freight movement for many commodities could belong not to the truckers but to the short train.

One advantage of a contemplated change from long trains to short trains for selected shippers is that the change need not be a radical move; initially, it can be made on a purely experimental basis so that both the railroad and the union can be fully satisfied as to the impact of the change on them before any full-scale operations are initiated. Its objectives are clear: a more marketable transportation service, an improved share of the transportation market, and enhanced job security in a healthier industry. Complete implementation of the short-train concept will require, in addition to identification of current barriers to railroad efficiency and service reliability, commensurate modification in management and union policies and practices, and preliminary experimentation with government cooperation, particularly in granting the railroads flexibility to design competitive freight rates relative to the truckers' rates.

Finally, every effort should be made by responsible union leadership to broaden the base of collective bargaining in the railroad industry. At present a railroad may deal with as many as 20 unions, which are splintered by craft distinctions. The continuing existence of the Brotherhood of Locomotive Engineers outside of the four operating brotherhoods that merged into the United Transportation Union has complicated negotiations materially and made the adoption of progressive policies toward technological change more difficult. The strongest type of union for weathering the storm of technological and economic changes would be a multicraft or semi-industrial union; with such a structure each craft would have a greater chance to forestall total displacement in changing times. Thus, I urge more union mergers within both the operating and nonoperating crafts.

CONCLUSION

The size of a work force is properly a function of management and employees can adequately be protected against management's possible abuse of its authority by a grievance procedure, culminated if necessary by grievance arbitration. This is the general rule and practice in the economy, which has proven to be an effective and enforceable safeguard against unsafe working conditions.

ACKNOWLEDGMENT

Parametric Study of Track Response

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This paper presents the results of a parametric study of track response using a comprehensive track analysis model. Track response parameters include rail and tie bending moments, rail displacement, tie rail-seat load, and the distribution of stresses in the ballast and subgrade. The effects of variations in tie size, tie spacing, ballast depth, and rail fastener stiffness are presented in graphs suitable for track design trade-off studies. Alternative wood and concrete tie track configurations are evaluated using equivalent maintenance criteria.

Experience from several foreign countries indicating advantages of longer tie life and reduced track maintenance for concrete versus wood ties has aroused considerable interest in developing concrete ties for main-line use in North America. However, few quantitative data are available for comparing wood and concrete tie loads and roadbed stresses, or long-term performance, as a basis for evaluating the technical and economic feasibility of alternative track and tie designs.

Current and past research has shown that the evaluation of track performance and design for vertical loads requires a capability for predicting realistic pressure distributions at the tie and ballast interface and at the ballast and subgrade interface. This requires a track analysis model that includes the effects of many track parameters.

The main purpose of the work presented herein is to use a MUlti-Layered Track Analysis (MULTA) model for vertical loads to develop track design guidelines that include the effects of various tie and fastener characteristics, tie spacing, and ballast depth on track response. Alternative wood and concrete tie track configurations based on equivalent maintenance criteria are evaluated for use in future life-cycle cost analyses.

DESCRIPTION OF TRACK
ANALYSIS MODEL

The analysis model selected for this program is a combination of an available multilayer model for the ballast and subgrade and a finite element model to combine the loads for individual ties and rails (load combination program). The load combination program was developed by the Association of American Railroads (AAR). It was modified by Battelle's Columbus Laboratories to incorporate influence coefficients from the multilayer roadbed model to provide a complete track model.

Figure 1 shows a schematic of this combination model known as MULTA. This provides a linear track

analysis that includes single or multiple wheel loads on two rails supported by ties of variable size and spacing and a finite bending rigidity. The tie-bearing area is divided into segments of approximately square dimensions, and these are used to generate influence coefficients for pressures and displacements from the multilayer roadbed model. This system of equations is solved using matrix analysis techniques to calculate ballast and subgrade stresses and rail and tie displacements.

REFERENCE TRACK PARAMETERS

A MULTA model of a track section having 11 ties and separate layers for the ballast and subgrade was used for this parameter study. The track was loaded vertically at the center tie of 1.07 MN (240 000 lbf) using the load for a single axle of a freight car and a wheel load of 133 kN (30 000 lbf). This is a linear analysis program, so results for heavier or lighter wheel loads can be obtained by direct scaling. Because MULTA presently handles a single vertical load per rail for each computer run, adjacent axle loads were not simulated. However, adjacent axle loads could be included by superposition. This effect is discussed later in the paper. The parameters of particular interest for this study were rail and tie displacement, vertical rail-seat load, tie bending moments at the center and rail-seat regions, maximum rail bending moment, displacement (strain) throughout the foundation, bulk stress at selected points in the foundation, vertical and deviatoric stress at selected points throughout the foundation, and tie-ballast interface pressures.

Table 1 lists the track parameters included in this study. Variations in tie size, stiffness, and spacing

and ballast depth were selected as the key parameters. The effect of varying rail size can be evaluated adequately using conventional track design procedures based on beam-on-elastic-foundation (BOEF) equations when the track modulus has been established. Work by Tayabji and Thompson (1) shows that variations in ballast and subgrade modulus over a typical range for field conditions do not cause large changes in predicted stresses. Track degradation under repeated load would vary considerably, however, for different materials. The roadbed material properties used for this study are based on average values reported in Tayabji and Thompson (1). For purposes of the parameter study, a reference track designated by the underlined parameters in Table 1 was used for baseline comparisons. (Measurement units reported in this paper are those used in the study; in most instances, SI units are reported without their customary equivalents. Further, because some studies are reported in customary units, no SI equivalents are given.)

TRACK MODEL EVALUATION

The MULTA model was evaluated previously by Prause, Harrison, Kennedy, and Arnlund (2) by comparing predicted and measured data for the distribution of tie and ballast pressures along the tie length and by comparing measured and predicted tie bending moments. When the input data are selected properly, predicted and measured results were in agreement except for ties that have a severe center-binding condition. This nonuniform support condition cannot be simulated with MULTA because a uniform elastic support model is used for the roadbed. MULTA has also been evaluated by comparing results from other track analysis models. This comparison is shown in Prause and Kennedy (3).

