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THE EFFECTS OF ACCELERATED BALLAST CONSOLIDATION

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15. Supplementary Notes Other railroads that participated in the tests are the Boston and Maine Corporation, the Penn Central Transportation Company, the Saint Louis and Southwestern Railway Company of the Southern Pacific Transportation Company, and the Missouri Pacific Railroad Company.

16. Abstract

The effects of accelerated ballast consolidation were tested on main-line tracks of the Boston and Maine, the Chessie, the Missouri Pacific, the Penn Central and the Saint Louis and Southwestern, and at three sites on the Southern. Tests were made before and after traffic, after surfacing and related track work had been completed, both with and without machine consolidation of the ballast in the cribs and shoulders. The resistance of individual ties and panels of track to lateral forces, track settlement under traffic, and other indicators of track stability were measured.

The average lateral resistance before traffic in sections of track with consolidated ballast was found to be equivalent to that reached after more than 400,000 tons (360,000 metric tons) of traffic on track with unconsolidated ballast. Settlement was found to be less in consolidated ballast, especially at joints. The differences diminished under traffic but were still evident after many thousands of tons of traffic. Some of the test results were not conclusive because of wide variations in local conditions and other factors. However, the results indicate that accelerated consolidation of ballast will be a valuable addition to track surfacing work in areas where continuous welded rail has a high probability of buckling under temperature stress after the ballast has been disturbed.

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An expression of appreciation is due the many maintenance-of-way engineers whose cooperation and dedication to their phases of this project enabled the test series to be accomplished. These people are too numerous to call out by name even though their collective contributions added materially to the value of the data collected.

Special recognition can be afforded William B. O'Sullivan, Senior Technical Advisor in the Office of Research and Development of the Federal Railroad Administration. Mr. O'Sullivan conceived this project, prescribed the general thrust of the technical investigation, and his counsel throughout provided highly useful guidance.

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1. INTRODUCTION

Surfacing and related maintenance work on conventional tie-on-ballast railroad track raise the ties and disturb the ballast. These actions break the bond between tie and ballast and also lower the density of the ballast. These changes, in turn, reduce the resistance of the ties to movement and thus reduce the stability of the track. They also lead to degradation of track geometry and a need for frequent maintenance. Vertical track stability is normally restored by tamping ballast under the ties, and horizontal stability is restored by the heavy dynamic wheel loads of passing traffic.

Until all the loose ballast is reconsolidated by traffic and horizontal stability is restored, continuous welded rail is more likely to buckle or shift laterally under thermal stress in locations where large temperature variations occur. In addition, after ties and ballast have been disturbed by track work, the unconsolidated ballast in the cribs and shoulders does not offer full lateral support to the ballast that has been tamped under the ties. The tamped ballast may then shift laterally under dynamic loads, permitting excessive and unequal settlement, and the degradation of track geometry that results may worsen ride quality and increase the frequency and cost of necessary track maintenance.

Lateral instability is a more serious problem on European track, where traffic is more frequent but where axle loads are lighter than on American track. Thus the periods of reconsolidation under traffic are longer than for track that carries heavy freight trains; and consequently, the costs of slow orders on traffic for these periods are relatively higher. Accordingly, as the use of continuous welded rail increased in

Europe, increasing attention was paid to the reconsolidation of ballast after track maintenance work, and finally ballast consolidation machinery was developed to shorten the time required to reconsolidate the ballast and restore track stability. Now the ballast in the cribs and shoulders is often consolidated immediately after ballast has been tamped under the ties and the track has been lined, and before traffic loads on the rails can lead to degradation of the improved track profile and alignment [1,2].

A review of European experience, although with different conditions of traffic and track construction, has indicated that the use of ballast-consolidating equipment has a potentially valuable role in the construction and maintenance of American track in those areas where track instability after maintenance has been particularly troublesome.

In addition to the variable settlement that may result from early traffic after normal tamping, the pedestals of tamped ballast under the ties are likely to transmit concentrated loads to the embankment, since the loose ballast in the cribs and shoulders cannot share effectively in the distribution of loads until it has been consolidated. These concentrated loads imposed during early traffic may damage embankments of marginal strength, especially during wet weather when moisture lowers the strength of embankment soils. The effect could be serious on sections of track where the embankment strength may be marginal, and where only a thin layer of ballast was installed or where the effective thickness of the ballast has been reduced by the infiltration of fine material. At such places, concentrated loads tend to cause small depressions in the top of the embankment that hold water and lead to rapid deterioration.

In early 1973, the Federal Railroad Administration (FRA) acquired a modern ballast consolidating machine under competitive bids in order to meet requirements for the construction of top quality track at the Transportation Test Center (TTC). In this procurement, the potential value of the equipment in regular track maintenance was also considered.

The consolidator was tested thoroughly in March 1973 [3] before final acceptance from the manufacturer by the FRA. Concurrently, in view of the potential of the consolidator for reducing operating and maintenance costs on some sections of track, the FRA proposed to make the consolidator available to the rail industry for use in a modest experimental program. The objective of this program was to provide the rail industry an introduction to the use of ballast consolidation equipment on its own track and an opportunity to consider any advantages in the routine use of a ballast consolidator.

The FRA proposed that the program be conducted on the high-traffic-density main tracks of a few cooperating carriers, with the technical results to be distributed to the industry. While the program was to be conducted on the lines of a few cooperating carriers, representatives of other roads were encouraged to participate actively in the program in a consultative capacity.

Interest in the proposal for research in ballast consolidation was very strong, and the project was initiated with a conference in March 1973 that was attended by 29 representatives of the railroad industry as well as by representatives of research organizations and equipment manufacturers. As a result of discussions during the conference and with assistance in the planning phase from the Research and Test Department of the Association of American Railroads (AAR), a series of tests was planned. These tests were designed to provide comprehensive data on the effects of ballast consolidation on the stability of track and on changes in track geometry under traffic [4]. The initial tests were begun in July 1973, in cooperation with five participating railroads as follows:

- Boston and Maine
- Missouri Pacific
- Penn Central
- Saint Louis and Southwestern
- Southern

In 1974, the Southern conducted a second test; in 1975, a special test was added in cooperation with the Chessie, and another special test was added in cooperation with the Southern.

2. PROJECT DESCRIPTION

The project consisted of a comprehensive investigation of the effects of accelerated ballast consolidation at widely separated locations on mainline track. The initial work consisted of five series of tests designed to collect data from each participating railroad and to investigate the results of maintenance work on mainline track both with and without the use of the consolidator.

A Plasser-American Consolidator, Model CPM 800, was used in the tests to consolidate the ballast in cribs and shoulders. It is shown in Figure 1. This machine had been acquired in accordance with the Federal Procurement Regulations for the Transportation Test Center (TTC) near Pueblo, Colorado. It is used on sections of test track that do not have sufficient traffic to consolidate the ballast in a reasonable time after the track has been installed or resurfaced for a test.

Four crib compactor heads, a shoulder compactor, and a shoulder ballast holder are shown in Figure 2. The crib compacting heads and shoulder compactors are statically loaded in the vertical direction by hydraulic cylinders. They are also dynamically loaded by an eccentric shaft that is turned by hydraulic power. The combined static and dynamic loads are applied to the ballast for a short, fixed interval of time to perform the consolidating function.

In cross section, the four crib compactor heads measure 14.5 by 5.5 inches (36.8 x 14.0 cm) above the V-shaped working faces. The two shoulder compactor heads measure 85 by 8 inches (216 x 20.3 cm) and the two shoulder ballast holders measure 85 by 11.75 inches (216 x 29.8 cm).

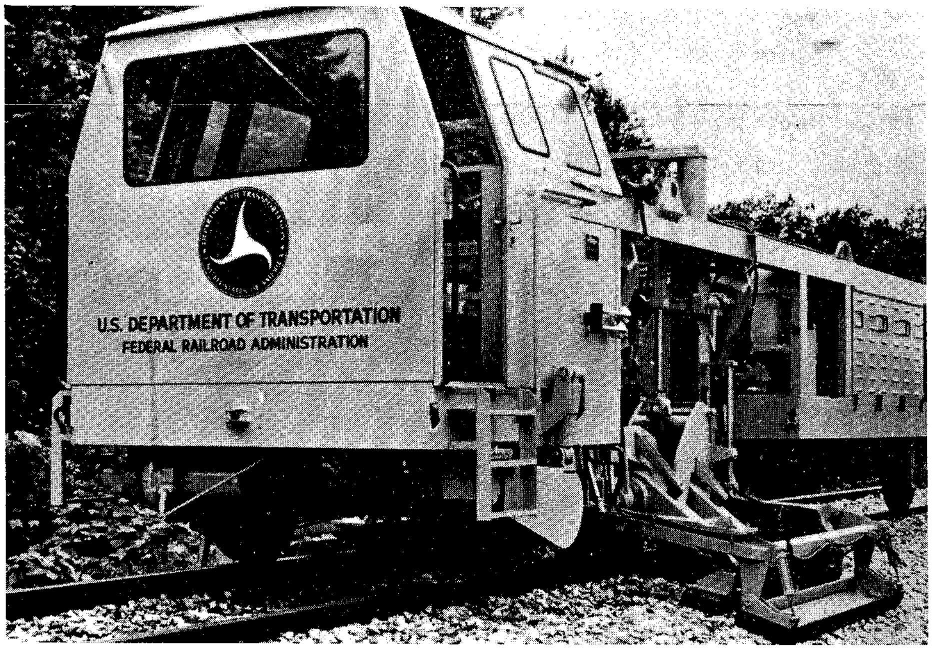

Figure 1. Plasser-American Consolidator, Model CPM 800

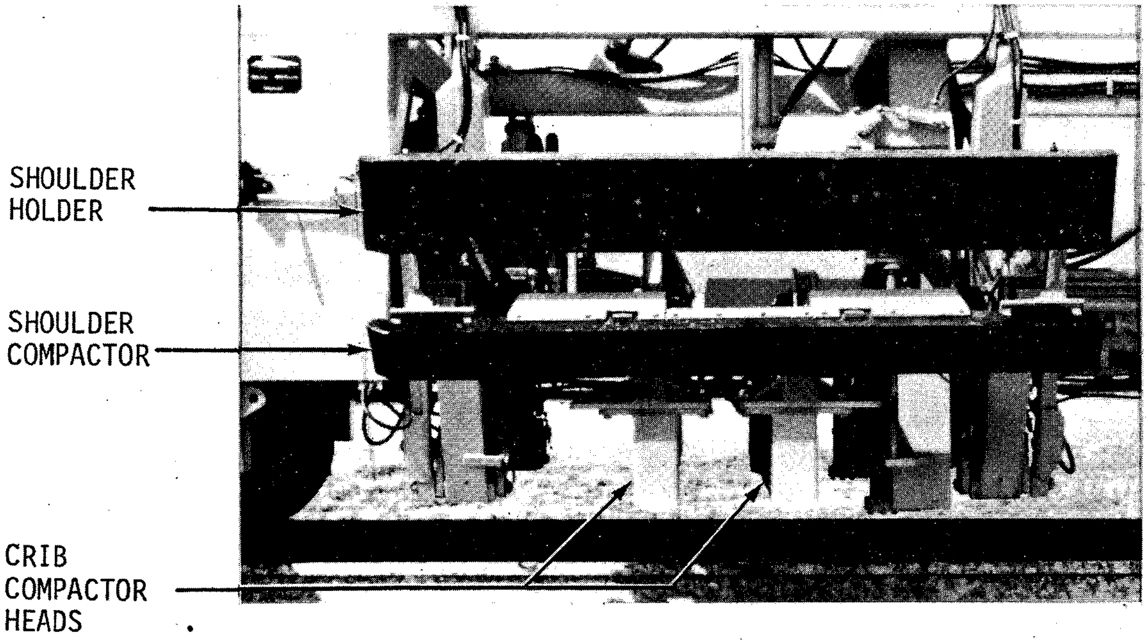

Figure 2. View of Compacting Heads of Ballast Consolidator

Prior to its use in the ballast consolidation tests, the consolidator had passed acceptance tests at the TTC [3] that provided information given in Table 1.

TABLE 1

Forces and Displacements Developed at Compactor Heads

	Crib Compactor	Shoulder Compactor
Static force	1250 lbs. (5.56 kN)	1500 lbs. (6.67 kN)
Dynamic force	1600 lbs. (7.12 kN)	1700 lbs. (7.56 kN)
Vertical amplitude	0.137 in. (3.5 mm)	0.14 in. (3.6 mm)
Frequency	38.8 Hz (2330 cpm)	24.5 Hz (1470 cpm)

When used in the ballast consolidation tests, the consolidator was operated behind the track liner after surfacing, tamping, and other track work had been completed. The consolidator was operated for periods of 5 seconds at each position on the ballast in half of the test sections where it was used and for periods of 3 seconds in the other sections, as the manufacturer advised that his recent trials of the equipment had shown that the shorter period of vibration would be adequate. Figure 3 shows the consolidator in operation on a section of test track.

From the tests, determinations were made on the effects of ballast consolidation in terms of track stability and degradation of track geometry under normal traffic after track surfacing. These determinations were made by measuring the resistance of individual ties to lateral and longitudinal loads and by measuring track settlement, joint profile, track modulus, and track geometry.

The FRA consolidator was shipped from Pueblo, Colorado to the first railroad scheduled to participate in Test MM-77 and then, in turn, to each succeeding railroad for a period of about 2 weeks of use and approximately 2 weeks in transit to the next participating railroad. The schedule for use of the consolidator was as follows:

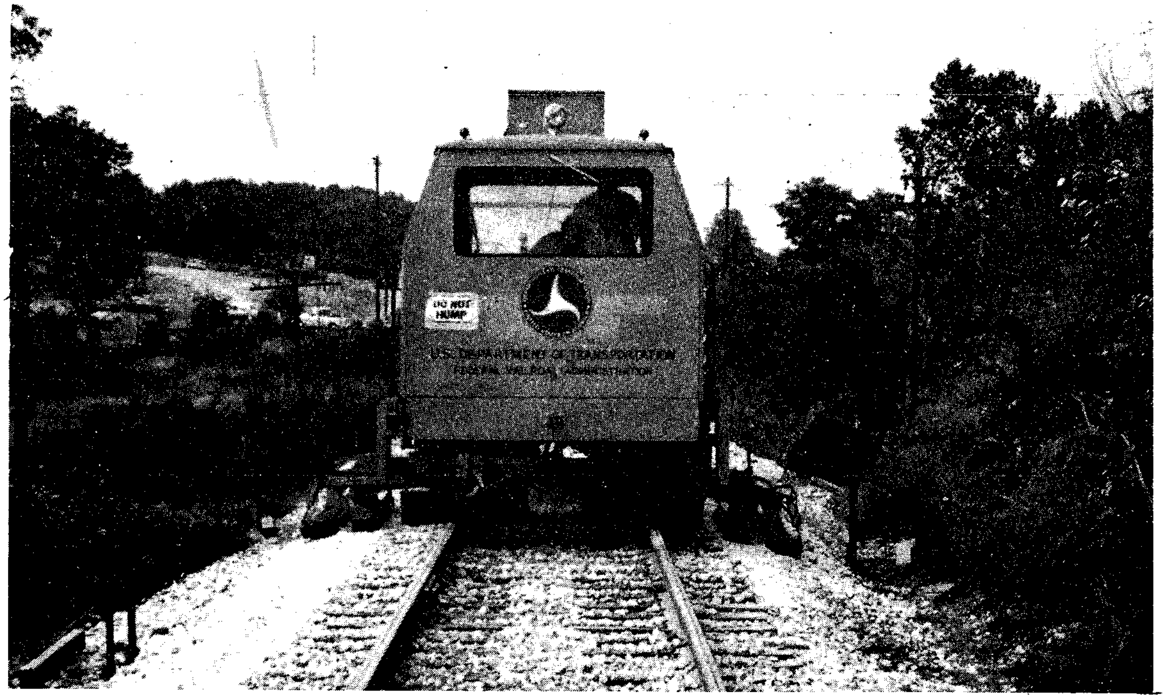

Figure 3. FRA Ballast Consolidator in Operation on Test Section of Track

- Southern: July 23 - August 3, 1973
- Boston and Maine: August 13 - September 7, 1973
- Penn Central: September 24 - October 19, 1973
- Saint Louis-Southwestern: November 5-16, 1973
- Missouri Pacific: November 26 - December 14, 1973

One of the 2 weeks of scheduled use of the consolidator was dedicated to:

- Operator familiarization and acquisition of proficiency.
- Conducting such user evaluation tests as the railroad wished to perform outside the designated test sections.

A second week was reserved for the ballast consolidation planned under Test MM-77.

Each of the five railroads participating in the initial series of tests reviewed its track maintenance program and selected a test zone with sections of track that were scheduled for maintenance during the availability of the consolidator. They then made plans to use the consolidator on two test sections--one curved and one tangent--each approximately 1/8 mile (0.2 kilometer) in length. In the immediate vicinity, but not necessarily contiguous to the consolidated sections, similar lengths of curved and tangent track were selected as unconsolidated test sections for comparison purposes.

Test instrumentation and procedures were developed after careful consideration of comments by representatives of the participating railroads, other interested railroads, and the American Association of Railroads (AAR); and after review of European experience in testing the effects of ballast consolidation [4].

Four of the five zones selected for tests in the initial series under Test MM-77 included both curved and tangent track. In these test zones the ballast was consolidated in the cribs and shoulders of one of the tangent test sections and one of the curved test sections after track surfacing and lining had been completed, and the ballast was left unconsolidated in the other two test sections. The fifth test zone had only tangent track. Here the ballast was consolidated in one tangent test section and left unconsolidated in a second tangent section.

During the test series, the data collected in each test section on each participating railroad and the approximate frequency of measurement were as follows:

- Tie displacement resistance in the longitudinal and lateral axes:

  Data was taken from a sampling of ties after surfacing and prior to traffic passing over the track, and again at approximately 0.5, 1.5, and 2.0 million gross tons - MGT (0.45, 1.36, and 1.81 million gross metric tons - MGMT).

- Track modulus:

  Data was taken after surfacing and prior to traffic passing over the track, and again at approximately 0.5, 1.5, 2.0, 5.0, and 10 MGT (0.45, 1.36, 1.81, 4.54, and 9.07 MGMT).

- Detailed joint profile:

  Data was taken after surfacing and prior to traffic passing over the track, and again at approximately 0.5, 2.0, 5.0, and 10 MGT (0.45, 1.81, 4.54, and 9.07 MGMT).

- Track settlement:

  Data was taken after surfacing and prior to traffic passing over the track, and again at approximately 0.5, 1.0, 1.5, 5.0, and 10 MGT (0.45, 0.91, 1.36, 4.54, and 9.07 MGMT).

- Track geometry (only by railroads having measuring cars):

  Data was taken after surfacing and prior to traffic passing over the track, and again at convenient intervals after traffic had passed over the track.

Initial difficulties were expected and were encountered in making measurements to the accuracy required for conclusive determination of the effects of consolidation, and tests were designed to check refinements in test equipment and procedures. Tests were also added to obtain information in two areas of special interest: the resistance of panels of track to lateral forces and the settlement of track at bolted rail joints. In addition, the Southern developed an extra test to measure the results of accelerated ballast consolidation in terms of the traffic required to effect equivalent consolidation.

3. TEST DESCRIPTIONS AND TEST ZONES

Test MM-77 [4] included track stability tests, track settlement tests, joint profile measurements, track modulus measurements, and track geometry surveys. These tests plus other tests that were added to the initial series later are listed in Table 2.

3.1 DESCRIPTIONS OF TESTS UNDER MM-77

3.1.1 TRACK STABILITY TESTS

Force versus displacement tests were made to provide indicators of track stability by determining the resistance of ties to lateral and longitudinal forces both with and without consolidation of ballast. Approximately forty ties in each of the four test sections in each test zone were disconnected from the rails by removing the spikes, tie plates, and rail anchors. In each test section, twenty ties were displaced laterally (normal to the track centerline) and twenty ties were displaced longitudinally (parallel to the track centerline). For the lateral resistance tests, a hydraulic jack was installed between the rail and a bracket fastened to the test tie. This arrangement is shown in a photograph of the test instrumentation in Figure 4, and in a diagram of the test instrumentation in Figure 5. Force was applied by a pump connected to the jack. Force levels were read from a pressure gage, and movement was measured by a displacement transducer that was connected to the test tie by a taut wire.

Instrumentation for longitudinal tie resistance tests was generally similar to that used for lateral tests, except that a pair of hydraulic jacks were used and special fixtures were installed to apply the longitudinal force near the center of the test tie. The instrumentation is shown in Figures 6 and 7.

TABLE 2
FIELD TESTS OF ACCELERATED BALLAST CONSOLIDATION

TEST NO.	MM-77	MM-77.1	MM-77.3	MM-151	MM-219
Purpose	Comprehensive investigation of effects of consolidation of ballast with mechanical equipment	Refinement of test instrumentation and procedures	Comprehensive measurement of lateral and vertical short-term effects of consolidation	Measurement of short-term effects of consolidation on settlement at joints	Measurement of the effects of consolidation on the resistance of panels of track to lateral forces
Dates	July 1973 - April 1974	October 1973	June-July 1974	June-July 1975	April and August 1975
Participants	Boston & Maine Missouri Pacific Penn Central Southern St. Louis Southwestern	Penn Central	Southern	Southern	Chessie
Specific Tests	Tie displacement vs. force Track settlement Joint profile Track modulus Track geometry	Tie displacement vs. force	Tie displacement vs. force Track settlement Track alignment	Settlement at bolted rail joints	Track-panel displacement vs. force
Test Intervals	Approximately 0, 0.5, 2, 5, and 10 MGT (0, 0.45, 1.81, 4.54, and 9.07 MGMT) of traffic, weather permitting	Single test	Daily and weekly	Measured during passage of each train during period of two weeks 0 to 155,000 GT (0 to 141,000 GMT) of traffic	0 and 7 MGT (0 and 6.35 MGMT) of traffic

NOTES:
GT: gross short tons
GMT: gross metric tons
MGT: million gross short tons
MGMT: million gross metric tons

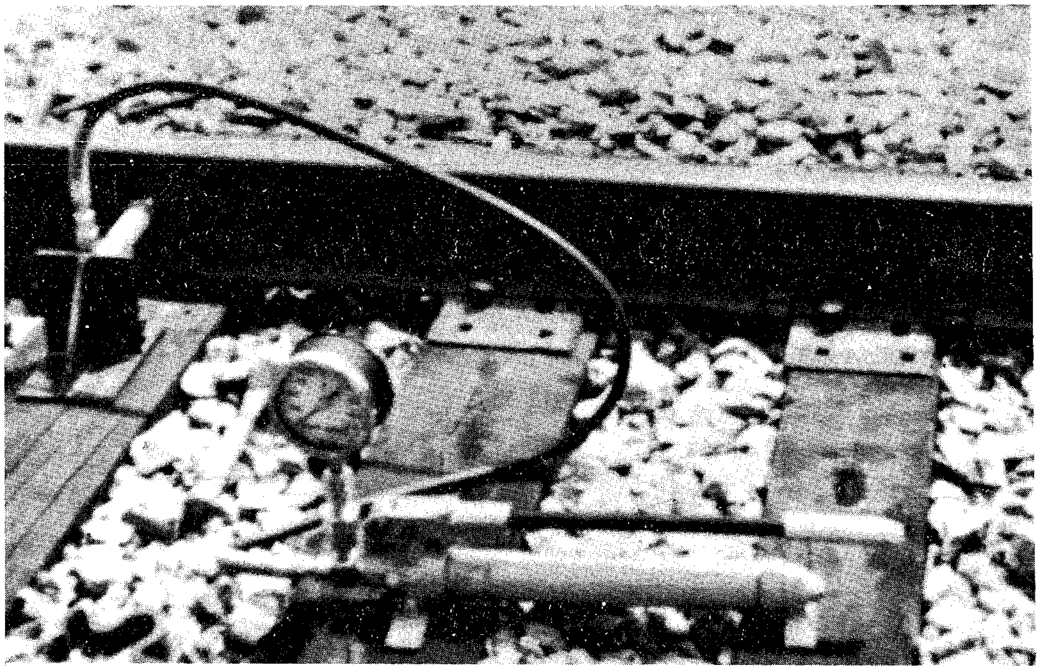

Figure 4. Test of Lateral Tie Resistance

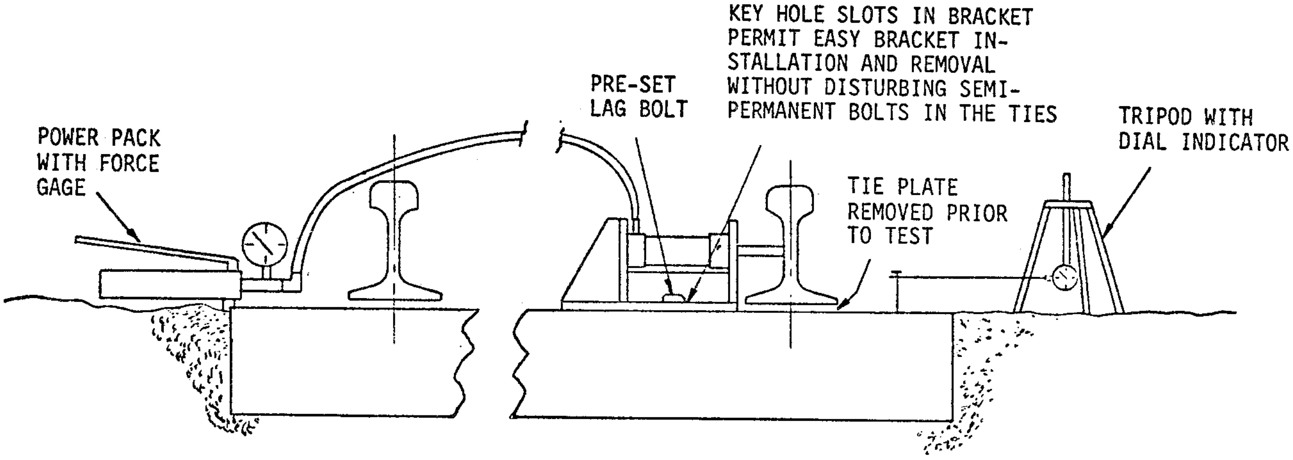

Figure 5. Lateral Tie Resistance Test Instrumentation

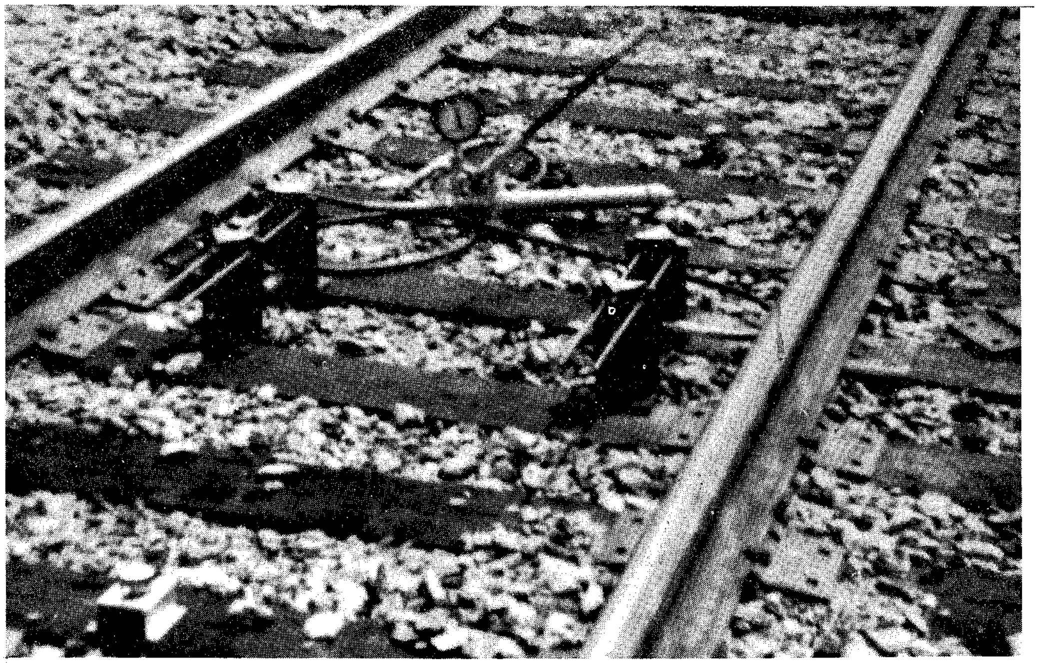

Figure 6. Test of Longitudinal Tie Resistance

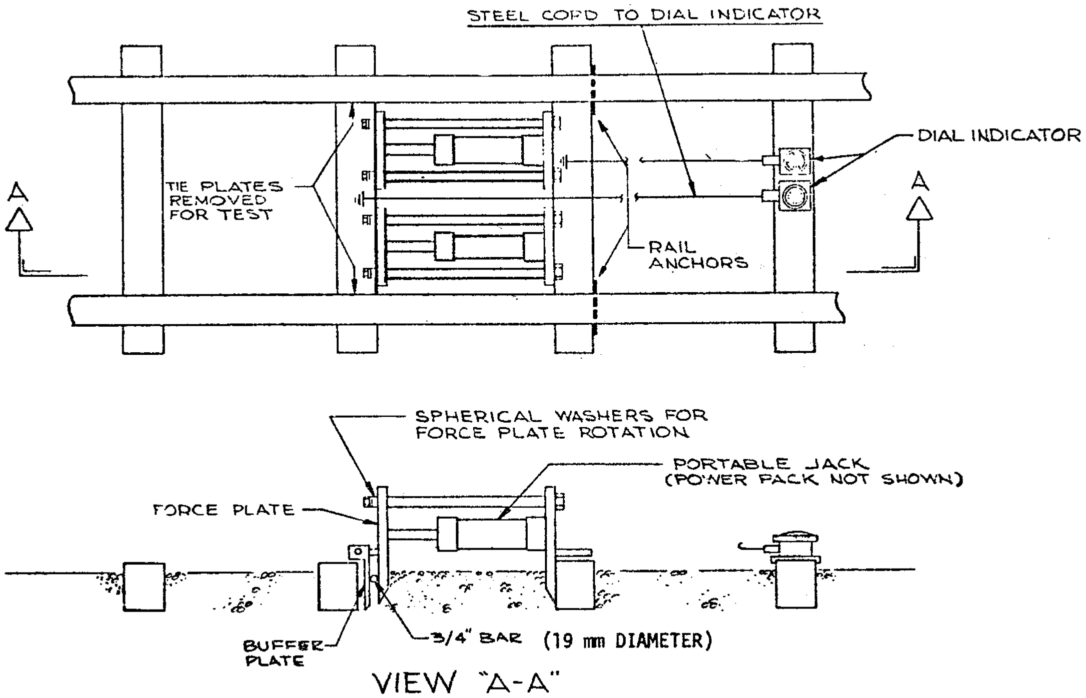

Figure 7. Longitudinal Tie Resistance Test Instrumentation as Modified for Test MM-77.1 on 3 October 1975, and Used Thereafter

The initial tie displacement tests were conducted after surfacing and other track work but before resumption of traffic. Tests were conducted again at approximately 0.5 and 2.0 MGT (0.45 and 1.8 MGMT) of traffic. Data were summarized by test section and by traffic tonnage. Summary data for each tonnage level were then compared to observe the differences between ties in consolidated and unconsolidated ballast. Also, data from one tonnage level to another were compared to observe the cumulative effects of traffic-induced consolidation on all test sections.

3.1.2 TRACK SETTLEMENT TESTS

Settlement surveys were made to determine the effect of ballast consolidation on variation in settlement within test sections and on overall track settlement. Rail profiles were measured in the four test sections using conventional optical surveying equipment (level, rod, and tape). Fixed reference stakes were installed in an initial survey, and rail profile was measured at stations 50 feet (15.24 m) apart before any maintenance work was performed. Rail profile was measured again after maintenance but before traffic, and after 5 MGT and 10 MGT (4.54 and 9.07 MGMT) of traffic. In three of the test zones, the station interval was reduced to 20 feet (6.1 m) in order to increase the density of the data.

3.1.3 JOINT PROFILE TESTS

Joint profiles were measured with a 48-inch (122 cm) straight edge with standoff blocks, which was placed on the running surface of a rail and centered over a joint. The original device had a direct contacting dial indicator gage which was moved along the straight edge to marked reference points at which it was used to measure the distance between the straight edge and the rail. Later in the tests, a straight edge was used with a taper gage to measure the gap between the straight edge and the rail at the reference points. Measurements were taken at 0.5, 2, 3, 6, 12, and 18 inches (1.27, 5.08, 7.62, 15.2, 30.5, and 45.7 cm) on either side of the joint.

All joint profile data obtained under Test MM-77 were from track with welded rail. Although the major effects of ballast consolidation at joints were expected to be evident only at bolted joints, data were collected at welded joints to permit deduction of impact forces that may be caused by surface irregularities.

3.1.4 TRACK MODULUS TESTS

Measurements were made of track deflections under load in order to obtain track modulus information and to determine if track sections with consolidated ballast had higher and more uniform vertical stiffness than the adjacent sections with unconsolidated ballast. Initially, measurements were made of the deflection of a tie under two different loads at five places in each test section. Static loads were applied by a locomotive and by a loaded freight car. A conventional surveyor's level and a rule attached to the rail were used to measure deflections.

As shown in Figure 8, the deflection measurement procedure was revised in later tests to include the measurement of the deflection of 13 ties, one below the center of a loaded truck and six on either side of the center tie. This procedure was used at three places in each test section.

3.1.5 TRACK GEOMETRY SURVEYS

Track geometry was surveyed by test cars on the two participating railroads that had test cars available, in order to find indications of the effect of ballast consolidation upon the resistance of the track to degradation under traffic. The geometry measurements included profile and alignment of both rails and cross-level. The first surveys were made after surfacing but before

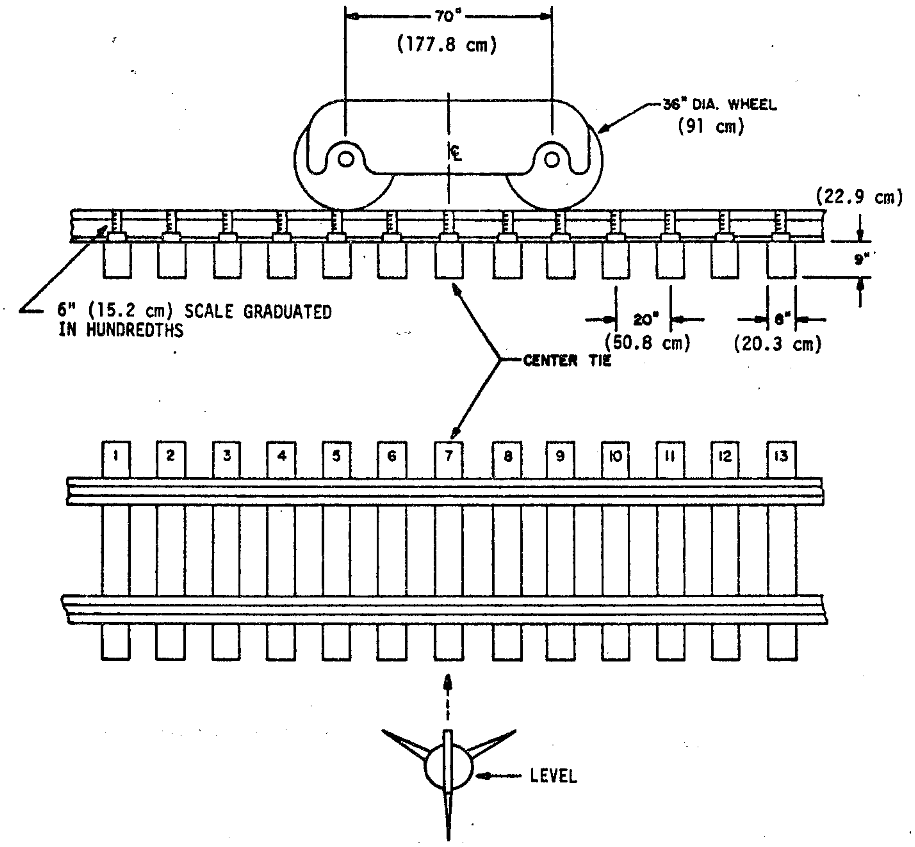

Figure 8. Track Modulus Test Equipment Arrangement

traffic, then at convenient intervals after traffic until approximately 10 MGT (9.07 MGMT) of traffic had passed over the test sections or until freezing temperatures invalidated further testing.

3.2 TEST ZONES UNDER TEST MM-77

In order to test the effects of accelerated ballast consolidation, convenient sections of mainline track that were scheduled for surfacing and related track maintenance work were selected by the railroads that participated in the tests.

A schematic diagram of a typical test zone is shown in Figure 9.

The test zones selected were in general conformance with Figure 9, with differences noted in the separate discussions of each

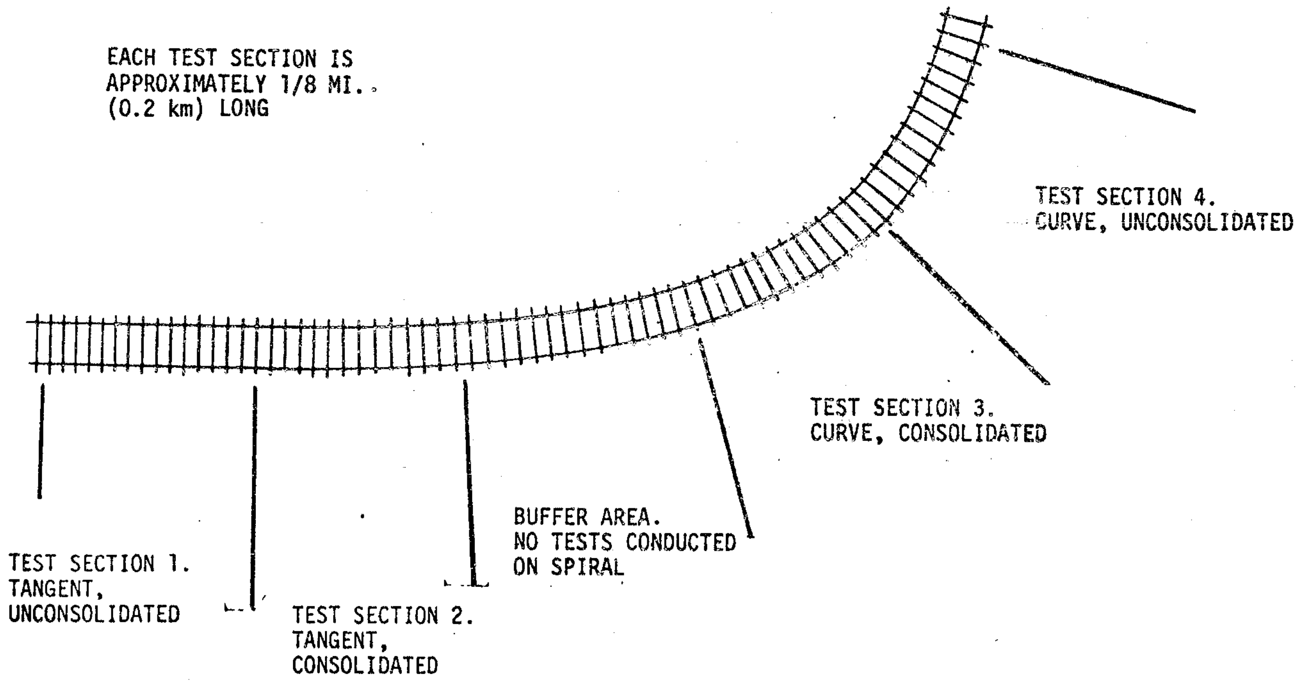

Figure 9. Typical Test Zone, Test Series MM-77

zone. Test zones for Test MM-77 are discussed under the names of the participating railroads, in chronological order of the dates the tests were begun.

3.2.1 SOUTHERN RAILWAY COMPANY

A test zone was selected on Track 1 of the double-track mainline of the Cincinnati, New Orleans and Texas Pacific Railroad 6 miles (9.7 km) north of Oneida, Tennessee. The test sections were arranged as indicated in Figure 9, and each is 1/8 mile (0.2 km) long.

Section 1 begins 332 feet (101 m) south of Milepost 202, and Section 3 begins at Milepost 203. Sections 3 and 4 are on a 2.2° curve with a 5-inch (12.7 cm) superelevation.

Track in the test zone is designated Class 4, freight, with a 60-mph (97 km/h) maximum operating speed. It carried approximately 25 MGT (22.7 MGMT) of traffic per year at the time of the tests. The embankment had been built prior to 1916 and had been used as a double track until Track 1 was retired in 1954; it was removed over a period of 2 years, and its bed was used as a service road for maintenance of the remaining track until 1973. In August 1973, Track 1 was rebuilt with continuous welded rail.

At the time of the initial test, no rail traffic except ballast trains and maintenance equipment had been over the subgrade for 20 years. The 132 lb. (59.9 kg) continuous welded rail was installed on new oak ties at 20-inch (51 cm) spacing. Each tie is 7 by 8 inches by 8.5 feet (18 x 20 x 259 cm). There are 397 ties in each test section. Ballast is crushed, metamorphic granite (granite-gneiss) AREA size 4. The track work included tamping with a multiple tamper over a 2- to 3-inch (5 to 7.6 cm) lift of ballast and lining with two passes of both tamper and liner, and ballast sweeping. Ballast in the cribs and shoulders of Test Sections 2 and 3 was consolidated by a 5-second application of the consolidator. No additional track work was done during the test period.

The track was opened to traffic under a slow order on 8 August 1973, after track construction and ballast consolidation had been completed and the initial tests had been made. Traffic tonnage and other data were recorded over a period of 168 days through 23 January 1974, by which time approximately 12 million gross tons (10.89 MGMT) of traffic had passed over the track in the test zone. Test dates and cumulative gross tons of traffic over the test track are listed in Table 3.

