Effect of Design Parameters on Track Support Systems

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A finite-element structural-analysis model for conventional railway-track support systems previously developed was used as the basis of a study of design parameters to establish the effects of the various parameters on the instantaneous-elastic response of a support system. The parameters studied were type and depth of ballast, type and depth of subballast, subgrade-support conditions, rail size, tie spacing, wheel loading, and number of missing ties. The study indicated that type of ballast and rail size do not significantly affect the instantaneous-elastic response of a support system, but the stabilized subballast, the subgrade-support condition, and the wheel loading are major parameters that do.

Over the years, sporadic efforts have been made to develop analytical methods for the evaluation of the structural response of railway-track support systems. The early attempts to model these systems were hampered by the lack of satisfactory theories for representing the behavior of their various components. In the last quarter century, however, extensive developments in track and pavement-system modeling have coincided with developments in electronic computer technology.

One of the major limitations of the track-system behavior models that have been developed is the inadequate representation of the structural behavior of the ballast and subgrade soil materials. In most models of track support systems, the ballast and subgrade system has been represented by an elastic half space or by a spring constant. The various types of models are listed below:

1. Beam on elastic foundation (1, 2),
2. Finite beam on elastic foundation (3, 4, 5, 6, 7),
3. Analytical solution for track structure subjected to moving and oscillating loads (8),
4. General Boussinesq (9),
5. Semiempirical [e.g. Japanese National Railway Equation (10)], and
6. Finite-element (11, 12, 13).

Numerous theories, techniques, and procedures have been developed for calculating stress and strain and deflection or deformation conditions in track support systems. Even the most recent developments in the methodology of track-structure analysis have concentrated on realistic representations of the rail, fastener, and tie components, while representing the ballast and subgrade either as springs or as linear-elastic-homogeneous materials. Most of the attention has been directed to the behavior of the rail, rather than to that of the ballast and subgrade soil.

Recent developments in highway and airfield-pavement technology have demonstrated that the repeated-load response of granular materials and subgrade soils is very much dependent on the stress conditions existing in the materials (14, 15, 16). Thus, a realistic representation of these materials in a model for track-system analysis requires that their stress-dependent nature be adequately considered. With the limitations of the existing methods and the requirements of a realistic analytical model in mind, a finite-element model—ILLI-TRACK—was developed that incorporates the basic components of the conventional railway-track support system (CRTSS) and can accommodate the stress-dependent structural response characteristics of the ballast, the subballast, and the subgrade. A detailed discussion of the development of the model has been given by Tayabji (17), and a brief description of it is presented below.

ILLI-TRACK MODEL

Figure 1 shows a typical longitudinal section and a typical transverse section of a CRTSS. Because of the three-dimensional geometry and the nonuniform loading conditions, an analysis of the conventional railway track structure should use a three-dimensional finite-element model to represent the system. However, the amount of discretization and the computer costs required for solution of the problem would be high and probably impractical.

However, when the symmetrical nature of the loading in the transverse direction is examined, it is apparent that a two-stage analysis might provide a reasonable engineering approach. In this analysis, the longitudinal analysis is followed by the transverse analysis.

The longitudinal analysis considers the point loads (corresponding to wheel loads), acting on a single rail sitting on a tie-ballast-subgrade system. Figure 2 shows a typical finite-element mesh, such as is used for this analysis. The rail and tie subsystem is represented as a continuous beam supported on tie springs. Rectangular planar elements are used to represent the ballast, the subballast, and the subgrade materials. The thickness of the elements is varied with depth by using a pseudoplane strain technique to account for the spread of loading in the direction perpendicular to the plane. This allows a two-dimensional model to simulate the three-dimensional load spread that is known to exist in practice. The displacement components are assumed to vary linearly over each element.

The transverse analysis uses an output from the longitudinal analysis as its input. Either the maximum reaction or the maximum deflection at a tie obtained from the longitudinal analysis is used as the input at a tie that rests on the ballast and subgrade subsystem. Again the pseudoplane strain technique is used. The tie can be represented either as a two-dimensional body or as a beam resting on the ballast. A rectangular element representation is used for the ballast, the subballast, and the subgrade materials, and the displacement components are assumed to vary linearly over each element. Figure 3 shows the finite-element mesh used for the transverse analysis. Triangular elements can be used to incorporate sloping ballast shoulders.

This finite-element model has been validated by using measured responses at section 9 of the Kansas Test Track (17). Good agreement was obtained between the measured responses and those calculated by using the model. As more appropriate field response data become available, it is expected that the model will be further validated. In its present state, the ILLI-TRACK model is not a design model, but rather an analysis tool.

The characteristics of stress-dependent materials can be determined in terms of the resilient modulus. For ballast materials and sandy soils, the stress-dependent resilient response can be incorporated by using Equation 1.

$$E_R = K\theta^n \qquad (1)$$

where

E_R = resilient modulus = repeated deviator stress/elastic or recoverable strain,
θ = sum of principal stresses = $\sigma_1 + \sigma_2 + \sigma_3$, and
K and n = constants determined from laboratory tests.

For fine-grained soils, the resilient modulus generally decreases as the deviator stress ($\sigma_d = \sigma_1 - \sigma_3$) increases. At higher values of the deviator stress, the resilient modulus is almost constant.

Stress-dependent characteristics have been incorporated in the ILLI-TRACK model. However, failure criteria and constitutive response models for granular materials subjected to stress states in which the confining stress is close to zero (tending to go into tension) or in which the principal stress ratio (σ_1/σ_3) exceeds a limiting value are not well defined. At present, when granular material element in the structural model satisfies the failure criteria [in terms of the minimum allowable minor principal stress (σ_3) or of the maximum principal stress ratio (σ_1/σ_3)], it can be assigned a low modulus value of 27.59 MPa (4000 lbf/in^2) to be used in the next step loading analysis. Analyses can also be carried out in which no failure criteria for granular materials are used; it is then assumed that the granular material would be stable under any state of stress and that the resilient modulus of a granular material element determined by using Equation 1 is valid, even when the failure criteria are satisfied. The omission of failure criteria considerations make the analysis less conservative, and thus the calculated responses are less severe.

