# Continuous Welded Rail Track Buckling Safety Assurance Through Field Measurements of Track Resistance and Rail Force

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Techniques and hardware for field measurement of two important continuous welded rail (CWR) track parameters for safety from buckling—the track lateral resistance and the rail neutral temperature—are presented. It is shown here that by controlling the two parameters above their respective permissible minimum values, CWR track buckling safety can be ensured. For the measurement of lateral resistance, a lightweight, portable device that tests the ties individually has been developed. Field data collected using the single-tie push test revealed that the scatter is within permissible limits if the data for three randomly selected ties in a 50-ft section of CWR are averaged. The data have also shown that the ties exhibit a softening resistance characteristic, a feature that has been ignored or not detected in work by other researchers. Rail neutral temperature can be measured using the principle that the vertical deflection of a rail beam freed from ties is measurably sensitive to the longitudinal rail force when a vertical load is applied to the rail section. On the basis of that principle a rail uplift device (RUD) that gives the absolute rail force without site-specific calibration has been developed. The rail force test data from RUD are in agreement with the theoretical predictions.

The Transportation Systems Center (TSC) provides technical support to FRA in the development of performance-based safety guidelines and specifications for continuous welded rail (CWR) track. A major problem with CWR track is lateral buckling under high thermal and vehicle loads. TSC recently completed a major analytical, experimental, and safety assessment study, which is discussed by the authors in another paper in this Record. The limitations of existing theories are discussed, and an advanced model that runs on a personal computer (TSC dynamic buckling model) and accounts for vehicle loads, nonlinearity in the lateral resistance, and all other significant parameters is described. Results from controlled full-scale buckling tests (*1–3*) that used artificial heating and moving train consists are also reported. The tests validated the theoretical model (*4*) and safety concepts and limits.

On the basis of the TSC computer model, and on the knowledge of two parameters (track lateral resistance and rail neutral temperature), it is now possible to assess the in situ buckling strength of CWR track for an improved assurance of safety from buckling.

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Recent developments in the concepts, methodology, and hardware for the measurement of track resistance and rail longitudinal force (neutral temperature), and their applicability to CWR track buckling safety assurance are described in this paper.

## BUCKLING SAFETY ASSESSMENT

The TSC dynamic buckling model can predict upper and lower buckling temperatures for given input data. The data can be divided into (a) primary inputs: rail size, car parameters (truck center spacing and wheel loads), track curvature, misalignments, and lateral resistance, and (b) secondary inputs: longitudinal resistance, track modulus, and tie-ballast friction coefficient. The primary input data have significant influence on track buckling response and therefore must be accurately known.

A lightweight, portable device has been developed that can be used to determine the lateral resistance of the track, the most difficult of the five primary inputs for the track engineer to estimate. This hardware and the associated test methodology can be used to determine the complete nonlinear resistance. Tie motion of only a fraction of an inch allows determination of the peak value. To determine the complete nonlinear response, ties may be displaced to larger deflections, or the response may be determined empirically, on the basis of correlation with existing field test data. The importance of the complete nonlinear resistance for buckling predictions is discussed by the authors in another paper in this Record.

Once the lateral resistance in the field and the critical buckling temperatures from the TSC model have been determined, the safety criterion to be applied is as follows.

For safe operations of CWR tracks with regard to buckling, the allowable temperature increase ($\Delta T_a$) should be greater than the difference between the maximum rail temperature ($T_M$) and the neutral or the force-free temperature ($T_N$).

$$\Delta T_a > T_M - T_N \quad (1)$$

$T_M$ depends on the ambient conditions for which data are generally available. $T_N$ is not necessarily the installation temperature. The neutral temperature can change substantially from its original value at installation because of several mechanisms discussed later. Its value must be upgraded each time track operations such as destressing, reanchoring, and lining are performed. Hardware and procedures, described later, have also been developed to determine the rail neutral temperature in the field. This method gives the absolute rail force and does not involve any specific site-dependent calibration and rail cutting.

Thus, Equation 1 can be used for buckling safety assessment once values for $\Delta T_a$ and $T_N$ are known. Among the primary parameters governing $\Delta T_a$, for the most commonly used wood-tie track with cut spike construction, the ballast lateral resistance is the only variable that generally can be controlled by the track engineer. Hence, in revenue service conditions, $\Delta T_a$ is essentially controlled by the lateral resistance. A minimum value for $\Delta T_a$ can therefore be ensured by stipulating a minimum permissible value for the resistance. Likewise, if a minimum value for $T_N$ is also stipulated, Equation 1 will be satisfied for all values of resistance and the neutral temperature above the respective permissible values. The track can be rapidly tested for the two permissible values through the use of available equipment. A go or no-go criterion can be used for buckling safety. If the lateral resistance is below the critical value, ballast can be added, or the existing ballast can be consolidated by traffic or other means. Likewise, if the neutral temperature falls below the critical value stipulated, rail destressing can be performed. A slow order should be imposed on trains until the track attains the minimum stipulated values. The minimum required lateral resistance and neutral temperature values can be made available to the track supervisor in the form of simple charts or graphs.

## LATERAL RESISTANCE

Track lateral resistance has been measured by a number of researchers in the United States and abroad. The currently recommended measurement scheme mobilizes a single tie; some previous techniques require lateral movement of a cut panel or the entire track section by a concentrated lateral load. In the case in which a single tie is mobilized, the resistance is directly represented by the load-deflection response of the tie, whereas in the case of the panel, the load-deflection response is a combined effect of rail flexural rigidity, rail longitudinal force, and nonuniform resistance offered by several ties. The panel deflection response is not directly usable as an input parameter in the buckling analysis, which requires individual tie resistance data. In past buckling investigations, single-tie push tests (STPTs) were not favored for the lateral resistance measurement because of the scatter, or variations, in the individual tie resistance values.

The advantages of the STPT over the panel test are

- STPTs yield a more fundamental characteristic of the ballast resistance;
- The test is easy to set up and perform;
- The hardware is portable and can be used by track crew with minimal training;
- If a discrete panel is used, rail cutting is destructive; and
- For the continuous panel, the data are substantially skewed by rail longitudinal forces that influence the deflection response.

The disadvantage of the STPT is the variation of results from tie to tie. However, an arithmetic average of the individual test results is adequate to determine the buckling and safe allowable temperatures from the safety limit charts currently under consideration. It will be shown in this paper that for a 50-ft section of CWR track, three randomly selected ties are adequate to yield a resistance value that can predict the lower buckling temperatures within 10°F.

### Test Hardware

Although STPTs were performed many years ago in the United States and abroad, they were restricted to very small tie displacements and did not cover the "softening" portion of the resistance characteristic. Further, the equipment used was bulky and not suitable for generation of a large data base. A new, lightweight, portable device with an X-Y plotter was therefore developed. The STPT device, shown in Figure 1, consists of a hydraulic control unit with a pump and a rig with a hydraulic cylinder. Once the spikes, rail anchors, and tie plates are removed, the rig assembly grabs the test tie, which is now free to move laterally under the rails. The hydraulic piston mounted on the rig creates the force required to move the tie against one of the rails. Hydraulic pressure can be provided by the hand pump or by an electric pump to speed the operation. Most reported testing was performed by the latter method.

A pressure transducer or load cell in line with the piston and a pressure gauge in the control unit (as a backup) indicate the load applied; a rotary potentiometer mounted on the tie measures the displacement with respect to the stationary second rail. The load-displacement relationship is plotted using the X-Y plotter.

### Typical Results

TSC conducted a large number of track characterization tests using the STPT device at the Transportation Test Center (TTC) in Pueblo, Colorado, and on a number of railroads. Detailed load deflection response curves for individual ties under a range of ballast and test conditions are presented by Pietrak et al. (*6*), and data analysis results and correlations among the parameters controlling the lateral resistance are presented elsewhere by Samavedam and Kish (*7*).

Typical results for relatively strong, medium, and weak tracks are shown in Figure 2. There are two salient points on the characteristics: the peak ($F_P$), occurring at displacements on the order of 0.25 in., and the limiting value ($F_L$), at about .5 in. or less. The softening behavior becomes pronounced for high $F_P$ (>1,000 lb), whereas for low $F_P$ (<1,000 lb), the resistance is practically constant with $F_L \cong F_P$.

Typical STPT data from tests conducted at TTC are shown in Figure 3. These data are averaged for a large number of tests in the test zones, each of which is several hundred feet long.

The data show the resistance values up to 2-in. tie displacement for granite and slag at fractional and large consolidation levels. On the basis of such data, the influence of consolidation, type of ballast, and minimum number of STPTs required to characterize the track resistance will be presented in the following sections.