TRACK FOUNDATION STRESSES

Vertical pressure distributions at the tie and ballast interface and on the subgrade at the ballast and subgrade interface were calculated for the ballast depths listed in Table 1. Deviatoric (σ_D) and bulk (θ) stress distributions along the tie were also calculated at selected depths through the foundation. Knutson and Thompson (4) have shown the dependence of resilient modulus (E_R) on these quantities. For ballast material, the resilient modulus is a function of θ; for typical subgrade materials the resilient modulus is a function of σ_D. The deviatoric stress is calculated midway through the ballast depth and at the ballast subgrade interface. Deviatoric stress is monitored at these two locations because the work of Raymond, Lake, and Boon (5) shows that foundation material is a function of deviatoric stress for both ballast and subgrade materials. Therefore, θ, and especially σ_D, are used to evaluate degradation in the ballast and subgrade. The reduction of
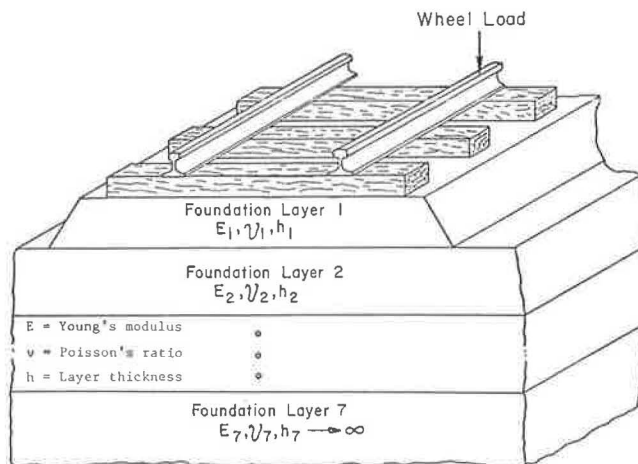
Figure 1. Schematic for track model.

Wheel Load

Foundation Layer 1
E_1, ν_1, h_1

Foundation Layer 2
E_2, ν_2, h_2

E = Young's modulus
ν = Poisson's ratio
h = Layer thickness

Foundation Layer 7
$E_7, \nu_7, h_7 \longrightarrow \infty$

Table 1. Track model parameters.

Item	Parameters[a]
Rail	67.5 kg/m, I = 3950 cm^4, E = 232.3 × 10^6 kPa, A = 86.13 cm^2
Wood tie	17.8 cm thick, 22.9 cm wide, 259.1 cm long, EI = 1349 × 10^7 N·cm^2, spacing = 0.50 m
Concrete tie	259.1 cm long, spacing = 0.51, 0.61, 0.76 m
Small	25.4 cm wide, EI = 2192 × 10^7 N·cm^2 A = 387 cm^2
Medium	26.7 cm wide, EI = 2902 × 10^7 N·cm^2 A = 413 cm^2
Large	26.7 cm wide, EI = 6719 × 10^7 N·cm^2 A = 529 cm^2
Ballast/subballast	E$_1$ = 241 000 kPa, ν_1 = 0.4, depth = 30.5, 61, 91.4 cm
Subgrade	E$_2$ = 80 400 kPa, ν_2 = 0.4, depth = infinite
Rail fastener stiffness	1.8, 3.5, 7, 17.5, 70 × 10^4 kN/m
Wheel load	133 kN

Note: 1 kg/m = 2 lb/yd, 1 cm = 0.4 in, 1 kPa = 0.15 lbf/in^2, 1 N·cm^2 = 0.035 lbf·in^2, 1 m = 0.3 ft, 1 kN = 225 lbf.
[a] Reference track parameters are underlined.

Figure 2. Effect of ballast, tie size, and tie spacing on track modulus.

Figure 3. Maximum tie center bending moments.
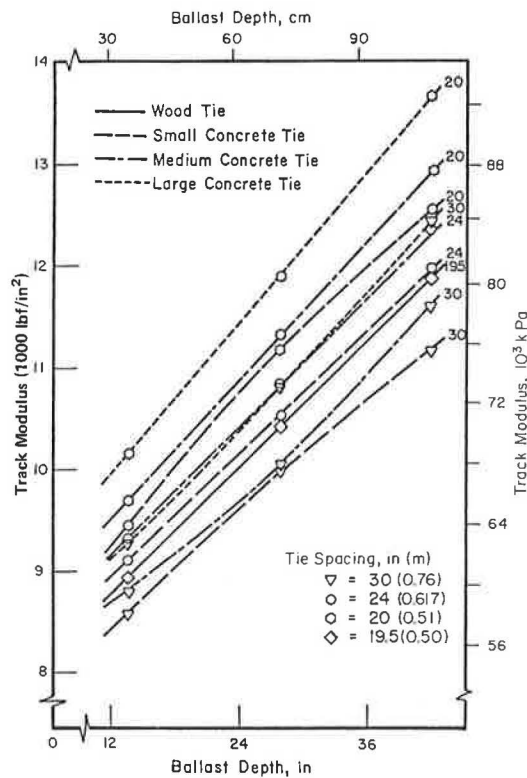
deviatoric stress by judicious selection of track design parameters is one of the main interests of this parametric study.

TRACK MODULUS

The track modulus (U) is defined as the force per inch of rail required to depress the track roadbed 1 in. This parameter has been used historically to quantify the effective stiffness or resilience of a track structure, and it is a key parameter in the BOEF analysis procedure used for conventional track design. Thus, the MULTA results have been used to calculate an effective track modulus in order to give a recognizable measure of the roadbed stiffness.

Figure 2 shows the range of track modulus data included in the parametric study of tie spacing, ballast depth, and tie size. Track modulus increases with increasing values of tie size and ballast depth and decreases with an increase in tie spacing. This effect of tie spacing is consistent with conventional track design procedures. However, the effect of ballast depth on track modulus is not usually considered, and it is obviously very significant.
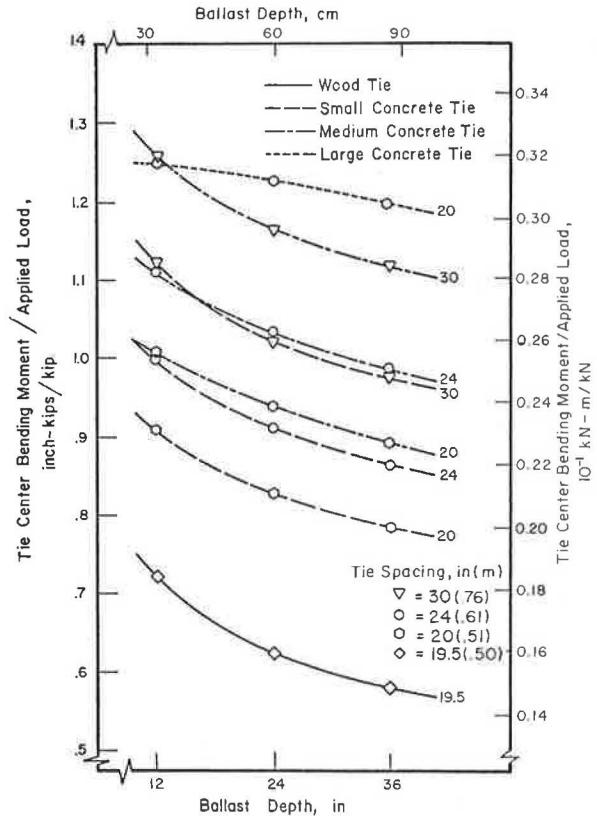
The calculations of track modulus shown in Figure 2 are based on the BOEF equations for vertical rail displacement in the form

