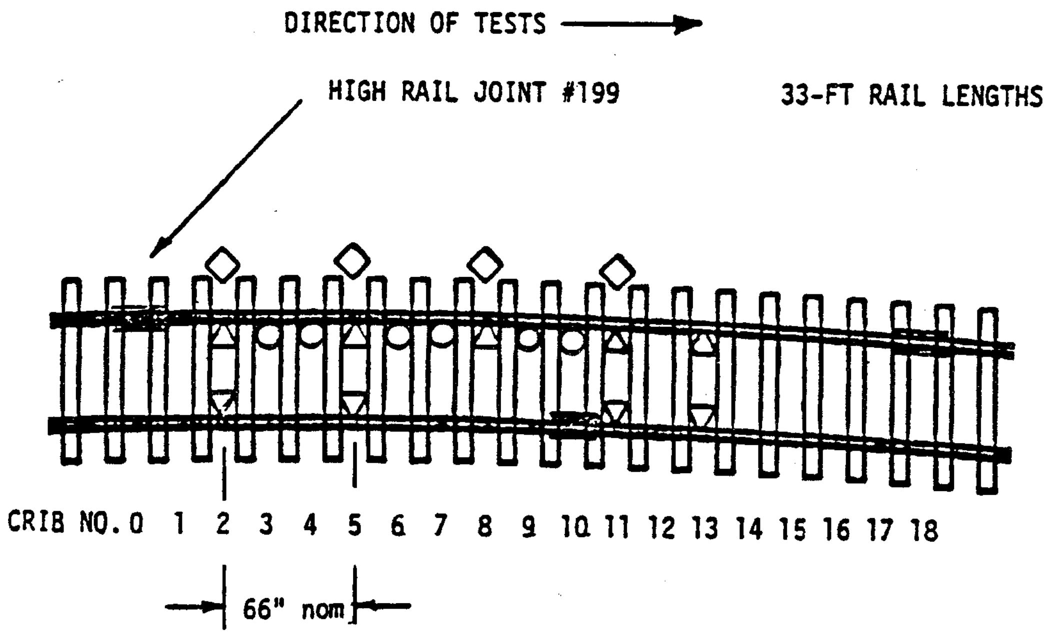


FIGURE 2-15 (CONCLUDED). SECTION 3.2: T-6 SURVEY ON 9/01/82



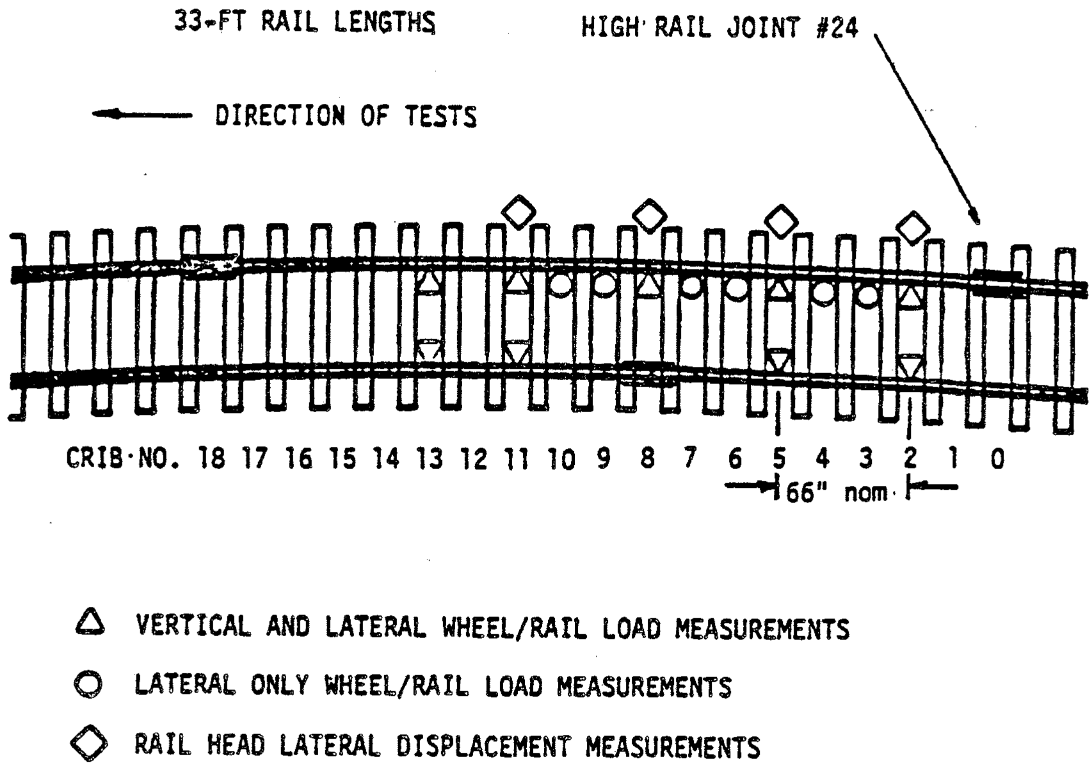
△ VERTICAL AND LATERAL WHEEL/RAIL LOAD MEASUREMENTS

○ LATERAL ONLY WHEEL/RAIL LOAD MEASUREMENT

◇ RAIL HEAD LATERAL DISPLACEMENT MEASUREMENT

CRIB NUMBER	DISTANCE FROM HIGH RAIL JOINT
2	42
3	59-1/2
4	77
5	97-3/4
6	120
7	143
8	164-3/4
9	187-3/4
10	207-1/4
11	225-1/2
13	263-1/2
	(IN. TO CRIB CENTERLINE)

FIGURE 2-16. WAYSIDE INSTRUMENTATION ARRAY FOR THE 6-DEGREE CURVE



CRIB NUMBER	DISTANCE FROM HIGH RAIL JOINT
2	44
3	67
4	88-1/2
5	109-1/2
6	133
7	155-1/4
8	176-1/4
9	196-3/4
10	218-1/2
11	242-1/2
13	287-1/2
	(INCHES TO CRIB CENTERLINE)

FIGURE 2-17. WAYSIDE INSTRUMENTATION ARRAY FOR THE 12-DEGREE CURVE

to provide samples of the total truck forces. Lateral transducers were placed in between the L/V transducers to assure capture of the lateral load time history through the zone.

As in many of the preceeding tests, ALD targets were used to determine the positions of the consist relative to the test track. For this test, two detectors were used. One was mounted on the locomotive at axle 3 and the other on the hopper car at axle 13. The two sensors were approximately 151 feet apart.

2.3 TEST CONDUCT

A total of 41 test runs were made between August 28 and 31, 1982. Sixteen were made on the 12-degree curve (Section 1) without crosslevel perturbations, six made on the same section with superimposed crosslevel perturbations, and nineteen made on the tangent and 6-degree curve (Test Sections 2.1, 2.2, 2.3, 3.1, and 3.2), as shown in Table 2-2. All except three runs were made in the primary test directions, i.e., from the 12-degree curve towards the 6-degree curve. The weather during the entire test was dry. However, the rail surface moisture condition varied during the test, especially for the first two or three passes of the test consist on each test day.

During the test, significant wear on the 6- and 12-degree curves was indicated by a sprinkling of steel filings along the ballast adjacent to high rail and the metal flow on the wheel tread and flange.

TABLE 2-2. SERIES I AND II TEST SCHEDULE

TEST SERIES I

Runs on 12-degree curve (Test Section 1) with no crosslevel

Run days: 8/28/82
8/29/82

RUN NO.	SPEED
2801	10
2802	10
2803	10 R
2804	13
2805	15
2901	5
2902	10
2903	10
2904	10
2905	15
2906	5
2907	15
2908	17.5
2909	15
2910	5**
2911	20

Runs on 12-degree curve (Test Section 1) with crosslevel

Run day: 8/31/82

RUN NO.	SPEED
3110	5
3111	10
3112	12
3113	14
3114	10 R
3115	8

TEST SERIES II

Runs on tangent and 6-degree curve (Test Sections 2.1, 2.2, 2.3, 3.1 and 3.2)

Run days: 8/30/82
8/31/82

RUN NO.	SPEED
3001	10**
3002	15
3003	17
3004	20
3005	23
3006	28
3007	25
3008	5*
3101	5
3102	10*
3103	20
3104	25
3105	28
3106	30
3107	15
3108	13
3109	18
3116	18**
3117	10 R **
3118	22**

R Reverse Direction
* No Onboard Data
** No Wayside Data

3. DATA ANALYSIS RESULTS

The analysis of the Bennington test data was conducted to determine vehicle response to track geometry irregularities in the 5 to 30 mph speed regime. The results of the test show:

1. that wheel rail forces in small radius curves are not strongly dependent on speed in the low speed regime.
2. that wheel rail forces increase with curvature.
3. that crosslevel irregularities on small radius curves produce high lateral to vertical (L/V) force ratios.
4. that alignment variations with larger amplitudes and longer wavelengths produce peak wheel/rail forces similar to those produced from smaller amplitude variations with shorter wavelengths.

In addition, the test data confirms the conclusions of earlier tests, such as the gage spreading nature of wheel rail forces resulting from irregularities on curves.

The hopper car used during the Bennington test was not entirely typical of a 100-ton, open top coal car. The major difference was that it was not fully loaded. The average wheel load was about 25,000 pounds and the approximate center of gravity (cg) was 80 inches above the rail. A typical, fully loaded coal car would have an average wheel load of 33,000 pounds and a cg height of 96 inches above the rail.

In some of the plots that follow, a balance speed of 20 mph is noted for both the 6- and 12-degree curves. This is only approximate as the actual superelevation in the curves varied. Distance based plots of wheel/rail force data have been created and used extensively in the analysis of the Bennington data. The onboard data were digitally recorded as 256 Hz, sampled at 64 Hz, and then displayed at a constant 50 ft/in. for the plots. This processing assumes that the vehicle speed was constant throughout the various test sections. Distance based plots facilitate the comparison of wheel force data from runs of different speed and with track geometry data which is recorded using a distance based process.

3.1 EFFECT OF SPEED ON SHARP CURVES

In the study of vehicle/track interaction, vehicle speed is a significant variable for most indices of train safety. The relationship between speed and vehicle response is the basis for establishing track speed limits. In previous tests[2] lateral wheel forces were shown to vary significantly with speed and unbalanced superelevation in curves in the 35 to 70 mph speed regime. The sensitivity of a vehicle's response to speed is particularly apparent when studying resonant phenomena such as rock and roll, carbody yaw, or hunting. The Starr, Ohio test[3] showed, however, that in the low-speed regime lateral forces were not significantly affected by vehicle speed in 5- to 6-degree curves. The lateral forces generated during curving at low speeds are primarily the result of flange and creep forces. Below the speed of 25 mph, the resultant lateral component of the inertia forces, which increase with the square of the velocity, is small when compared to the creep forces and is only apparent when considering the total truck force. This test was designed to investigate the conditions of the low speed passage of a freight consist over curves of 10 or more degrees. At Bennington two curves were used, a 6-degree and a 12-degree curve. The data from the 12-degree curve are presented in this section.

Parametric studies using the SIMCAR program indicated that a standard 100-ton freight truck would generate significant lateral wheel forces while negotiating a 12-degree curve at any speed. The studies also showed that lateral forces resulting from steady state curving would be increased by high rail alignment perturbations. At Bennington, the first test series was conducted under these conditions at speeds ranging from 5 to 20 mph. The single wheel lateral forces for the hopper car were compared over the speed range. Examples of three time-history force traces at 5, 15, and 20 mph are shown in Figure 3-1. From this figure, three observations are evident:

1. The patterns of the responses are remarkably consistent over the three speeds shown. This indicates a highly deterministic response to the imposed perturbations.
2. Peak lateral wheel forces increase by only 5 kips, from 17 kips to 22 kips, as speed is increased from 5 to 20 mph.
3. Small variations in the regularity of the alignment perturbations can result in large variations in wheel force. This is most strongly evidenced by the lateral force response at the fourth cusp which has a double peak.

Figure 3-2 shows a single measure of several wheel force traces from 5 to 20 mph. The two shaded data points are from the first two runs on August 29, 1981. These were conducted in the morning with no prior conditioning or geometry survey runs. The rail was, apparently, slightly damp or otherwise contaminated. If these runs are ignored for the moment as conditioning runs, the important conclusion that the lateral forces are high, regardless of the speed, is apparent. The wheel/rail force is 17 kips at 5 mph and while the trend is that lateral forces increase with speed, the inertia forces increase slowly in this curve and speed regime.

The findings drawn in Figures 3-1 and 3-2, which depict only a small part of the test data, are further substantiated by a closer review of the repeatability of the tests. Figure 3-3 compares the lateral wheel force

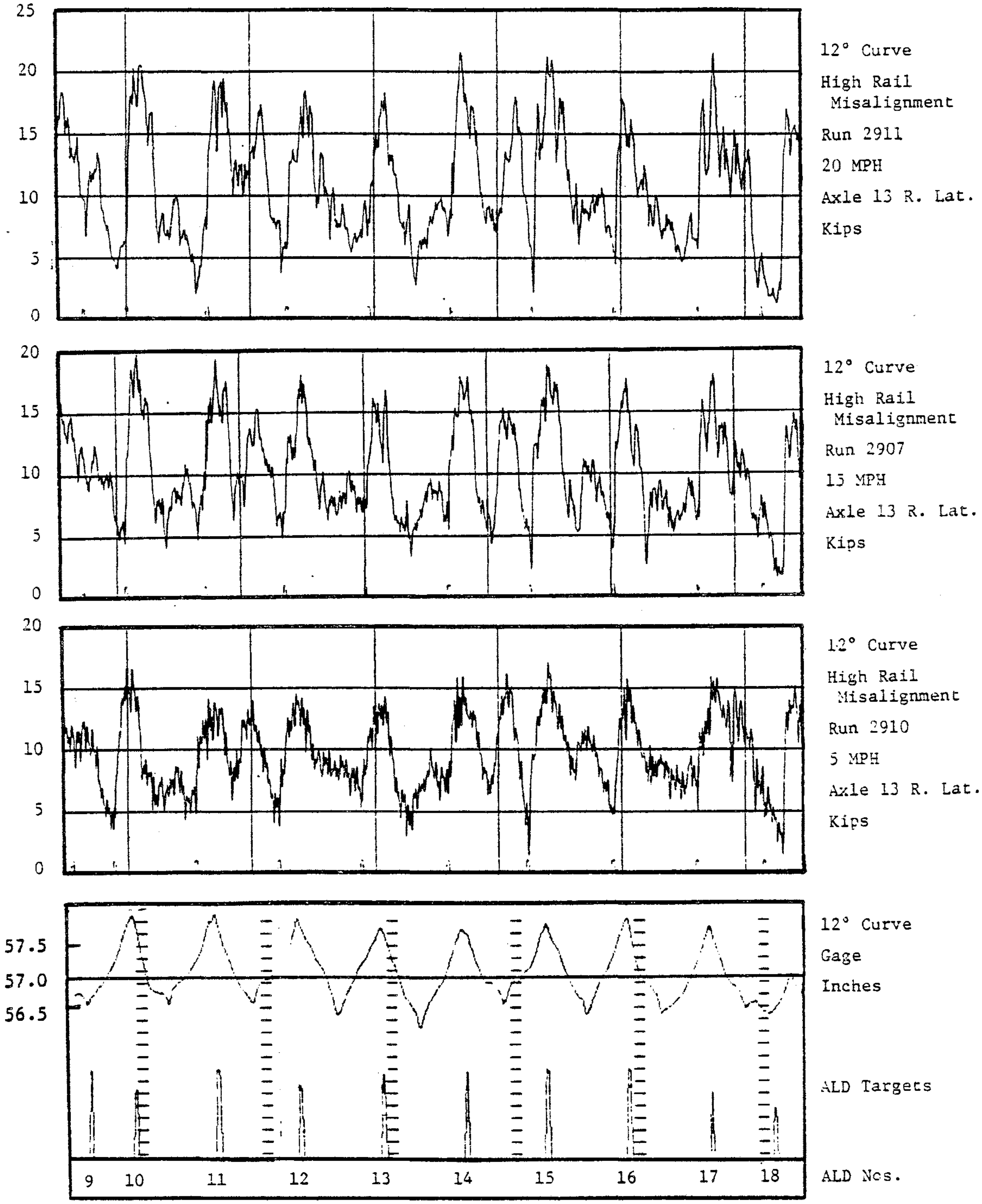


FIGURE 3-1. EFFECT OF SPEED ON HOPPER CAR LATERAL WHEEL FORCES

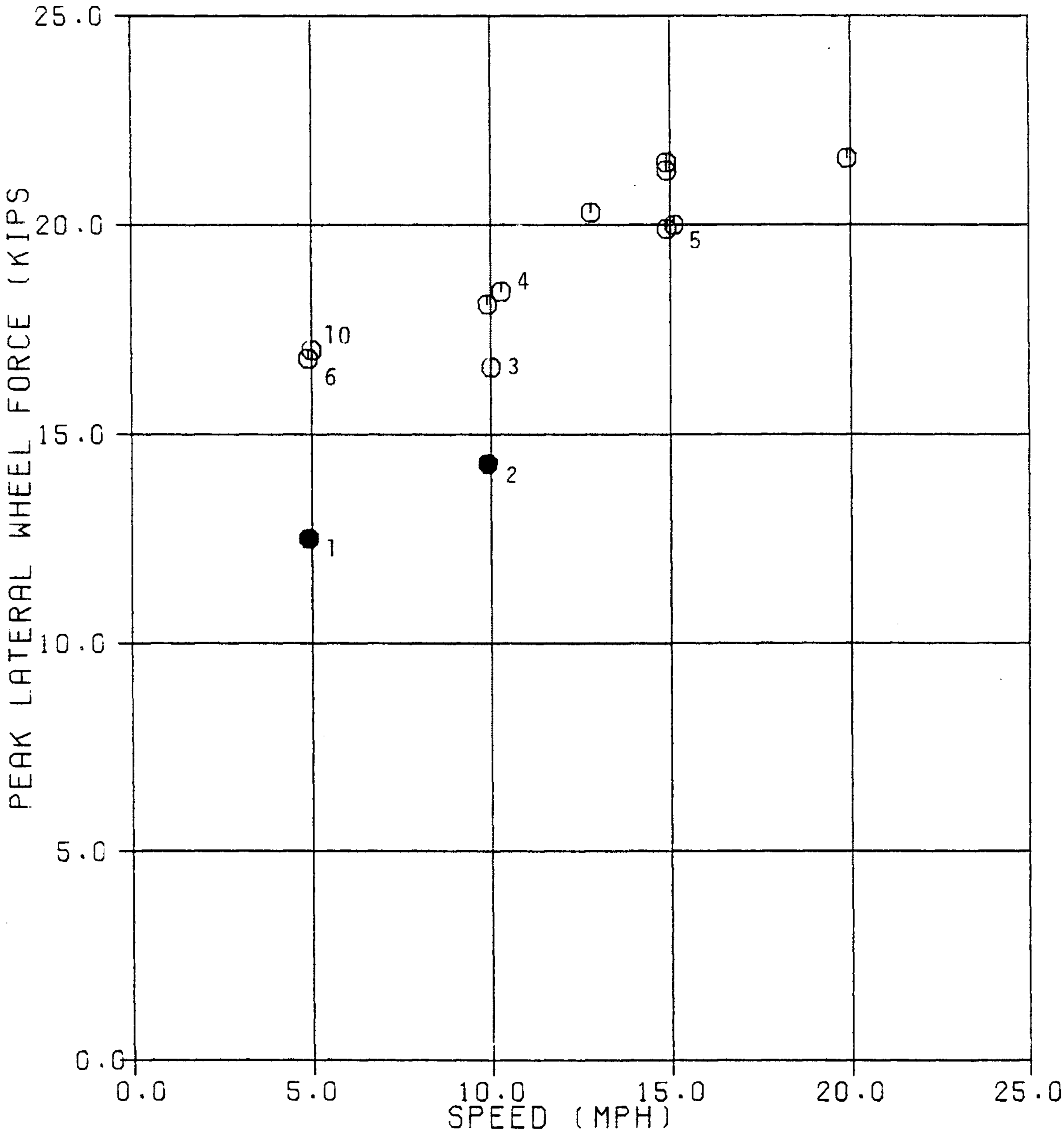


FIGURE 3-2. PEAK LATERAL WHEEL FORCES VS. SPEED - HOPPER CAR AXLE 13 RIGHT, SECTION 1, 12-DEGREE CURVE (NUMBERS INDICATE RUN ORDER.)

