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16. Abstract

Thermal buckling of railroad tracks in the lateral plane is an important problem in the design and maintenance of continuous welded rail (CWR) tracks. The problem is manifested through derailments which are attributable to track buckling, indicating a need for developing better control on the allowable safe temperature increase for CWR tracks.

The work reported here is a part of a major investigation conducted by the Transportation Systems Center for the Federal Railroad Administration on the thermal buckling of CWR tracks in the lateral plane with the objective of developing guidelines and recommendations for buckling prevention.

THE
This report presents the results of Phase III dynamic buckling tests on tangent and curved tracks conducted in 1986 with the main objective of validating the safety limits under current development. The tracks were subjected to vehicular traffic at maximum permissible speeds with the rails artificially heated to the theoretical maximum allowable temperature. Test data on rail forces, lateral and longitudinal displacements, and L/V ratios were collected. The test results are compared with the theoretical predictions and conclusions of practical interest are presented.

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PREFACE

This report was sponsored by the U.S. Department of Transportation, Federal Railroad Administration, Office of Research and Development, Washington, DC.

The report presents the results of track dynamic buckling tests conducted in 1986 for the purpose of assessing the safety criteria and standards under development for CWR tracks under dynamic conditions. The tests constitute a major part of the Transportation Systems Center's (TSC) track stability research program being conducted for the Federal Railroad Administration (FRA). The purpose of this program is to develop guidelines and specifications for the prevention of track buckling induced derailments.

The tests were conducted jointly with the Association of American Railroads (AAR) at the Transportation Test Center, under contract DTFR53-82-C-00282, and with Foster-Miller, Inc. under contract DTRS57-83-C-00071. The data reduction and analysis was performed by TSC and Foster-Miller, Inc.

Thanks are due to Mr. H. Moody of the FRA for his support throughout the various phases of the test program and to Messrs A. Sluz, J. Pietrak, and M. Thurston for support in test conduct and analysis.

Acknowledgements are also due to Mr. D. Read of the AAR for his efforts in conducting the tests, and Gopal Samavedam of Foster-Miller.

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METRIC / ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x - 32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES	0	1	2	3	4	5	6	7	8	9	10

CENTIMETERS 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 | 25.40

QUICK FAHRENHEIT-CELCIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and/or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10 286.

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EXECUTIVE SUMMARY

The increased utilization of continuous welded rail (CWR) tracks in the United States has resulted in a number of accidents attributable to train derailments induced by thermal buckling of railroad tracks. In an effort to improve the safety of CWR tracks, experimental and analytical investigations are being conducted by the Transportation Systems Center (TSC) supporting the safety mission of the Federal Railroad Administration (FRA). This report describes a part of these investigations dealing with the dynamic buckling behavior of CWR tracks.

This report presents the results of Phase III dynamic buckling tests conducted in 1986 at the Transportation Test Center (TTC) on tangent and 5-degree curved tracks. The main objectives of the tests were:

a. Assessment of minimum required lateral resistance for CWR tracks to ensure safety at the maximum rail temperature increase typically experienced in revenue service when subjected to train operations at the maximum permissible speed.

b. Assessment of track stability as affected by braking and truck hunting in the presence of rail compressive force (thermally induced).

To realize the first objective four major tests were carried out. Two tests were on tangent track representing two different lateral resistances. Likewise, two tests on the 5-degree curve were performed at different lateral resistance values.

The tracks were prepared to Class 5 standards and subjected to traffic under a long consist at maximum permissible or

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achievable speeds with the rails heated electrically up to the theoretical allowable temperature. The rail forces, lateral misalignments, and lateral to vertical force ratios were closely monitored and the safety of track was assessed.

In the braking tests, air brakes with a reduction of 12 lbs/in^2 pressure were applied to the ten-car consist moving at 40 mph at the theoretical maximum allowable temperature. For the hunting test, an empty vehicle with worn wheels was included in the consist.

The following conclusions were drawn from the tests:

a. The dynamic theory previously developed gives a reasonable indication of the CWR dynamic buckling strength when subjected to vehicle traffic and thermal loads.

b. The CWR safety criteria under current development has been partially validated for the limited traffic and the speeds achievable in the tests.

c. Tangent track can withstand vehicular traffic and thermal forces generated at the allowable temperature increase as determined in the safety criteria. Five-degree curves also appear to withstand vehicle operations at the current theoretical allowable temperature, but the margin of safety is less than that of tangent, particularly under several train passes.

d. The minimum margin of safety of $20^{o}F$ adopted in the safety criteria appears to be adequate for the limited braking loads simulated in these tests.

LIST OF SYMBOLS AND ABBREVIATIONS

α	coefficient of thermal expansion
E	Young's modulus for rail steel
A	rail cross-sectional area
I	rail moment of inertia about vertical axis
T	rail temperature
$T_{S,sta}$	static lower buckling temperature*
$T_{B,sta}$	static upper buckling temperature
$T_{S,dyn}$	dynamic lower buckling temperature*
$T_{B,dyn}$	dynamic upper buckling temperature
T_{all}	allowable rail temperature
T_N	rail neutral temperature
ΔT	temperature increase
P	rail force
F_o	lateral resistance
f_o	longitudinal resistance
$2L_o$	length of initial misalignment
δo	amplitude of initial misalignment
k_v	track modulus in the vertical direction
μ	coefficient of friction between tie and ballast
R	radius of curved track
L/V	ratio of lateral to vertical load

*These temperatures were called "safe temperatures" in earlier works. This terminology can be misleading in some cases of track with weak resistance. For clarity of definitions, this new terminology is introduced here.

I. INTRODUCTION

Buckling safety of continuous welded rail (CWR) tracks subjected to thermal and vehicle loads has been of concern to the Federal Railroad Administration (FRA). The Transportation Systems Center (TSC) is providing technical support to the FRA in the research and development of safety specifications and guidelines for use in the railroad industry. The work presented in this report is the Phase III part of a major program sponsored by FRA on track dynamic buckling strength evaluation. The tests were conducted by the Association of American Railroads (AAR) at the Transportation Test Center (TTC) during July and August of 1986, with TSC as the test monitor and with participation by Foster-Miller, Inc.

Previous tests under this program (Phases I & II) were also conducted at TTC in 1983 and 1984. The results of these tests were analyzed and presented in (1). A brief review of the test results is included in this report (Section 2) to provide the background supporting the establishment of buckling safety concepts and criteria, which are presented in Section 3.

The Phase III activities presented in this report consist of four major tests, designated here as Curve I, Curve II, Tangent I, and Tangent II for convenience. In each case, the rails were heated to the allowable temperature and subjected to train operation at maximum permissible (or achievable) speeds. Curves I & II represent tests on the same 5-degree curved CWR track at different ballast consolidation levels and hence at different lateral resistance levels. Likewise, Tangents I and II represent the two major tests on the same tangent track at two different lateral resistance levels.

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The tests include determination of track parameters (such as the lateral resistance), measurements (such as lateral and longitudinal displacements, rail temperatures and forces, L/V due to wheels) and other required data for validation of theoretical models.

This report presents comparisons of test data with the theoretical predictions, and partial validation of safety limits for buckling prevention currently under development.

2. REVIEW OF PREVIOUS DYNAMIC BUCKLING TESTS

Dynamic buckling tests were carried out in 1983 (Phase I) and in 1984 (Phase II) by AAR at TTC with participation by Foster-Miller and under test direction and monitoring of TSC. The main purpose of Phase I was to identify principal dynamic buckling mechanisms and the parameters for the development of buckling analysis. The theoretical predictions of dynamic buckling response and the margin of safety concept developed using the theory (2) were verified in Phase II. Both Phase I and II were conducted on tangent and 5-degree curved, wood tie tracks with cut spikes in the balloon loop at TTC.

2.1 PHASE I TESTS

The specific tests in Phase I, besides track characterization tests, are described in the following subsections.

2.1.1 Explosive Buckling Test

The objective of this test was to determine the buckling strength of the track under the influence of stationary vehicles (locomotive and hopper car) and compare it with the static buckling strength of CWR tracks.

A lateral line defect of 0.75 inches over a length of 32 ft was set under each vehicle (hopper car and locomotive), and the rails were heated by electric current until explosive buckling occurred under the hopper car. This experiment showed that the track under the locomotive was more stable laterally than under the hopper car, due to the shorter uplift regime under the locomotive as discussed in (2).

2.1.2 Safe Temperature Test

The aim here was to establish buckling safety by allowing multiple passes at different speeds as the rails were being heated up to the theoretical lower dynamic buckling temperature.

A tangent track with a lateral resistance of 52 lb/in was used on one of the two tests. The track was nominally straight; the rails were heated to 75^{O}F over the neutral temperature, and subjected to a ten-car consist traffic with speeds up to 40 mph. No noticeable misalignments were developed in the track.

In the second test, a 5-degree curve with similar lateral resistance as the tangent was subjected to temperature rise and traffic by the same consist. An initial misalignment of about 0.4 inches at the center grew rapidly to 2 inches at the third pass of the consist when the rail temperature was about 60^{O}F above neutral.

An analysis of the results showed that the compressive force in the rails was nonuniform and was much reduced at the ends of the test zone compared to that at its center. Consequently, the "infinite track theory" could not be sensibly applied to the test scenario. However, it can be concluded that the lateral resistance value that may be adequate for tangent tracks, can be inadequate for curves.

2.2 PHASE II TESTS

The tests were performed at the same tangent and the 5-degree curve location as in Phase I, but the test zone was increased from 200 m to 300 m and, in addition, the outside zones were stiffened longitudinally by replacing the wood ties with concrete ties and unit anchors for the purpose of obtaining a more uniform compression force in the central zone. Instead of the ten-car consist used in Phase I, only a two-vehicle (hopper car, GP-40 locomotive) consist was used to facilitate a better monitoring of individual truck influences. The following were the major tests performed in Phase II.

2.2.1 Safe Temperature Test

The purpose of this test was to investigate the behavior of tangent track with small initial alignment imperfections and known lateral resistance when subjected to high compressive forces (due to the temperature rise equal to the lower dynamic buckling temperature increase) and limited vehicle traffic at speeds up to 40 mph.

The rails were first heated up to the theoretical lower static buckling temperature, which was determined to be 82°F above the stress-free temperature (equivalent to a force of 210 kips/rail). The heating continued up to the lower dynamic buckling temperature of 90°F above the stress-free temperature, generating a force of 233 kips/rail. At this temperature level, forward and reverse passes of the two-vehicle train consist were made at a speed of 5 mph. This was repeated at 25 mph, and a final pass at 40 mph was made to complete the test. The initial misalignment of 0.62 inches grew by only 0.05 inches due to the rail heating and traffic. The track strength was adequate to withstand vehicle and thermal loads up to the theoretical dynamic lower buckling temperature increase.

2.2.2 Progressive Buckling Test

The purpose of the test was to induce progressive dynamic buckling in order to provide a verification of the dynamic theory developed (2) and an estimate of the "lower buckling" temperature that could not be determined in the explosive buckling test carried out in Phase I.

To induce progressive buckling, about 60 ft of tangent track was weakened by tamping and setting a 5 inches lateral imperfection at the center. The tamping reduced the lateral resistance from its previous value of 64.8 lb/in to 54.5 lb/in, and by means of the Track Lateral Pull Test device (TLPT) an imperfection of 5 inches was set at the center of the test zone with the rail at its neutral temperature. This imperfection, coupled with the low lateral resistance, was theoretically determined to be sufficient for the progressive buckle to develop in the track. The hopper car was spotted over the imperfection symmetrically to induce uplift, thereby simulating a quasi-dynamic condition. As the rails were heated, the track lateral deflection at the center increased from the initial value of 5 inches to about 17 inches at the final temperature of about 80°F over the neutral temperature. Good agreement is found between the theoretical and test results as seen in Figure 1. It is concluded that the "lower buckling temperature" for the track with similar resistance values, but with no lateral misalignments, would be on the order of 80°F.

2.2.3 Margin of Safety Tests

The purpose of these tests was to show that tracks with inadequate dynamic margin of safety can be unstable under traffic.

Experimental verification of the margin of safety concept was carried out on the 5-degree curve. Two tests were performed. In the first test, the theoretical dynamic margin of safety (DMS) (i.e., the difference between the dynamic upper and lower buckling temperatures, was 15°F. At the theoretical dynamic lower buckling temperature, the track did not develop significant additional misalignment (over the initial value of 0.375 inches at its center) when subjected to train passes at speeds of up to 40 mph. The theoretical and experimental response curves are shown in Figure 2.

For the second test on the 5-degree curve, the track resistance was reduced to correspond to that of a weak, "recently maintained" track. This track sustained a temperature increase of 40°F without significant misalignment growth. Above 40°F the misalignments grew with train passage, reaching 2 inches at 60°F as shown by the triangles in