$$U = [(P/Y_o)^4 /64\ EI]^{1/3} \qquad (1)$$

where

Y_o = maximum rail displacement predicted by MULTA,
P = wheel load, and
EI = rail bending stiffness.

SUMMARY OF TRACK RESPONSE

The following sections summarize the results from the parametric study of tie size, tie spacing, and ballast depth in graphs suitable for track design and performance trade-off studies.

Tie Bending Moments

Maximum tie center bending moments normalized to the wheel load are shown in Figure 3. The center bending moment increases as tie spacing and tie size increase, but increasing the ballast depth reduces the bending moment. Tie center moments increase approximately 40 percent in going from the small concrete tie to the large concrete tie and approximately 75 percent when going from the wood tie to the large concrete tie. The tie center moments decrease about 16 percent when going from a 30-cm (12-in) ballast depth to a 90-cm (36-in) ballast depth.

Figure 4 shows that tie rail-seat bending moment increases with tie size, tie spacing, and ballast depth. Both tie center and rail-seat moments increase significantly with tie size and tie spacing. Rail-seat bending moments increase about 10 percent when using the large concrete ties instead of the small concrete ties, and about 23 percent when using the large concrete ties compared to the wood ties. Rail-seat moment increases less than 3 percent when going from a 30-cm ballast depth to a 90-cm ballast depth, and ballast depths greater than 90 cm have a negligible effect.

These predicted tie bending moments do not include the effects of nonuniform support conditions found in typical track. Tie center bending moments in particular can be much higher with center-bound ties and can change with end-bound ties.

Rail Displacement

Figure 5 shows rail displacement normalized by the applied wheel load as a function of ballast depth, tie size, and tie spacing. This comparison shows a slight increase in displacement with tie spacing—about a 10 percent increase when tie spacing changes from 50 cm (20 in) to 75 cm (30 in). This is a much smaller change than would be predicted by conventional track design procedures. Rail displacement decreases slightly (about 7 percent) when the tie size is changed from the small to the large concrete tie. Rail displacement also decreases with an increase in track stiffness, i.e., a deeper ballast. When the ballast depth is increased from 30 cm to 90 cm, the displacement is reduced by about 20 percent. Figure 5 shows that synthetic ties of different size, spacing, and ballast depth can reduce track displacements from that of the wood tie track structure. This result has been confirmed in practice.

Rail-Seat Load

Figure 6 shows the variation in tie vertical rail-seat load (q_o). The rail-seat load increases with a corresponding increase in each of the varied parameters, as expected. When the small synthetic tie configuration was changed to the large tie configuration, q_o increased about 6 percent, but changing ballast depth from 30 cm to 90 cm increased q_o by about 13 percent. An increase in synthetic tie spacing from 50 cm to 75 cm amounted to about a 33 percent increase in q_o. It is apparent from Figure 6 that the rail-seat loads will be consistently higher with synthetic ties used in place of wood ties because of the increased tie spacing and higher track stiffness from the wider ties.

Figure 4. Maximum tie rail-seat bending moment.
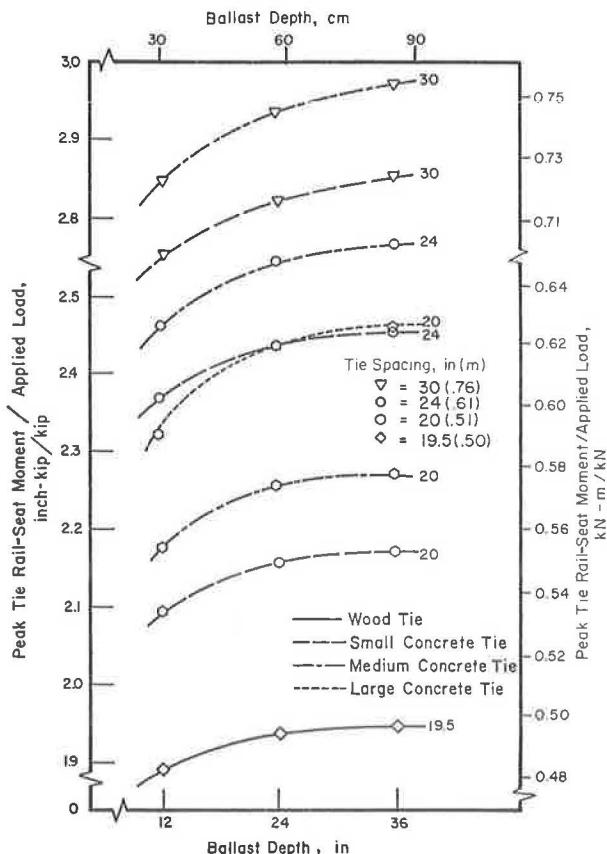
Ballast Stresses

The deviatoric and bulk stresses have been selected as important quantities to monitor because these stresses influence track degradation rate. Figures 7 and 8 show the stress levels in the ballast for different tie sizes, tie spacing, and ballast depth. Figure 7 shows that comparable levels of peak deviator stress midway through the ballast depth can be obtained for several combinations of tie spacing and ballast depth. Using a 30-cm ballast depth for reference, an increase in ballast depth of 3.8-7.6 cm (1½-3 in) is about equivalent to a 2.54-cm (1-in) reduction in tie spacing with regard to its effect on reducing ballast pressure. Maximum deviator stress decreases rapidly as ballast depth increases—decreasing about 44 percent as ballast depth is increased from 30 cm to 90 cm for the 75-cm tie spacing, about 36 percent for the 49-cm (19½-in) spaced wood ties, and about 30 percent for the 50-cm spaced concrete ties. As ballast depth increases, the level of deviator stress converges to within 20.67 kPa (2.5 lbf/in²) of a common value for all ties and tie spacing.