With these considerations in mind, a study of the

Figure 1. Typical longitudinal and transverse sections of conventional railway track.

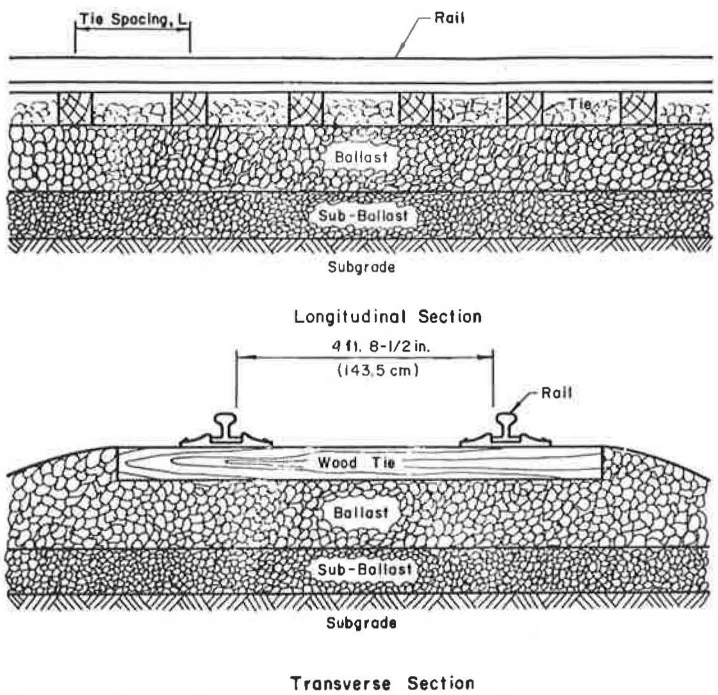
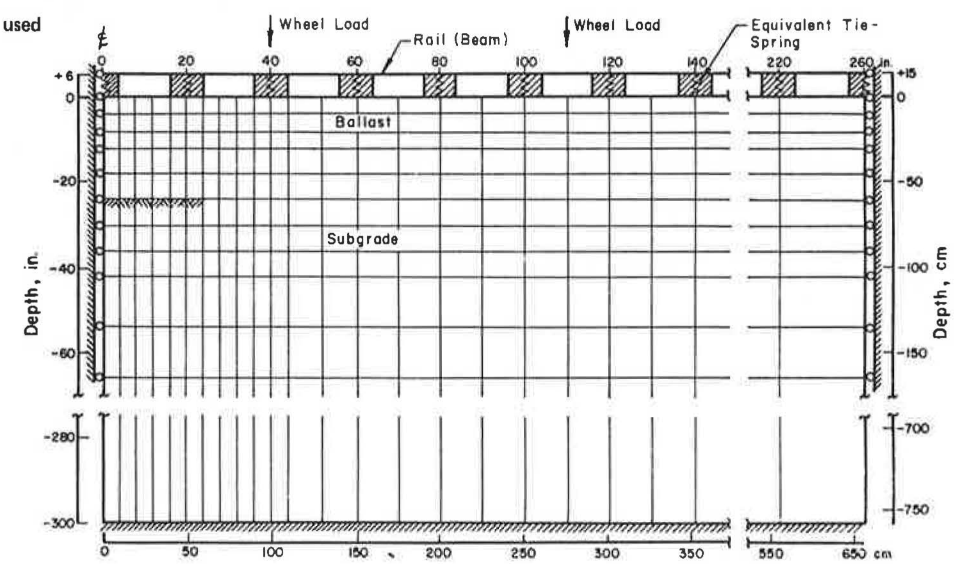


Figure 2. Typical finite-element mesh used for longitudinal analysis.



design parameters was conducted to evaluate the relative differences among the responses of different track systems. The failure criteria selected for the ballast were a σ_1/σ_3 value of 10 and a σ_3 value of 0. Loading was applied in three increments. Because the selection of the failure criteria was arbitrary, the study also included analyses of track sections for which no failure criteria were used.

STUDY OF DESIGN PARAMETERS

An important feature of the design of a track support system is the judicious selection of the optimum design based on factors such as available resources, anticipated performance, and level-of-service requirements. One method used in the selection of an optimum design is to conduct a parameter study or a sensitivity analysis and evaluate the effects of the critical design parameters on the response of the system. The structural model used to evaluate the response of a track support system should therefore be capable of incorporating the critical design parameters. The ILLI-TRACK model possesses this capability and was used to study the effects of various design parameters on the response of the track support system.

Reference Track

A reference track was designed to allow the comparison of the structural responses of track support systems with different design parameters. The characteristics of the track are given below (1 kg/m = 2.0 lb/yd, 1 cm^4 = 0.023 in^4, 1 GPa = 145 037 lbf/in^2, and 1 m = 3.3 ft):

Characteristic	Value
Rail	
Linear mass, kg/m	68
Moment of inertia, cm^4	3954
E, GPa	20.7
Timber ties	
Size, m	0.23 by 0.18 by 2.59
Spacing, m	0.51
Compressive modulus, MPa	8618
Crushed stone ballast	
Resilent response model, E_R	$5082\theta^{0.58}$
Poisson's ratio	0.35
Subballast	—
Subgrade (embankment)	
Poisson's ratio	0.47

The resilient-response curve data for the average subgrade are given below (1 kPa = 0.145 lbf/in^2):

σ_D (kPa)	E_R (kPa)
0.7	102 180.0
42.8	55 160.0
249.6	19 990.0

The reference loading was taken to be two trucks of two adjacent freight cars, each car having a gross mass of 108.8 Mg (240 000 lb), thus giving an approximate wheel load of 133 kN (30 000 lbf). The truck spacing was 3.81 m (150 in), and the axle spacing was 1.78 m (70 in).