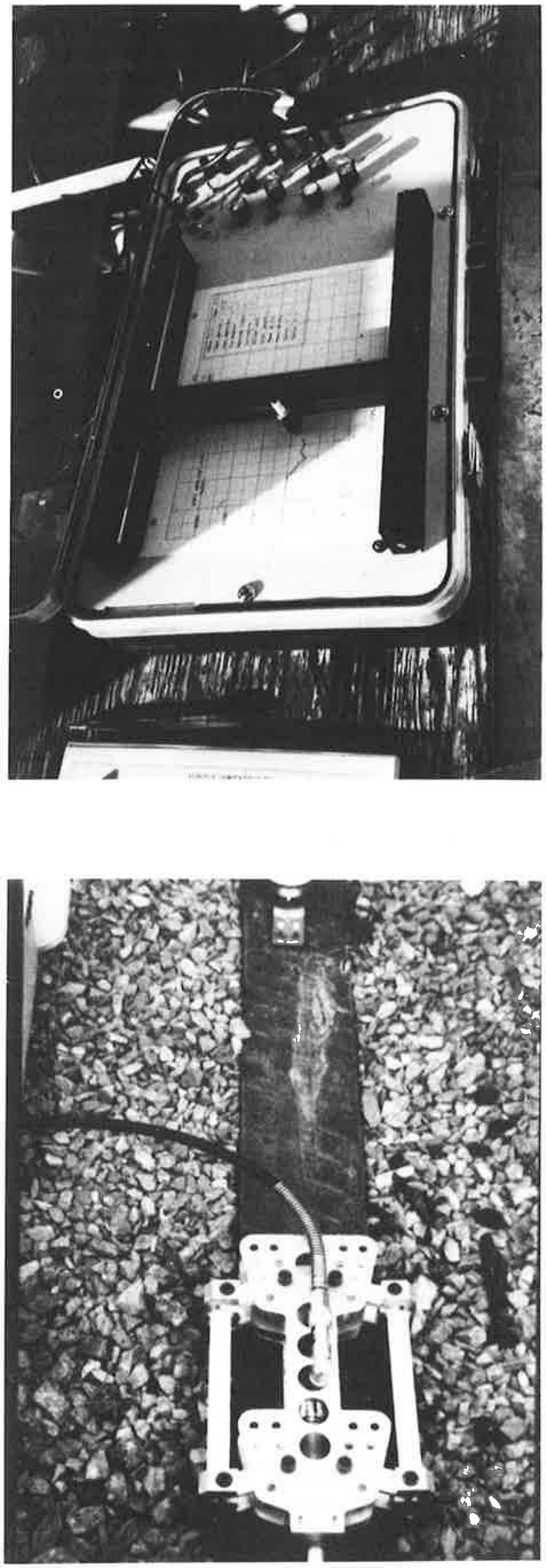


**FIGURE 1 STPT device with plotter.**

### Correlation Study

From the previous data, it is seen that ties need to be laterally displaced over a large distance ($\approx$5 in.) to capture the limiting resistance values. This may be undesirable in revenue service track. Therefore, a correlation between the peak value ($F_P$), which can be easily determined at small displacements, and the limiting value ($F_L$) will be developed here for use in the buckling model. Attempts will also be made to correlate the peak value to the traffic tonnage [in million gross tons (MGT)], but there are some difficulties, as seen later. Finally, the scatter in the peak values for a given track will be presented, and the sampling size, that is, the number of required STPTs over a given track segment for the purpose of averaging the peaks, will be determined.

#### *Limiting Versus Peak Resistance Values*

Considerable test data have been generated to correlate the limiting resistance ($F_L$) with the peak value ($F_P$). This correlation depends on the type of ballast material. For granite ballast, the linear regression analysis of the data has given the following equation:

$$F_L = (0.3\ F_P + 500)\ \text{lb} \quad \text{for } F_P > 726\ \text{lb} \tag{2}$$

For $F_P \leqslant 726$ lb, the case of weak track, it can be assumed that $F_L = F_P$.

For slag ballast, the equation is

$$F_L = (0.06\ F_P + 600)\ \text{lb} \quad \text{for } F_P > 638\ \text{lb} \tag{3}$$

For $F_P \leqslant 638$ lb, $F_L = F_P$.

The ability of granite to provide higher limiting lateral resistance is seen from the equations plotted in Figure 4. It must be noted that the foregoing empirical equations are based on the tests on slag- and granite-ballasted tracks at TTC, which had a shoulder width of about 12 to 14 in. The equations may not be strictly applicable to other track conditions. A significant scatter also exists in the test data. The equations are provided to show that it may not be necessary to push test ties over large lateral displacements to determine the full characteristic. Knowledge of the peak value alone may be adequate and can be easily determined at small displacements without significantly damaging the track.

#### *Effect of Track Consolidation*

It is known that consolidation under traffic (measured by tonnage accumulation in MGT) increases lateral resistance to some limit. Beyond this limit, consolidation has little effect. However, there is a problem in correlating MGT with the absolute value of track lateral resistance. The problem is that immediately after tamping or other maintenance operation, the track resistance drops to a low but unknown value. The subsequent increase in the resistance from this condition would depend on the MGT level of consolidation. Due to the nonlinear relationship between the lateral resistance and MGT, it is difficult to predict the absolute resistance at a given MGT.

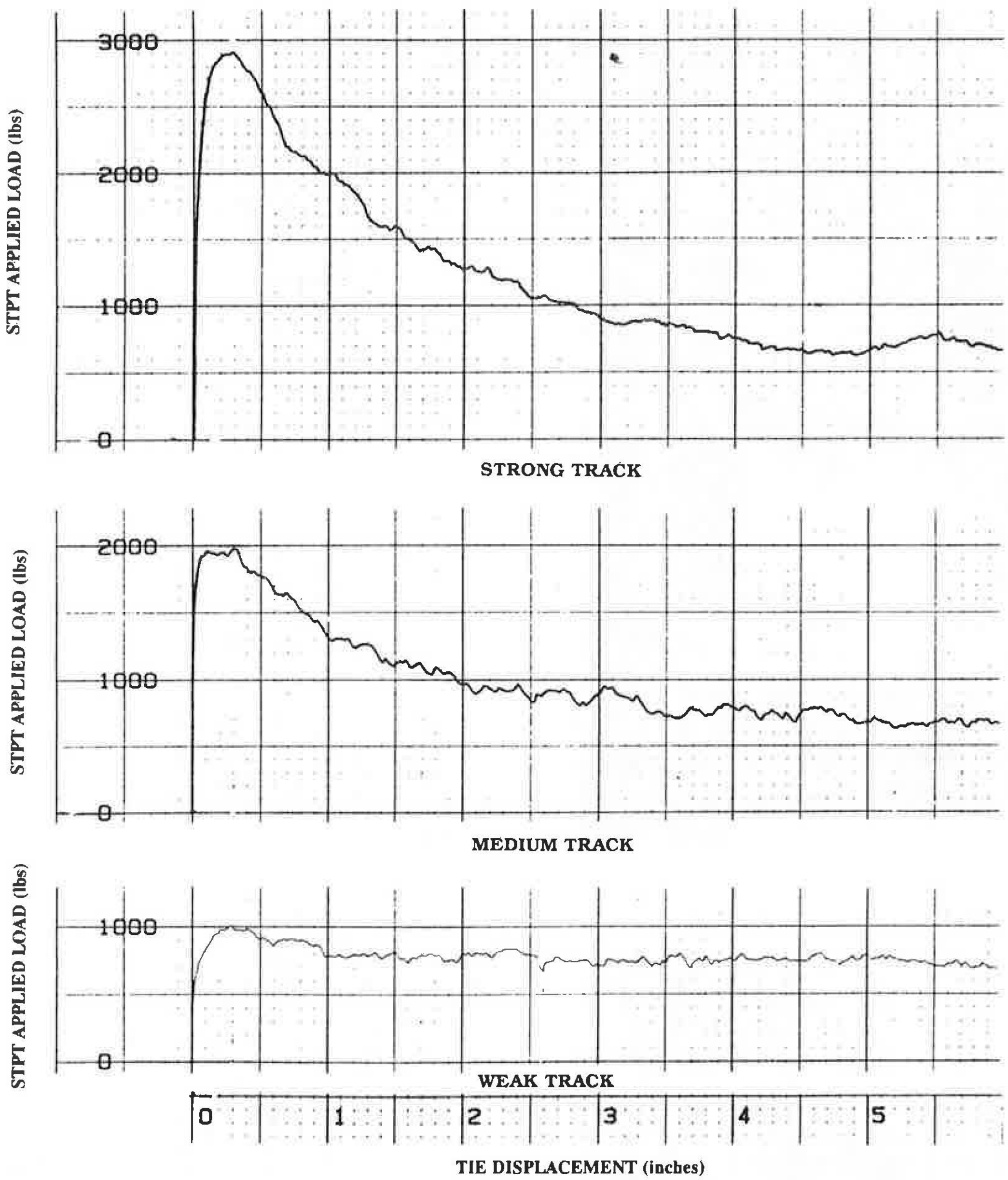



**FIGURE 2 Typical STPT track response.**

Tests to understand the influence of consolidation on the peak resistance values were conducted on three zones of slag, traprock, and granite ballast, respectively, that were subjected to the same traffic levels. The averages of STPT results are shown in Figure 5. Clearly, the resistances at zero MGT for the three zones were not equal, even though the same tamping procedure was employed at each zone. The starting values (1,800 lb for slag, 1,520 lb for granite, and 1,200 lb for traprock) should be considered as site-specific and cannot be attributed to a particular ballast. Previous track operations at these locations, tie condition and age, and resistance levels before tamping can play an important role in the reduced resistance levels after tamping.