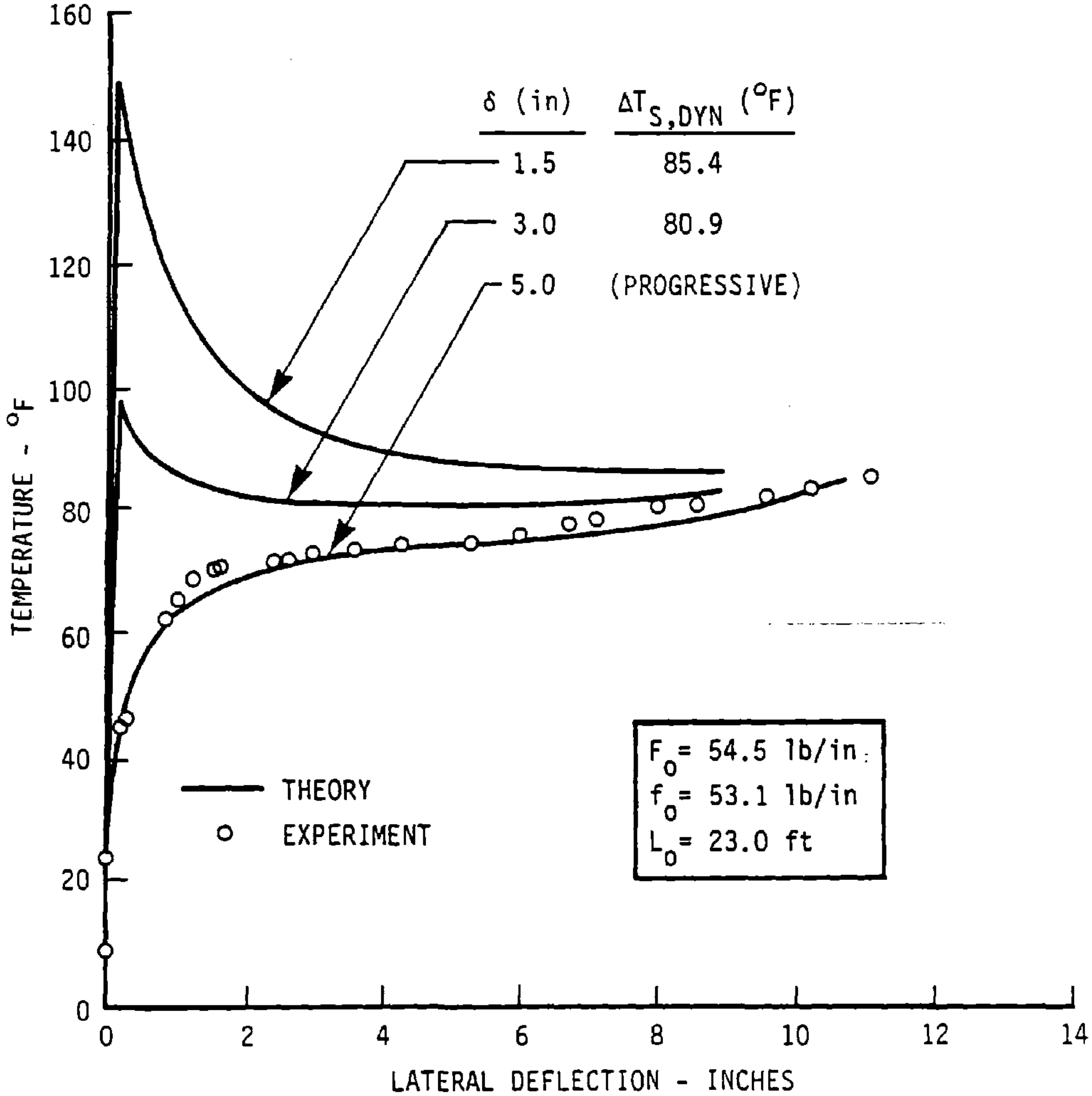

FIGURE 1. PROGRESSIVE BUCKLING OF TANGENT TRACK

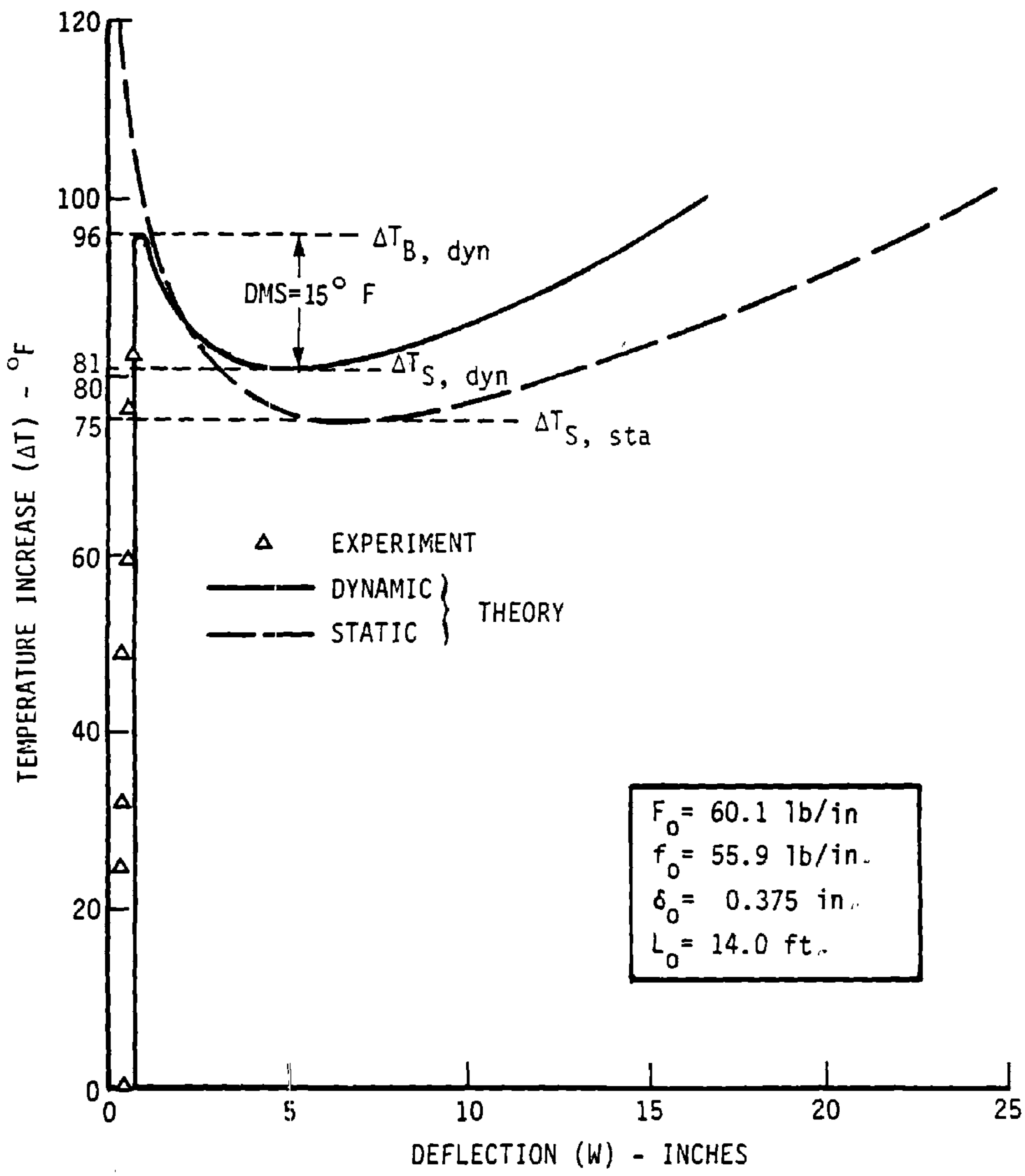

FIGURE 2. DYNAMIC BUCKLING RESPONSE FOR CURVE WITH FINITE MARGIN OF SAFETY

Figure 4. At 62^{o}F, the curve buckled out to a deflection of 9 inches, as shown in Figure 3. The test results are in good agreement with the theory (see Figure 4) and indicate that CWR tracks might be dynamically unstable at temperature increases that may not cause buckles under static conditions (without vehicle traffic). The results also provide further confirmation for the required dynamic margin of safety.

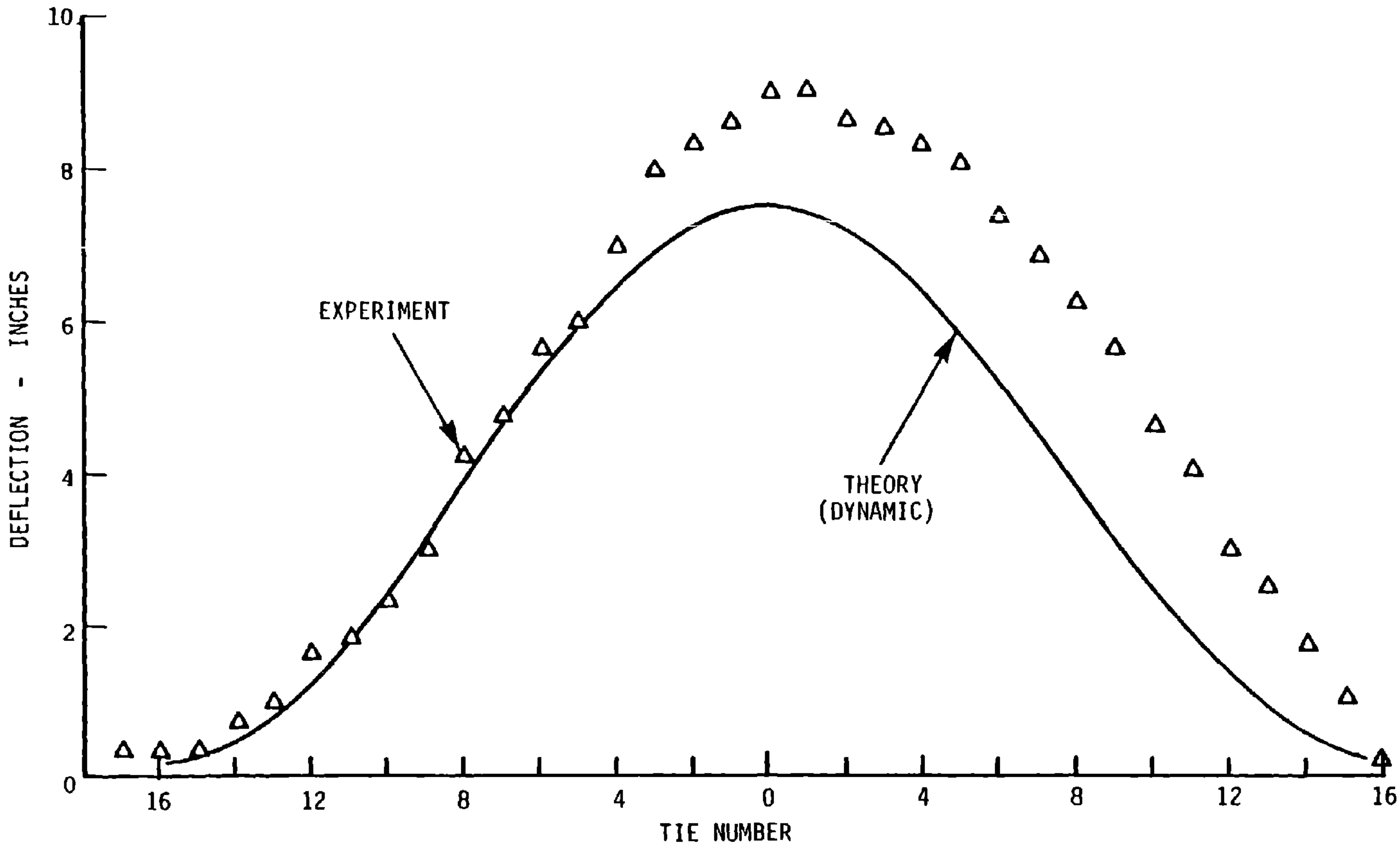

FIGURE 3. BUCKLED SHAPE OF TRACK

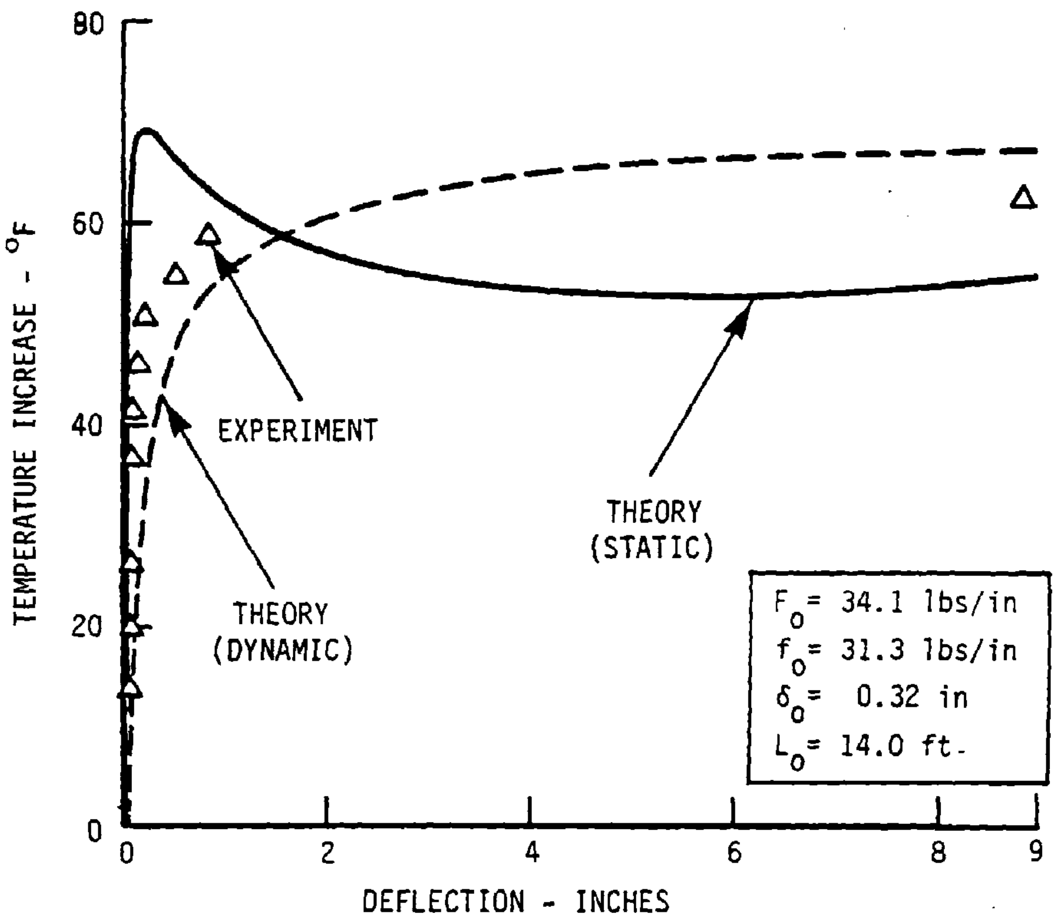

FIGURE 4. BUCKLING RESPONSE OF CURVE WITH ZERO MARGIN OF SAFETY

3. BUCKLING SAFETY CONCEPTS AND CRITERIA

On the basis of the dynamic buckling theory (2) and recent buckling test results and conclusions described in Section 2, TSC is currently developing safety concepts and criteria for buckling prevention of CWR tracks. Additional field tests are being planned for a direct verification of the criteria developed. Phase III tests which were carried out in 1986, were intended to verify the safety criteria for tangent and 5-degree curves. The safety criteria will be briefly described here, followed by Phase III test results.

3.1 BACKGROUND

In the early works (3,4), the safe allowable temperature increase for CWR is considered to be the lower buckling temperature $T_{S,sta}$ on the static response curve as in Figure 5. Above this temperature, the track shows multiple equilibrium configurations and can buckle out. It will certainly buckle out to a large lateral displacement at the peak, $T_{B,sta}$ which is the upper buckling temperature. This temperature is generally much higher than the minimum temperature $T_{S,sta}$. Therefore, railroad engineers have been concerned that the use of $T_{S,sta}$ as safe allowable is conservative and a criterion based on the buckling temperature $T_{B,sta}$ might give them more flexibility in their operations on CWR tracks.

The static response curve is determined by the track lateral and longitudinal resistances, rail area and moment of inertia, and the initial lateral misalignments. It is independent of vehicle parameters such as the wheel load, speed, and the resulting dynamic effects. Although vehicle effects were recognized to be important in buckling safety criteria by many railroad organizations, a systematic quantification and inclusion in the safety criteria has been

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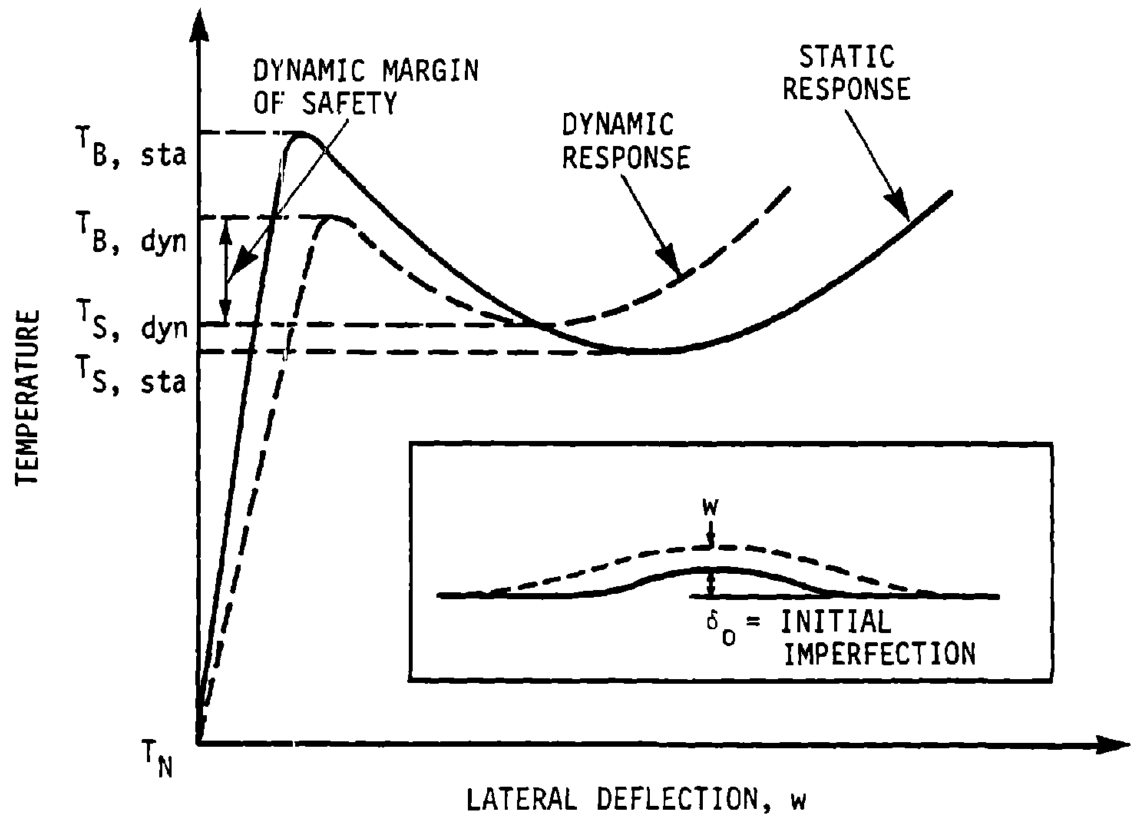
possible only recently due to the theoretical and experimental works (1,2) on dynamic buckling of CWR.

In one of the dynamic buckling modes resulting from the track uplift caused by the central bending wave (2), the temperature-deflection response curve (Figure 5), shows the upper dynamic buckling temperature $T_{B,dyn}$ to be less than the static buckling temperature $T_{B,sta}$, although the lower



$T_{S,\ sta}$ = LOWER STATIC BUCKLING TEMPERATURE
$T_{B,\ sta}$ = UPPER STATIC BUCKLING TEMPERATURE
$T_{S,\ dyn}$ = LOWER DYNAMIC BUCKLING TEMPERATURE
$T_{B,\ dyn}$ = UPPER DYNAMIC BUCKLING TEMPERATURE

FIGURE 5. BUCKLING RESPONSE CURVE

temperatures $T_{S,dyn}$ and $T_{S,sta}$ are approximately equal to one another.

It is clear that if the upper buckling temperature should be used in the safety criteria, it should be the upper dynamic buckling temperature $T_{B,dyn}$ and not the upper static buckling temperature. Since at this buckling temperature, the track will certainly buckle out, the difference between this and the maximum allowable rail temperature can be considered as an index of the margin of safety. Tests in Phase II have shown that a $20^{\circ}F$ margin of safety may be adequate to run the traffic at the maximum allowable rail temperature increase with a reasonable level of confidence.

3.2 SAFETY STANDARDS DEVELOPMENT

One proposal for safety standards under current investigations by TSC uses the following safety criteria.

Criterion 1: The maximum allowable rail temperature increase over the stress-free (neutral) temperature should be equal or below the $T_{S,dyn}$ (lower dynamic buckling temperature).

$$T_{all} \leq T_{S,dyn} \tag{1}$$

Criterion 2: There should be at least a $20^{\circ}F$ margin of safety between the upper dynamic buckling temperature $T_{B,dyn}$, and the maximum allowable temperature.

$$T_{B,dyn} - T_{all} \geq 20^{\circ}F \tag{2}$$

It is implied that the foregoing criteria will be applied for all vehicles. The primary vehicle parameters influencing the dynamic buckling temperature are wheel loads and truck center spacing. In addition, the track parameters mentioned earlier are also of importance; the most important being the lateral resistance. In regard to vehicles, the most influencing car type is either a hopper or a tank car, depending on track parameters, according to the theory developed (2).

Criterion 1 does not completely eliminate the concern that T_S could be too conservative. However, the $T_{B,dyn}$ is not too much larger than $T_{S,dyn}$; hence, in view of the dynamic buckling theory, criterion 1 may not be very conservative. Besides, it is expedient to avoid multiple equilibrium configurations that would be available for the track at temperatures higher than $T_{S,dyn}$.