Figure 7 also shows that increasing the tie size for a given tie spacing reduces the level of deviator stress in general, but the range of tie width evaluated in this study was limited. However, an anomaly exists with 50-cm tie spacing because the larger tie actually increases ballast stress compared to a smaller tie for thin layers of ballast. The large concrete tie generates higher deviatoric stress midway through the ballast layer than the medium synthetic tie. This is due to the high stress at the tie end that is generated when the tie stiffness is quite high relative to the roadbed stiffness. In this study, the large concrete tie was three times stiffer than the small concrete tie and five times stiffer than the wood tie. When the tie is quite stiff relative to the roadbed, the pressure distribution under the tie would

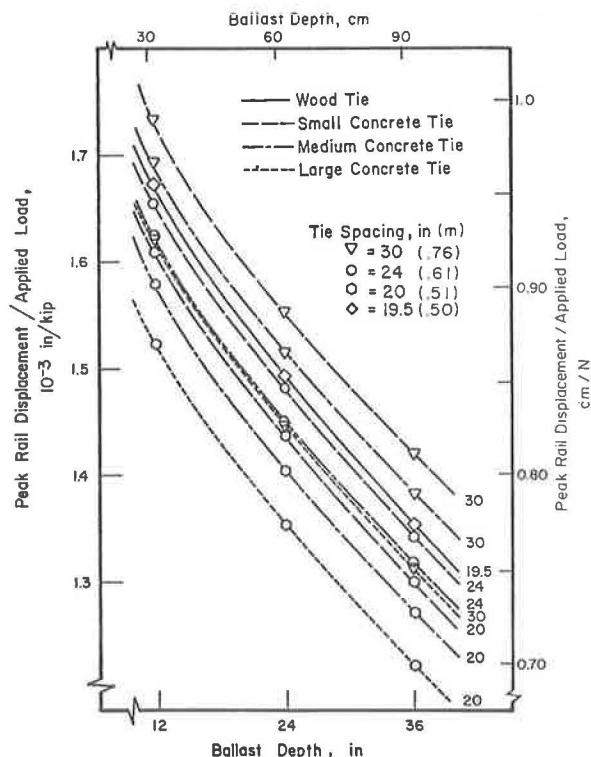**Figure 5. Maximum rail displacement.**
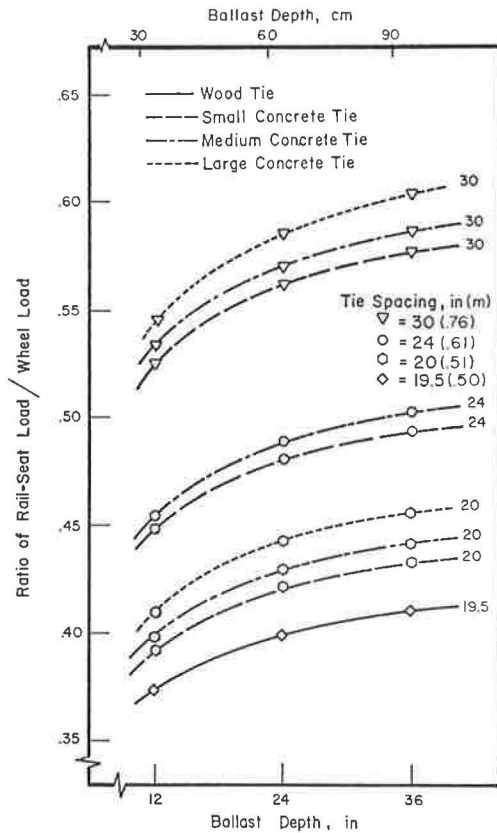
Figure 6. Rail-seat load.

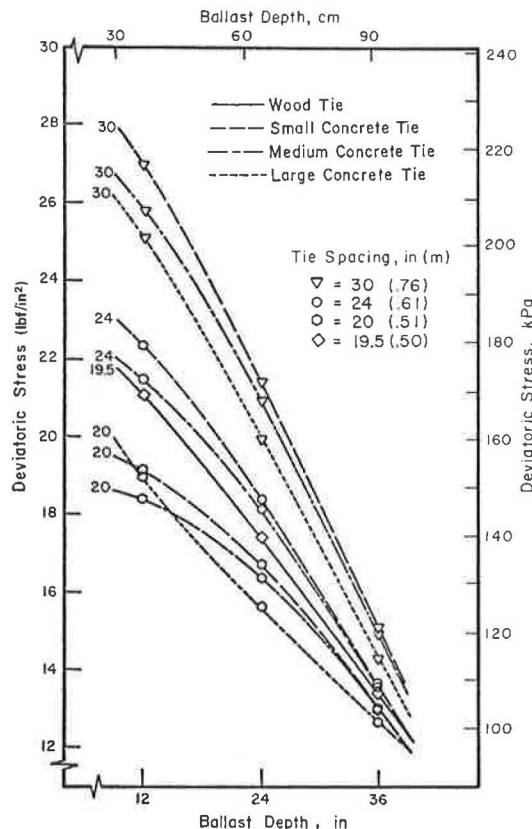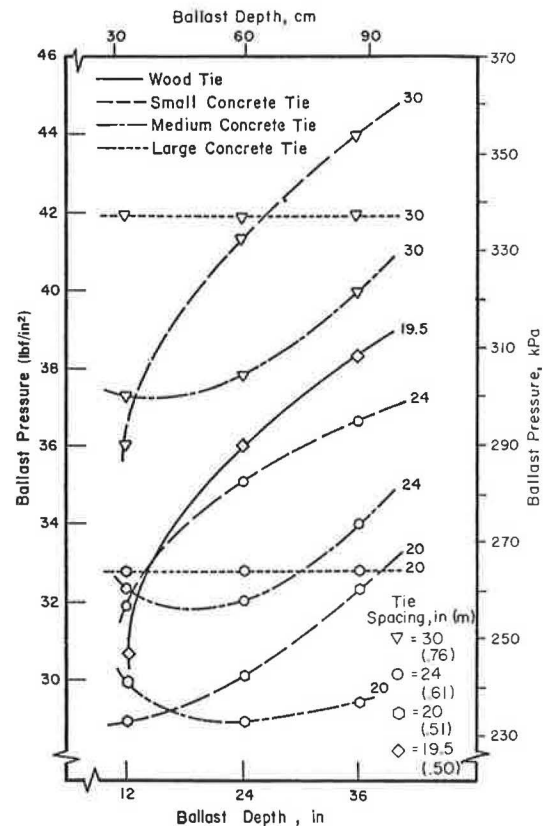Figure 7. Maximum deviatoric stress midway through ballast.