Except as noted in Table 3, the tests included tie displacement, joint profile, track settlement, track modulus, and track geometry surveys. Track settlement was measured with surveyor's instruments at stations on both rails, 50 feet (15.24 m) apart in all test sections.

TABLE 3
Test Dates and Cumulative Gross Tons of Traffic

Date	Traffic		Test Description
	MGT	MGMT	
18 July 1973	-		Test zone and test tie selection
23-26 July 1973	0		All tests except track geometry survey
8 August 1973	0		Track geometry survey only
15 & 16 August 1973	0.5	0.45	Tie displacements and joint profiles only
29 & 30 August 1973	1.5	1.36	All tests except track geometry survey
11 September 1973	2.3	2.08	Track geometry survey only
17 October 1973	5.0	4.54	Track settlement and modulus
9 January 1974	11.0	9.98	Track settlement only
23 January 1974	12.0	10.89	Track geometry only

3.2.2 BOSTON AND MAINE CORPORATION

A test zone was selected in Massachusetts, on the mainline of the Fitchburg Division. The test zone extends northward (railroad east) from Station 32243 + 20, and crosses the Gardner-Ashburnham township line in Test Section 4. Milepost 61 is at the beginning of Test Section 3. The test sections are arranged as indicated in Figure 9. Each is 1/8 mile (0.2 km) long. In Section 3, the curve is 1°35' with a 1-inch (2.5 cm) superelevation; and in Section 4, it is 2°00' with a 1-5/8 inch (4.1 cm) superelevation.

Track in the test zone is designated Class 4, freight, with a 50-mph (80 km/h) maximum operating speed. It carried approximately 19 MGT (17.2 MGMT) of traffic per year at the time of the tests. It is build with 112 lb. (50.8 kg) continuous welded rail that was installed in 1972 in a relaying operation, but it also includes some 132 lb. (59.9 kg) bolted rail in Test Section 4. The 376 ties in each test section are 7 by 8 inches by 8.5 feet (18 x 20 x 259 cm) at 21-inch (53 cm) spacing. Approximately 40% of the ties were replaced in 1952; and 38% in 1972; the remainder are over 25 years old. The ballast is crushed granite, AREA size 4, on a cinder base.

Pretest track work included a ballast lift of 1 to 2 inches (2.5 to 5 cm) over all test sections, tamping with multiple tamper, ballast sweeping and lining, and consolidation of ballast in the cribs and shoulders of Sections 2 and 3 by a 3-second application of the consolidator as recommended by the equipment manufacturers. No additional track maintenance was done during the entire test period.

Track surfacing and ballast consolidation were completed and the track opened to traffic on 20 August 1973. Traffic tonnage and other data were recorded over a period of 65 days, through 24 October 1973, by which time approximately 2.78 MGT (2.52 MGMT) of traffic had passed over the test track. Test dates and cumulative gross tons of traffic over the test track are listed in Table 4.

TABLE 4

Test Dates and Cumulative Gross Tons of Traffic

Date	Traffic		Test Description
	MGT	MGMT	
13 August 1973	-		Test zone selection
20 & 21 August 1973	0	0	All tests except track modulus on Sections 3 and 4
31 August 1973	0.5	0.45	Track geometry survey only
17 & 18 September 1973	1.0	0.91	All tests except tie displacement in Sections 3 and 4 and track geometry
22 & 23 October 1973	2.7	2.45	All tests except track geometry
24 October 1973	2.8	2.54	Track geometry survey only

Except as noted in Table 4, the tests included tie displacement, track settlement, joint profile, track modulus, and track geometry surveys.

3.2.3 PENN CENTRAL TRANSPORTATION COMPANY

A test zone was selected on the double-tracked mainline between Buffalo and Chicago, just east of Conneaut, Ohio. The test section arrangement is similar to that indicated in Figure 9, with the section numbers reversed and with a distance of over 1.5 miles (2.4 km) between Sections 2 and 3 where the track crosses the Pennsylvania-Ohio state line. Test Section 1, with unconsolidated ballast, begins 1,035 feet (315 m) west of Milepost 111 and extends westward 708 feet (216 m) to Section 2, consolidated, which is 833 feet (254 m) long.

Test Sections 1 and 2 are on a 0°30' curve with a 1/4-inch (6.4 mm) superelevation. There are 425 ties in Section 1 and 500 ties in Section 2. Section 3, unconsolidated, and Section 4, consolidated, are both on tangent track; each is 666 feet (203 m) long and contains 400 ties.

Track in the test zone is maintained as Class 5, freight, with a 70-mph (113 km/h) maximum operating speed. It carried approximately 40 MGT (36.3 MGMT) of traffic per year at the time of the tests. The 140-lb. (63.5 kg) continuous welded rail in the test zone was installed in 1970. The ties are oak, 7 by 9 inches by 8.5 feet (18 x 23 x 259 cm) at 20-inch (51 cm) spacing. New ties were installed on the curve in 1966, and some new ties were installed on the tangent in 1966 and 1973. Ballast is crushed limestone, AREA size 4.

The track work before the tests included replacing approximately 21 percent of the ties in the tangent sections, placing a 2-inch (5 cm) ballast lift, tamping with a multiple tamper, lining with a wire liner, and ballast sweeping. Ballast was consolidated by a 5-second application of the consolidator in Section 2, and by a 3-second application of the consolidator in Section 4. No additional track maintenance was performed during the test period.

The track was opened to traffic on 10 October 1973, after track surfacing and consolidation had been completed and the initial tests had been made. Traffic tonnage and other data were recorded over a period of 175 days through 3 April 1974, by which time approximately 15 MGT (13.6 MGMT) of traffic had passed over the test sections. Test dates and cumulative gross tons of traffic passing through the test zone are listed in Table 5.

TABLE 5

Test Dates and Cumulative Gross Tons of Traffic

Date	Traffic		Test Description
	MGT	MGMT	
20 & 21 September 1973	-		Selection of test sections and test ties
8-10 October 1973	0	0	All tests
15 & 16 October 1973	0.5	0.45	All tests
29-31 October 1973	1.7	1.54	All tests
18 December 1973	6.4	5.80	Track settlement only
13 February 1974	11.0	9.98	Track settlement only
3 April 1974	15.0	13.6	Track settlement only

The tests included tie displacement, track settlement, joint profile, and track modulus, except as noted in Table 5.

3.2.4 SAINT LOUIS AND SOUTHWESTERN RAILWAY COMPANY

A test zone was selected on the mainline near Stuttgart, Arkansas, about a half mile (0.8 km) south of Roe. It includes just two test sections on tangent track, each approximately 1/4 mile (0.4 km) long, as no curved track that was suitable for tests was scheduled for maintenance at the time the ballast consolidator was available. Section 1, with consolidated ballast, begins at Station 11696 + 384 and extends 1,320 feet (402 m) northward (railroad west) to the end of Section 2 which is 1,350 feet (411 m) long and has unconsolidated ballast. Milepost 222 is 247 feet (75 m) from the southern end of Section 2.

Track in the test zone is designated Class 5, freight, with a 70-mph (113 km/h) maximum operating speed. It carried approximately 41 MGT (37.2 MGMT) of traffic per year at the time of the tests.

The 112-lb. (50.8 kg) continuous welded rail is relaid rail that was installed in 1965. The test zone includes bolted joints at tie numbers 1270 and 1293 and at 1281 and 1303. The ties are oak, 7 by 9 inches by 9 feet (18 x 23 x 274 cm) at 20-inch (51 cm) spacing. All tie displacement tests were on new ties. Ballast is crushed granite, AREA size 4.

The track maintenance work before the tests included replacing approximately 50 percent of the ties, placing a 1.5-inch (3.8 cm) lift of ballast, tamping with a multiple tamper, lining, and ballast sweeping. Ballast was consolidated in Section 1 by a 5-second application of the consolidator. No additional track maintenance work was done during the test period.

The track was opened to traffic on 14 November 1973, after track maintenance and ballast consolidation had been completed and the initial tests had been made. Traffic tonnage and other data were recorded over a period of 86 days through 8 February 1974, by which time approximately 10 MGT (9.07 MGMT) of traffic had passed over the track in the test zone. Test dates and cumulative gross tons of traffic through the test zone are listed in Table 6.

Except as noted in Table 6, the tests included tie displacement, joint profile, and track settlement.

3.2.5 MISSOURI PACIFIC RAILROAD COMPANY

A test zone was selected on the mainline about 7 miles (11.3 km) south of Little Rock, Arkansas, adjacent to the Higgins siding. The test sections are arranged as the reverse of Figure 9, with section numbers in numerical order from the left, starting with 1, curve, unconsolidated. Each section is a little longer than

TABLE 6

Test Dates and Cumulative Gross Tons of Traffic

Date	Traffic		Test Description
	MGT	MGMT	
6 November 1973	-		Selection of test zone and test ties
12-14 November 1973	0	0	All tests
19 & 20 November 1973	0.75	0.68	All tests except track settlement
26-28 November 1973	2.0	1.81	All tests except track settlement
28 December 1973	5.0	4.54	Track settlement only
8 February 1974	10.0	9.07	Track settlement only

1/8 mile (0.2 km). The test zone extends southward from Station 404 + 86, with Section 1 beginning 1,620 feet (494 m) south of Milepost 353.

Track in the test zone is designated Class 4, freight, with a 50-mph (80 km/h) maximum operating speed. It carried approximately 18 MGT (16.3 MGMT) of traffic per year at the time of the tests.

The rail is 119-lb. (54 kg) continuous welded rail, laid new in 1964. The test sections vary in length from 666 feet to 780 feet (203 m to 238 m) and the number of ties vary accordingly. The oak ties measure 7 by 9 inches by 8.5 feet (18 x 23 x 259 cm) and are spaced at 19.5 inches (50 cm); they were installed in 1972. Ballast is crushed granite, AREA size 4.

Track work consisted of placing a 2-inch (5 cm) lift of ballast, tamping with multiple tamper, ballast sweeping, and track lining. Ballast was consolidated in the cribs and shoulders of Sections 2 and 3 by a 3-second application of the consolidator. There was no additional track work performed during the entire test period.

Test data and cumulative gross tons of traffic that passed over the test zone are listed in Table 7. The test, except where noted, included tie displacement, track settlement, joint profile, and track modulus.

TABLE 7

Test Dates and Cumulative Gross Tons of Traffic

Date	Traffic		Test Description
	MGT	MGMT	
5 November 1973	-		Test zone inspection
3 & 4 December 1973	0	0	All tests
17 & 18 December 1973	0.75	0.68	All tests except settlement
14 & 15 January 1974	2.0	1.81	All tests except settlement
11 March 1974	5.0	4.54	Track settlement and track modulus only

Track maintenance and ballast consolidation were completed and the tracks opened to traffic on 4 December 1973. Traffic tonnage and other data were recorded over a period of 97 days through 11 March 1974, by which time approximately 5 MGT (4.54 MGMT) of traffic had passed over the test sections.

3.3 TEST MM-77.1, INSTRUMENTATION TEST

Test MM-77.1 [5] was a special addition to the series of five ballast consolidation tests. It was designed to determine if the modifications that had been made to the test measurement equipment were satisfactory and if the modified equipment performed as intended. It included lateral and longitudinal measurements of force versus tie displacement on ties in a section of mainline track of the Penn Central that had not been disturbed by recent track maintenance work.

Modifications to test equipment and procedures had been designed to facilitate the work and to increase the accuracy of the test results. One important change was a procedure for jacking the rail and removing the tie plates from the test ties without disturbing the bond between the ties and the ballast, as the procedure used previously appeared to have caused some slight disturbance.

The equipment used for lateral tie displacement tests, as modified, is illustrated in Figures 4 and 5. The modifications to the equipment and procedures for the lateral displacement test included:

- Connection of each end of a test tie to a displacement gage.
- Use of a very fine test wire from the test tie to the displacement gage.
- Use of small springs on each displacement gage to maintain tension in the test wire.
- Positioning of test gages and wire exactly along the centerline of the test tie.
- Use of a bubble level to check for tie rotation during tests.
- Measurement of tie displacement after the force had been relaxed in order to measure elastic recovery.

The equipment for longitudinal tie displacement tests, as modified, is illustrated in Figures 6 and 7. The modifications to equipment and procedures for the longitudinal tie displacement tests included:

- New, stronger test brackets designed to apply the force at the center of the test tie.
- Steel bearing plates placed on the tie during the test in order to avoid damage from the large jacking forces.
- A second displacement gage mounted to indicate any displacement of the restraining tie.
- Use of small springs to maintain tension in the test wires and prevent any slackening or kinking of the wire.
- An added check for parallelism of the test brackets.

- Use of a bubble level to indicate any rotation of the test tie.
- Measurement of tie displacement after the jacking force had been relaxed in order to measure elastic recovery.

The test zone selected was on the mainline track of the Penn Central near Bowie, Maryland, south of Milepost 121. The tests were conducted on track 1, designated Class 4, freight, with a 50-mph (80 km/h) maximum operating speed. The track carried approximately 15 MGT (13.6 MGMT) of traffic per year at the time of the tests. The track consists of 140-lb. (63.5 kg) continuous welded rail on yellow pine ties at 21-inch (53 cm) spacing. Ties measure approximately 6 by 8 inches by 8.5 feet (15 x 20 x 259 cm). Ballast is crushed granite, AREA size 4.

Two lateral tie and two longitudinal tie displacement tests were made on 3 October 1973 in dry, warm weather. The ties were in good condition and were seated firmly in hard-packed ballast that was tightly bound with fine material. No work was done that would disturb the ties before the tests.

3.4 TEST MM-77.3

Test MM-77.3 [6] was added to the test series at the suggestion of engineers of the Southern Railway Company in order to obtain additional data for evaluation of the effects of ballast consolidation. They designed the test in order to obtain data that would be useful in a comparison of the effects of ballast consolidation by machine to the effects of ballast consolidation by traffic. The test included measurements of lateral forces versus displacements of wood ties, dynamic track settlement, and cumulative settlement after maintenance work had been completed on sections of tangent track, both with and without ballast consolidation. Tests provided information on the effects of timbering and surfacing on the stability of track with continuous welded rails, as well as information on the effectiveness of accelerated ballast consolidation by machine.

The lateral stability tests were conducted at several levels of traffic to approximately 1.7 MGT (1.54 MGMT). For these tests, forces were applied to individual ties with a special load frame designed by Southern engineers in order to minimize operating time and to impart a slowly increasing force to the tie. The load frame is illustrated in Figures C-3 and C-4 of Appendix C.

Force was measured with a strain gage-type load cell, while displacement was measured with a potentiometric displacement transducer and also with a dial gage. Outputs from the load cell and the displacement transducer were amplified and transmitted to an X-Y plotter to produce a continuous load versus displacement curve while a tie was displaced a distance of 0.5 inch (12.7 mm).

A minimum of 16 ties (half new ties and half old ties whenever possible) were tested in each of the two consolidated and two unconsolidated test sections. As undisturbed ties were used for each test at four different levels of traffic in each of the test sections, a total of 264 ties were tested for lateral stability.

Dynamic track settlement under traffic was measured with test equipment designed by Southern engineers to provide the required accuracy and minimize the number of ties required for tests. The instrumentation consisted of a weighted platform on adjustable screw legs, supporting a cantilever beam on which a movement sensor was mounted above the end of a test tie as shown in Figures C-8 and C-9 of Appendix C. Tie movements were transmitted by a steel test wire from the sensor to a constant-speed chart where they were recorded by a stylus.

Four sets of instruments were used simultaneously at each test zone to measure settlement at two ties in consolidated ballast and two ties in unconsolidated ballast.

Cumulative settlement of the track and alignment changes were measured with conventional surveying equipment in two sections of consolidated and two sections of unconsolidated curved track, and in two sections of consolidated and two sections of unconsolidated tangent track. Measurements were made at three points in two consolidated and two unconsolidated test sections, and at five points in each of the remaining four test sections. In each test section, stakes were driven to establish a base line and survey nails were set in ties at intervals of 25 feet (7.6 m) to provide measurement points along the centerline of the track. Measurements were made after the completion of maintenance and a small amount of traffic, and at three intervals during approximately 3 weeks of traffic.

The test zones selected by Southern for validation of instrumentation and procedures were in the vicinity of Burke, Virginia and Charlotte, North Carolina. Tests were made on 34 ties in undisturbed ballast in order to obtain reference data.

The zones selected for field tests were on the mainline of the Southern near Liberty, South Carolina. Two zones on tangent track were selected for lateral stability tests, and four separate test zones were selected for dynamic settlement tests. Each test zone had a section with consolidated ballast and one with unconsolidated ballast. A typical test zone arrangement for a dynamic settlement test is shown in Figure 10.

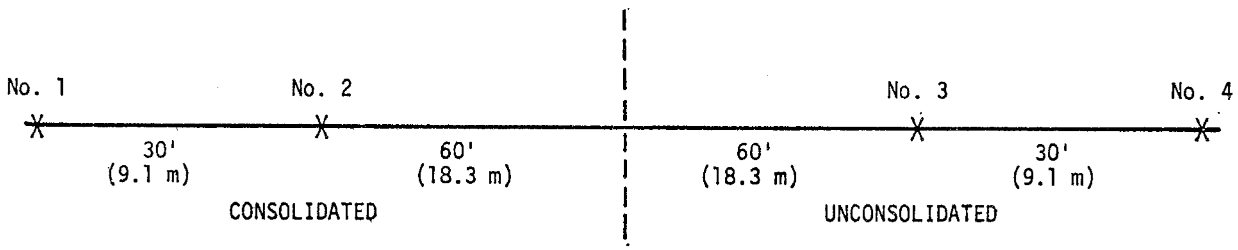

Figure 10. Typical Location of Test Instrumentation for Dynamic Settlement Tests from Appendix C

Cumulative settlement was measured in two test zones near Liberty, South Carolina, at Mileposts 505 and 505.5; and in two test zones near Lowell, North Carolina, at Milepost 394 plus 0.6 and at Milepost 304. Each zone had a test section with consolidated ballast and an adjacent section with unconsolidated ballast.

Track in the test zones is maintained as Class 4, freight, with a 60-mph (97 km/h) maximum operating speed. The track consists of 132-lb. (59.9 kg) continuous welded rail on oak ties at 20-inch (51 cm) spacing. The ties measure approximately 7 by 8 inches by 8.5 feet (18 x 20 x 259 cm). Ballast is crushed granite, AREA size 4.

Track work before testing consisted of inserting approximately 30 percent new ties, surfacing with a lift of 2 to 3 inches (5 to 7.6 cm) on crushed granite ballast, tamping with a multiple tamper, lining, and ballast sweeping. Ballast in the cribs and shoulders of the consolidated test sections was treated with a 3-second application of the consolidator. No additional track maintenance was performed during the test period.

Lateral stability tests were made during the period 10 June through 7 September 1974, by which time approximately 1.7 MGT (1.54 MGMT) of traffic had passed over the track in the test zones. Dynamic settlement measurements were made during the passage of the first train across the track in each of the four separate test zones. Cumulative settlement and alignment changes were measured at weekly intervals over periods of 3 weeks in June and July 1974. Approximately 400,000 GT (363,000 GMT) of traffic passed through the test zones during the 3-week periods.

3.5 TEST MM-151 - SETTLEMENT AT BOLTED JOINTS

Test MM-151 on Southern track was designed by FRA and ENSCO engineers in order to investigate the effects of accelerated ballast consolidation on settlement at bolted rail joints [7,8] in tangent and curved track, after the completion of timbering and surfacing. The objective of the test was to collect data on the absolute vertical settlement at 24 joints in order to obtain a time history of traffic versus settlement at the joints. The history of traffic versus settlement was considered important because of the relation of settlement to track stability and ride quality. The greatest settlement that occurs under traffic after ballast has been disturbed by maintenance is usually seen at joints. This results from the extra dynamic vibrations that occur during the movement of wheels over the gap between rail ends and from the abrupt change in stiffness of the rail at joints that reduces its ability to distribute loads. Any mismatch or batter at the rail ends imposes large dynamic loads on the tie directly beneath the two rail ends.

Initially, the tests were planned for a track carrying 1 to 2 MGT (0.91 to 1.81 MGMT) of traffic per month and with a passing siding that would permit the track to be closed during the installation of test instrumentation. However, it was not found feasible to fit the test work into the schedule for surfacing and timbering this track, and the test had to be conducted on a single track carrying 300,000 GT (272,000 GMT) of traffic per month.

The test zone was selected jointly by engineers of the Southern and ENSCO. The test zone selected is east of Greenville, Tennessee, extending westward from Milepost 153 as shown in Figure 11. The curve in the test zone is 2.2°, with 3 inches (7.6 cm) of superelevation.

Track in the test zone is operated as Class 4, freight, with a 60-mph (97 km/h) maximum operating speed, and consists of 132-lb. (59.9 kg) bolted rail on 7 by 8 inch by 8.5 foot (18 x 20 x 259 cm) oak ties at 21-inch (53 cm) spacing. Ballast is crushed granite, AREA size 4.

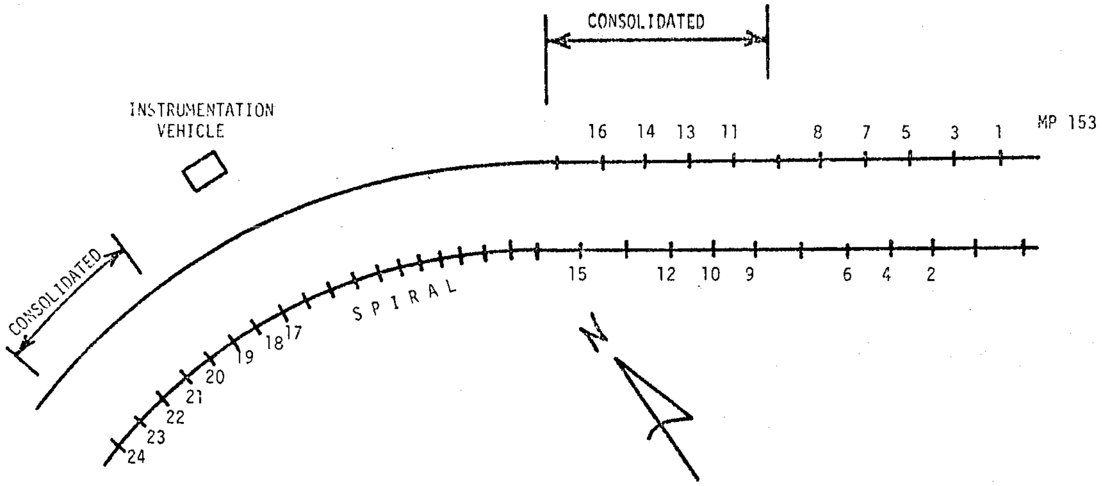

Figure 11. Diagram of Test Zone for MM-151. Joints Selected for Measurement of Tie Settlement are Numbered 1 through 24.

Tests were made after timbering and surfacing had been completed on track sections both with and without ballast consolidation, before traffic, and at intervals under traffic. Absolute settlements were measured with 24 displacement transducers, each mounted on a stiff steel beam and connected to the end of a test tie by a short wire as indicated in Figure 12. The outputs of the transducers were transmitted to strip chart recorders, and instrumentation was adjusted and maintained so that absolute and relative values of the settlements at joints could be taken directly from the charts.

The test concept and instrumentation were originally conceived by engineers of Southern. The instrumentation is generally similar to that used for measuring dynamic settlement under Test MM-77.3, as illustrated in Appendix C. However, the scope of the test was expanded and the instrumentation was refined, based on the experience with Test MM-77.3, so that absolute measurements could be recorded at 24 rail joints simultaneously.

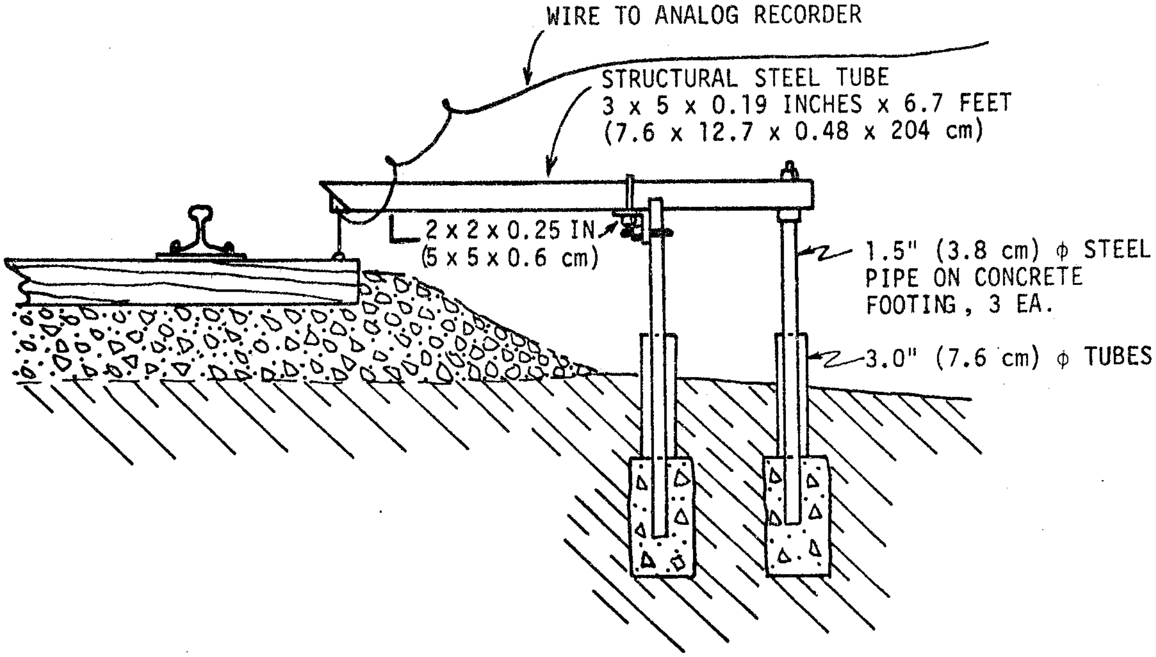

Figure 12. Schematic Installation of Displacement Transducer to Measure the Settlement at Joint

Preparations for the collection of test data included the fabrication of 24 reference platforms that were installed adjacent to the test joints. The concrete footings shown in Figure 12 provided firm support for the three steel pipes on which the steel test beam was mounted. The pipes were protected from surface vibrations by hollow tubes installed as shown. In order to avoid thermal stresses and deflections, the test beams were protected from sunlight by encasing them in foil-backed fiberglass insulation. This can be seen in photographs of the test instrumentation, Figures 13 and 14. The steel beams and transducers were mounted on the stable platforms during the interval between the completion of track work and the first traffic. Crosslevel and gage were measured daily at each test joint with a precision level and gage bar.

Figure 13. View of Test Zone MM-151 with Instrumentation Installed

Figure 14. Typical Insulated Beam Holding Displacement Transducer Above Tie at Test Joint

The settlement data from the 24 displacement transducers were displayed on four 6-channel strip chart recorders. By using a circuit designed to withstand shock and vibration and by rezeroing and calibrating the recorders daily, it was possible to record absolute vertical settlement data over the entire two-week test period.

Pretest track work included replacement of approximately 30 percent of the ties, installation of a 2-inch (5 cm) lift of ballast over all test sections, tamping with a multiple tamper, ballast sweeping, and lining. In addition, the ballast was consolidated in the cribs and shoulders where indicated in Figure 11 by a 5-second application of the consolidator. Additional ballast was spread since the consolidation had depressed the ballast in the cribs, but no other track work was done during the test period.

Track work and ballast consolidation were completed on 17 July, and the track was opened to the first traffic at 7:00 p.m. Test data and traffic tonnage were recorded over a period of 14 days, ending at 10:30 a.m. on 31 July. By that time, 155,000 gross tons (141,000 GMT) of freight traffic had passed over the track. The weather was hot and dry both before and during the test. A slight rain fell once during the test period, but it only dampened the top of the ballast.

3.6 TEST MM-219 - LATERAL STABILITY OF TRACK PANELS

Test MM-219 was planned by Chessie System engineers and was conducted on a mainline section of Chessie track near Richmond, Virginia. The objective of this test was to evaluate the effectiveness of mechanical consolidation in restoring the resistance of freshly disturbed track to lateral loads and to evaluate the differences in the resistance of panels with different types of ties. The test was also designed to obtain baseline lateral resistance data from panels of track in undisturbed ballast that had been in service for several years.

The test zone selected was a level, tangent section of mainline track at Sabot Station, approximately 10 miles (16 km) west of Richmond. This location was chosen because it had a passing siding which permitted removal of the track from service for test preparation, easy highway access, and wide shoulders to accommodate test equipment.

The test zone was prepared by repositioning the rail, so that the joints were opposite each other, and separate 39-foot (11.9 m) panels of track could be isolated for test by removing the joint bars. The appropriate ties were installed in six test panels, and four control panels were selected. Figure 15 shows the layout of the test zone. The panels that were tested are listed in Table 8.

Track in the test zone is designated as Class 4, freight, with a 50-mph (80 km/h) maximum operating speed. It consists of 132-lb. (59.9 kg) rail laid in 1956 on 7 by 9 inch by 8.5 foot (18 x 23 x 259 cm) oak ties at 20-inch (51 cm) spacings. Two of the test panels consisted of Gerwick RT 7S concrete ties with Pandrol 607A clips. Ballast is crushed limestone, AREA size 4, on a sandy clay subgrade. The annual traffic at the time of the test was approximately 25 MGT (22.7 MGMT).

Track maintenance work before testing consisted of inserting new ties as noted, surfacing with a 2-inch (5 cm) lift of crushed limestone ballast, tamping with a multiple tamper, lining, ballast sweeping, and consolidating the ballast in the designated panels by 5-second applications of the consolidator.

A diagram of the test instrumentation is shown in Figure 16. The instrumentation was developed and operated by Reaction Instruments, a subcontractor of the Chessie. A gradually increasing lateral force was applied at the center of a test panel by a hydraulic jack. The jack was fastened by bridle and spreader bar to two clips attached to the base of the rail

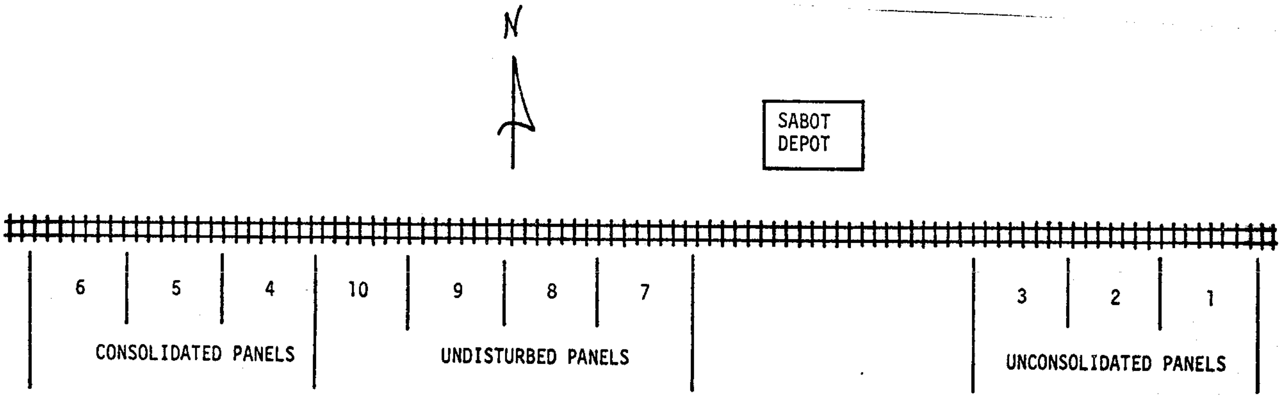

Figure 15. Diagram of Test Zone, Test MM-219, with Track Panels that were Prepared for Tests Numbered 1 through 10

TABLE 8

MM-219 Test Summary

Apr. 1975 Tests Zero Traffic			Aug. 1975 7.0 MGT Traffic		
Panel No.	Test No.	Ties	Panel No.	Test No.	Ties
1	1	22 New Wood	1	7	22 New Wood
2	2	16 Old Wood 6 New Wood	2	8	16 Old Wood 6 New Wood
3	3	17 New Concrete	3	9	17 New Concrete
4	4	22 New Wood	4	10	22 New Wood
5	5	16 Old Wood 6 New Wood	5	11	16 Old Wood 6 New Wood
6	6	17 New Concrete	6	12	17 New Concrete

Panel No.	Test No.	Ties
7	13	16 Old Wood 6 Wood Installed in mid-1974
8	14	22 Old Wood
9	15	16 Old Wood 6 Wood Installed in mid-1974
10	16	22 Old Wood

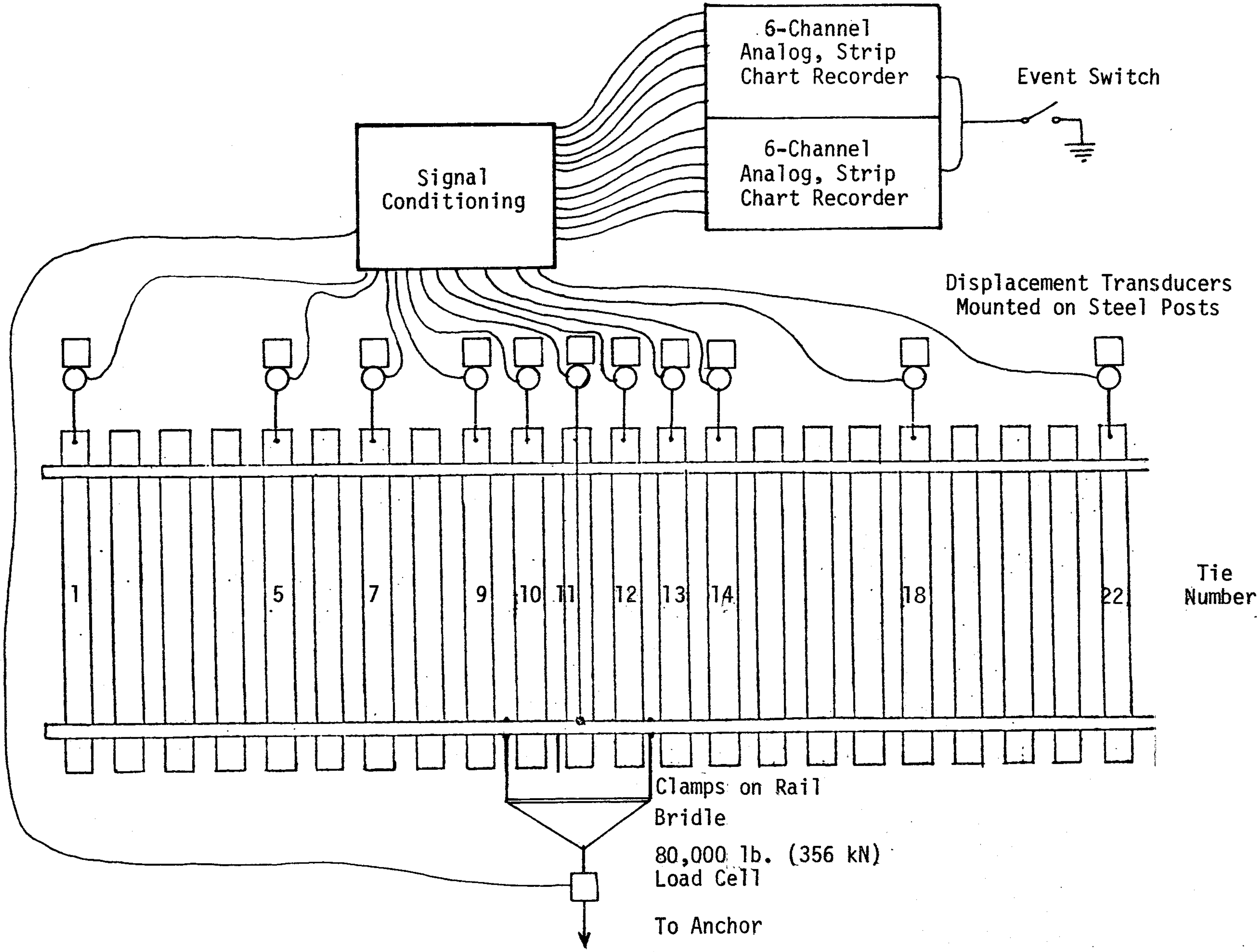

Figure 16. Arrangement of Instrumentation for Test on Panel A, West

5.5 feet (168 cm) apart in order to simulate the lateral load transfer of a standard 2-axle truck. The jack was anchored by a wire rope attached to a crawler tractor (D9 Caterpillar) with its bulldozer blade dug into the ground.

A hydraulic gear pump with an electric motor supplied a large volume of fluid at medium pressure to the hydraulic jack, and a hand pump was used for low-volume high pressure in order to apply loads to the test panel at required speeds. The load applied was measured by a load cell that had a precision strain gage, and the signal from the load cell was conditioned and recorded in pounds on a strip chart.

Displacement transducers were connected to the ends of selected ties in the test panel as indicated in Figure 16. The outputs from the transducers were transmitted to signal-conditioning equipment and subsequently recorded directly in inches on two strip chart recorders with six channels each. This provided a continuous record of the applied lateral forces and the resulting displacements. In operation, the hydraulic jack was gradually pressurized to increase the lateral force on the track panel. As the force increased, it was recorded on the strip charts along with the corresponding displacements. After the track panel yielded (shown by continuing displacement without change of force), the jack was depressurized and the test for that panel was ended. Figure 17 shows a typical test scene, with a panel of wood ties resisting a large lateral force.

Measurements of lateral force versus displacement were made on a total of ten individual test panels as listed in Table 8. Six of the test panels had been disturbed by track surfacing just before the first tests, and four were undisturbed panels. The ballast was consolidated in three of the disturbed test panels and unconsolidated in the other three. One panel in each of these groups of three had all new wood ties; one had mixed old and new wood ties; and one had new concrete ties.

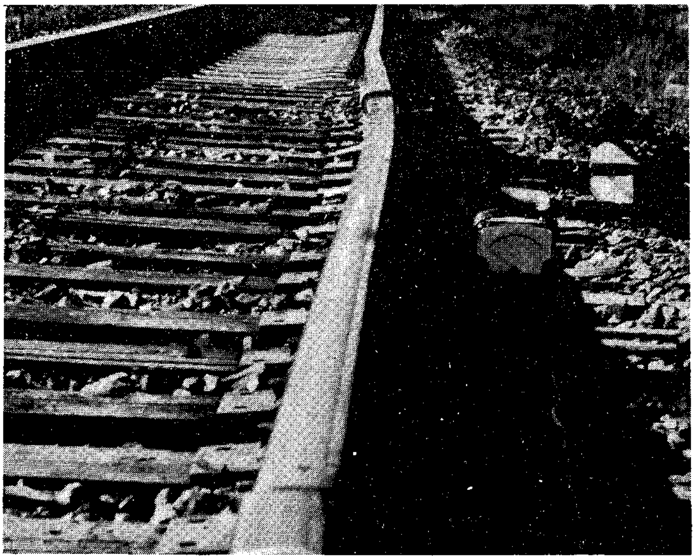

Figure 17. Lateral Resistance Test of Panel with Wood Ties

The lateral force was applied in the plane of the track panel in order to avoid the development of large vertical force components that would tend to lift the panel or force it down and thus change its lateral resistance. Measurements were made to detect movements of the panels that would indicate the development of vertical force components. Two steel posts were driven in the ground on either side of each test panel, and a taut wire was stretched between them above the rail heads. Distances from the wire to the rail heads were measured before and after testing. Vertical movement of the panel was found by averaging the changes in the distances from the rail heads to the wire. Any angular movement of the panel was found from the difference between the two changes in distance from railhead to wire.

Test panels 1 through 6 were tested after maintenance but before traffic in April 1975. These same panels were tested again after approximately 7 MGT (6.4 MGMT) of traffic. The four undisturbed control panels, 7 through 10, were also tested in August.

4. FACTORS AFFECTING TEST RESULTS

Numerous factors have been identified that affect field tests of ballast consolidation. Most of the factors are related to conditions in a specific test location, and their relative importance varies greatly with weather at the time of testing as well as with location. These factors include:

- The types of soils in the upper layer of the embankment below the ballast layer.
- Conditions of the embankment.
- Moisture content of embankment soils.
- Depth of ballast.
- Type and gradation of ballast aggregate.
- Condition of ballast.
- Moisture content of ballast.
- Height of the ballast lift.
- Type and size of ties.
- Age and condition of ties tested
- Type and condition of rail anchors.
- Type and condition of tie plates and fasteners.
- Weight, as related to the moment of inertia of rail,
- Type and condition of joints.
- Weather conditions during tests.
- Grade of track.
- Track curvature.
- Normal train speed.
- Maximum wheel loads and traffic tonnage.
- Accuracy and reliability of test equipment.
- Proficiency of equipment operators

Embankment soils of different types and variations within general classifications perform differently under similar loads. This is especially noticeable when a period of very dry or very rainy weather causes large changes in the moisture content of embankment soils. Expansive clays shrink as they dry and swell as they absorb moisture, usually in a nonuniform manner along a length of track. This effect may completely mask any differences that might otherwise be measured in the settlement of sections of track with consolidated ballast as compared to track with unconsolidated ballast and subjected to the same traffic. It may also mask and distort the values of track modulus that are computed from deflections under load. Variations in the strength of an embankment become more extreme when the embankment is in poor condition. Poor drainage conditions and depressions in the top of embankments that hold rainwater will increase greatly the variation in moisture content of the soils and the variations in the shrinking and swelling of embankment soils.