Data on peak resistance values collected at various increments in MGT are shown in Figures 5 and 6. These data clearly indicate that the resistance values increase monotonically up to some level. Figure 6 is of particular interest because it shows the significant gain in peak lateral resistance for small increments in consolidation. Such data will be helpful in determining slow-order duration for reduced train speeds soon after tamping or similar track operations.

### *Sampling Size*

Because of inherent variations in the ballast and tie conditions, not all the STPTs in a given section will yield the same values. The longer the section is, the greater will be the scatter in the individual resistance values. Besides the section length, the scatter will depend on the track maintenance standards

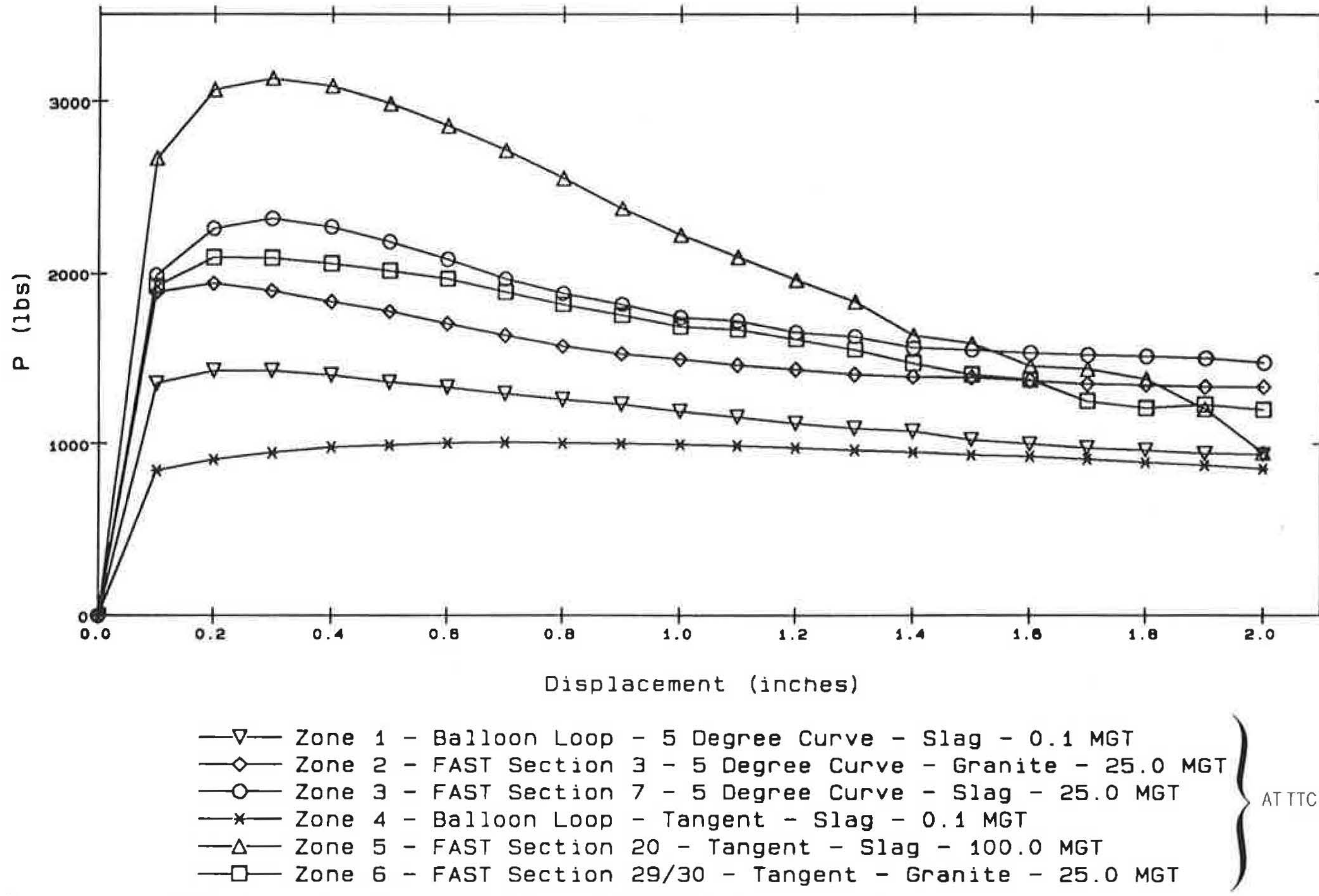



**FIGURE 3** **Ballast resistance characterization tests (average STPT behavior summary for 2-in. tie displacement).**

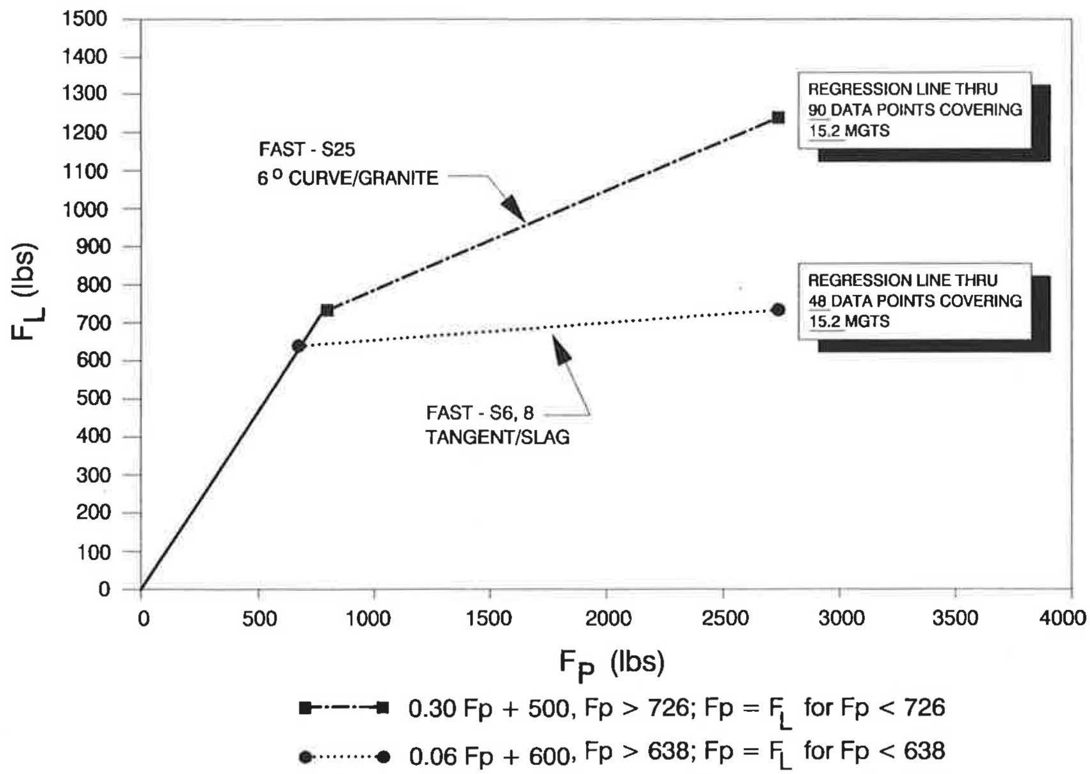



**FIGURE 4** **Peak versus limit resistance (limit values occurred at tie displacements of 4 in. or larger).**

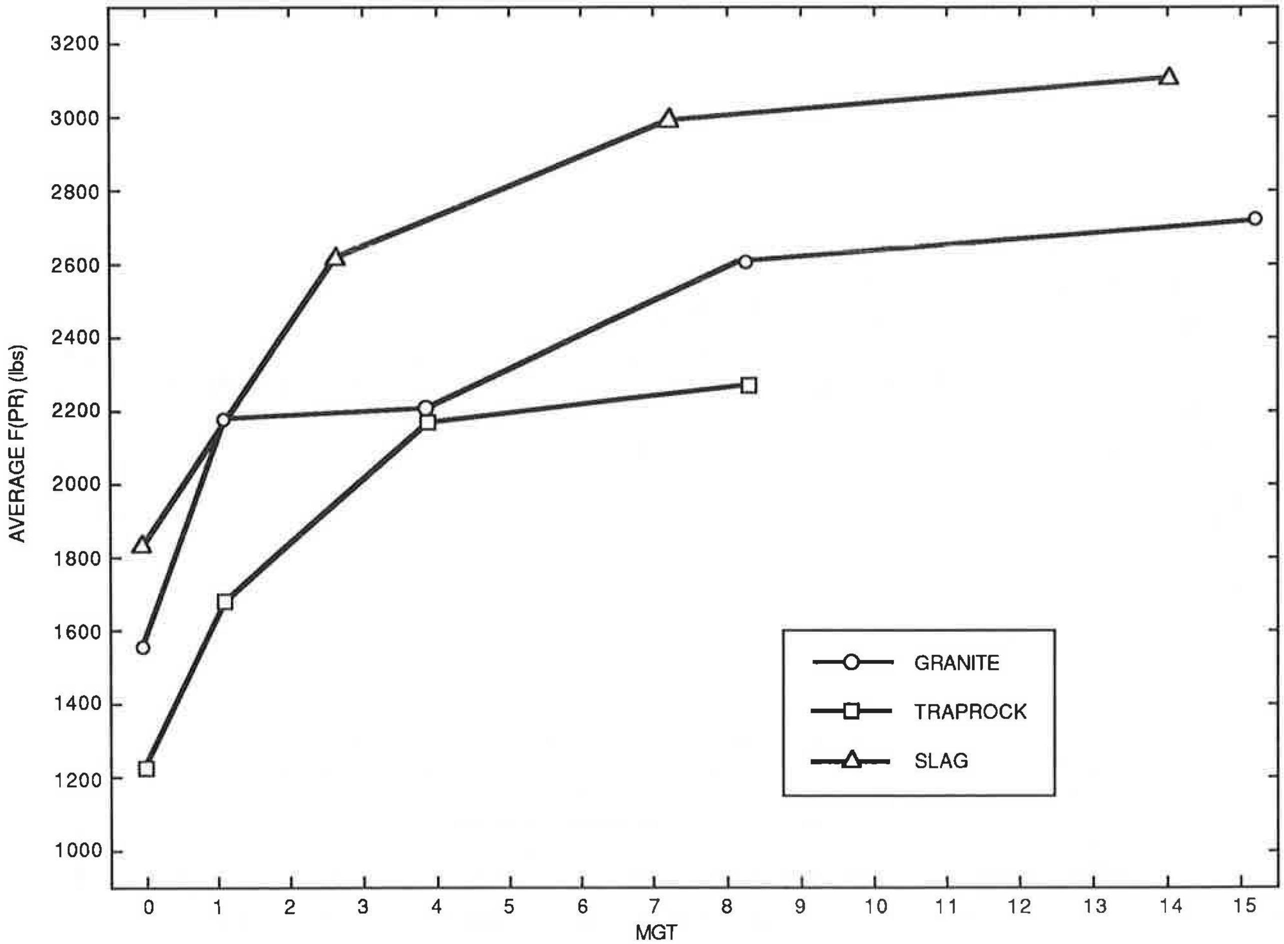



**FIGURE 5** Ballast consolidation influence.

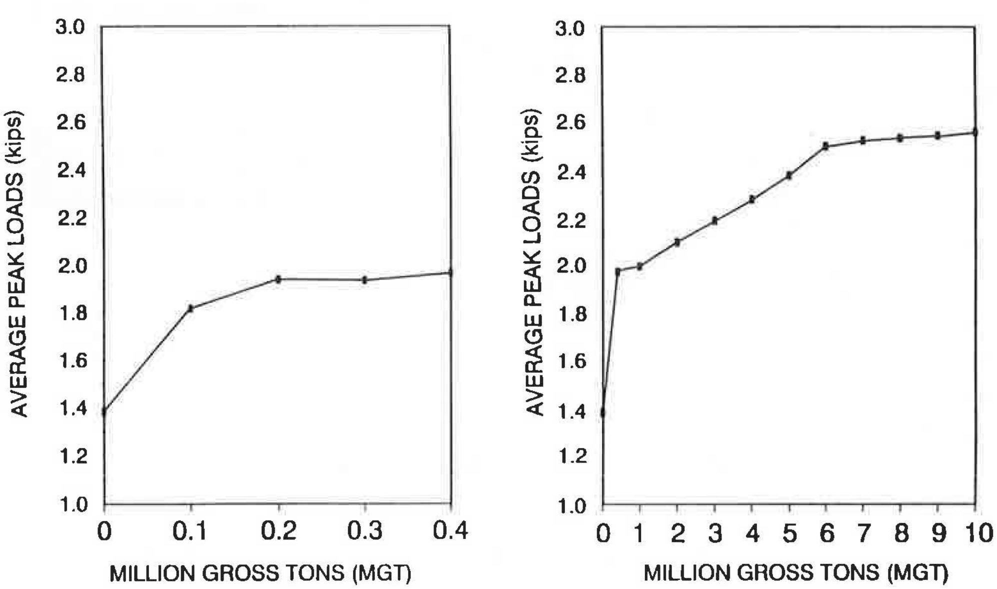



**FIGURE 6** Fast ballast resistance characterization tests—consolidation influence (tangent track, granite ballast).

of the railroad. Tests have also indicated that for a given track section, the scatter increases with the increasing consolidation level.