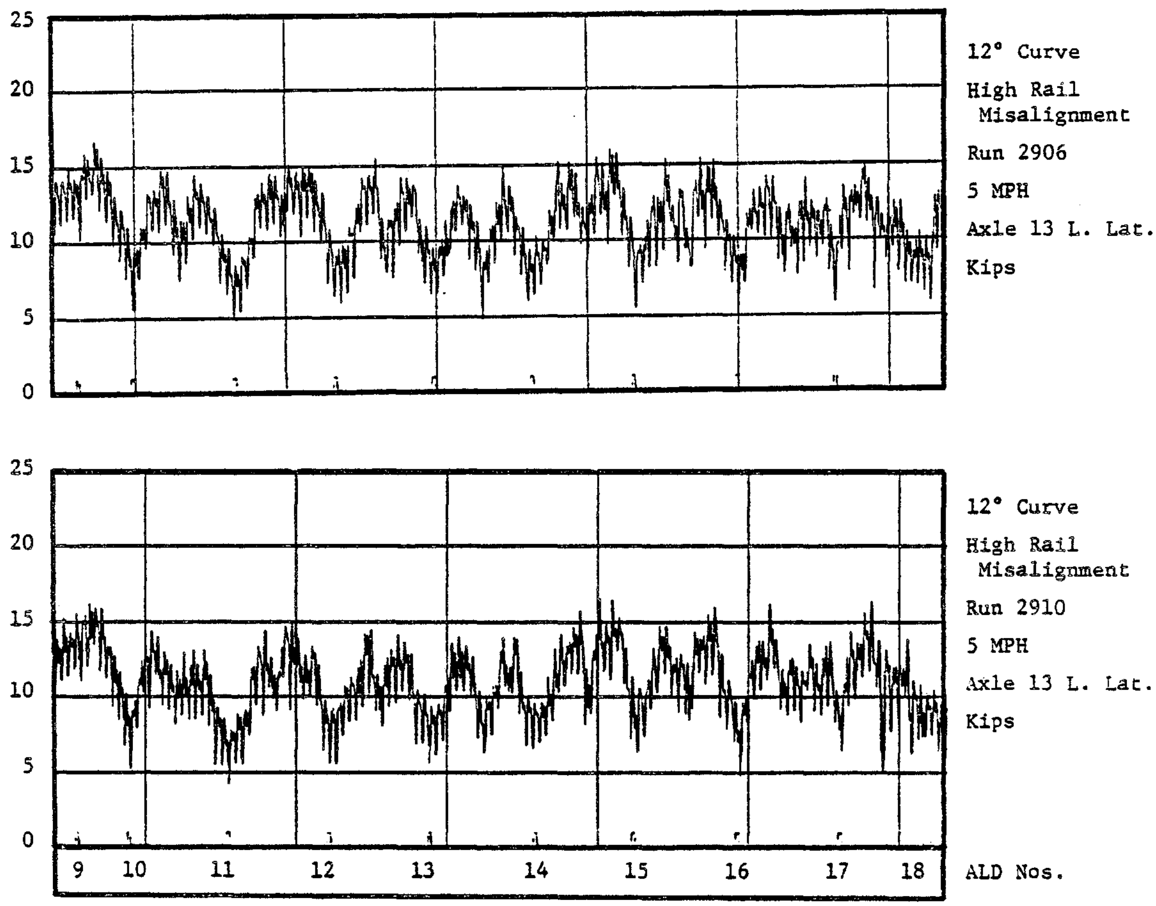


FIGURE 3-3. REPEATABILITY OF LOW-RAIL FORCES

signatures for two different test runs over the 12-degree curve, each at 5 mph. The pattern is nearly identical, again demonstrating the deterministic nature of the vehicle response. This suggests that valid conclusions may be derived from a statistically limited set of test data.

The principle qualification to the conclusion of repeatability is that the independent test variable, i.e., rail surface condition, must be controlled. The rail surface condition varies continuously during testing with the greatest changes noted after the first few passes of the test consist at the beginning of each test day. As the time between wheel passes increases, especially overnight, moisture, rust, dust, and other contaminants accumulate on the rail head and form a lubricant for the wheel/rail interface. With the passage of each wheel, the head of the rail is cleaned, which causes the coefficient of friction to increase.

In the 12-degree curve, the leading wheelset of each truck was continuously in flange contact on the high rail. While the high rail is in flange contact, the low-rail lateral wheel force is limited by the coefficient of friction and the vertical force. In Figure 3-4, time histories of the low-rail wheel forces from two test runs at 5 mph are compared. The lower time history is from the first run of a test day before any appreciable amount of traffic. The peak lateral wheel force is about 10 kips implying a coefficient of friction between 0.3 and 0.4. During the same test day, on the sixth test run, another 5 mph run was made. The low-rail time history trace at the top of Figure 3-4 shows that the peak lateral force had increased to almost 15 kips, suggesting a friction coefficient of between 0.5 to 0.6. Figure 3-3 shows that this force level was repeated again on the tenth run of that day showing that the rail surface

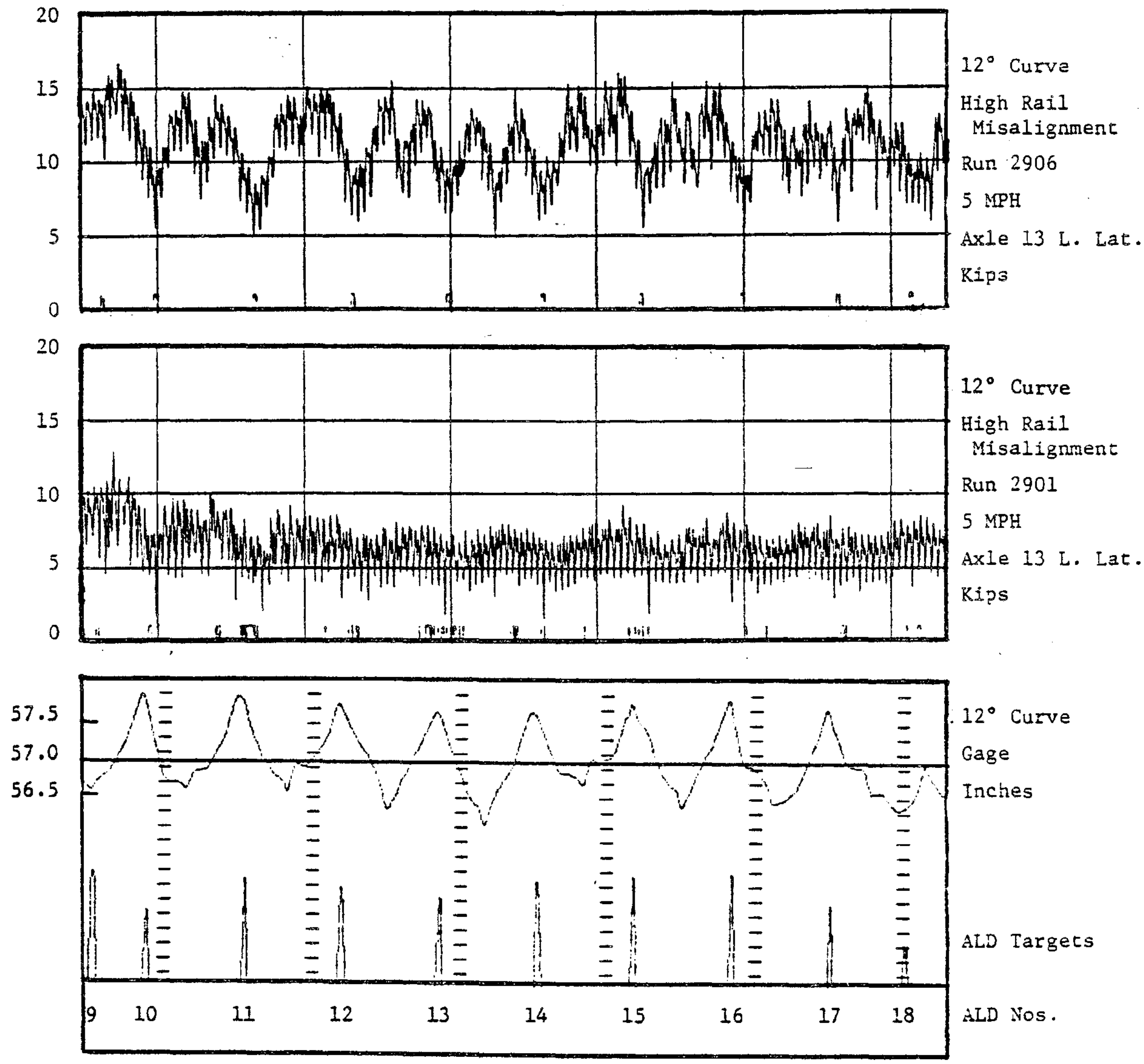


FIGURE 3-4. EFFECT OF RAIL SURFACE CONDITION ON LOW-RAIL FORCES

condition stabilizes after a few consist passes. During the Bennington tests, other sources of rail surface contamination such as rain, snow, excessive amounts of fuel or grease left on the rail by the consist, or curve lubrications were not present.

Vertical wheel forces are affected by both the vertical and lateral irregularities in the track. High-rail misalignment, as well as crosslevel, can produce significant wheel unloading because the lateral excitation is well below the center of gravity of the car inducing a roll motion. Figure 3-5 shows two traces of hopper car high rail vertical wheel forces at 5 and 20 mph on the 12-degree curve. Traces of gage and crosslevel track geometry are also shown, spatially correlated with the resultant wheel forces. The figure shows that the variations in vertical wheel force closely follow the variations in high-rail alignment (indicated by the gage trace). The amplitude of the vertical force variations changes with speed, as the frequency of the lateral inputs approaches the carbody roll natural frequency. Peak-to-peak variations are about 30 kips at 20 mph while only about 10 kips at 5 mph.

While extreme vertical wheel force unloading can lead to wheel lift, the primary concern during this test was wheel climb. As the lateral-to-vertical (L/V) ratio increases, the tendency toward wheel climb increases assuming a constant angle of attack, flange angle, and coefficient of friction. During the test, the L/V ratio was affected by the variations in both lateral and vertical forces. Although lateral wheel forces increased slowly with speed, Figure 3-6 shows that the L/V ratio increased significantly for the 20 mph run, whereas the vertical wheel force variations had increased due to the roll response of the hopper car. The shaded plot points (Figures 3-6, 3-8, 3-10, 3-13, and 3-16) are from the first two runs on August 29, 1981.

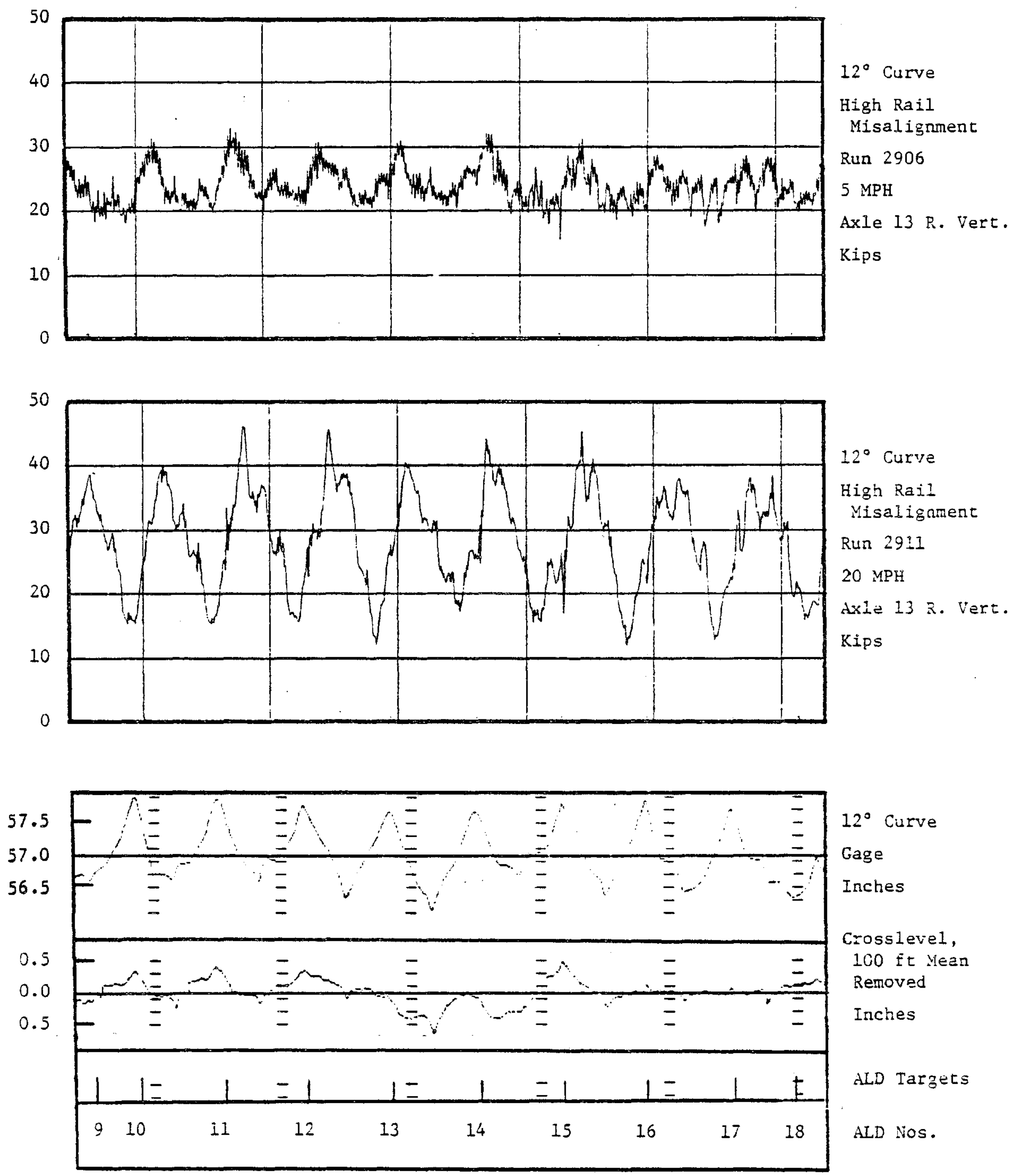


FIGURE 3-5. HOPPER CAR VERTICAL WHEEL FORCE RESPONSE TO HIGH-RAIL MISALIGNMENT AND NATURAL CROSSLEVEL

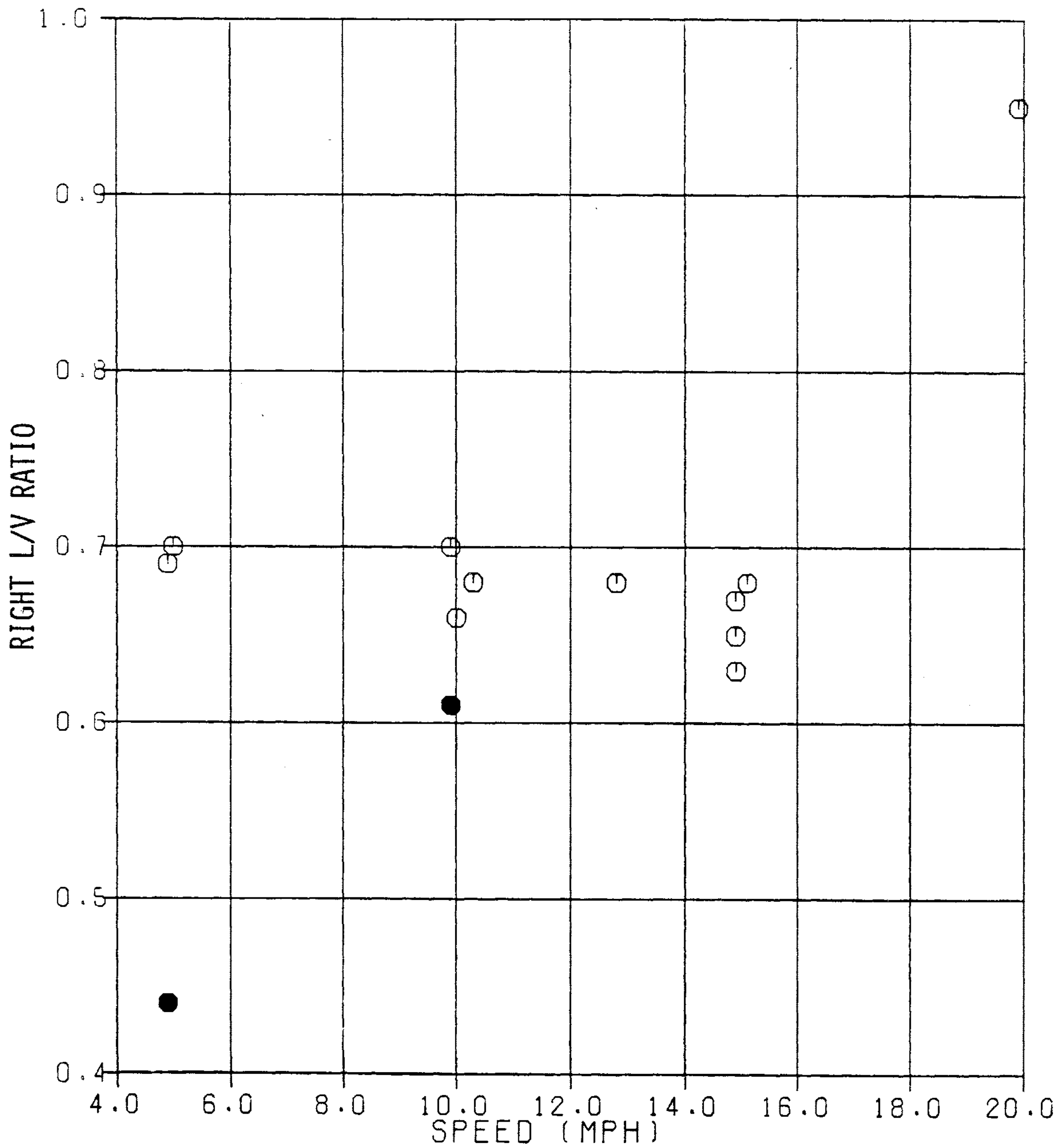


FIGURE 3-6. PEAK L/V RATIO VS. SPEED - HOPPER CAR AXLE 13 RIGHT, SECTION 1, 12-DEGREE CURVE

The rear truck of the four-axle locomotive was also instrumented for wheel force measurements. Figure 3-7 shows time history traces for locomotive single wheel, high-rail lateral forces at three speeds over the 12-degree test curve with high-rail alignment perturbations. The signatures do not show the responses to individual perturbations as clearly as the hopper car traces (Figure 3-1), primarily due to design differences between locomotive and freight suspensions and different truck and wheel base sizes. However, the effect of vehicle speed is slight over this speed range, from a peak of about 17 kips at 5 mph to about 23 kips at 20 mph. Peak lateral forces are plotted together in Figure 3-8. A mild trend with speed can be seen and substantial force levels are present at even 5 mph. Also seen are the low lateral force measurements from runs early in the day before the coefficient of friction had stabilized.

As with the hopper car (Figure 3-5), the locomotive vertical wheel forces varied with speed in response to the high-rail alignment perturbations and naturally occurring crosslevel. However, these force variations were fairly small when compared to the hopper car vertical force variations. Time history traces of vertical wheel forces are shown in Figure 3-9 for 5 and 20 mph runs. The resulting effect on peak statistics of the L/V ratio is shown in Figure 3-10.