Criterion 2, which is the outcome of Phase II tests on the tangent and the 5-degree curve, is intended to account for all other dynamic effects empirically.

Typical theoretical results of the criteria are shown in Figure 6 for Class 5 tracks (as an example). The lateral resistance is varied over a range, whereas other required parameters are kept constant at the respective values shown in the figure. The misalignment amplitudes are kept constant at 0.75 inches for tangent and 0.625 inches for the 5-degree curve, but the wave lengths are determined by the lateral resistance as given by the formula

$$2L_o = \left[\frac{72\ EI\ \delta_o}{F_o}\right]^{1/4} \tag{3}$$

Here

$2L_o$ = length of imperfection
EI = flexural rigidity of rails (lateral plane)

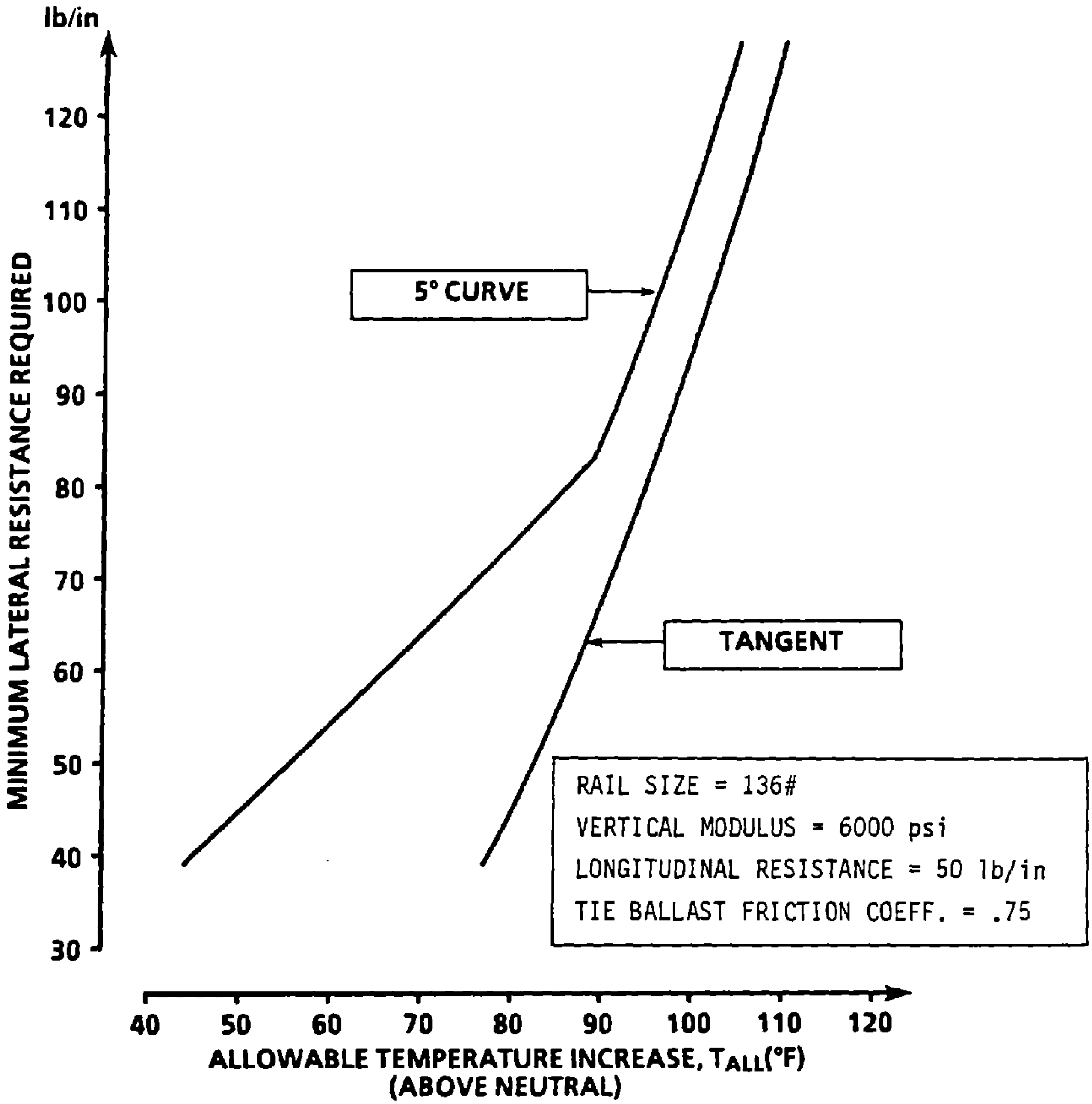


FIGURE 6. TYPICAL SAFETY LIMITS FOR BUCKLING PREVENTION (CLASS 5 TRACK)

δ_o = amplitude of misalignment

F_o = lateral resistance

which is derived in (5).

3.3 IMPLICATIONS OF PROPOSED CRITERIA

An important implication in the proposed criteria is that CWR tracks should have distinct dynamic buckling and safe temperatures. For very low lateral resistances, the response characteristics can be "progressive," as shown in Figure 4. For tangent and curves up to 5 degrees, this problem is not serious; but for higher degree curves particularly for Class 3 and 4 tracks where large imperfections can exist, the response is generally progressive even at reasonably high track resistances.* Clearly, for such cases, alternate criteria will be required. This is the subject under current investigation by TSC. Phase IV tests are being planned to define the basis of the criteria for high-degree curves.

It should be stressed that the safety curves in Figure 6 are preliminary and presented here only for the purpose of comparison with experimental results. The data are also restricted to other assumed parameters, i.e., longitudinal resistance, vertical track modulus, tie-ballast friction coefficient, and the rail size (136# lb).

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*It is to be noted that many European railroads prohibit the use of CWR for curves higher than 5 degrees, due to the difficulties in controlling the rail neutral temperature and maintaining large ballast shoulders required for high lateral resistance.

4. PHASE III TEST OBJECTIVES

In this report, analyses of the four major tests carried out in Phase III in 1986 by AAR at TTC will be presented. The main objectives of the tests, which were proposed in the test plan and requirements document prepared by TSC (6) were:

(i) Assessment of minimum required lateral resistance for CWR tracks to ensure safety at the maximum temperature increase (typically experienced in the revenue service) when subjected to a train operation at the maximum permissible speed

(ii) Assessment of track stability as affected by braking and truck hunting in the presence of compressive rail force (thermally induced).

4.1 TECHNICAL DISCUSSION

Objective (i): Assessment of minimum lateral resistance required.

On the basis of the dynamic buckling theory, the minimum required lateral resistance for buckling safety of CWR can be calculated for a given rail temperature increase. Other parameters such as the longitudinal resistance, maximum permissible misalignment, rail size, curvature, etc., are to be fixed, and a dynamic margin of safety of at least 20°F should be prescribed.

To realize this objective, dynamic buckling experiments were conducted on a 5-degree curve and a tangent track at different lateral resistance values (Curve I 64 lb/in, Curve II

77 lb/in, Tangent I 53 lb/in, Tangent II 62 lb/in). These resistance values were obtained through different consolidation levels. The resistance values for Curve I and Tangent II are representative of the "low end" of the permissible range.

Appropriate initial misalignments permissible for Class 5 track were artificially set in the central zone of each test section. The tracks were subjected to traffic under a long consist at maximum permissible or achievable speeds with the rails heated up to the theoretical allowable temperatures. Several passes of the consist were made while the growth of lateral misalignments were closely monitored in real time.

Objective (ii): Assessment of vehicle braking and hunting on the lateral stability of CWR tracks.

This objective was included because some railroad researchers consider that dynamic buckling can be precipitated by the forces generated due to braking and hunting. Tests reported in Reference (7) indicated that compressive forces generated in each rail due to the braking of a heavy locomotive can be of the order of 10 tons. The compressive force will have to be resisted by track segments which are vertically unloaded, and will be additive to the force due to temperature increase. Hence, the apparent reduction in the dynamic buckling temperature due to braking is of the order of 5 to 10°F depending on the rail section.

The safety limits under current development have a dynamic margin of safety of 20°F and are expected to cover the effect of braking on buckling safety. Experiments were conducted to verify this aspect.

An evaluation of truck hunting effect on CWR track buckling is considered to be important because this phenomenon is more prevalent in CWR than in the jointed tangent tracks, and also it could lead to hard flange contact at 30 to 50 ft intervals with significant L/V, which would contribute to track lateral shift and eventual buckling under thermal loads.

A hunting car was included in the train consist to determine the effect of truck hunting on the lateral stability of Tangent II test track.

5. MEASUREMENTS AND PARAMETERS

5.1 TEST MEASUREMENTS

The following measurements were made for each of the four dynamic buckling tests.

Rail Temperature using thermocouples spot welded to the rail web was continuously monitored during the heating tests, and the values in ^{o}F were printed on the datalogger output (HP9826 Multiprogrammer).

Longitudinal Rail Force was measured using the standard four-arm strain gauge bridge configuration (two longitudinal gauges and two vertical gauges). The gauge circuit gives the mechanical strain after compensating for thermal strains. The rail force was calculated using the formula

$$P = \frac{AEe}{2(1 + \nu)}$$

where

A = rail cross-sectional area
E = modulus = 30×10^6 psi
ν = Poisson's ratio = 0.3
e = bridge output in mechanical strain

The datalogger was programmed to yield the rail force in kips. The force was continuously monitored during the tests at various locations on the two rails.

Displacement - The lateral displacement of the track was measured with respect to fixed posts using a rotary potentiometer. The longitudinal displacements of the rails at

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the ends were also measured using the same type of instrument. All the instruments were connected to the datalogger.

Vertical Loads on the rails due to vehicles were measured using the standard four-arm strain gauge bridge circuit as in the previous tests (1).

Lateral Load - The lateral load generated on the rail, as the wheel negotiated the lateral imperfections, was measured using the standard strain gauge bridge circuit, as in the previous tests (1).

The instrument deployment is shown in Figure 7. The instrumentation was connected to the signal conditioning units in the data van, which was situated near the center of the test zone. The outputs from the signal conditioning units were connected to a 24-channel datalogger, which was programmed for output in engineering units.

5.2 TRACK PARAMETERS

Prior to the commencement of each of the major tests, the following track parameters were quantified to provide inputs for theoretical predictions.

5.2.1 Track Lateral Resistance

This parameter was determined from the Single Tie Push Tests (STPT). Table 1 provides the results for all the tests involved.

To arrive at an equivalent constant resistance (F_o) value, the STPT peak resistance values have been averaged out, and the average value per test section has been divided by the factor 1.3. This is an approximate factor determined from the track characterization studies conducted earlier by TSC. The equivalent resistance values are shown in Table 2.

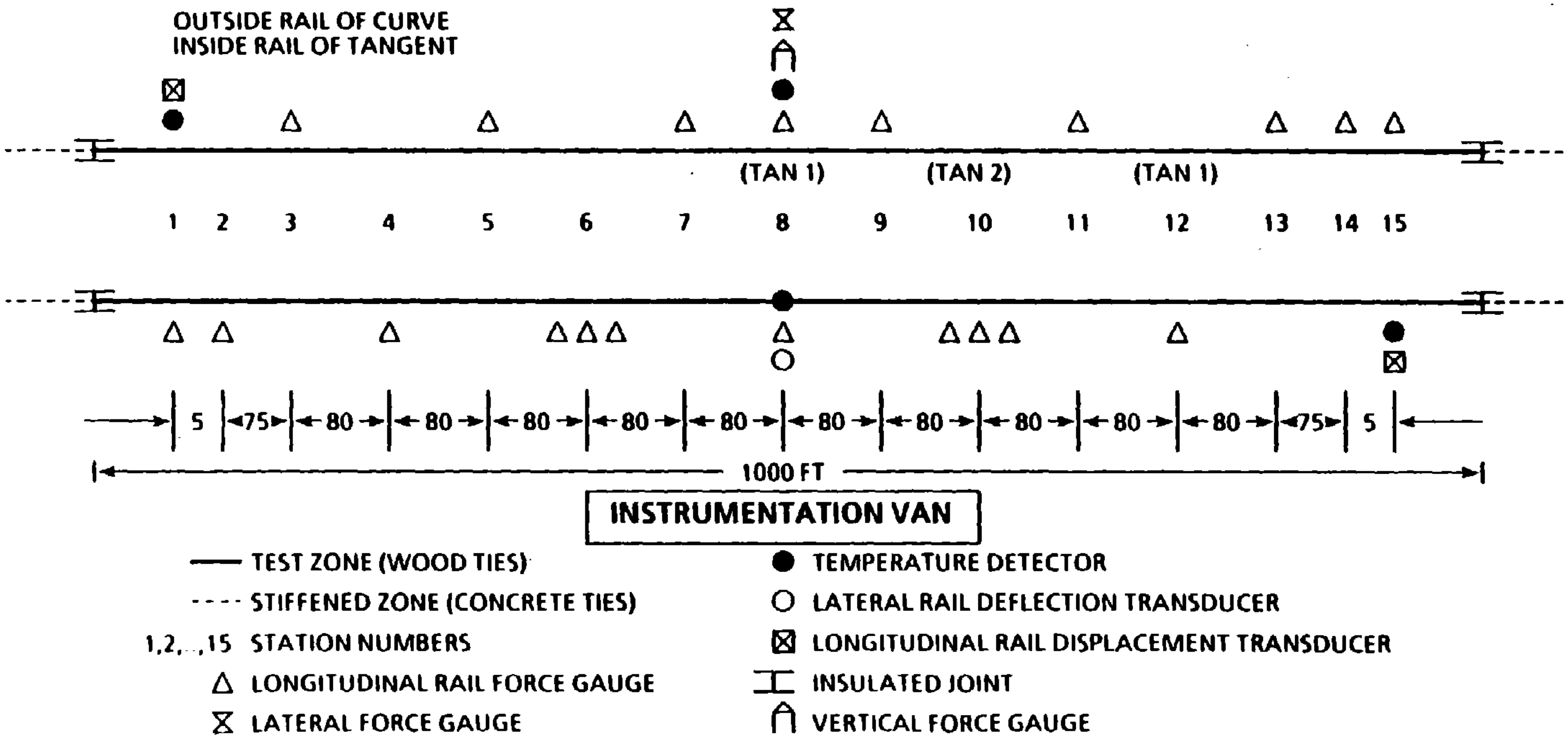

FIGURE 7. TYPICAL INSTRUMENTATION DEPLOYMENT

TABLE 1. SINGLE TIE PUSH TEST RESULTS

TEST TRACK	CONSOLIDATION LEVEL (MGT)	TIE NUMBER*	PEAK VALUE (LB)	COMMENTS
Curve I (Balloon)	0.15	2 + 31	1,437	
		2 + 41	1,414	
		4 + 18	1,616	
		4 + 21	1,531	
		4 + 30	1,637	
		4 + 33	1,600	
		5 + 18	1,709	
		5 + 21	1,593	
		5 + 30	1,966	
		5 + 33	1,941	
		5 + 35	1,817	
		5 + 45	1,683	
		7 + 16	1,541	
		7 + 28	1,745	
		8 + 24	1,486	
		8 + 32	2,481	
		10 + 6	1,214	Post Test
		10 + 16	1,733	
Curve II (Balloon)	1.356	4 - 15	1,875	
		4 + 15	1,766	
		8 - 20	1,700	
		8 - 11	2,079	
		8 - 9	1,800	
		8 + 9	2,000	
		8 + 11	2,200	
		8 + 20	2,580	
Tangent I	0.05	4 - 18	1,187	
		4 - 15	1,635	
		4 + 15	1,355	
		6 - 18	1,307	
		6 - 15	1,381	
		6 + 15	1,493	
		6 + 18	1,565	
		8 - 20	1,443	
		8 - 16	1,377	
		8 + 16	1,281	
		8 + 20	1,256	
		12 - 20	1,468	
		12 - 16	1,366	
		12 + 16	1,440	
		12 + 20	1,162	
Tangent II	1.02	5 - 20	1,638	
		5 - 16	1,297	
		5 + 16	1,298	TLPT Zone
		5 + 20	1,182	Discard the Values
		5 + 18	1,195	
		5 + 26	1,556	
		7 - 20	1,565	
		7 - 16	1,609	
		7 + 16	1,461	
		7 + 20	1,518	

* Tie Number: Location Number + Number of Ties, (See Figure 7)

TABLE 2. EQUIVALENT LATERAL RESISTANCE VALUES, F_o

TEST TRACK	CONSOLIDATION LEVELS (MGT)	STPT AVERAGE OF PEAKS	LATERAL RESISTANCE F_o, LB/IN
Curve I	0.15	1,675	64
Curve II	1.37	2,002	77
Tangent I	0.05	1,381	53
Tangent II	1.02	1,600	62

From Table 2, it is seen that for both the curve and the tangent, the ballast consolidation increased the lateral resistance at the rate of 10.7 lb/in. per 1 MGT. However, the two cases do not show equal resistance values at the same levels of consolidation. This is probably due to the differences in the actual levels of consolidation prior to tamping as well as variations in tamping procedures for the tangent and curved tracks. Also, the curved track cribs were fully ballasted, whereas the ballast level in the tangent track was about 2 inches below the tie surface.

5.2.2 Longitudinal Resistance

This is the resistance offered to the rail longitudinal movement by anchors and/or ballast. When idealized as a constant value at all displacement levels, this can be determined from the slope of the function representing the rail force along the track. In Section 7, the test data on distributions of rail force for Curves I and II and Tangents I and II are shown. The computed longitudinal resistance values from the data are shown in Table 3.