The structural responses of particular interest were

Figure 3. Typical finite-element mesh used for transverse analysis.

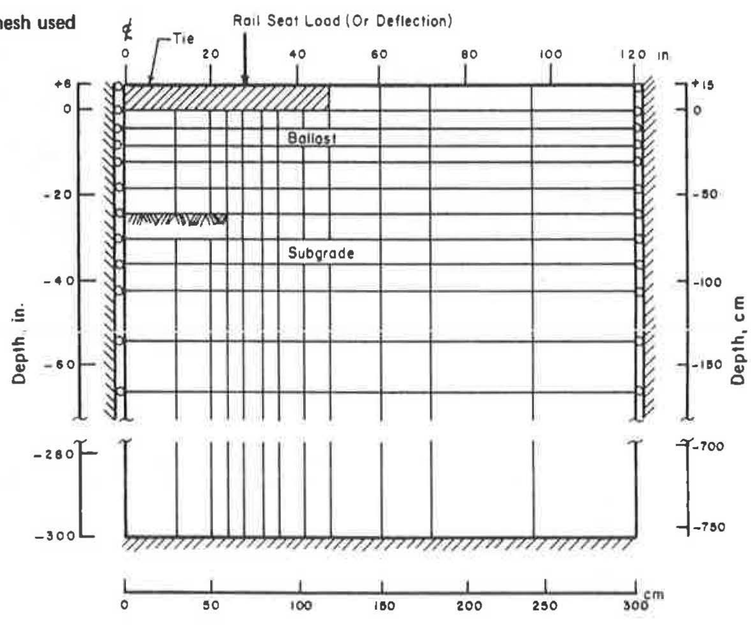


Table 1. Responses of sections with type of ballast as variable.

Response	Failure Criteria Used: Crushed Stone	Failure Criteria Used: Blast-Furnace Slag	Failure Criteria Used: Well-Graded Crushed Stone	No Failure Criteria Used: Crushed Stone	No Failure Criteria Used: Blast-Furnace Slag	No Failure Criteria Used: Well-Graded Crushed Stone
Maximum rail deflection, mm	2.5	2.0	2.3	1.8	1.8	1.8
Maximum rail moment, kN·m	33.6	29.3	31.5	27.1	27.6	27.7
Maximum ballast vertical stress, kPa	788.1	533.7	564.0	369.5	367.5	396.5
Maximum subgrade vertical stress, kPa	182.0	140.0	143.4	135.1	136.5	137.2
Maximum subgrade vertical strain	0.001 15	0.000 71	0.000 83	0.000 75	0.000 79	0.000 80

Note: 1 mm = 0.039 in, 1 kN·m = 8820 lbf·in, and 1 kPa = 0.145 lbf/in^2.

the rail deflections and moments, the ballast and subgrade vertical stresses, and the subgrade vertical strain. When considering the effect of a particular design parameter, only its input value was changed; all other design parameters were kept constant.

Variable: Type of Ballast

The following types of ballast were evaluated (1 cm = 0.39 in):

Section	Description
1 (reference)	No. 4 gradation crushed stone, $E_R = 5092\theta^{0.58}$
2	No. 4 gradation blast-furnace slag, $E_R = 1957\theta^{0.77}$
3	Well-graded crushed stone (max size 2.5 cm, 20 percent smaller than no. 40, E_R $3582\theta^{0.59}$)

The comparison of the responses of the three sections shown in Table 1 indicates that the influence of type of ballast on the transient response of the track support system is not large. However, different ballast materials have characteristically different permanent deformations (rutting or loss of alignment) behavior and particle breakdown (degradation) when subjected to repeated application of a particular state of stress. While the transient responses when different ballasts are used may be similar, the ballasts may have different durability properties. Therefore, when ballast types are compared, the factors affecting their long-term behavior must be considered in addition to their transient structural responses.

Variable: Depth of Ballast

The following depths of crushed stone ballast were evaluated for 68 and 57 kg/m (136 and 115 lb/yd) rails (1 cm = 0.39 in):

Figure 4. Responses of track system for varying depths of ballast: (a) 20.3 cm, (b) 30.5 cm, and (c) 61 cm.