3.2 RESPONSES DUE TO CURVATURE VARIATIONS

Studies using the SIMCAR program predict that the severity of a vehicle's response to alignment irregularities is significantly affected by track curvature. As curvature increases, the lateral forces required to steer the vehicle increase due to the dimensional constraints of the truck and the wheel profile. In the 5 to 20 mph speed regime, a significant component of the curve negotiation force is the lateral creep force generated on the nonflanging wheel,

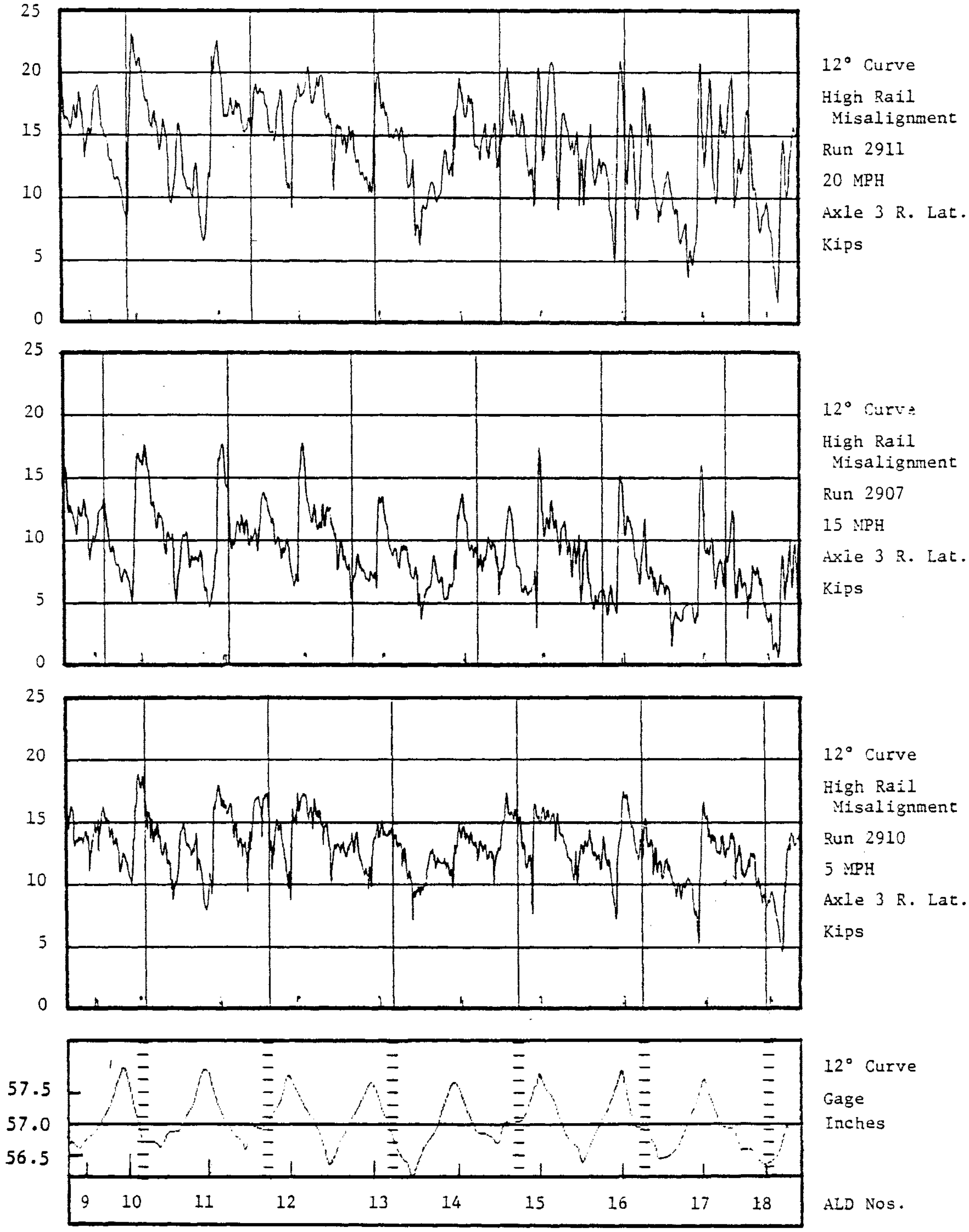


FIGURE 3-7. EFFECT OF SPEED ON LOCOMOTIVE LATERAL WHEEL FORCES

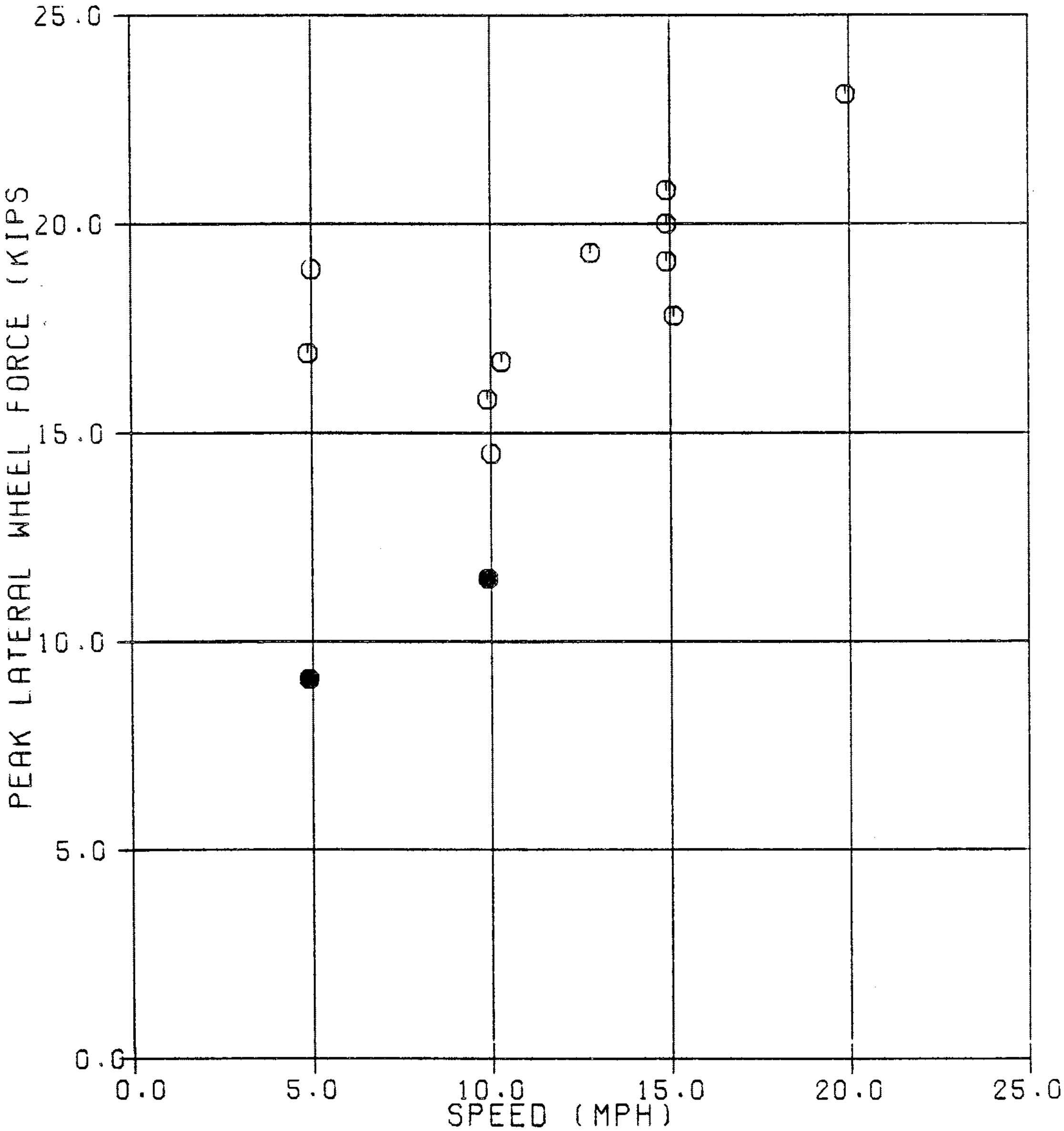


FIGURE 3-8. PEAK LATERAL WHEEL FORCES VS. SPEED - LOCOMOTIVE AXLE 3 RIGHT, SECTION 1, 12-DEGREE CURVE

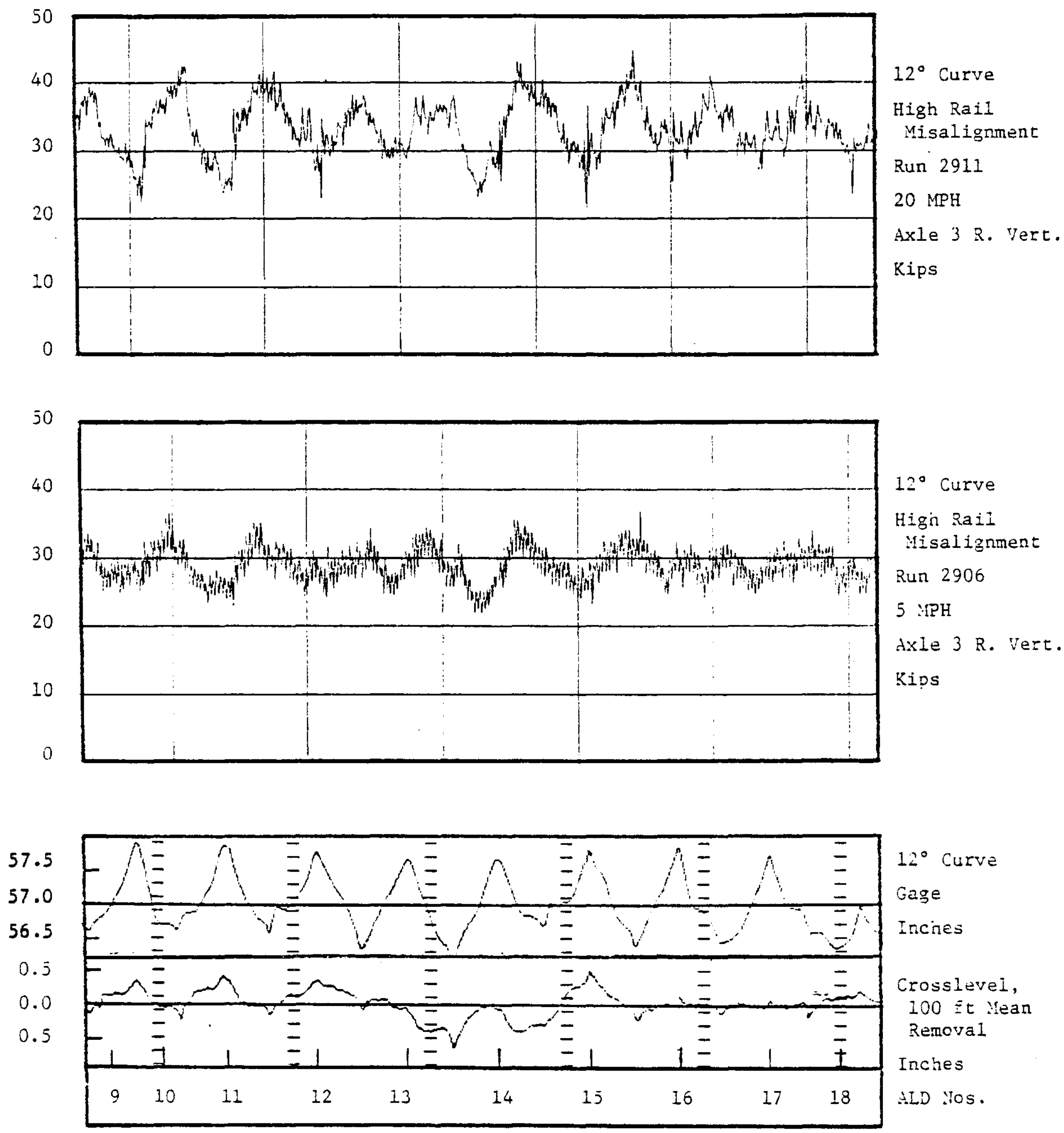


FIGURE 3-9. LOCOMOTIVE VERTICAL WHEEL FORCE RESPONSE TO HIGH-RAIL MISALIGNMENT AND NATURAL CROSSLEVEL

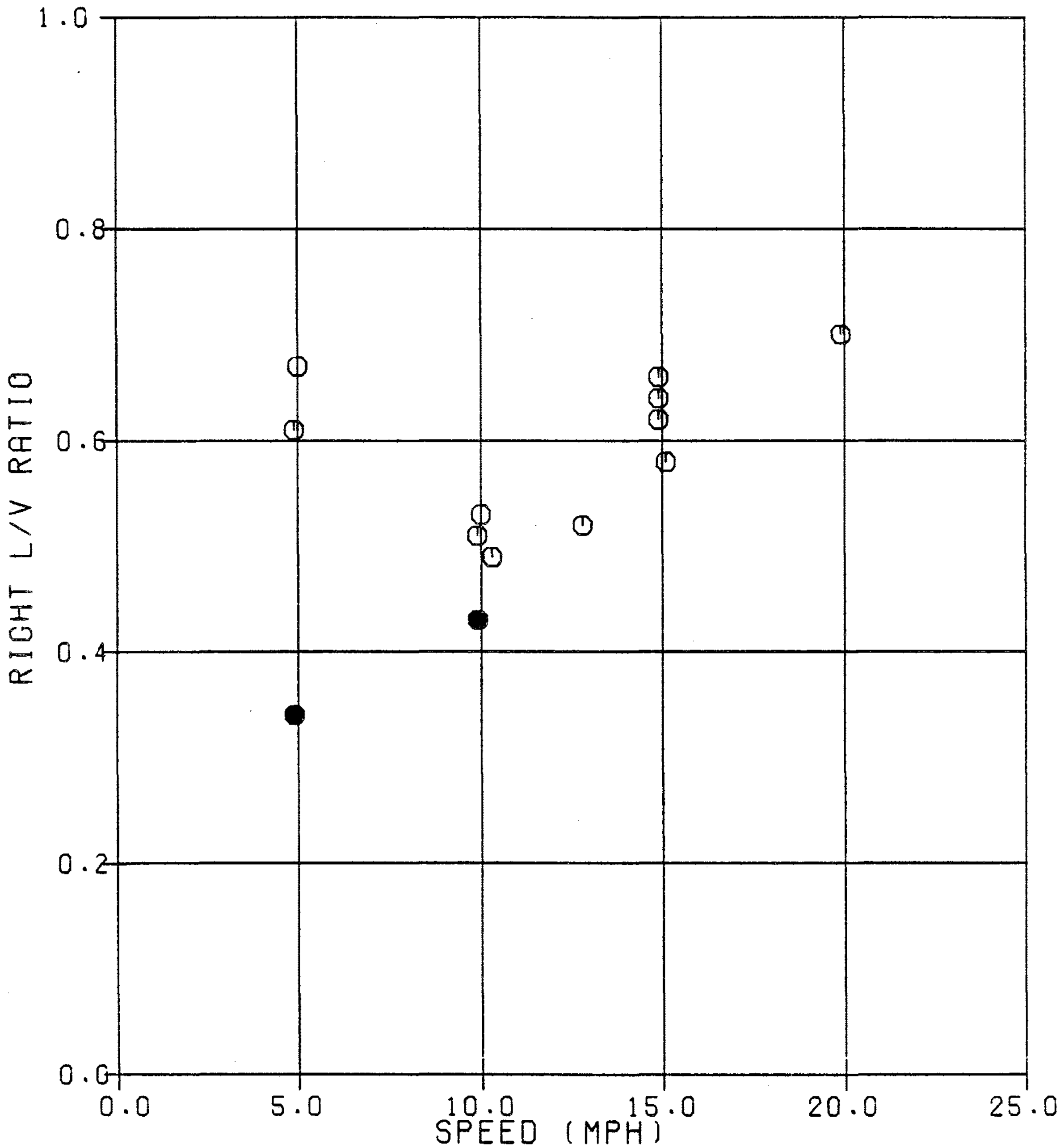


FIGURE 3-10. PEAK L/V RATIO VS. SPEED - LOCOMOTIVE AXLE 3 RIGHT, SECTION 1, 12-DEGREE CURVE

which increases with increasing curvature. Furthermore, the angle of attack between the wheel and the high rail increases with increasing curvature. The test data allow comparisons between wheel forces on 6-degree and 12-degree curves with nearly identical high-rail alignment perturbations for the hopper car and the locomotive.

Figure 3-11 shows hopper car lateral wheel force traces on the 6- and 12-degree curves at 10 mph. Figure 3-12 shows the same comparison at 20 mph. These figures show that the lateral wheel forces follow the general pattern of the high-rail alignment for the 6- and 12 degree curves and that the relative response is similar for both the 10 and 20 mph speed regimes. On the 6-degree curve, the lateral wheel forces fell well below 5 kips during about half of each perturbation cycle, whereas forces rarely fell below 5 kips on the 12-degree curve. Furthermore, the figures show that peak lateral wheel forces are about 5 kips greater on the 12-degree curve than on the 6-degree curve.

Figure 3-13 shows a comparison between peak values of lateral wheel force for several runs on both the 6- and 12-degree curves for the hopper car.

The same comparison is provided for the locomotive of the test consist. Figure 3-14 shows high-rail, single wheel force traces from 10 mph test runs on the 6- and 12-degree curves with high-rail alignment perturbations. Figure 3-15 shows the same comparison for 20 mph test runs. Again, as with the hopper car lateral wheel forces, the striking feature of the force traces is that the wheel forces were rarely less than 5 kips on the 12-degree curve, while on the 6-degree curve, forces were less than 5 kips for about half of each perturbation cycle. In fact, the wheelset instrumentation on the locomotive allows accurate measurements of negative forces, clearly showing the portions of each