Although the computer model described by the authors in another paper in this Record can account for the individual tie variations, it is not practical or desirable to test a large number of ties for buckling safety predictions. The question therefore arises whether a minimum (optimum) number of single-tie tests can be established for a given section length, the average of which can be considered as the resistance for the section under consideration. Such an average can then be used as an input parameter in the buckling model.

To address the foregoing question, a large number of tests was performed at TTC on different track sections and at different consolidation levels. Test sections about 50 ft long were considered for the case studies. In each section, alternating ties were tested, and the average of the 15 tested ties was considered to be the lateral resistance for the section.

If fewer than 15 ties in each section were tested, the average of these results would clearly differ from the overall average ($F_o$). Suppose three ties whose peak resistance values are $F_1$, $F_2$, and $F_3$ were selected randomly. The percentage error with respect to the overall average is equal to $(F_m - F_o)/F_o$, where the average of $F_1$, $F_2$, and $F_3$ is $F_m$.

The percentage error was determined in five trials through the use of a random number generator (each trial yields one set of $F_1$, $F_2$, and $F_3$), and the maximum error produced in these trials for each of the six test sections is plotted in Figure 7. This is repeated for all the zones previously referred to in Figure 3.

From Figure 7 it is seen that the maximum error is about 20 percent. This error generally translates into an error of about 10°F in the lower buckling temperature from the buckling model discussed by the authors in another paper in this Record. Factors of safety built into the safe allowable temperatures may make the 10°F uncertainty tolerable. Hence,