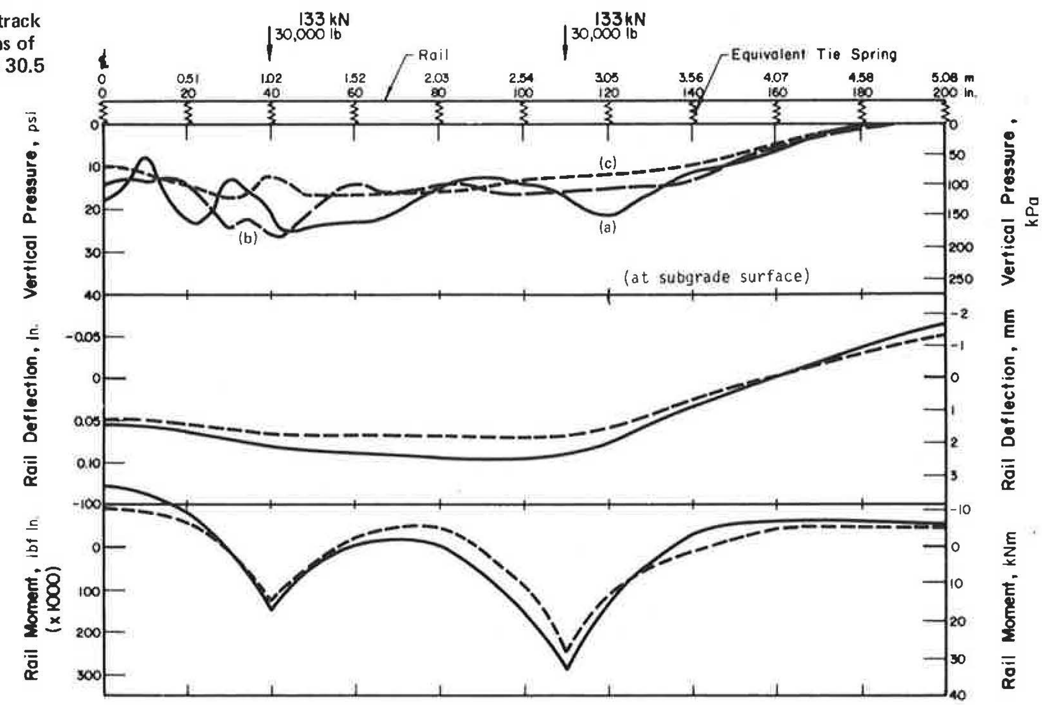


Table 2. Responses of sections with depth of ballast as variable (68 kg/m rail).

	Depth of Ballast (cm)					
	Failure Criteria Used			No Failure Criteria Used		
Response	20.3	30.5	61.0	20.3	30.5	61.0
Maximum rail deflection, mm	2.5	2.5	1.8	1.8	1.8	1.5
Maximum rail moment, kN·m	33.1	33.6	29.3	27.6	27.1	25.6
Maximum ballast vertical stress, kPa	606.8	788.1	633.0	347.5	369.5	416.5
Maximum subgrade vertical stress, kPa	166.9	182.0	121.4	147.5	135.1	109.6
Maximum subgrade vertical strain	0.001 09	0.001 15	0.000 65	0.000 86	0.000 75	0.000 54

Note: 1 mm = 0.039 in, 1 kN·m = 8820 lbf·in, and 1 kPa = 0.145 lbf/in².

Table 3. Responses of sections with depth of ballast as variable (57 kg/m rail).

	Depth of Ballast (cm)					
	Failure Criteria Used			No Failure Criteria Used		
Response	20.3	30.5	61.0	20.3	30.5	61.0
Maximum rail deflection, mm	2.8	2.3	2.0	1.8	1.8	1.5
Maximum rail moment, kN·m	30.1	25.6	26.6	25.5	25.3	23.5
Maximum ballast vertical stress, kPa	750.9	649.5	757.1	364.7	392.3	449.5
Maximum subgrade vertical stress, kPa	193.1	182.0	130.3	152.4	140.0	111.7
Maximum subgrade vertical strain	0.001 52	0.000 94	0.000 78	0.000 94	0.000 83	0.000 60

Note: 1 mm = 0.039 in, 1 kN·m = 8820 lbf·in, and 1 kPa = 0.145 lbf/in².

Section	Depth (cm)
1	20.3
2 (reference)	30.5
3	61.0

The response of the track system is shown for the 68-kg/m rail in Figure 4. There was little difference in the responses for the 20.3 and 30.5-cm ballast depths, but there was a significant reduction in rail deflection and subgrade stress and strain when the 61.0-cm ballast depth was used. The pertinent results are summarized in Table 2.

The effect of the depth of ballast when 57-kg/m rail was used is summarized in Table 3. The trends in the responses are similar to those for the 68-kg/m rail. The rail moment remains relatively constant for the 20.3 and 30.5-cm depths of ballast. The 61.0-cm thick ballast layer tends to transmit the vertical stress on the subgrade more uniformly than do the thinner ballast layers for both of the types of rail considered.

To evaluate the effect of using a stabilized-soil layer, similar analyses were conducted for the 68-kg/m rail and the three depths of ballast, but with a 15.2-cm (6 in) layer of stabilized-soil subballast having a constant modulus value of 345 MPa (50 000 lbf/in²) incorporated into the sections. The results are summarized in Table 4. The use of the stabilized-soil layer tends to minimize the differences in the structural responses caused by changes in the ballast depth.

Table 4. Responses of sections incorporating stabilized subballast with depth of ballast as variable (68 kg/m rail).

	Depth of Ballast (cm)		
Response	20.3	30.5	61.0
Maximum rail deflection, mm	1.8	1.8	1.8
Maximum rail moment, kN·m	28.2	27.1	27.5
Maximum ballast vertical stress, kPa	566.8	595.7	635.0
Maximum subgrade vertical stress, kPa	138.6	129.6	102.0
Maximum subgrade vertical strain	0.000 79	0.000 71	0.000 48

Note: 1 mm = 0.039 in, 1 kN·m = 8820 lbf·in, and 1 kPa = 0.145 lbf/in².

Table 5. Responses of sections with type of subballast as variable.

	Failure Criteria Used				No Failure Criteria Used		
Response	None	Stabilized Soil (E = 345 MPa)	Stabilized Soil (E = 6900 MPa)	Sandy	None	Stabilized Soil (E = 345 MPa)	Stabilized Soil (E = 6900 MPa)
Maximum rail deflection, mm	2.5	1.8	1.5	2.0	1.8	1.5	1.5
Maximum rail moment, kN·m	33.6	27.1	23.6	28.4	27.1	26.0	23.5
Maximum ballast vertical stress, kPa	788.1	595.7	537.8	738.5	369.5	406.8	477.8
Maximum subgrade vertical stress, kPa	182.0	129.6	122.7	138.6	135.1	121.3	122.0
Maximum subgrade vertical strain	0.001 15	0.000 71	0.000 42	0.000 77	0.000 75	0.000 63	0.000 40