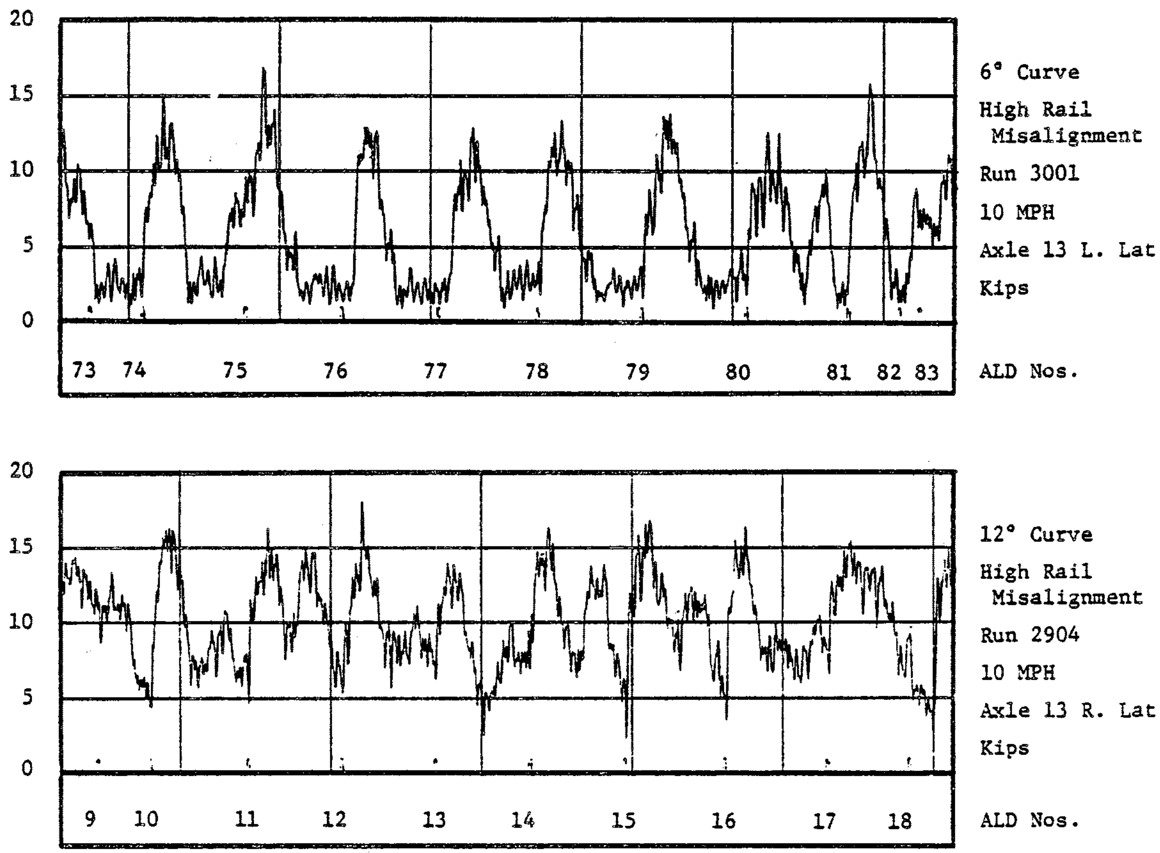


FIGURE 3-11. EFFECT OF CURVATURE ON HOPPER CAR HIGH-RAIL LATERAL WHEEL FORCES AT 10 MPH

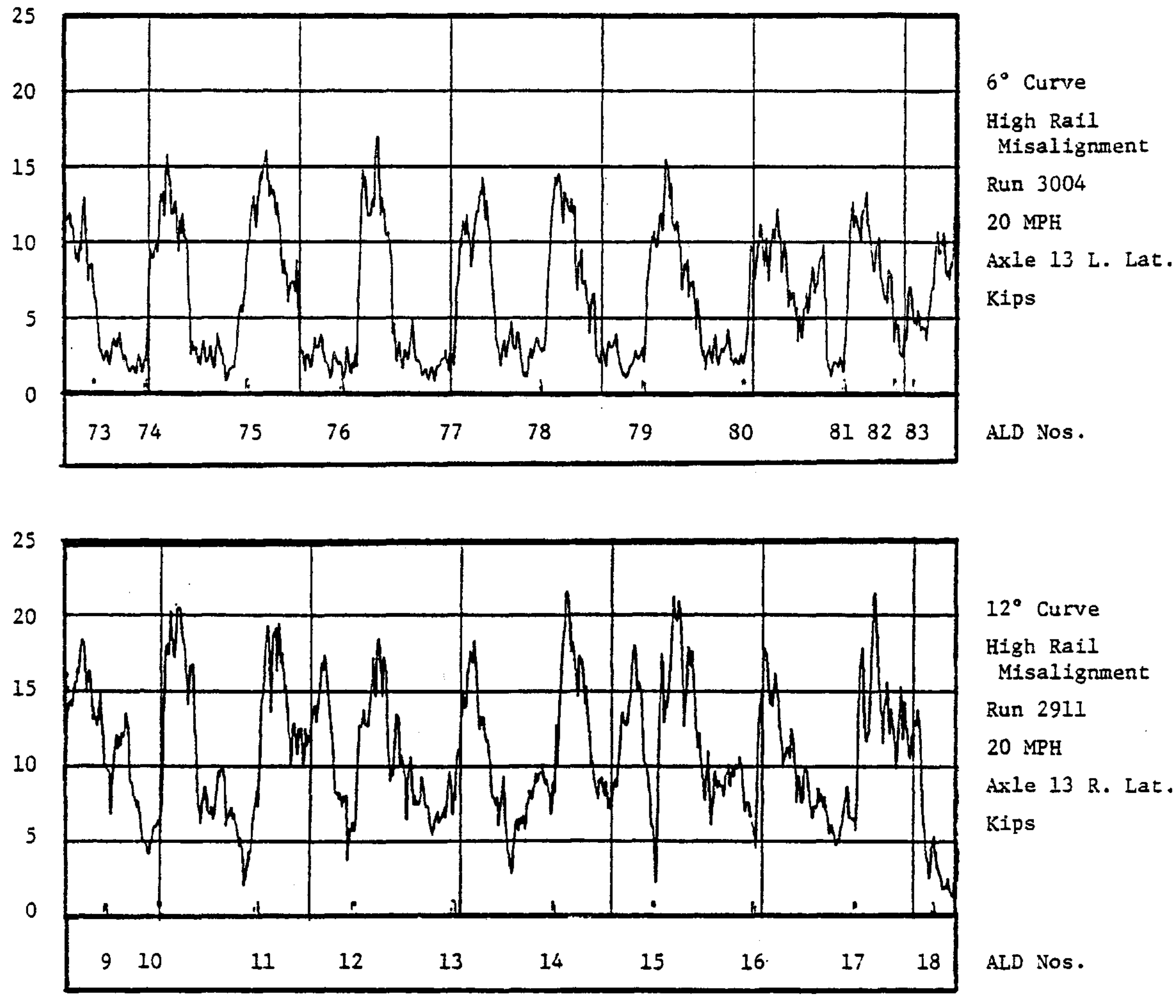


FIGURE 3-12. EFFECT OF CURVATURE ON HOPPER CAR HIGH-RAIL LATERAL WHEEL FORCES AT 20 MPH

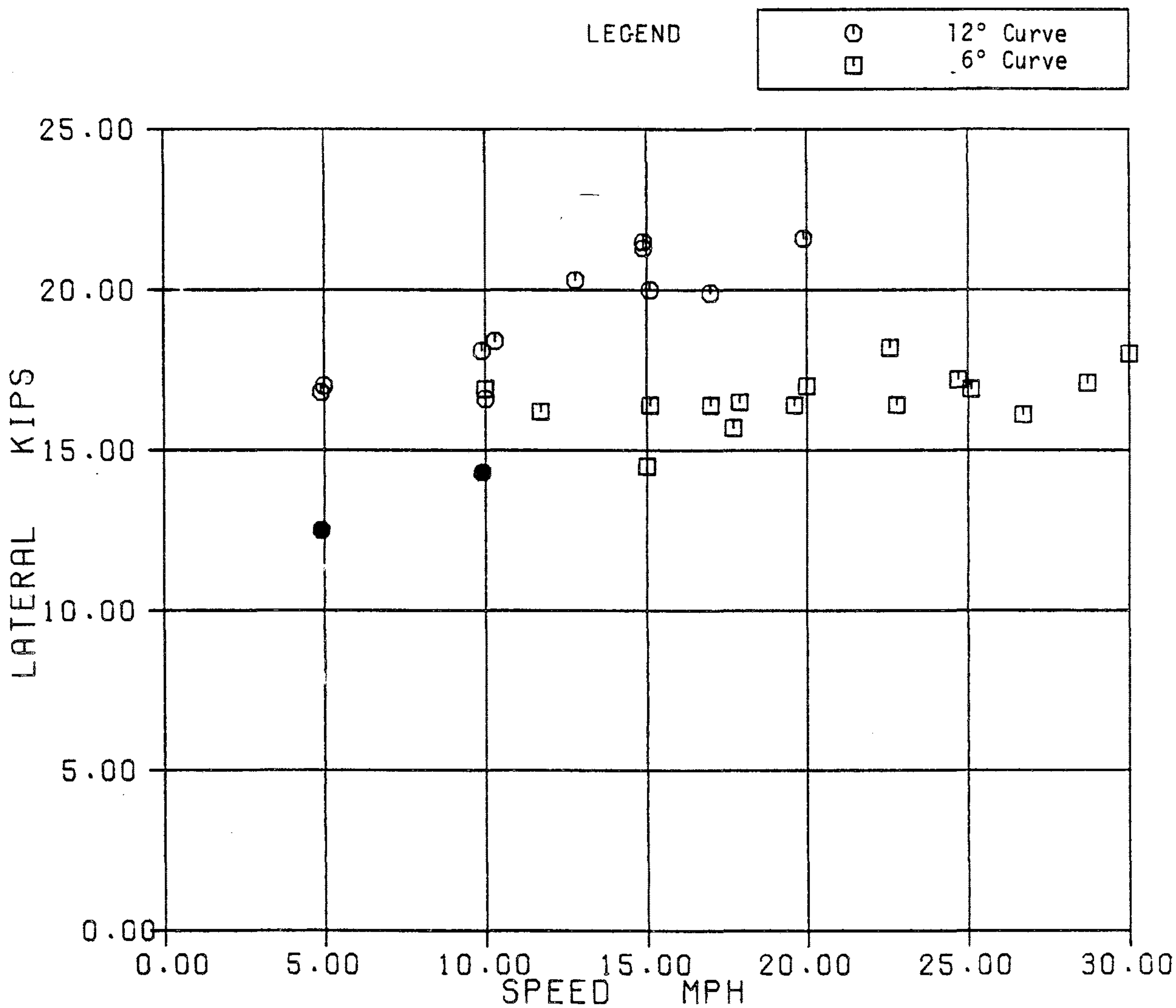


FIGURE 3-13. HOPPER CAR PEAK LATERAL WHEEL FORCES VS. SPEED FOR 6- AND 12-DEGREE CURVE WITH HIGH-RAIL ALIGNMENT PERTURBATIONS ONLY

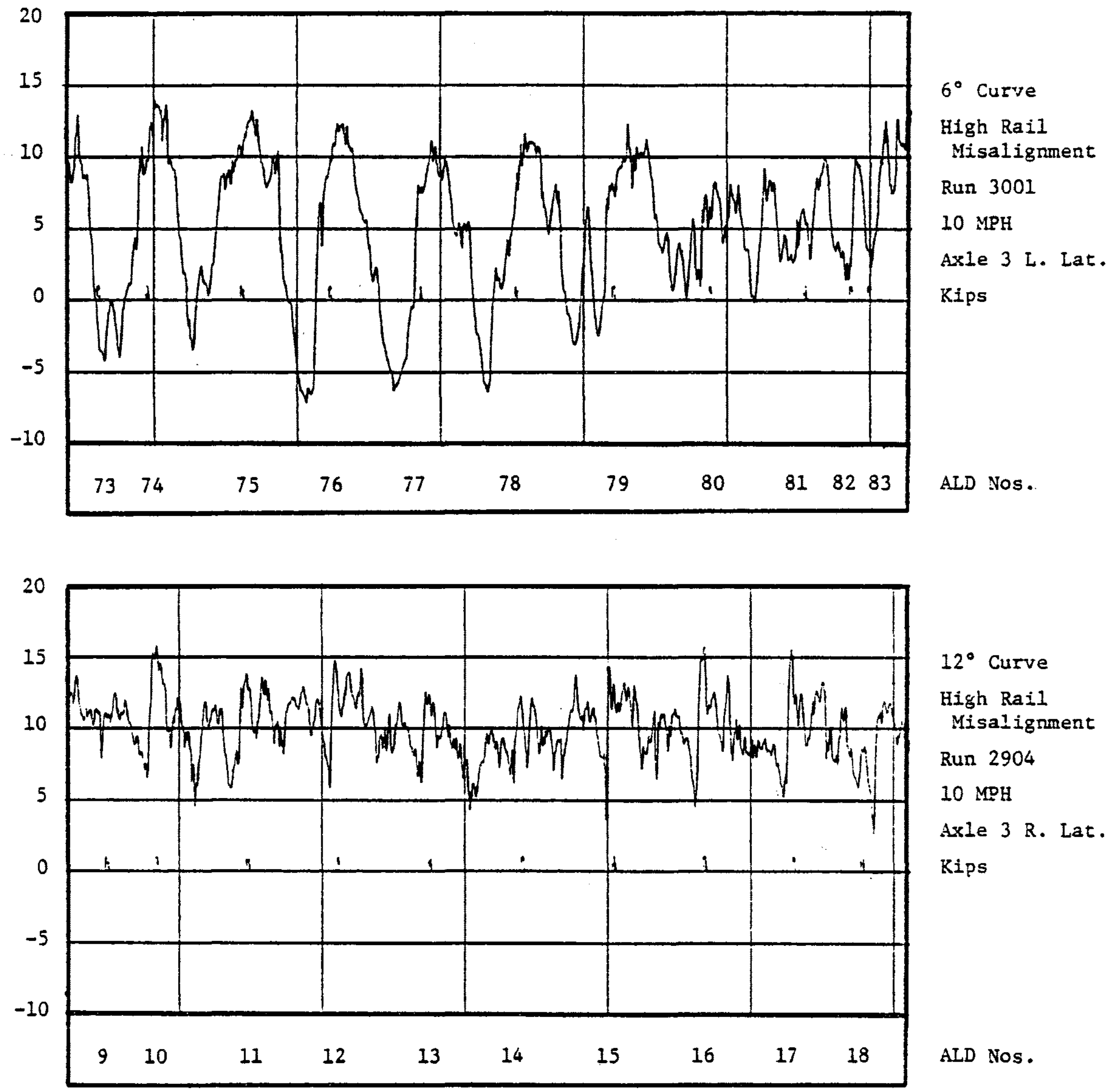


FIGURE 3-14. EFFECT OF CURVATURE ON LOCOMOTIVE HIGH-RAIL LATERAL WHEEL FORCES AT 10 MPH

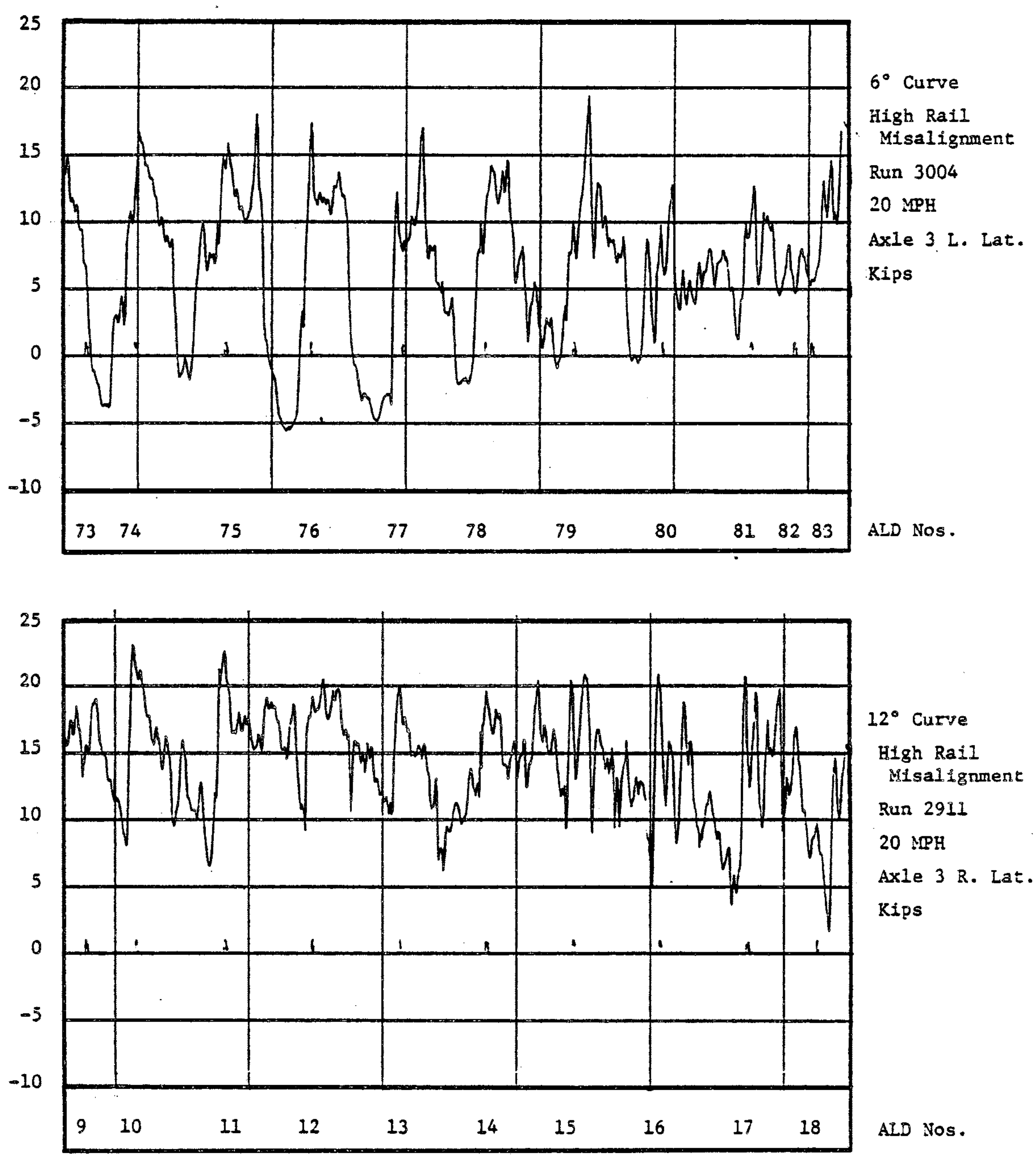


FIGURE 3-15. EFFECT OF CURVATURE ON LOCOMOTIVE HIGH-RAIL LATERAL WHEEL FORCES AT 20 MPH

perturbation cycle where the high-rail wheel is moving toward the track center line and is no longer in flange contact. Flanging of the leading high-rail wheel was continuous on the 12-degree curve as evidenced by the force traces as well as the wear patterns seen on the rail.

The peak force values are slightly greater on the 12-degree curve than on the 6-degree curve. This difference in locomotive peak wheel force values due to curvature is found across the speed range of the test, as shown in Figure 3-16.

Another effect of curvature on vehicle response is found on the low-rail lateral wheel forces. It is presumed that low-rail lateral forces on the lead axle of a freight car or locomotive are due entirely to tread forces rather than flange forces. This is supported by analytical modeling and is verified by observations during the tests. It was observed that the gage face of the low rail was not worn by flange contact as was the high rail. The low-rail lateral forces must therefore be determined by the wheel/rail contact geometry, the relative velocities of the surfaces, the rail surface friction characteristics, and the vertical force on the interface. Figure 3-17 shows low-rail lateral forces of the hopper car at 10 mph on both the 6- and 12-degree perturbed curves. The forces are regularly in the range of 10 to 15 kips and the forces are positive or gage widening. The fluctuations in force follow the shape of the high-rail alignment perturbations. In fact, a comparison with the concurrent high rail forces (see Figure 3-11) indicates that the high- and low-rail lateral forces generally increase and decrease in unison. That is, the high-rail flange forces caused by following the high-rail alignment perturbations are reacted through the wheelset and are partially balanced by

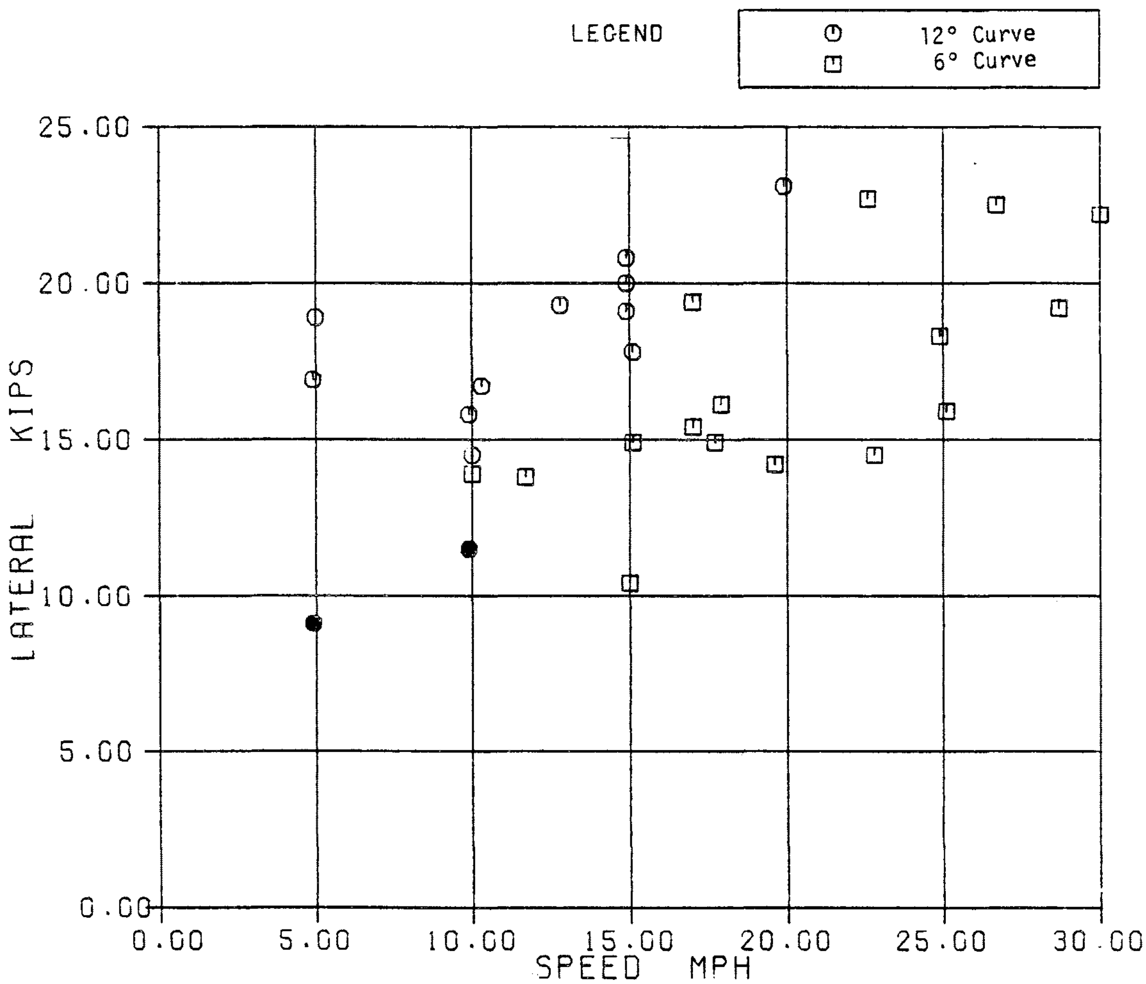


FIGURE 3-16. LOCOMOTIVE PEAK LATERAL WHEEL FORCES VS. SPEED FOR 6- AND 12-DEGREE CURVES WITH HIGH-RAIL ALIGNMENT PERTURBATIONS ONLY

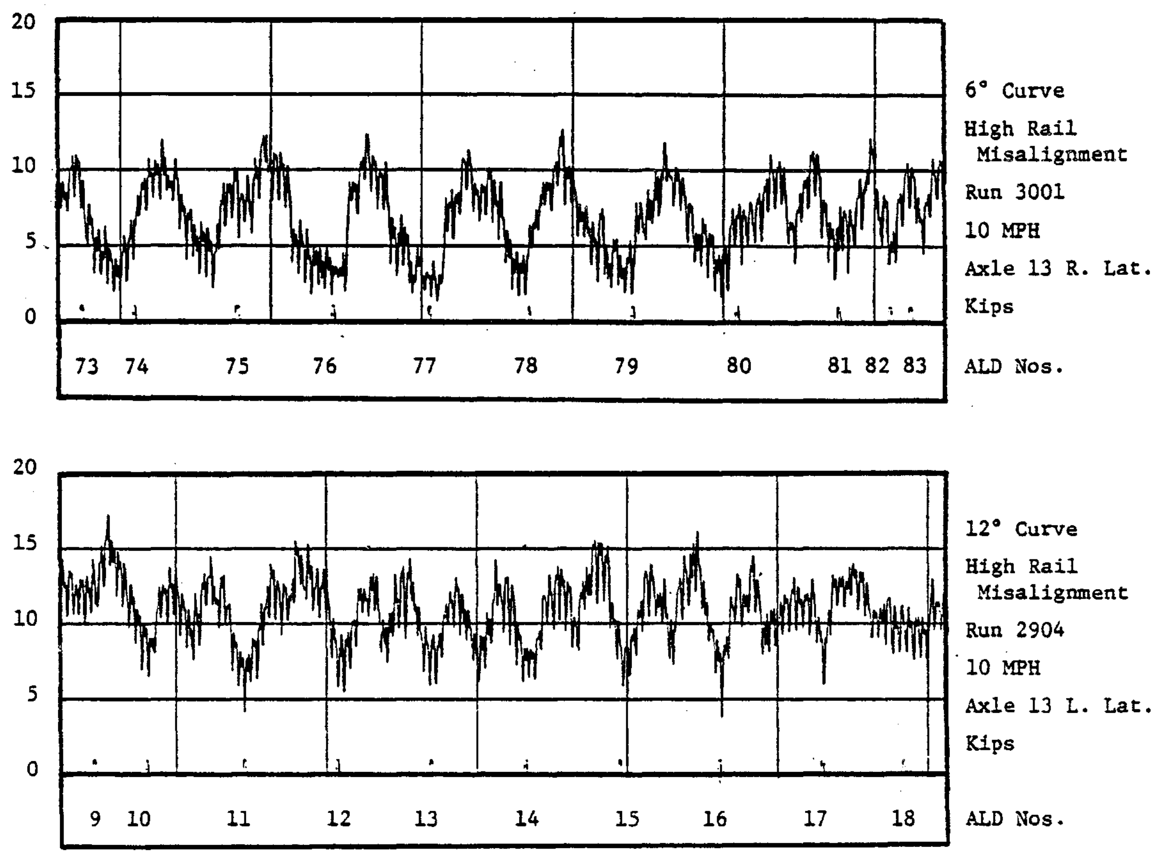


FIGURE 3-17. EFFECT OF CURVATURE ON HOPPER CAR LOW-RAIL LATERAL WHEEL FORCES

low-rail wheel tread friction forces. The difference in the wheel force response between the two curves is that the lateral forces are generally higher in the 12-degree curve and rarely reduce to less than 5 kips.