Figure 8. Maximum vertical ballast pressure at tie ballast interface.

resemble that of a rigid punch on an elastic medium. The vertical pressure at the ends of the tie would be very high (theoretically infinite) and reduce to some minimum value at the tie center. The punch effect of the stiff, large tie causes high stresses at the end of the tie on the relatively flexible roadbed with only 30 cm of ballast. Thus, crushing and flow of the ballast at the ends of the tie may be a problem. This loss of ballast support at the tie ends has been observed recently at the Facility for Accelerated Service Testing track in Pueblo, Colorado. Loss of ballast at the tie ends may also be increased by vibration aggravated by tie center-binding and rail corrugation.

The effect of too thin a ballast layer for a stiff tie should not be ignored. As the ballast depth is increased, ballast stiffness and, thus, roadbed stiffness increase. Therefore, the ratio between tie and roadbed stiffness decreases and the punch effect is reduced.

Maximum bulk stress at a location midway through the ballast for the same parameter variations behaved in much the same manner as the deviatoric stress. The stress level reduced rapidly and converged to within 13.78 kPa (2 lbf/in^2) of a common value as ballast depth increased from 30 cm to 90 cm. The punch effect of using a large concrete tie with a thin ballast layer was evident. Increasing the size without properly increasing ballast depth could minimize the advantages of a larger tie.

The maximum pressure on the ballast surface under ties is one of the criteria used in conventional track design procedures. A maximum allowable pressure at 448 kPa (65 lbf/in^2) is typical. Figure 8 shows the maximum vertical ballast pressure predicted by MULTA. Increasing tie spacing increases the ballast pressure in all cases, as expected. Increasing track

Figure 9. Maximum subgrade deviatoric stress.

Figure 10. Maximum-minimum deviatoric stress ratio across tie midway through ballast.
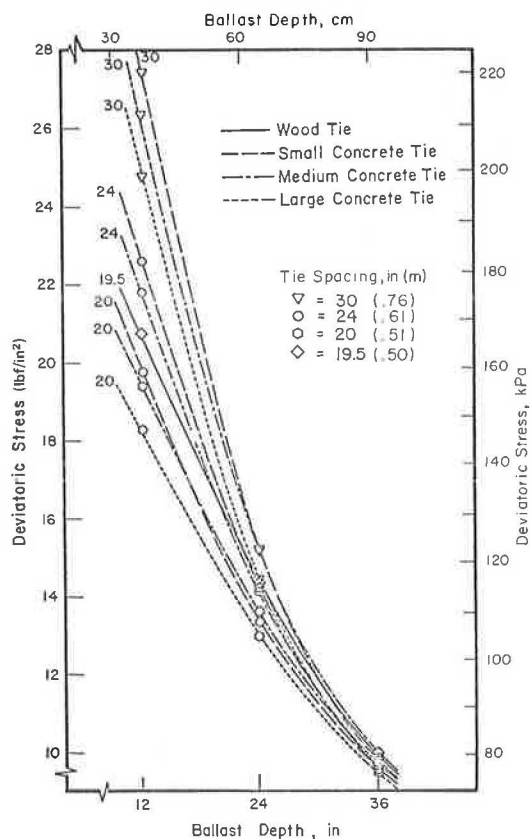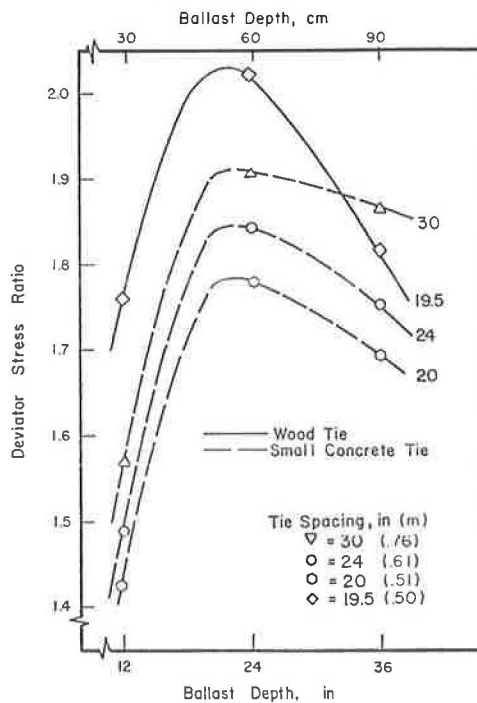

stiffness by increasing ballast depth also causes some increase in ballast pressure due to the increase in rail-seat load. However, the interaction between tie and roadbed stiffness is also evident, thus obscuring any clear trends. Increasing the roadbed stiffness with a relatively flexible tie such as wood or the small and medium-sized concrete ties does increase the maximum ballast pressure. However, the ballast pressures from the stiff large tie are independent of ballast depth and can provide some advantage over the smaller ties at the same spacing on deep ballast due to the more uniform pressure distribution along the tie length.

Subgrade Stresses

Figure 9 shows the maximum subgrade deviator stress that occurs at the ballast and subgrade interface. The maximum deviator stress is very sensitive to increases in ballast depth and tie spacing. For ballast depths of about 30 cm, stress increases from increasing tie spacing can be offset by equal changes in ballast depth. For ballast depths greater than about 75 cm, the effects of tie size and spacing become negligible.

The maximum vertical subgrade stress at the ballast and subgrade interface behaved in the same manner as the subgrade deviatoric stress. The maximum values of subgrade stress decreased rapidly with increased ballast depth. Vertical stress on the subgrade increased with a corresponding increase in tie spacing, but this effect can be offset by a small increase in ballast depth. The vertical stress converged to a common value for all tie sizes and spacings for ballast depths greater than about 61 cm (24 in).

Ballast and Subgrade Stress Distribution

The previous data showed maximum stresses that occur at some point under a tie. Although the maximum stress is certainly a major factor in track performance, the variations in stress under a tie and along the track length also contribute to degradation. Nonuniform ballast stresses cause differential compaction and flow under the ties leading to an end-bound or center-bound support condition. Uniform ballast stresses would hopefully cause uniform settlement. This would minimize the effects of nonuniform support condition and reduce the peak pressures to the average pressure, thereby effectively utilizing the entire bearing area of the tie.