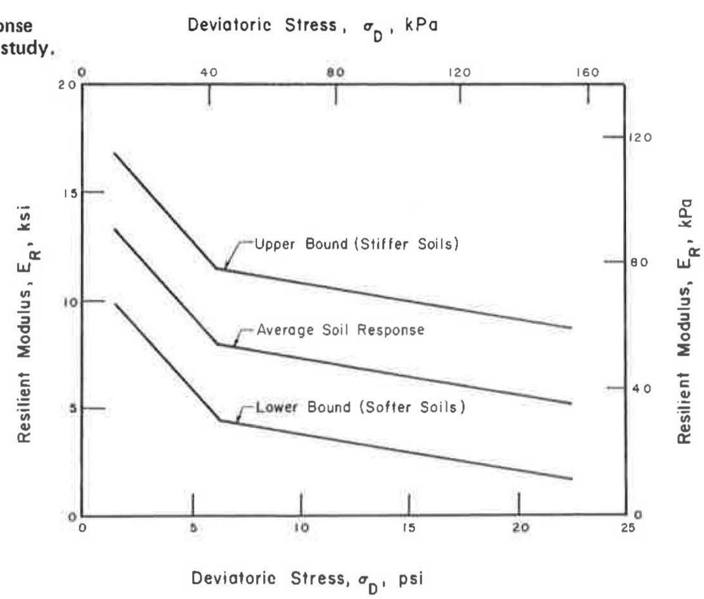
Note: 1 mm = 0.039 in, 1 kN·m = 8820 lbf·in, and 1 kPa = 0.145 lbf/in².

Table 6. Responses of sections with depth of stabilized subballast as variable.

	Depth of Subballast (cm)					
	Failure Criteria Used			No Failure Criteria Used		
Response	0	15.2	30.5	0	15.2	30.5
Maximum rail deflection, mm	2.5	1.8	1.8	1.8	1.5	1.5
Maximum rail moment, kN·m	33.6	27.1	27.7	27.1	26.0	25.0
Maximum ballast vertical stress, kPa	788.1	595.7	608.1	369.5	406.8	430.2
Maximum subgrade vertical stress, kPa	182.0	129.6	113.8	135.1	121.3	110.3
Maximum subgrade vertical strain	0.001 15	0.000 71	0.000 57	0.000 75	0.000 63	0.000 50

Note: 1 mm = 0.039 in, 1 kN·m = 8820 lbf·in, and 1 kPa = 0.145 lbf/in².

Figure 5. Bounds for resilient-response curves for fine-grained soils used in study.



Variable: Type of Subballast

The materials normally used as subballasts are lower quality granular materials (usually used as a filter layer) or stabilized soils. The thicknesses of subballast commonly used range from about 15 to 31 cm. The following types were evaluated (1 MPa = 145 lbf/in^2):

Section	Description
1 (reference)	No subballast
2	15.2-cm deep stabilized soil layer, constant E = 345 MPa
3	15.2-cm deep stabilized soil layer, constant E = 6900 MPa
4	15.2-cm deep sandy subballast, E_R $6700\theta^{0.36}$

The effect of type of subballast is shown in Table 5. The inclusion of a stabilized soil layer has a significant effect on the structural response of the track support system. The rail deflections and moments are reduced, and the vertical stress is uniformly transmitted to the subgrade. The section with no subballast has localized zones of high vertical stresses at the subgrade surface under the tie below the wheel load. The slab-type behavioral mechanism of the stiffer stabilized layer tends to minimize the development of tensile stresses and the dilation tendency within the ballast layer, which allows the ballast material to achieve higher moduli values. There is also a significant reduction in the vertical strain at the surface of the subgrade in the stabilized layer sections. The responses with and without the use of ballast failure criteria are similar for sections with stabilized-soil layers.

Variable: Depth of Subballast

The following depths of stabilized subballast having a constant E-value of 345 MPa were evaluated (1 cm = 0.39 in):

Section	Depth (cm)
1 (reference)	No subballast
2	15.2
3	30.5

The effect of the depth of the stabilized subballast is shown in Table 6. The use of a 15.2-cm stabilized-soil layer greatly improves the structural response of the track support system. However, except for a reduction in the subgrade strain, there was no appreciable difference in the responses of sections with 15.2 and 30.5-cm stabilized soil layers.

Variable: Subgrade

The subgrade is one of the most variable of the components of a track support system. The resilient response of fine-grained subgrade soils primarily depends on the type of soil and its degree of saturation, volumetric water content, compaction, and stress state.

Typical average, upper bound, and lower bound resilient-response curves for fine-grained soils are shown in Figure 5 (15). The upper bound response corresponds to stiffer (stronger) soils, and the lower bound response corresponds to softer (weaker) soils. The following stiffnesses of soils were evaluated:

Section	Stiffness
1	Softer
2 (reference)	Average
3	Stiffer

The effect of subgrade stiffness is shown in Table 7. Comparison of the rail deflections for the three subgrade soils indicates that the resilient response of the subgrade has a substantial effect. Although the vertical subgrade stresses tend to be similar in all three cases, the softer subgrade will also have a lower shear strength and a lower resistance to the accumulation of permanent deformation with repeated-load applications. The analysis without the use of failure criteria indicates that as the support system becomes stiffer, the maximum ballast vertical stress increases. When the subgrade becomes stiffer, the maximum subgrade vertical stress also increases. This can be attributed to the fact that as the track support system becomes stiffer, there is less rail deformation, and the wheel loads are distributed to fewer ties.

Variable: Rail

There are many types of rails currently in use in the United States. Rail weights usually range from 57 kg/m (115 lb/yd) for lines with light traffic density to 70 kg/m (140 lb/yd) for lines with heavy traffic density. For this study, the following types of rail were evaluated (1 kg/m = 2.0 lb/yd and 1 cm^4 = 0.023 in^4):

Section	Linear Mass (kg/m)	Moment of Inertia (cm^4)
1	57	2730
2	66	3671
3	68	3950

The effect of type of rail is shown in Table 8. The responses of the track support system are similar for the 66 and 68 kg/m rails. The maximum rail deflection and the maximum rail moment of the 57 kg/m rail are slightly lower than those of the 66 and 69 kg/m rails. This probably indicates that for a well-maintained track, the type of rail has minimal influence on the transient response of the track support system. Although the rail moments of stiffer rails are larger, the maximum tensile rail stress is almost constant when ballast failure criteria are used and decreases from 70 MPa^2 (10 200 lbf/in^2) for the 57 kg/m rail to 58 MPa^2 (8500 lbf/in^2) for the 69 kg/m rail when ballast failure criteria are not used.