The low-rail lateral wheel forces of the locomotive also show substantial values at 10 mph, a peak of about 13 kips on the 6-degree curve and about 17 kips on the 12-degree curve, as shown in Figure 3-18. The forces on the 12-degree curve are about 5 kips higher than on the 6-degree curve and rarely reduce to less than 10 kips.

These variations in lateral wheel force due to curvature are accompanied by variations in vertical wheel force, which are primarily caused by local profile irregularities rather than by curvature and superelevation. The L/V ratio is, therefore, generally higher on a sharper curve than on a curve with a large radius since the lateral forces are consistently higher.

3.3 RESPONSES DUE TO CROSSLEVEL VARIATIONS

The vertical wheel force response and associated carbody roll of a locomotive or freight car have a substantial effect on safety measures including the L/V ratio. These vertical force and roll responses can potentially have large variations and are particularly speed-dependent because of fundamental response resonances which are within the test conditions. These characteristics are best examined on tangent track using natural track geometry with a variety of crosslevel and alignment variation wavelengths and amplitudes. Figure 3-19 shows the roll response of the hopper car on tangent track. The roll angle varies between 0.5 and 2 degrees across this speed range. More important, however, are the variations in vertical wheel forces due to these relatively

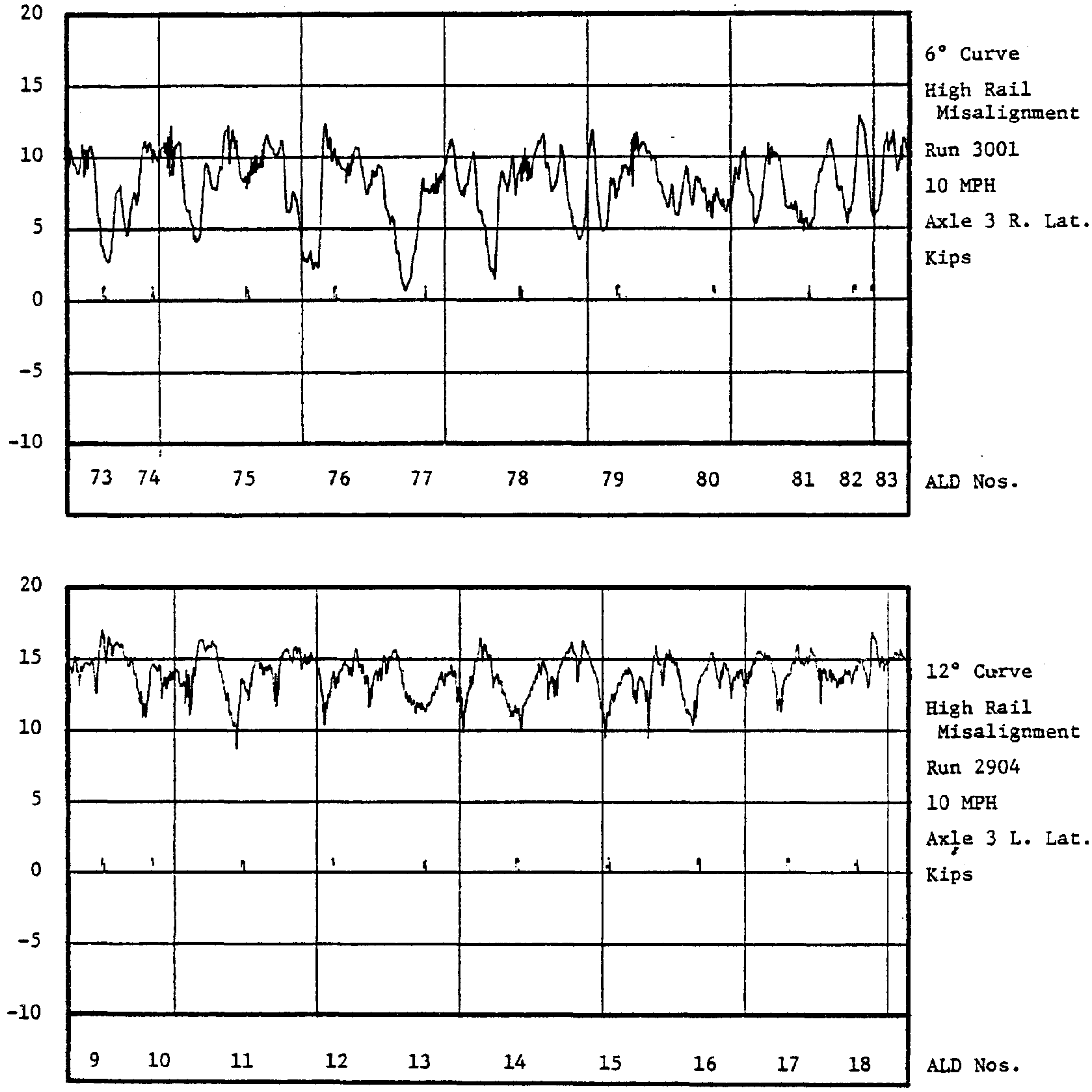


FIGURE 3-18. EFFECT OF CURVATURE ON LOCOMOTIVE LOW-RAIL LATERAL WHEEL FORCES

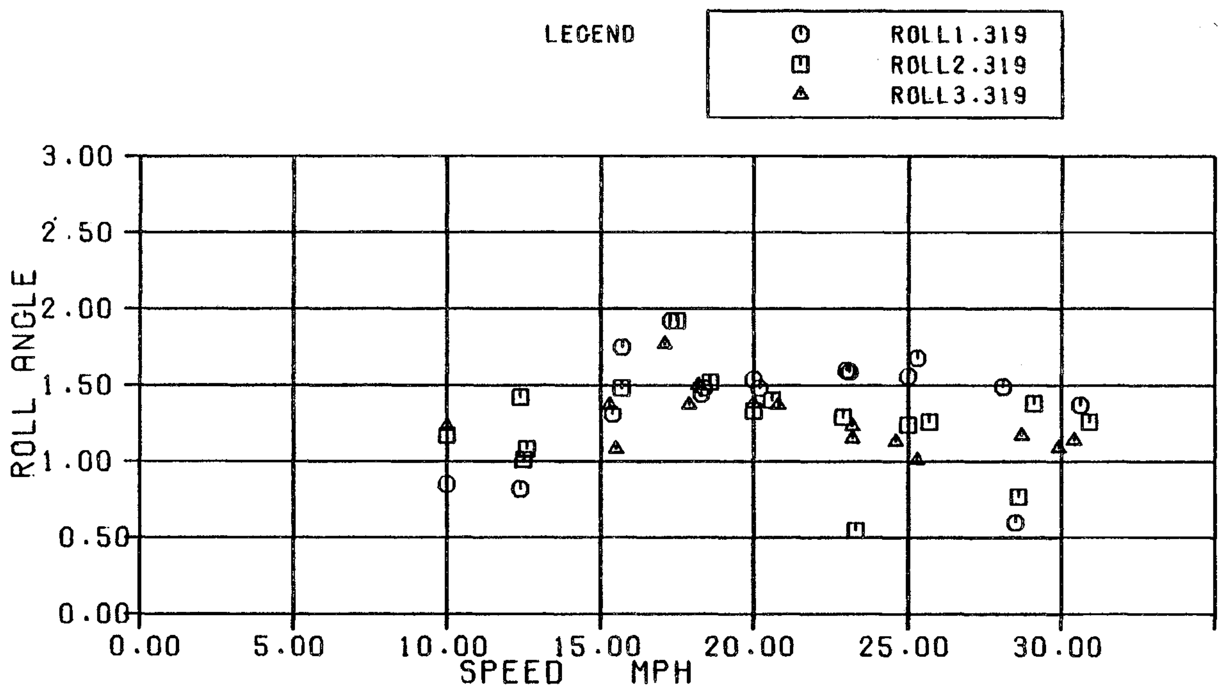


FIGURE 3-19. HOPPER CAR ROLL ANGLE VS. SPEED

small crosslevel perturbations. In Figures 3-20a and b, the minimum and maximum vertical wheel forces of the hopper car are shown as a function of speed on tangent track. The maximum wheel unloading occurs at about 20 mph. Figures 3-21a and b show similar vertical force data for the locomotive with its maximum wheel unloading occuring at about 18 mph, although the trend is not as clear as it is with the hopper car.

The test included two conditions of crosslevel perturbation in the 6- and 12-degree curve. The designed first level was to have zero crosslevel. Actual loaded track geometry measurements showed irregular crosslevel variations on the order of 0.375 to 0.5 inch over the 12-degree test sections. The crosslevel index (CLI)[6] was 0.2 inch. For the third test series, crosslevel perturbations were installed. The mid-rails of both high and low rails were shimmed up 0.625 inches for 6 rail lengths. The CLI for this section was 0.35 inch. These crosslevel perturbations were used to investigate the effects of vertical wheel unloadings, particularly on the high-rail profile, and of roll motions of the carbody in small radius curves. The test runs were conducted over the 12-degree curve before and after the design crosslevel perturbations were installed. The runs show the locomotive and hopper car vertical wheel force responses to crosslevel and the correlated effect on lateral wheel forces and L/V ratios.

The hopper car showed a small amount of wheel unloading, with variations of about 10 kips, on the 12-degree curve at 10 mph with only the naturally occurring crosslevel. Although the natural crosslevel (and profile) variations are not well correlated with the lateral alignment variations, the high-rail misalignment pattern of the perturbations is clear in much of the vertical response. This suggests that, in this case, the variations in vertical force