The longitudinal resistance values obtained in Phase III are significantly lower than those in the previous tests (1). The low values could be due to the fact that the rail anchors

TABLE 3. LONGITUDINAL RESISTANCE VALUES

TEST	F_o, LONGITUDINAL RESISTANCE
Curve I	26 lb/in
Curve II	20 lb/in
Tangent I	26 lb/in
Tangent II	32 lb/in

were not squeezed tight and a gap of about 1/8 inch remained between anchors and some ties, (the anchoring machine being inoperational at the time of these tests). This condition permitted some relative longitudinal movement between ties and rails, thus reducing the overall longitudinal resistance.

5.2.3 Lateral Misalignments

The lateral misalignments were measured before and after the conduct of each test. In the central zone, permissible misalignments for Class 5 tracks were intentionally set before the commencement of the dynamic buckling tests. The misalignments were measured using a moving and stationary "string line" for the tangent track, and using a "reference rail" in the case of the curve.

Table 4 shows the amplitude of the misalignments at the center prior to rail heating and train operation. The length of misalignment calculated using Equation 3 is also shown in this table. The measured wavelengths are higher than the theoretically calculated values by about 10 to 20 percent.

5.2.4 Vertical Modulus

Vertical track modulus (VTM) was measured using the VTM car which loads rails through hydraulic means. The rail deflection

TABLE 4. AMPLITUDES AND LENGTHS OF INITIAL MISALIGNMENTS

TEST	δ_o (IN)	$2L_o$ (FT)
Curve I	0.55	25.4
Curve II	0.70	25.8
Tangent I	0.88	28.0
Tangent II	0.81	26.6

was measured using a wayside level. A typical load deflection relationship obtained in the tests is shown in Figure 8.

From the load deflection relationships, using Hetenyi's model of beams on elastic foundation, the stiffness is computed. The results ranged from 2,500 to 3,500 psi. The factors contributing to the scatter were:

a. VTM machine was not in proper working order; the load was not distributed equally on the two rails.

b. Tracks were not uniform, and track preparation was not up to the desired quality.

c. A nonlinear analysis would provide better representation of foundation modulus as a function of vertical deflection.

The average value of 2,500 psi obtained in the tests is adopted here for theoretical predictions of Curves I and II and Tangents I and II buckling response.

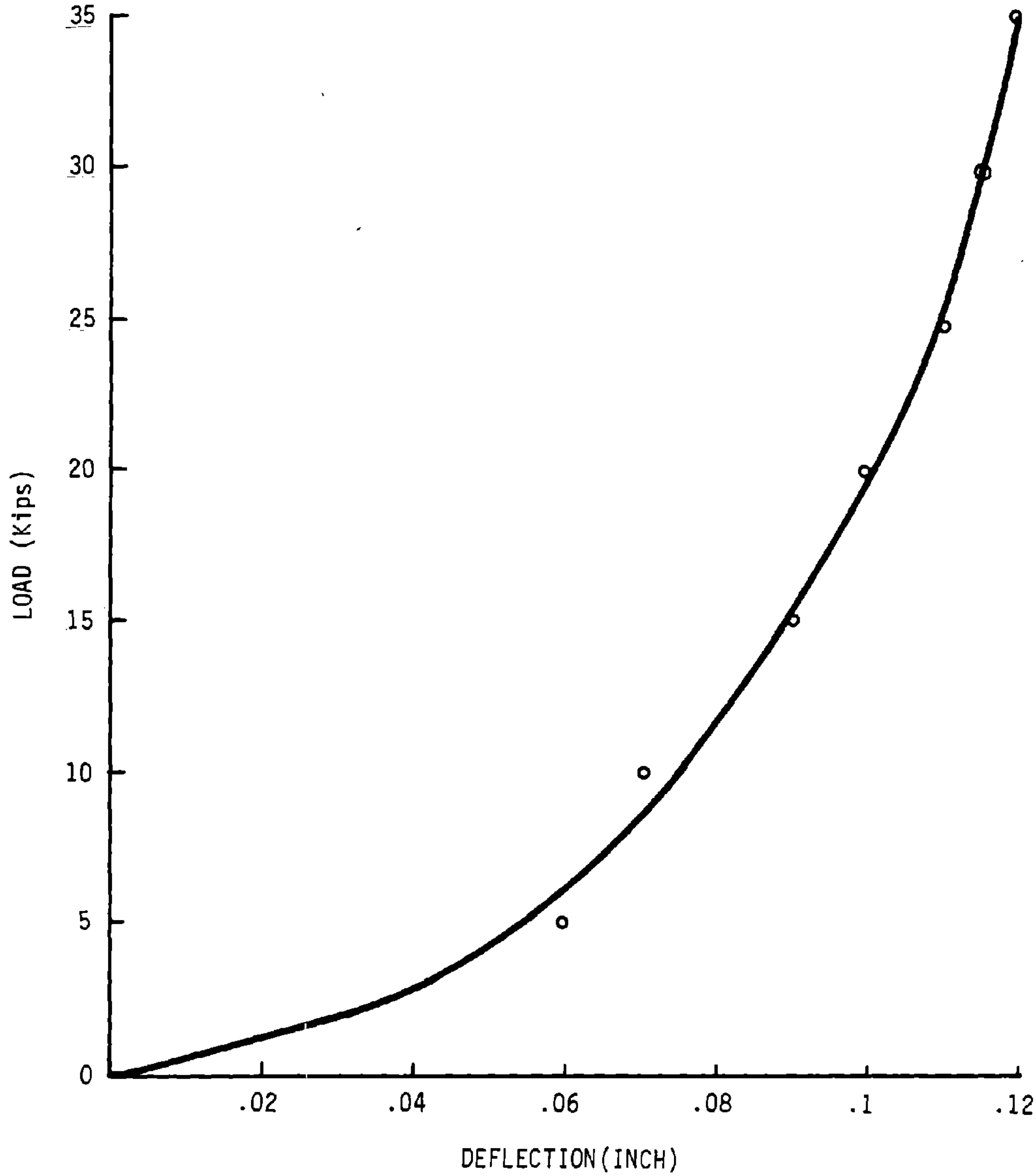

FIGURE 8. LOAD DEFLECTION RELATIONSHIP FOR VERTICAL TRACK MODULUS

5.2.5 Tie-Ballast Friction Coefficient

This parameter was determined using the STPT rig. Lead weights were placed on ties to represent a loaded condition. The friction coefficient μ is calculated using the formula

$$\mu = \frac{(\text{Loaded resistance - Unloaded Resistance})}{\text{load}}$$

Significant amount of scatter in the results ranging from 0.5 to 1 was found. Possible drawbacks of the test were:

a. Same tie was used for both loaded and unloaded resistance.

b. Peak values occurring at small displacements of the Single Tie Push Tests were used in the resistance calculation; the "constant leveled" values of resistance at large displacements (1 to 2 inches) would have been appropriate for this calculation, but these were not measured.

An average value of 0.7 has been used for the purpose of theoretical predictions.

6. TEST CONDUCT

The test conduct for the major tests (Curves I and II, and Tangents I and II) will be described in this section.

The track preparation was carried out prior to the test conduct, according to the requirements in the test definition and plan document (6). However, the test sites were not in the FAST loop as originally planned; the curved track tests were carried out on the 5-degree curve in the balloon loop, and the tangent tests were on the TTT (Transit Test Track). Figure 9 shows the locations of these sites at TTC, Pueblo.

As in Phase II tests, the heated test zone was about 1,000 ft. The end sections beyond the heated zone were longitudinally stiffened up with every tie anchored.

Rail heating was provided using the same two substations employed in the previous tests.

The rails were instrumented as per the instrumentation deployment, Figure 7, and de-stressed to provide zero references for the strain gauges. The de-stressing operation consisted of cutting the rails, removing anchors and allowing rails to move freely in the longitudinal direction, and finally welding them at the desired neutral temperature. The neutral temperature results will be presented in Section 7.

After the rail de-stressing, track characterization - which included measurement of track lateral resistance (using Single Tie Push Tests and Track Lateral Pull Tests) and other parameters described in Section 5 - was carried out. Specified misalignments were set in the central zone.

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SITE DESCRIPTION

- 136RE CWR rail
- 7" x 9" x 8'6" wood ties
- Cut spikes
- 14" AREA 'A' punch plates
- Channel type anchors every tie boxed
- Recently tamped slag ballast
- 12"-15" shoulders
- Curved site: 5 degree curve with 3 inches of superelevation and 0.5% grade
- Tangent site: 1.5% grade

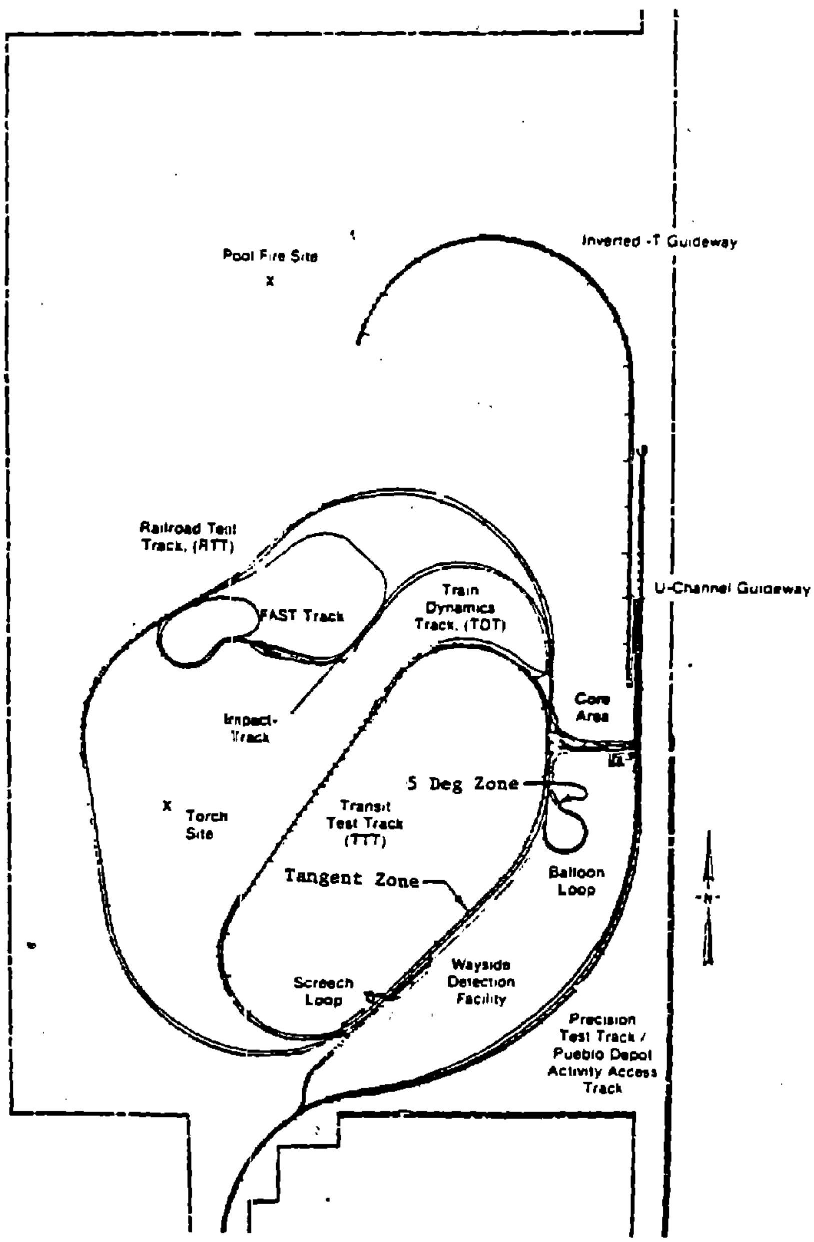


FIGURE 9. SITE LOCATION

6.1 DYNAMIC BUCKLING TESTS

An initial imperfection permissible as per Class 5 alignment standards was intentionally set at the center of test track.

A long consist was used in the dynamic buckling tests. The number of vehicles in the consist varied with the tests, the minimum number being 42, which include a mix of hopper and tank cars and three locomotives. The rail heating was done incrementally, and the current was shut off when the train passed through the test zone. The maximum speed was limited either by the permissible speed for Class 5 tracks or whatever could be achieved in the tests. For the curved track, the maximum speed achieved was 40 mph, the permissible speed being 43 mph. For Tangent I, the speed was restricted to 20 mph. All the passes on Curve I, II and Tangent I were made using a manned locomotive in the consist. For Tangent II, the locomotives in the test consist were operated remotely by a manned locomotive on an adjacent unheated parallel track. The maximum speed reached was 55 mph, although the permissible speed for Class 5 tracks is 80 mph for freight train operations.

The maximum rail temperature reached was equal to or greater than the theoretical allowable (determined for the particular track parameters using the dynamic buckling theory (2)). The growth in the lateral misalignment, the rail longitudinal forces, the vertical and lateral forces generated at the misalignment as the consist negotiated the imperfection, and the rail temperatures were closely monitored during the tests and the track stability under the traffic assessed.

6.2 BRAKING TESTS

This test was performed after the dynamic buckling test without track renewal. For this, the consist size was reduced to ten vehicles which included three locomotives. The consist entered the test zone at about 40 mph when the rail temperature was at its theoretical allowable, and service brake application of 12 psi reduction in brake pipe pressure, were applied such that the locomotive could stop just in front of the central imperfection. A second braking test was also performed, which was similar to the first one, except the brakes were applied when the locomotives were passing over the misalignments.

The growth in misalignment amplitude and the rail force increment due to the braking action were monitored in this test.

6.3 HUNTING TESTS

Hunting tests were performed on the tangent track. A hunting vehicle with worn wheels was included in the ten-car consist. The consist made passes at the hunting speed (63 mph determined experimentally before the start of tests), when the rail temperature was at its allowable value. The resulting L/V and the track lateral misalignments were some of the key parameters monitored during this test.

7. TEST RESULTS AND ANALYSES

The test matrix, results, and analyses for each of the major tests (Curves I and II and Tangents I and II) will be presented here.

7.1 CURVE I DYNAMIC BUCKLING RESPONSE

The test matrix is shown in Table 5. The initial runs were made with 63 cars and 3 locomotives in the consist. Some of the cars were later removed for mechanical reasons, and subsequent runs on Curve I had only 42 cars and the 3 locomotives. The maximum speed permissible for the curve was 43 mph, which was nearly achieved in the test.

7.1.1 Temperature Distribution

The temperature distribution in the two rails was not quite uniform. The difference between the two rails was under $5^{o}F$, and the variation from the center to the end in each rail was also about $5^{o}F$. The temperatures quoted under ΔT_{expt} column are the average values of the rail temperature increases (over the neutral temperature) at the center. The temperatures under ΔT_t column are the theoretical equivalent temperature increases corresponding to the rail force. This would have been the precise temperature rise required to develop the same rail force in an infinitely long track uniformly heated. This temperature is appropriate and conservative for use in the safety limits. The theoretical equivalent temperatures are always lower than the actual values observed in the test. The difference is attributed to inadequate restraints at the ends of the test zone.

TABLE 5. CURVE I TEST MATRIX

RUN NUMBER	SPEED MPH	RAIL FORCE KIPS/RAIL	ΔT_t	ΔT_{expt}	L/V	δ_o IN	NUMBER OF CARS	LOCOMOTIVE POSITION (BACK OR FRONT)	UP OR DOWN HILL
1									
a	15	24.5	10	10	-	0.55	63	B	U
b	40	30.9	12	15	-	0.50	63	F	D
2									
a	15	47.8	18.5	20	-	0.48	63	B	U
b	40	54.2	21	25	-	0.48	63	F	D
3									
a	15	80.5	31	35	-	0.47	63	B	U
b	40	85.5	33	40	-	0.47	63	F	D
4									
a	15	103.5	40	45	0.46	0.48	63	B	U
b	40	103.8	40	50	0.36	0.48	63	F	D
5									
a	20	129.3	50	55	0.48	0.48	63	B	U
b	40	125.9	48.8	55	0.30	0.50	63	F	D
6									
a	20	158	61.2	65	0.47	0.53	63	B	U
b	40	149.8	58	65	0.25	0.52	63	F	D
c	20	156.8	60.8	65	0.19	0.49	42	B	D
7									
a	20	175	67.8	75	0.23	0.54	63	B	D
b	20	172	66.6	70	0.35	0.52	42	F	U
c	20	179	69.4	75	0.39	0.52	42	B	D
d	40	179.5	69.5	70	0.42	0.54	42	F	U

7.1.2 Rail Force Distribution

The rail force distribution was uneven due to longitudinal movement at the ends of test zone. (stiffness" was not sufficiently high due to the lc longitudinal resistance as discussed in subsectioı Figure 10 shows the distribution of the longitudiı the two rails at $\Delta T = 55^{O}F$, before the final run. two rails were not subjected to equal levels of fc values quoted in Table 5 are the averages for the the center. The average force is appropriate to ι buckling is largely controlled by the total force rails.

7.1.3 L/V Ratio

The peak values of wheel L/V (lateral/vertical vehicle negotiated the lateral misalignment at the shown in Table 5. In the final run at 40 mph, the carrying its maximum compressive force, the peak I and this did not result in any significant increme lateral deflection. A portion of the strip-chart the final run is shown in Figure 11.