The depth of ballast has been observed to have important effects upon track stability, since the ability of the ballast to distribute loads is a function of ballast depth. The type and gradation of ballast in a track have been shown by numerous experiments, as well as by careful observation of track performance, to have a close relation to track stability. A major function of the ballast is to hold the rail-tie subsystem to the established alignment and profile. The resistance of the ballast mass to deformation depends largely on the degree of mechanical interlock developed among the pieces of ballast. This, in turn, depends in part on the size, shape, gradation, weight, hardness, and surface texture of the aggregate used for ballast. Two extremes would be crushed granite and rounded gravel. The degree of interlock that can be attained is affected also by the condition of the ballast. Interlock is weakened by an excess of fines among the ballast particles. In the extreme case, when mud from an overloaded embankment has been pumped up through the ballast layer, the layer loses the characteristic of ballast and responds to loads somewhat like a matrix of soil with small stones suspended in it.

Free water from rainfall or from other sources tends to lubricate the ballast and the ties, causing changes in the response of the ballast layer to dynamic loads and reducing the coefficient of friction between ballast and ties and also between the ballast particles. It also has the somewhat opposite effect of causing wood ties to swell, unless they are new and thoroughly impregnated with creosote, and the swelling tends to increase the resistance of the ties to lateral forces.

The height of a ballast lift is known to have some relation to loss of track stability after maintenance work but before reconsolidation of the ballast has occurred. The greater the lift, the greater the proportion of unconsolidated ballast in the cribs and shoulders.

The type and size of ties affect the bond that develops between the ties and the ballast, and the area of tie surface that is in contact with ballast. Hard ballast can be expected to dig into softwood ties faster than it does into oak and much faster than it does into plane-faced concrete ties. Old wood ties are found to be indented by pieces of ballast and to be bonded more firmly in the ballast mass than are new ties. Creosote on the surface of new wood ties has a lubricating effect, while the heavier weight of concrete ties increases their resistance to lateral and longitudinal displacement where this is not negated by the uplift forces developed ahead of rolling loads.

The rail anchors or clip-type fasteners, of course, can transfer longitudinal stresses from rails to ties adequately only when these components are in good condition and when a sufficient number are operative.

Tie plates and fasteners provide limits to the amount of initial lateral movement of the rail that could occur under stress and could initiate buckling before the lateral movement is resisted by the ties under the rail. In addition, torsional resistance of the fasteners enables the rail-tie substructure to resist lateral loads and distribute them among several ties by a truss action in the horizontal plane. This is illustrated in Figure 18, a simplified diagram of an extreme example of rails fastened rigidly to ties. In such a case, the track would respond to lateral loads as a deep Vierendeel truss with short panels. It would be very stiff in the horizontal plane, thus distributing a lateral force over many ties. However, when spikes and tie plates are used, torsional resistance is near minimum. Other types of fasteners develop greater torsional resistance, but none of them develop more than a fraction of the stiffness that would be developed with the rigid connections indicated in Figure 18.

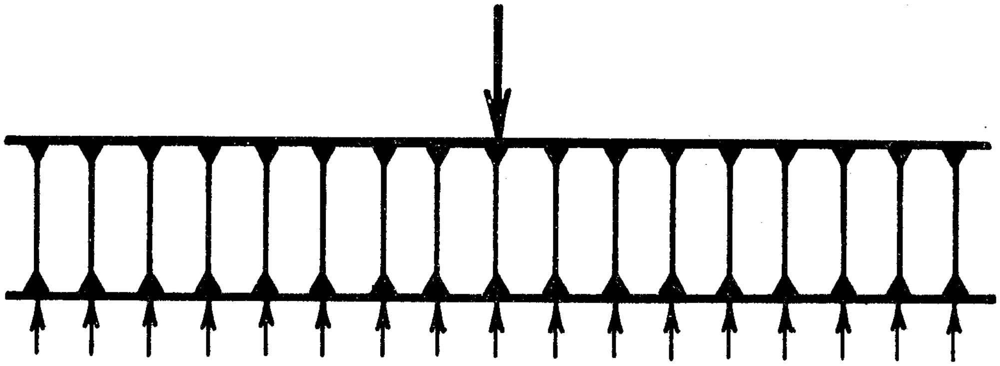

Figure 18. Rigid Connections Between Rails and Ties

A comprehensive discussion of the torsional resistance of various fasteners to rotation in the plane of the track is available in Reference 9.

The moments of inertia of the rail about horizontal and vertical axes have large effects on vertical and lateral stability, and consequently on changes in the track structure caused by traffic in the intervals between tests. The type and condition of joints which determine the stiffness of the rail at the locations of joints have similar effects.

Weather conditions may affect field tests if they cause large changes in the moisture content of the ballast or in the embankment soils, or if water is frozen to the ballast and ties in cold weather. In addition, foul weather may interfere with test procedures and make the collection of accurate data difficult.

The grade of the track, degree of curvature and superelevation, normal train speeds, maximum wheel loads, and tonnage of traffic all have effects on the rate of consolidation of ballast, on the rate of change of track geometry, and on track stability. Accordingly, they have effects on tests that vary from test zone to test zone and are difficult to evaluate. In planning the tests, efforts were made to minimize the effects of location-dependent variables by testing closely adjacent sections of consolidated and unconsolidated track, both tangent and curved in each test zone. This procedure eliminated local variations in some factors and tended to minimize the variations in others.

The accuracy of the data collected is limited to the accuracy and reliability of the test equipment. Equipment limitations were recognized in the initial planning of the ballast consolidation tests. The arrangements of test equipment and the procedures used in European tests were studied, and modifications were designed to adapt them to American track and to improve them where possible. Experience gained during the first tests of the series was used in the design of further improvements of test equipment and test procedures. Automatic measurement of displacement, as well as applied forces and time, was introduced into the later tests; and automatic recording on strip charts was used to provide complete and continuous records.

5. TEST RESULTS

5.1 TEST MM-77

A preliminary report of progress on work under Test MM-77 was provided in Reference 10.

5.1.1 TRACK STABILITY

Data from tests of the resistance of individual ties to lateral and longitudinal forces are provided in Appendix A. The data were extracted from the records of ties chosen randomly to show the load levels at the same movement for all the ties listed. A 4-mm lateral displacement was used for comparison with the results obtained under Test MM-77.3. However, this introduced some bias as many of the ties were not displaced laterally as far as 4 mm by the forces applied, and these ties tended to show greater resistance to movement. A 2-mm distance was also used as a displacement at which to compare tie resistance, since this is considered a significant movement in relation to buckling effects and it could be used in comparisons of longitudinal as well as lateral resistance. Most of the ties tested for longitudinal stability were not displaced as far as 4 mm by the maximum available test force. In many cases where the force applied was not measured at exactly 2- or 4-mm displacement, figures were obtained by simple interpolation between the forces recorded for displacements just above and just below 2 mm or 4 mm.

Great variation is seen in the resistance of ties at 2- and 4-mm displacements even among the small number of ties listed in the sample in Appendix A.

It can be seen clearly from the sample in Appendix A that before traffic was run over the track, the ties on consolidated ballast generally offered much greater resistance to movement than the ties on unconsolidated ballast. Before traffic, the average lateral resistance for a 2-mm displacement of the ties listed in consolidated ballast was 420 pounds (1.87 kN) or 33 percent more than that of ties in unconsolidated ballast. Before traffic at 4-mm displacement, the average lateral resistance of the same ties as consolidated ballast was 480 pounds (2.14 kN) higher, again 33 percent more than the resistance of the ties in unconsolidated ballast.

The force-displacement records of all 343 ties tested on five railroads were examined at 2-mm displacement before traffic. The average lateral resistance of the ties in consolidated ballast was found to be 36% higher than the lateral resistance of ties in unconsolidated ballast. Other data are given in Table 9.

TABLE 9

Resistance of Ties to Lateral Forces at 2-mm Displacement, Before Traffic

	Consolidated		Unconsolidated	
	Pounds	Kilonewtons	Pounds	Kilonewtons
Range	950 to 2950	4.23 to 13.12	400 to 2150	1.78 to 9.56
Median Value	1650	7.34	1200	5.34
Mean	1670	7.43	1230	5.47
Standard Deviation	330	1.47	250	1.11

The same ties were tested again at traffic levels near 0.5 and 1.5 MGT (0.45 and 1.36 MGMT), depending on weather conditions and schedules of the participating railroads. The ties in consolidated ballast continued to show slightly more resistance to movement than the ties in unconsolidated ballast. This is indicated in Table 10 the data for which was taken from the sample in Appendix A. In the table, the forces at displacements of 2 mm were lumped for traffic levels from 0.5 to 1.0 MGT (0.45 to 0.90

MGMT) and the mean was computed. The same was done for traffic levels from 1.5 to 2.0 MGT (1.36 to 1.81 MGMT) and for displacements of 4 mm. It is noted that the mean values for the sample ties in Appendix A at zero traffic are only slightly different from the mean values given in Table 9 for all 343 ties tested at 2-mm displacement, which suggests that the samples in Appendix A are representative.

TABLE 10

Resistance of Ties to Lateral Forces at 2- and 4-mm Displacements

Traffic MGT & M (Metric Tons)	Displacement Millimeters	Consolidated		Unconsolidated	
		Pounds	Kilonewtons	Pounds	Kilonewtons
0	2 4	1700 1930	7.56 8.58	1280 1450	5.69 6.45
0.5 (0.45) to 1.0 (0.90)	2 4	2390 2670	10.63 11.88	2060 2270	9.16 10.10
1.5 (1.36) to 2.0 (1.81)	2 4	2230 2710	9.92 12.05	2210 2530	9.83 11.25

Large variations are apparent in the longitudinal resistance of the sample of ties listed in Appendix A. When tested before traffic under forces applied along the longitudinal axis of the track, the average resistance developed at 2-mm displacement by ties in consolidated ballast was approximately 470 pounds (2.09 kN) or 18% more than that of ties in unconsolidated ballast. Some of this difference in resistance is still seen after many tons of traffic in the tables in Appendix A.

5.1.2 TRACK SETTLEMENT

Samples of settlement measurements are provided in Appendix A. Data from tangent sections only were tabulated in order to reduce the effects of location factors that are somewhat more noticeable in curved sections of track. Measurements that showed the effects of freezing were omitted.

Averages were computed for the settlements of track on consolidated ballast on each railroad at each level of traffic listed in Appendix A. The same was done for track on unconsolidated ballast, and the results were tabulated in Table 11.

TABLE 11

Cumulative Settlement of Track in Inches and Millimeters ( ) at Various Levels of Traffic

MGT		0.5	1.0	1.5	1.7	2.7	5.0	6.4	10	15
MGMT		0.45	0.91	1.36	1.54	2.45	4.54	5.80	9.07	13.6
Southern	C			0.31 (7.9)			0.53 (13.5)			
	U			0.60 (15.2)			0.96 (24.4)			
Boston & Maine	C		0.32 (8.1)			0.54 (13.7)				
	U		0.43 (10.9)			0.55 (14.0)				
Penn Central	C	0.42 (10.7)			0.42 (10.7)			0.60 (15.2)		1.08 (27.4)
	U	0.41 (10.4)			0.43 (10.9)			0.73 (18.5)		1.23 (31.2)
Saint Louis & Southwestern	C							0.40 (12.4)	0.53 (14.0)	
	U							0.62 (15.7)	0.68 (17.3)	
Missouri Pacific	C						0.60 (15.2)			
	U						1.10 (27.9)			

NOTES: C - Consolidated ballast, U - Unconsolidated ballast

Large variations are apparent among the settlements measured on different tracks. However, with the exception of the Penn Central track at 0.5 MGT (0.45 MGMT), the average settlement of the unconsolidated track was larger in every case.

Although the average settlement was less in consolidated ballast, the individual measurements tabulated in Appendix A show numerous instances where the settlement of rail on consolidated ballast is larger than that of rail on unconsolidated ballast in adjacent sections of track. However, even without an analysis of variance, the variation in settlement found within a test section was generally less for rail on consolidated ballast than for rail on unconsolidated ballast.

5.1.3 JOINT PROFILE MEASUREMENTS

Joint profiles were measured at welded joints in continuous welded rails. Under rolling traffic, the small variations in the rails at the welds and the disturbance of the steel characteristics caused by welding could act as impact generators, and one could expect more settlement at welded joints than between joints. However, the joint profile measurements in the continuous welded rail of the track tested under Test MM-77 did not show significant differences between rail on consolidated ballast and rail on unconsolidated ballast, and the data are not included in the appendices.

Much larger impact effects and larger settlements were expected at bolted rail joints. Accordingly, Test MM-151 was planned for the measurement of the settlement of ties at bolted joints.

5.1.4 TRACK MODULUS

The tests showed the many difficulties that can be encountered in efforts to obtain exact measurements of track modulus except under ideal conditions. The scatter of data obtained was such that the results were not considered significant. Accordingly, data from track modulus tests are not included in the appendices.

5.1.5 TRACK GEOMETRY

Full-scale copies of representative strip charts of track geometry measurements made by the test cars of the Boston and Maine and the Southern are included in Appendix A. Since the systems used are different, the results obtained by the two test cars are not directly comparable.

It had not been expected that accelerated consolidation of ballast in cribs and shoulders would not normally have an appreciable effect on track geometry. An exception could be a track with a weak embankment subject to large differential settlements that might be reduced by accelerated consolidation, or a track particularly subject to buckling effects that might be prevented by accelerated consolidation. These extreme conditions did not exist on the tracks tested.

The Southern tests was on a new track, substantially built with clean granite ballast on an old and stable embankment. Although a statistical analysis was not performed because the data were not digitized, a visual examination of the charts of track geometry in sections of consolidated or unconsolidated ballast indicates that there is no significant difference. This is consistent with the sample of track settlement measurements in Appendix A. The sample shows slightly more settlement for the Southern track with unconsolidated ballast at 1.5 MGT (1.36 MGMT) of traffic, but no increase in the small variations in settlement seen within test sections having consolidated ballast.

The Boston and Maine test was on a track with lighter (112 lb.) (50.8 kg) rail and granite ballast on a cinder base. It was resurfaced with a ballast lift of 1 to 2 inches (2.5 to 5 cm) before the tests. When the strip chart records are examined, the variations in rail profile measured in sections with unconsolidated ballast appear slightly larger than the rail profile variations where the ballast was consolidated. This also is consistent with the samples of track settlement measurements made at 1.0 MGT (0.91 MGMT) of traffic. These show slightly more settlement in the unconsolidated sections and slightly larger variations in the settlement within the unconsolidated sections.

When the charts for the curved sections of track are compared for changes in alignment, it appears that the small changes were slightly smaller in the consolidated sections on both railroads.

5.2 TEST MM-77.1

The validation tests on Penn Central track of changes to procedures and equipment for measuring lateral and longitudinal stability (resistance of individual ties to horizontal forces) were found to be feasible and effective. No requirements for additional changes were indicated by these tests.

During this test, the lateral forces required to displace the test ties 2 mm were 1,200 and 1,400 pounds (5.34 and 6.23 kN); at 4-mm displacement, the lateral forces were 1,450 and 1,400 pounds (6.45 and 6.23 kN), respectively. The longitudinal forces required to displace two other test ties 2 mm were 5,000 and 3,900 pounds (22.24 and 17.35 kN), respectively.

Note that there was no test numbered MM-77.2. A test that had been considered would have extended the Test MM-77 series and would have provided more data of a similar nature without much improvement in the statistical confidence level. Accordingly, it was omitted.

5.3 TEST MM-77.3

Detailed information on Test MM-77.3 and the test results are provided in the Southern Railway Company report that is attached as Appendix C. Brief highlights only are offered in this section.

5.3.1 LATERAL STABILITY

Tests of individual ties after track work and a small amount of traffic showed that new ties in consolidated ballast had an average resistance to lateral forces that was 370 pounds (1.65 kN) or 45% higher than the resistance of new ties in unconsolidated ballast, at a displacement of 4 mm. The test showed that consolidation restored an average of 20% of the lateral resistance that had been lost during the disturbance of ties and ballast by maintenance work. This effect is shown in Figure 19, taken from Appendix C.

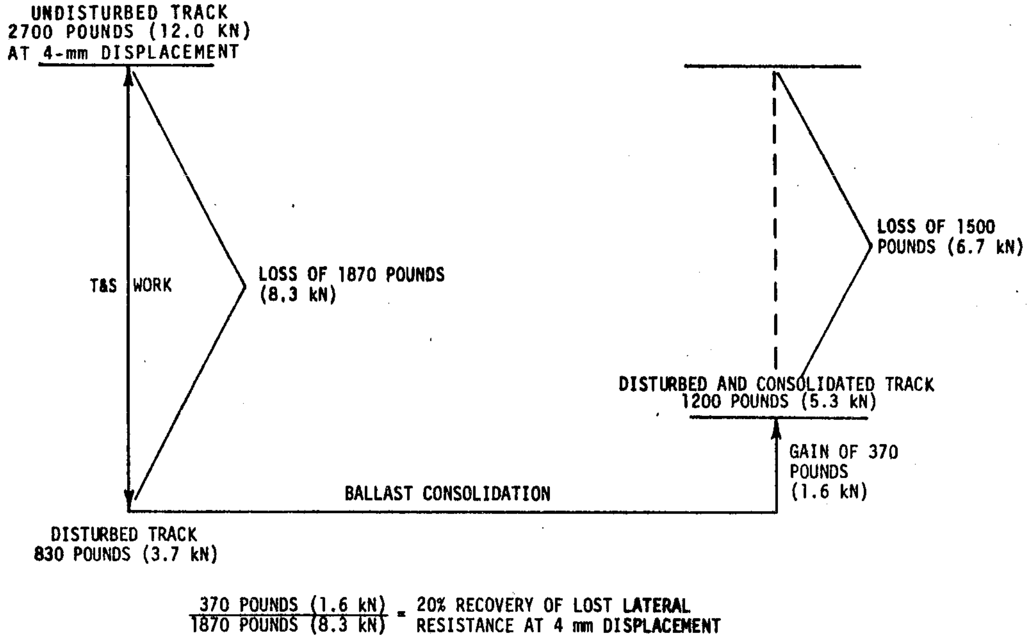

Figure 19. Changes in Lateral Resistance Caused by Surfacing and Accelerated Ballast Consolidation

The test data show that the disturbance of the ballast structure by timbering and surfacing had reduced the resistance of individual ties to lateral forces by 1,870 pounds (8.32 kN) or 70%. The data also indicate that the accelerated consolidation had increased the resistance of ties to lateral forces by average amounts equivalent to the effects of a minimum of approximately 200,000 GT (181,000 GMT) of traffic. They also show that a difference in lateral resistance between ties in consolidated and unconsolidated ballast still existed after 1.7 MGT (1.54 MGMT) of traffic.

When old ties in ballast that had been disturbed by surfacing are compared to old ties in undisturbed ballast after a small amount of traffic, it was found that 69% of their resistance to lateral forces had been lost. A comparison of new ties in disturbed ballast to old ties in undisturbed ballast showed the new ties had 73% less lateral resistance. Additionally, old ties in disturbed ballast were found to have approximately 100 pounds (0.44 kN) or 12% more resistance to lateral forces than new ties in disturbed ballast.

5.3.2 TRACK SETTLEMENT

The initial settlement was measured at test ties in each of four test zones, during the passage of the first trains, after track work and accelerated consolidation had been completed. Although the trains that crossed the different test zones were not the same, the tonnages and wheel loads were in the same general range. The average settlement of the seven ties tested in unconsolidated ballast was only 0.025 inch (0.64 mm) or 14% more than the average of ties in consolidated ballast. A sample trace of settlement from the strip chart record is shown in Appendix C, Figure C-12. It shows clearly the settlement and partial recovery of the ties under dynamic loads from train wheels.

The measurements of cumulative track settlement in each of the four test zones during periods of approximately 3 weeks and 1 MGT (0.91 MGMT) of traffic provided a large scatter of data. The data scatter is considered indicative of the effects of location-dependent factors discussed in Section 4, and also the passage of a locomotive and one car over Test Zones 3 and 4 before the initial survey was made. Examination of the data indicates no significant differences between the settlement of the track on consolidated and unconsolidated ballast. Overall indications are that the track settled an average of about 0.25 inch (6.4 mm) under approximately 45,000 GT (40,800 GMT) of traffic; and it settled an average of 0.50 inch (12.7 mm) under 1.0 MGT (0.91 MGMT) of traffic.

Measurements of changes in track alignment did not indicate any significant differences between tangent sections with consolidated and unconsolidated ballast. On curved track the lateral movement measured on the consolidated sections was only 30% of the change that occurred in the unconsolidated sections. All but one of the lateral changes were noted to be toward the outside of the curves in both the consolidated and unconsolidated sections. A small amount of traffic passed over the test zones before the initial location measurements were made.

5.4 TEST MM-151

Data from the measurement of settlement at bolted rail joints in track of the Southern System are provided in Appendix D. Data on changes in crosslevel and in gage are also included in the appendix. Related information was reported in Reference [11].

The average cumulative settlement versus traffic at joints in consolidated and unconsolidated tangent track under traffic is plotted in Figure 20. Similar data for joints in curved track (all joints on the inside rail) are plotted in Figure 21. These plots show that the rail joints settled more in unconsolidated ballast than in consolidated ballast under early traffic. This effect continued under later traffic, although the percentage difference in settlement gradually decreased.

The test was ended at 155,000 GT (140,600 GMT) of traffic; and, at the time, settlement was continuing at about the same rate as it had at 40,000 GT (36,300 GMT). At 155,000 GT (140,600 GMT), the joints on unconsolidated ballast in tangent track had settled an average of approximately 0.48 inch (12 mm) which was 18% more than the joints on consolidated ballast had settled. At the same level of traffic, the joints in curved track on unconsolidated ballast had settled an average of over 0.51 inch (13 mm), which was 23% more than the joints on consolidated ballast had settled. The measurements tabulated in Appendix D indicate that the variation in settlement at joints was approximately the same for sections in consolidated and unconsolidated ballast.

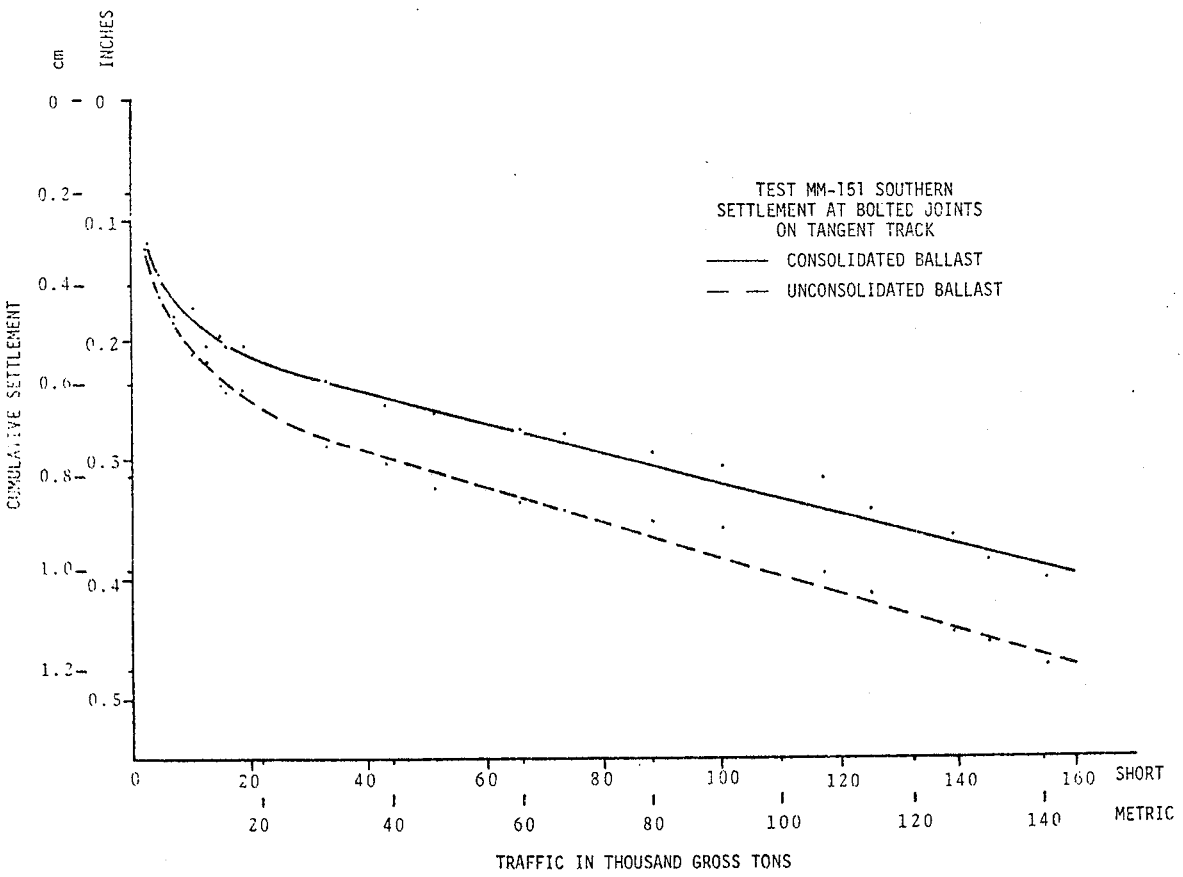

Figure 20. Settlement Versus Traffic at Bolted Joints in Tangent Track

A comparison of Figures 20 and 21 shows that the settlement at the heavily loaded joints on the inside of the curve was larger under early traffic than it was at joints on tangent track. However, as more traffic passed over the track and the total settlement increased, the relative difference in settlement between the two sets of joints decreased.

Crosslevel changes are summarized in Tables 12 and 13. In all but four cases, the bolted joint settled more than the rail opposite the joint on the same tie; and in those exceptional cases, there was no difference in the measured change in crosslevel. On the curve, all of the joints tested were on the inside rail, and all settled more than the rail opposite to them.

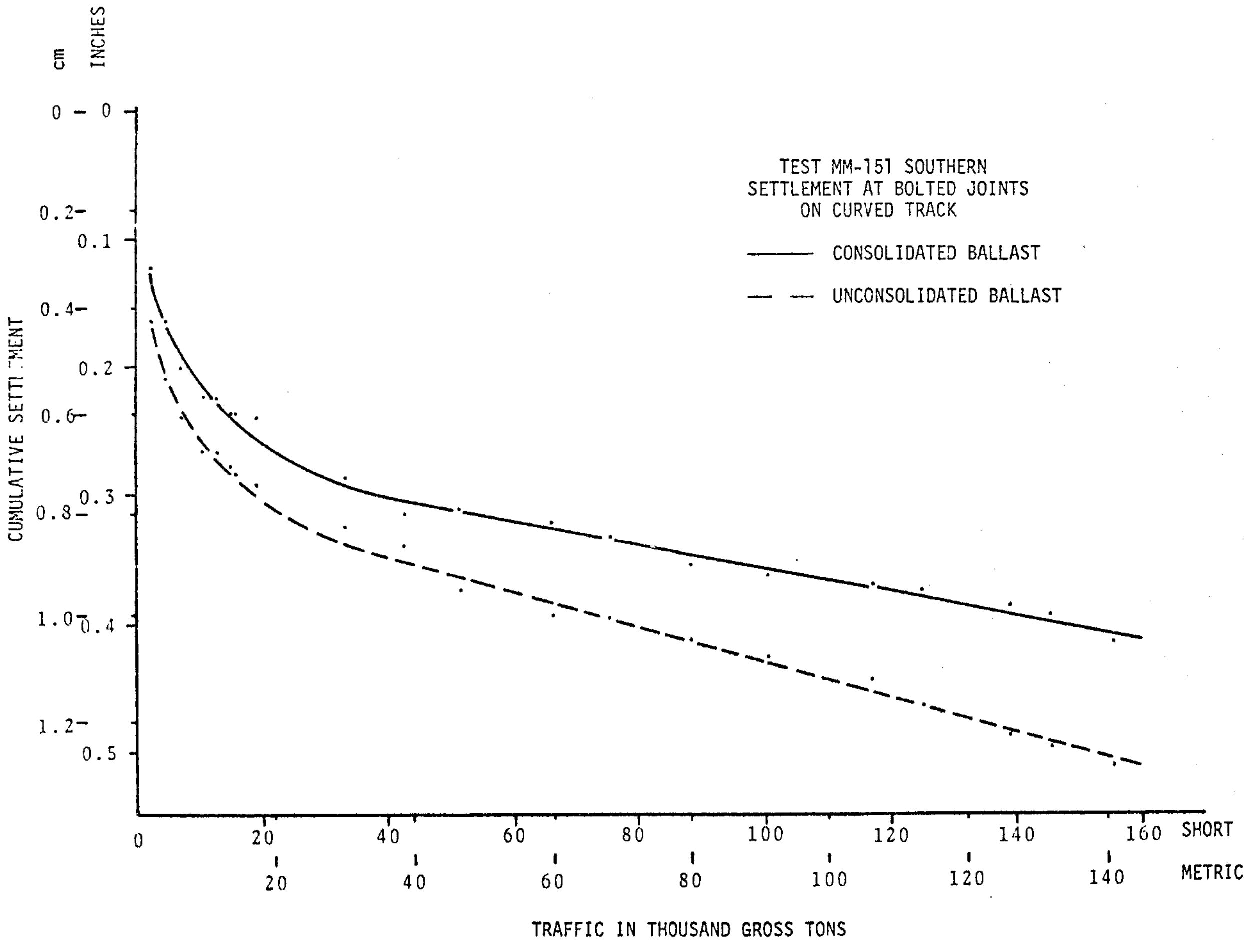

Figure 21. Settlement Versus Traffic at Bolted Joints in the Inner Rail of Curved Track

TABLE 12

Crosslevel in Inches Versus Cumulative Traffic in Gross Tons

	Tangent Unconsolidated							
Joint Numbers	1	2	3	4	5	6	7	8
At 0 Traffic	-0.38	-0.28	-0.31	-0.09	-0.03	0.25	-0.16	-0.37
At 155,000 GT	-0.41	-0.19	-0.31	-0.03	-0.03	0.38	-0.22	-0.43
Net Change	-0.03	0.09	0	0.06	0	0.13	-0.06	-0.06
	Tangent Consolidated							
Joint Numbers	9	10	11	12	13	14	15	16
At 0 Traffic	-0.03	0.09	-0.16	0	-0.25	-0.19	0.06	0.13
At 155,000 GT	0	0.16	-0.25	0.09	-0.31	-0.19	0.19	0.13
Net Change	0.03	0.07	-0.09	0.09	-0.06	0	0.13	0
	Curve							
	Unconsolidated				Consolidated			
Joint Numbers	17	18	19	20	21	22	23	24
At 0 Traffic	0.25	0.38	0.44	0.63	0.38	0.44	0.66	0.50
At 155,000 GT	0.31	0.44	0.50	0.66	0.47	0.47	0.91	0.59
Net Change	0.06	0.06	0.06	0.03	0.09	0.03	0.25	0.09

TABLE 13

Crosslevel in Millimeters Versus Cumulative Traffic in Gross Metric Tons

	Tangent Unconsolidated							
Joint Numbers	1	2	3	4	5	6	7	8
At 0 Traffic	- 9.7	-7.1	-7.9	-2.3	-0.8	6.4	-4.1	- 9.4
At 141,000 GMT	-10.4	-4.8	-7.9	-0.8	-0.8	9.7	-5.6	-10.9
Net Change	-0.7	2.3	0	1.5	0	3.3	-1.5	- 1.5
	Tangent Consolidated							
Joint Numbers	9	10	11	12	13	14	15	16
At 0 Traffic	-0.8	2.3	-4.1	0	-6.4	-4.8	1.5	3.3
At 141,000 GMT	0	4.1	-6.4	-2.3	-7.9	-4.8	4.8	3.3
Net Change	0.8	1.8	-2.3	-2.3	-1.5	0	3.3	0
	Curve							
	Unconsolidated				Consolidated			
Joint Numbers	17	18	19	20	21	22	23	24
At 0 Traffic	6.4	9.7	11.2	16.0	9.7	11.2	16.8	12.7
At 141,000 GMT	7.9	11.2	12.7	16.8	11.9	11.9	23.1	15.0
Net Change	1.5	1.5	1.5	0.8	2.2	0.7	6.3	2.3

The crosslevel was measured to 1/32 inch (0.79 mm) and converted to decimals to the nearest 0.03 inch (0.76 mm) in Tables 12 and 13. The 3 inches (7.6 cm) of superelevation on the curve are omitted from the table. The south rail (inside of the curve as shown in Figure 11) was taken as the base rail. Accordingly, at zero traffic, a positive number in the table indicates that the north rail was higher than the south rail, while a negative number shows that the north rail was lower. A positive change indicates that the south rail settled more than the north rail, while a negative change indicates that the north rail settled more than the south rail. Bolted joints numbered 2, 4, 6, 9, 10, 12, 15, and 17 through 24 were on the south rail, and all showed positive changes in crosslevel.

The gage measurements and changes in gage tabulated in Appendix D do not indicate any patterns or anomalies. The largest change measured after 155,000 GT (141,000 GMT) of traffic was -0.10 inch (-2.54 mm); and, at most of the joints, the change measured was ±0.03 inch (0.76 mm) or less.

5.5 TEST MM-219

Data on the lateral stability of panels of track measured on the Chessie System are provided in Appendix E. Lateral forces and displacements are summarized in Tables 14 and 15. Related information was reported in Reference [12].

The ballast consolidator was used in Test Panels 4, 5, and 6. The cumulative traffic was estimated on undisturbed Panels 7, 8, 9, and 10; and these undisturbed track panels had very high resistance to lateral forces. At a force of 12,000 pounds (53.38 kN), their average displacement was less than 0.06 inch (1.52 mm); while at the same force, the two wood tie panels in unconsolidated ballast had an average displacement of 1.27 inches (32.26 mm), and the two wood tie panels in consolidated ballast had an average displacement of 0.33 inch (8.38 mm). It should be noted that the entire test area was flooded with over 8 feet (2.45 m) of silt-laden water for several days in the spring of 1973.

TABLE 14

Summary of Lateral Forces and Corresponding Displacements in Pounds and Inches

Test Panel	Displacement, Inches, at				Force Thousands		Traffic MGT
	12,000	15,000	Yield	Maximum	Yield	Maximum	
1 Wood	1.74	-	1.74	2.29	12.0	12.25	0
2 Wood	0.59	-	1.53	3.00	14.0	14.4	0
3 Conc	0.70	1.88	1.88	2.12	15.1	15.0	0
4 Wood C	0.36	-	0.63	2.37	13.5	14.3	0
5 Wood C	0.29	0.94	0.94	1.82	15.0	15.6	0
6 Conc C	0.12	0.33	1.84	2.05	20.0	20.25	0
1 Wood	0.20	0.47	0.77	2.10	15.25	15.25	7
2 Wood	0.19	0.35	0.87	2.30	17.0	17.0	7
3 Conc	0.06	0.20	1.29	2.13	18.5	19.6	7
4 Wood C	0.11	0.20	0.25	1.00	16.0	16.3	7
5 Wood C	0.06	0.11	0.42	1.92	17.5	17.5	7
6 Conc C	0.29	1.10	1.28	2.80	15.4	15.4	7
7 Wood U	0.03	0.05		0.48		27.0	180
8 Wood U	0.02	0.03		0.10		26.0	180
9 Wood U	0.09	0.11		0.22		26.0	180
10 Wood U	0.08	0.11		0.31		28.5	180

Notes: C - Consolidated Ballast U - Undisturbed Ballast

TABLE 15

Summary of Lateral Forces and Corresponding Displacements in Kilonewtons and Millimeters

Test Panel	Displacement at				Force		Traffic MGMT
	53.38 kN	66.72 kN	Yield	Maximum	At Yield	Maximum	
1 Wood	44.2	-	44.2	58.2	53.38	54.5	0
2 Wood	15.0	-	38.9	76.2	62.27	64.1	0
3 Conc	17.8	47.8	47.7	53.8	67.16	66.7	0
4 Wood C	9.1	-	16.0	60.2	60.05	63.6	0
5 Wood C	7.4	23.9	23.9	46.2	66.72	69.4	0
6 Conc C	3.0	8.4	46.7	52.1	88.96	90.1	0
1 Wood	5.1	11.9	19.6	53.3	67.83	67.8	6.35
2 Wood	4.8	8.9	22.1	58.4	75.62	75.6	6.35
3 Conc	1.5	5.1	32.8	54.1	82.29	87.2	6.35
4 Wood C	2.8	5.1	6.4	25.4	71.17	72.5	6.35
5 Wood C	1.5	2.8	10.7	48.8	77.84	77.8	6.35
6 Conc C	7.4	27.9	32.5	71.1	68.50	68.5	6.35
7 Wood U	0.8	1.3		12.2		120.1	163
8 Wood U	0.5	0.8		2.5		115.7	163
9 Wood U	2.3	2.8		5.6		115.7	163
10 Wood U	2.0	2.8		7.9		126.8	163

Notes: C - Consolidated Ballast U - Undisturbed Ballast

The tables in Appendix E show that the resistance to lateral force at 0.2-mm displacement averaged 15,750 pounds (70.06 kN) for the four undisturbed panels. The average resistance of the two wood tie panels in unconsolidated ballast at 2-mm displacement was 6,200 pounds (27.6 kN), an equivalent loss of 61% of their resistance during surfacing. For the two wood tie panels in consolidated ballast the resistance was 35% larger, or 8,350 pounds (37.1 kN).

At displacements of 4 mm, the undisturbed panels showed an average resistance of 23,500 pounds (104.5 kN). This average includes an estimated 29,000 pounds (129 kN) of resistance for panel 8 which had been displaced to a total of only 2.5 cm. At 4-mm displacements, the two panels with wood ties in unconsolidated ballast had an average resistance of 7,650 pounds (34 kN), an equivalent loss of 67% after surfacing. The two panels with wood ties in consolidated ballast had an average resistance of 10,000 pounds (44.5 kN), or 31% more than the panels in unconsolidated ballast. This was equivalent to a loss of 57% of the resistance of the undisturbed panels.

The maximum track panel displacements versus increasing lateral forces, before traffic, are plotted in Figures 22 and 23 for the panels that were disturbed by surfacing, with and without accelerated ballast consolidation.

The maximum displacements versus lateral forces are plotted in Figure 24 for the panels with concrete ties. The figure shows that the panels with concrete ties had a much larger improvement in resistance with accelerated consolidation of ballast than did panels with wood ties. Before traffic, the panel with concrete ties in unconsolidated ballast had 16% higher resistance to lateral forces than the panels with wood ties. The panel with concrete ties in consolidated ballast had 40% higher resistance than the panels with wood ties in consolidated ballast. This panel, Number 6, showed an atypical loss of lateral resistance after 7 MGT (6.35 MGMT) of traffic. The test engineer was informed that a sun kink had displaced Panel 6 three weeks before the August test, which would have reduced the bond between ties and ballast and lowered the resistance of the panel. Many possible factors could have caused a buckle to occur at an isolated panel of concrete ties in a wood tie track where there would be an abrupt change in longitudinal rail stress, but at the time it was not feasible to determine which factors were dominant.