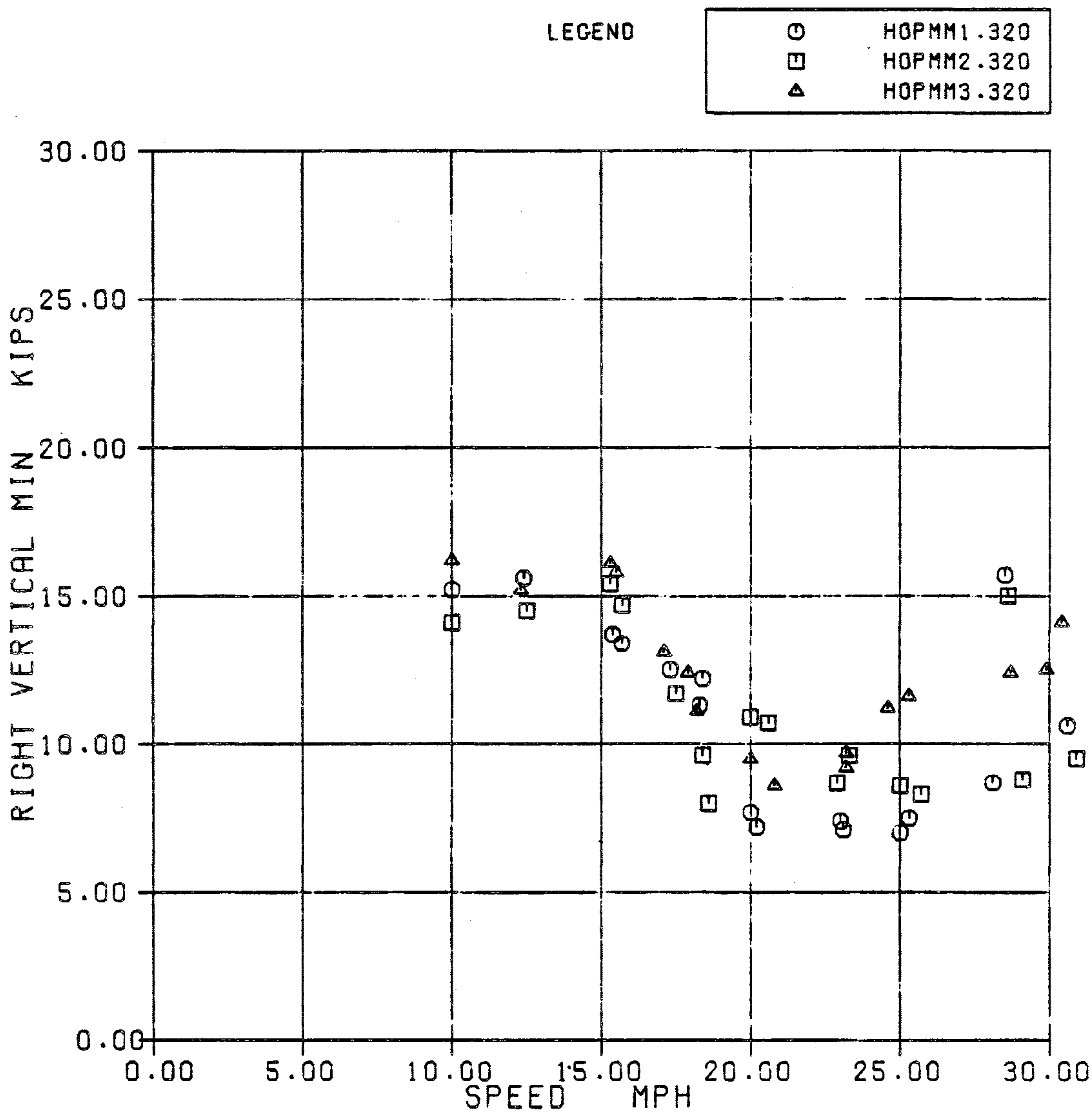


FIGURE 3-20A. HOPPER CAR MINIMUM VERTICAL WHEEL FORCES VS. SPEED

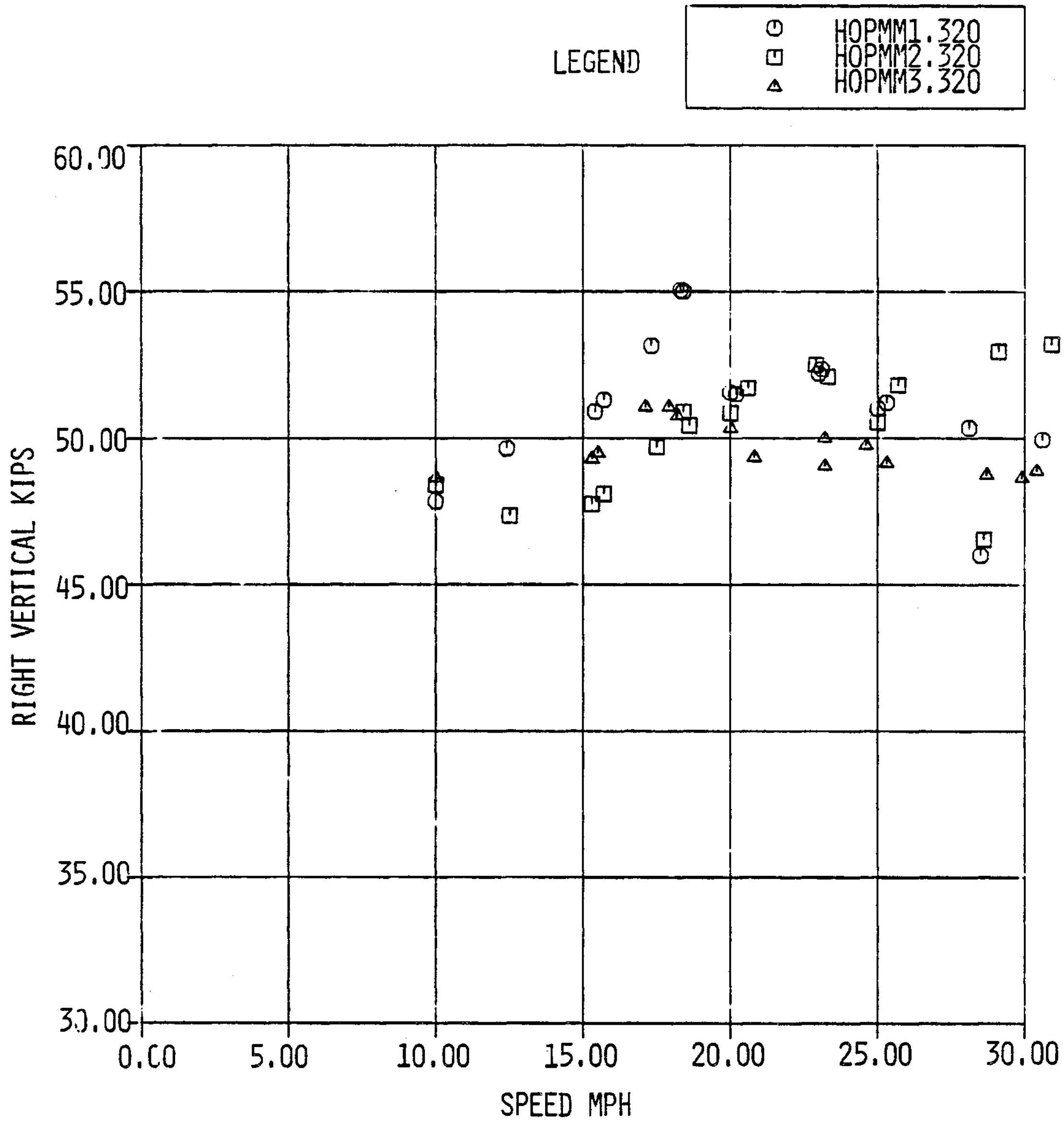


FIGURE 3-20B. HOPPER CAR MAXIMUM VERTICAL WHEEL FORCES VS. SPEED

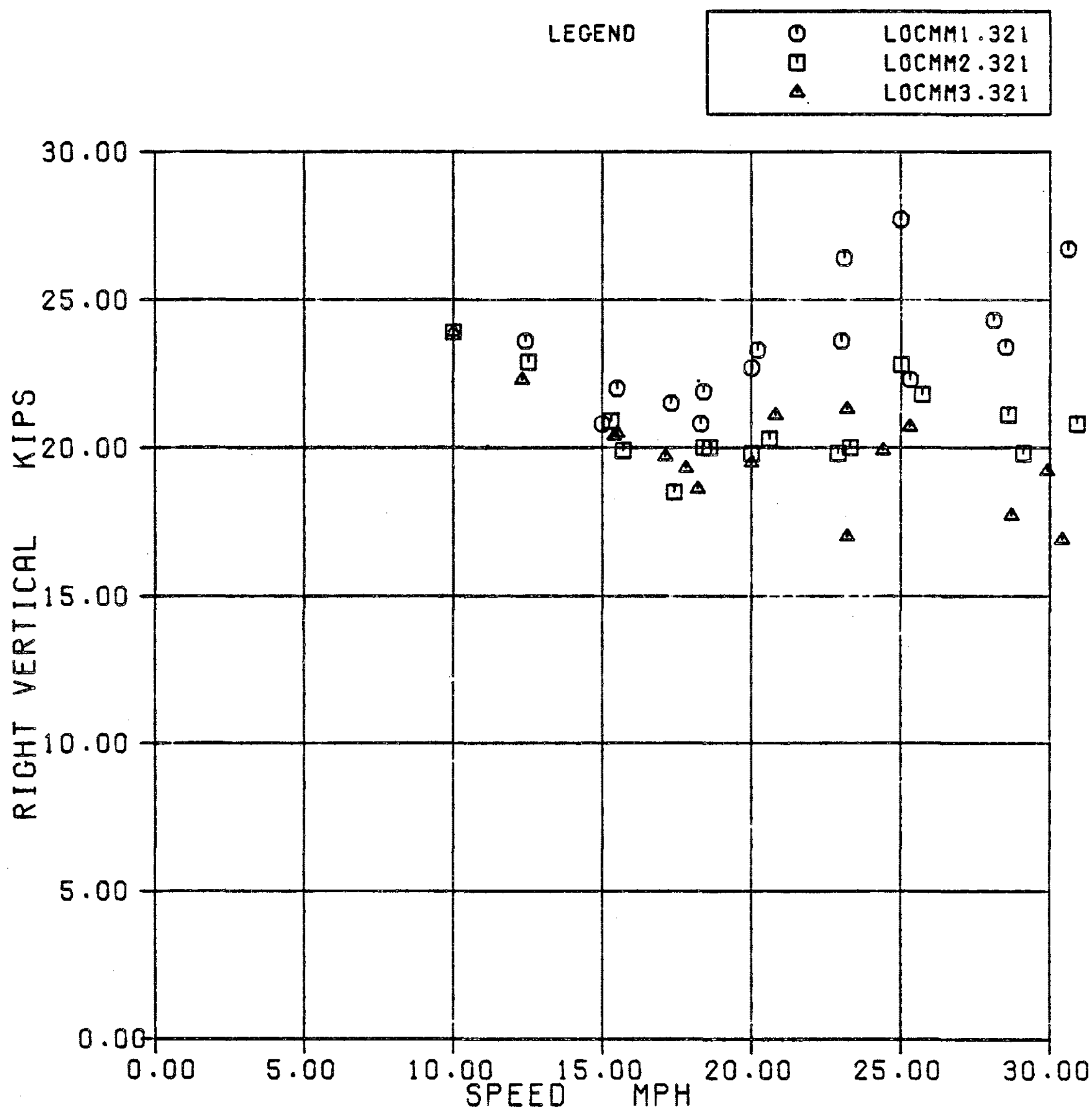


FIGURE 3-21A. LOCOMOTIVE MINIMUM VERTICAL WHEEL FORCES VS. SPEED

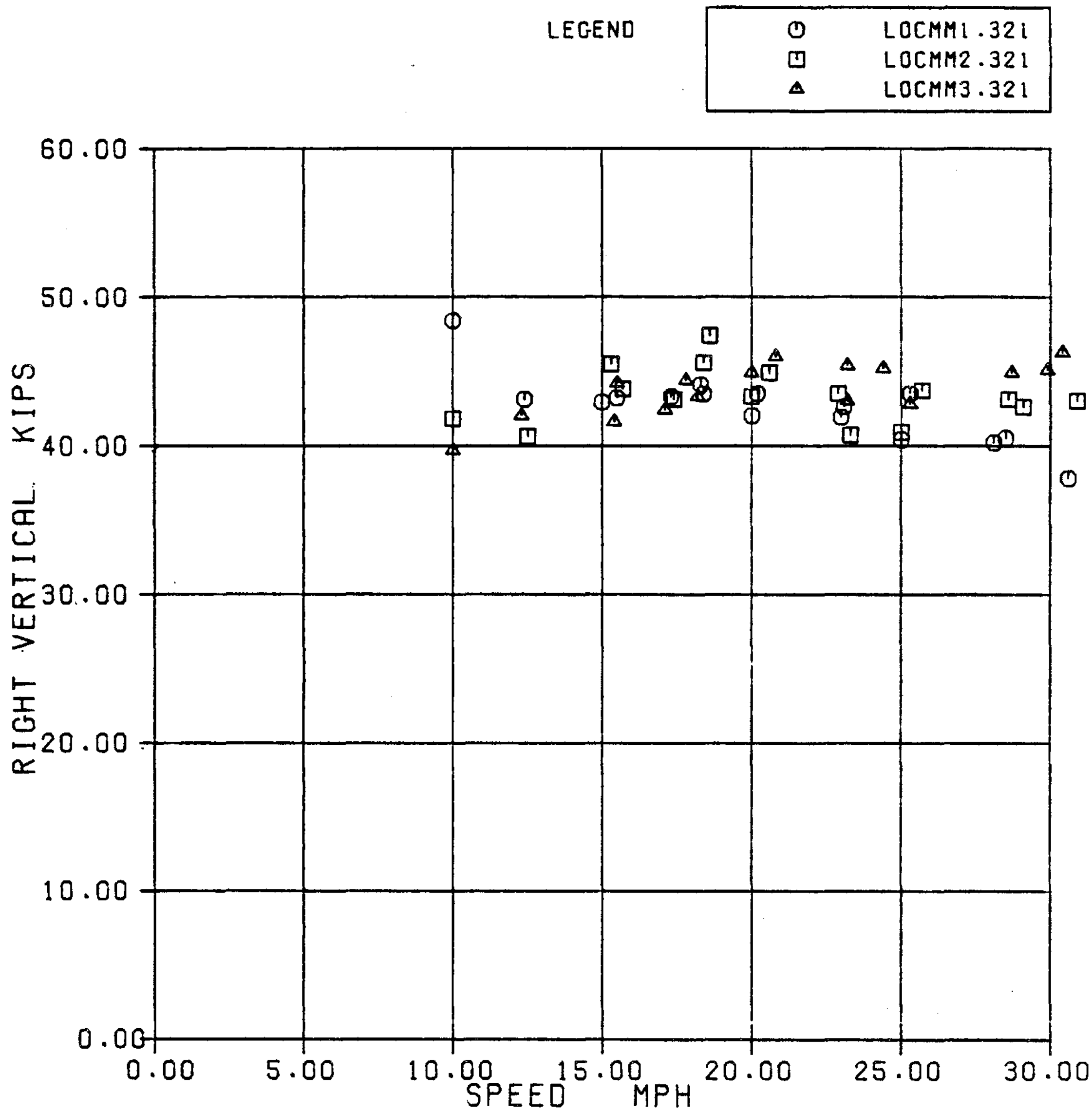


FIGURE 3-21B. LOCOMOTIVE MAXIMUM VERTICAL WHEEL FORCES VS. SPEED are primarily due to the alignment perturbations rather than the natural crosslevel variations. The vertical wheel force time history with only the natural crosslevel is shown in the top trace in Figure 3-22. With the addition of 0.625 inch crosslevel perturbations, vertical force variations increased to about 25 kips at 10 mph. This is shown in the middle trace on Figure 3-22. At 14 mph, vertical force variations increased to about 30 kips. This is shown in the lower trace of Figure 3-22. This speed is about 5 mph below the predicted roll resonance speed for these perturbations. Therefore, no higher speed tests were run because of the risk of wheel climb derailment.

The hopper car lateral wheel forces were affected somewhat by the addition of the crosslevel perturbations, although not dramatically. Figure 3-23 shows lateral wheel forces on the 12-degree curve at about 15 mph, with high-rail alignment perturbations and with and without the crosslevel perturbations.

The locomotive lateral wheel forces are shown, in a similar format, in Figure 3-24. The vertical force responses to the natural crosslevel perturbations combined with the high-rail alignment perturbations resulted in variations of about 10 kips. There is some indication that the responses follow the alignment perturbations although it is not particularly strong. The addition of the crosslevel perturbation raises the variations to about 25 kips at 10 mph, and to about 35 kips at 14 mph. The lateral forces with and without crosslevel perturbations are shown in Figure 3-25. Comparing the traces, the peak lateral forces are generally higher for the run with crosslevel. However, a more significant difference is that large lateral forces are developed just before the high-rail joint identified by the ALDs, where the vertical force is a minimum. These lateral forces are generated because the low-rail wheel has a