7.1.4 Analyses

The theoretical dynamic response (temperature deflection) is shown in Figure 12. The theoretica temperature according to the safety criteria prese Section 3, would be $70.3^{O}F$ above the neutral tempe seen in Table 5, the temperature rise in the test $70^{O}F$. The initial misalignment amplitude of 0.55 not increase with the train passes. In fact, Tabl indicates that the misalignment was stabilized, wi tendency to change with further passes at this ter Hence, $70^{O}F$ rise could be considered as allowable particular conditions of the track and train. Alt degree of conservatism in this allowable limit cou determined in the experiment, the limiting tempera dynamic buckling temperature $T_{B,dyn}$; hence, there

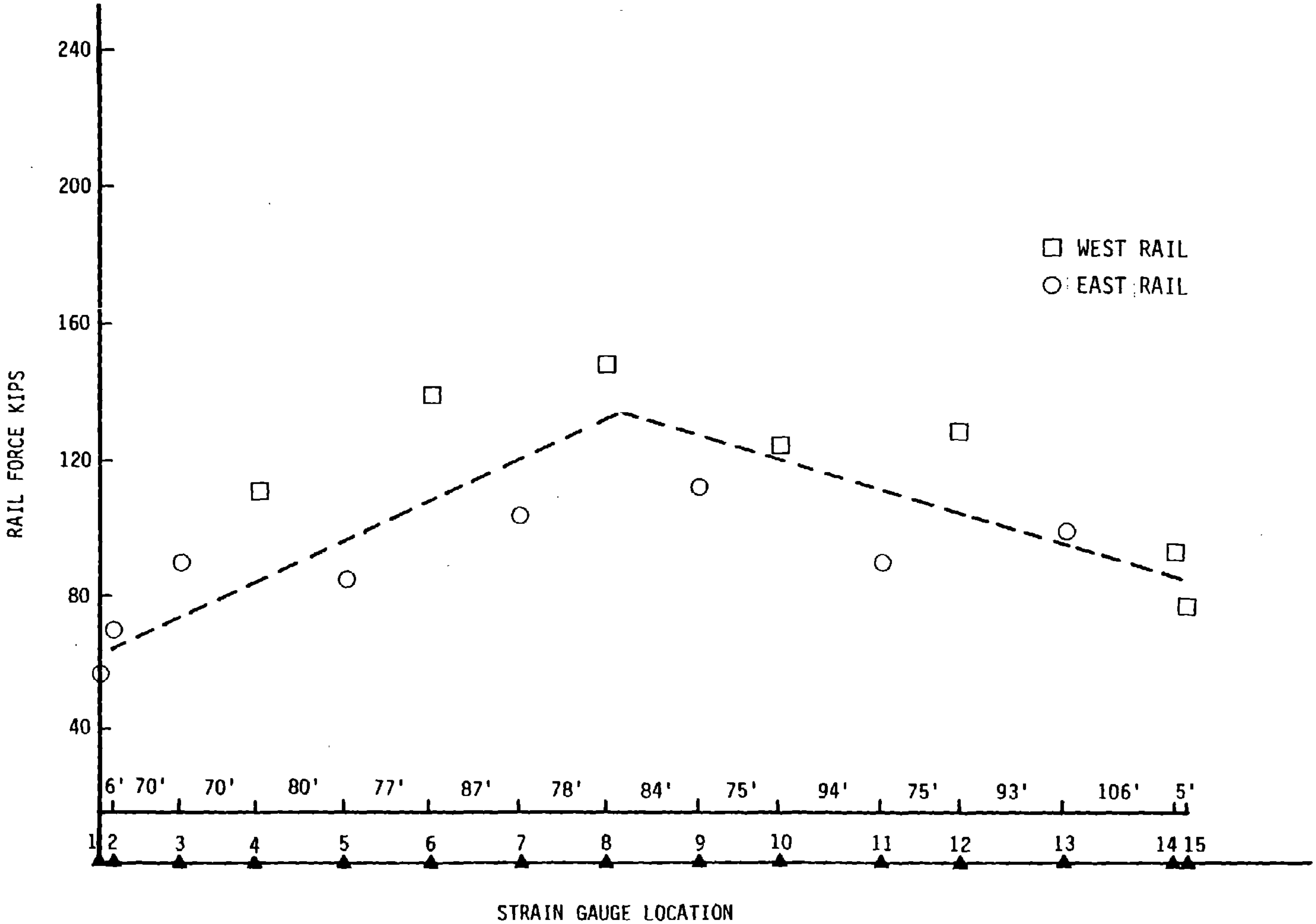


FIGURE 10. RAIL FORCE DISTRIBUTION (CURVE I)

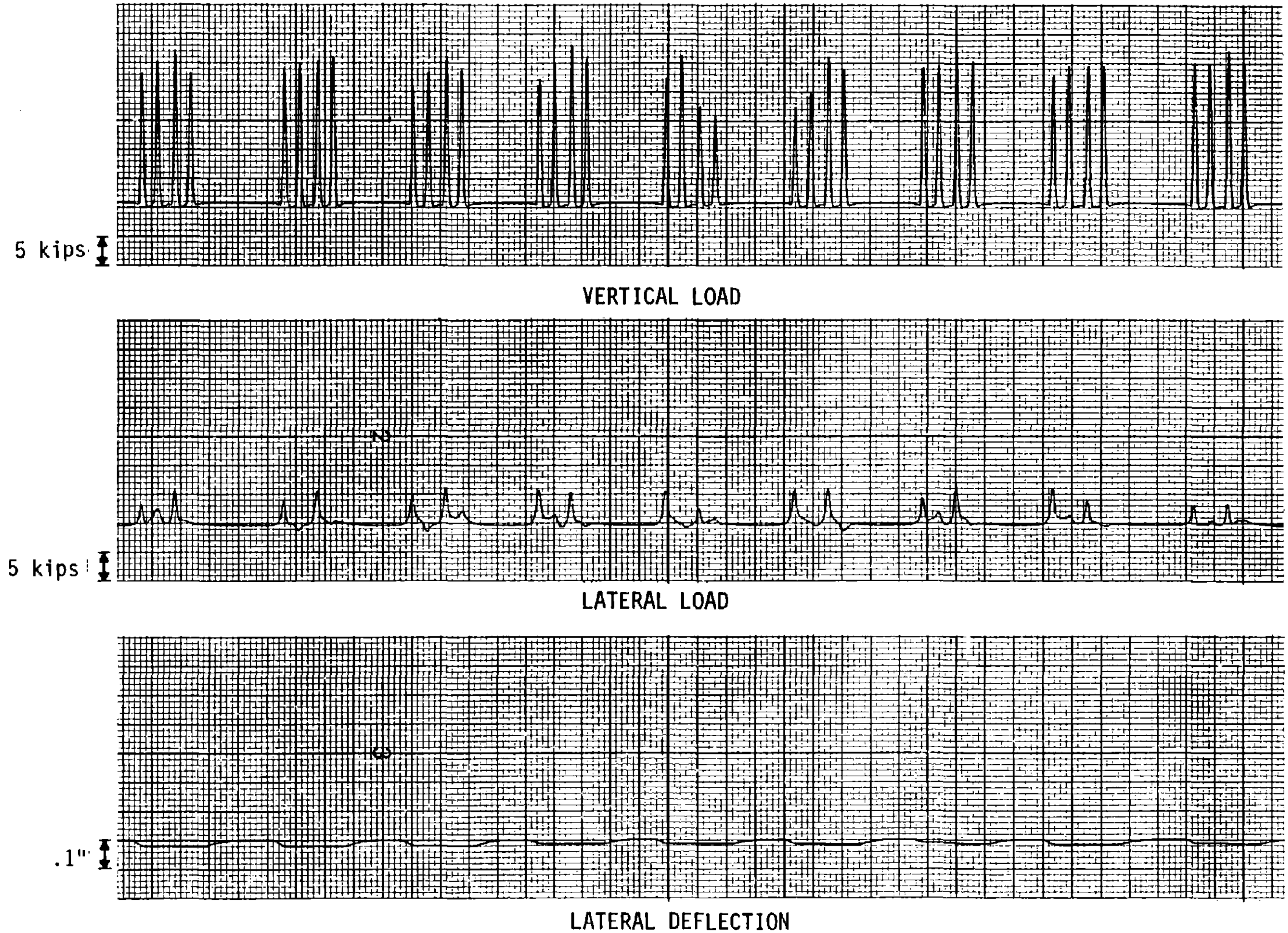


FIGURE 11. STRIP CHART RECORD FOR CURVE I

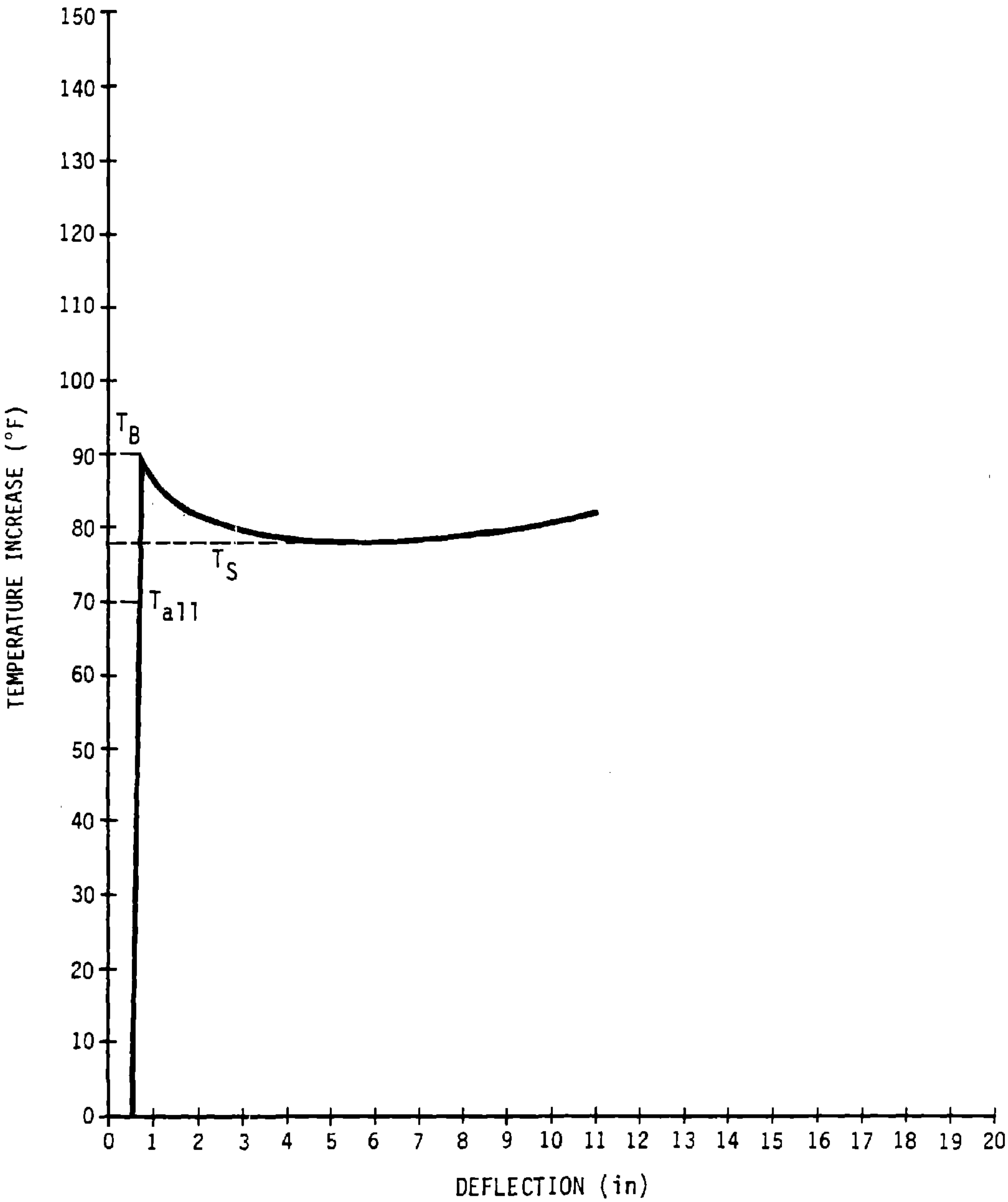


FIGURE 12. THEORETICAL DYNAMIC RESPONSE BEHAVIOR FOR CURVE I TRACK CONDITION

than a $20^{o}F$ conservatism, which happened to be the margin of safety in this problem.

From the strip-chart records in Figure 11, it can be seen that the lateral deflection increment oscillated with the passage of each car in the final run. The displacement increment in this oscillation was almost zero, when the misalignment was between two adjacent cars, and reached the peak value of 0.02 inches when it was between the trucks of a car. This phenomenon, which was also observed in Phase II tests, supports the theory that the central bending uplift wave is a principal cause of track dynamic buckling behavior.

The oscillatory behavior of lateral displacement is not considered to be serious from the buckling point of view because it did not leave significant residual deflections.

Although the misalignment became stabilized readily with the train passes, a contributing factor for this could be the passes made at speeds below the balance speed for the curve (30 mph) which might have exerted lateral forces that could reduce the misalignment. Regardless of the low-speed runs, it can be concluded that Curve I test results partially validated the safety criteria presented in Section 3.

7.2 CURVE II DYNAMIC BUCKLING RESPONSE

The test matrix for Curve II, with higher consolidation level, is shown in Table 6. A total of seven passes were made in the uphill direction. Because the imperfection did not seem to have stabilized in the test, the final runs (Runs No. 6 and 7) at high compressive load levels were made at lower speeds (20 mph) to reduce potential damage to the track and vehicles in case of any buckling occurrence.

TABLE 6. CURVE II TEST MATRIX

RUN NUMBER	SPEED MPH	RAIL FORCE KIPS/RAIL	ΔT_t	ΔT_{expt}	L/V	δ_o IN	NUMBER OF CARS	LOCOMOTIVE POSITION (BACK OR FRONT)	UP OR DOWN HILL
1	40	101	39	45	0.33	0.5	43	F	U
2	40	165	64	70	0.32	0.55	43	F	U
3	40	176	68	75	0.5	0.58	43	F	U
4	40	148	56	70	0.5	0.7	52	F	U
5	40	170	66	83	0.59	0.75	52	F	U
6	20	186	72	88	0.46	0.79	52	B	U
7	20	205	79.5	96	0.54	0.84	52	F	U

7.2.1 Temperature Distribution

For the first three runs, there was a difference of about $10^{o}F$ between the end and central thermocouples. The two central thermocouples on each rail differed by about 2 to $3^{o}F$. For the subsequent runs, which were performed on the following day, the instrumentation system had to be reset because of some initial malfunction. The discrepancy between the equivalent theoretical ΔT_t corresponding to the force and the actual temperature data became larger, as seen in Table 6. This was most likely due to changes in the effective rail neutral temperature caused by rail longitudinal movement.

7.2.2 Rail Force Distribution

Typical rail force distribution in Curve II at $\Delta T = 84^{o}F$ is shown in Figure 13. The force distribution was nonuniform due to the same reasons explained earlier for Curve I.

7.2.3 L/V Ratio

The peak L/V ratios in each run are shown in Table 6. The values are slightly higher than those obtained for Curve I. A portion of the strip-chart record for the final run is shown in Figure 14.

7.2.4 Analyses

The theoretical response is shown in Figure 15. The allowable temperature increase according to the safety criterion under consideration (Section 3) equals the "dynamic safe" temperature which is about $75.7^{o}F$ over the neutral temperature. The force at the allowable temperature is about 196 kips. The actual peak force reached in the test was 205 kips. The initial misalignment amplitude of 0.5 inches grew to 0.84 inches due to the limited train passes.