Variable: Tie Spacing

Normal tie spacings for CRTSSs in the United States range from 50.8 cm to 61.0 cm. In this study, the following tie spacings were evaluated (1 cm = 0.39 in):

Section	Tie Spacing (cm)
1	50.8
2	61.0
3	76.2

The responses of the three tracks to the loading of 133-kN (30 000 lbf) wheel loads are summarized in Table 9. The effect of tie spacing is twofold. Closer spacing leads to an increase in the overlapping effects of adjacent ties in the ballast and the subgrade, but smaller tie reactions at each tie. An increase in the tie spacing leads to a decrease in the overlapping effects in the ballast and the subgrade, but larger tie reactions. Thus, when the tie spacing is small, the overlapping effects of adjacent ties dominate, while when the tie spacing is larger, the effects of individual tie reactions dominate the response under the ties. Nevertheless, the overall effect of an increase in tie spacing is to produce more severe responses in the track support system. An in-

Table 7. Responses of sections with stiffness of subgrade as variable.

Response	Failure Criteria Used			No Failure Criteria Used		
	Softer	Average	Stiffer	Softer	Average	Stiffer
Maximum rail deflection, mm	3.0	2.5	2.0	2.3	1.8	1.5
Maximum rail moment, kN·m	34.9	33.6	32.4	29.0	27.1	25.9
Maximum ballast vertical stress, lbf/in^2	637.1	788.1	725.4	348.2	369.5	389.6
Maximum subgrade vertical stress, lbf/in^2	168.2	182.0	171.0	128.2	135.1	144.1
Maximum subgrade vertical strain	0.001 30	0.001 15	0.000 80	0.001 00	0.000 75	0.000 61

Note: 1 mm = 0.039 in, 1 kN·m = 8820 lbf·in, and 1 kPa = 0.145 lbf/in^2.

Table 8. Responses of sections with type of rail as variable.

Response	Type of Rail (kg/m)					
	Failure Criteria Used			No Failure Criteria Used		
	57	66	68	57	66	68
Maximum rail deflection, mm	2.3	2.5	2.5	1.8	1.8	1.8
Maximum rail moment, kN·m	25.6	31.7	33.6	25.3	26.7	27.1
Maximum ballast vertical stress, kPa	649.5	791.5	788.1	392.3	375.1	369.5
Maximum subgrade vertical stress, kPa	182.0	183.4	182.0	140.0	136.5	135.1
Maximum subgrade vertical strain	0.000 94	0.001 16	0.001 15	0.000 83	0.000 77	0.000 75

Note: 1 mm = 0.039 in, 1 kN·m = 8820 lbf·in, and 1 kPa = 0.145 lbf/in^2.

Table 9. Responses of sections with tie spacing as variable.

Response	Tie Spacing (cm)					
	Failure Criteria Used			No Failure Criteria Used		
	50.8	61.0	76.2	50.8	61.0	76.2
Maximum rail deflection, mm	2.5	2.8	3.3	1.8	2.0	2.3
Maximum rail moment, kN·m	33.6	30.4	34.6	27.1	27.8	29.9
Maximum ballast vertical stress, kPa	788.1	599.9	842.6	369.5	398.5	466.1
Maximum subgrade vertical stress, kPa	182.0	151.0	193.7	135.1	142.0	146.1
Maximum subgrade vertical strain	0.001 15	0.001 08	0.001 40	0.000 75	0.000 85	0.000 95

Note: 1 mm = 0.039 in, 1 kN·m = 8820 lbf·in, 1 kPa = 0.145 lbf/in^2.

Table 10. Responses of sections with wheel loads as variable.

Response	Wheel Load (kN)						
	Failure Criteria Used				No Failure Criteria Used		
	89	133	267	356	89	133	267
Maximum rail deflection, mm	1.5	2.5	6.4	8.9	1.0	1.8	4.1
Maximum rail moment, kN·m	20.2	33.6	67.3	91.3	17.7	27.1	55.1
Maximum ballast vertical stress, kPa	357.9	788.1	899.8	1210.1	251.7	369.5	732.2
Maximum subgrade vertical stress, kPa	106.8	182.0	304.8	385.4	93.1	135.1	265.4
Maximum subgrade vertical strain	0.000 48	0.001 15	0.002 00	0.002 79	0.000 47	0.000 75	0.001 60

Note: 1 mm = 0.039 in, 1 kN·m = 8820 lbf·in, and 1 kPa = 0.145 lbf/in^2.

crease in tie spacing leads to an increase in rail deflection and moment, an increase in ballast vertical stress, and an increase in subgrade vertical stress and strain.

Variable: Loading

The four wheel loads shown below were evaluated (1 kN = 224 lbf):

Section	Wheel Load (kN)
1	89
2	133
3	267
4	356

The effect of loading is shown in Table 10. Increases in the wheel load lead to increasingly detrimental responses of the track support system. For example, an increase from 89 kN (20 000 lbf) to 267 kN (60 000 lbf) increases the maximum rail deflection and the maximum subgrade vertical strain by a factor of more than four and the maximum rail moment and the maximum subgrade vertical stress by factors of about three. The increase in rail moment with increased loading is significant because it can lead to earlier rail failures due to fatigue.