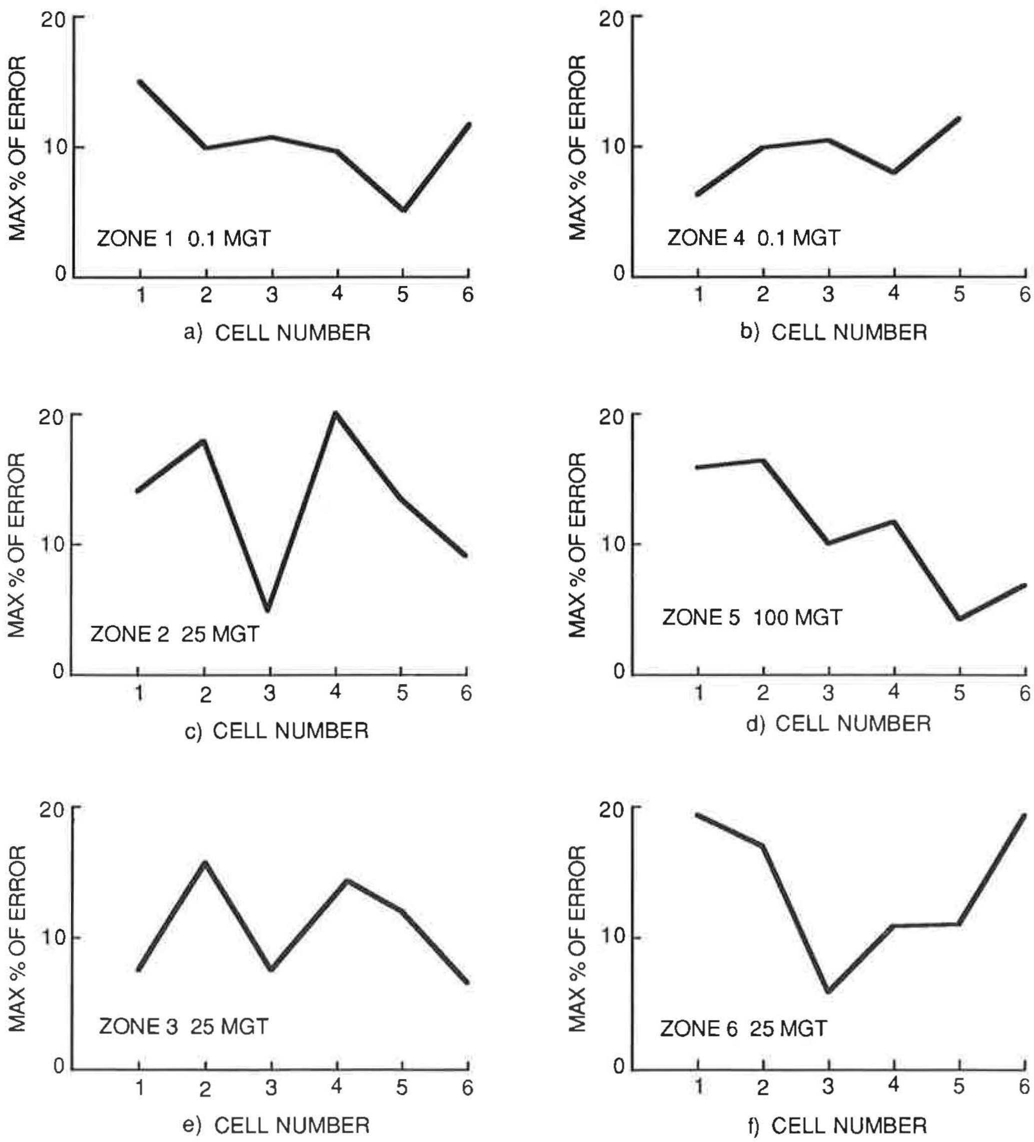



**FIGURE 7 Error due to finite sampling of test ties.**

it is concluded that a sample of three randomly selected ties for every 50-ft section may be adequate in the field application of STPT. Clearly, a linear extrapolation of this result would imply testing six ties for 100-ft sections. However, by visual inspection and proper engineering judgment, the number of STPTs required per unit of length can further be reduced as the length of the section increases. These and other practical considerations will be dealt with in upcoming studies.

Results for a sample size of five ties per 50-ft section, not presented here, indicate a maximum error of 10 percent, which is more than adequate from a practical point of view.

Figure 7 also indicates that tracks with low consolidation levels have a lower percentage error than highly consolidated tracks. This is fortunate because STPT is more important for tracks with low consolidation levels.

## RAIL FORCE AND NEUTRAL TEMPERATURE MEASUREMENT

As stated earlier, the neutral or force-free temperature of CWR can be different from the initial temperature at installation. If the rail force $P$ is known at a given rail temperature $T$, then assuming the rails are fully constrained, the neutral temperature $T_N$ can be calculated from the equation

$$P = AE\alpha\,(T - T_N) \tag{4}$$

where

$A$ = rail cross-sectional area,
$E$ = modulus, and
$\alpha$ = coefficient of thermal expansion.

TABLE 1 MAINTENANCE ACTIONS THAT INFLUENCE RAIL NEUTRAL TEMPERATURE VARIATIONS

| Maintenance Activity | Problem |
|---|---|
| CWR installation at extreme temperatures | Hard to control a uniform laying temperature via rail heating, cooling, and destressing |
| Destressing | Difficulty in ensuring uniform rail temperatures during welding and anchoring |
| Replacing broken rail | Rail stress free temperature is usually not known, hence it is difficult to adjust to it |
| Lining, lifting and tamping | Rail longitudinal stress distribution altered |

Of course, the rails are not fully constrained, but the equation can still be used to define a variable neutral temperature. Mechanisms contributing to neutral temperature variations are discussed elsewhere (*8*). The mechanisms include rail longitudinal movements, track lateral shift and radial breathing in curves, and track vertical settlement. Rail longitudinal movement is caused by train braking and acceleration forces or by differential thermal forces (sun and shade). Track lateral shift can be caused by truck excessive hunting, lateral forces generated due to curving, or negotiation of lateral misalignments. Rail force can cause radial breathing of curves in weak ballast conditions. Vertical differential settlement of rails can occur on new or recently surfaced track or in areas of weak subgrade conditions.

These natural mechanisms demand that CWR neutral temperature be determined from time to time. Track maintenance operations, given in Table 1, can also affect the neutral temperature. It is desirable to determine the rail neutral temperatures after the track undergoes any of these operations. This is particularly important in spring and summer to ensure permissible values for buckling safety. Field data collected by TSC (*8*) using the strain gage affixed to rail on a number of revenue service tracks and tracks at TTC showed that the neutral temperature could drop from a typical installation value of 90°F to 50°F, thus significantly increasing the buckling risk on a hot day.

### Measurement of Rail Force

Rail force measurement by Berry gage, strain gage, and the British Rail vibrating wire are well known but are not practical for use in the field, as explained elsewhere (*9*). They cannot provide the absolute rail force and need an initial reference level, usually obtained by cutting the rail. The vibrating wire technique requires that a hole be cut in the rail web. A number of other techniques (*10*) have been tried, some of which are listed in Table 2. These techniques generally suffer from problems of reliability, sensitivity to the rail residual stresses, and site-specific calibration requirements. To address these problems, a new technique has been recently developed, and a prototype test fixture has been used to validate the technique through field tests. The technique is founded on a well-known principle of mechanics, and it provides the absolute force without site-specific calibration. It is not destructive but requires removal of spikes and anchors from the test section rail.

The technique, which is based on rail uplift induced bending response, was originally described elsewhere by Kish and Samavedam (*9*).

### Rail Uplift Method

If the rail is freed from the ties over some length, restrained vertically at the ends of the freed portion, and subjected to a concentrated uplift load at the center, the resulting deflection depends on the magnitude of the rail longitudinal force. Clearly, longitudinal compressive load will increase the deflection of the beam-column, and tensile force will reduce it. For a given length of rail, the vertical force required to pro-

TABLE 2 SUMMARY OF RAIL LONGITUDINAL STRESS MEASUREMENT TECHNIQUES

| Technique | Comment |
|---|---|
| Flexural wave propagation | Sensitive to the rail-tie structure damping |
| X-ray diffraction | Measures surface layer strains only |
| Acousto-elastic | Sensitive to rail microstructure |
| Magnetic coercion | Sensitive to rail microstructure and residual stress |
| Barkhausen noise | Very difficult under field conditions |
| Electromagnetic-acoustic transducer (EMAT) | Sensitive to rail microstructure and rail surface condition |
| Laser "spackle" | More useful in lab application due to accuracy required for mapping laser interference patterns |

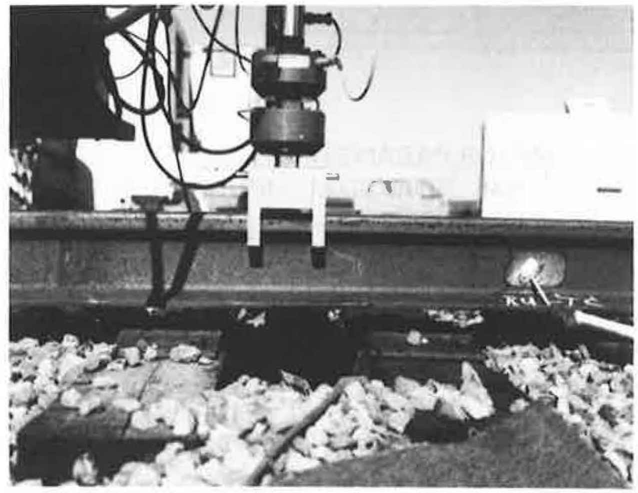


**FIGURE 9 Fixture used in the uplift tests.**

duce a specified deflection is a measure of these rail forces. The concept implementation is based on the fact that the rail can be conveniently held at the two end points by the wheels of a rail car. This automatically fixes the length of the rail and boundary conditions at the ends of the rail beam. The spikes and anchors between the inner wheels of the two trucks of the car must be removed. Figure 8 shows schematically the rail uplift method; Figure 9 shows the rail-car-mounted hydraulic fixture lifting the test rail.