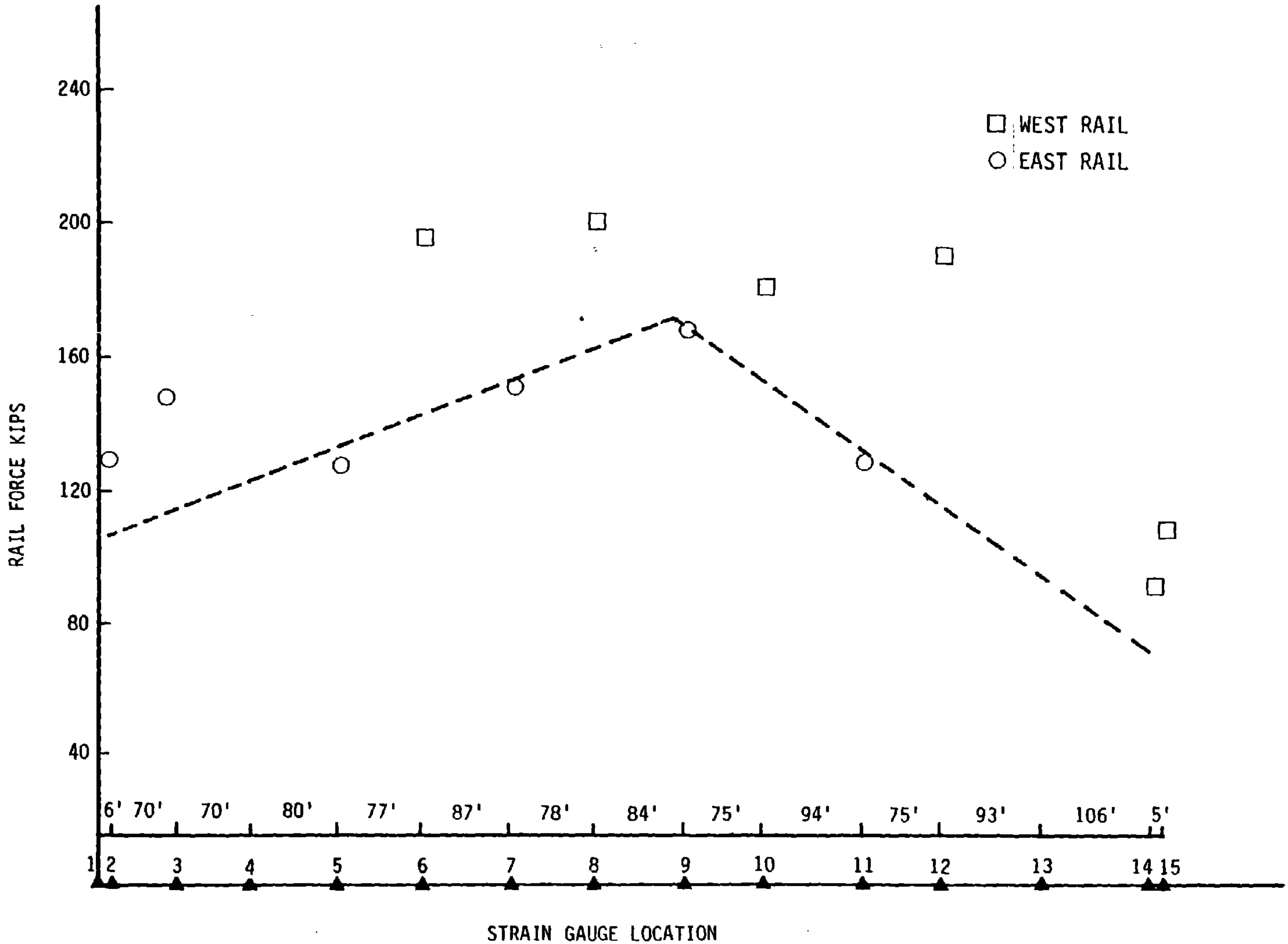


FIGURE 13. RAIL FORCE DISTRIBUTION (CURVE II)

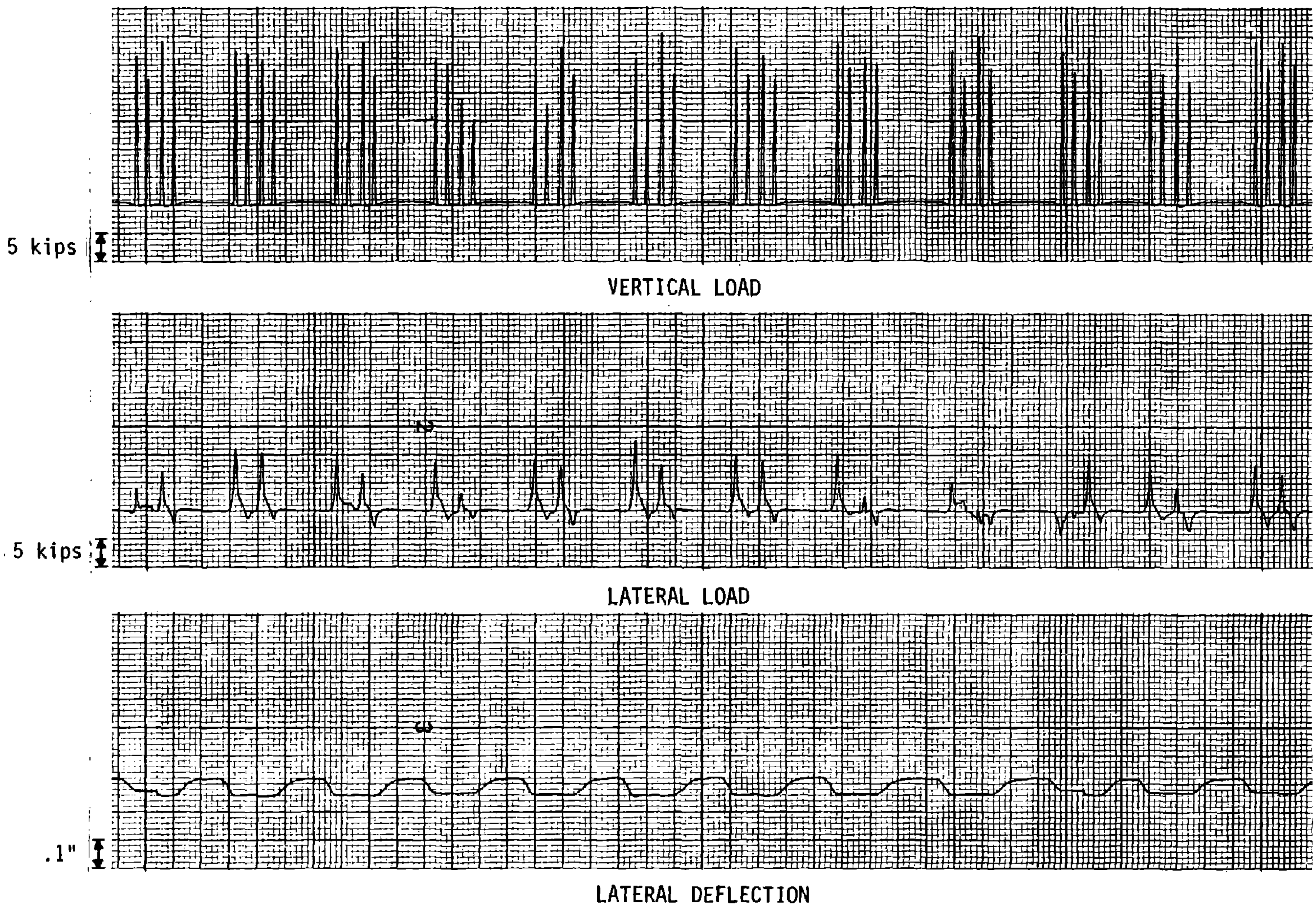


FIGURE 14. STRIP CHART RECORD FOR CURVE II

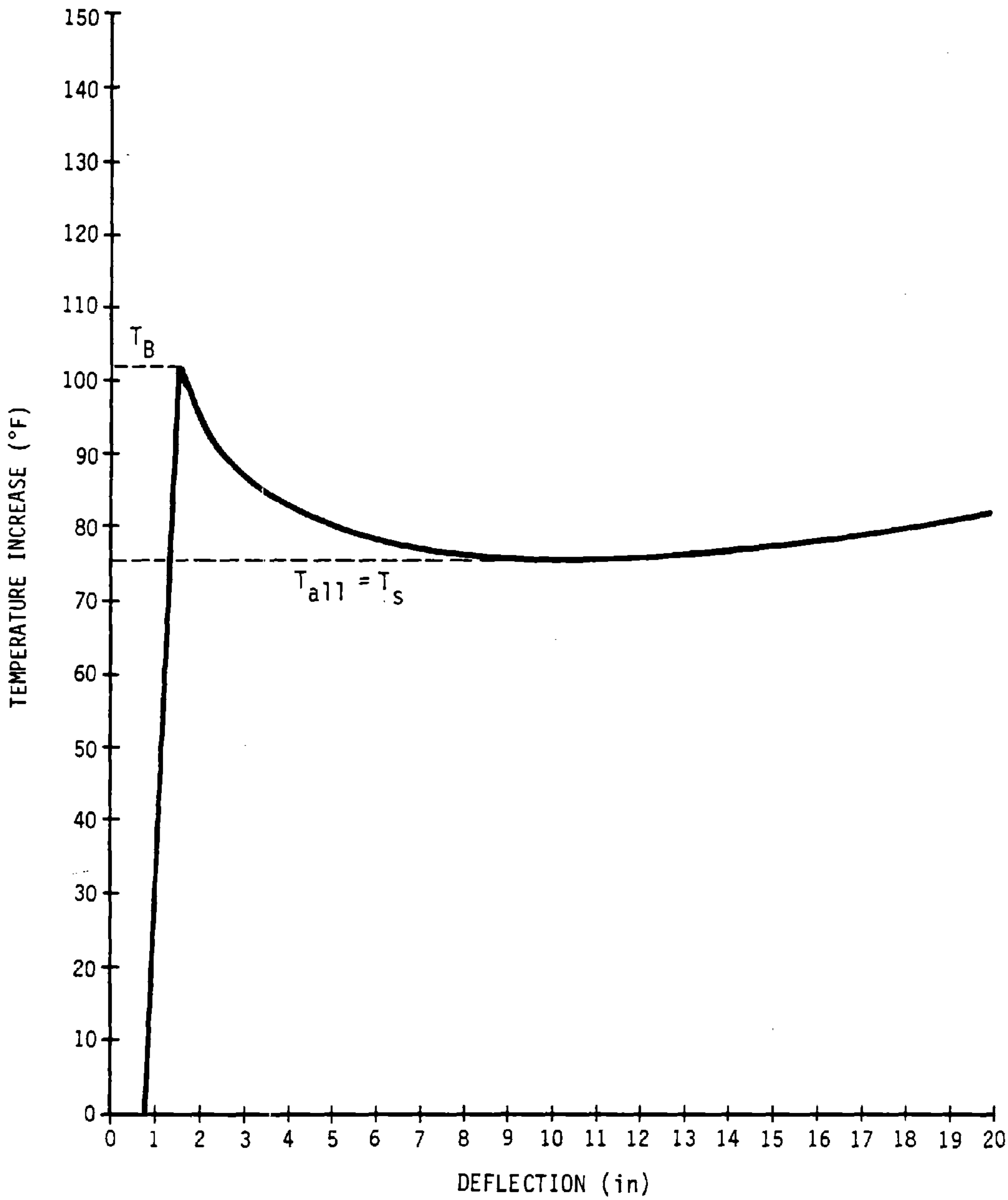


FIGURE 15. THEORETICAL DYNAMIC RESPONSE BEHAVIOR FOR CURVE II TRACK CONDITION

The increment of 0.05 inches misalignment for each pass is considered to be significant. Clearly the misalignment was not stabilized to the same extent as it was in Curve I. Furthermore, there was a significant oscillatory behavior of the track in the lateral plane with the passage of each car. This can be seen from the strip chart record (Figure 14) taken during the test. The amplitude of oscillation was about 0.06 inches, which was about three times the value observed for Curve I. Despite the foregoing factors, the track performance appeared to be adequate for the limited amount of traffic at the maximum temperature increase. Unfortunately, it is not possible to conclude that the track would sustain safe operation, under additional passes, particularly at the maximum allowable speeds (43 mph). Note that the final two runs in the test were performed at low speed (20 mph).

It should also be pointed out that a Track Lateral Pull Test (TLPT) was conducted at the center of Curve II prior to the commencement of dynamic buckling tests, for the purpose of measuring the track lateral resistance. This could have weakened the central zone, making the effective resistance less than the value used in the theoretical calculation of the allowable temperature.

7.3 TANGENT I DYNAMIC BUCKLING RESPONSE

The test matrix for Tangent I is shown in Table 7. Although the permissible speed for Class 5 tangent is 80 mph for freight trains, the speed was restricted to 20 mph in all the runs due to the strict order imposed by the TTC administration, whose reasoning was that a buckle under the tangent could not be foreseen, and the risk associated with buckling of CWR track under a manned locomotive was great.

7.3.1 Temperature Distribution

The temperature distribution in the rails was reasonably uniform. The two rails differed by no more than about four

TABLE 7. TANGENT I TEST MATRIX

RUN NUMBER	SPEED MPH	RAIL FORCE KIPS/RAIL	ΔT_t	ΔT_{expt}	L/V	δ_o IN	NUMBER OF CARS	LOCOMOTIVE POSITION (BACK OR FRONT)	UP OR DOWN HILL
1	20	157	60.8	67	0.41	0.88	58	B	D
2	20	182	70.5	78	0.31	0.89	48	F	U
3	20	208	80.6	90	0.30	0.91	48	F	U
4	20	207	80.2	91.5	0.30	0.91	48	B	D
5	20	228	88.3	99	0.28	0.94	48	F	U
6	20	222	86	97	0.23	0.95	48	B	D
7	20	239	92.6	103.5	0.35	0.98	48	F	U
8	20	237	91.8	105.5	0.29	0.99	48	B	D

degrees at the center. The rail temperature at the end: not significantly differ from the values at the center. However, the theoretical equivalent temperature ΔT_t di: from the experimental ΔT_{expt}, (Table 7) significantly rail force values. Apart from the inadequate end restr to low longitudinal resistance, another contributing fa this situation could be the insertion of new joints in rails after de-stressing operations. This was required the insulated joints needed replacement and redesign as could not withstand the high voltage of the rails and w arcing in the preliminary rail heating test, performed rail de-stressing operations.

7.3.2 Rail Force Distribution

The distribution of rail compressive forces is show Figure 16 for $\Delta T_{expt} = 105.5^{o}F$. The two rails did not equal forces. There was a difference of about 40 kips the two rails, at the central location. As in curved t tests, the distribution was "triangular," a significant of force loss occurring at the ends of the test zone due longitudinal resistance of the track within and outside test zone.

7.3.3 L/V Ratio

The L/V ratio measured in the tangent track test was 0.3, as seen in Table 7. The L/V values are small, due low speeds of the vehicle consist. A typical strip-char record of lateral and vertical forces in Tangent I is sh Figure 17.

7.3.4 Analyses

The theoretical response is shown in Figure 18. The theoretical allowable temperature increase, according to criterion described in Section 2, is about $72.5^{o}F$ (187 kips/rail). The maximum force reached in the test 239 kips/rail, corresponding to an equivalent theoretica temperature increase of $92.6^{o}F$. The misalignment amplit

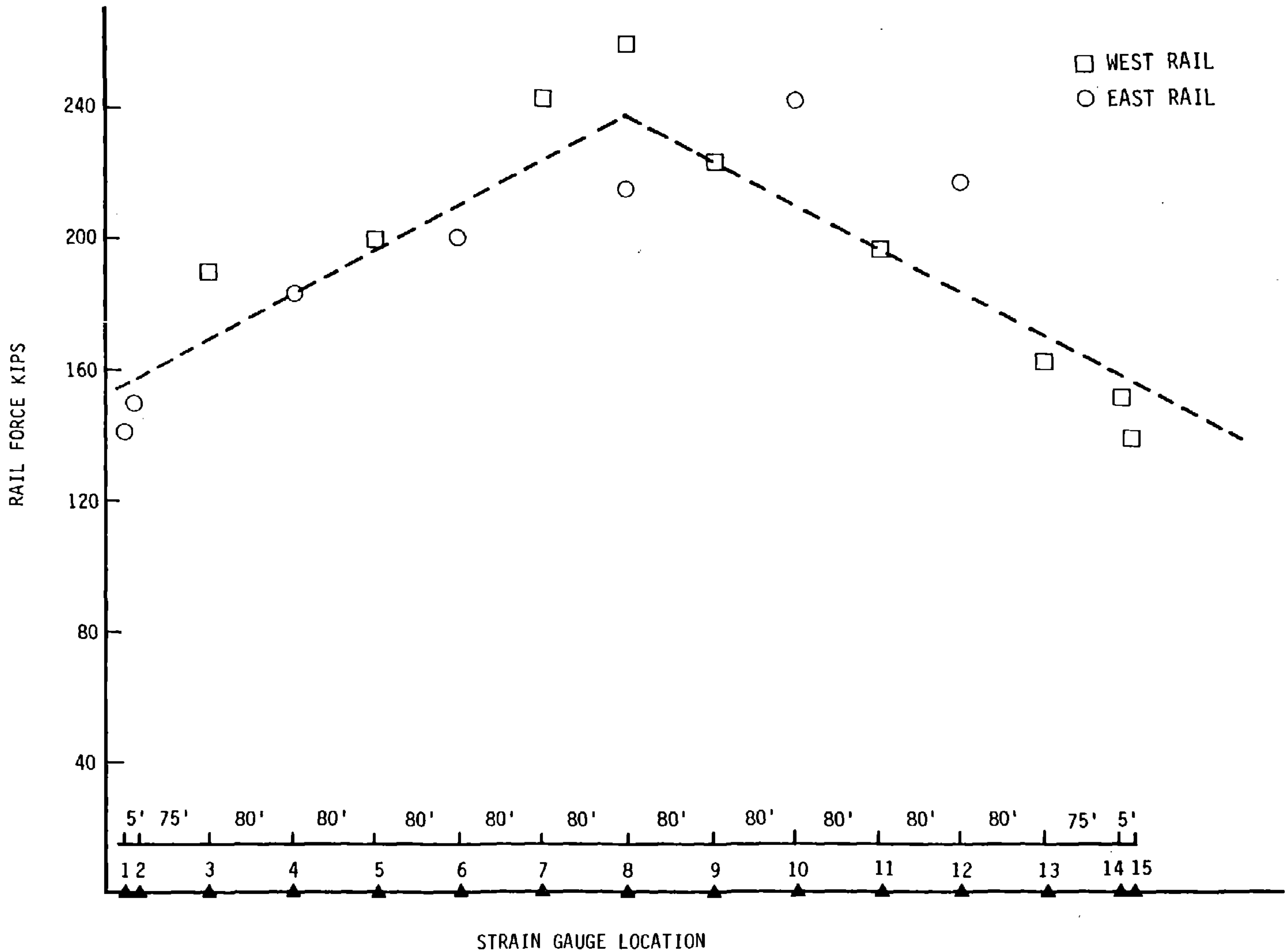


FIGURE 16. RAIL FORCE DISTRIBUTION (TANGENT I)