Variable: Number of Missing Ties

The effects of missing or hanging ties on the response of the following systems were evaluated:

Section	Ties Missing
1 (reference)	0
2	1
3	2 in a row
4	3 in a row

These sections are illustrated in Figure 6. Figure 7 shows the deflection profile of the ballast surface relative to that of the rail, demonstrating the detrimental effect of missing ties. In a normal track section without missing ties, this relative displacement of ballast particles is small, but when there are missing ties, it is greatly accentuated. The significance of this can be realized if the permanent deformation characteristics of the open-graded ballast-aggregate matrix are considered. The overall strain of an aggregate mass is a result of the deformation of individual particles and of the relative sliding between the particles. In an open-graded aggregate matrix, the portion of the strain due to the sliding tends to dominate, especially at higher values of σ_1/σ_3. The relative sliding between aggregate particles is largely irreversible, and thus the deflection profile of the ballast surface (Figure 7) that develops due to missing ties can lead to a loss of alignment in the ballast surface at a faster rate and result in poorly performing track.

These results also show that an increase in the number of adjacent missing ties results in an increase in the maximum rail deflection, the maximum subgrade vertical strain, and the maximum tie reaction.

DISCUSSION OF RESULTS

In this design parameter study, it was assumed that all sections considered were properly maintained sections, i.e., there were no gaps between rail and tie or between tie and ballast. Firm seating was assumed of the rail on the tie and of the tie on the ballast; this factor must be considered when interpreting the results of the study.

Figure 6. Sections with missing ties.

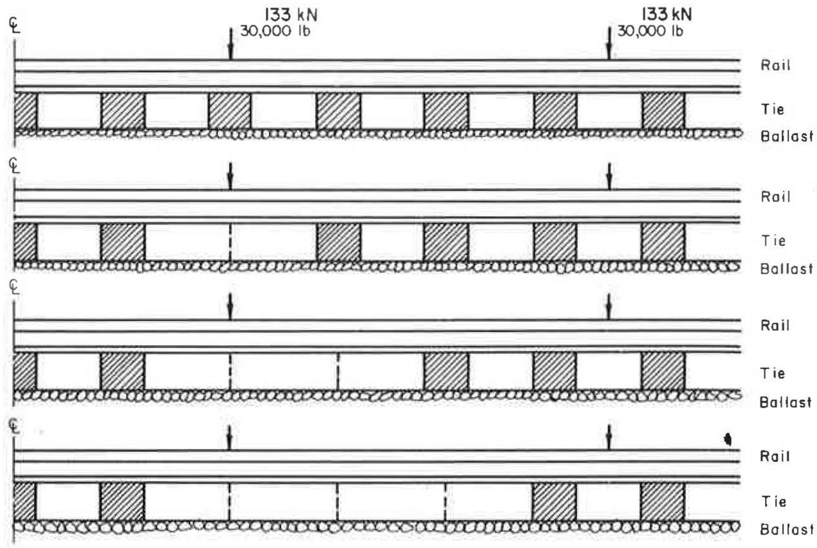
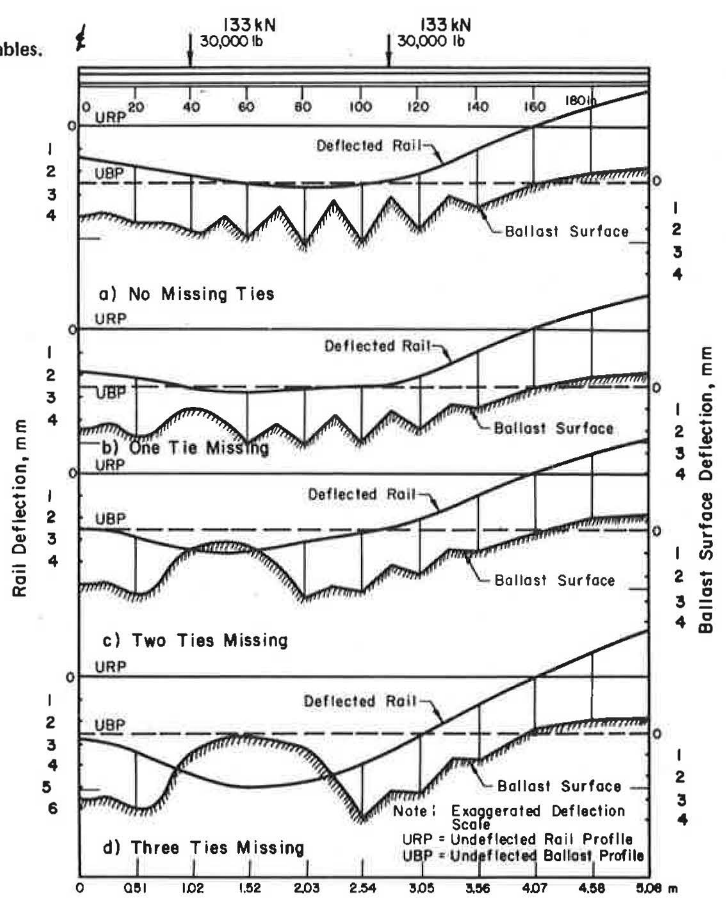


Figure 7. Deflection profiles of sections with missing ties as variables.



Use of the failure criteria for ballast leads to generally more detrimental responses, and the magnitude as well as the distribution of pressure in the ballast layer is affected. When the ballast failure criteria are not used, the responses of the track support system are less detrimental, and the trend of them is as expected.

Basically, the stiffness of a CRTSS is derived from two sources—the rail subsystem and the foundation subsystem, which includes the ballast, the subballast, and the subgrade. The variability in the stiffness of the foundation subsystem has less effect on the response of the CRTSS when the stiffness of the rail subsystem is high (i.e., the 68 kg/m rail). Thus, the use of a stiffer rail might be advantageous for a poorly maintained track with substantial foundation subsystem variability and poorly maintained ties.