Nonuniform stresses on the subgrade cause depressions or rutting. These depressions will collect and retain moisture in climates with significant rainfall, and the resulting local reduction in subgrade strength will cause a rapid increase in the rate of settlement and pumping. This possibility was recognized by Salem and Hay (6), and they recommended a ballast depth of about 46 cm (18 in) to minimize subgrade pressure variations along the track with wood ties spaced at 53 cm (21 in). However, significant subgrade pressure variations remain under the tie even with ballast depths of 46 cm. This indicates that even greater ballast depths may be required to achieve a uniform pressure distribution and eliminate subgrade rutting under the rails. This observation has previously been ignored in track design.

Several pressure ratios have been calculated as a quantitative measure of the uniformity of roadbed pressure distributions. A pressure ratio for the maximum to minimum pressure variation under a tie and for the maximum to minimum pressure variation from under the tie to midway between ties at the rail-seat region gives an indication of the tie and track pressure variations. A pressure ratio close to 1.0 represents

the ideal pressure distributions to minimize differential ballast degradation and rutting in the subgrade. Figures 10 and 11 show these two pressure ratios in the ballast for the small concrete tie compared to the referenced wood tie track. The stiffer concrete tie produces a more uniform pressure distribution under the tie (Figure 10) for practically all tie spacing and ballast depth combinations, but the wood tie track shows more uniform pressures along the track (Figure 11). In-creasing tie spacing causes a relatively large increase in pressure ratio along the track compared to under the tie, but the pressure variations under the tie are higher and are, therefore, the more critical design problem.
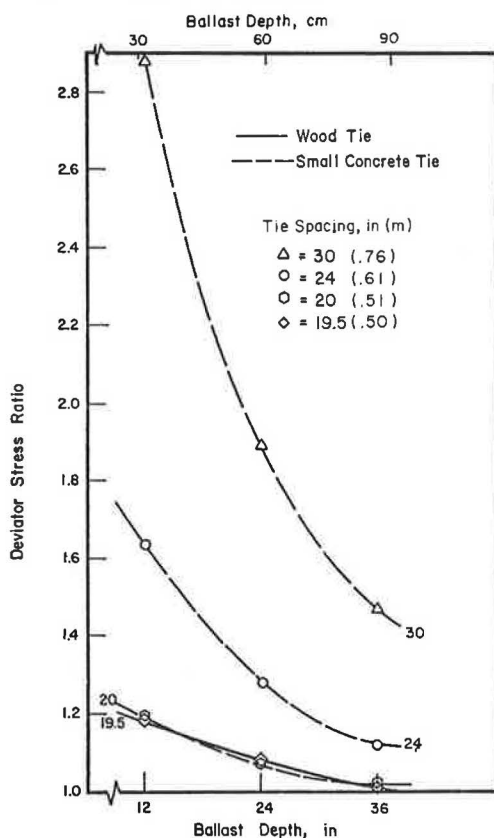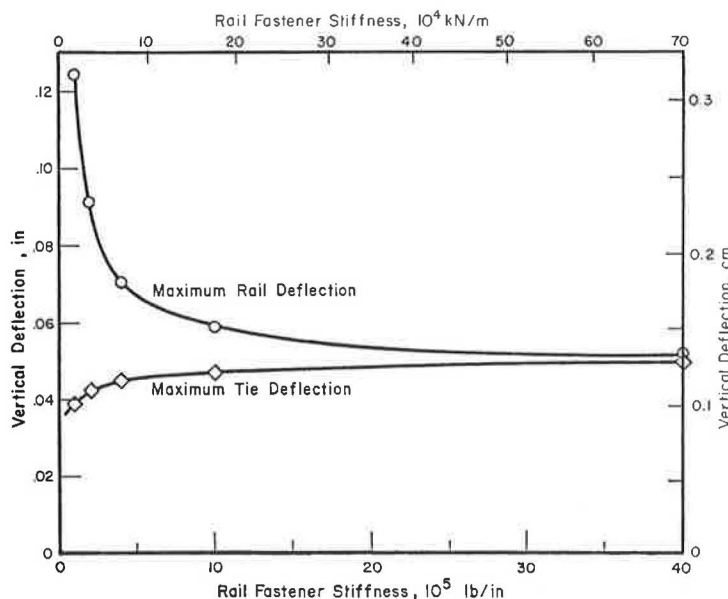
The same pressure ratios were calculated at the subgrade as a measure of potential rutting. Increasing ballast depth effectively attenuates subgrade pressure variations both under the tie and along the track. The effects of increasing the tie spacing are relatively minor for ballast depths greater than about 61 cm. The subgrade pressure variations under the tie are more important than those along the track for ballast depths greater than about 30 cm.

Effect of Rail Fastener Stiffness

The results presented in the previous paragraphs were based on a rail fastener having a nominal vertical stiffness (spring rate) of 40×10^5 lb/in, typical of many fasteners currently being used with concrete ties in the United States. This stiffness represents the total load-deflection characteristics for a rail fastener assembly consisting of rail restraining devices and a tie pad. Rail fasteners are simulated in the MULTA program by linear vertical springs between the rail base and each tie.

Figure 12 shows that reducing the rail fastener stiffness increases rail displacements significantly when the fastener stiffness is less than about 500 000 lb/in. This reduction in stiffness also distributes the wheel load over more ties so that the maximum rail-seat loads and, therefore, tie deflections are reduced. The effect of varying the rail fastener stiffness depends on the stiffness of the fastener relative to the effective roadbed stiffness at each tie. When the fastener is rigid relative to the roadbed, the track response is governed by the roadbed stiffness and the deflection of the rail fastener is very small, as the right side of Figure 12 indicates. When the fastener is very flexible relative to the roadbed, the track response is governed by the fastener stiffness as indicated on the left side of Figure 12.

Figure 13 shows that a flexible rail fastener does reduce the maximum rail-seat load and the tie and ballast pressure. The maximum tie bending moments

Figure 11. Maximum-minimum deviatoric stress ratio along track midway through ballast.

Figure 12. Effect of rail fastener stiffness on maximum rail and tie deflections.