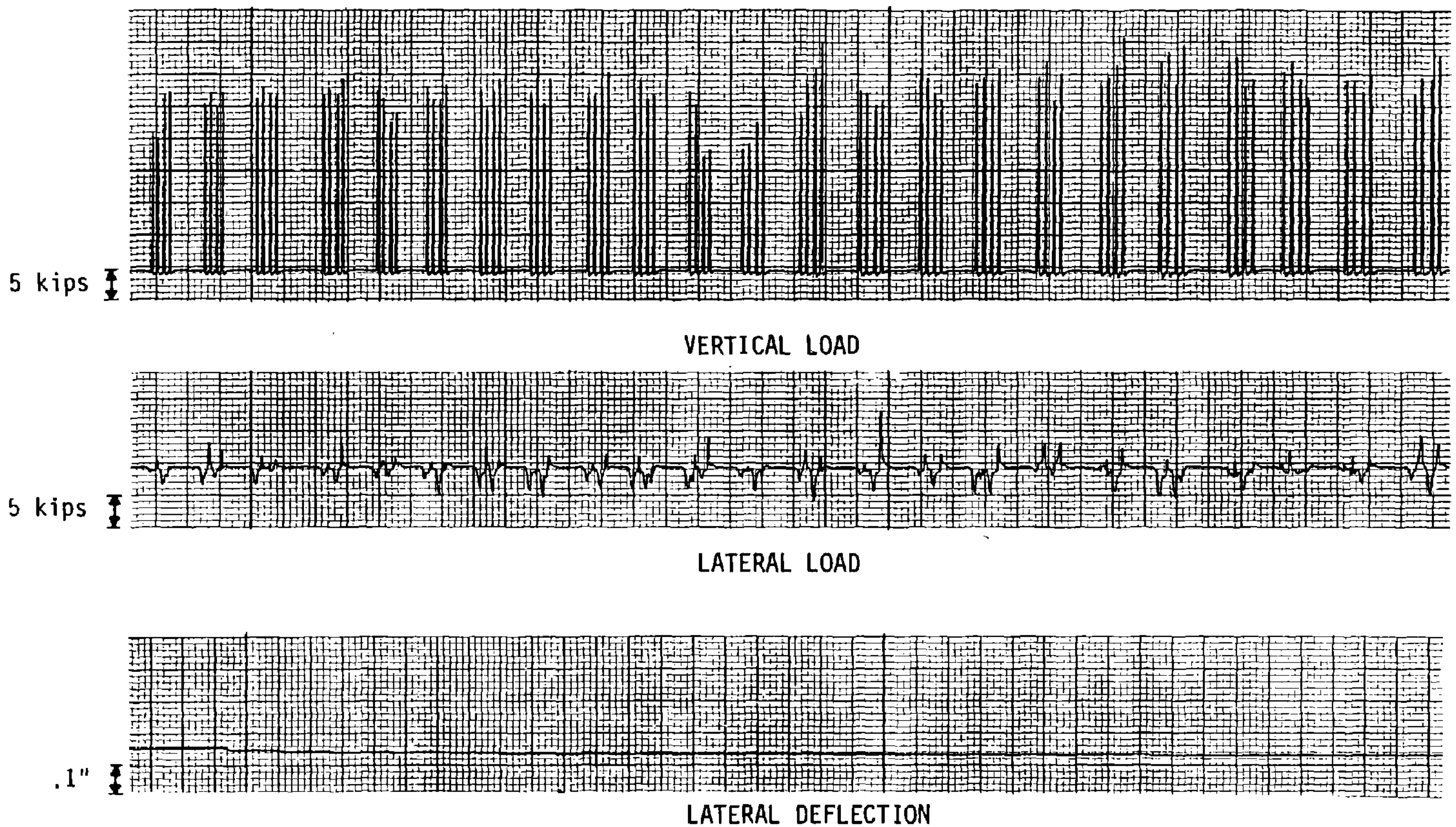


FIGURE 17. STRIP CHART RECORD FOR TANGENT I

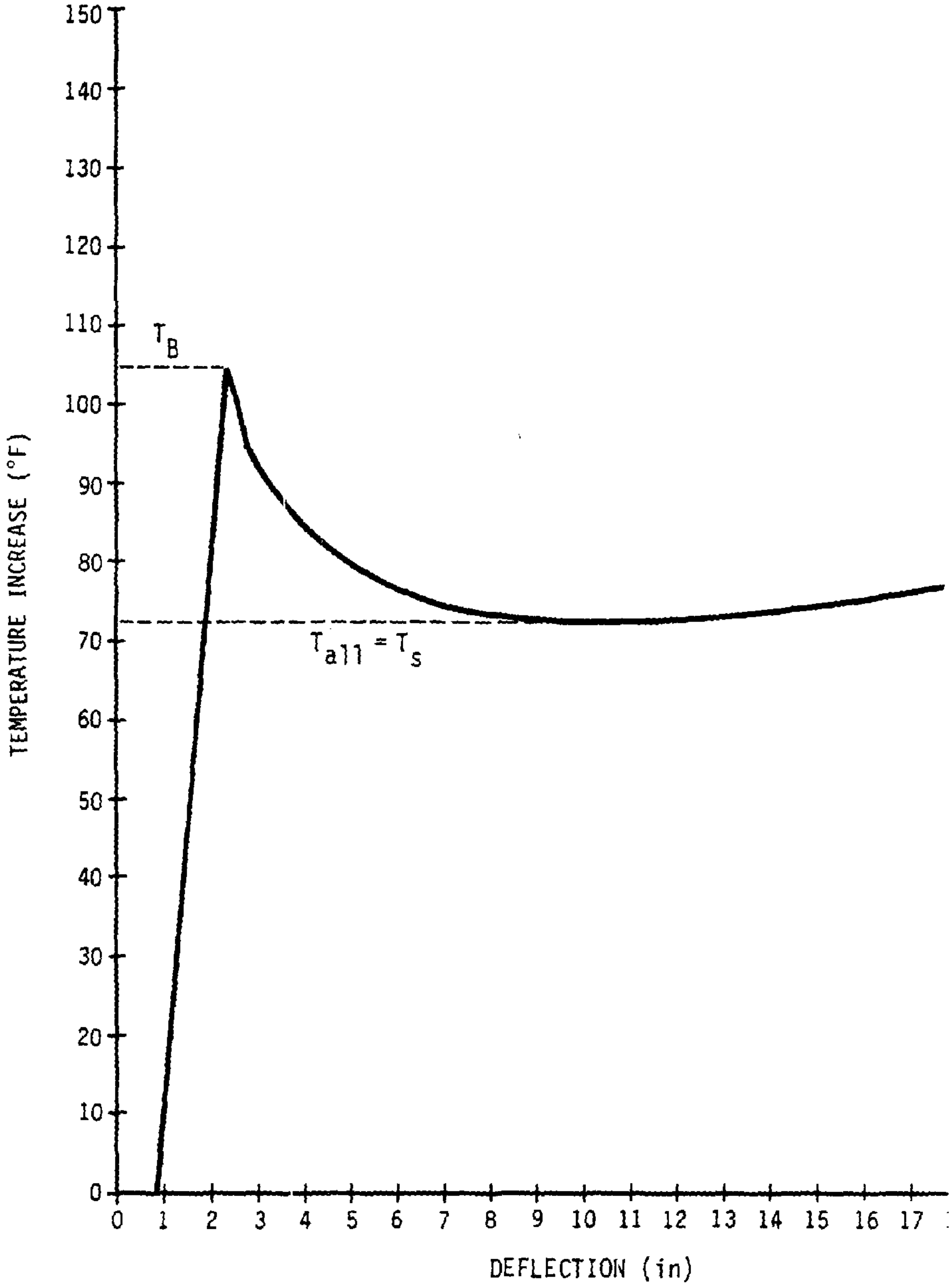


FIGURE 18. THEORETICAL DYNAMIC BUCKLING RESPONS
FOR TANGENT I TRACK CONDITION

grew from 0.88 to 0.99 inches at the end of all runs. growth was only about 0.01 inches at the allowable temperature. The track could therefore be considered t(a stable condition under traffic at the allowable tempe:

It should be stated that complete verification of tl safety limits described in Section 3 was not accomplish(to the lack of high-speed runs at the allowable tempera(However, the additional low-speed passes in the test at rail temperature higher than the allowable might compen: some extent for the required high-speed runs at the all(temperature.

Note that there was a margin of safety of about 10°I at the peak temperature reached in the test. Hence, no significant lateral track movement took place under the amount of traffic at this temperature, even though the temperature was about 20°F higher than the theoretical allowable. It can be concluded that Tangent I tests pr(partial verification of the safety criteria presented ir Section 3.

7.4 TANGENT II DYNAMIC BUCKLING RESPONSE

The test matrix for Tangent II is shown in Table 8. maximum speed reached in the test, using remote-controll locomotives was about 55 mph (the permissible for Class tangent is 80 mph for freight trains according to curren regulations).

7.4.1 Temperature Distribution

The temperature distribution was reasonably uniform difference between the end and central locations was und 5°F). The theoretical equivalent temperature rise is lo than the temperature in the test by about 15 percent at rail force of 259 kips/rail. This was due to inadequate restraint, as in the earlier tests.

TABLE 8. TANGENT II TEST MATRIX

RUN NUMBER	SPEED MPH	RAIL FORCE KIPS/RAIL	ΔT_t	ΔT_{expt}	L/V	δ_o IN	NUMBER OF CARS	LOCOMOTIVE POSITION (BACK OR FRONT)	UP OR DOWN HILL
1	38	181	70	76	0.52	0.81	67	F	D
2	40	196	76	85	0.53	0.83	67	F	D
3									
a	50	213	83	94	0.49	0.86	67	F	D
b	52	211	82	91	0.55	0.87	67	F	D
c	55	221	85	98	0.53	0.78	67	F	D
4	50	246	95	108	0.55	0.79	67	F	D
5									
a	31	259	100	115	0.48	0.81	67	F	D
b	50	259	100	115	0.65	0.82	67	F	D

7.4.2 Rail Force Distribution

The distribution of rail compressive force is shown Figure 19 for ΔT_{expt} = 94°F before Run 3a. As in the T test, there was a difference of about 47 kips between t rails at the central location, and the distribution was "triangular" for the same reasons explained in the earl analyses.

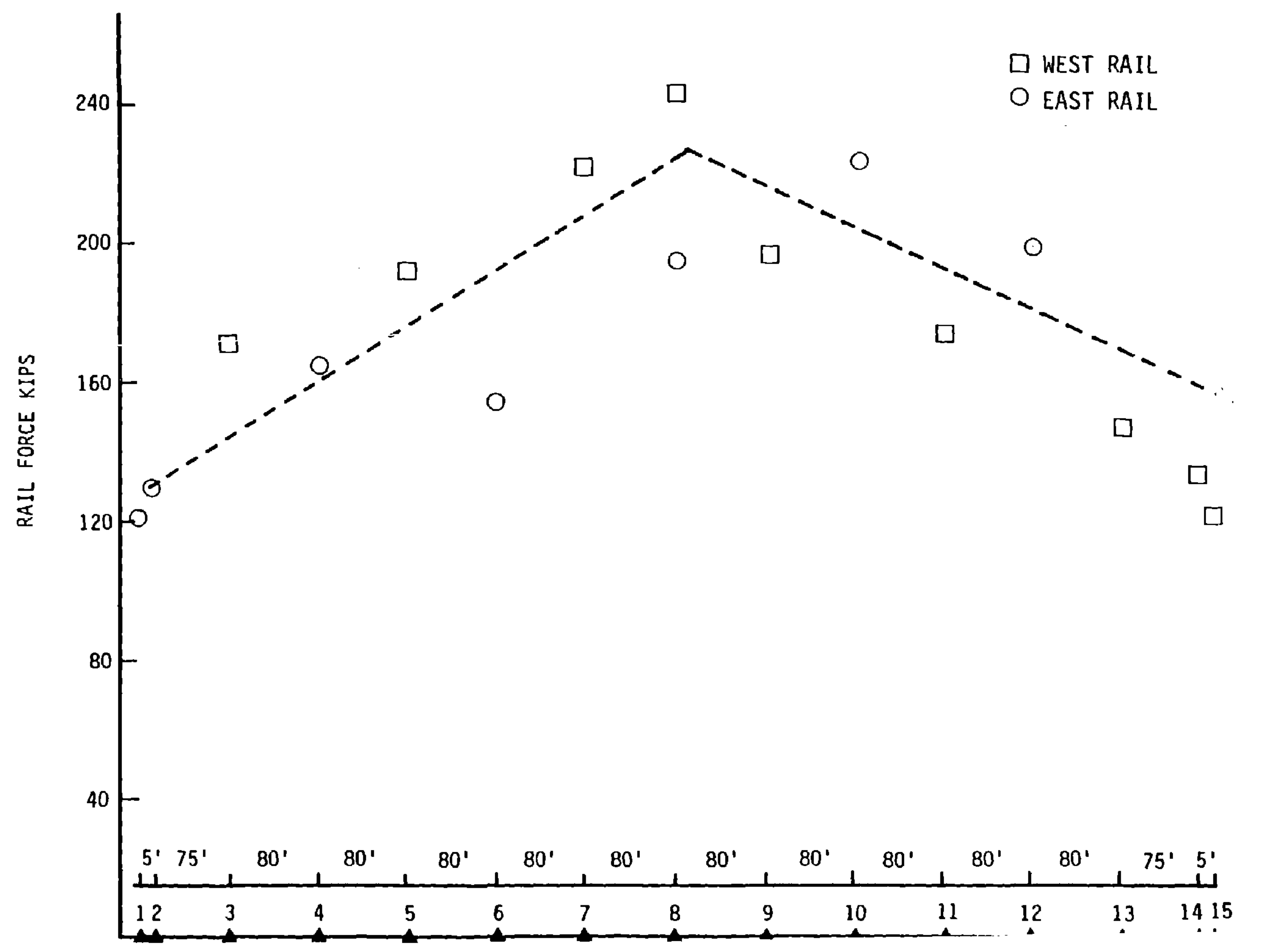
7.4.3 L/V Ratio

A typical strip-chart record of lateral and vertica generated as the consist negotiated the lateral imperfe shown in Figure 20. The L/V ratios are much greater th observed for the Tangent I. This is due to higher spee the consist in the Tangent II test. The L/V are also g than those recorded for Curves I and II. In fact, the in Tangent II (0.65) was the largest value in all the te

7.4.4 Analyses

The theoretical response is shown in Figure 21. The theoretical allowable temperature increase according to criterion presented in Section 3, is 79°F, with the corresponding rail force being 204 kips/rail. In the te maximum force reached was 259 kips/rail, the theoretical equivalent temperature being 100°F. The misalignment gr 0.05 inches after the first three passes and thereafter appeared to be stable under subsequent runs. The subsec runs were made on the following day, which allowed the r cool off overnight to some temperature lower than the ne temperature.

As in Tangent I, the permissible speed for Class 5 t (i.e., 80 mph for freight trains) was not reached in the Tangent II tests. However, the additional passes made a temperature higher than the allowable might have compens for the high-speed runs to some extent. Note that even highest temperature reached in the test, there was a



WEST RAIL
EAST RAIL
RAIL FORCE KIPS
240
200
160
120
80
40
5' 75' 80' 80' 80' 80' 80' 80' 80' 80' 80' 80' 75' 5'
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