The primary response of a CRTSS is not very dependent on the type of ballast used: The E_R versus θ resilient-response curves for most ballasts lie in a very narrow band (18). Thus, standardized E_R versus θ resilient-response curves for the various types of ballast could be used in analyzing the primary response of a CRTSS.

However, the long-term behavior of ballast under repeated (traffic) loading and changing environmental conditions is significantly dependent on the type of ballast, and this should be considered when evaluating different ballast types.

The effect of a variable foundation subsystem can be reduced by using a stabilized subballast. This type of subballast aids in distributing the load more uniformly on the subgrade and maintains the ballast-aggregate matrix in a more confined state, which allows the ballast to develop higher stiffness.

The development of stiffness at the bottom of the ballast layer is very much dependent on the stiffness of the underlying layer (19). When the ratio of the moduli values of the ballast layer and the layer under it is less than a certain value, a horizontal compressive stress will develop at the bottom of the ballast layer. When that ratio is above a certain value, a horizontal tensile stress will develop at the bottom of the ballast layer. With the use of a stabilized layer, a very low modular ratio can be maintained, which results in the development of a horizontal compressive stress at the bottom of the ballast layer. Thus, the ballast layer can develop higher stiffness; the response of a CRTSS with a stabilized layer is more favorable under traffic loading than is that of a CRTSS without a stabilized layer.

One of the more variable components in a CRTSS is the subgrade. Variation in the subgrade support can result from such conditions as type of soil, moisture content, frost action, and compaction. The variation in the strength of the subgrade soils is one of the most important parameters affecting the response of a CRTSS. Thus, on a given track section with a nonuniform (in terms of stiffness) subgrade, the response due to traffic loading can be very erratic. The desirability of uniform and stable subgrades is apparent.

The results of the study indicate that the type of rail has little effect on the system response of a CRTSS subjected to vertical loading. However, the use of stiffer rail might be advantageous for lateral stability considerations and for a track with substantial variability of the support system.

Increased tie spacing leads to detrimental responses in terms of the maximum rail deflection and the pattern of subgrade vertical stress. Increased tie spacing leads to localized concentration of stress on the subgrade (below the ties).

Over the years, many tracks in the United States have been deteriorating because of increased traffic frequency, heavier wheel loads, and inadequate maintenance. Increased wheel loading leads to an increasingly detrimental response of the CRTSS and results in an early failure of the CRTSS. When increased wheel loading is anticipated on a given line, it is necessary to evaluate the CRTSS to ensure that the response patterns in all of the components (rail, tie, ballast, subballast, and subgrade) are acceptable.

SUMMARY AND CONCLUSIONS

Summary

An acceptable structural analysis of a CRTSS cannot consider it as composed of only rails and ties. A large portion of the structural strength is derived from the ballast, the subballast, and the subgrade—i.e., the ballast, the subballast, and the subgrade also act as load-carrying media. Like other structural materials, the ballast, the subballast, and the subgrade have limiting (or allowable) response patterns. Therefore any analysis of a CRTSS should include the evaluation of the response patterns within all the components.

The mechanistic characterization of the ballast and the subgrade has been achieved by using the results of repeated-load triaxial tests. However, the open-graded nature of the ballast-aggregate matrix, when considered as a part of a CRTSS, does not lend itself to proper simulation in the structural model because the ballast in crib and shoulder areas is in a free state—i.e., it is subject to unrestricted displacement in at least one direction when subjected to loading. In a confined state, ballast has a potential for developing very high stiffness, but in a free state, it can generate very little resistance to loading.

The finite-element model should be considered as an input to a larger model or system for predicting the performance of a CRTSS. Because performance is evaluated with respect to the ability of the CRTSS to fulfill its functional requirements, it is essential to establish performance criteria for the whole system as well as for each subsystem.

Conclusions

The following conclusions were derived from this study:

1. When the developmental state of procedures for material characterization and the lack of availability of pertinent field response data are considered, the ILLI-TRACK model adequately characterizes the primary response of a CRTSS when subjected to vertical loading.

2. There are a large number of conditions that exist in an actual CRTSS, and it would be impracticable to attempt to satisfy all of them in a theoretical model. In certain cases, the effects of some conditions can be evaluated by using the results of the finite-element model and incorporating them carefully.

3. One of the most critical design factors appears to be that of the interface of the ballast and the subgrade. Ballast laid directly on a low-strength subgrade can be detrimental to the satisfactory performance of a CRTSS. The desirability of a stiff layer (e.g., a stabilized subballast) between the ballast and the subgrade has been demonstrated in this study.

4. The material testing, analysis, and design of a CRTSS should direct special attention to the ballast, the subballast, and the subgrade materials.

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**Dr. Tayabji was at the University of Illinois when this work was performed.*

Improvement in Rail Support

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An on-going investigation on rail support material is briefly summarized. Static and repeated-load triaxial compression and extension tests on a dolomite ballast are reported, and their significance to track design is discussed. Model tests using static and repeated loading on a small scale with Ottawa sand as a foundation material and on a large scale with rail track, ballast, subballast, and sandy subgrade were made, and the significance to tie and track design of their results is discussed.

The replacement and upkeep of fills and tracks cost Canadian railways an estimated $100 000 000 annually, of which about 40 percent is spent for the procurement, distribution, and rehabilitation of ballast. The potential savings that would accrue from research and the better use of track-support materials is therefore very large. A complete assessment of the economic importance of ballast in policies and practice, however, should include the costs of derailments and of the restricted speed and other delays caused by deteriorating track support.

The Canadian railways are at present mainly freight carriers, but as high-speed passenger trains are developed and put into service, the length of track traveled per vehicle will increase, and the technical and financial requirements of the track will tend to dominate these costs. Despite this, in comparison with the research effort devoted to such items as control systems, switching, and guidance systems, there has been little research devoted to track design. It is not surprising then that the Canadian Institute of Guided Ground Trans-