Figure 13. Effect of rail fastener stiffness on maximum vertical rail-seat load and ballast pressure.
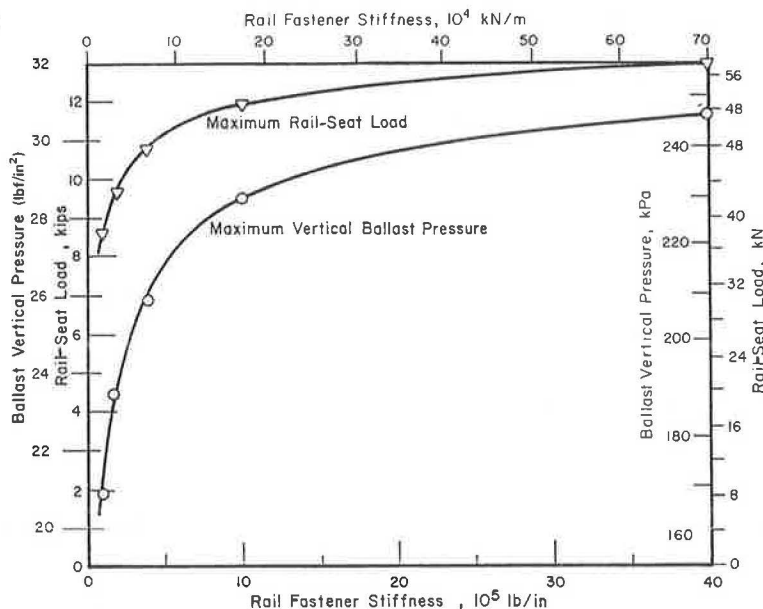

Table 2. Typical rail fastener vertical stiffness data.

Fastener Type	Toe Load (kN per clip)	Clip Stiffness (10^4 kN/m per clip)	Total Fastener Stiffness (10^4 kN/m)
Very flexible	-	-	1.75-3.50
Flexible	7.1-12.0	0.035-0.123	8.75-28.0
Rigid	-	0.35-8.76	35.0-123

Note: 1 kN = 225 lbf, 1 kN/m = 68 lbf/ft.

Figure 14. Tie spacing and ballast depth requirements to give same maximum subgrade deviatoric stress as wood tie track.
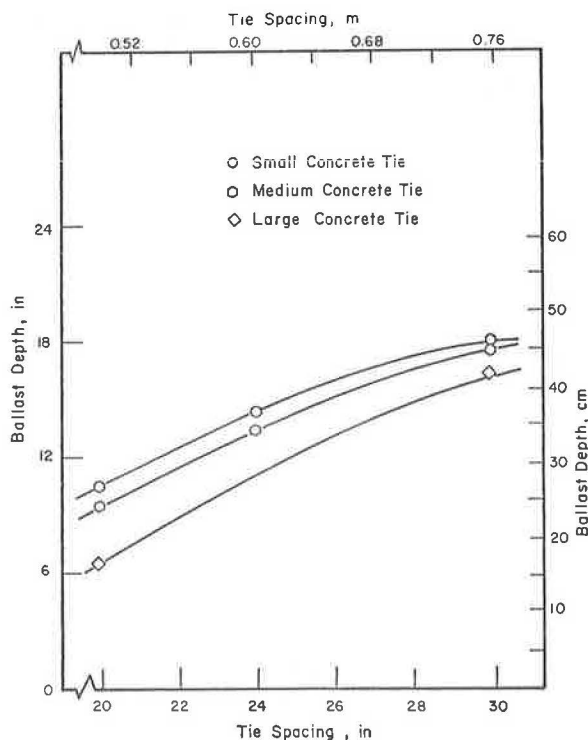
and subgrade pressures would be reduced accordingly. Rail bending moments are increased somewhat, but this is not usually critical unless a relatively small rail is used.

It is important to realize that practically all of the

rail fasteners currently being used for concrete ties in the United States are relatively rigid compared to the roadbed. Table 2 shows some typical stiffnesses for three general classes of fastener. Very flexible fasteners are used for direct fixation transit track, such as in Toronto, where it is important to attenuate ground vibrations in subways. These fasteners restrain the rail by thick pads of rubber and are sufficiently flexible to reduce tie loads. However, they are not designed for the higher axle loads of U.S. railroads.

The flexible fastener category includes several different configurations with metal retaining clips having considerable flexibility. However, these are generally installed in the United States with a relatively thin ($\frac{1}{8}$-$\frac{3}{16}$ in) rubber or plastic rail pad that is very stiff relative to the clip. This produces a fastener with a vertical stiffness of 5 to 16 $\times$ 10^5 lb/in, which provides very little reduction of track loads. The stiffness of the rail pad determines the total stiffness of the fastener assembly for these designs.

Rigid fasteners include several configurations of stiff metal clips with thin rail pads of very hard material. The rail pad must be quite stiff to avoid fatigue failures of the rigid clip and attachment hardware. The stiffness of these fasteners is typically in the 20 to 70 $\times$ 10^5 lb/in range, and this cannot be expected to produce any substantial reduction of static or dynamic rail loads.

These results show that rail fasteners must have a vertical stiffness less than about 500 000 lb/in in order to provide any significant benefit by distributing wheel loads over more ties. These conclusions are based on a static analysis where the load is assumed to be constant. A second potential benefit of a flexible fastener is in reducing dynamic loads resulting from track irregularities, such as joints or rail welds and wheel flats. The increased stiffness of concrete tie track is undesirable from the standpoint of producing higher dynamic forces that adversely affect mainte-

Table 3. Comparison of concrete tie track designs expected to perform in the same manner as standard wood tie track.

Concrete Tie Type	Tie Spacing (m)	Ballast Depth (cm)			
		Equal Subgrade Vertical Stress[a]	Equal Subgrade Deviator Stress[b]	Equal Ballast Surface Vertical Stress[c]	Equal Ballast Deviator Stress[d]
Small	0.55	27.9	30.5	43.2	26.7
	0.61	30.5	36.8	26.7	40.6
	0.69	33.0	41.9	22.9	53.3
	0.76	35.6	45.7	22.9	62.2
Medium	0.55	24.1	27.9	-	17.8
	0.61	26.7	34.3	-	34.3
	0.69	29.2	40.6	-	48.3
	0.76	31.8	44.5	-	59.7
Large	0.55	19.1	21.6	-	21.6
	0.61	22.9	27.9	-	30.5
	0.69	26.7	35.6	-	43.2
	0.76	31.8	40.6	-	55.9

Notes: 1 m = 3.3 ft, 1 cm = 0.4 in.
Wood tie reference track is 17.8-cm x 22.9-cm x 259-cm wood ties at 0.50-m spacing.
[a] Maximum subgrade vertical stress = 93.3 kPa.
[b] Maximum subgrade deviator stress = 166.4 kPa.
[c] Maximum ballast vertical stress = 246.8 kPa.
[d] Maximum ballast deviator stress midway in ballast layer = 169.6 kPa.

nance of both track and vehicles. Previous studies by Battelle Laboratories (7, 8) and others have shown that it is desirable to introduce resilience into the rail fastener to compensate for this increased stiffness. Development efforts in Europe and the USSR of fasteners having multiple thick elastomeric pads indicates that increased flexibility is a major design objective. This trend appears to have been ignored in the United States where recent fastener modifications have included reducing the thickness and increasing the durometer of pads to improve fatigue life of the rail clips—all steps that increase fastener stiffness.