Displacement curves are plotted in Figure 25 for Panel 6 at various levels of applied lateral force up to a total of 16,500 pounds (73.4 kN). Points on the curves were plotted from the data for each concrete test tie. The dip in the center of the curves plotted at forces below 12,000 pounds (53.4 kN) results

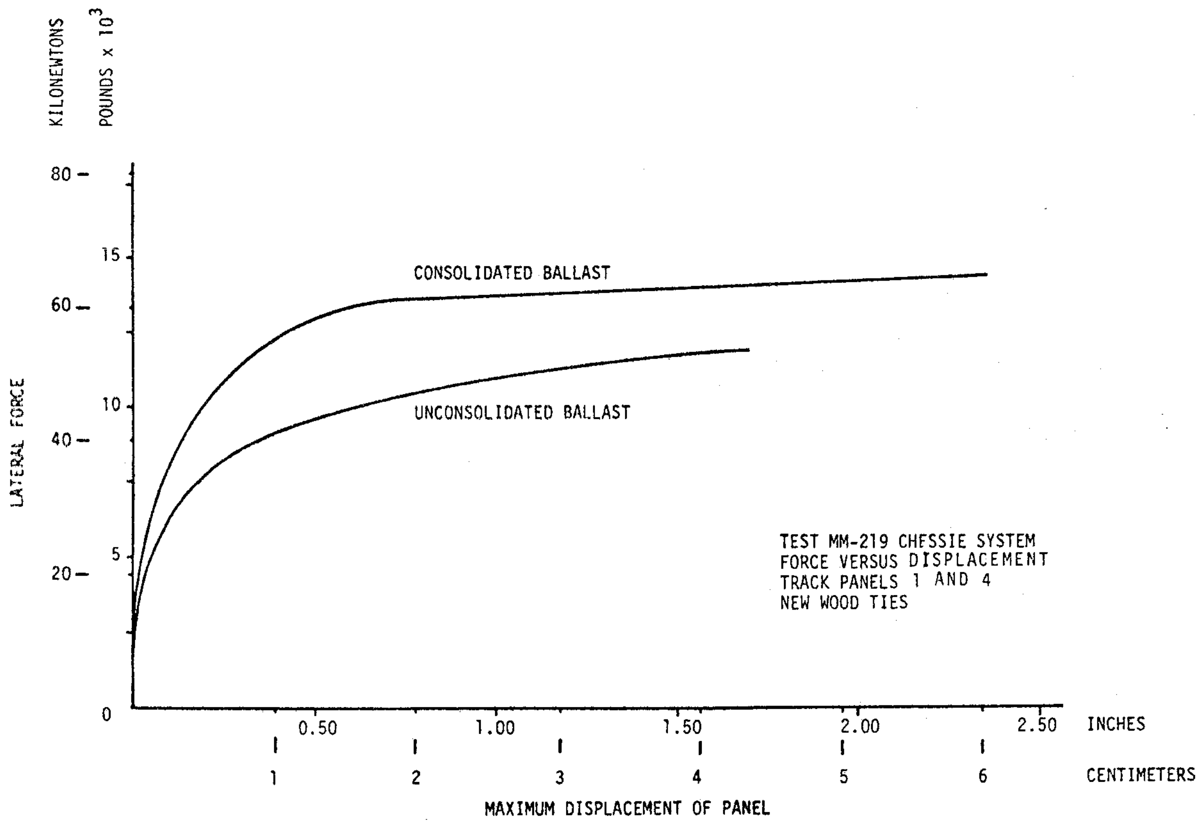

Figure 22. Displacements of Panels 1 and 4 Before Traffic

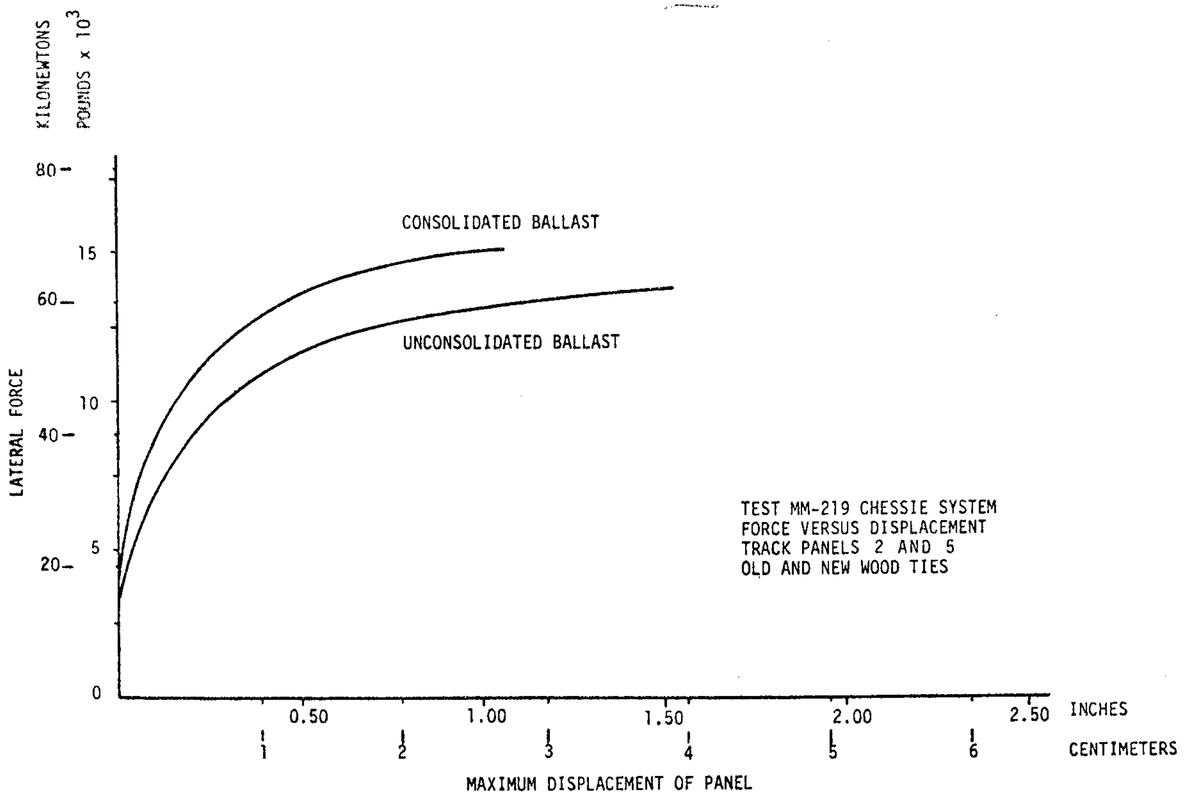

Figure 23. Displacement of Panels 2 and 5 Before Traffic

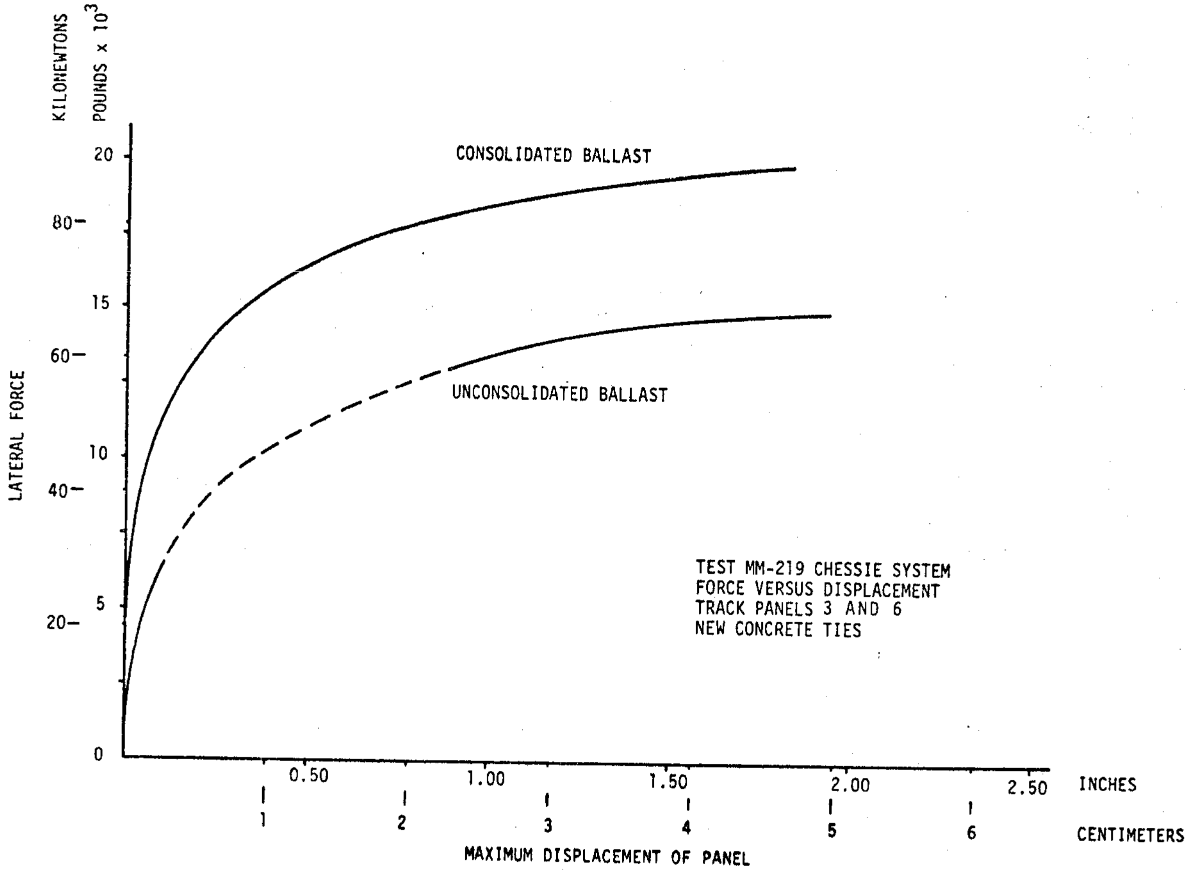

Figure 24. Displacement of Panels 3 and 6 Before Traffic

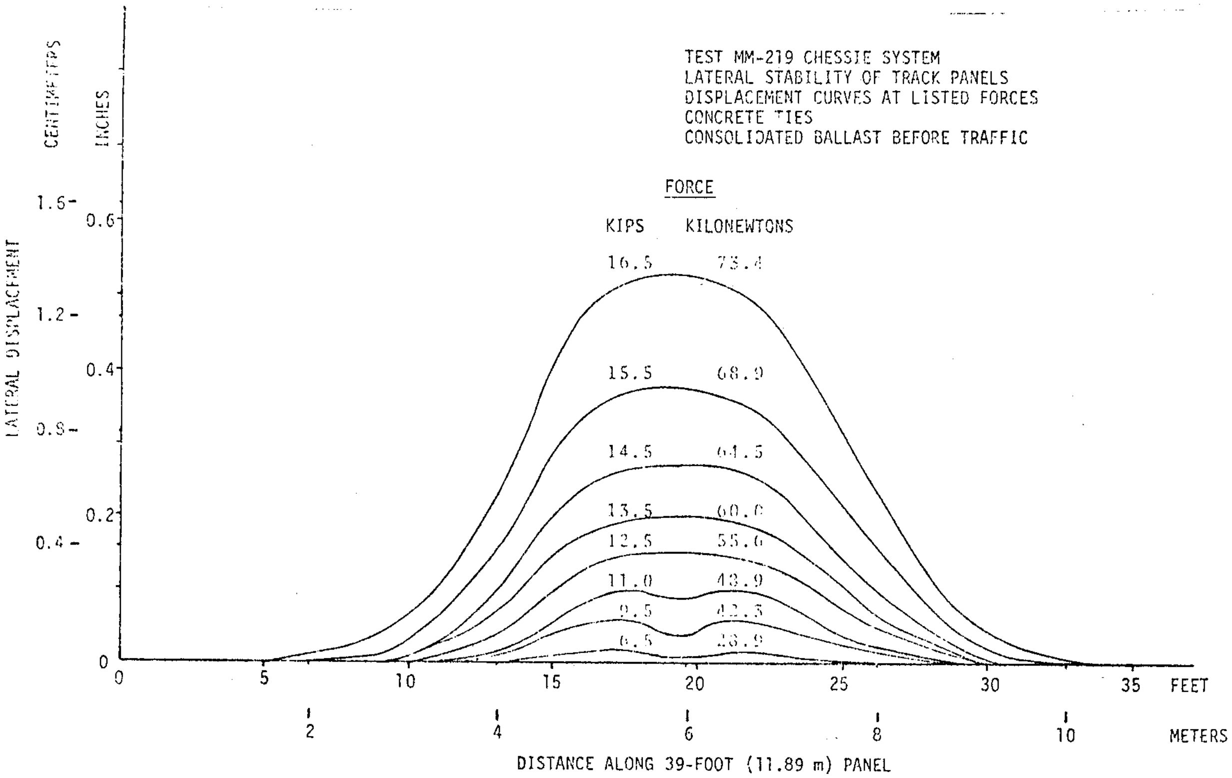

Figure 25. Displacement Curves for Panel 6 Before Traffic

from resistance of the ties and deflection of the rail between the two points of application of the load which were 5 feet (1.5 m) apart.

The effects of accelerated ballast consolidation were not very pronounced after 7 MGT (6.35 MGMT) of traffic. When tested at yield after 7 MGT (6.35 MGMT) of traffic, the panels with wood ties on unconsolidated ballast showed an average gain of 3,150 pounds (14.01 kN) of lateral resistance, or 24%, for a total resistance of 16,150 pounds (71.84 kN) at yield. The panels with consolidated ballast gained only 2,500 pounds (11.12 kN), an increase of 18% for a total resistance of 16,750 pounds (74.50 kN) at yield. For comparison, the undisturbed panels of wood ties developed resistances over 26,000 pounds (115.70 kN) before yield.

The lateral forces applied to the track panels did not appear to cause any vertical movement that would have significantly affected the lateral resistance of the panels during the tests. The slight movements that were detected are listed in Appendix E.

6. DISCUSSION OF TEST RESULTS

6.1 GENERAL

The results of the tests vary greatly because of the many factors discussed in Section 4. However, some generalities can be stated if they are related to the associated test conditions.

- Tests on both individual ties and track panels indicate that consolidation increased lateral resistance of freshly disturbed track on the average by approximately 40%.
- Consolidation produced the least improvement in lateral resistance in one of the zones where all new wood ties were tested, with a minimum of approximately 17%, and produced the greatest improvement in a zone where all old wood ties were tested with a maximum of approximately 55%.
- Consolidation of freshly disturbed ballast produced an average lateral stabilizing effect equal to the effects of approximately 440,000 GT (400,000 GMT) of traffic when measured at 4-mm displacement.
- Consolidation reduced the vertical settlement at joint ties caused by 155,000 GT (141,000 GMT) of traffic. The average reductions were approximately 20% in curved track and 15% in tangent track.
- The duration of consolidation time produced little difference between 3-second and 5-second application of the consolidator.

Test results indicated that accelerated ballast consolidation will improve track stability in general and thus may reduce track maintenance, but the level of this improvement could not be estimated from the limited data collected from the tests.

6.2 EFFECTS OF LOCAL CONDITIONS

In many cases, the location-related factors discussed in Section 4 appeared to dominate and to obscure partially the measurable effects of ballast consolidation. The most significant local factor appeared to be a high moisture content in the ballast resulting from rain. This is discussed in Appendix C.

The age of the wood ties that were tested also appeared to be a significant factor in the five series of tests under Test MM-77 [4]. The smallest average improvement in lateral resistance, 17%, was obtained in one of the test zones where all the ties were new, creosoted hardwood. The largest average increase, 55%, was obtained in a test zone where all the ties had been installed the preceding year.

In three of the four test zones under Test MM-77 that included curved track, the average improvement in resistance obtained by machine consolidation was found to be much larger in curved track than in tangent track. The factors related to this difference in results have not been identified.

In spite of the many environmental factors that affected test results, increased lateral and longitudinal resistance and reduced track settlement were obtained by accelerated ballast consolidation in every location. However, the amount of improvement varied greatly. It is noted that changes in the procedure for removing tie plates developed under Test MM-77.1 did not appear to have a significant effect upon test results.

6.3 DURATION OF MACHINE CONSOLIDATION

Test results from sections on which the consolidator was used for 5-second periods were compared to results from sections on which it was used for 3-second periods, but no consistent differences could be seen.

6.4 LATERAL RESISTANCE OF TIES

Under Test MM-77, the average lateral resistance of individual ties in consolidated ballast in the five separate test zones varied from 17% to 56% more than that of ties in unconsolidated ballast at zero traffic and 2-mm displacement. The overall average increase was 36% of the overall average resistance of ties in unconsolidated ballast. The test zone that showed the smallest increase, 17%, from accelerated ballast consolidation had new creosoted oak ties in new granite ballast. It had been built on an old roadbed, and ballast trains may have partially consolidated all the ballast. This seems to be indicated by the high average lateral resistance of the new ties in unconsolidated ballast, 1,230 pounds (5.47 kN) at zero traffic and 2-mm displacement.

A broad implication is that machine consolidation of ballast is more effective for old wood ties than for new wood ties. The results of Test MM-77.3 also indicate more improvement from consolidation in the resistance of old ties than new ties. This can be seen in the graphs of lateral force versus displacement provided in Appendix C, at low levels of traffic. However, this effect is not apparent from the results of tests on the Saint Louis and Southwestern under Test MM-77 where only new ties were tested in tangent track. In the test zone, the average lateral resistance of ties in consolidated ballast, at zero traffic and 2-mm displacement, was 44% above the resistance of ties in unconsolidated ballast. It is also noted in the results of Test MM-219 that the panel of new wood ties showed approximately the same percent of increase in resistance from machine consolidation as the panel of mixed old and new wood ties did.

Excluding the data under Test MM-77 on the test of all new ties, that showed only 17% improvement from consolidation, the data from the other four test zones showed an overall average resistance to lateral forces that was 40% higher for ties in consolidated ballast than for ties in unconsolidated ballast at zero traffic and 2-mm displacement. This is close to the difference measured on the Southern under Test MM-77.3, where half the ties tested were new and half were old and the average lateral resistance of ties in consolidated ballast at 4-mm displacement was found to be 45% higher than the resistance of ties in unconsolidated ballast. However, the average resistances of both groups of ties were lower in Test MM-77.3 than in Test MM-77, 1,200 pounds (5.34 kN) in consolidated ballast and 830 pounds (3.69 kN) in unconsolidated ballast. These lower resistances may have resulted from heavy rainfall up to a week before Test MM-77.3.

An analysis in Appendix B shows an improvement in lateral resistance obtained by machine consolidation equivalent to the effects of 100,000 to 200,000 GT (91,000 to 181,000 GMT) of traffic. It is based on the tests of new ties in new ballast which gave the lowest results of tests in any of the five test zones under Test MM-77.

When the data summarized in Table 9 for all five test zones under Test MM-77 are considered, a simple, graphical analysis indicates that the accelerated consolidation increased the average lateral resistance of ties an amount equivalent to the effects of 400,000 GT (363,000 GMT) of traffic at 2-mm displacement, and 440,000 GT (400,000 GMT) of traffic at 4-mm displacement. The indicated levels of equivalent traffic are comparable to the findings discussed in Appendix C. These findings show a minimum advantage from machine consolidation equivalent to the effects of approximately 162,000 GT (147,000 GMT) of traffic and an average advantage equivalent to the effects of approximately 453,000 GT (411,000 GMT), when measured at 4-mm displacement.

6.5 LATERAL RESISTANCE OF PANELS

Test engineers of the Southern and others considered the lateral resistance of individual ties to be an indicator of lateral track stability, but not as good a measure of it as the lateral resistance of track panels would be. They hypothesized that, when an individual tie begins to move under a lateral load, part of the load placed on the tie is transferred through consolidated ballast to adjacent ties. The load transfer mechanism involved is similar to that shown in demonstrations of the effectiveness of roof bolting. In these demonstrations, a bolt is run through the open ends of a container of aggregate. The bolt is then tightened to consolidate the aggregate; and the container can then be turned up without the consolidated aggregate falling from the open ends, as it is held in place by transfer of load to the sides of the container.

As expected, panels of ties under Test MM-219 showed much higher total lateral resistances than the average resistance that was found when individual ties were tested separately. However, the test results did not indicate any consistent correlation between the resistance of panels and the resistance of single ties tested separately.

The resistances recorded for panels of wood ties were compared to the average resistance of single ties that had been tested under similar conditions of unconsolidated and consolidated ballast at zero traffic and undisturbed ballast.

At displacements of 2 and 4 mm, the total lateral resistances of panels of wood ties were found to be approximately five times the average resistance of a single tie under Test MM-77 and MM-77.1, in both consolidated and unconsolidated ballast. At 4-mm displacement, the panels in consolidated ballast had eight times as much resistance, and the panels in unconsolidated ballast had nine times as much resistance as single ties under Test MM-77.3. At displacements of 0.5 inch (12.7 mm), the panels in consolidated ballast had ten times as much resistance, and the panels in unconsolidated ballast had 12 times as much resistance as a single tie under Test MM-77.3.

In undisturbed ballast at 4-mm displacements, the panels of wood ties showed a total resistance that was nine times the average resistance shown by a single tie under Test MM-77.3. At both 2- and 4-mm displacements, the same panels had ten times the average resistance of a tie under Test 77.1.

6.6 DURATION OF THE EFFECTS OF ACCELERATED BALLAST CONSOLIDATION.

Examination of Table 10 shows that after 2 MGT (1.81 MGMT) of traffic, ties in consolidated ballast still had slightly higher average resistance to lateral forces than did the ties in unconsolidated ballast. This is seen even though some of the ties had lower resistance after additional increments of traffic, possibly because the ties had been disturbed in the previous tests.

The persistence of the effects of consolidation is shown clearly in the graphs in Appendix C that summarize the results of Test MM-77.3. The difference between the lateral resistances of ties in consolidated and unconsolidated ballast is generally shown to be larger after 1.7 MGT (1.54 MGMT) of traffic than at lower levels of traffic.

A somewhat similar persistence can be seen in the effects of machine consolidation upon the settlement of track under traffic. The summary of average track settlement in Table 11 shows that track with consolidated ballast settled less than track with unconsolidated ballast in every case except Penn Central track at 0.5 MGT (0.45 MGMT); the table also shows that differences increased in favor of consolidated ballast at higher levels of traffic.

The difference in settlement at joints at bolted rail was also found to increase under traffic in favor of consolidated ballast, up to 155,000 GT (141,000 GMT) the limit of data collection under Test MM-151. In all instances the rate of settlement decreased with traffic.

6.7 LATERAL STABILITY OF TRACK ON CURVES

Survey data in Appendix C for the curved test sections at Test Sites 2 and 4 show a smaller range of lateral movement for track on consolidated ballast than for track on unconsolidated ballast: after 3 weeks of traffic, zero to 0.10 inch versus 0.05 to 0.42 inch (0 to 2.5 mm versus 1.3 mm to 10.7 mm). The average lateral movement was also smaller for the track on consolidated ballast, 0.04 inch versus 0.16 inch (1.0 versus 4.1 mm). However, the sum of the squares evaluation in Appendix C indicated that the differences in lateral movement found during the periods in which the track was surveyed were not significant.

6.8 POTENTIAL VALUE OF ACCELERATED BALLAST CONSOLIDATION

The value of the increase in resistance to lateral forces and the reduction in settlement provided by accelerated ballast consolidation depend on many local factors of track condition, traffic, and environment. These factors vary greatly from place to place on any major railroad as well as among the many railroads that comprise the industry. Evaluation of these factors requires the judgment of experienced engineers who know conditions and costs on their railroads. Considerations include:

- The cost of slow orders that are put into effect while traffic is reconsolidating disturbed ballast.
- The possibility of sun kinks that may occur in some areas after track maintenance during hot weather.
- The possibility of damage to embankments of marginal strength that may occur while pedestals of ballast tamped under ties are transmitting concentrated loads.
- Possible reductions in the frequency of resurfacing and other track maintenance.

7. CONCLUSIONS

The tests demonstrated that accelerated ballast consolidation increases lateral resistance substantially before traffic has reconsolidated track that has been disturbed by surfacing and related track work. This is true for individual ties and for panels of track. The initial increases in lateral resistance vary greatly, but they average about 40% of the lateral resistance of ties in unconsolidated ballast at small displacements. The increase in the lateral resistance of panels of track at zero traffic and 4-mm displacement was in the range of the percent of improvement shown by individual ties.

It is apparent that machine consolidation of ballast will be of value on American railroads in those locations where continuous welded rail has a high probability of buckling under temperature stress after track has been disturbed by surfacing and related maintenance work.

8. REFERENCES

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4. Operational Test Procedure, FRA Consolidator Test Series, Test Objective MM-77, Federal Railroad Administration technical document with revisions, 27 June - 1 December 1973.

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APPENDIX A

Sample data from tests of lateral and longitudinal track stability and measurements of track settlement under Test MM-77. Ties listed were chosen casually. No attempt was made to select representative ties except that ties were omitted if difficulties in testing them had been noted in the logs.

SOUTHERN LATERAL TRACK STABILITY

Approximate Lateral Resistance of Ties in Pounds									
	Traffic Million Gross Tons	Unconsolidated				Consolidated			
		Tangent		Curve		Tangent		Curve	
		Tie No.	Force	Tie No.	Force	Tie No.	Force	Tie No.	Force
2 Millimeter Displacement	0	16	1100	17	1200	180	1400	88	1300
		25	1150	25	1100	197	1750	99	1550
		33	1100	32	1200	205	W 1650	113	1000
		40	1300	83	1500	213	2050	121	1100
	0.5	16	2200	17	2050	180	2500	88	1900
		25	2050	25	2000	197	2350	99	2150
		33	2750	32	1250	205	2400	113	W 1300
		40	2500	83	2000	213	2950	121	1400
	1.5	16	1900	17	2150	180	2000	88	2550
		25	2300	25	2300	197	2250	99	2750
		33	2400	32	1750	205	2500	113	1850
		40	1850	83	2100	213	2650	121	1900
4 Millimeter Displacement	0	16	1200	17	1250	180	1500	88	1450
		25	1400	25	1100	197	W 1850	99	1700
		33	1300	32	1300	205	1700	113	1050
		40	1450	83	1650	213	2100	121	1250
	0.5	16	2500	17	2300	180	2800	88	2150
		25	2800	25	2350	197	2750	99	W 2400
		33	2950	32	1400	205	2750	113	1400
		40	2850	83	2450	213	3600	121	1600
	1.5	16	2350	17	2500	180	2350	88	2700
		25	2900	25	2650	197	2700	99	2750
		33	2750	32	2000	205	2800	113	1950
		40	2200	83	2500	213	3050	121	2100

Note: W Tests were made while the ballast was wet.

SOUTHERN LONGITUDINAL TRACK STABILITY

Approximate Resistance of Ties in Pounds									
	Traffic Million Gross Tons	Unconsolidated				Consolidated			
		Tangent		Curve		Tangent		Curve	
		Tie No.	Force	Tie No.	Force	Tie No.	Force	Tie No.	Force
Longitudinal Test 2 Millimeter Displacement	0	21	3200	21	4550	169	3400	93	2350
		29	4050	29	2450	177 W	3550	109	1800
		37	3000	35	2900	186	2750	117	2950
		44	4100	43	3600	194	4250	124	3450
	0.5	21	2650	21	2700	169	2100	93	3800
		29	1900	29	4300	177	4100	109 W	1950
		37	2300	35	3050	186	2350	117	3000
		44	2350	43	2500	194	5200	124	3600
	1.5	21	1800	21	2650	169	1850	93	4000
		29	2550	29	3900	177	2900	109	1800
		37	2200	35	3550	186	2700	117	2150
		44	2850	43	3950	194	3050	124	3400

Note: W Tests were made while the ballast was wet.

BOSTON AND MAINE LATERAL TRACK STABILITY

Approximate Lateral Resistance of Ties in Pounds

	Traffic Million Gross Tons	Unconsolidated				Consolidated			
		Tangent		Curve		Tangent		Curve	
		Tie No.	Force	Tie No.	Force	Tie No.	Force	Tie No.	Force
2 Millimeter Displacement	0	186	1400	50	1550	157	1850	183	1850
		194	1600	60	1200	171	2150	196	1750
		200	1450	70	1500	191	1900	212	2000
		212	1650	80	1250	203	1700	222	1600
	1	186	2300			157	2150	183	2100
		194	2300			171	2800	196	2400
		200	2050			191	2500	212	3700
		212	2000		(1)	203	2000	222	2100
	2	186	2600	50	2800	157	2050	183	2400
		194	2850	60	2200	171	3300	196	2150
		200	2400	70	2600	191	2600	212	3200
		212	2400	80	2350	203	2150	222	1900
4 Millimeter Displacement	0	186	1600	50	1800	157	2000	183	2300
		194	1650	60	1350	171	2550	196	2000
		200	1600	70	1650	191	2200	212	2400
		212	1900	80	1400	203	2100	222	1750
	1	186	2550			157	2300	183	2350
		194	2500 (2)			171	3100	196	2500
		200	2250			191	3000	212	2300
		212	2050		(1)	203	2450	222	4000
	2	186	2900	50	3650	157	2500	183	3000
		194	3100	60	2300	171	3850	196	2700
		200	2750	70	2800	191	2950	212	3700
		212	2600	80	2400	203	2500	222	2250

Note: (1) Tests omitted because of bad weather.

(2) Estimate. The test was stopped at 3.18 mm to avoid damage to equipment.

BOSTON AND MAINE LONGITUDINAL TRACK STABILITY

Approximate Resistance of Ties in Pounds									
	Traffic Million Gross Tons	Unconsolidated				Consolidated			
		Tangent		Curve		Tangent		Curve	
		Tie No.	Force	Tie No.	Force	Tie No.	Force	Tie No.	Force
2 Millimeter Displacement	0	216	1150	54	3250	154	2200	180	3550
		226	1650	74	1900	160	2650	208	1700
		234	2200	104	3300	166	2450	217	2500
		248	2400	109	3650	186	3100	240	3400
	1	216	2850			154	180	180	4500
		226	2600			160	5000	208	1500
		234	1900			166	1400	217	3000
		248	2300		(1)	186	1900	240	2100
	2	216	3150	54	5000	154	5200	180	4100
		226	3250	74	3050	160	4050	208	2150
		234	2575	104	5100	166	3700	217	3490
		248	3151	109	3370	186	4050	240	3800

Note: (1) Tests omitted because of bad weather.

PENN CENTRAL LATERAL TRACK STABILITY

Approximate Lateral Resistance of Ties in Pounds										
	Traffic Million Gross Tons	Unconsolidated				Consolidated				
		Tangent		Curve		Tangent		Curve		
		Tie No.	Force	Tie No.	Force	Tie No.	Force	Tie No.	Force	
2 Millimeter Displacement	0.0	23	1250	19	1100	4	1400	17	1500	
		45	1300	33	1150	16	1600	27	1850	
		69	1000	92	1400	26	1700	57	1600	
		85	1700	137	1350	36	1450	123	1850	
	0.5	23	2300	19	1600	4	2300	17	2200	
		45	1950	33	1950	16	2200	27	2750	
		69	1950	92	2600	26	2450	57	1800	
		85	2600	137	2150	36	2100	123	2500	
	1.7	23	2400	19	1600	4	2900	17	2150	
		45	W 2100	33	W 2300	16	W 2550	27	W 2300	
		69	2250	92	2650	26	2500	57	1950	
		85	2750	137	2700	36	2150	123	2550	
4 Millimeter Displacement	0.0	23	1400	19	1300	4	1600	17	1750	
		45	1550	33	1250	16	1700	27	2100	
		69	1250	92	1600	26	2000	57	1700	
		85	2200	137	1600	36	1600	123	2350	
	0.5	23	2400	19	1700	4	2650	17	2450	
		45	2350	33	2200	16	2400	27	3150	
		69	2250	92	2850	26	3000	57	2150	
		85	2900	137	2450	36	2200	123	2750	
	1.7	23	2500	19	2800	4	3150	17	2550	
		45	W 2450	33	W 2550	16	W 2700	27	W 3300	
		69	2650	92	3500	26	3400	57	2300	
		85	3350	137	3700	36	2450	123	2900	

Note: W Tests were made while the ballast was wet.

PENN CENTRAL LONGITUDINAL TRACK STABILITY

Approximate Resistance of Ties in Pounds									
	Traffic Million Gross Tons	Unconsolidated				Consolidated			
		Tangent		Curve		Tangent		Curve	
		Tie No.	Force	Tie No.	Force	Tie No.	Force	Tie No.	Force
2 Millimeter Displacement	0.0	14	2150	12	2950	7	4350	21	4200
		27	2550	98	2850	18	3800	53	2550
		41	2650	132	1800	30	2950	67	2550
		111	2300	166	2900	88	1750	119	3800
	0.5	14	3250	12	3150	7	4750	21	4400
		27	3000	98	4750	18	4250	53	4050
		41	5900	132	1950	30	5050	67	4200
		111	3100	166	4800	88	2800	119	5100
	1.7	14	2800	12	4150	7	4150	21	4450
		27	3900	98	5300	18	4700	53	3150
		41 W	5400	132 W	2400	30 W	4900	67 W	4100
		111	2650	166	4000	88	3000	119	4450

Note: W Tests were made while the ballast was wet.

SAINT LOUIS AND SOUTHWESTERN LATERAL TRACK STABILITY

Approximate Resistance of Ties in Pounds									
	Traffic Million Gross Tons	Unconsolidated				Consolidated			
		Tangent		Tangent		Tangent		Tangent	
		Tie No.	Force	Tie No.	Force	Tie No.	Force	Tie No.	Force
2 Millimeter Displacement	0	916	1000	1093	1900	374	1350	488	1550
		926	1250	1105	1050	401	2150	492	1700
		952	1100	1116	1000	420	2200	502	1350
		969	1050	1138	1300	450	1400	522	1200
	0.75	916	1850	1093	1400	374	1950	488	2100
		926	1550	1105	1650	401	2450	492	2300
		952	1500	1116	1500	420	2650	502	1800
		969	1550	1138	2000	450	1900	522	1550
	2.0	916	1950	1093	1650	374	1800	488	2200
		926	W 1850	1105	W 1850	401	W 1950	492	W 2600
		952	1800	1116	1600	420	3150	502	2300
		969	1700	1138	1850	450	2000	522	2050
4 Millimeter Displacement	0	916	1100	1093	2250	374	1500	488	1800
		926	1550	1105	1300	401	2350	492	1900
		952	1200	1116	1100	420	2600	502	1700
		969	1200	1138	1550	450	1850	522	1300
	0.75	916	1900	1093	1500	374	2100	488	2300
		926	1800	1105	1800	401	2850	492	2400
		952	1700	1116	1550	420	3200	502	2150
		969	1700	1138	2100	450	2100	522	1900
	2.0	916	2100	1093	1800	374	2000	488	2400
		926	2100	1105	2000	401	2000	492	2600
		952	W 1800	1116	W 1800	420	W 2000	502	W 2600
		969	1900	1138	2000	450	2150	522	2300

Notes: W Tests were made while the ballast was wet.
All test sections were tangent track.

SAINT LOUIS AND SOUTHWESTERN LONGITUDINAL TRACK STABILITY

Approximate Resistance of Ties in Pounds									
	Traffic Million Gross Tons	Unconsolidated				Consolidated			
		Tangent		Tangent		Tangent		Tangent	
		Tie No.	Force	Tie No.	Force	Tie No.	Force	Tie No.	Force
2 Millimeter Displacement	0	947	2750	1143	1700	11	2850	93	3050
		962	2650	1183	2050	30	3550	103	2850
		1008	1950	1200	3300	44	2200	137	5500
		1021	2850	1237	2750	53	4650	176	3600
	0.75	947	4200	1143	2750	11	3350	93	2550
		962	4150	1183	3200	30	3600	103	3700
		1008	2700	1200	3250	44	4600	137	4200
		1021	4450	1237	4250	53	4100	176	2800
	2.0	947	4250	1143	2900	11	3400	93	3050
		962	4600	1183	3950	30 W	3350	103 W	2850
		1008	4000	1200	3200	44	3300	137	4000
		1021	2900	1237	3950	53	3300	176	4200

Note: W Tests were made while the ballast was wet.
All test sections were tangent track

MISSOURI PACIFIC LATERAL TRACK STABILITY

Approximate Lateral Resistance of Ties in Pounds									
	Traffic Million Gross Tons	Unconsolidated				Consolidated			
		Tangent		Curve		Tangent		Curve	
		Tie No.	Force	Tie No.	Force	Tie No.	Force	Tie No.	Force
2 Millimeter Displacement	0	5	1500	54	1350	3	1900	12	1800
		21	1300	64	W 1150	35	1900	37	W 1850
		31	1250	84	1100	55	2100	58	1800
		45	1200	138	1050	99	2100	98	1900
	0.75	5	2200	54	2850	3	2500	12	3850
		21	1950	64	3200	35	2650	37	2700
		31	1600	84	2250	55	2450	58	3150
		45	1550	138	2650	99	2800	98	3850
	2.0	5	2350	54	2450	3	1850	12	3300
		21	W 1800	64	W 3050	35	W 2300	37	W 2900
		31	1750	84	2350	55	2000	58	2900
		45	2250	138	2500	99	2100	98	3700
4 Millimeter Displacement	0	5	1600	54	1400	3	2150	12	2000
		21	1500	64	W 1300	35	2400	37	W 2150
		31	1400	84	1200	55	2400	58	1900
		45	1300	138	1200	99	2400	98	2150
	0.75	5	2250	54	3000	3	3000	12	4000
		21	2100	64	3300	35	2700	37	2800
		31	1800	84	2400	55	2500	58	3200
		45	1700	138	2700	99	3150	98	4200
	2.0	5	2500	54	2800	3	2050	12	3700
		21	W 1950	64	W 3200	35	W 2550	37	W 3150
		31	2000	84	2500	55	2350	58	3300
		45	2400	138	2600	99	2700	98	3950

Note: W Tests were made while the ballast was wet.

MISSOURI PACIFIC LONGITUDINAL TRACK STABILITY

Approximate Resistance of Ties in Pounds									
	Traffic Million Gross Tons	Unconsolidated				Consolidated			
		Tangent		Curve		Tangent		Curve	
		Tie No.	Force	Tie No.	Force	Tie No.	Force	Tie No.	Force
2 Millimeter Displacement	0	9	2700	14	1700	13	2600		
		41	2550	32	1550	25	2450		
		57	2350	42	1900	37	2150		
		96	2050	58	1600	57	3100		(1)
	0.75	9	4000	14	4150	13	3600	4	3650
		41	3350	32	3950	25	3100	16	2750
		57	4100	42	2950	37	3900	32	4900
		96	3700	58	4200	57	3550	63	4600
	2.0	9	3850	14	4550	13	3850	4	3150
		41	3200	32	4250	25	2800	16	3200
		57	4050	42	3350	37	3800	32	3300
		96	3600	58	3050	57	4800	63	4100

Note: (1) Test omitted because of bad weather.