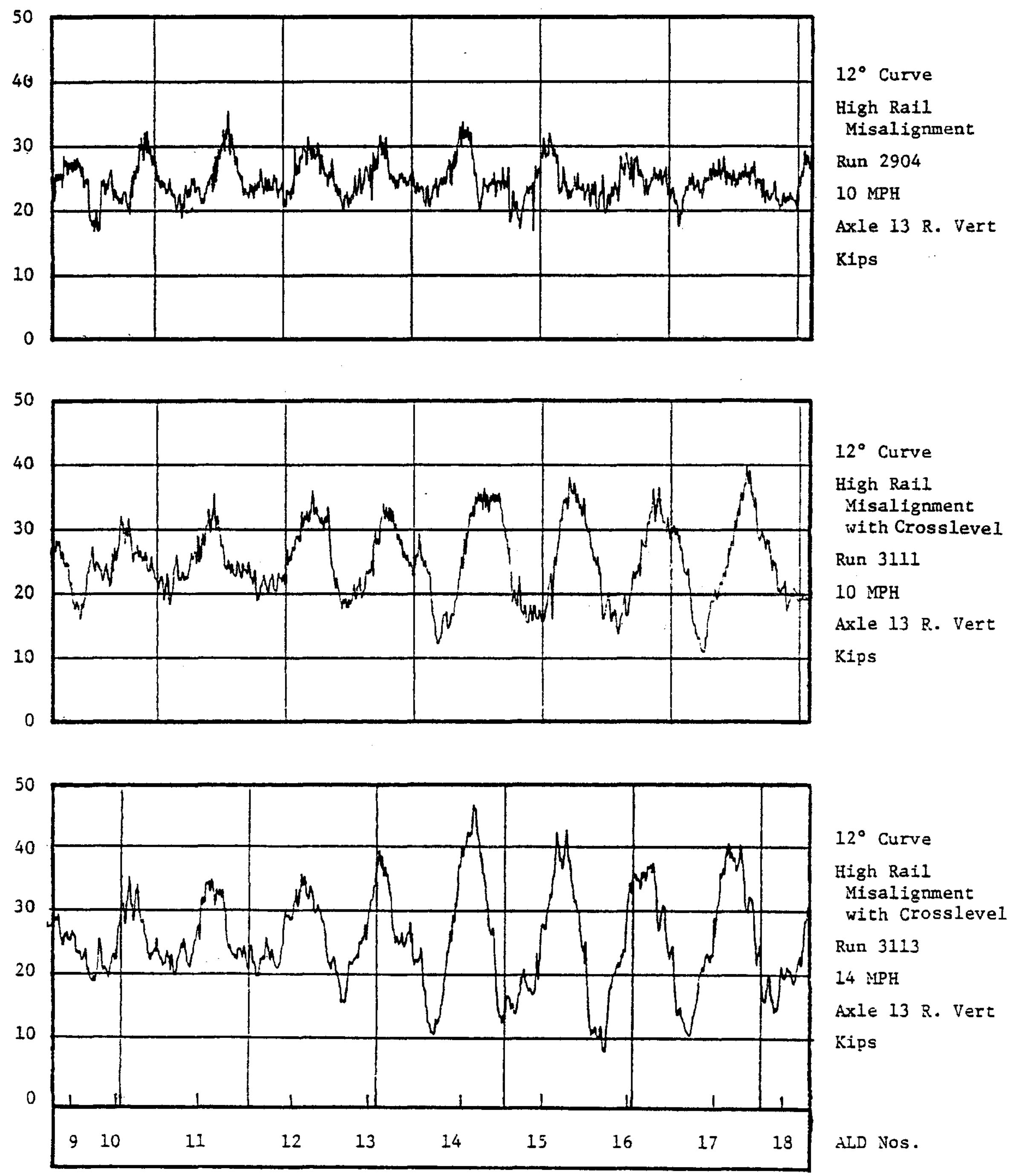


FIGURE 3-22. EFFECT OF CROSSLEVEL ON HOPPER CAR HIGH-RAIL VERTICAL WHEEL FORCES

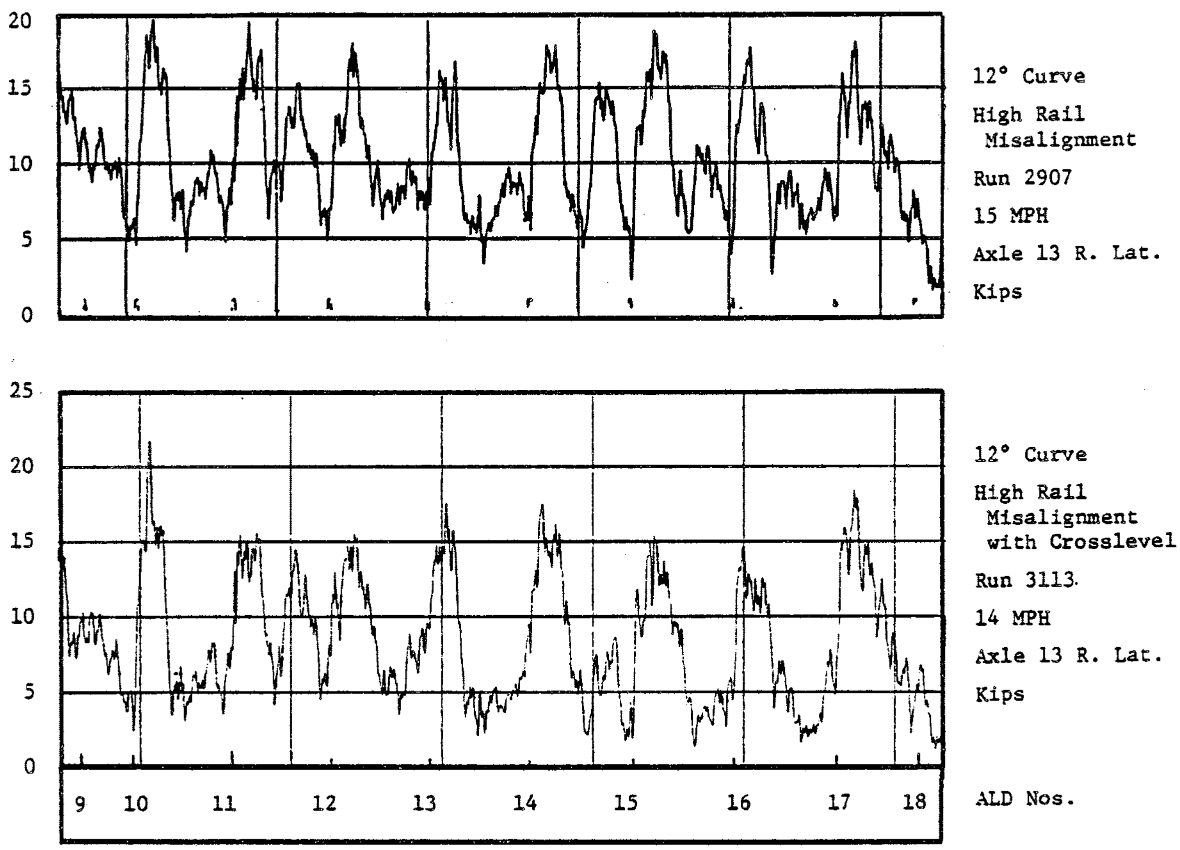


FIGURE 3-23. EFFECT OF CROSSLEVEL ON HOPPER CAR HIGH-RAIL LATERAL WHEEL FORCES

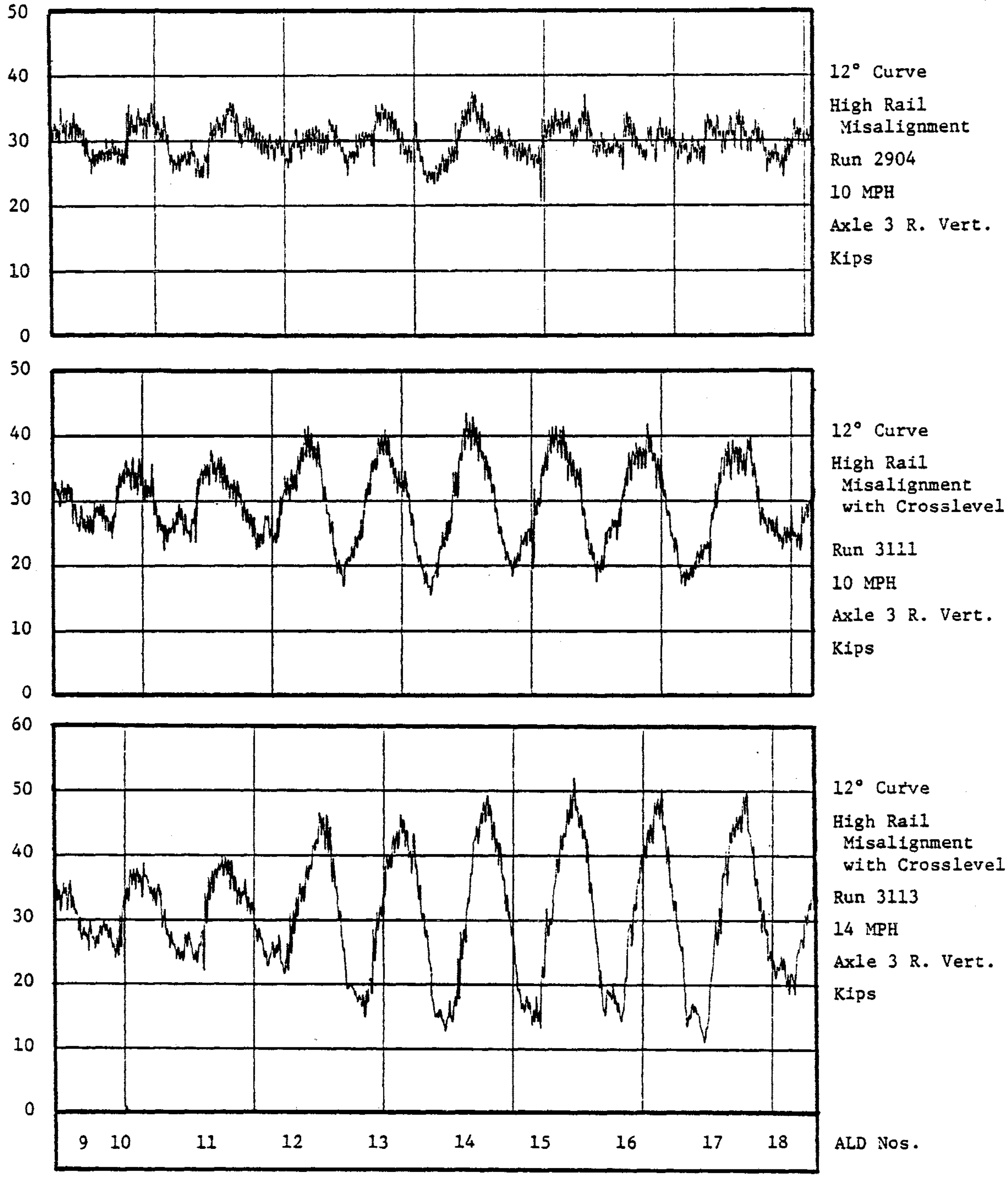


FIGURE 3-24. EFFECT OF CROSSLEVEL ON LOCOMOTIVE HIGH-RAIL VERTICAL WHEEL FORCES

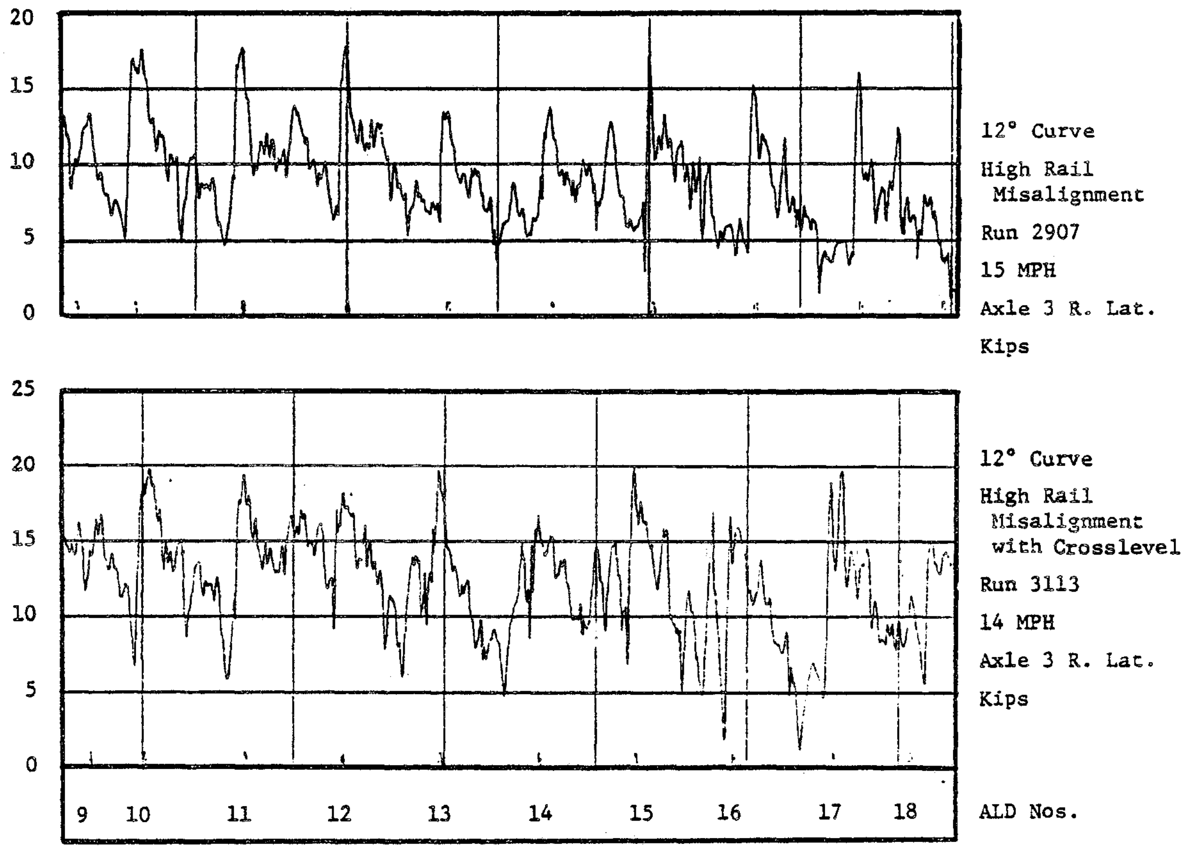


FIGURE 3-25. EFFECT OF CROSSLEVEL OF LOCOMOTIVE HIGH-RAIL LATERAL WHEEL FORCES

large lateral tread force due to the severe curvature and large vertical load. This large tread force and the low-rail forces the wheelset into flange contact on the high rail. This lateral force occurring when the vertical force is a minimum produces a high L/V ratio on the high rail. If this condition is combined with a gage narrowing condition, or is a case where the wheelset has a significant lateral velocity at the point of flange contact, a climb derailment could be expected. Figure 3-26 shows the L/V ratio of a single high-rail wheel of the hopper car as a function of speed. Figure 3-27 shows the L/V ratios of the locomotive. The high L/V ratio at 14 mph for the locomotive was considered as the safety limit in that it corresponds to the Nadal limit[7] based on a positive angle of attack, a friction coefficient of 0.5, and a flange angle of about 67 degrees.

3.4 RESPONSES DUE TO SINUSOIDAL ALIGNMENT VARIATIONS

Four test zones were established on tangent track and the 6-degree curve to examine the wheel force responses of the locomotive and hopper car to sinusoidal alignment variations. The four zones, differing in wavelength, amplitude, and curvature, were designed as follows:

Test Zone	Wavelength, (feet)	Design Amplitude, (inches)	Curvature (degrees)	62 ft. MCO	31 ft. MCO
39-foot sinusoids	39	1.33	0	0.48	1.2
50-foot sinusiods	50	1.25	0	1.1	0.85
90-foot sinusiods	90	4.5	0	3.5*	1.2
50-foot 6-degree sinusiods	50	1.25	6		

*Waiver from FRA, Office of Safety.

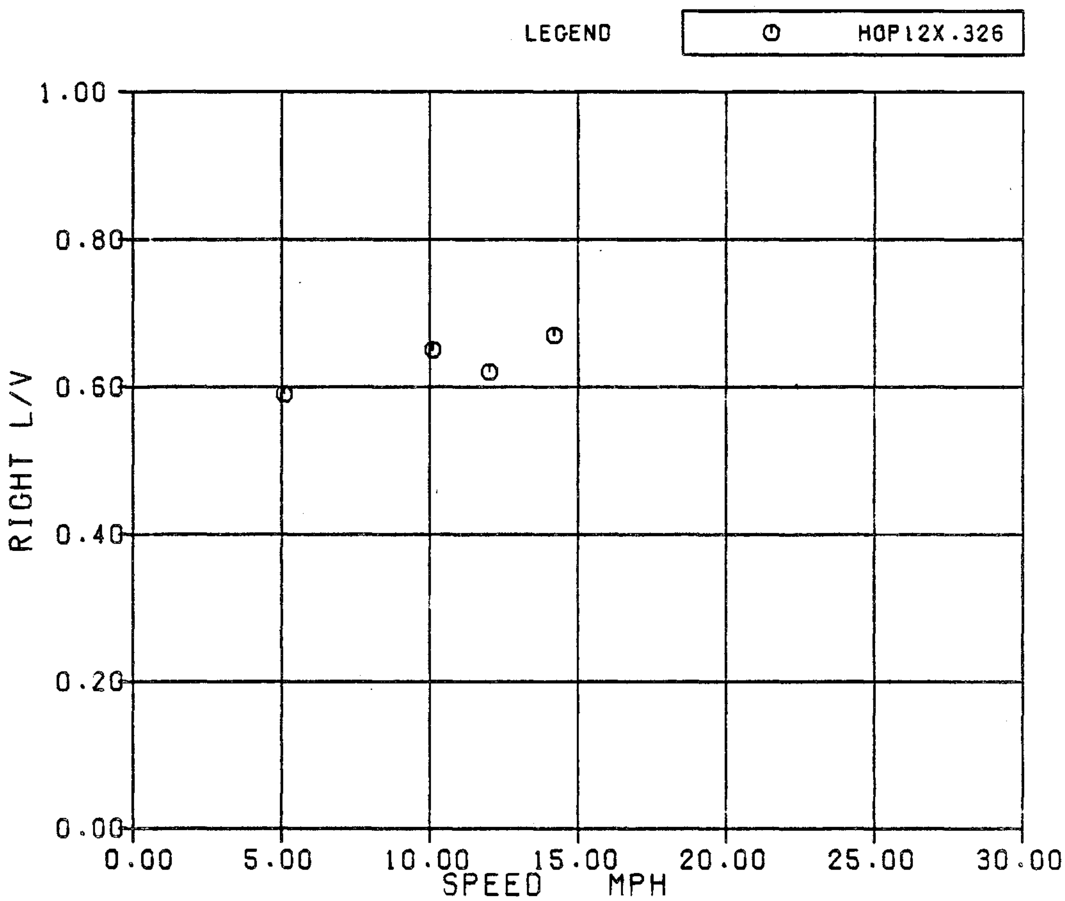


FIGURE 3-26. HOPPER CAR L/V RATIO VS. SPEED-AXLE 3 RIGHT, SECTION 1, 12-DEGREE CURVE WITH CROSSLEVEL PERTURBATIONS

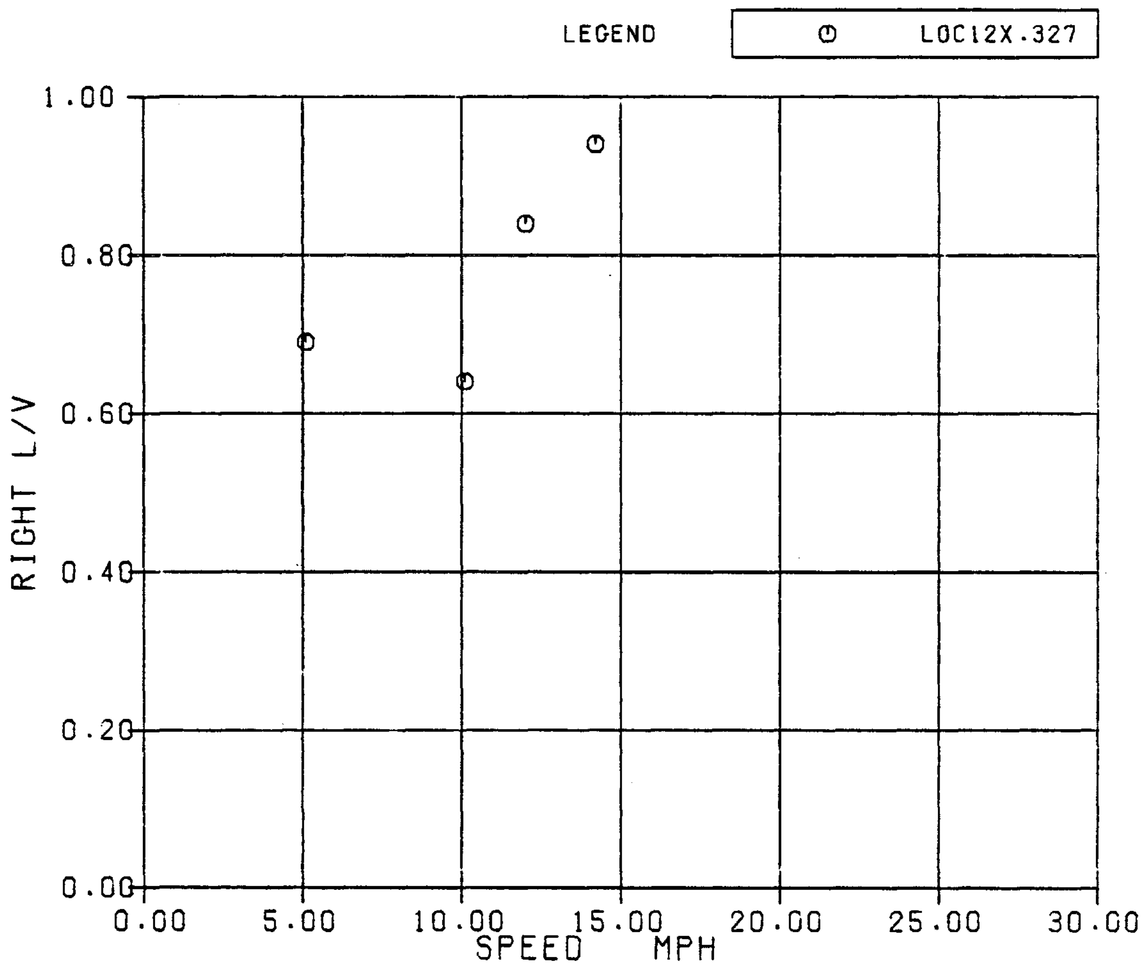


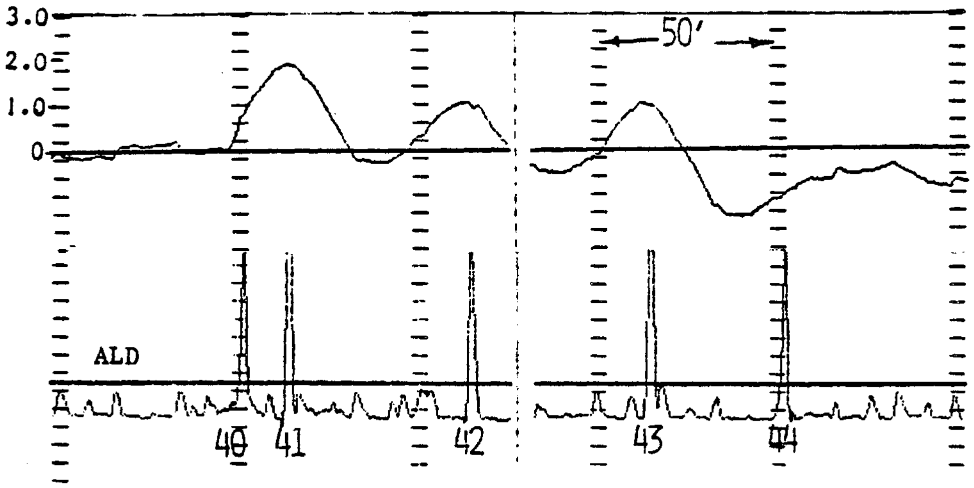
FIGURE 3-27. LOCOMOTIVE L/V RATIO VS. SPEED-AXLE 3 RIGHT, SECTION 1, 12-DEGREE CURVE WITH CROSSLEVEL PERTURBATIONS

The amplitudes and wavelengths were selected prior to the test based on the results of analytical studies. The combinations were chosen to produce approximately equal lateral wheel force responses at a given test speed. Figure 3-28 shows T-6 track geometry car measurements of right rail alignment for the two 50-foot sinusoid sections, one on tangent track and the other on the 6-degree curve. As seen in the figure, the alignment variations are not precisely as designed. The sinusoidal variations of the 6-degree curve are very irregular with some strong long wavelength components and large gage variations. In addition, the gage in the 6-degree curve varied significantly.

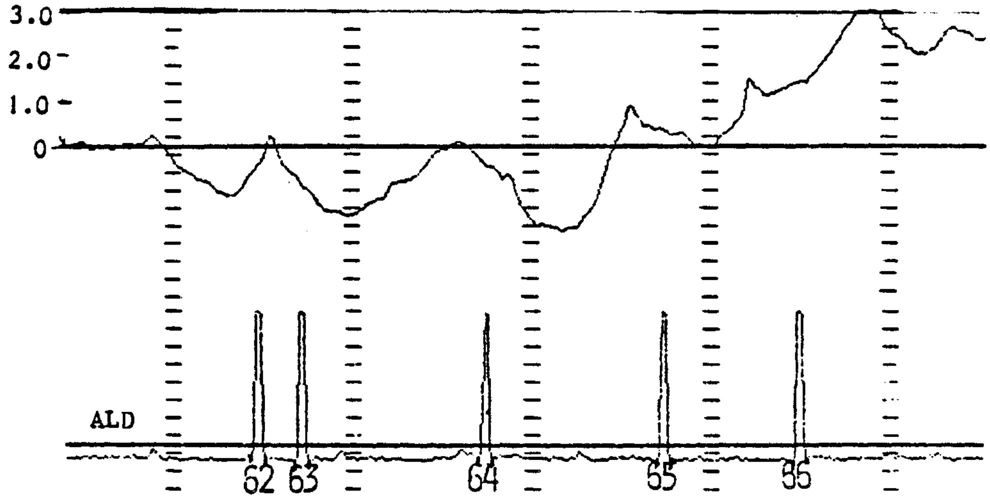
The track geometry for the other sections was also irregular but generally to much a lesser extent. Without considerable effort, it would be difficult to accurately assess the amplitude and frequency content of the various sections. However, the fundamental wavelength and amplitude are apparent and useful comparisons can be made between the tangent sections.

The hopper car right lateral wheel forces at 20 mph are shown in Figure 3-29 for the three sections. A significant feature of the response at 20 mph is that the forces are gage widening. Another significant feature is that the lateral wheel forces in the three sections are fairly similar with the major difference being the duration of the force response pulses and the duration of the null response period between peaks.

In Figure 3-30, time histories from three runs at 10, 20 and 30 mph through the 50-foot sinusoids in the tangent zone are shown. A slight trend of increasing lateral force with speed might be inferred. However, the responses are remarkably similar.