It is recognized that, once fastener resilience is given a high design priority, achieving a successful design is no small challenge. Maintaining adequate lateral restraint against gauge spread and rail roll-over while reducing the vertical stiffness is the major problem. Another problem is that stiffness characteristics of most elastomers vary considerably with temperature, making it difficult to maintain uniform performance throughout the year. However, the reduction of impact loads and the improvement in load distribution that can be obtained with more flexible fasteners should be adequate to encourage additional development efforts by industry.

DESIGN FOR EQUIVALENT TRACK PERFORMANCE

The lack of criteria to relate track response parameters in the form of ballast and subgrade stresses to quantitative predictions of track degradation rate make it difficult to compare different track structure designs in a meaningful way. However, it is possible to select track structures expected to give equal performance with regard to surface maintenance by comparing selected track response parameters from the parametric study.

For example, Figure 14 shows those concrete tie track designs that have the same maximum subgrade deviatoric stress as a wood tie track with 49.5-cm (19.5-in) tie spacing and 30 cm (12 in) of ballast. All calculations are based on 136 lb/yd rail and the same subgrade and material properties used for the parametric study. These results show that relatively small increases in ballast depth will compensate for substantial increases in tie spacing.

Table 3 summarizes the equivalent track design parameters for several tie spacings based on equal subgrade and ballast stresses. Equivalent designs are shown based on maximum vertical stresses as used in

conventional design procedures and maximum deviator stress, which is recommended as a more suitable indication of long-term performance.

This comparison shows that the greatest ballast depths for a selected tie spacing will be required to equalize the ballast deviator stress. Both ballast and subgrade deviator stress criteria require greater ballast depths and, therefore, a more conservative design than the vertical stress criteria used for conventional track design. These summary data also show that the larger concrete tie has the advantage of requiring less ballast depth or wider spacing for comparable performance. This results primarily from the increase in bending stiffness because the tie width is almost the same for the small, medium, and large concrete ties. A substantial increase in width would give an added performance advantage to the large tie.

Increasing ballast depth also reduces the subgrade pressure variations as measured by the pressure ratios under the tie and along the track. An exercise similar to that shown in Table 3 could be done using equal pressure ratios as the criteria. The difficulty is that an overall performance index that combines these different parameters with appropriate weighting factors for track degradation is needed to further quantify track design.

SUMMARY

MULTA, a track analysis model, was developed in order to predict realistic stress distributions in the ballast and subgrade. This model also includes the effect of tie bending and changes in ballast depth, ballast and subgrade material properties, tie size, and tie spacing. This is a significant improvement over conventional track design practice.

Results from the MULTA model with vertical loading show the influence of tie bending stiffness on the variations in tie-ballast pressure along the tie length. Wood ties and small concrete ties that are flexible relative to the roadbed cause maximum pressures under the rail-seat region. Large concrete ties with a high bending stiffness relative to the roadbed stiffness can cause maximum pressure close to the tie ends. The maximum stress levels in the ballast and subgrade are major factors in track settlement, but nonuniform stress distribution on the subgrade under the tie and along the track can cause local depressions or rutting. These depressions will collect water resulting in possible slow drainage. The local reduction in subgrade strength from excess moisture will cause a rapid increase in settlement and pumping. For this reason,

both the maximum ballast and subgrade stresses and a ratio of maximum to minimum stress as a measure of stress variation are recommended as critical factors for track design. Increasing tie spacing causes a relatively large increase in pressure ratio along the track, but the pressure variations under ties are higher and are therefore the more critical design problem. Track design data generated with the MULTA program can be used to evaluate the effects of changing ballast depth, tie size, and tie spacing on roadbed stresses. The parametric study showed that a track system with various combinations of synthetic tie size, tie spacing, and ballast depth gave equal or superior roadbed stress conditions when compared to a track structure with wood ties.

Results from the parametric evaluation of vertical rail fastener stiffness showed that the distribution of track loads can be improved by using a flexible fastener with a vertical stiffness less than about 500 000 lb/in. Other studies show that a flexible fastener can also reduce impact loads from wheel flats and rail joints and thereby can compensate for the normal increased stiffness of concrete over wood tie track. European and Russian fastener development efforts have been concentrated on designing more flexible rail fasteners. This trend has been largely ignored in the United States, where all fasteners currently used with concrete ties are rigid relative to the track. Maintaining adequate lateral restraint against gauge spread and rail rollover is the major design problem in developing a fastener with a lower vertical stiffness. However, the reduction in impact loads and the improved load distribution that can be obtained with more flexible fasteners should be adequate to encourage additional development efforts by the industry.

ACKNOWLEDGMENT

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Effects of Ride Environment on Intercity Train Passenger Activities

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The ability to read, write, talk, and sleep on a transit vehicle has been cited frequently in the ride quality literature as an important factor in passengers' comfort and satisfaction with transportation systems. A field study of passenger activities on intercity trains was conducted to quantify and describe the relation between the relative frequencies of various passenger behaviors and the physical parameters of ride quality. Vibration in six degrees of freedom, acoustic noise, temperature, relative humidity, and illumination were measured at the same time as observations of passenger activity were made aboard 77 Amtrak vehicles on 14 trains between Newark, New Jersey, and Washington, D.C. Rotational vibration rates (1-20 Hz) were found to be negatively correlated with the observed performance of social and motor activities and positively correlated with resting behaviors. Linear vibrations did not significantly affect observed activity frequencies. Noise levels resulting primarily from passengers' conversations were negatively correlated with frequencies of sleeping. Activity levels also varied with vehicle type and time of day. Multiple regression techniques were used to develop linear equations of physical ride quality and trip variables that predict approximately 20 percent of the variance in activity levels. Individual differences are postulated to explain the remaining activity variance. The activity equations could be used to specify acceptable levels of ride quality factors for passenger activity performance in the design of advanced transportation systems.