SOUTHERN TRACK SETTLEMENT SURVEY, TEST MM-77

ELEVATIONS OF TOP OF RAILS IN FEET ABOVE RR DATUM AT SELECTED LOCATIONS

LEFT RAIL							
Unconsolidated Tangent				Consolidated Tangent			
Location	Traffic (MGT)			Location	Traffic (MGT)		
	0	1.5	5.0		0	1.5	5.0
0.00	1318.09	1318.07	1318.00	700.00	1313.57	1313.54	1313.50
50.00	1317.82	1317.76	1317.73	750.00	1313.23	1313.19	1313.15
100.00	1317.53	1317.48	1317.45	800.00	1312.88	1312.85	1312.82
150.00	1317.24	1317.18	1317.16	850.00	1312.54	1312.52	1312.49
200.00	1316.91	1316.85	1316.83	900.00	1312.21	1312.19	1312.16
250.00	1316.60	1316.55	1316.51	950.00	1311.87	1311.85	1311.85
300.00	1316.28	1316.22	1316.18	1000.00	1311.51	1311.48	1311.48
350.00	1315.96	1315.89	1315.85	1050.00	1311.20	1311.17	1311.17
400.00	1315.62	1315.56	1315.53	1100.00	1310.89	1310.86	1310.86
450.00	1315.32	1315.27	1315.23	1150.00	1310.59	1310.57	1310.56
500.00	1314.97	1314.92	1314.89	1200.00	1310.32	1310.29	1310.27
550.00	1314.61	1314.57	1314.55	1250.00	1310.02	1310.00	1309.97
600.00	1314.26	1314.22	1314.20	1300.00	1309.76	1309.75	1309.73
650.00	1313.91	1313.88	1313.85				
RIGHT RAIL							
0.00	1318.08	1318.03	1318.00	700.00	1313.59	1313.57	1313.52
50.00	1317.82	1317.76	1317.73	750.00	1313.24	1313.21	1313.18
100.00	1317.53	1317.48	1317.46	800.00	1312.89	1312.86	1312.83
150.00	1317.24	1317.18	1317.16	850.00	1312.54	1312.52	1312.48
200.00	1316.92	1316.87	1316.84	900.00	1312.21	1312.19	1312.17
250.00	1316.61	1316.56	1316.53	950.00	1311.87	1311.85	1311.85
300.00	1316.29	1316.23	1316.20	1000.00	1311.50	1311.46	1311.46
350.00	1315.98	1315.92	1315.88	1050.00	1311.19	1311.15	1311.16
400.00	1315.66	1315.59	1315.57	1100.00	1310.89	1310.85	1310.85
450.00	1315.34	1315.29	1315.25	1150.00	1310.59	1310.56	1310.56
500.00	1314.98	1314.94	1314.91	1200.00	1310.31	1310.29	1310.27
550.00	1314.62	1314.59	1314.57	1250.00	1310.02	1310.00	1309.98
600.00	1314.27	1314.24	1314.22	1300.00	1309.76	1309.75	1309.73
650.00	1313.92	1313.89	1313.87				

BOSTON AND MAINE TRACK SETTLEMENT SURVEY TEST MM-77 ELEVATIONS OF TOP OF RAILS IN FEET ABOVE RR DATUM AT SELECTED LOCATIONS

Location	Unconsolidated Tangent					
	South Rail			North Rail		
	Traffic (MGT)					
	0	1.0	2.7	0	1.0	2.7
3700.00	114.220	114.200	114.175	114.210	114.180	114.165
3750.00	114.820	114.800	114.775	114.820	114.800	114.775
3800.00	115.390	115.360	115.335	115.390	115.360	115.330
3850.00	115.960	115.920	115.910	115.960	115.910	115.905
3900.00	116.510	116.480	116.465	116.510	116.470	116.465
3950.00	117.060	117.030	117.020	117.060	117.030	117.020
4000.00	117.580	117.540	117.535	117.580	117.540	117.535
4050.00	118.140	118.120	118.115	118.140	118.120	118.115
4100.00	118.670	118.640	118.635	118.680	118.640	118.635
4150.00	119.180	119.140	119.135	119.190	119.150	119.145
4200.00	119.700	119.660	119.645	119.710	119.660	119.665
4250.00	120.230	120.190	120.175	120.230	120.170	120.175
4300.00	120.760	120.720	120.715	120.760	120.720	120.715
4320.00	120.970	120.920	120.905	120.970	120.920	120.915

Location	Consolidated Tangent					
	South Rail			North Rail		
	Traffic (MGT)					
	0	1.0	2.7	0	1.0	2.7
3000.00	106.555	106.535	106.520	106.555	106.545	106.520
3050.00	107.090	107.065	107.045	107.090	107.065	107.045
3100.00	107.600	107.570	107.555	107.600	107.575	107.560
3150.00	108.140	108.105	108.095	108.140	108.115	108.100
3200.00	108.675	108.655	108.640	108.675	108.655	108.645
3250.00	109.200	109.175	109.165	109.205	109.185	109.175
3300.00	109.740	109.725	109.705	109.745	109.715	109.705
3350.00	110.290	110.265	110.250	110.290	110.265	110.250
3400.00	110.840	110.825	110.805	110.850	110.815	110.795
3450.00	111.400	111.375	111.355	111.400	111.365	111.345
3500.00	111.960	111.930	111.905	111.950	111.920	111.895
3550.00	112.540	112.510	112.490	112.540	112.510	112.485
3600.00	113.090	113.055	113.035	113.080	113.055	113.025
3650.00	113.655	113.630	113.610	113.650	113.625	113.595
3660.00	113.760	113.730	113.710	113.765	113.720	113.695

PENN CENTRAL TRACK SETTLEMENT SURVEYS, TEST MM-77

ELEVATIONS OF TOP OF NORTH RAIL IN FEET ABOVE RR DATUM AT SELECTED LOCATIONS

Unconsolidated Tangent					Consolidated Tangent				
	Traffic (MGT)					Traffic (MGT)			
Location	0	0.5	1.7	6.4	Location	0	0.5	1.7	6.4
20.00	100.230	100.189	100.188	100.158	20.00	100.180	100.138	100.142	100.111
40.00	100.200	100.160	100.155	100.130	40.00	100.213	100.170	100.173	100.150
60.00	100.183	100.149	100.150	100.130	60.00	100.213	100.178	100.180	100.170
80.00	100.170	100.141	100.138	100.117	80.00	100.218	100.197	100.178	100.172
100.00	100.163	100.133	100.125	100.098	100.00	100.238	100.205	100.202	100.200
120.00	100.135	100.107	100.102	100.081	120.00	100.262	100.233	100.235	100.232
140.00	100.117	100.086	100.086	100.060	140.00	100.298	100.263	100.267	100.257
160.00	100.108	100.074	100.078	100.050	160.00	100.332	100.300	100.305	100.290
180.00	100.112	100.078	100.077	100.047	180.00	100.362	100.332	100.333	100.312
200.00	100.110	100.074	100.075	100.044	200.00	100.373	100.335	100.342	100.317
220.00	100.113	100.084	100.083	100.055	220.00	100.410	100.371	100.380	100.352
240.00	100.082	100.052	100.050	100.027	240.00	100.430	100.405	100.402	100.391
260.00	100.073	100.037	100.033	100.006	260.00	100.460	100.429	100.428	100.418
280.00	100.063	100.026	100.025	100.002	280.00	100.473	100.443	100.442	100.440
300.00	100.042	100.012	100.010	99.987	300.00	100.517	100.483	100.485	100.440
320.00	100.040	100.002	100.005	99.980	320.00	100.553	100.516	100.515	101.507
340.00	100.040	100.010	100.008	99.982	340.00	100.615	100.583	100.582	100.570
360.00	100.033	100.004	100.010	99.987	360.00	100.648	100.612	100.613	100.597
380.00	100.022	99.991	100.000	99.974	380.00	100.680	100.652	100.656	100.629
400.00	100.025	99.992	99.990	99.959	400.00	100.732	100.692	100.697	100.660
420.00	100.030	99.995	99.995	99.972	420.00	100.765	100.730	100.730	100.700
440.00	100.010	99.978	99.973	99.950	440.00	100.800	100.765	100.770	100.752
460.00	100.013	99.983	99.980	99.958	460.00	100.850	100.813	100.816	100.797
480.00	100.017	99.988	99.985	99.964	480.00	100.872	100.841	100.843	100.835
500.00	100.018	99.979	99.980	99.957	500.00	100.897	100.856	100.857	100.854
520.00	100.024	100.000	99.993	99.977	520.00	100.939	100.909	100.905	100.903
540.00	100.038	100.006	99.995	99.980	540.00	100.971	100.947	100.934	100.934
560.00	100.060	100.032	100.016	99.993	560.00	101.005	100.984	100.970	100.969
580.00	100.090	100.053	100.040	100.012	580.00	101.052	101.002	101.007	100.992
600.00	100.110	100.075	100.066	100.049	600.00	101.082	101.040	101.033	101.017
620.00	100.142	100.097	100.100	100.075	620.00	101.140	101.099	101.092	101.075
640.00	100.155	100.093	100.100	100.068	640.00	101.172	101.120	101.128	101.107
660.00	100.185	100.134	100.140	100.102	660.00	101.228	101.172	101.182	101.170

SAINT LOUIS AND SOUTHWESTERN TRACK SETTLEMENT SURVEY, TEST MM-77
ELEVATIONS OF TOP OF RIGHT RAIL IN FEET ABOVE RR DATUM AT SELECTED LOCATIONS

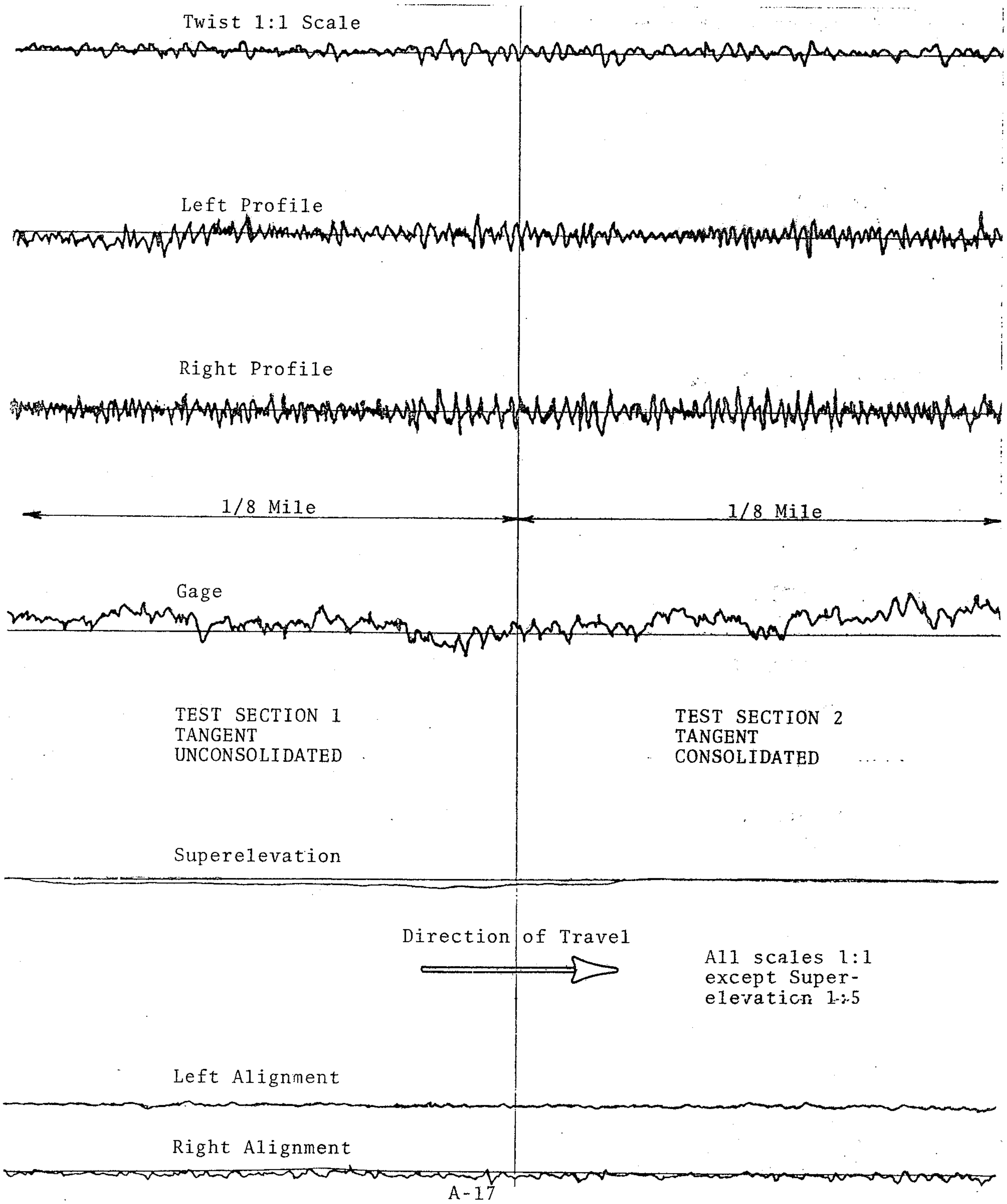
Unconsolidated Tangent				Consolidated Tangent			
	Traffic (MGT)				Traffic (MGT)		
Location	0	6.4	10.0	Location	0	6.4	10.0
1340.00	102.180	102.100	102.100	0.00	101.050	101.020	101.040
1360.00	102.170	102.090	102.070	20.00	101.120	101.080	101.070
1380.00	102.160	102.090	102.070	40.00	101.180	101.160	101.160
1400.00	102.150	102.080	102.070	60.00	101.240	101.210	101.210
1420.00	102.110	102.090	102.090	80.00	101.310	101.280	101.290
1440.00	102.110	102.070	102.080	100.00	101.380	101.350	101.350
1460.00	102.110	102.070	102.070	120.00	101.430	101.350	101.390
1480.00	102.100	102.060	102.060	140.00	101.500	101.460	101.450
1500.00	102.090	102.050	102.060	160.00	101.560	101.530	101.520
1520.00	102.070	102.030	102.050	180.00	101.620	101.580	101.570
1540.00	102.060	102.020	102.000	200.00	101.670	101.620	101.620
1560.00	102.040	102.000	101.990	220.00	101.700	101.660	101.660
1580.00	102.020	101.980	101.970	240.00	101.740	101.710	101.710
1600.00	102.000	101.970	101.960	260.00	101.780	101.760	101.750
1620.00	101.990	101.940	101.930	280.00	101.840	101.820	101.800
1640.00	101.980	101.930	101.940	300.00	101.890	101.870	101.860
1660.00	101.970	101.920	101.910	320.00	101.930	101.910	101.890
1680.00	101.950	101.900	101.900	340.00	101.970	101.950	101.920
1700.00	101.950	101.890	101.890	360.00	102.040	101.990	101.960
1720.00	101.930	101.880	101.870	380.00	102.050	102.030	102.000
1740.00	101.930	101.860	101.850	400.00	102.090	102.070	102.050
1740.00	101.910	101.860	101.850	420.00	102.140	102.100	102.070
1780.00	101.910	101.850	101.840	440.00	102.180	102.150	102.110
1800.00	101.900	101.850	101.830	460.00	102.210	102.180	102.140
1820.00	101.880	101.830	101.810	480.00	102.240	102.220	102.180
1840.00	101.870	101.830	101.830	500.00	102.280	102.240	102.200
1860.00	101.870	101.810	101.810	520.00	102.320	102.290	102.280
1880.00	101.860	101.810	101.810	540.00	102.360	102.320	102.320
1900.00	101.850	101.800	101.800	560.00	102.400	102.350	102.360
1920.00	101.840	101.790	101.780	580.00	102.440	102.400	102.400
1940.00	101.830	101.780	101.770	600.00	102.460	102.420	102.420
1960.00	101.830	101.760	101.760	620.00	102.480	102.450	102.440
1980.00	101.810	101.740	101.750	640.00	102.500	102.470	102.460

MISSOURI PACIFIC TRACK SETTLEMENT SURVEY, TEST MM-77
ELEVATIONS OF TOP OF RAILS IN FEET ABOVE RR DATUM AT SELECTED LOCATIONS

	Unconsolidated Tangent					Consolidated Tangent			
	East Rail		West Rail			East Rail		West Rail	
	Traffic (MGT)					Traffic (MGT)			
Location	0	5.0	0	5.0	Location	0	5.0	0	5.0
0.00	98.060	97.980	98.050	97.970	36.00	97.780	97.720	97.770	97.710
1.00	98.070	97.990	98.040	97.970	37.00	97.780	97.720	97.770	97.720
2.00	98.060	97.980	98.040	97.970	38.00	97.770	97.710	97.770	97.710
3.00	98.050	97.970	98.040	97.970	39.00	97.760	97.710	97.760	97.710
4.00	98.030	97.960	98.030	97.950	40.00	97.770	97.710	97.760	97.710
5.00	98.030	97.950	98.030	97.950	41.00	97.770	97.720	97.770	97.710
6.00	98.030	97.950	98.030	97.950	42.00	97.770	97.710	97.760	97.710
7.00	98.030	97.950	98.030	97.940	43.00	97.770	97.710	97.760	97.700
8.00	98.030	97.950	98.010	97.940	44.00	97.770	97.710	97.760	97.700
9.00	98.020	97.950	98.020	97.940	45.00	97.760	97.710	97.760	97.700
10.00	98.020	97.940	98.020	97.930	46.00	97.750	97.700	97.760	97.700
11.00	98.030	97.930	98.020	97.920	47.00	97.750	97.700	97.760	97.700
12.00	98.010	97.920	98.010	97.910	48.00	97.750	97.690	97.750	97.700
13.00	98.000	97.910	98.000	97.900	49.00	97.750	97.700	97.740	97.700
14.00	97.990	97.900	97.990	97.890	50.00	97.740	97.690	97.740	97.690
15.00	97.980	97.890	97.980	97.870	51.00	97.740	97.680	97.740	97.690
16.00	97.970	97.880	97.960	97.870	52.00	97.730	97.670	97.730	97.670
17.00	97.960	97.880	97.960	97.870	53.00	97.730	97.680	97.730	97.680
18.00	97.950	97.860	97.950	97.860	54.00	97.730	97.680	97.730	97.690
19.00	97.940	97.860	97.940	97.830	55.00	97.730	97.690	97.730	97.680
20.00	97.930	97.830	97.930	97.830	56.00	97.730	97.680	97.730	97.680
21.00	97.930	97.830	97.930	97.830	57.00	97.730	97.680	97.730	97.680
22.00	97.930	97.820	97.930	97.830	58.00	97.730	97.680	97.730	97.680
23.00	97.910	97.810	97.920	97.810	59.00	97.730	97.680	97.720	97.680
24.00	97.910	97.800	97.910	97.790	60.00	97.720	97.670	97.720	97.680
25.00	97.890	97.790	97.890	97.790	61.00	97.720	97.670	97.720	97.670
26.00	97.880	97.770	97.870	97.770	62.00	97.710	97.660	97.720	97.660
27.00	97.850	97.750	97.840	97.740	63.00	97.700	97.670	97.700	97.660
28.00	97.830	97.740	97.830	97.720	64.00	97.700	97.670	97.700	97.670
29.00	97.820	97.720	97.820	97.710	65.00	97.700	97.660	97.690	97.660
30.00	97.820	97.720	97.810	97.710	66.00	97.690	97.650	97.680	97.650

Southern Railway Company

Track Geometry
8 August 1973 Test



Southern Railway Company

Track Geometry
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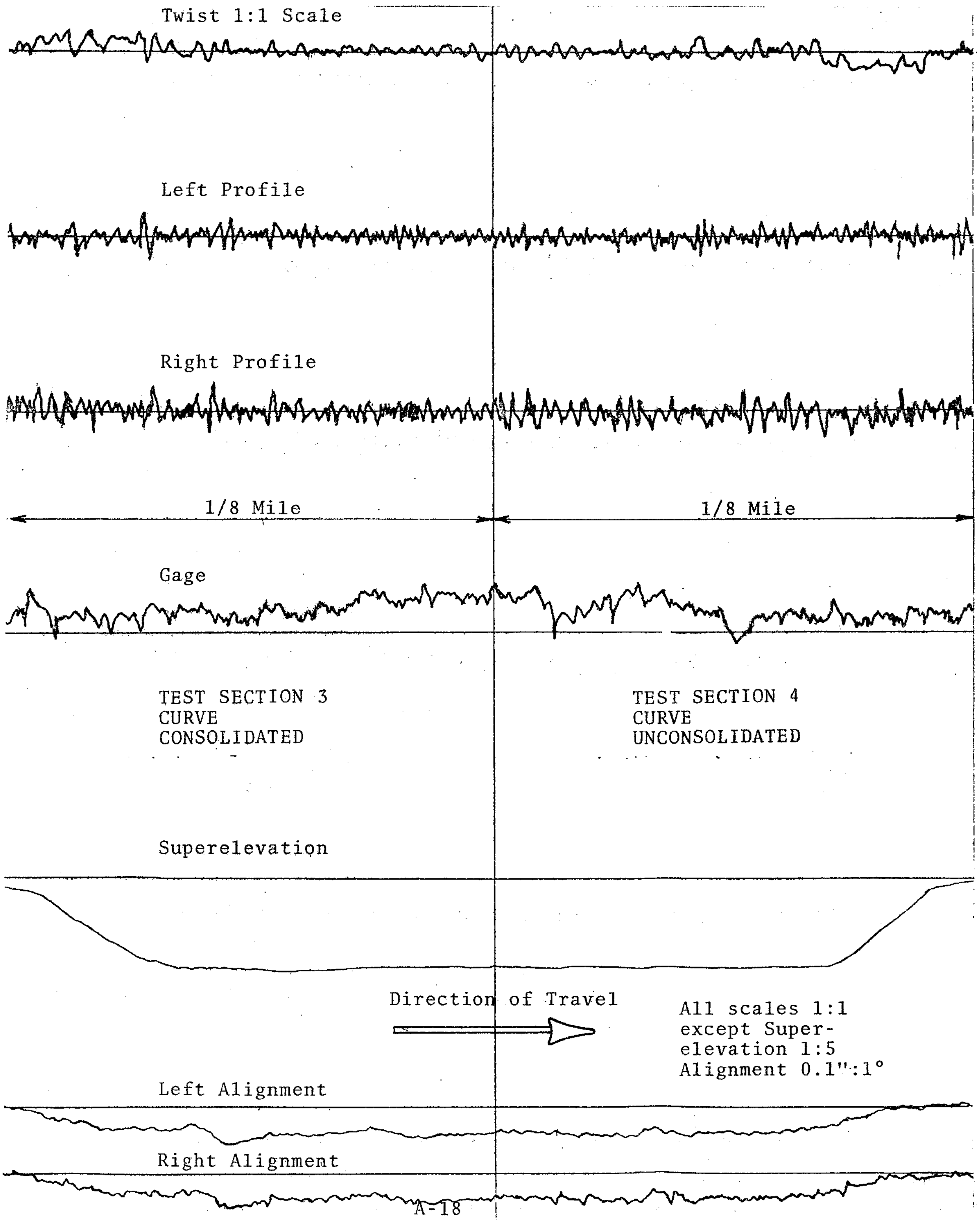
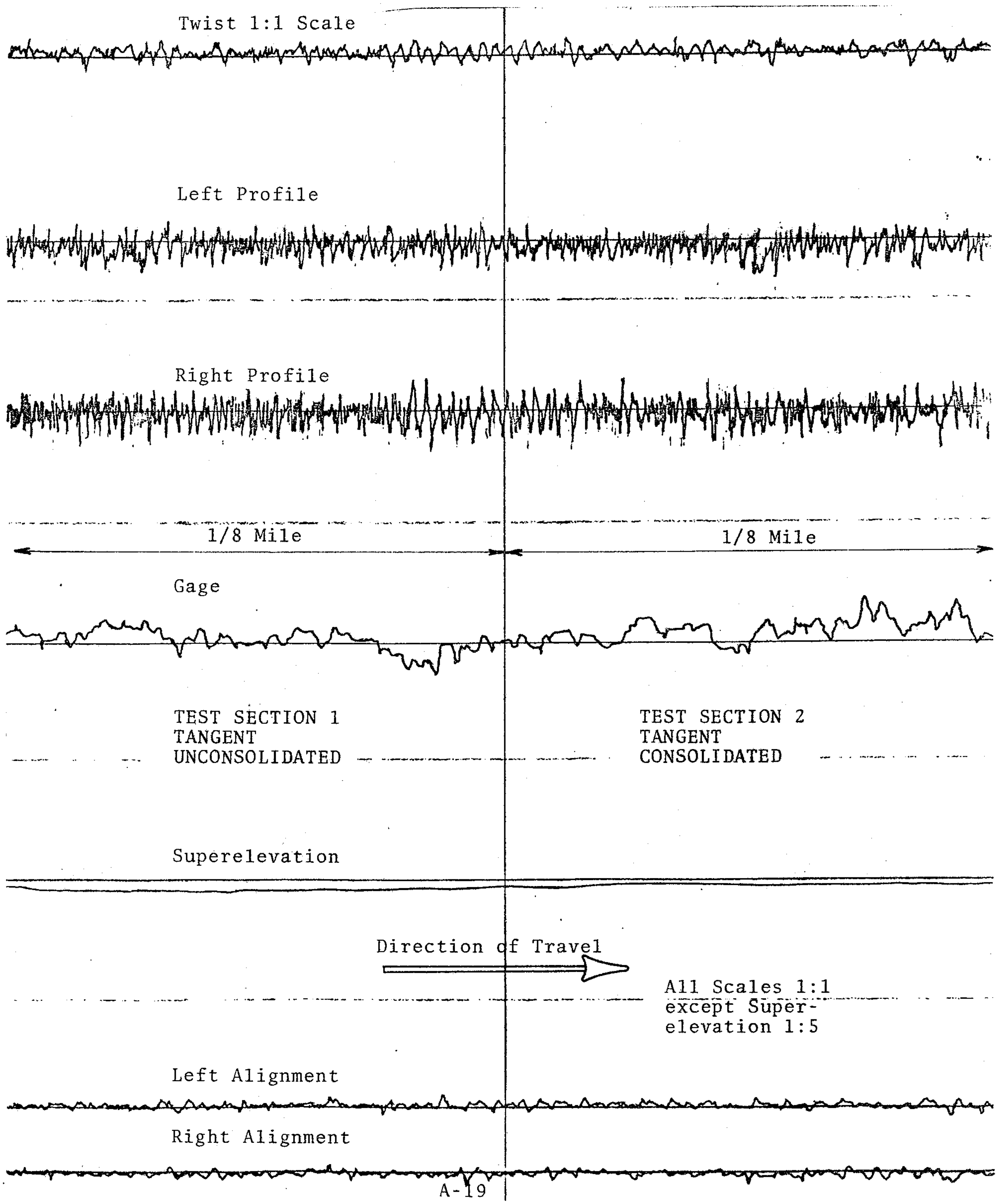


Southern Railway Company

Track Geometry
11 September 1973



Southern Railway Company

Track Geometry
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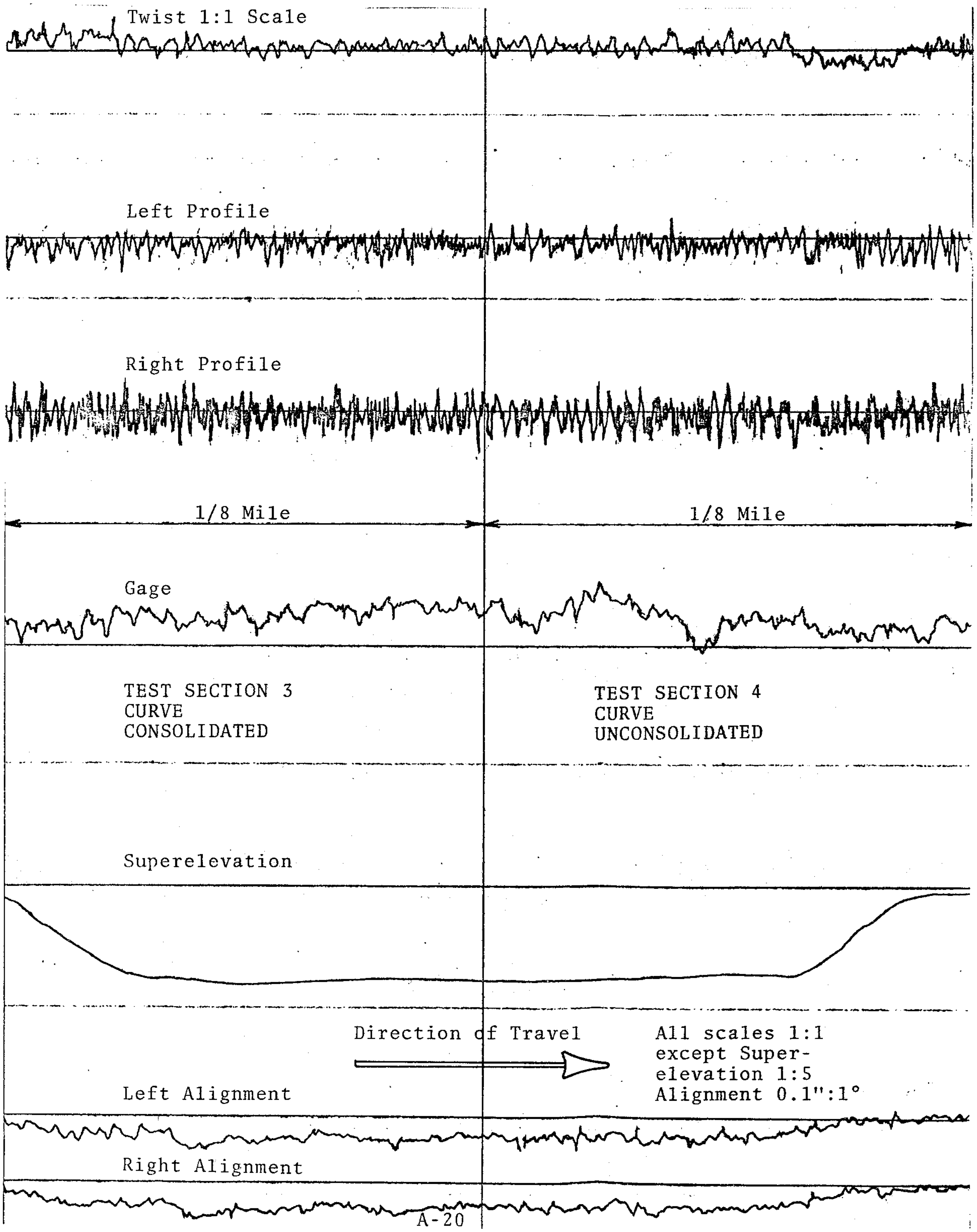
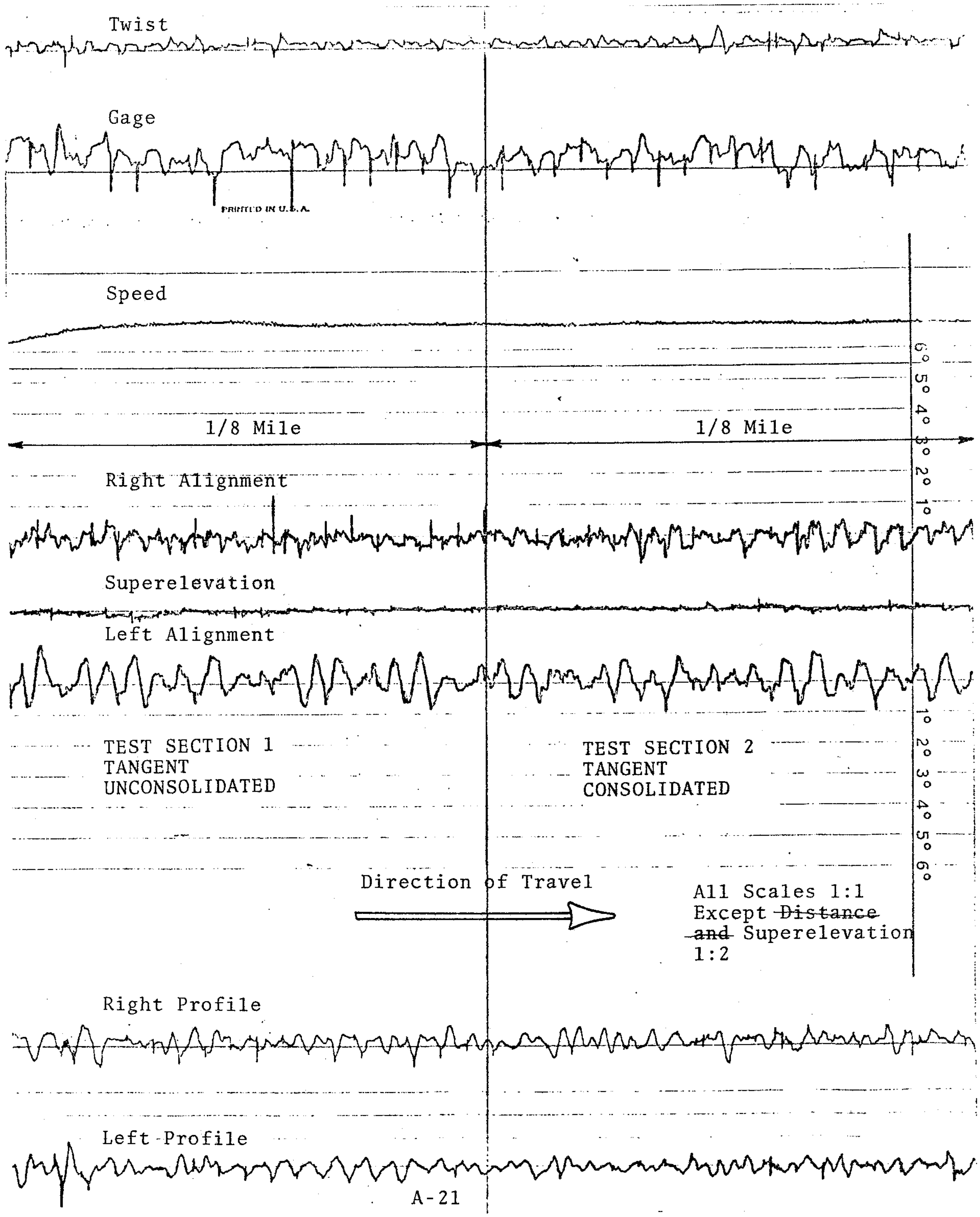


Boston and Maine Corporation

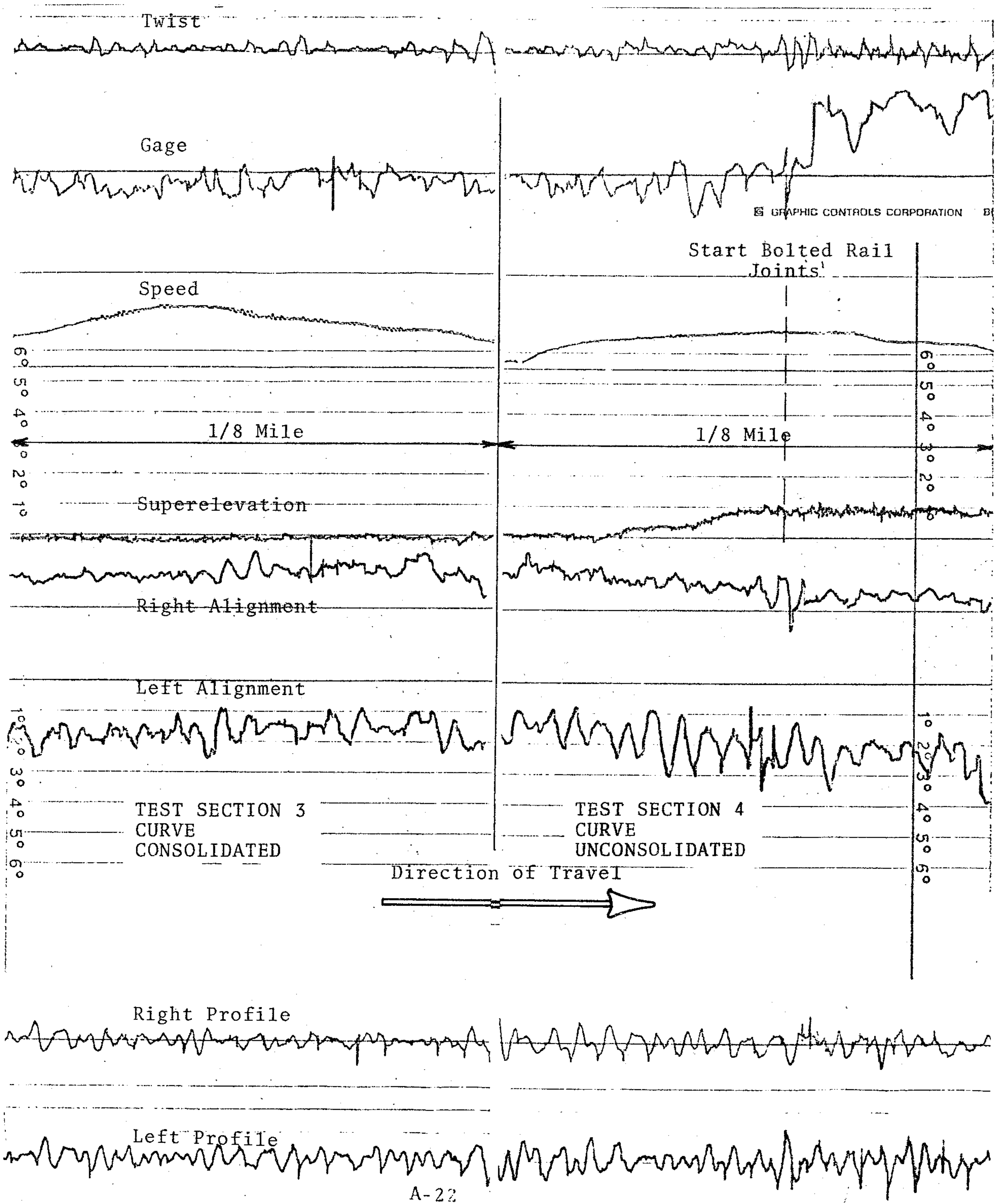
Track Geometry
20 August 1973



All Scales 1:1
Except ~~Distance~~
~~and~~ Superelevation
1:2

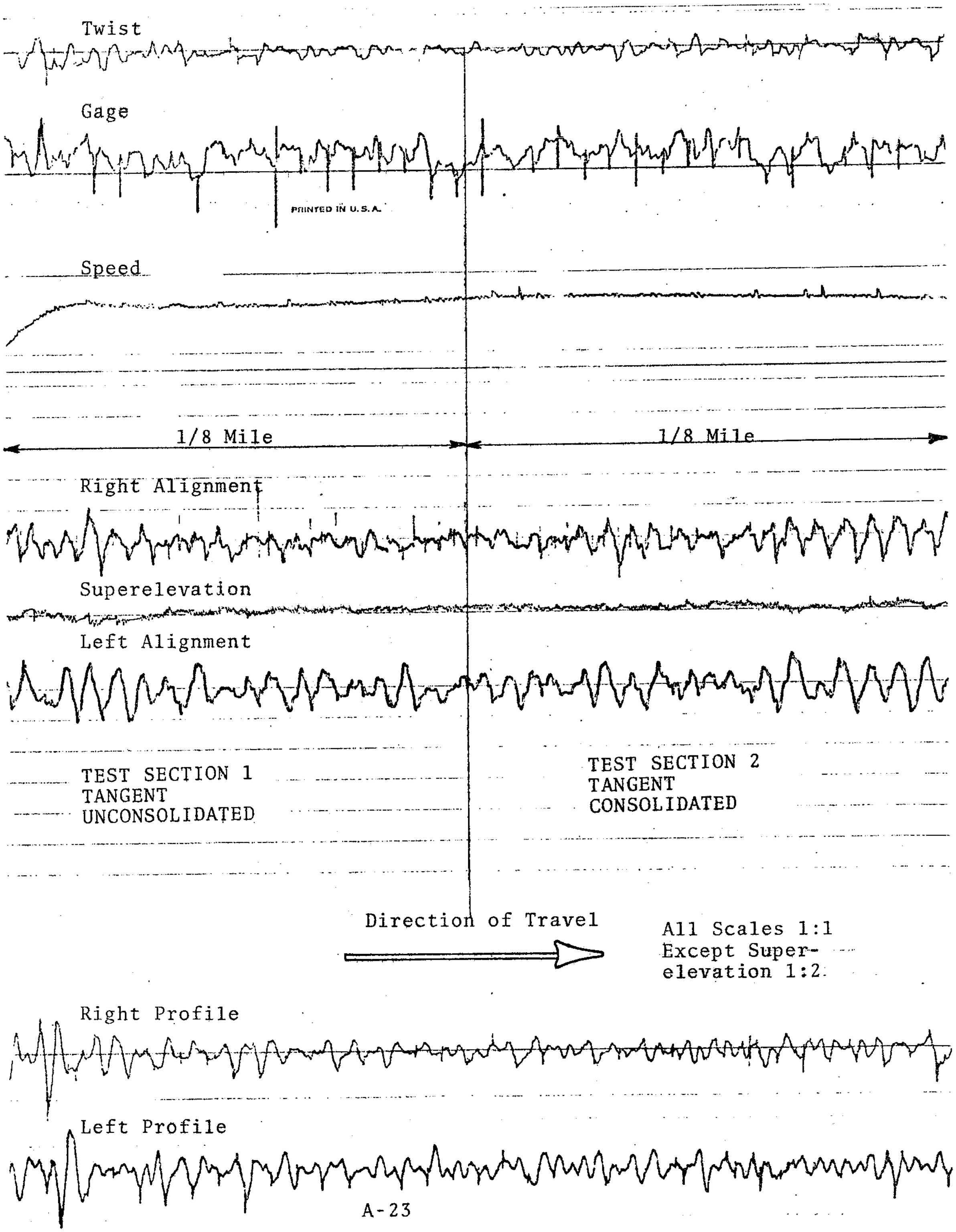
Boston and Maine Corporation

Track Geometry
21 August 1973



Boston and Maine Corporation

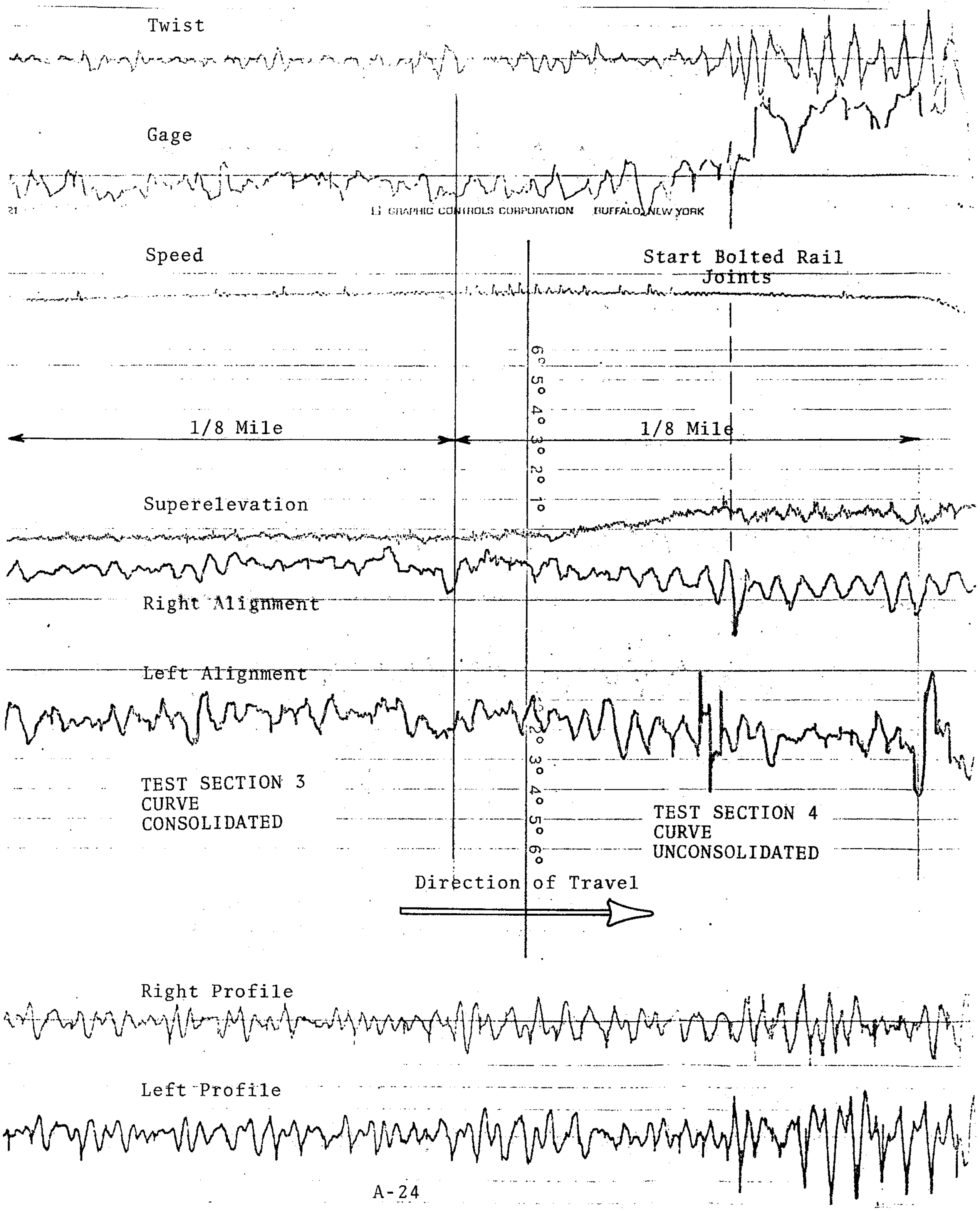
Track Geometry
24 October 1973



All Scales 1:1
Except Super-
elevation 1:2

Boston and Maine Corporation

Track Geometry
24 October 1973



APPENDIX B

Preliminary Analysis of the Effects of Accelerated Ballast Consolidation on the Lateral Resistance of Wood Ties in Railroad Track

B.1 DESCRIPTION OF FIELD TESTS

The data used in this analysis was obtained from tests of tangent track of the Boston and Maine Corporation and of the Southern Railway Company. The test sections of track were raised and surfaced, and part of each section was treated with the ballast consolidator of the Federal Railroad Administration, FRA. On each railroad, 12 to 20 ties in both the unconsolidated and consolidated sections were unfastened from the rails, and lateral force was applied to each of them by a hydraulic jack. The applied force was measured at a number of increments of tie movement until the total movement was approximately 4 mm (0.16 inch). This test sequence was repeated after approximately 1 and 2 million gross tons (MGT) of traffic on the B&M, and after 0.5 million and 1.5 MGT of traffic on the Southern. The data acquired were used to define the force vs displacement curves for the lateral resistance of wood ties after track maintenance, accelerated consolidation of ballast by machine, and consolidation by traffic.

B.2 ANALYSIS OF THE DATA

The data points established for the force displacement curve of each tie were used to calculate the force required to move the tie 0.5, 1, 2, 3, 4, and 5 mm. The values at the different displacements were obtained by interpolation from the field data using second-order polynomials calculated from the three nearest data points. Extrapolation of the force-displacement curves beyond the limits of available data was not attempted.

The estimates of the force levels obtained were used to calculate the mean force required to move the ties 0.5 mm to 4 mm as a function of accelerated consolidation, amount of traffic prior to the tests, and test locations.