An analytical model, shown in Figure 10, has been developed to calculate the vertical deflection produced by different levels of rail force. This model proved that the deflection is measurably sensitive within the range of longitudinal forces of interest in buckling safety assessment. Results from the model were used to conduct parametric studies required to

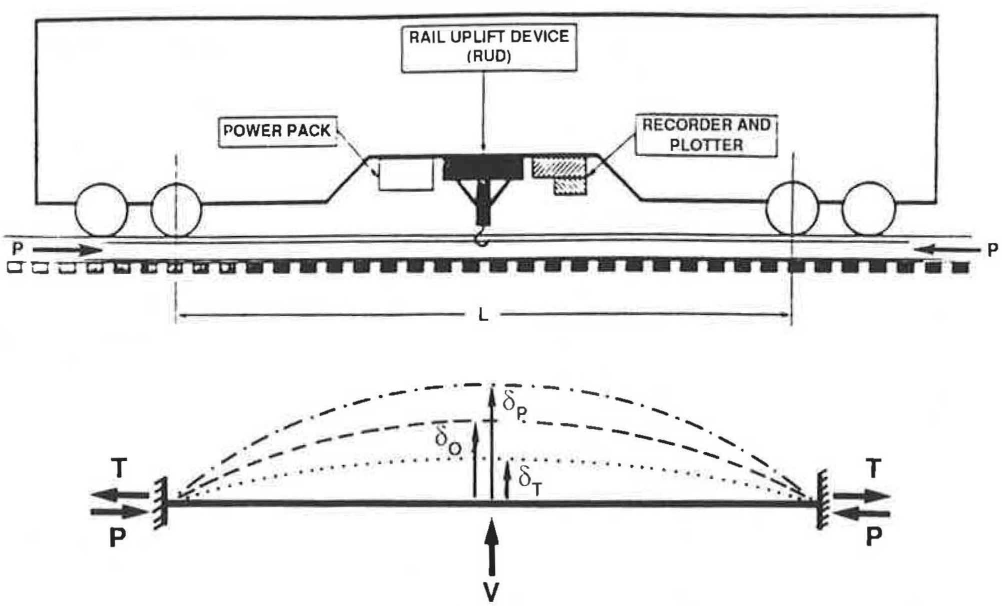
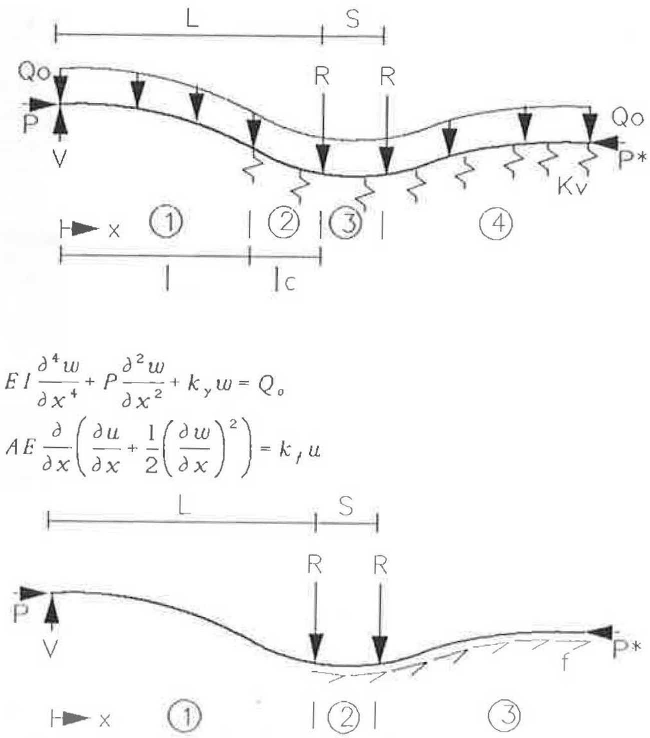



**FIGURE 8 Schematic of rail uplift concept.**

**MAJOR PARAMETERS:**

* RAIL SIZE AND MOMENT OF INERTIA
* VERTICAL AND LONGITUDINAL TRACK STIFFNESS
* CAR PARAMETERS:
  (i) TRUCK CENTER SPACING
  (ii) AXLE SPACING
  (iii) VERTICAL WHEEL LOAD




$$EI\frac{\partial^4 w}{\partial x^4} + P\frac{\partial^2 w}{\partial x^2} + k_y w = Q_o$$

$$AE\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial x} + \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2\right) = k_f u$$

**FIGURE 10 Beam bending–rail uplift analysis.**

plan the tests, design the test fixture, and assess measurement sensitivity. Figure 11 shows the influence of rail size on the uplift force required for different levels of longitudinal force.

### Test Results

Tests were conducted at TTC on a tangent and a 5-degree curved track. A special instrumentation car with inner wheel spacing of 340 in. was adapted to provide a maximum central vertical force of 30 kips. The test sections were instrumented with strain gages, shown in Figure 12, to measure the rail force. The variation in the rail force was achieved by destressing at reasonably high neutral temperatures for tensile loads and by artificial rail heating for compressive force levels. The rail force was correlated with the required vertical load for a 2-in. rail uplift.

Figure 13 shows data on a typical section, which fall on a straight line as theory predicts. Figure 14 shows the regression lines for the eight tested sections of the tangent. From these data the rail force can be determined within an error band of ±12.5 kips. This error is generally tolerable in buckling safety assessment. Figure 15 shows the mean regression line for all the test data and also the theoretical prediction. Agreement between the theory and the test is seen from the figure.

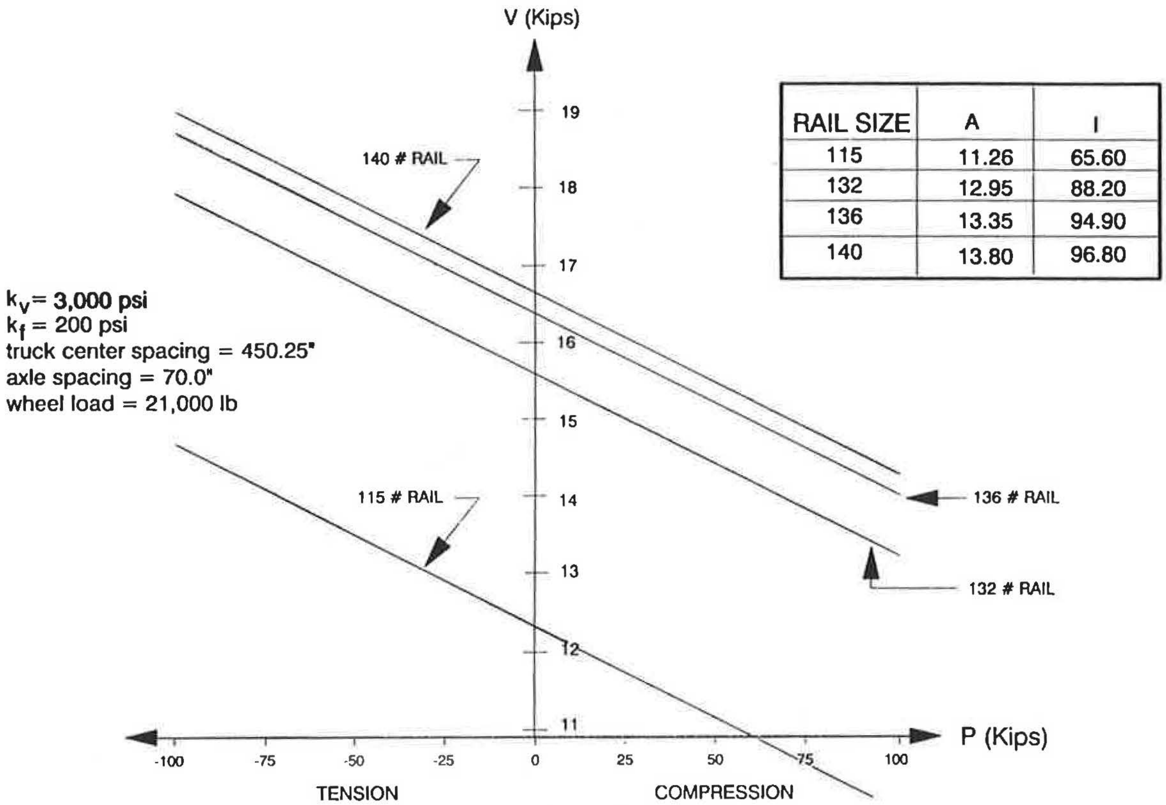
Test data have also been collected on a 5-degree curve. The responses of high and low rails differ from one another and from that of the tangent, as seen in Figure 16. Differences are attributed to the wheel load variations in high and low rails as well as difference in the "effective lengths" of the rail beam under the wheels. Accounting theoretically for these variations resulted in agreement with the recorded data on the curves. Thus, the proposed technique is universal in application and does not need site-specific calibration for curves, provided the superelevation is known. However, this conclusion should be firmly established through additional tests. Some correction may also be needed in cases of excessive rail wear. These and other issues dealing with automated schemes of spike pullout, power pack operations, and measurement of deflection with car-mounted devices will be addressed in a future research program by TSC.

## SAFETY ASSURANCE APPLICATIONS

As demonstrated by the authors in another paper in this Record and shown in Figure 17, buckling safety assurance may be attained through appropriate safety criteria of allowable temperature increase (or rail longitudinal force) for various levels of track lateral resistance. Within this framework, the required track resistance can be measured and monitored by the appropriate STPT measurements, and the corresponding allowable rail force determined by a rail car–mounted rail uplift device. This prototype safety assurance concept is undergoing additional research and field implementation studies.