Section 2.2, Tangent 50 Foot Sinusiods



Section 3.1, 6 Degree Curve, 50 Foot Sinusiods

FIGURE 3-28. T-6 TRACK GEOMETRY CAR RIGHT RAIL ALIGNMENT DESIGN VARIATIONS FOR TWO 50-FOOT SINUSOID TEST SECTIONS

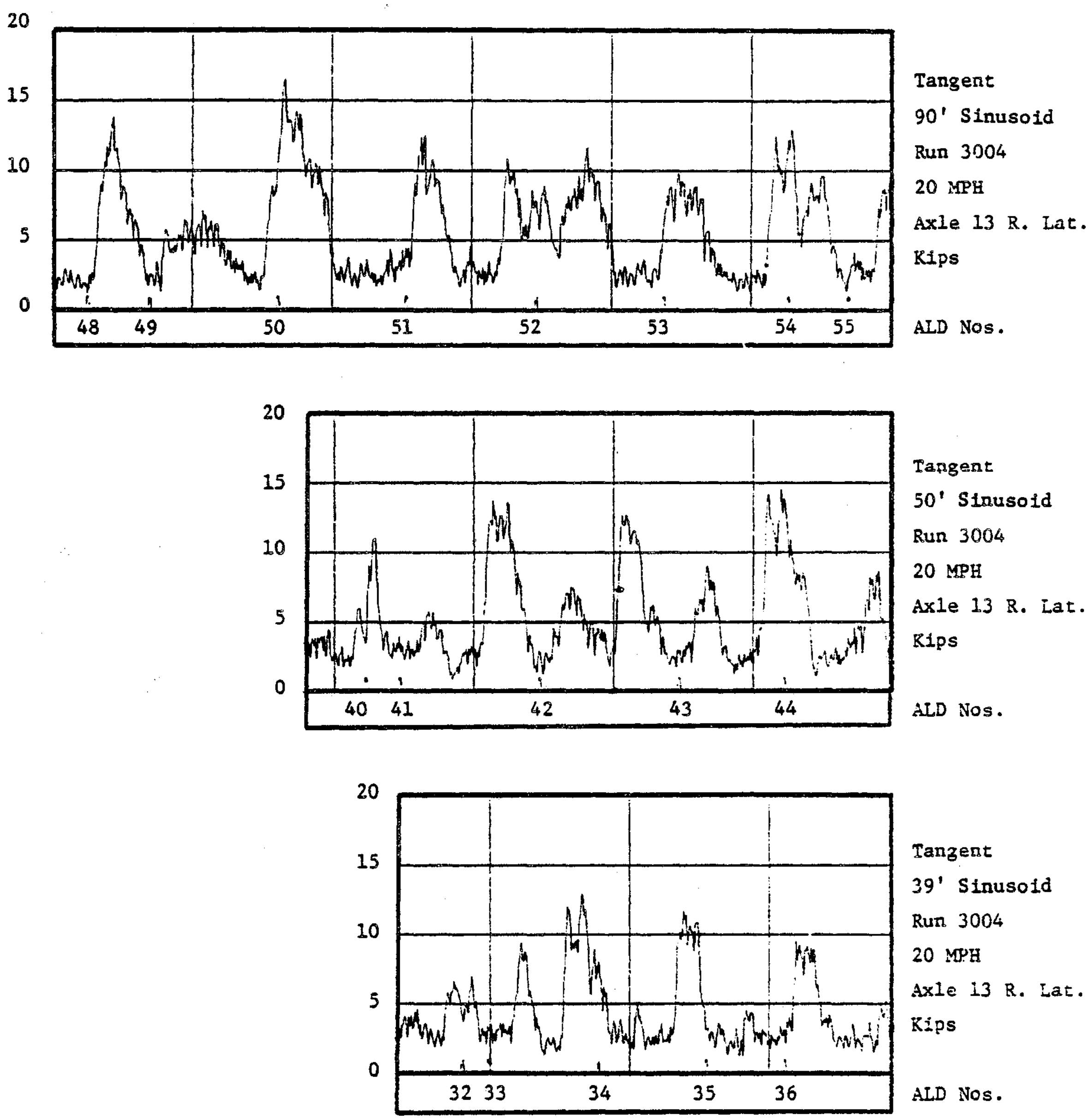


FIGURE 3-29. HOPPER CAR LATERAL WHEEL FORCES ON THREE TANGENT SINUSOIDAL SECTIONS

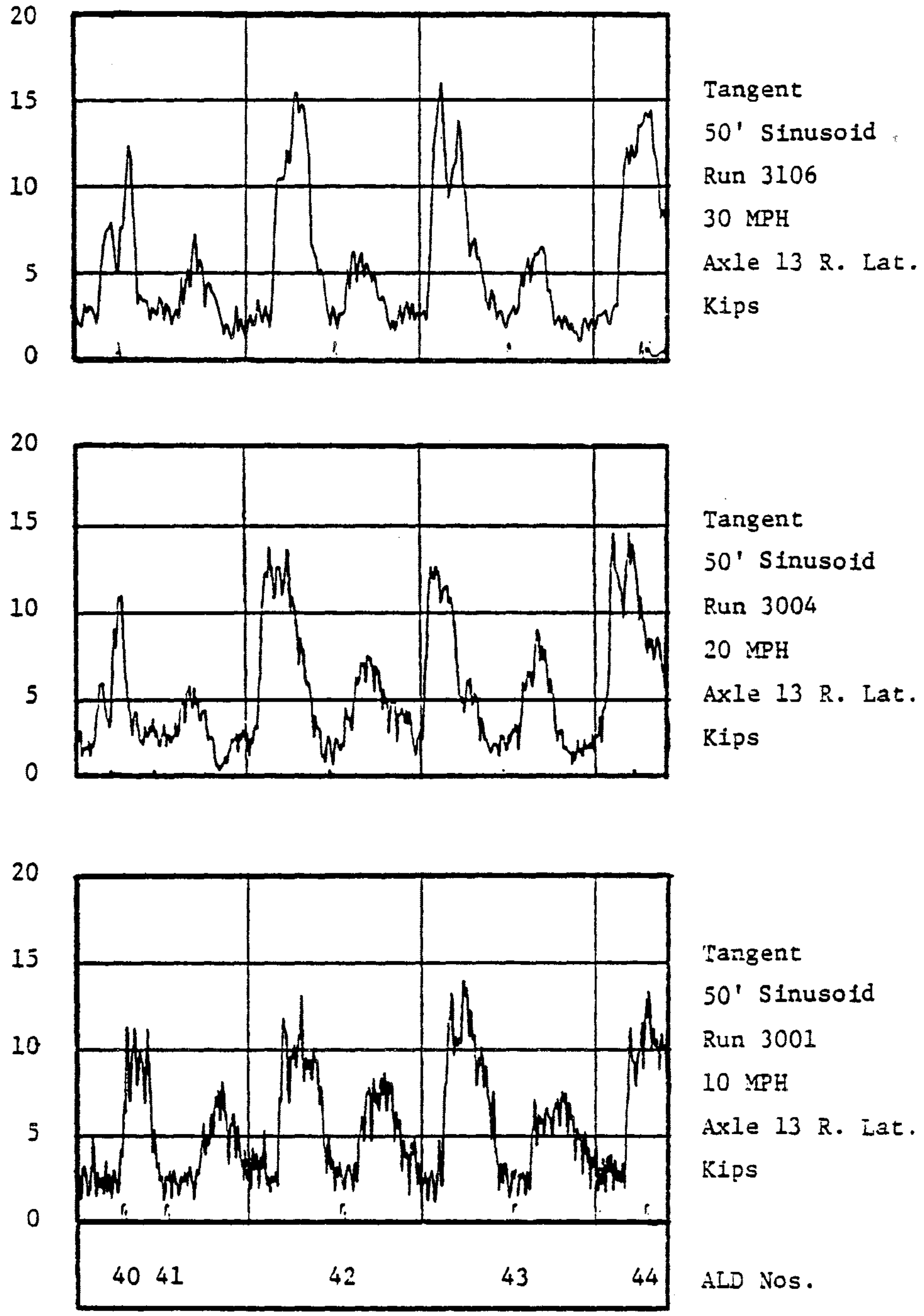


FIGURE 3-30. EFFECT OF SPEED ON HOPPER CAR LATERAL RESPONSE TO 50-FOOT SINUSOIDS IN THE TANGENT ZONE

In Figure 3-31, peak right lateral wheel forces for the hopper car are plotted versus speed for the three tangent alignment sections. In this figure no significant trend of increasing force as a function of increasing speed can be identified. The forces from the three sections are approximately equal.

Time histories from test runs at 10, 20, and 30 mph through the 50-foot sinusoids in the target zone are shown in Figure 3-32 for the leading axle of the trailing truck of the locomotive, axle 3. As with the hopper car forces, there is a slight increase in the peak force with increasing speed. However, the force responses are very similar. In addition, the force time histories for the locomotive, axle 3, shown in the figure are similar to the hopper car, axle 13, traces shown in Figure 3-30. Peak lateral wheel forces for the leading axle of the trailing truck of the locomotive are plotted versus speed for the three alignment sections in Figure 3-33. A trend of increasing lateral force with increasing speed is seen. However, the increase is slight. The significant feature is that the three alignment sections with different amplitudes and wavelengths all produced similar magnitudes of response. This shows the strong dependence of vehicle response on the alignment variation wavelength.

Finally, Figure 3-34 shows time histories of the lateral wheel force response for the hopper car, comparing the response to the 50-foot sinusoids in the 6-degree curve to the response of the tangent track. High rail on left wheel forces are shown for the curve. Unfortunately, the track geometry was not sufficiently controlled in the 6-degree curve to reach any meaningful conclusions regarding the influence of curvature on the severity of the alignment variation. However, the figure does show an influence on the duration of the high lateral loads which can be attributed to the curvature.

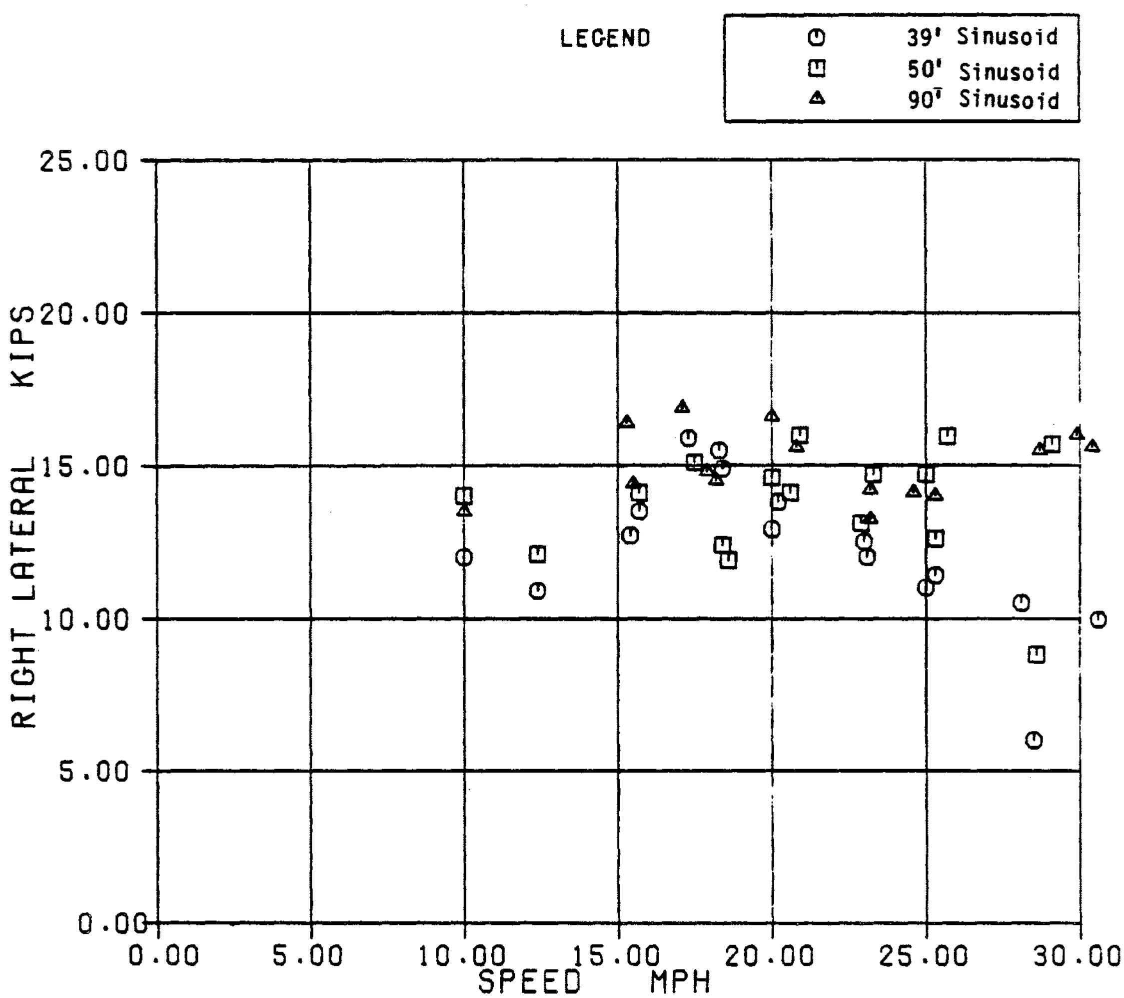


FIGURE 3-31. HOPPER RIGHT LATERAL WHEEL FORCES VS. SPEED FOR THREE TANGENT ALIGNMENT SECTIONS

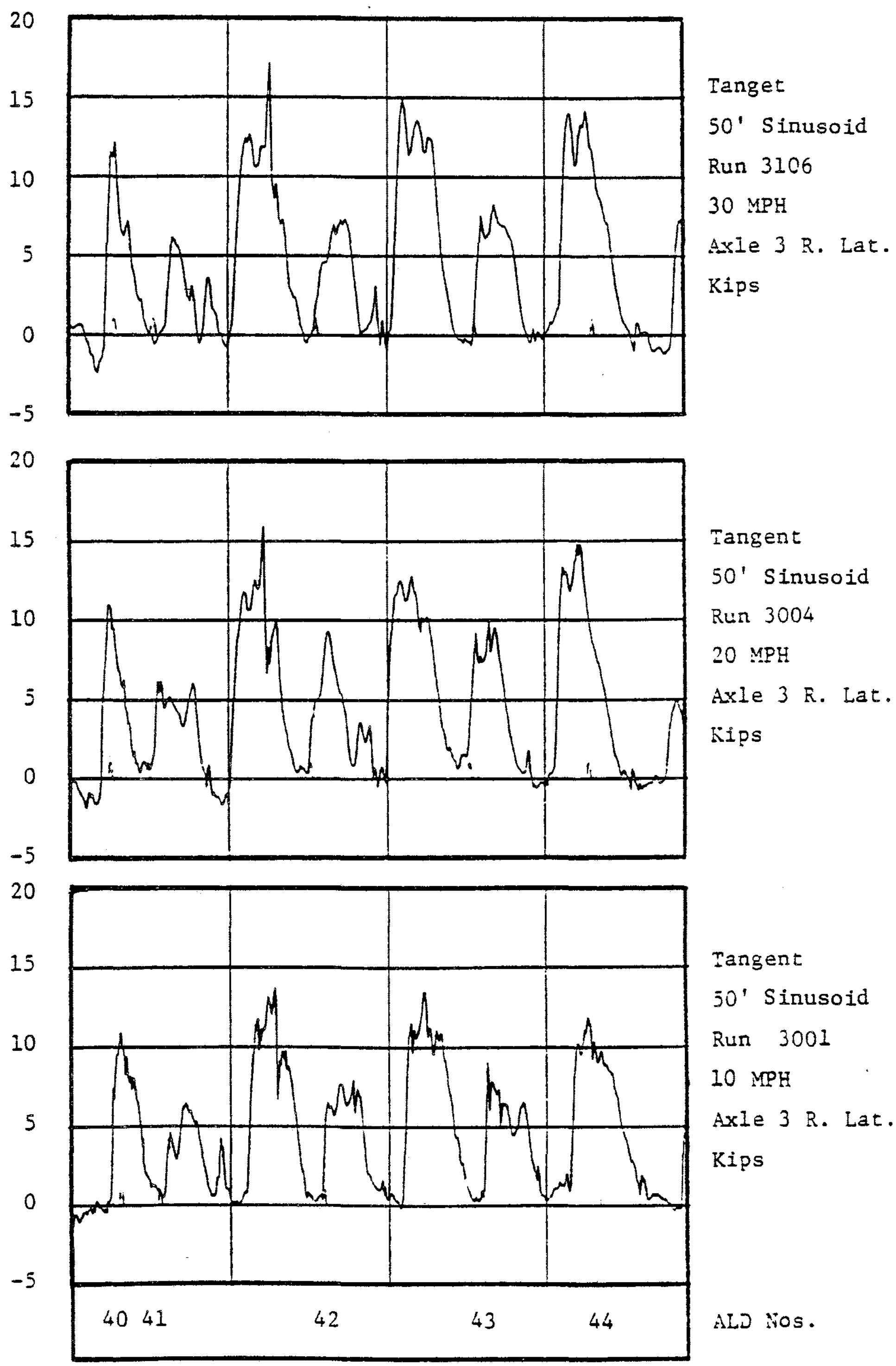


FIGURE 3-32. EFFECT OF SPEED ON LOCOMOTIVE LATERAL RESPONSE TO 50-FOOT SINUSOIDS

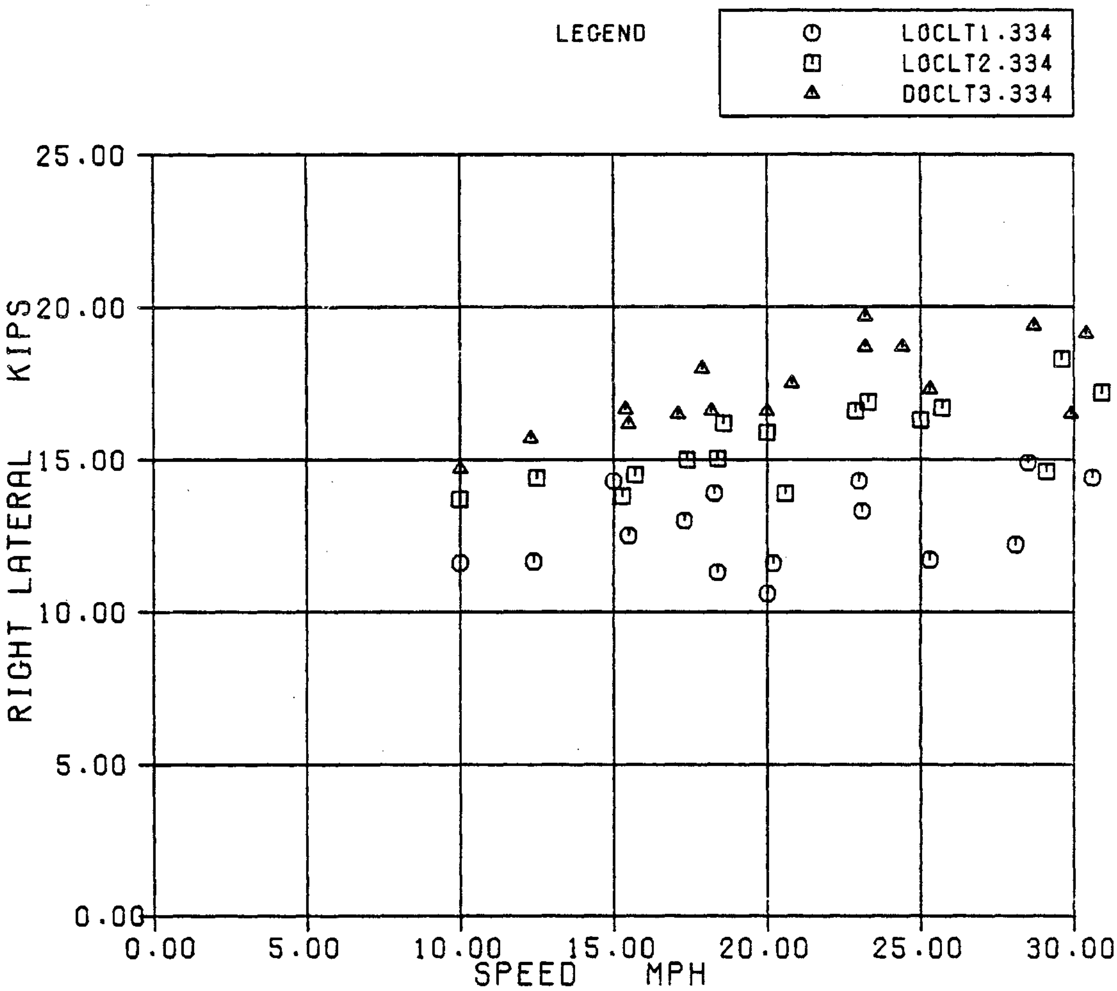


FIGURE 3-33. LOCOMOTIVE RIGHT LATERAL WHEEL FORCES VS. SPEED FOR THREE TANGENT ALIGNMENT SECTIONS

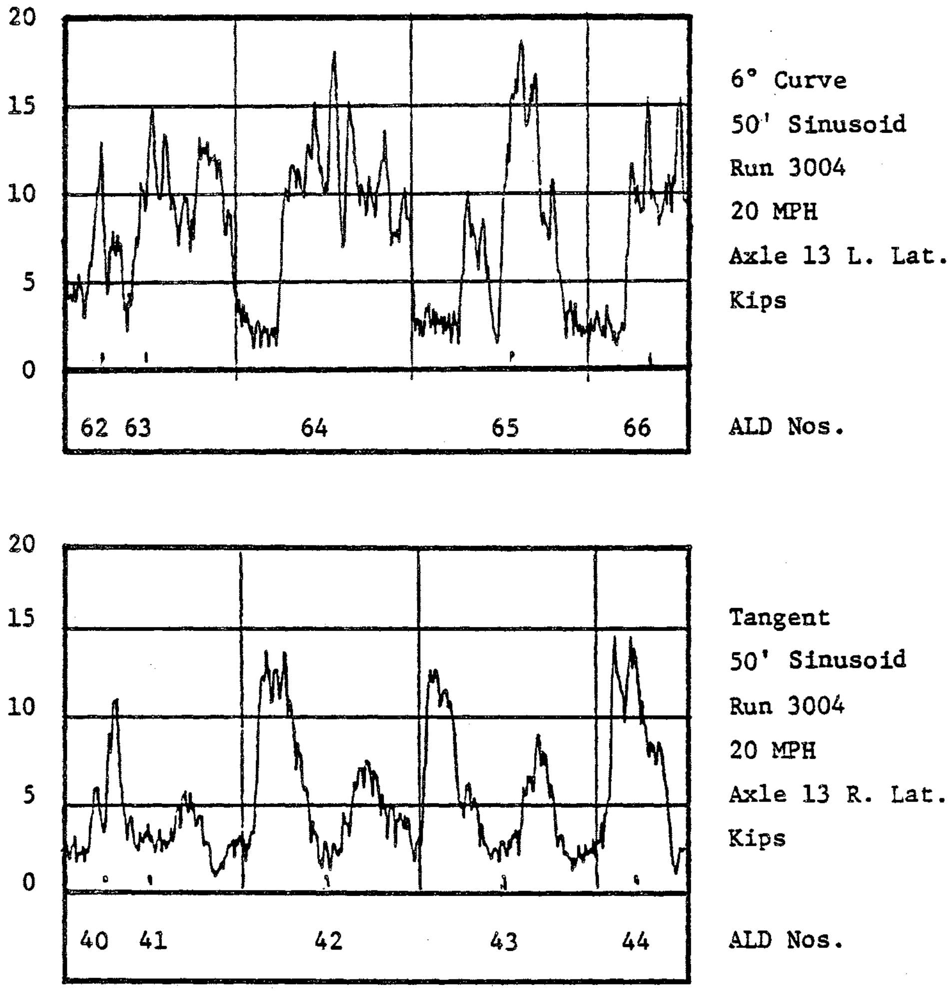


FIGURE 3-34. EFFECT OF CURVATURE ON LATERAL RESPONSE TO 50-FOOT SINUSOIDS

4. RESULTS AND CONCLUSIONS

The results of the Bennington tests resolve five important issues relative to the understanding of vehicle track interaction.

1. The test data demonstrate that large lateral wheel rail forces are generated on small radius curves (about 500-foot radius or 12 degrees) at low speeds (5 mph) and that these forces are relatively insensitive to speed. Peak lateral forces varied by only 5 kips (from 17 to 22 kips) over the speed range of 5 to 20 mph.

2. The low rail wheel forces show that coefficients of friction as large as 0.5 do exist on track. These coefficients allow the generation of large gage spreading forces on the order of 23 kips on the high rail and 15 kips on the low rail. This is important because these are the loads used in determining the minimum adequate rail restraint capacity characteristics.

3. The Bennington test verifies that lateral forces resulting from high rail alignment variations do increase with curvature. The significance of this finding is that geometry specifications of alignment must take curvature into account.

4. The test data from the 12-degree curve demonstrate that the combination of crosslevel and high rail alignment variations results in high lateral to vertical (L/V) force ratios. These high L/V ratios, along with the curvature, indicate a significant risk of wheel climb derailment. The importance of this finding is that crosslevel may have to be more closely controlled on small radius curves than on tangent track.

5. The wheel/rail forces measured in the three sinusoidal alignment sections on the tangent track test sections show that the vehicle response is sensitive to variations in wavelength while relatively insensitive to speed.

The importance of the wavelength and amplitude sensitivities is that the 62-foot midchord offset method of measuring alignment variations does not produce a uniform measure of the variation severity as defined by lateral force levels and potential risk of gage widening or wheel climb derailments.

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