The test used to determine the statistical significance of the effect of accelerated consolidation was based on a standard test for the difference of two means where the standard deviations are neither known nor assumed to be equal.[1] This test takes into account both the scatter of data and the number of ties tested in determining the significance of the calculated difference of forces. The calculated mean forces for each level of tie displacement and the statistics "t" and "degrees of freedom" based on the difference between consolidated and unconsolidated track are listed in Table 1. In general, the consolidated ties had significantly greater resistance to lateral movement than the unconsolidated ties prior to exposure to traffic (i.e., there is a 98% to 99.5% certainty that the differences in the mean forces were caused by accelerated consolidation rather than the scatter of the data). The confidence limits are shown in Table 2. It appears from this analysis that accelerated ballast consolidation results in a real improvement of the lateral tie resistance initially, but that the relative effect is small after the track has been exposed to 0.5 million gross tons of traffic.

The data from the B&M tests include lateral resistance forces for ties which were tested after 1 MGT and 2 MGT of traffic. Since the differences between the resistance of ties in consolidated and unconsolidated ballast were small at 2 MGT, it appears reasonable to use the values obtained at 2 MGT of traffic as benchmark values for stabilized ties. The initial resistance can then be divided by the stabilized value to obtain the ratio of initial resistance to find resistance at various displacements. This ratio can be thought of as the amount of stabilization recovery. The results of such calculations are tabulated in

---

[1] Bowker, A.H.; Lieberman, G. J.; Engineering Statistics, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1959, pp. 173-174.

TABLE 1

Statistical Analysis of the Reliability of Recorded Improvement in the Resistance of Ties to Lateral Forces as a Result of Accelerated Ballast Consolidation

		Consolidated			Unconsolidated				
	Displacement mm	Mean Force lbs.	SIG (MF) lbs.	No.	Mean Force lbs.	SIG (MF) lbs.	No.	T	DF
B&M 0 Traffic	.5	1250.65	53.4821	19	1049.24	70.9644	19	2.26655	35.18
	1.0	1476.50	47.6119	19	1247.77	63.4085	20	2.88459	36.50
	2.0	1759.52	53.9074	19	1490.20	68.2853	20	3.09567	37.30
	3.0	1902.09	52.9044	19	1606.16	78.1680	20	3.13521	34.58
	4.0	2031.91	59.6171	19	1716.87	71.0966	19	3.39541	36.82
	5.0	2129.49	73.1505	4	2012.94	12.9412	2	1.56892	3.31
B&M 1.0 MGT	.5	1949.57	86.5961	19	1932.47	140.1441	16	.10376	26.88
	1.0	2152.98	69.8683	19	2080.20	110.4225	17	.55696	28.85
	2.0	2325.66	74.6929	18	2227.32	99.3278	17	.79129	31.86
	3.0	2469.13	73.6970	18	2352.38	94.4563	15	.97452	29.56
	4.0	2506.22	89.8557	14	2378.48	117.0323	9	.86575	18.51
B&M 2.0 MGT	.5	1788.59	56.0953	19	1875.55	79.2968	19	-.89537	34.01
	1.0	2060.49	80.4729	19	2149.41	89.2221	19	-.74004	37.58
	2.0	2383.71	103.3447	19	2448.36	103.5448	19	-.44190	38.00
	3.0	2613.64	118.3793	19	2587.80	110.9722	18	.15927	36.94
	4.0	2825.62	130.7362	18	2725.08	115.0065	18	.57744	35.39
Southern 0 Traffic	.5	1170.37	79.3845	13	949.68	59.7483	9	2.22118	21.70
	1.0	1276.04	65.0552	15	1073.94	43.7663	12	2.57752	24.96
	2.0	1401.21	68.5209	15	1202.28	41.0579	13	2.49042	23.76
	3.0	1466.73	68.9947	15	1285.72	38.5600	13	2.29006	22.79
	4.0	1532.16	65.8440	15	1328.76	46.6949	11	2.51989	25.03
Southern 0.48 MGT	.5	1581.14	51.5444	13	1524.69	58.7075	15	.72252	27.88
	1.0	1961.69	67.4053	13	1963.75	74.3273	15	-.02053	27.97
	2.0	2693.37	388.3041	13	2370.08	125.8732	15	.79200	14.93
	3.0	2523.85	123.7795	13	2517.22	122.3756	15	.03808	27.82
	4.0	2511.98	153.0773	10	2473.40	99.4617	11	.21134	17.12
	5.0	2250.51	243.8706	3	2174.31	156.2218	3	.26310	4.81
Southern 1.43 MGT	.5	1739.97	48.1775	12	1533.59	60.2436	11	2.67551	21.42
	1.0	1873.49	73.3036	15	1783.59	44.1844	14	1.07369	24.07
	2.0	2130.96	95.5559	15	2130.45	69.4854	14	.00432	26.80
	3.0	2288.94	108.7506	15	2311.75	81.8489	14	-.16759	27.25
	4.0	2378.31	143.0013	9	2423.72	101.9316	11	-.25857	16.72

TABLE 2

Probability that the Force Required to Move a Tie Laterally is Greater for Ties in Consolidated Ballast than for Ties in Unconsolidated Ballast

$P(MF_c|\text{displ.} > MF_u|\text{displ.})$

B&M Data			
Tie Displacement mm	Zero Tons	One Million Tons	Two Million Tons
0.5	98%	50%	20%
1.0	99.5%	70%	25%
2.0	99.5%	75%	35%
3.0	99.5%	80%	55%
4.0	99.5%	80%	70%

Southern Data			
Tie Displacement mm	Zero Tons	478,000 Tons	1,430,000 Tons
0.5	98%	75%	99%
1.0	99%	50%	85%
2.0	99%	75%	50%
3.0	98%	50%	50%
4.0	99%	50%	40%

Table 3. For all displacements and for both railroads, the effect of ballast consolidation was to raise the initial lateral tie resistance from 0.6% to 0.7% of its final expected value.

Examination of the Southern data reveals little difference between the resistance of the consolidated and unconsolidated ties after 0.5 million tons of traffic, although its is possible that this is a result of the disturbance of the same ties in earlier tests. The recorded decrease in the lateral tie resistance between 0.5 and 1.5 million tons apparently resulted from the same disturbance. Plotting the force versus tonnage figures for consolidated and unconsolidated ties, as in Figure 1, provides a rough estimate of the upper bound of the effect of the consolidator under the conditions that applied to the tests. The straight-line interpolation shown in Figure 1 probably overstates the effect of the consolidator and, also, the initial

TABLE 3

Ratio of Initial Lateral Tie Resistance to Long-Term Lateral Resistance

	Displacement mm	Initial Force lb.	Force after 2 million tons lb.		Ratio
B&M Unconsolidated Ballast	0.5	1049	1876		.56
	1.0	1248	2149		.58
	2.0	1490	2448		.58
	3.0	1606	2588		.62
	4.0	1717	2725		.62
				Avg. Ratio	.59
B&M Consolidated Ballast	0.5	1250	1789		.70
	1.0	1476	2060		.72
	2.0	1760	2384		.74
	3.0	1902	2614		.73
	4.0	2032	2826		.73
				Avg. Ratio	.72
Southern Unconsolidated Ballast	0.5	950	1534		.62
	1.0	1074	1784		.60
	2.0	1202	2130		.56
	3.0	1286	2312		.56
	4.0	1329	2424		.55
				Avg. Ratio	.58
Southern Consolidated Ballast	0.5	1170	1739		.67
	1.0	1276	1875		.68
	2.0	1401	2131		.66
	3.0	1467	2289		.64
	4.0	1532	2378		.64
				Avg. Ratio	.66

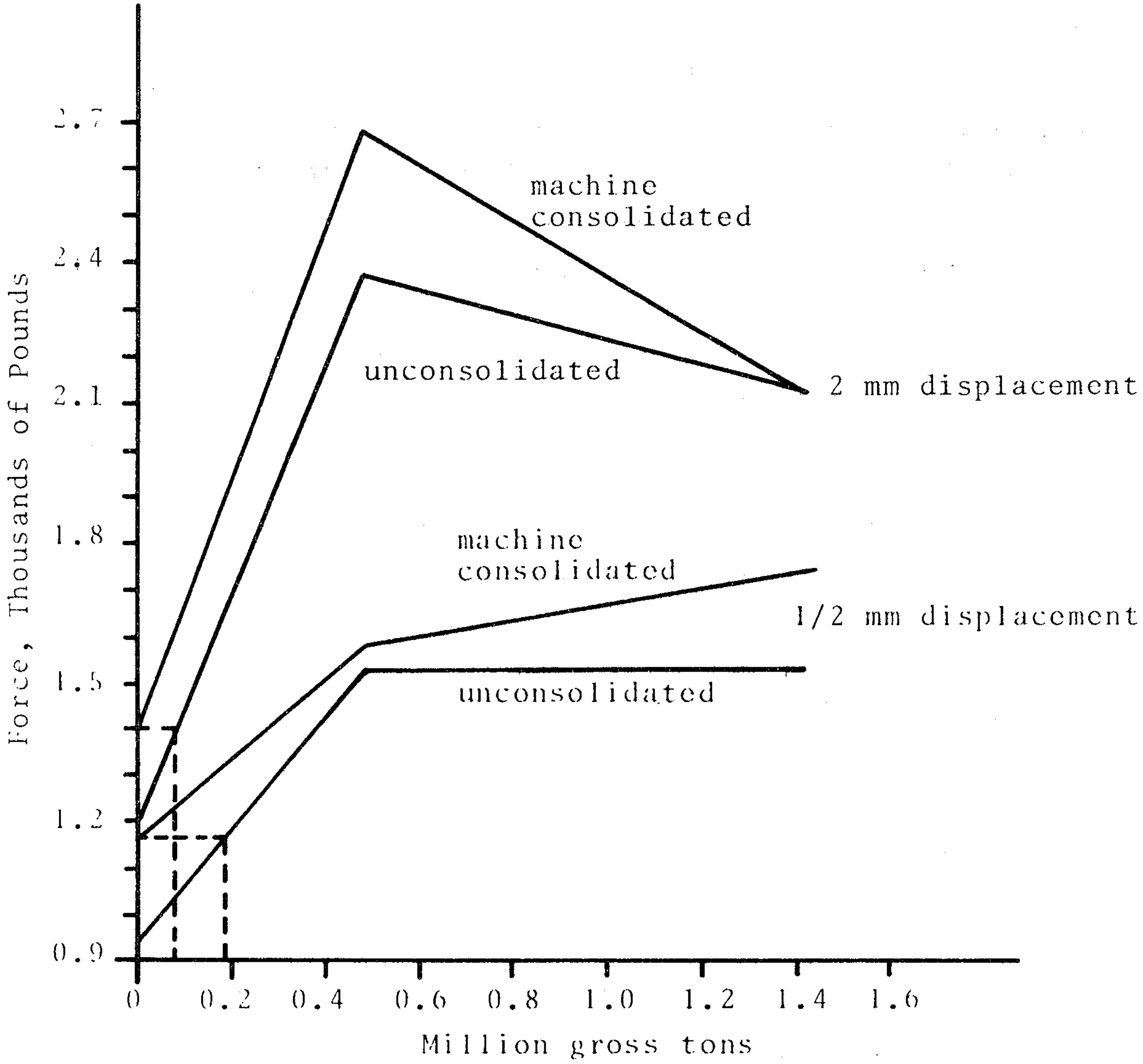


Figure 1. Effect of Traffic-Induced Consolidation on the Force Required to Move a Wood Tie 0.5 mm and 2 mm laterally (CNO&TP Railroad Test Data)

improvement of the unconsolidated ties due to traffic is probably more rapid than shown by the straight line. However, from this type of analysis on the Southern data it can be estimated that consolidation produces an improvement in lateral tie resistance which is equivalent to 100,000 to 200,000 gross tons of traffic over freshly disturbed track. If the same estimating technique is used on data in Appendix A from the B&M data, the equivalent improvement from consolidation would be equal to 300,000 gross tons of traffic.

The computer program used to calculate the numbers and statistics in this section is sufficiently general that it could be used in later analysis of consolidator data. This program is available from the Department of Transportation, Federal Railroad Administration Computer Library.

APPENDIX C

The Effects of Ballast Consolidation on Continuous Welded Track, Test MM-77.3

Southern Railway Company
Research & Tests Laboratory
Alexandria, Vrginia
July 7, 1975

TABLE OF CONTENTS

ABSTRACT

The resistance of wood ties to lateral forces was measured in a series of tests conducted on mainline track of the Southern System. One group of ties was in ballast that had not been disturbed for several years. Other groups were old and new ties in ballast that had been disturbed by timbering and surfacing (T&S), both with and without machine consolidation of the ballast. The tests of ties in disturbed ballast were made at four levels of traffic. Measurements were also made of the dynamic settlement of track under the first trains that passed over test sites or zones after T&S work and ballast consolidation, using specially designed test instrumentation. In addition, cumulative changes in track elevation and alignment were measured by surveyors.

Test results showed that the wood ties in undisturbed ballast had an average lateral resistance of 2,700 pounds at 4 mm of displacement, while old ties in disturbed ballast had a resistance of only 830 pounds, a loss of 1,870 pounds; old ties in disturbed ballast that had been compacted by a ballast consolidator had a resistance of 1,200 pounds, which was 370 pounds or 45% more than ties in unconsolidated ballast, and equivalent to a recovery of 20% of the 1,870 pounds of resistance lost during T&S work.

When measured at 4-mm and 0.5-inch displacements, the increase in resistance caused by machine consolidation of ballast was found to be equivalent to the effects of a minimum of 200,000 tons and an average of approximately 500,000 tons of traffic. The measurements of dynamic settlement and longer term settlement indicated that machine consolidation of ballast did not reduce track settlement significantly; however, the test data did indicate that the settlement was more uniform in track on consolidated ballast.

BALLAST CONSOLIDATION TESTS

BACKGROUND

It has long been recognized by railway engineers and maintenance personnel that track ballast compacts or consolidates under traffic, and that this compaction can be influenced by various maintenance and operational factors. Accurate prediction and control of ballast consolidation represent a significant step forward in the maintenance of the track and roadbed. The purpose of this report is to summarize the experimental ballast consolidation program recently made in welded track on Southern Railway, and to illustrate the important influence ballast stability can have on a track structure.

TEST OBJECTIVE

The objective of this test was twofold: (1) to evaluate the effectiveness of ballast consolidation (compaction by mechanical vibration) in stabilizing the track structure after the track had been disturbed by maintenance activities, and (2) to determine the effects of timbering and surfacing on the stability of track with welded rail.

The ballast in designated test sections was compacted by a ballast consolidator built by the Plasser Corporation (a modified Roadmaster Tamper frame) and owned by the Federal Railroad Administration. It was used in the tests for a period of 4 weeks. This consolidator compacted the ballast in the crib and shoulder areas by mechanical vibration at a frequency of 38 Hz in the crib with dynamic force up to 1,600 pounds, and 24 Hz on the shoulder with dynamic force up to 1,700 pounds. Each application of the consolidator lasted 3 seconds.

TEST ZONES AND SCHEDULES

In order to arrange the tests in coordination with train schedules and with schedules for T&S work, a number of test zones or sites were selected. Test sites near Burke, Virginia and Charlotte, North Carolina were selected for the verification of test procedures and instrumentation, and for the measurement of the lateral resistance of ties in undisturbed ballast. Lateral resistance tests were made on ties in disturbed ballast in tangent track at two test sites, and dynamic settlement was measured in tangent track at four test sites near Liberty, South Carolina. Cumulative settlement was measured on curved track and on tangent track at two test sites near Liberty, South Carolina, and at two test sites near Lowell, North Carolina. Every zone or test site had a section of track with consolidated ballast and an adjacent section with unconsolidated ballast.

Tests on ties in undisturbed ballast were scheduled to coincide with intervals in traffic. Dynamic settlement tests were scheduled during the passage of the first trains over track after the completion of T&S work and ballast consolidation. Lateral resistance tests of ties in disturbed ballast and cumulative track settlement measurements were made after the completion of T&S work and ballast consolidation, at the lowest level of traffic that was feasible and at higher levels of traffic to a maximum of approximately 1.7 million gross tons.

Additional information on the test sites is provided in Attachment CI, along with a discussion of test procedures.

TEST RESULTS

Since it is known that track ballast compacts under normal traffic tonnage and that tie resistance to movement increases as the ballast compacts, the value of artificially compacting ballast must therefore lie in the area of (1) promoting rapid ballast compaction without the need of accumulated tonnage, and (2) promoting the uniform settlement of ballast to preserve the track surface and line.

If the individual lateral tie tests are taken as representative of track lateral resistance, it would appear that the immediate effect of consolidation is to restore 20% of the lateral resistance of the track structure that is lost during T&S work. This is shown in Figure C-1.

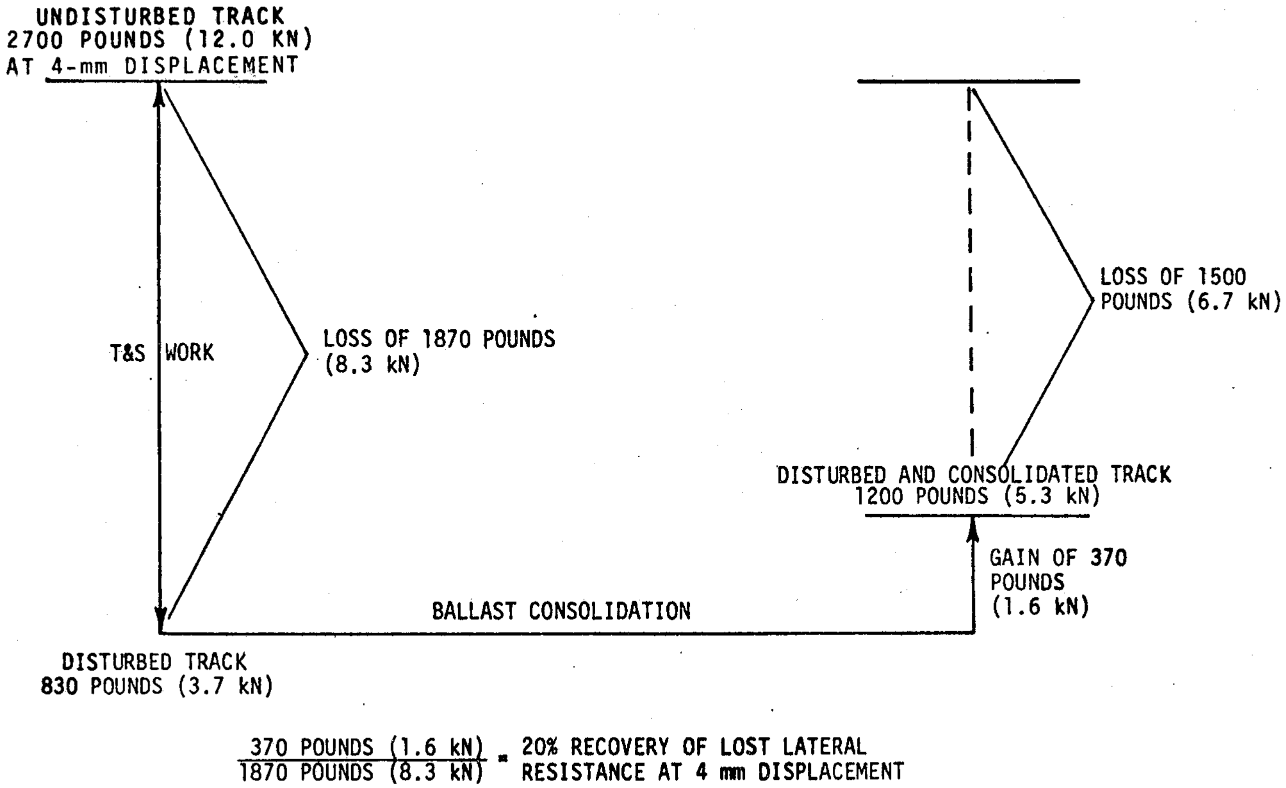


Figure C-1. Average Changes in Lateral Resistance of Individual Ties

Figure C-1 was developed from the following averages of test results:

Measured Lateral Resistance of Ties in Undisturbed Track - 2,700 lbs. @ 4-mm displacement

Measured Lateral Resistance of Ties in Disturbed Track - 830 lbs. @ 4-mm displacement

$\frac{830 \text{ lbs.}}{2700 \text{ lbs.}} = 0.307$, or a 69% loss of lateral resistance without ballast consolidation

$\frac{1200 \text{ lbs.}}{2700 \text{ lbs.}} = 0.444$, or a 56% loss of lateral resistance with ballast consolidation

With respect to an equivalent track stability from accumulated tonnage, the test data indicate a minimum (or guaranteed) advantage between 162,000 and 227,000 gross tons of traffic. The average advantage is between 453,000 and 647,000 gross tons, which is based on data from new crosstie tests in consolidated and unconsolidated ballast sections. The measurements of both the long-term settlement and the dynamic settlement indicated that the consolidator does not retard or prevent track settlement to any significant degree; but there is support from the test data that settlement is more uniform in consolidated track. However, by far the most significant effect of ballast consolidation is the initial increase in lateral resistance of disturbed track when the ballast is compacted.

The results of the evaluations of test data can be summarized in the following statements:

- Disturbing the ballast structure of a track by timbering and surfacing can result in a 69% loss of lateral resistance of individual ties (2700 lbs. to 830 lbs.).
- Replacing a tie during timbering and surfacing work can further reduce the lateral resistance by 4% for a total reduction of 73% (830 lbs. to 730 lbs.).

- The rate of settlement (vertical) of track is greatest under the first trains following timbering and surfacing work and decreases with tonnage.

- Under normal conditions, approximately 1.75 to 2 million gross tons of traffic are required to compact disturbed ballast to 50% of its full compaction level.

- The effect of the ballast consolidator was to increase the lateral resistance of ties in disturbed ballast (timbered and surfaced track). In other words, the effect was to reduce the loss of lateral resistance from 69% to 56% on a scale where 100% represents the resistance of ties in undisturbed ballast. The minimum effect of the consolidator can be equated to having approximately 200,000 tons of traffic pass over the track.

Accurate surveys of vertical settlement and changes in alignment were made by Ralph Whitehead & Associates under subcontract of ENSCO, Inc. The results of their surveys are provided in Attachment CIII of this report. Attachments CI and CII give detailed descriptions of the other tests, specific test results, and calculations of lateral resistance.

ATTACHMENT CI
TEST PROCEDURES

LATERAL RESISTANCE OF INDIVIDUAL TIES

To measure the resistance of the track structure to buckling and misalignments, the lateral resistance of individual crossties was tested. Spikes, adjacent rail anchors, and tie plates were removed from the selected ties before testing to isolate them from the surrounding track structure. Figure C-2 illustrates this test arrangement.

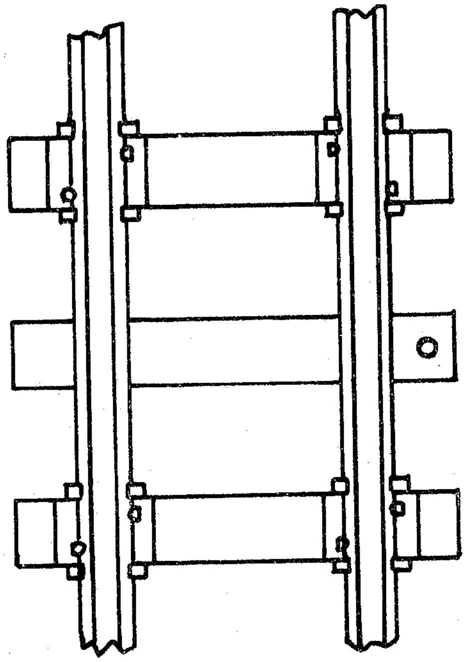


Figure C-2. Diagrammatic Arrangement for Test of Lateral Resistance of Tie

To accomplish the test with minimum preparation of the tie, a load frame was developed that would pull the tie parallel to the plane of the surrounding track structure, and would require only one simple connection to the tie. The load frame is shown in Figures C-3 and C-4. One part of the frame rests on top of

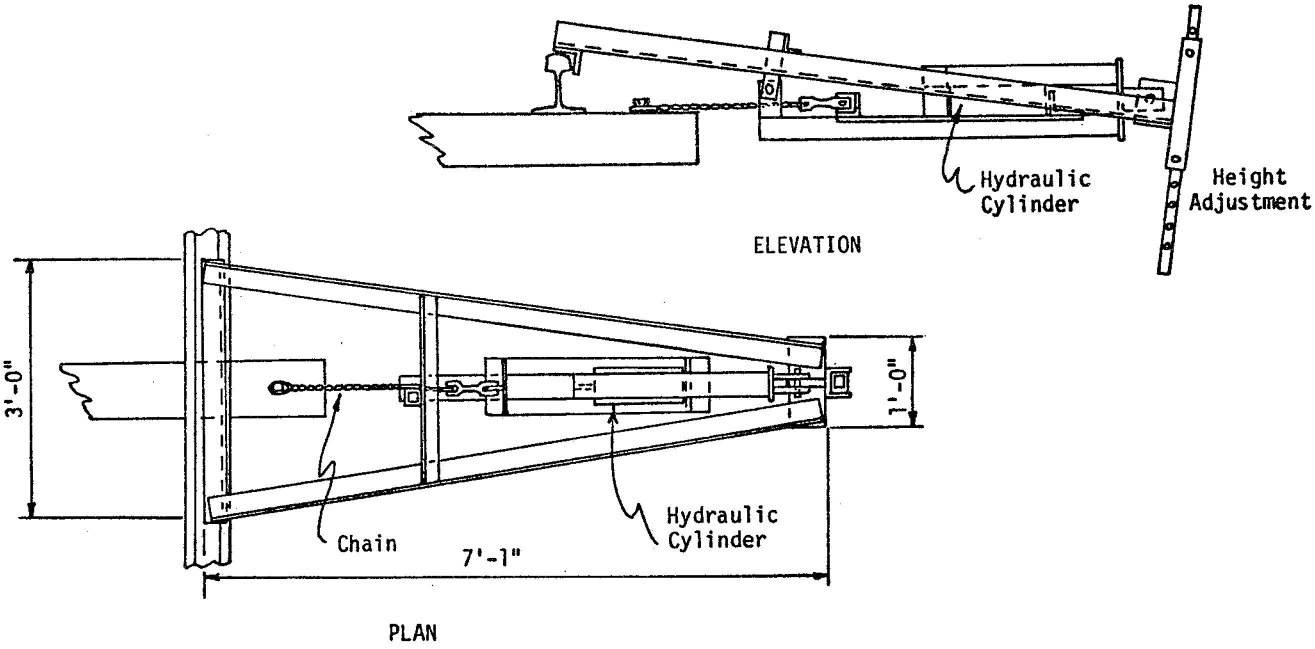


Figure C-3. Schematic of Load Frame Used for Test of Lateral Resistance of Tie

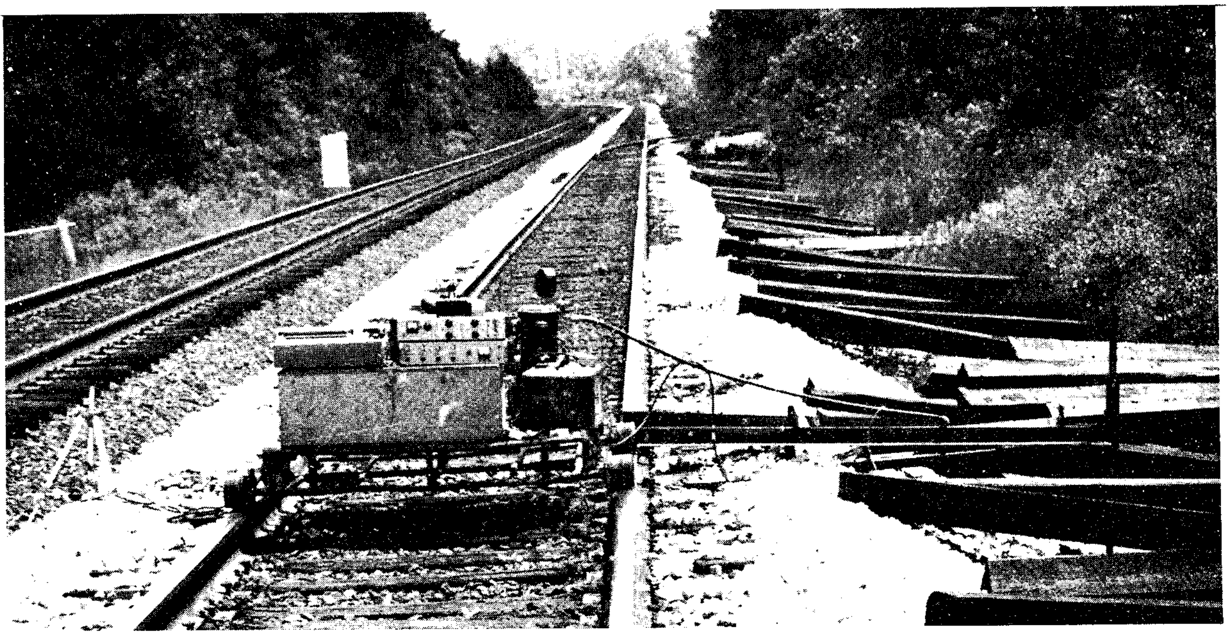


Figure C-4. Arrangement of Instrumentation for Test of Lateral Resistance of Tie the rail, while the opposite end is mounted on an adjustable column so that the force can be applied horizontally. The frame has a 30-ton capacity hydraulic cylinder jack to apply a steady, slowly increasing force to the tie.

Force is measured by using a full bridge, strain-gage-type load cell in series with a chain connected to a large nail driven into the test tie. Details of the connection methods and the load cell are shown in Figure C-5.

Tie movement was measured with a dial gage and with a potentiometric displacement transducer installed in parallel, as shown in Figure C-6, and attached to the test tie by a taut wire. The dial gage was used to calibrate the transducer and to verify tie movement.

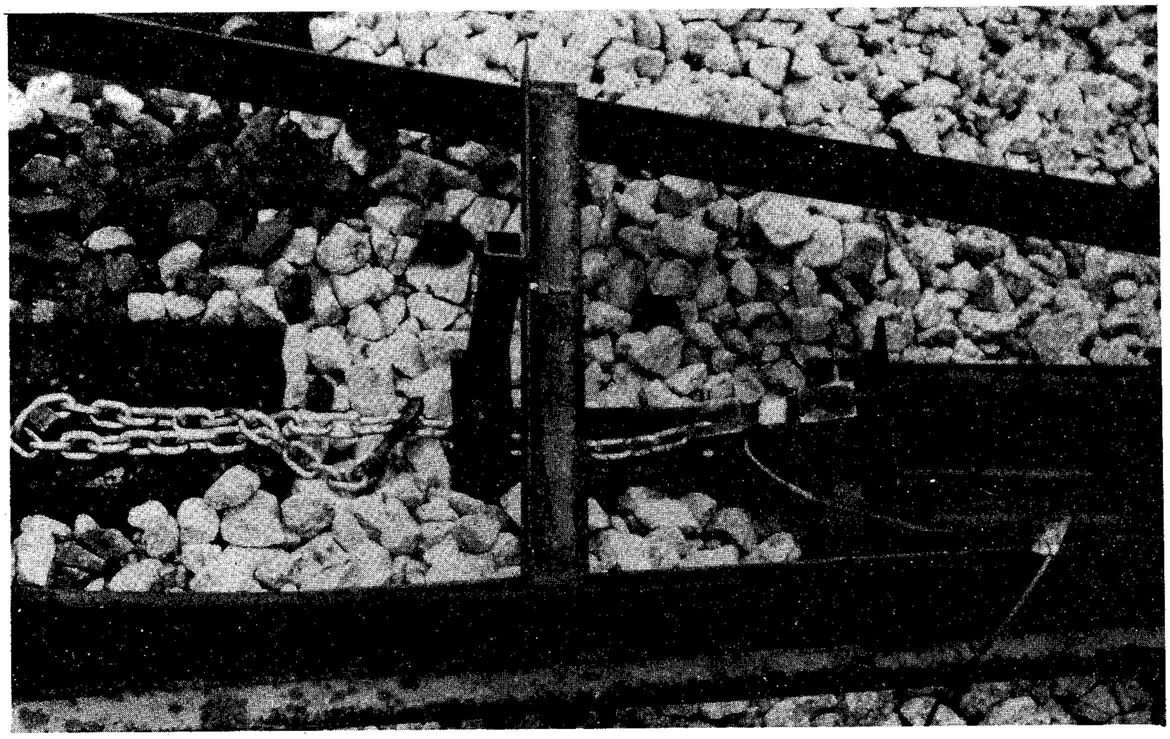


Figure C-5. Lateral Tie Test Frame Showing Load Cell and Tie Connection

Figure C-6. Test Instrumentation Dial Gage and Displacement Transducer Used to Measure Lateral Displacement of Tie

During the tests the outputs of the load cell and the displacement transducer were conditioned by amplifiers and transmitted to the X and Y axis connections of an X-Y plotter. In this manner, a continuous load displacement diagram was obtained. Figure C-7 is an example of the curves obtained. Ties were displaced 1/2 inch (12.7 mm) to generate the curve. The test usually required a 10 to 15 minute setup time, with about 30 seconds devoted to the actual pull on the tie.

DYNAMIC AND VERTICAL SETTLEMENT OF TRACK UNDER TRAFFIC

For the short-term effect of traffic on track on both consolidated and unconsolidated ballast, instruments of the type shown in Figures C-8 and C-9 were developed. These instruments consisted of a weighted platform on jackscrews from which a cantilever beam projected. The jackscrews rested on the subgrade as supports for a stable reference platform, and the cantilever

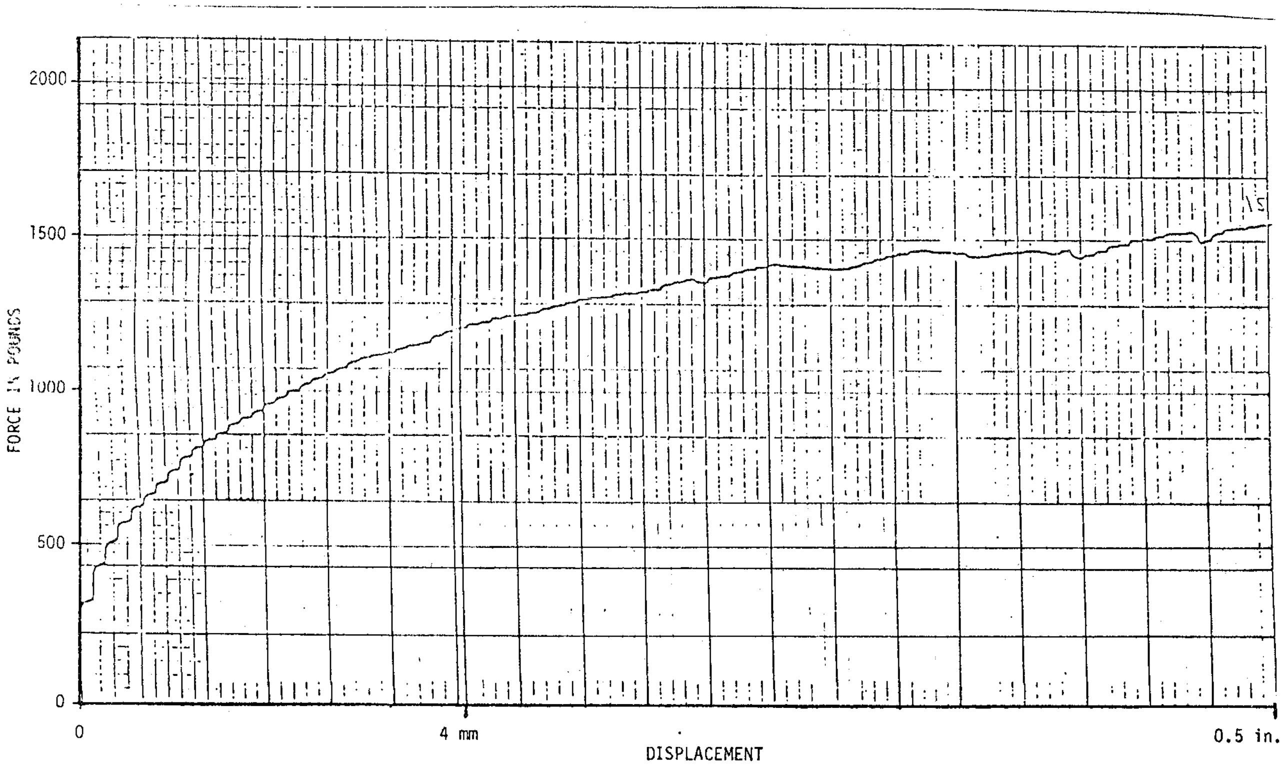


Figure C-7. Sample Test Data Diagram of Continuous Lateral Load vs. Tie Displacement

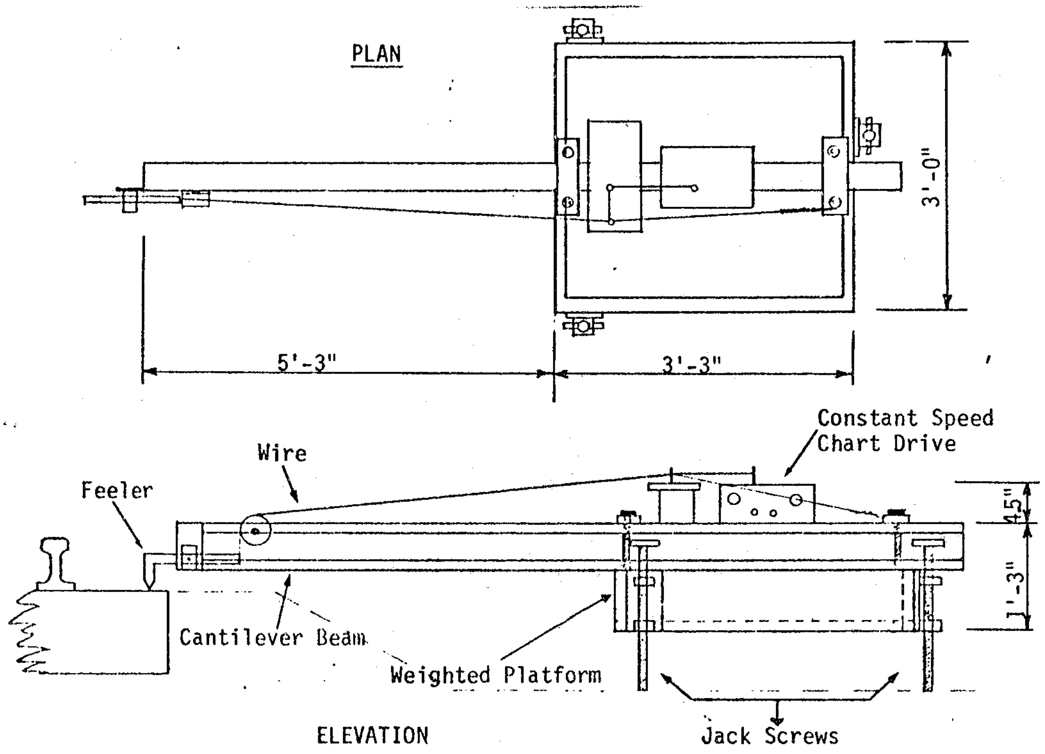


Figure C-8. Schematic of Instrumentation for Measuring Vertical Movement of Test Tie

Figure C-9. Instrumentation for Measuring Vertical Movement of Test Tie

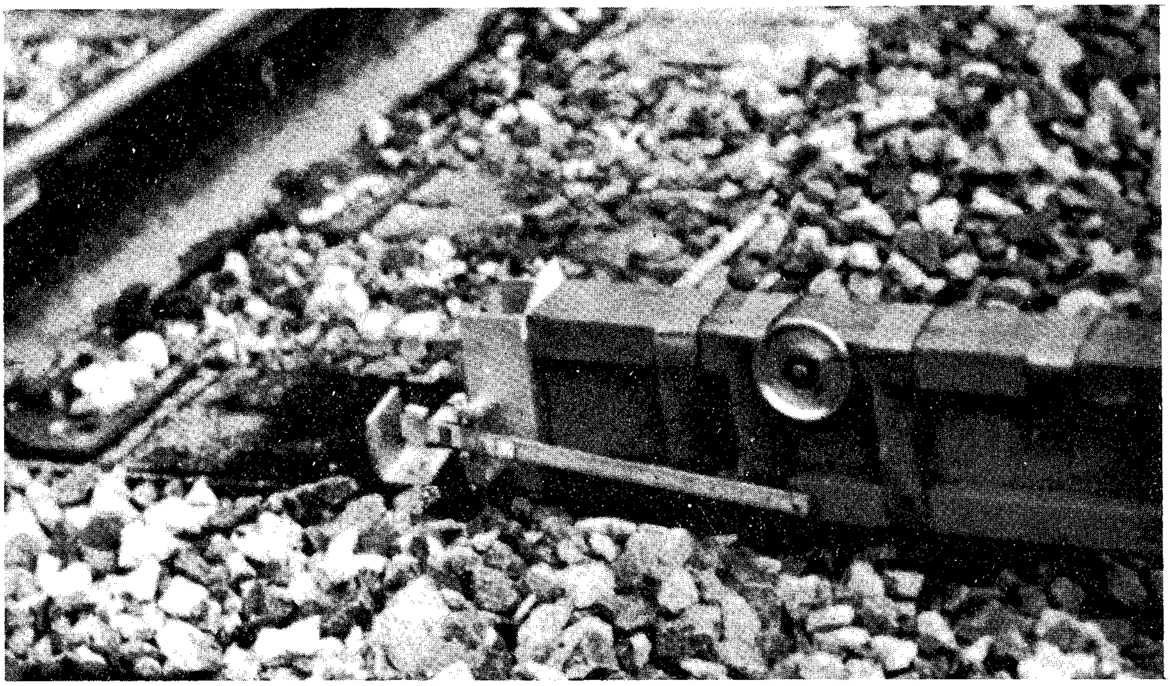


Figure C-10. Close View of Instrumentation for Measuring Vertical Movement of Test Tie, Showing "Feeler" Resting on Top of Tie beam projected out to the track. At the end of the cantilever beam, a "feeler" rested on the end of a tie, or the base of the rail, as shown in Figure C-10.