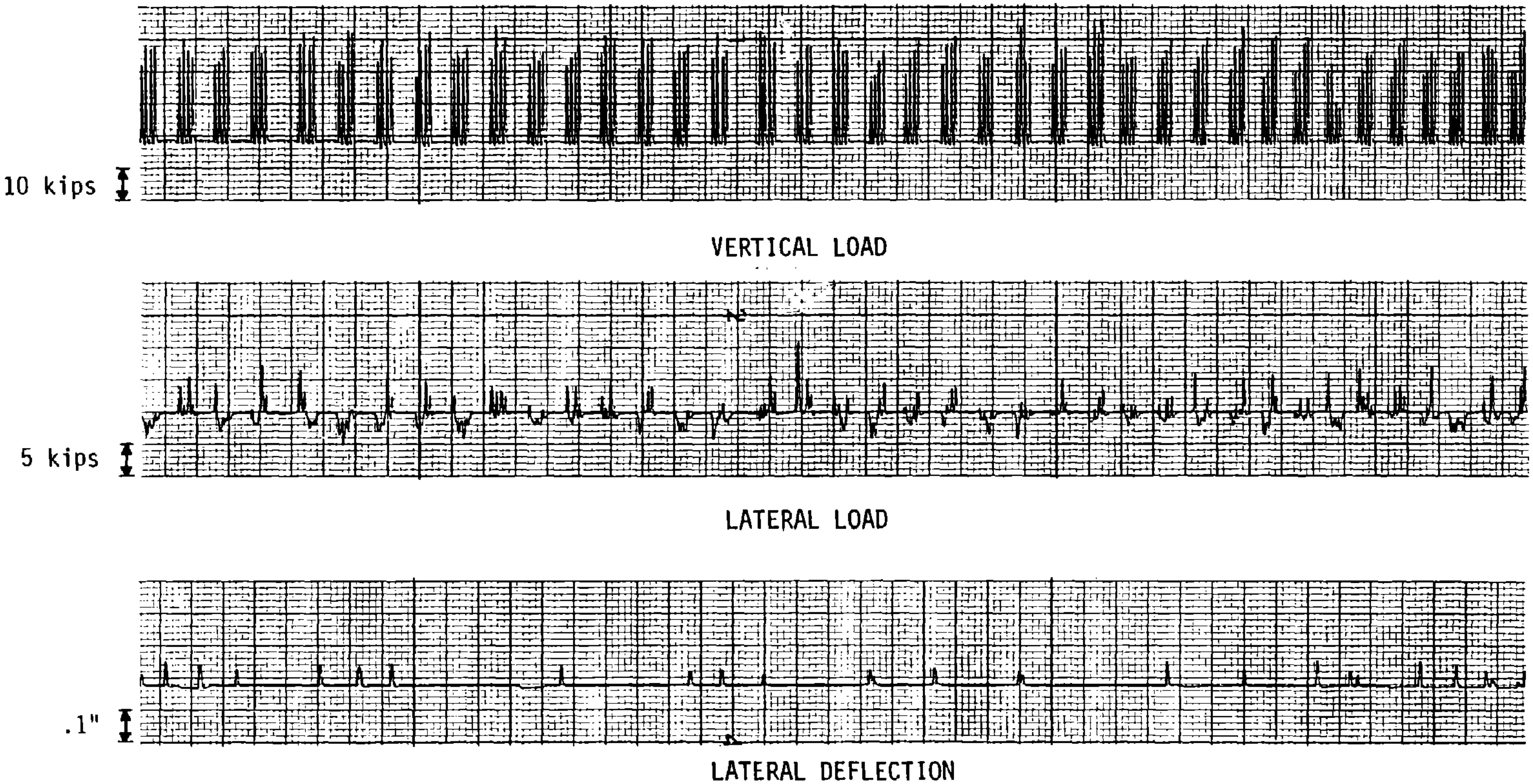


FIGURE 20. STRIP CHART RECORD FOR TANGENT II

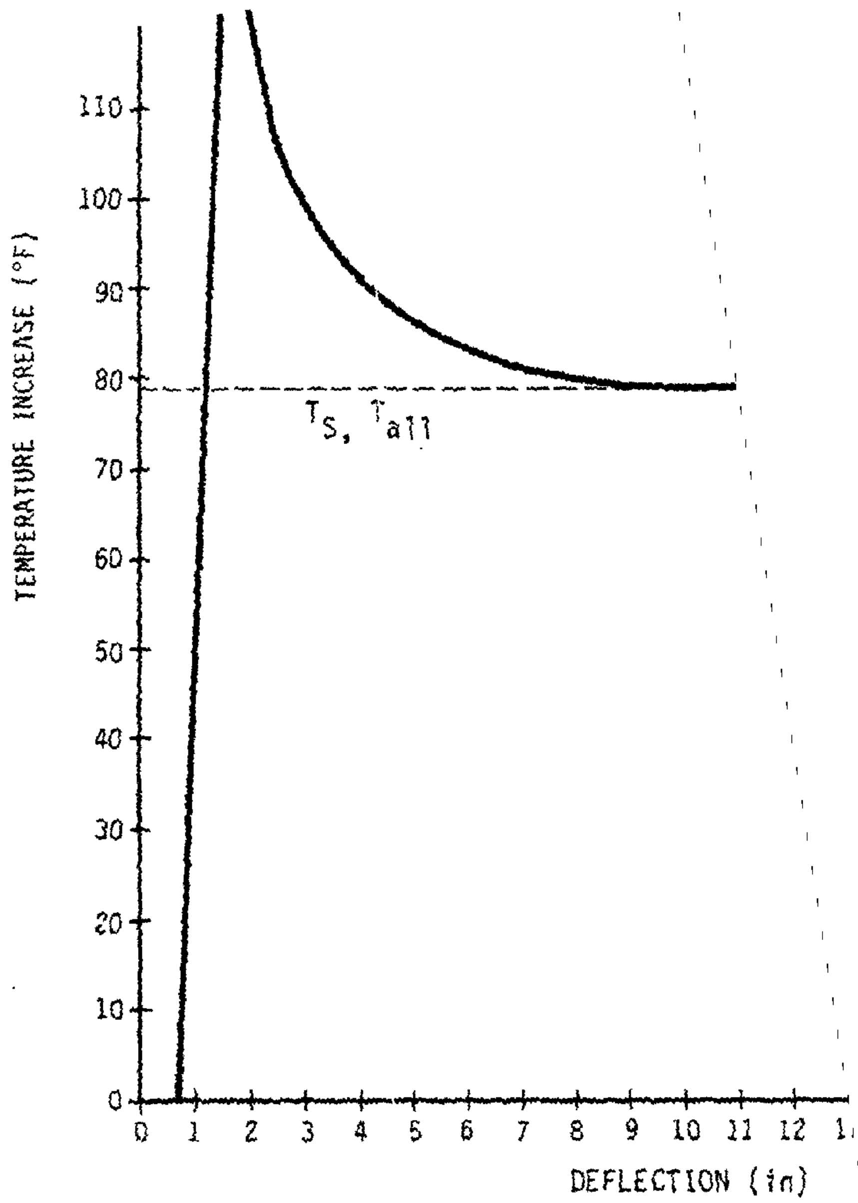


FIGURE 21. THEORETICAL DYNAMIC BUCKLI
FOR TANGENT II TRACK CON

theoretical margin of safety of 34°F against buckling. It can be concluded that the track was stable at the allowable temperature increase under the limited amount of traffic simulated, and the safety criteria presented in Section 3 was partially validated.

7.5 BRAKING TESTS

Braking tests on Curves I and II resulted in an increase in the compressive force of about 5 kips in each of the rails in front of the consist. A corresponding decrease in the force in the rails behind the consist was also observed. The train braking action resulted in an increase of the lateral misalignment amplitude by 0.02 inches for both Curve I and II tests.

In the case of Tangent I and II tests, the braking action produced peak shifts in the rail force of about 10 kips. However, there was no corresponding increment in the lateral misalignment amplitude.

Although full braking action (e.g., emergency brakes) was not simulated, the test results are indicative that the tracks can withstand loads due to vehicle braking in addition to the thermal loads at the allowable temperature increase. The additional compressive force generated is within the margin of safety of 20°F (50 kips) proposed in the safety criteria (Section 3).

7.6 HUNTING TESTS

The truck hunting tests were performed on Tangent II. The hunting vehicle was an empty hopper car with worn wheels, situated at the end of the consist. The hunting speed was 63 mph. The strip-chart recording (Figure 22) showed no significantly large lateral force due to hunting. There was also no change in the amplitude of the initial lateral misalignment.

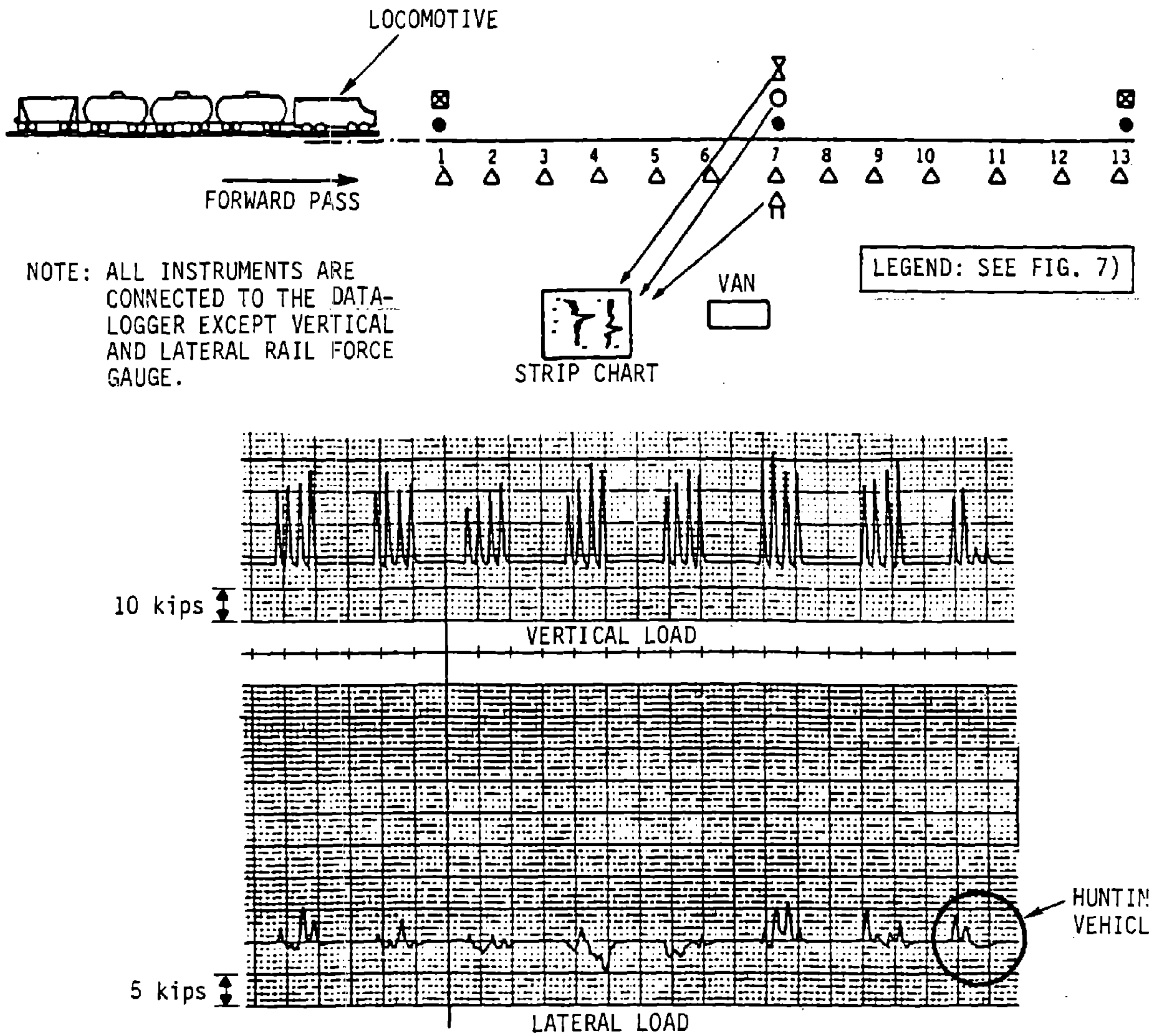


FIGURE 22. INSTRUMENTATION ARRANGEMENT AND RESULTS FOR TRUCK HUNTING EFFECT ON TRACK DYNAMIC STABILITY

To obtain the full effect of hunting, several hunting cars should have been used in the test, increasing the probability of inducing a large lateral force at the center of the lateral misalignment.

The tests carried out are not adequate to firmly conclude that hunting has any significant influence on CWR track buckling.

8. CONCLUSIONS

The following conclusions are drawn from the results of the four major tests presented in the previous section.

a. The dynamic theory (2) gives a reasonable indication of the CWR dynamic buckling strength when subjected to vehicle traffic and thermal loads. The theory can be used as a basis for the development of safety limits for use in the industry.

b. The CWR track buckling safety criteria under current development along the lines presented in Section 3 have been partially validated for the limited traffic and the maximum speeds achievable in the tests.

c. The speed of the consist operated by a manned locomotive in Tangent I was restricted to 20 mph for operator safety. In the Tangent II test, the remote controlled locomotive permitted a higher speed (55 mph). Although this speed is still lower than the maximum possible speed of freight trains on Class 5 track (80 mph), several runs were sucessfully made on the tangent tracks at temperatures higher than the theoretical allowables. The peak wheel (L/V) recorded was 0.65, but this did not contribute to any significant lateral shift of the tangent track. It may be concluded that the tangent tracks can withstand thermal loads and limited train operations at the allowable rail temperature increase.

d. For the curved tracks, all the runs were made essentially at or below the theoretical allowable temperature. However, unlike the tangent track tests, there was an oscillatory behavior of the lateral displacement of the curve, particularly in the Curve II test. For Curve II, the misalignment growth did not seem to have stabilized under traffic even in the final run at the allowable temperature. (The final run was made at 20 mph - well below the permissible speed of 43 mph.) It was doubtful whether the track could have withstood an additional number of passes by the consist at the permissible speed without producing a significant increase in the lateral misalignment or a buckle. For the 5-degree curve, the safety criteria presented in Section 3 may not, therefore, be conservative and will require further experimental investigation under a number of train passes.

e. The train braking action can generate a compressive force on the order of 10 kips in each rail. The minimum margin of safety of 20°F adopted in the safety criteria presented in Section 3 appears to provide adequate compensation for the additional compressive forces due to braking loads.

f. The truck hunting effect on the stability of tangent tracks could not be determined in the Phase III test program.

8.1 RECOMMENDATIONS

a. In the track safety assessments, a clear distinction must be drawn between safety under limited traffic (fractional MGT or number of passes) and the safety under "unlimited" traffic. With increase in the number of train passes, the lateral misalignment tends to grow, but the lateral resistance increases. At the rail allowable temperature, the misalignment should stabilize at a finite number of passes without further growth and buckling potential. The number of passes required for stabilization, or the maximum number of permissible passes (in terms of traffic tonnage) for a preset allowable growth of misalignment amplitude should be determined.

b. There are several parameters required in the theoretical predictions using the dynamic buckling theory. There is a significant scatter in some of the parameters (such as coefficient of friction, vertical track modulus). A lower or upper bound that leads to conservative estimates of the theoretical allowable temperature must be determined for typical tracks for use in the safety limits data generation.

c. The longitudinal resistance measured in Phase III tests was unrealistically low. This resulted in a low end stiffness and nonuniform compressive force buildup. Proper anchoring and more effective end stiffening should be used in future tests.

APPENDIX A
PHOTO ILLUSTRATIONS

(These are copies of original photographs taken by TTC staff during the tests.)

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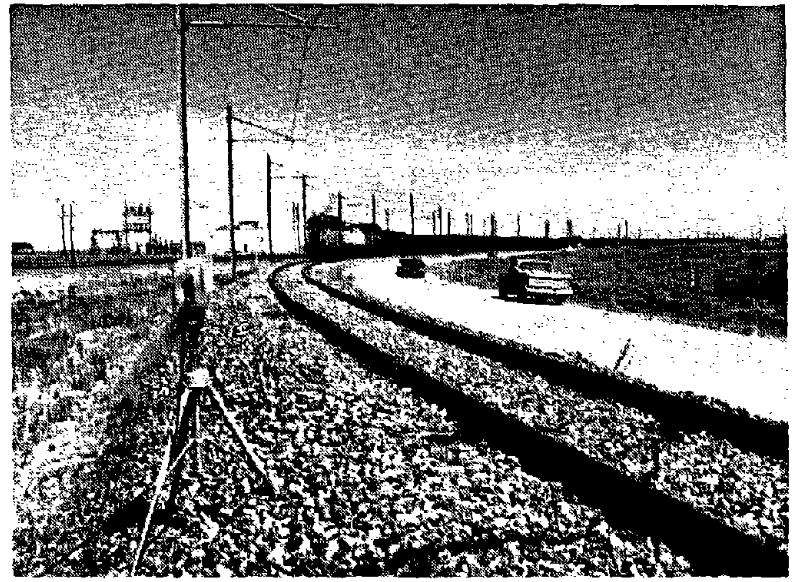
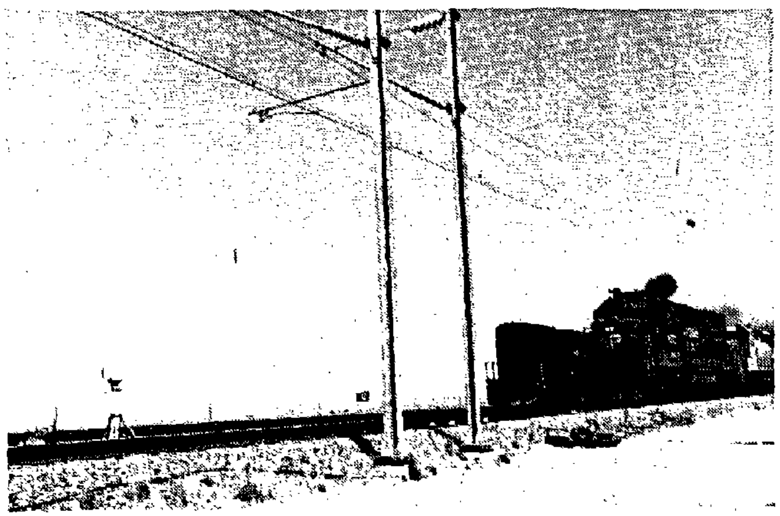
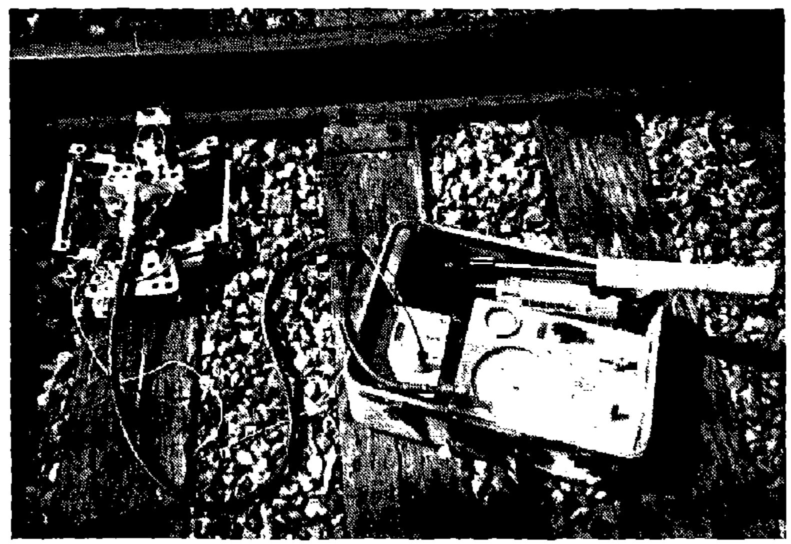
1) TANGENT TRACK WITH STIFFENED ENDS



2) CURVED TRACK SITE



3) BUCKLING TEST USING REMOTE-CONTROLLED LOCOMOTIVES



4) SINGLE TIE PUSH TEST DEVICE

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