## CONCLUSIONS

• Techniques have been developed and prototype hardware is available for the measurement of track resistance and rail longitudinal force (neutral temperature), which, in turn, can indicate incipient buckles or buckling prone conditions. Ad-




| RAIL SIZE | A | I |
|---|---|---|
| 115 | 11.26 | 65.60 |
| 132 | 12.95 | 88.20 |
| 136 | 13.35 | 94.90 |
| 140 | 13.80 | 96.80 |

**FIGURE 11** Rail size influence on uplift force versus longitudinal force (605 RFC car, 2-in. deflection).

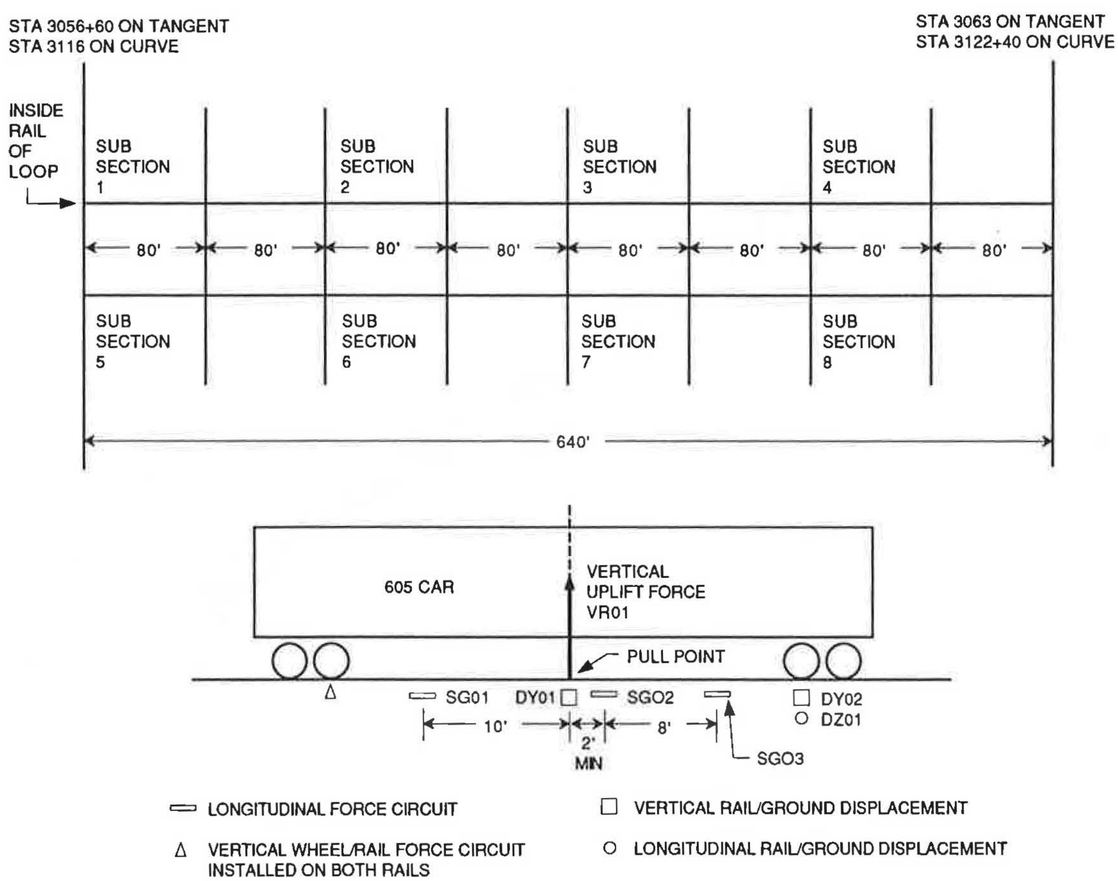



**FIGURE 12** Rail uplift test layout and instrumentation.

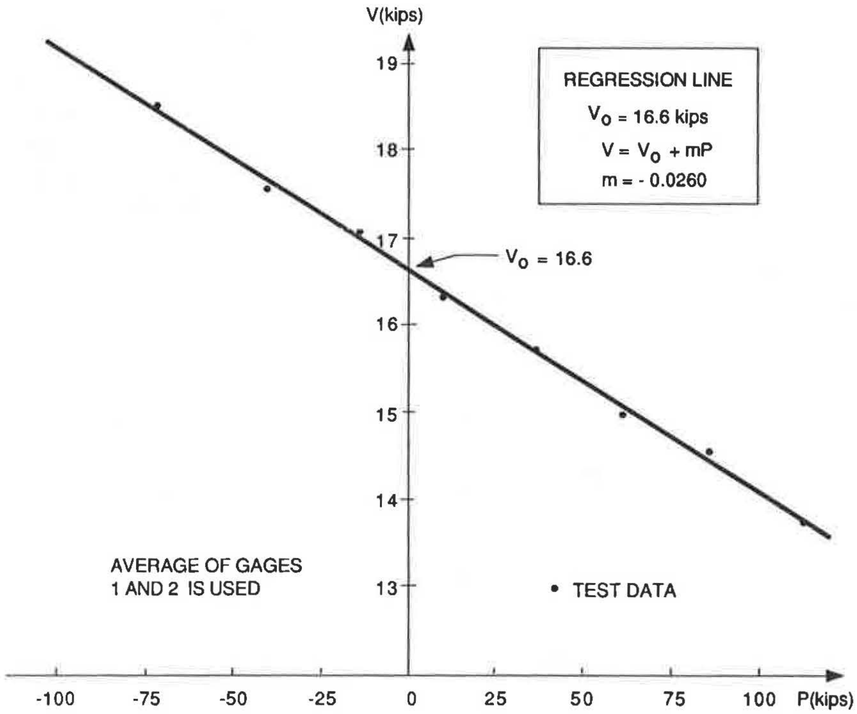



**FIGURE 13** Typical uplift force (*V*) versus rail force (*P*) for tangent track (section 4).

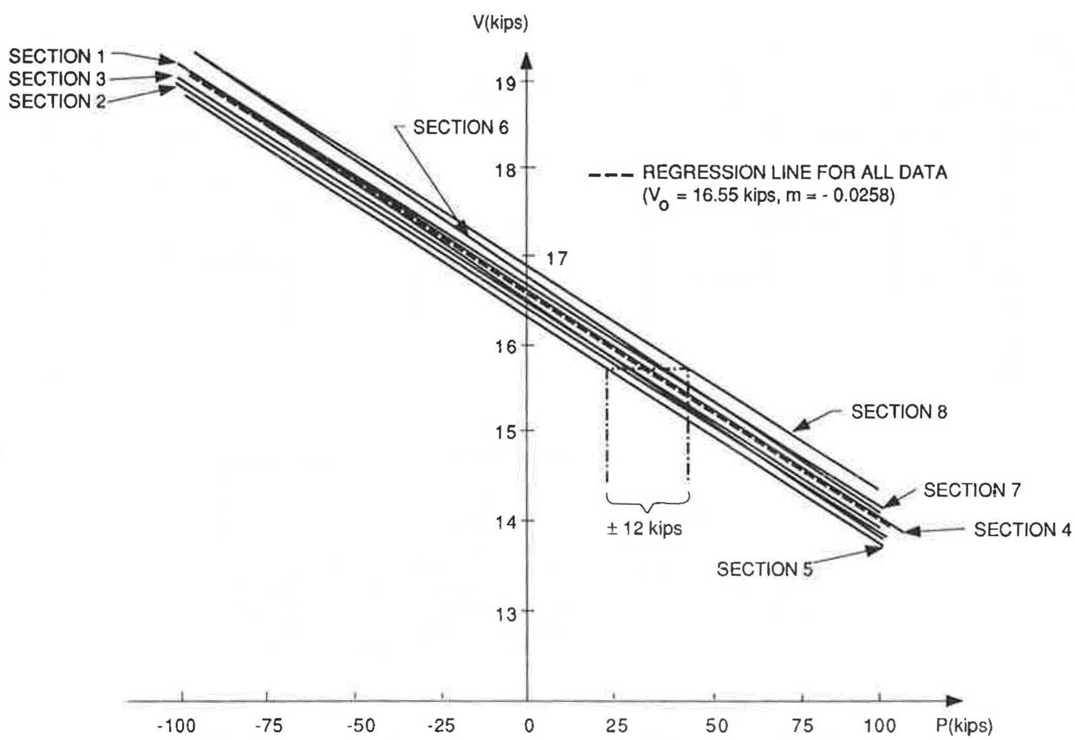



**FIGURE 14** *V* versus *P* regression lines for tangent track.

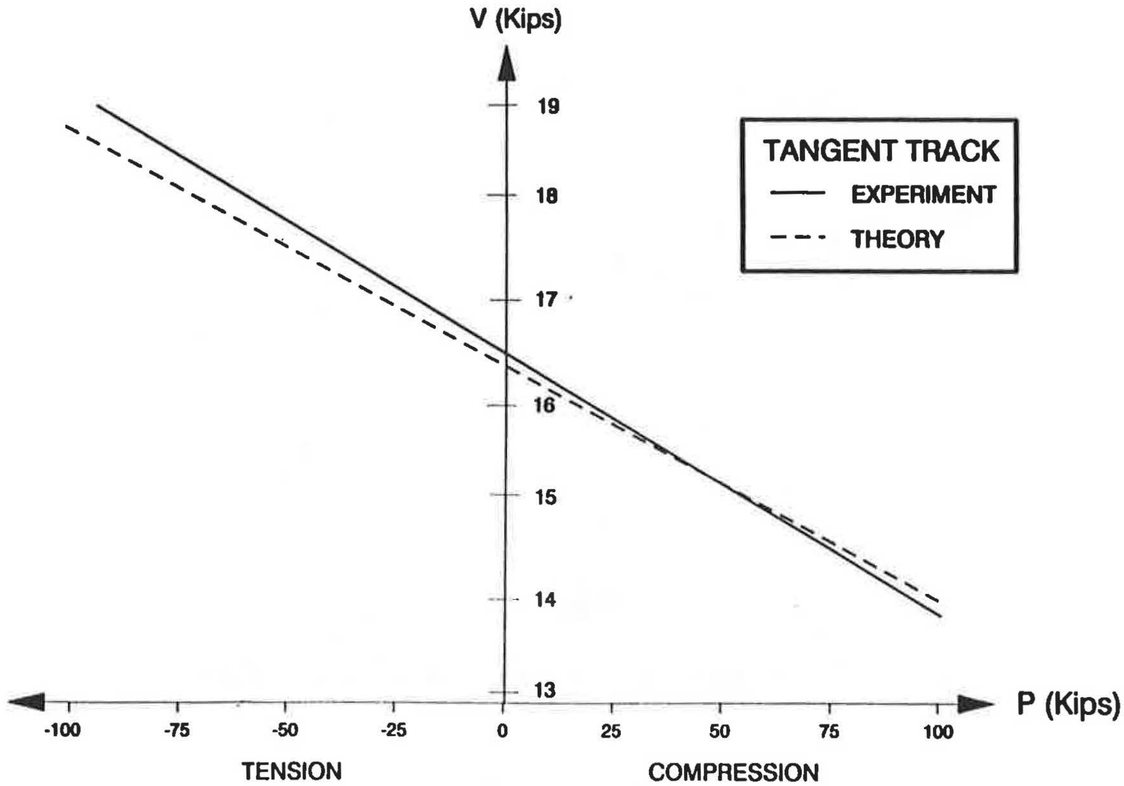



**FIGURE 15** Comparison of theoretical and experimental *V* versus *P* behavior.

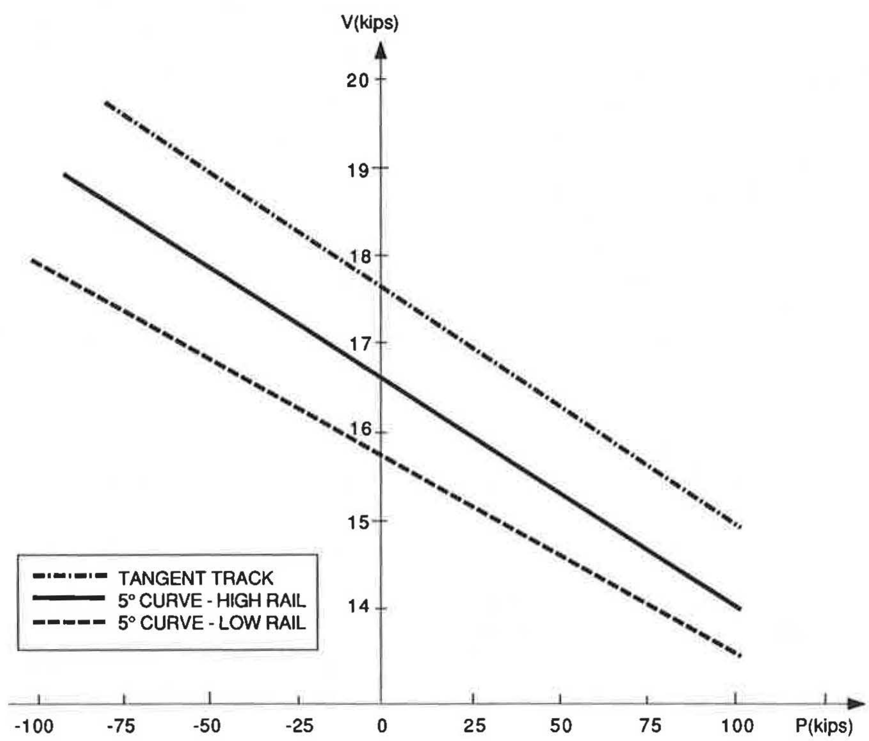



**FIGURE 16** Comparison of *V* versus *P* regression lines for tangent and 5-degree curve track.

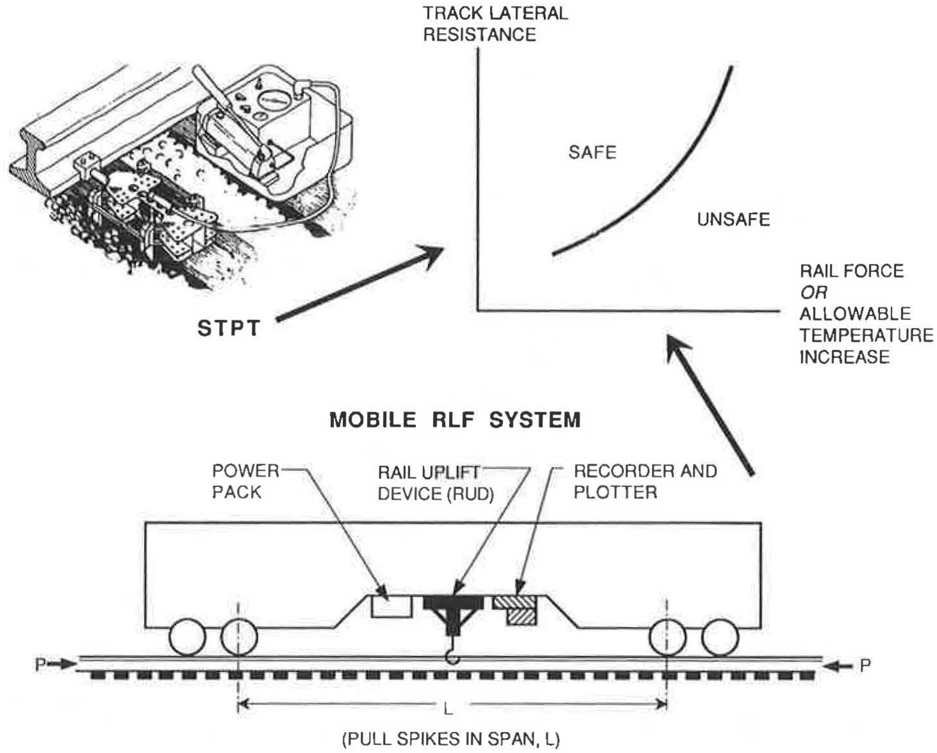



**FIGURE 17 Safety limit concept for buckling prevention.**

ditionally, these techniques can provide useful tools to guide maintenance activities for improved CWR track safety.

- The track lateral resistance has a nonlinear softening characteristic, on which there are two salient points: a peak value occurring at a fractional lateral displacement, and a limit value at displacements of a few inches. The peak value is sensitive to the consolidation level (MGT). For tamped and weak tracks, the peak and limiting values are very close. The limiting value does not increase at the same rate as the peak value with increased consolidation.
- The STPT device developed is portable and convenient for a quick evaluation of lateral resistance. Both peak and limiting values of resistance can be determined using this device. However, it is adequate to determine the peak value, which involves mobilizing the tie by no more than ¼ in. The limiting value can be estimated by the empirical formulas provided here.
- Although STPT results show scatter, it is usually not severe enough to affect safe buckling safety limit computations. The average of three randomly selected STPT values per 50-ft CWR track segment is adequate for buckling safety assurance of the segment.
- Rail force and hence the neutral temperature can be measured by the rail uplift device developed here. The method is not destructive but requires removal of spikes and anchors under the car. The method yields absolute rail force without site-specific calibration. The accuracy of the method, based on the tests conducted, is within ±12.5 kips, which is deemed sufficient for buckling safety assurance.

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