The vertical motion of the tie, caused by a train passing over it, was transmitted to a constant speed chart by a thin wire as shown in Figure C-11. An output of one of these instruments is shown in Figure C-12, with a train sketched to show the interpretation of the waveform generated. Since the chart

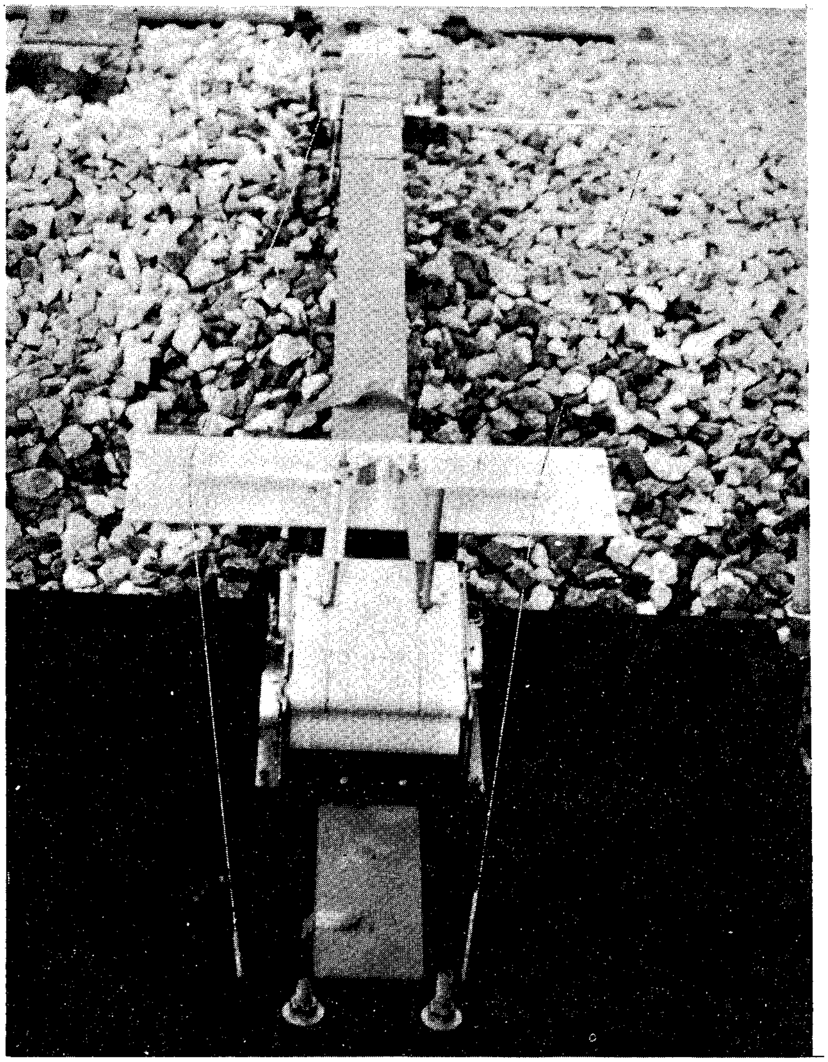


Figure C-11. Top View of Instrumentation for Measuring Vertical Movement of Tie, Showing Constant Speed Chart and Wires that Actuate Pens

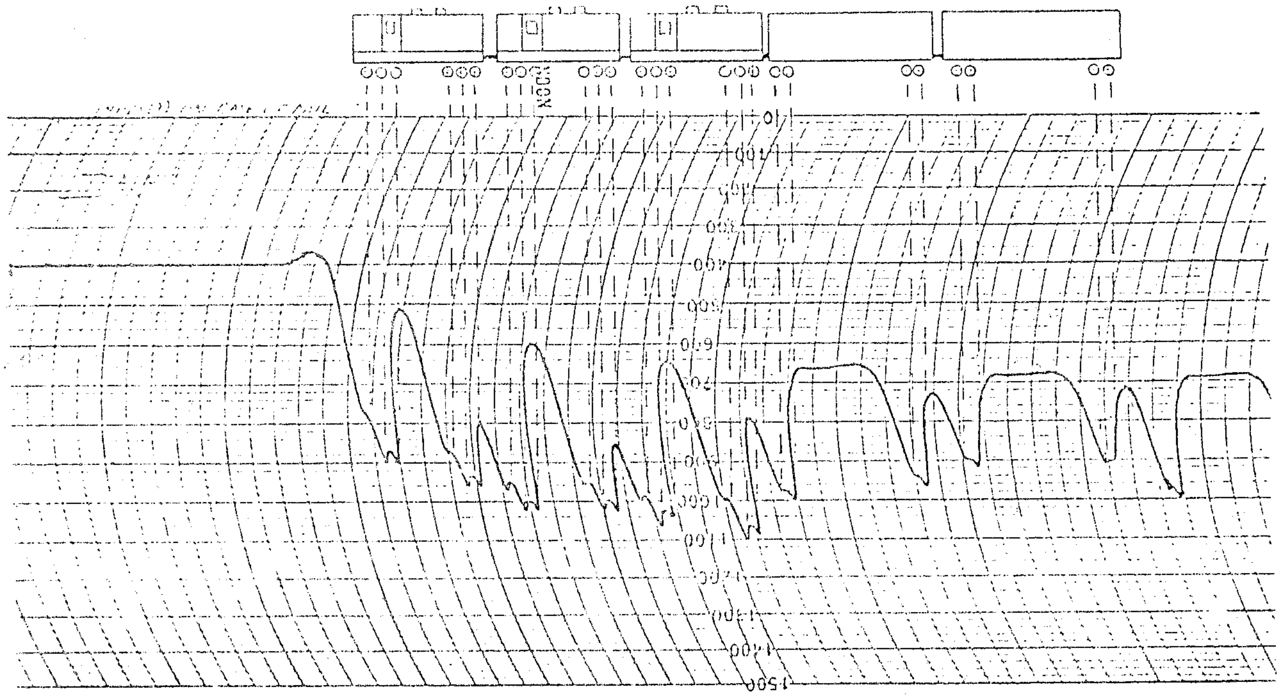


Figure C-12. Sample Diagram of Vertical Movement of Test Tie Recorded as Train Passed Over Test Site

was driven at a constant speed, this graph represents the varying vertical response of a crosstie or another selected point on the track structure to the wheels of a train passing over it. This graph also represents the approximate waveform of the track structure under a train that is passing the measurement point at a constant speed. If the instrument is indexed on the base of the rail, the relationship between the wheels and the elastic deformation of the rail is resolved, as shown in Figure C-12.

The instruments were spaced approximately as shown in Figure C-13, a diagram of a typical test site.

CUMULATIVE SETTLEMENT AND CHANGES IN ALIGNMENT

In order to measure longer term effects of traffic on both consolidated and unconsolidated track, surveying techniques were used. The primary object of this experiment was to record the

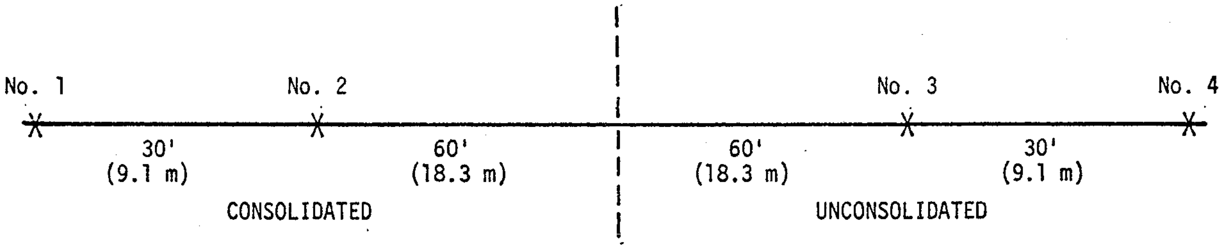


Figure C-13. Diagram of Typical Test Site

initial track position in space relative to some fixed reference point, and to measure the vertical and horizontal displacements of the track after a period of 3 weeks. To be able to do this in the situations that existed with respect to available track time, it was necessary to use short test sections in order to keep surveying times short. The test sites were also short to keep the accuracy of the surveying techniques high. Test sites were on the order of 400 feet long, half being unconsolidated. Measurements on vertical settlement were made to the nearest 0.001 foot. The surveying was contracted to Ralph Whitehead and Associates by the FRA, and their reported results were analyzed by Southern for inclusion in this report as Attachment CIII.

ATTACHMENT CII
RESULTS OF EXPERIMENTS

UNDISTURBED BALLAST VS DISTURBED BALLAST

The first part of the experimental program was to measure the lateral resistance of ties in undisturbed ballast. This was done so that the effects of the consolidator could be compared to the effects of long-term consolidation by traffic, with the track in the undisturbed state. It was soon discovered that large forces were required to displace ties in undisturbed ballast: one tie requiring up to 7,900 lbs. to displace it 0.33-inch. Thirty-four ties in undisturbed ballast were tested from a number of sites. Since undisturbed ties required high forces for displacement, the 5/16 by 6 inch lag screw connection to the test tie, originally used, often failed before a full 1/2-inch (12.7-mm) displacement occurred. Drive screws, 3/4 inch by 8 inches, were used later, but limitations in the strength of the chain and frame prevented full 1/2-inch displacement of some ties. As a result, force data from tests of undisturbed ties are compared to data for disturbed ties at displacements of 4 mm instead of 1/2 inch. This also makes the data comparable to similar work done in Europe.

As shown in Table C-1, the following conclusions apply to the effects of timbering and surfacing on the lateral stability of individual crossties. When old ties in disturbed ballast are compared with old ties in undisturbed ballast, timbering and surfacing result in a 69% loss of lateral resistance. This was found from the measurement of forces required to displace ties 4 mm. Similar examination of the forces applied to displace new ties showed a 73% loss of lateral resistance. When new ties are compared to old ties, it is seen that old ties in

TABLE C-1

Results of Tests of Lateral Resistance of Old Ties in Disturbed and Undisturbed Ballast

Ties in Undisturbed Ballast

6 x 2378 = 14268 lbs.
2 x 5959 = 11918 lbs.
8 x 2405 = 19240 lbs.
18 x 2590 = 46620 lbs.
n = 34 92046 lbs.

n = number of ties

$x = \frac{92046}{34} =$ 2707 lbs. @ 4 mm displacement

New Ties vs Undisturbed Ties

$\frac{732}{2707} = 0.27$, or a 73% loss

Ties in Disturbed Ballast

Old	New
n = 39	n = 22
x = 828 lbs.	x = 732 lbs.

Old Ties vs Undisturbed Ties

$\frac{828}{2707} = 0.31$, or a 69% loss

Old Ties vs New Ties

$\frac{732}{828} = 0.88$, or a 12% difference

disturbed ballast have about 12% (or 100 lbs.) more lateral resistance than new ties in the same ballast. This is an important difference which must be taken into account when designing experiments for other ballast treatments.

The high forces seen in undisturbed ballast require some interpretation before conclusions can be drawn about the actual lateral resistance of the track. As shown in the free-body diagram (Figure C-14) of a crosstie in ballast, lateral resistance can come from three sources. These are the end component, the crib component, and the bottom component. Since the end of the tie was exposed in many of the undisturbed ballast test sites, it could not have contributed much to the high forces measured; also the bottom component is limited by the weight of the tie. In undisturbed ballast, it is thought that most of the force generated by lateral displacement of an individual tie is the result of wedging and compression of the ballast in the crib between neighboring ties. This means that the measurement

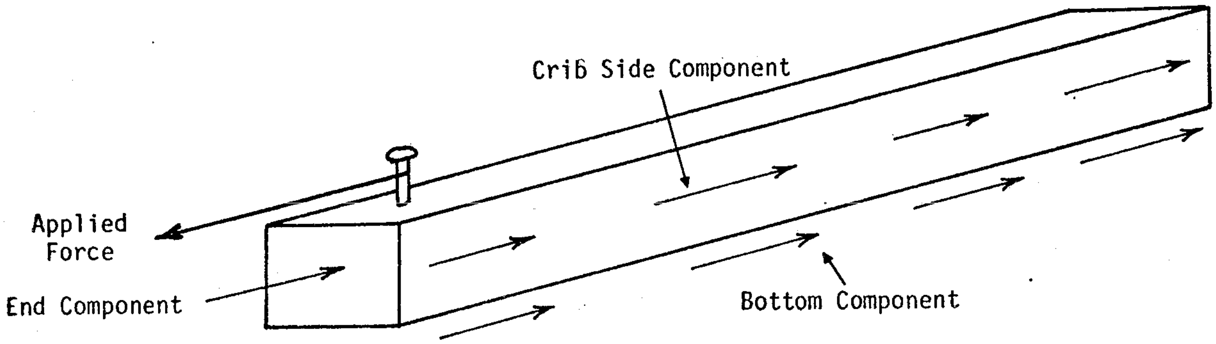


Figure C-14. Diagram Showing Three Sources of Lateral Resistance of a Crosstie in Ballast

was not of direct track lateral resistance. The force is transmitted to the test ties's immediate neighbors, and is not representative of the true contribution of the tie to track lateral resistance. This is a limitation to the usefulness of the individual tie test, but a test of individual ties is the only one that can be conducted in track without disturbing track geometry. The individual tie test is a useful parameter for judging track lateral resistance, but is not a direct measure of it.

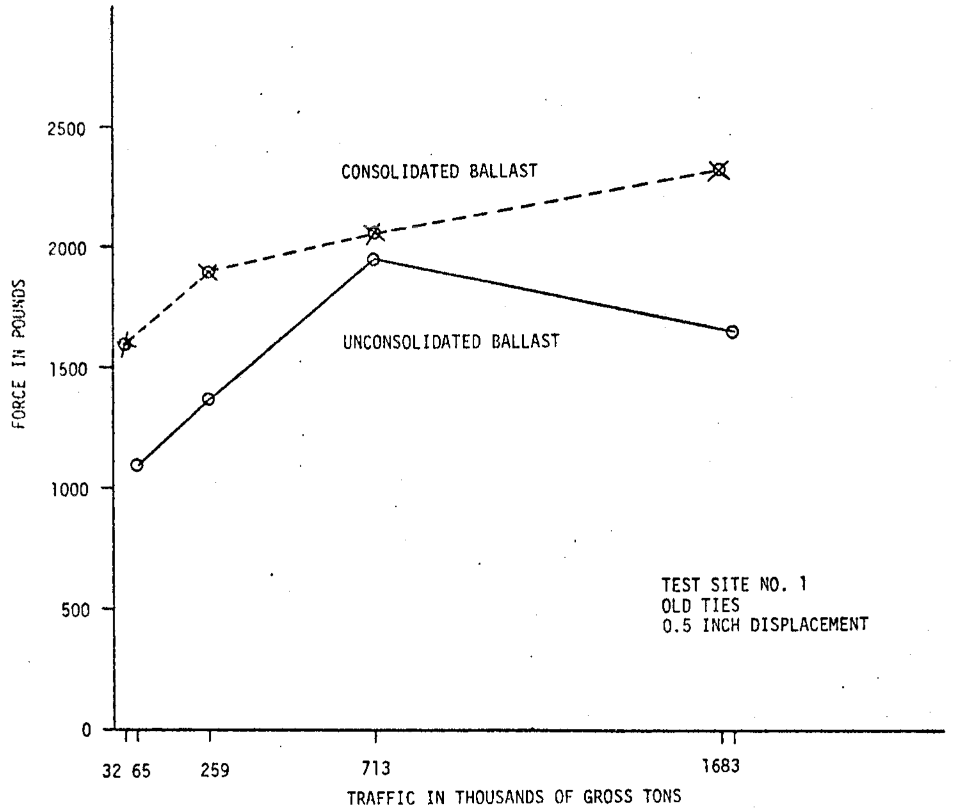
CONSOLIDATED BALLAST VS UNCONSOLIDATED BALLAST

To test for the effects of consolidation, four test sites were prepared for the measurement of long-term stability in terms of cumulative settlement, using surveying techniques; four test sites were prepared for the measurement of dynamic settlement; and two sites were prepared for lateral tie tests. At each of the test sites, the ballast was consolidated in one section of track and left unconsolidated in a second section, after surfacing and related track work had been completed. The consolidator used was owned by the FRA. The consolidation period was set at 3 seconds.

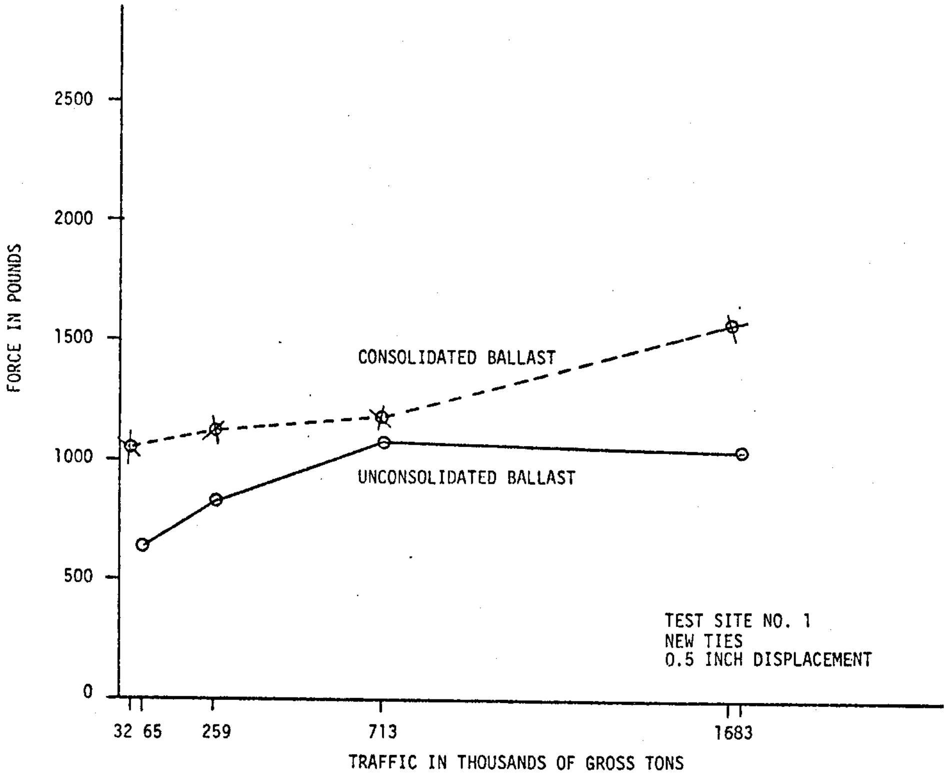
Each of the two sites for lateral tie tests was selected on the basis of access and the availability of a long section of tangent track with unanchored ties. Unanchored ties were always selected for testing, since this simplified tie preparation. Each tie selected for testing also had to be reasonably perpendicular to the rails and parallel to its two immediate neighbors, and also have cribs in good condition on both sides. Since the ties were being tested in disturbed ballast and the forces for displacement were low, an ordinary spike was used as a connection to the test tie. Sixteen or more ties were tested in each of the test sections. Thus, 16 ties were tested in the consolidated section of test site 1, and 16 ties were tested in the unconsolidated section of test site 1; and the same numbers of ties were tested in the sections of test site 2. Equal numbers of new and old ties were chosen when this did not require too much movement of test equipment. This was important since the difference in the lateral resistance of new and old ties is on the order of the consolidation effect and must be accounted for in the design of the experiment.

Each test involved the measurement of lateral forces and displacement for 64 to 72 individual ties not tested previously. For the entire series of tests of consolidated vs. unconsolidated ties at four levels of traffic, a total of 264 individual ties were tested. Testing was done in 2 days at each level of traffic. Day 1 involved test site 1, testing the consolidated section first. Day 2 involved test site 2, testing the unconsolidated section first. The order of testing was the same in each test, so that if instrumentation problems were involved, such as temperature effects on the instrumentation, they would be detectable in the data.

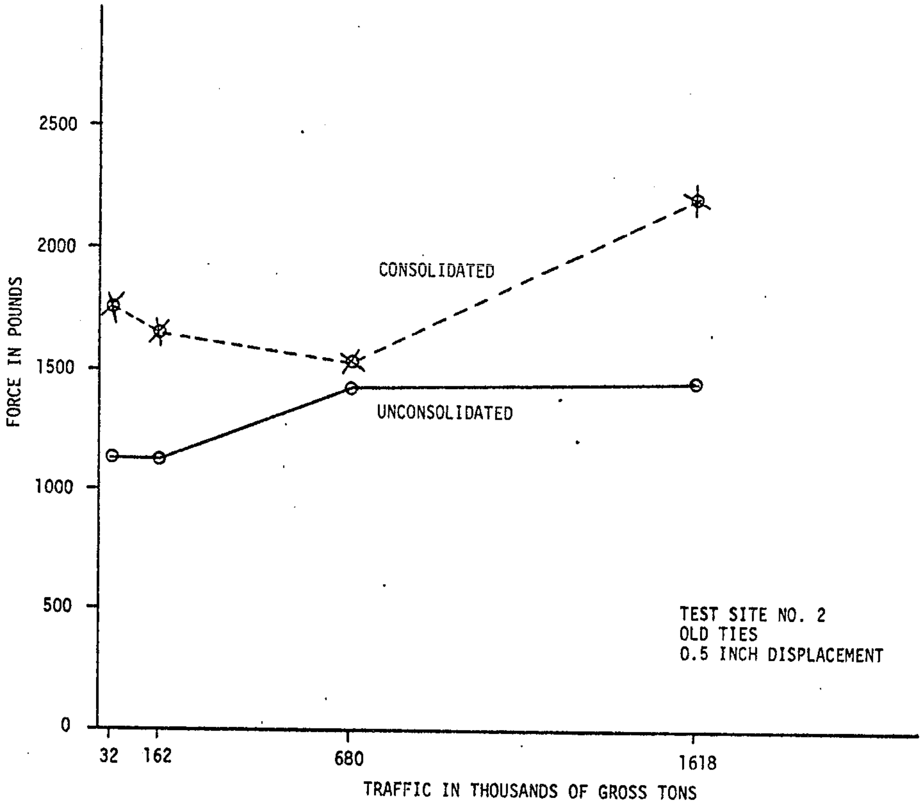
Data were collected on the lateral resistance versus displacement of new ties in consolidated ballast and new ties in unconsolidated ballast, and similar data were collected for old ties. The data were averaged and the results are shown in Graphs C-1 through C-8 which are plots of the resistance of ties at either 4-mm or 0.5-inch (12.7-mm) displacements at the stated levels of traffic. Four tests were conducted, each at a different



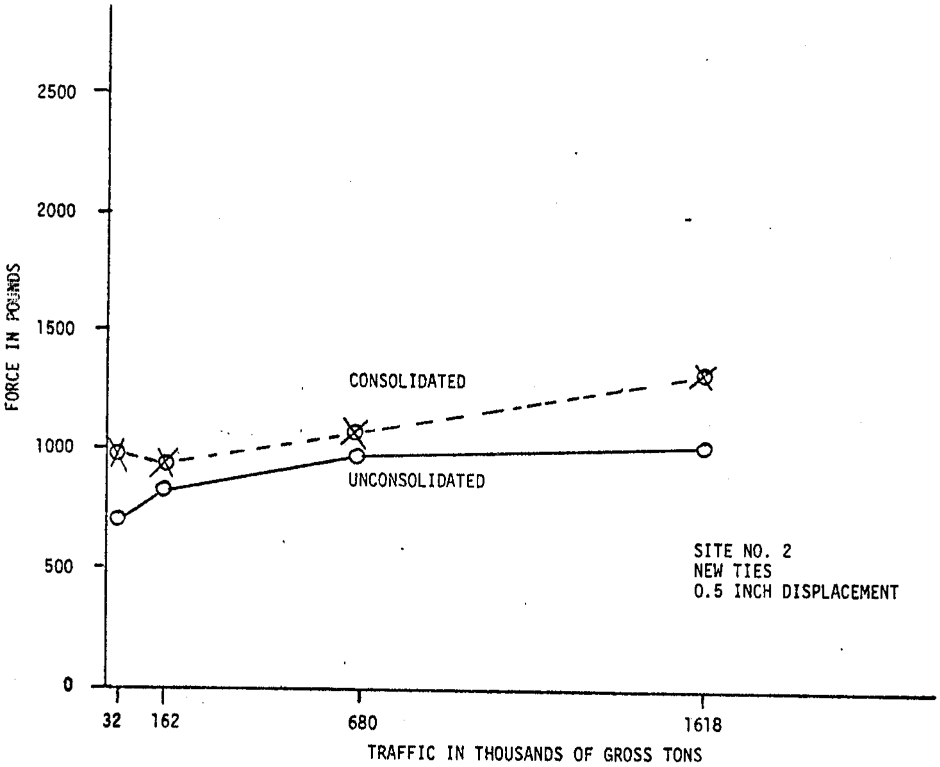
Graph C-1. Average Resistance of Old Ties Versus Traffic at Test Site No. 1



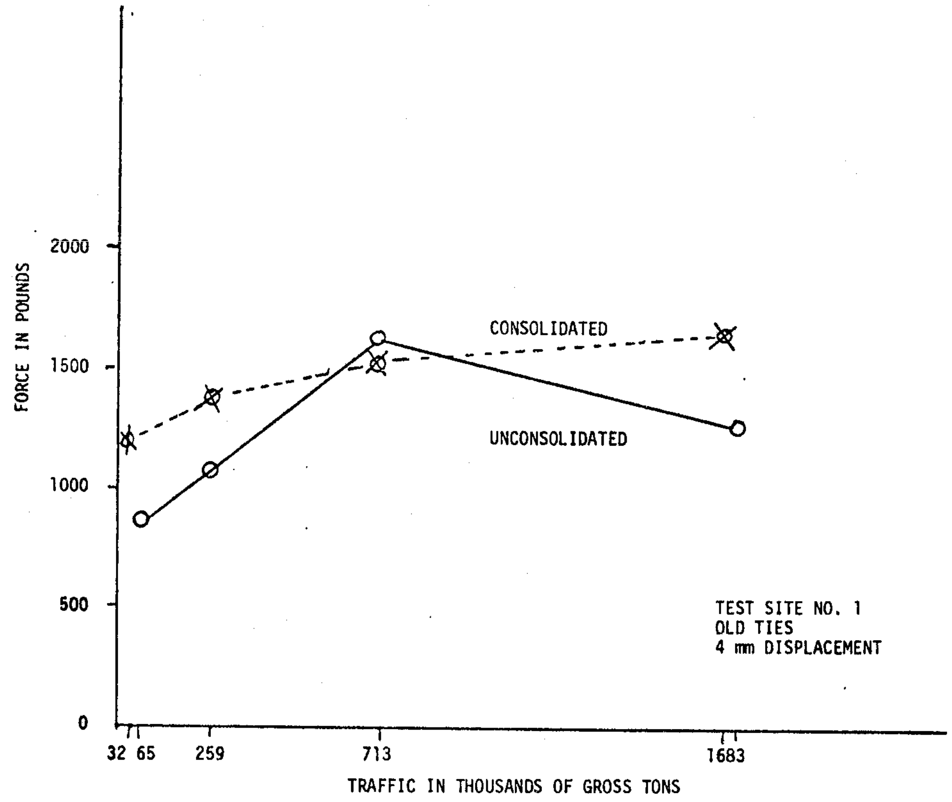
Graph C-2. Average Resistance of New Ties Versus Traffic at Test Site No. 1



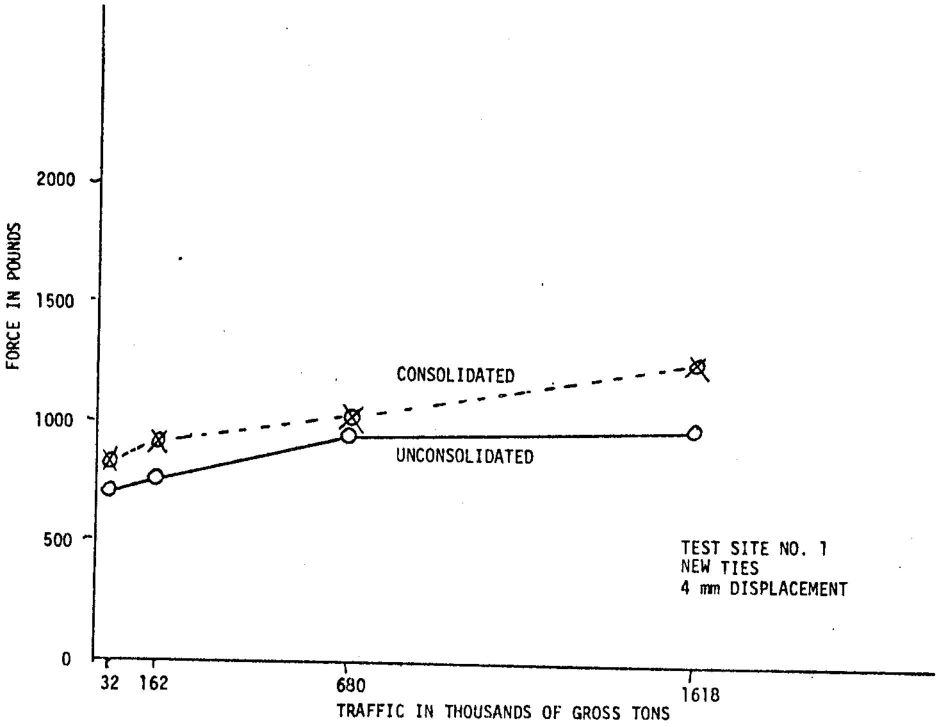
Graph C-3. Average Resistance of Old Ties Versus Traffic at Test Site No. 2



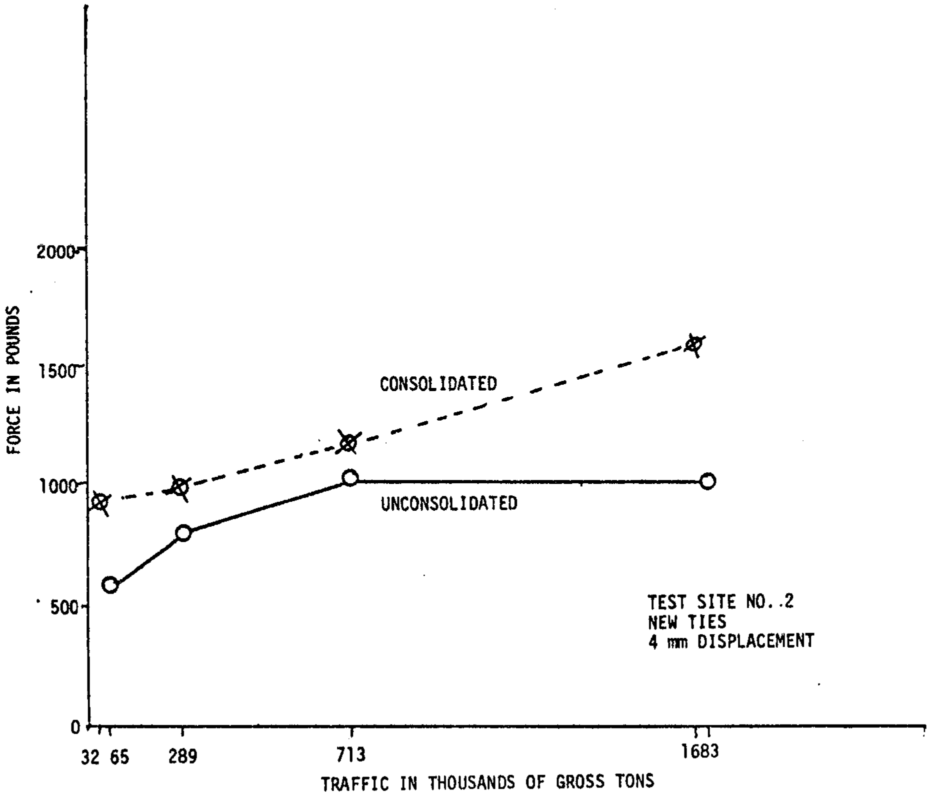
Graph C-4. Average Resistance of New Ties Versus Traffic at Test Site No. 2



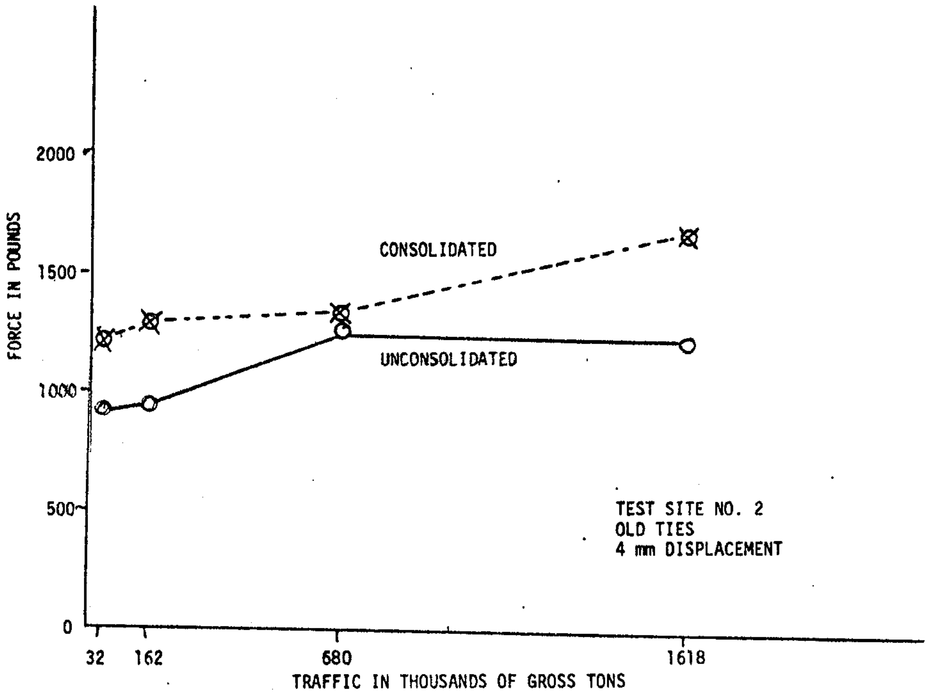
Graph C-5. Average Resistance of Old Ties Versus Traffic at Test Site No. 1



Graph C-6. Average Resistance of New Ties Versus Traffic at Test Site No. 1



Graph C-7. Average Resistance of New Ties Versus Traffic at Test Site No. 2

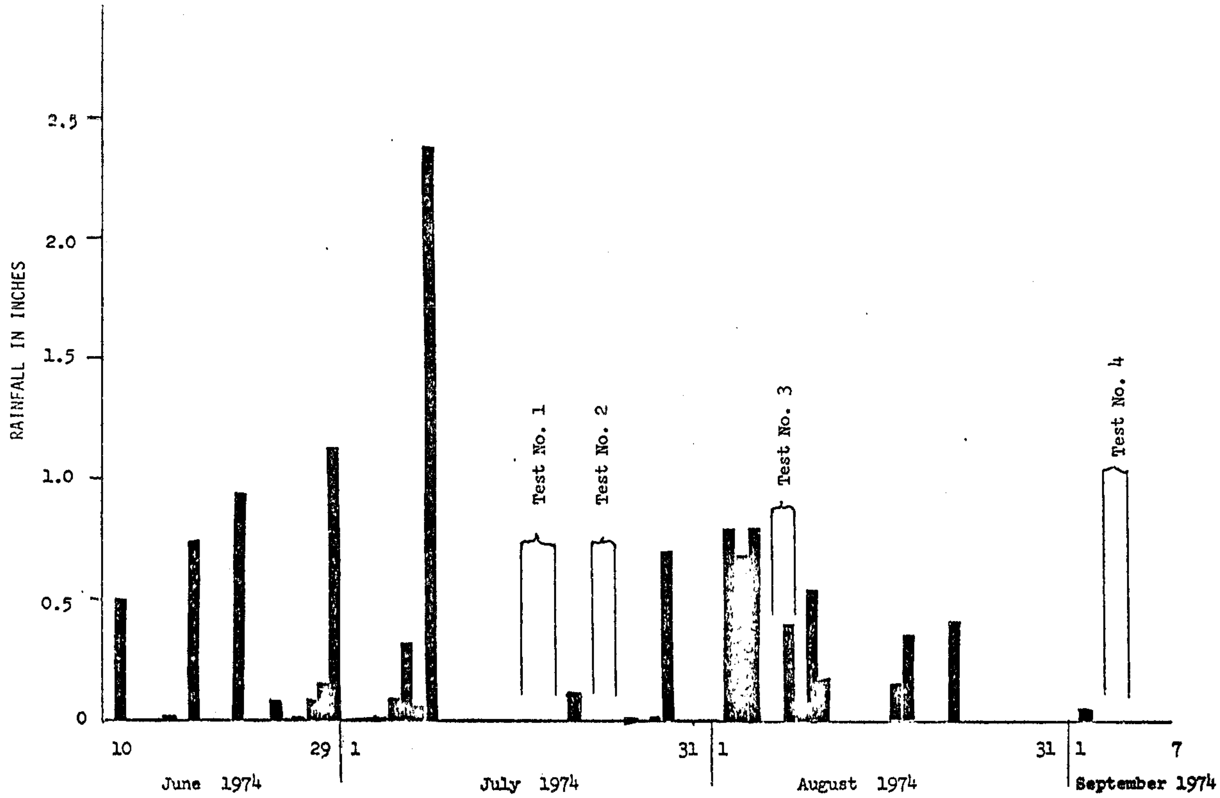


Graph C-8. Average Resistance of Old Ties Versus Traffic at Test Site No. 2

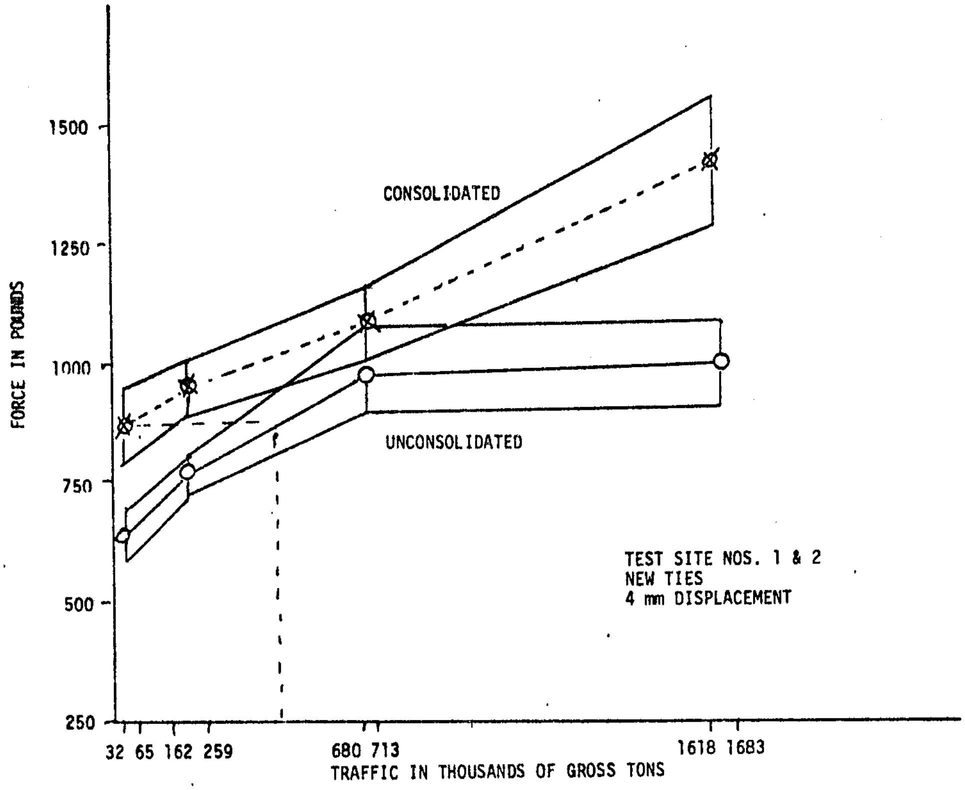
level of traffic as indicated on the graphs. Unfortunately, sufficient time was not available to test the ties before the first trains crossed the test zones. The initial tests were made at the lowest level of traffic feasible.

As indicated by Graphs C-1 through C-8, the relationship between the lateral resistances of ties and tonnage is not a simple one. Part of the problem is that the data has substantial scatter in it. This is not an instrumentation artifact, but is the nature of the phenomena. No two ties are alike, and picking consistent samples on the basis of visual appearance is difficult. However, in spite of the scatter, some clear trends are apparent in Graphs C-1 through C-8. The data at the first three tonnage levels reflect expected trends; that is, a monotonic increase of lateral resistance of consolidated and unconsolidated ties. The data at the fourth tonnage level upset this trend. A possible reason for this can be seen from a plot of the daily rainfall shown in Graph C-9. Clearly, ballast moisture between the second and fourth tests could have had a large effect, when the results of the third test are considered. However, other factors related to stress redistribution within the ballast mass may also have affected the rate of ballast consolidation. This indicates a serious problem since there is no control on effects that are on the order of magnitude of consolidation itself. The fourth test, at 1.7 million gross tons of traffic, showed that the effects of consolidation persist for long periods.

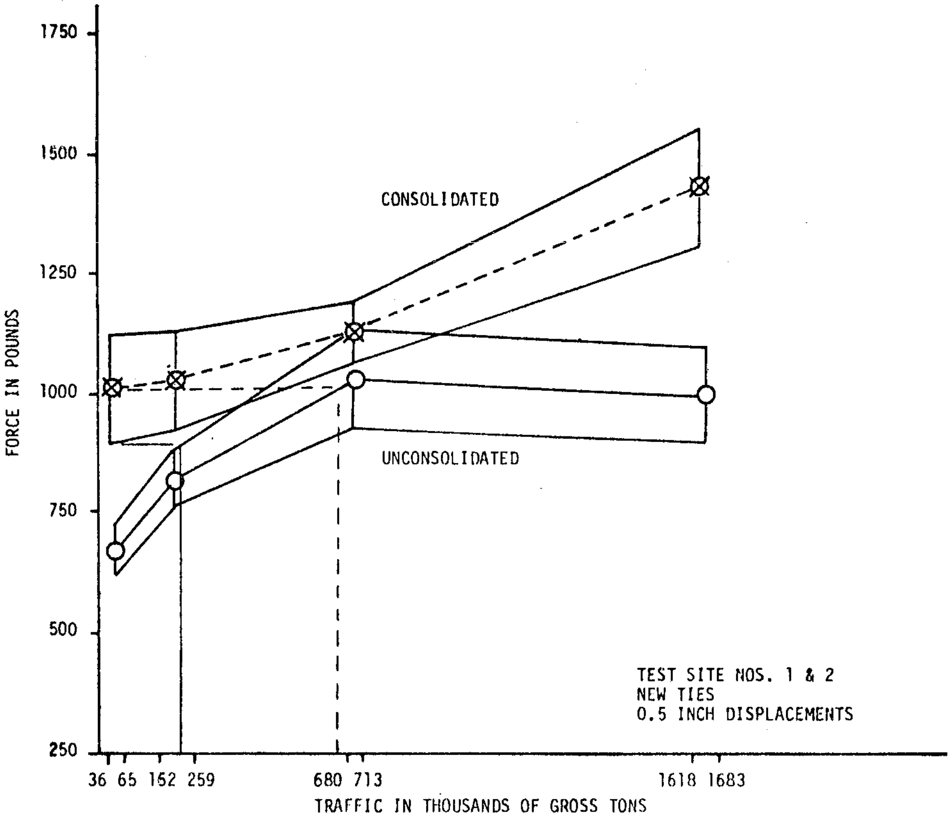
To answer the primary question regarding the advantages of the consolidator in terms of equivalent tons of traffic, the results from test sites 1 and 2 were pooled, and data summary Graphs C-10 and C-11 were prepared. This involved averaging the tonnages and lateral resistances shown in Graphs C-1 through C-8. From the pooled data, 95% confidence intervals



Graph C-9. Daily Rainfall at the Time of the Tests



Graph C-10. Overall Average Resistance of New Ties



Graph C-11. Overall Average Resistance of New Ties

were calculated using the T-Test and plotted on Graphs C-10 and C-11. On these two graphs, the 95% confidence intervals are joined by lines, giving a scatter band.

An estimate of the minimum advantage of consolidation is established where a line on Graph C-10 or C-11 through the lower limit of the 95% confidence interval for the first test of consolidated ties crosses the upper limit of the scatter band of the unconsolidated ties. An estimate of the average advantage is established where the horizontal line drawn from the sample mean of the first test crosses the average line of the unconsolidated ties. When the force required for a displacement of 4 mm is considered, a minimum advantage of 162,000 gross tons is seen. At the force necessary for a displacement of 1/2 inch (12.7 mm), a 227,000 gross ton minimum advantage is seen. Since the displacement at which forces are measured is arbitrary, the tonnage advantage is also to an extent arbitrary. The force at the larger 1/2-inch (12.7-mm) displacement is considered more representative of a track buckling situation than the force at the small 4-mm displacement. Also, larger differences are seen in the forces at the 12.7-mm displacement between old and new ties, and between ties in consolidated and unconsolidated ballast. Therefore, the 227,000 gross tons are taken as a minimum advantage.

DYNAMIC VERTICAL SETTLEMENT UNDER TRAFFIC

In order to conduct a valid test, the instrumentation had to be set up after all work was finished on the track, but before the passage of the first train over the track. The test required one instrument and 1 day of preparation for each data point. Accordingly, each site was prepared for test separately, and the four sets of instruments were installed at each of the four sites in turn before the first train passed over it. The instrumentation operated properly in 14 of the tests which were valid in all other respects. The residual vertical settlement in the track produced by the passage of the first train was recorded at 14 separate points. Seven of the test points were in consolidated ballast and seven were in unconsolidated ballast. Table C-2 shows the individual and average settlements. The individual settlements are paired for adjacent points at the same test sites.

TABLE C-2

Dynamic Settlement After Passage of
First Trains Over the Test Sites (in Inches)

Unconsolidated	Consolidated
0.31	0.15
0.24	0.24
0.104	0.08
0.156	0.125
0.13	0.137
0.153	0.140
0.125	0.173
$\bar{x}$ = 0.174	$\bar{x}$ = 0.149

The statistical assumption that each of the numbers in Table C-2 represents the effects of trains of equal tonnage is reasonably well met, even though four different trains were involved. While a simple comparison of the sample averages indicates consolidated track will settle $\frac{0.174 - 0.149}{0.174} = 14\%$ less than unconsolidated track, this difference is not statistically significant at the 95% confidence level for a paired T-Test. The manufacturer of the consolidator reported that tests on European track had shown a 50% reduction in settlement, and the test methods were designed to detect large and significant effects, not small and subtle effects the evaluation of which would require large quantities of test data.

CUMULATIVE SETTLEMENT

Surveying techniques were used to record the settlement of track over periods of 3 weeks. The accumulated settlement (over the 3-week test periods) showed no significant difference in the total settlement of consolidated and unconsolidated track, as shown in Table C-3 and Attachment CIII. What it did show was that after T&S work, the track structure will settle about 1/2 inch under 1 million gross tons of traffic. Data from the dynamic settlement tests indicate the track will settle about 1/4 inch under the first four or five trains. In other words, the first four or five trains, of about 90 cars each, will settle the track 50% of the cumulative settlement that will be reached after 100 trains, and 90% of that cumulative settlement will occur by the time approximately 40 trains have passed over the test track. Comparisons of standard deviations of the settlement data, as shown in Table C-4, indicate the track on consolidated ballast settled more uniformly than track on unconsolidated ballast. The lateral movement of the track under traffic was evaluated by a sum of squares method, and it was also found to be less in consolidated ballast than unconsolidated ballast, as shown in Table C-5.

TABLE C-3

Data for Pooled Averages of Cumulative Settlement at Reference Points on Track

Settlement in Feet

Traffic Period	Unconsolidated Ballast One Week	 Two Weeks	 Three Weeks	Consolidated Ballast One Week	 Two Weeks	 Three Weeks
Site #1	.023	.031	.023	.036	.047	.046
	.017	.017	.020	.033	.042	.042
	.032	.039	.042	.042	.053	.052
Site #2	.012	.002	.002	.028	.036	.041
	.048	.058	.066	.029	.038	.045
	.110	.126	.136	.035	.044	.053
Site #3	.028	.034	.038	.020	.015	.026
	.028	.031	.037	.032	.032	.041
	.028	.037	.039	.030	.030	.041
	.031	.037	.042	.028	.025	.040
	.029	.035	.037	.029	.028	.041
	.025	.033	.035			
Site #4	.028	.033	.035	.040	.049	.049
	.037	.041	.044	.033	.041	.042
	.038	.036	.037	.040	.046	.051
	.022	.030	.031	.032	.040	.043
	.035	.040	.040	.029	.036	.041
	.046	.055	.058	.032	.036	.039

n = 18 n = 17

$\bar{x}$ = .0343 $\bar{x}$ = .0397 $\bar{x}$ = .0423 $\bar{x}$ = .0323 $\bar{x}$ = .0375 $\bar{x}$ = .0431

s = .0209 x = .0247 x = .0270 s = .0054 s = .0096 s = .0063

$\bar{\bar{x}} \geqq .41''$ $\bar{\bar{x}} \geqq .48''$ $\bar{\bar{x}} \geqq .51''$ $\bar{\bar{x}} \geqq .39''$ $\bar{\bar{x}} \geqq .45''$ $\bar{\bar{x}} \geqq .52''$

n = number of ties
x = standard deviation

TABLE C-4

Standard Deviation Comparison of Settlement Data in Feet

SITE #1	Unconsolidated (accumulated settlement)	$s = .0119$
	Consolidated	$s = .00503$
SITE #2	Unconsolidated	$s = .670$
	Consolidated	$s = .00611$
SITE #3	Unconsolidated	$s = .0378$
	Consolidated	$s = .00237$
SITE #4	Unconsolidated	$s = .00475$
	Consolidated	$s = .00950$

TABLE C-5

Data for Sum of Squares Evaluation of Cumulative Lateral Movement After Three Weeks of Traffic

Lateral Movement in Feet

	Unconsolidated Ballast	Consolidated Ballast
SITE #1	.009 E	.018 E
	.011 E	.011 E
	.012 E	.010 E
	$\frac{\sum x_1^2}{n} = .115 \times 10^{-3}$	$\frac{\sum x_1^2}{n} = .182 \times 10^{-3}$
SITE #2	.035 E	.002 W
	.011 W	.001 W
	.009 W	.000 W
	$\frac{\sum x_1^2}{n} = .476 \times 10^{-3}$	$\frac{\sum x_1^2}{n} = .167 \times 10^{-5}$
SITE #3	.004 E	.008 E
	.007 E	.005 E
	.002 E	.000 E
	.002 E	.003 E
	.008 W	.002 E
	.009 W	
	$\frac{\sum x_1^2}{n} = .363 \times 10^{-4}$	$\frac{\sum x_1^2}{n} = .204 \times 10^{-4}$
SITE #4	.016 W	.002 W
	.012 W	.007 W
	.011 W	.005 W
	.006 W	.000 W
	.004 W	.008 W
		.002 W
	$\frac{\sum x_1^2}{n} = .115 \times 10^{-3}$	$\frac{\sum x_1^2}{n} = .243 \times 10^{-4}$
	$\frac{\sum x^2}{n_T} = .151 \times 10^{-3}$	$\frac{\sum x^2}{n_T} = .469 \times 10^{-4}$

ATTACHMENT CIII

LONG-TERM TRACK STABILITY SURVEYS IN CONNECTION WITH T.O. MM-77.3
SOUTHERN RAILWAY CONSOLIDATOR TESTS
LIBERTY, SOUTH CAROLINA MP 505
LOWELL, NORTH CAROLINA MP 394

RALPH WHITEHEAD & ASSOCIATES
CONSULTING ENGINEERS
CHARLOTTE, NORTH CAROLINA

Stability surveys began on June 10, 1974 near MP 505 near Liberty, SC where Test Sites 1 and 2 were set up. Surveys were continued at these sites through July 1, 1974. Test Sites 3 and 4 were set up in Lowell, NC near MP 394 on July 2, 1974 and weekly surveys were made through July 23, 1974. Field data including sketches, stability measurements, and survey conditions are included in this report.

General survey procedures were as follows: test zones were established and marked, and designated portions of these zones were consolidated while other portions were not consolidated.

Vertical stability measurements were made using a Zeiss Ni-2 self-leveling level and a Frisco leveling rod equipped with a vernier. Temporary benchmarks were established away from the track and "P-K" nails were driven into the ties to serve as points for leveling. Care was taken to protect the benchmarks and points. Careful procedures were followed to insure accuracy of the readings themselves which were made to the nearest thousandth of a foot (0.001').

Lateral stability measurements were made using a Zeiss Optical Scale Repeating Theodolite (TH43) equipped with an optical plummet, an engineer's scale divided into hundredths of a foot (0.01') and a plumb bob where required. Tacks were set in hubs to establish an optical baseline from which movement could be measured. "P-K" nails were set on this baseline after consolidation had taken place. On the tangent test sites and where possible on the curved test sites, lateral movement was measured directly through the instrument by reestablishing the baseline and reading the scale which was placed on the "P-K". Where required, a plumb bob was used. Scale readings were made to the hundredth of a foot (0.01') with estimates to the nearest thousandth of a foot (0.001'). The hubs themselves were 2" x 2" wood stakes. Locations of these hubs and tacks are shown in the sketches. Movement of those hubs driven deep into ballast between ties was a concern; however, through referencing and checks, no movement occurred.

Generally, initial test layouts and measurements were made directly after surfacing and consolidation and before any train traffic occurred over the track. The date and time of completion of each survey were recorded.

Any variations and peculiarities in the tests are noted in the tables or in the figures that show the layouts of the test sites. The field data are tabulated along with summarizations of weekly and accumulated settlements.

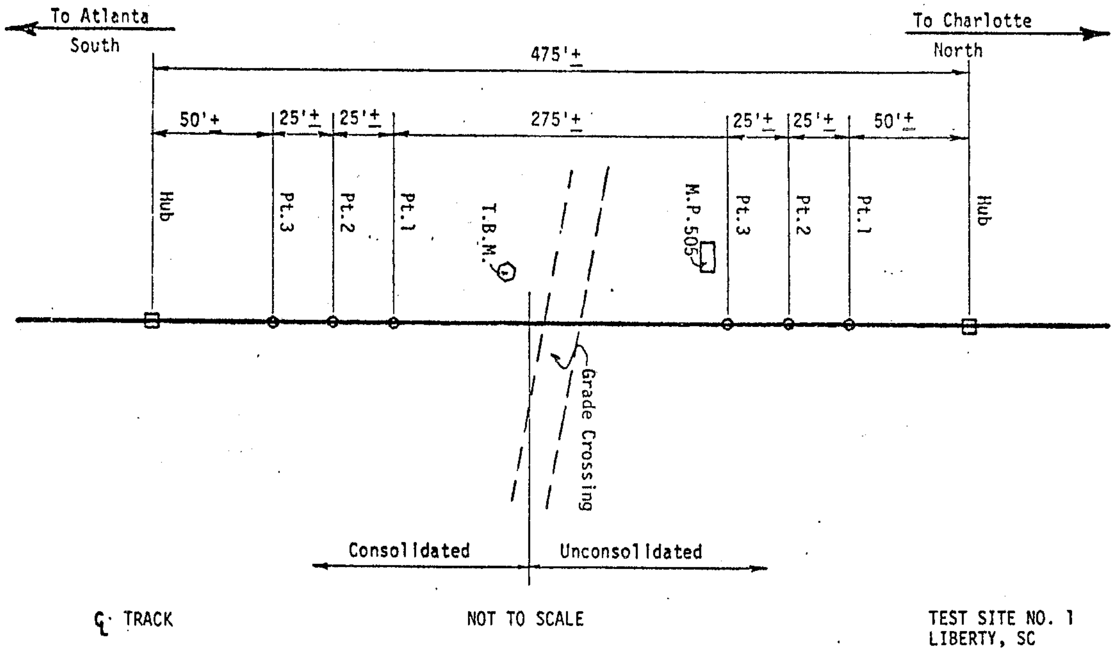


Figure C-15

TABLE C-6

TEST SITE #1

Test Site #1 was located at M.P. 505 near Liberty, S. C. on a tangent of track. All initial elevations were taken, as well as initial horizontal locations on the unconsolidated section, before any train traffic occurred. Horizontal locations on the consolidated section were made the following morning, after traffic had occurred. Two hubs were set in ballast to establish a base line.

	Elevation				Weekly Settlement			Accumulated Settlement		
Point	June 10	June 17	June 24	July 1	June 10-June 17	June 17-June 24	June 24-July 1	June 10-June 17	June 10-June 24	June 10-July 1
Time of Completion	3:00 PM	11:30 AM	11:30 AM	12:10 PM						
Unconsolidated Section:										
1	100.627	100.604	100.596	100.604	0.023	0.008	+0.008	0.023	0.031	0.023
2	100.417	100.400	100.400	100.397	0.017	0.000	0.003	0.017	0.017	0.020
3	100.241	100.209	100.202	100.199	0.032	0.007	0.003	0.032	0.039	0.042
Consolidated Section:										
1	98.120	98.084	98.073	98.074	0.036	0.011	+0.001	0.036	0.047	0.046
2	97.907	97.874	97.865	97.865	0.033	0.009	0.000	0.033	0.042	0.042
3	97.694	97.652	97.641	97.642	0.042	0.011	+0.001	0.042	0.053	0.052

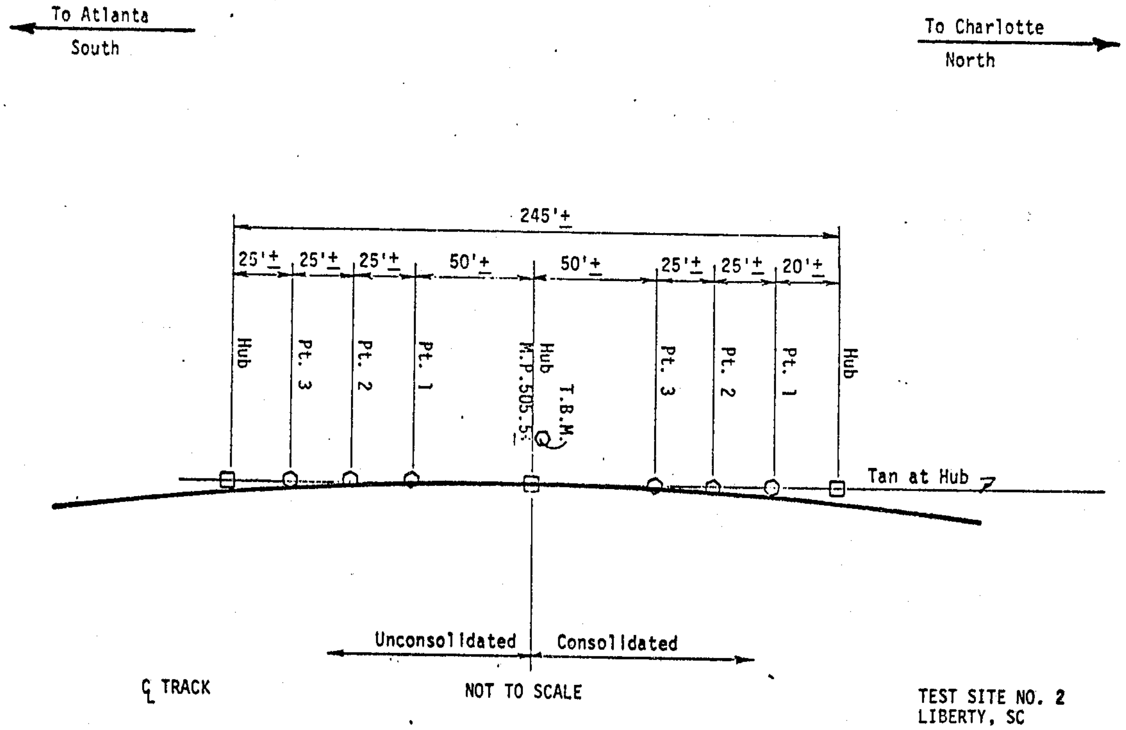


Figure C-16

TABLE C-7

TEST SITE #2

Test Site #2 was located at M.P. 505.5 near Liberty, S. C. in a 4.0 degree curve. One hub was set in ballast and two hubs were set away from the track on tangent. During the first week one of the hubs was disturbed by work crews, however it was reset on the following Monday and no problems were incurred.

	Elevation				Weekly Settlement			Accumulated Settlement		
Point	June 10	June 17	June 24	July 1	June 10-June 17	June 17-June 24	June 24-July 1	June 10-June 17	June 10-June 24	June 10-July 1
Time of Completion	4:30 PM	11:50 AM	12:30 PM	11:20 AM						
Unconsolidated Section:										
1	100.010	100.022	100.012	100.008	+0.012	0.010	0.004	+0.012	+0.002	0.002
2	100.061	100.013	100.003	99.995	0.048	0.010	0.008	0.048	0.058	0.066
3	100.069	99.959	99.943	99.933	0.110	0.016	0.010	0.110	0.126	0.136
Consolidated Section:										
1	100.149	100.121	100.113	100.108	0.028	0.008	0.005	0.028	0.036	0.041
2	100.134	100.105	100.096	100.089	0.029	0.009	0.007	0.029	0.038	0.045
3	100.136	100.100	100.092	100.083	0.036	0.008	0.009	0.036	0.044	0.053

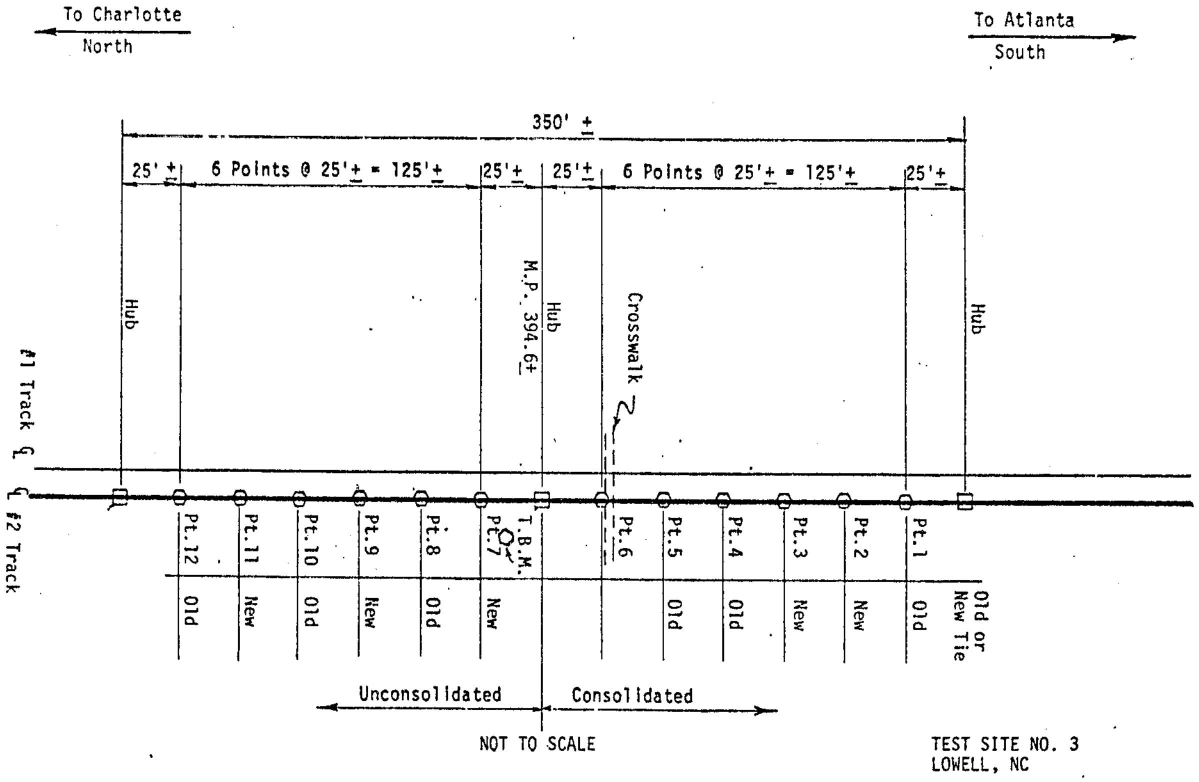


Figure C-17

TABLE C-8

TEST SITE #3

Test Site #3 was located in Lowell, N. C. near M.P. 394.3 on a tangent of track. Three hubs were set in ballast and twelve (12) points were set in ties. Point No. Six (6) was covered by an asphalt crosswalk during the first week and no further measurements were made on this point. Neither consolidation or surveying occurred over the zone until one locomotive and one car had passed over the newly surfaced track.

	Elevation				Weekly Settlement			Accumulated Settlement		
Point	July 2	July 9	July 16	July 23	July 2- July 9	July 9- July 16	July 16- July 23	July 2- July 9	July 2- July 16	July 2 July 23
Consolidated Section:										
1	102.163	102.143	102.148	102.137	0.020	+0.005	0.011	0.020	0.015	0.026
2	102.078	102.046	102.046	102.037	0.032	0.000	0.009	0.032	0.032	0.041
3	101.959	101.929	101.929	101.918	0.030	0.000	0.011	0.030	0.030	0.041
4	101.868	101.840	101.843	101.828	0.038	+0.003	0.015	0.028	0.025	0.040
5	101.761	101.732	101.733	101.720	0.029	+0.001	0.013	0.029	0.028	0.041
6	101.593	(Covered during first week)								
Unconsolidated Section:										
7	101.098	101.070	101.064	101.060	0.028	0.006	0.004	0.028	0.034	0.038
8	101.032	101.004	100.001	100.995	0.028	0.003	0.006	0.028	0.031	0.037
9	100.938	100.910	100.901	100.899	0.028	0.009	0.002	0.028	0.037	0.039
10	100.851	100.820	100.814	100.809	0.031	0.006	0.005	0.031	0.037	0.042
11	100.788	100.759	100.753	100.751	0.029	0.006	0.002	0.029	0.035	0.037
12	100.699	100.674	100.666	100.664	0.025	0.008	0.002	0.025	0.033	0.035

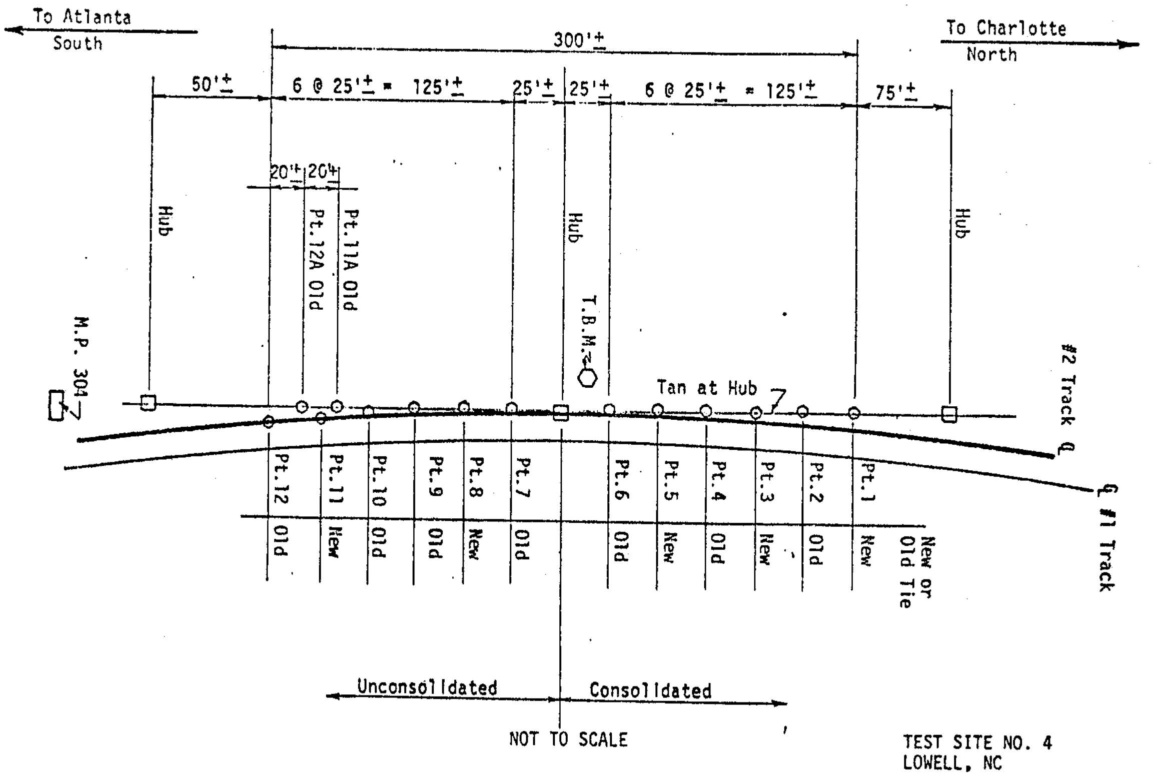


Figure C-18

TABLE C-9

TEST SITE #4

Test Site #4 was located in Lowell, N. C. near M.P. 393.9 on a curve. One hub was set in ballast while two (2) more hubs were set outside the track on a tangent. Because of scheduling problems with the T&S Crew, all intermediate points on tangent were not put in at the same time and adjustments in procedure were made, however, there should be no effects. On this site as on Test Site #3, no consolidation or surveying occurred until one locomotive and one car had passed over the newly surfaced track.

Some of the markings and hubs at Test Site #4 were tampered with during the first week of testing. These points were reset and referenced and were undisturbed for the rest of the test period.

	Elevation				Weekly Settlement			Accumulated Settlement		
Point	July 2	July 9	July 16	July 23	July 2- July 9	July 9- July 16	July 12- July 23	July 2- July 9	July 2- July 16	July 2- July 23
Consolidated Section:										
1	100.999	100.959	100.950	100.950	0.040	0.009	0.000	0.040	0.049	0.049
2	101.051	101.018	101.010	101.008	0.033	0.008	0.002	0.033	0.041	0.042
3	101.160	101.120	101.114	101.109	0.040	0.006	0.005	0.040	0.046	0.051
4	101.281	101.249	101.241	101.238	0.032	0.008	0.003	0.032	0.040	0.043
5	101.396	101.367	101.360	101.355	0.029	0.007	0.005	0.029	0.036	0.041
6	101.549	101.517	101.513	101.510	0.032	0.004	0.003	0.032	0.036	0.039
Unconsolidated Section:										
7	101.916	101.888	101.883	101.881	0.028	0.005	0.002	0.028	0.033	0.035
8	101.982	101.945	101.941	101.938	0.037	0.004	0.003	0.037	0.041	0.044
9	102.107	102.079	102.071	102.070	0.028	0.008	0.001	0.038	0.036	0.037
10	102.060	102.028	102.020	102.019	0.022	0.008	0.001	0.022	0.030	0.031
11	102.163	102.128	102.123	102.123	0.035	0.005	0.000	0.035	0.040	0.040
12	102.242	102.196	102.187	102.184	0.046	0.009	0.003	0.046	0.055	0.058

TABLE C-9

Lateral Displacements in Feet

All Displacements are Measured From the Baseline and are not Cumulative

TEST SITE #1

South (Consolidated)					
		Date			
		6-17	6-24	7-1	
	New or Old Tie	Time			Direction of Movement
		11:00 a.m.	11:00 a.m.	11:50 a.m.	
PT-1	--	0.015	0.021	0.018	East
PT-2	--	0.005	0.017	0.011	East
PT-3	--	0.003	0.017	0.010	East
North (Unconsolidated)					
PT-1	--	0.008	0.011	0.009	East
PT-2	--	0.010	0.016	0.011	East
PT-3	--	0.007	0.015	0.012	East

TEST SITE #2

South (Unconsolidated)					
		Date			
		6-17	6-24	7-1	
	New or Old Tie	Time			Direction of Movement
		1:50 p.m.	12:30 p.m.	11:30 a.m.	
PT-3	--	0.041	0.030	0.035	East
PT-2	--	0.012	0.008	0.011	West
PT-1	--	0.015	0.008	0.009	West
North (Consolidated)					
PT-1	--	0.003	0.001	0.002	West
PT-2	--	0.003	0.002	0.001	West
PT-3	--	0.000	0.000	0.000	West

TEST SITE #3

Consolidated					
		Date			
		7-9	7-16	7-23	
	New or Old Tie	Time			Direction of Movement
		9:30 a.m.	11:30 a.m.	1:30 a.m.	
PT-1	Old	0.009	0.006	0.008	East
PT-2	New	0.008	0.003	0.005	East
PT-3	New	0.007	0.002	0.000	East
PT-4	Old	0.010	0.008	0.003	East
PT-5	Old	0.012	0.008	0.002	East
Unconsolidated					
PT-7	New	0.011	0.012	0.004	East
PT-8	Old	0.002	0.008	0.007	East
PT-9	New	0.011	0.011	0.002	East
PT-10	Old	0.009	0.014	0.002	East
PT-11	New	0.002	0.008	0.008	West
PT-12	Old	0.009	0.004	0.009	West

TEST SITE #4

Consolidated					
		Date			
		7-9	7-16	7-23	
	New or Old Tie	Time			Direction of Movement
		11:30 a.m.	1:30 p.m.	2:00 p.m.	
PT-1	New	0.012	0.003	0.002	West
PT-2	Old	0.018	0.007	0.007	West
PT-3	New	0.007	0.010	0.005	West
PT-4	Old	0.006	0.002	0.000	West
PT-5	New	0.005	0.008	0.008	West
PT-6	Old	0.007	0.006	0.002	West
Unconsolidated					
PT-7	Old	0.009	0.015	0.016	West
PT-8	New	0.002	0.013	0.012	West
PT-9	Old	0.007	0.005	0.011	West
PT-11A	Old	0.007	0.010	0.006	West
PT-13A	Old	0.000	0.002	0.004	West

APPENDIX D

Data From Test MM-151
Settlement at Bolted Joints in Rail on Consolidated and Unconsolidated Ballast

TEST MM-151

Cumulative Settlement in Inches at Bolted Joints

Date	Time	Tonnage	Test Joints on Tangent Track, Unconsolidated							
			1	2	3	4	5	6	7	8
7/17	1834	2333	0.134	0.087	0.118	0.084	0.152	0.184	0.082	0.161
7/17	2104	4717	0.161	0.139	0.148	0.126	0.213	0.245	0.102	0.181
7/18	0515	7297	0.170	0.157	0.167	0.157	0.233	0.286	0.122	0.181
7/18	0943	10197	0.196	0.174	0.177	0.179	0.273	0.327	0.122	0.241
7/18	2026	12763	0.214	0.192	0.197	0.179	0.283	0.327	0.153	0.261
7/18	2200	15034	0.214	0.200	0.217	0.189	0.294	0.337	0.163	0.301
7/19	0505	15944	0.232	0.209	0.217	0.189	0.283	0.347	0.174	0.320
7/19	1006	19062	0.214	0.209	0.197	0.200	0.304	0.347	0.143	0.323
7/20	0945	33617	0.268	0.270	0.187	0.263	0.364	0.418	0.184	0.376
7/21	0840	42625	0.277	0.279	0.315	0.273	0.385	0.439	0.184	--
7/22	0806	51502	0.268	0.296	0.315	0.284	0.385	0.449	0.184	0.407
7/23	0830	66019	0.304	0.314	0.315	0.294	0.405	0.480	0.184	0.413
7/24	0755	75772	0.304	0.314	0.315	0.315	0.405	0.480	0.204	0.409
7/25	0805	88201	0.304	0.322	0.325	0.315	0.425	0.490	0.204	0.426
7/26	0759	100244	0.313	0.331	0.335	0.326	0.425	0.501	0.214	0.437
7/27	0836	117451	0.357	0.383	0.364	0.357	0.466	0.536	0.225	0.488
7/28	0757	125750	0.375	0.383	0.394	0.368	0.496	0.572	0.245	0.498
7/29	0759	139311	0.393	0.418	0.453	0.399	0.526	0.594	0.245	0.549
7/30	0725	145529	0.411	0.436	0.453	0.399	0.526	0.615	0.255	0.560
7/31	0725	155568	0.438	0.444	0.453	0.420	0.557	0.628	0.265	0.590

One measurement was missed at Test Joint No. 8 because of malfunction of recorder.

TEST MM-151

Cumulative Settlement in Inches at Bolted Joints

Date	Time	Tonnage	Test Joints on Tangent Track, Consolidated							
			9	10	11	12	13	14	15	16
7/17	1834	2,333	0.104	0.098	0.145	--	0.144	0.140	0.124	0.082
7/17	2104	4,717	0.157	0.137	0.181	0.050	0.172	0.180	0.166	0.122
7/18	0515	7,297	0.188	0.157	0.236	0.114	0.208	0.200	0.197	0.143
7/18	0943	10,197	0.188	0.098	0.245	0.100	0.216	0.220	0.207	0.092
7/18	2026	12,763	0.209	0.118	0.272	0.124	0.234	0.230	0.249	--
7/18	2200	15,034	0.220	0.118	0.272	0.138	0.234	0.230	0.259	0.099
7/19	0505	15,944	0.228	0.137	0.290	0.150	0.238	0.240	0.270	0.103
7/19	1006	19,062	0.264	0.118	0.281	0.150	0.226	0.240	0.259	0.096
7/20	0945	33,617	--	0.167	0.326	0.150	0.274	0.279	0.311	0.144
7/21	0840	42,625	--	0.176	0.362	0.188	0.282	0.299	0.332	0.153
7/22	0806	51,502	--	0.186	0.399	0.202	0.256	0.299	0.332	0.156
7/23	0830	66,019	--	0.196	0.417	0.202	0.290	0.319	0.353	0.171
7/24	0755	75,772	0.300	0.196	0.362	0.214	0.298	0.319	0.373	0.174
7/25	0805	88,201	0.303	0.196	0.362	0.226	0.398	0.329	0.373	0.184
7/26	0759	100,244	0.308	0.216	0.380	0.226	0.428	0.339	0.384	0.187
7/27	0836	117,451	0.327	0.215	0.408	0.252	0.400	0.359	0.394	0.195
7/28	0757	125,750	0.345	0.235	0.447	0.264	0.414	0.379	0.456	0.215
7/29	0759	139,311	0.357	0.255	0.485	0.276	0.440	0.399	0.477	0.235
7/30	0725	145,529	0.365	0.255	0.505	0.326	0.484	0.419	0.498	0.243
7/31	0725	155,568	0.373	0.265	0.524	0.340	0.504	0.429	0.519	0.259

Four measurements were missed at Test Joint No. 9,
one at Joint No. 12 and one at Joint No. 16,
because of malfunction of recorder.

TEST MM-151

Cumulative Settlement in Inches at Bolted Joints

			Test Joints on Curved Track							
			Unconsolidated				Consolidated			
Date	Time	Tonnage	17	18	19	20	21	22	23	24
7/17	1834	2,333	0.191	0.203	0.132	0.137	0.101	0.104	0.102	0.179
7/17	2104	4,717	0.254	0.224	0.182	0.176	0.141	0.145	0.133	0.242
7/18	0515	7,297	0.297	0.264	0.202	0.195	0.151	0.186	0.173	0.294
7/18	0943	10,197	0.297	0.285	0.243	0.234	0.191	0.197	0.184	0.315
7/18	2026	12,763	0.318	0.274	0.253	0.225	0.181	0.207	0.184	0.326
7/18	2200	15,034	0.350	0.285	0.253	0.225	0.201	0.307	0.194	0.336
7/19	0505	15,944	0.350	0.285	0.253	0.244	0.201	0.207	0.204	0.336
7/19	1006	19,062	0.350	0.285	0.283	0.254	0.221	0.207	0.184	0.347
7/20	0945	33,617	0.424	0.346	0.344	0.293	0.272	0.248	0.235	0.399
7/21	0840	42,625	0.424	0.356	0.364	0.215	0.302	0.298	0.245	0.420
7/22	0806	51,502	0.445	0.386	0.364	0.313	0.302	0.269	0.255	0.420
7/23	0830	66,019	0.445	0.407	0.395	0.332	0.322	0.269	0.255	0.441
7/24	0755	75,772	0.466	0.407	0.384	0.332	0.332	0.280	0.265	0.452
7/25	0805	88,201	0.466	0.427	0.405	0.352	0.342	0.311	0.306	0.462
7/26	0759	100,244	0.487	0.427	0.425	0.371	0.362	0.311	0.306	0.473
7/27	0836	117,451	0.508	0.457	0.435	0.381	0.372	0.311	0.306	0.494
7/28	0757	125,750	0.530	0.488	0.445	0.400	0.382	0.311	0.306	0.504
7/29	0749	139,311	0.540	0.508	0.486	0.420	0.402	0.331	0.316	0.504
7/30	0725	145,529	0.551	0.528	0.486	0.430	0.402	0.321	0.327	0.525
7/31	0725	155,568	0.551	0.528	0.516	0.449	0.433	0.342	0.347	0.536

TEST MM-151

Arithmetic Mean Settlement at Bolted Joints in Inches

Date	Thousand Gross Tons	Tangent		Curve	
		Unconsolidated	Consolidated	Unconsolidated	Consolidated
7/17 - 1834	2.3	0.125 in.	0.120 in.	0.166 in.	0.122 in.
7/17 - 2104	4.7	0.164 in.	0.146 in.	0.209 in.	0.165 in.
7/18 - 0515	7.3	0.184 in.	0.180 in.	0.240 in.	0.201 in.
7/18 - 0943	10.2	0.211 in.	0.171 in.	0.267 in.	0.222 in.
7/18 - 2026	12.8	0.219 in.	0.205 in.	0.268 in.	0.225 in.
7/18 - 2200	15.0	0.239 in.	0.196 in.	0.278 in.	0.235 in.
7/19 - 0505	15.9	0.246 in.	0.207 in.	0.283 in.	0.237 in.
7/19 - 1006	19.1	0.242 in.	0.204 in.	0.293 in.	0.240 in.
7/20 - 0945	33.6	0.290 in.	0.236 in.	0.352 in.	0.289 in.
7/21 - 0840	42.6	0.307 in.	0.256 in.	0.340 in.	0.316 in.
7/22 - 0806	51.5	0.324 in.	0.261 in.	0.377 in.	0.312 in.
7/23 - 0830	66.0	0.339 in.	0.278 in.	0.395 in.	0.322 in.
7/24 - 0735	75.8	0.343 in.	0.280 in.	0.397 in.	0.332 in.
7/25 - 0805	88.2	0.351 in.	0.296 in.	0.413 in.	0.355 in.
7/26 - 0759	100.2	0.360 in.	0.309 in.	0.428 in.	0.363 in.
7/27 - 0836	117.5	0.397 in.	0.319 in.	0.445 in.	0.371 in.
7/28 - 0757	125.8	0.416 in.	0.344 in.	0.466 in.	0.376 in.
7/29 - 0759	139.3	0.447 in.	0.366 in.	0.489 in.	0.388 in.
7/30 - 0725	145.5	0.457 in.	0.387 in.	0.499 in.	0.394 in.
7/31 - 0725	155.6	0.474 in.	0.402 in.	0.511 in.	0.415 in.

TEST MM-151

Crosslevel Measurements at Bolted Joints, in Inches

Test Joint Nos.	Date Day in July 1975													Change
	17	20	21	22	23	24	25	26	27	28	29	30	31	
1	-3/8	-15/32	-7/16	-7/16	-7/16	-13/32	-13/32	-13/32	-7/16	-7/16	-15/32	-7/16	-13/32	-1/32
2	-9/32	-11/32	-1/4	-9/32	-5/16	-1/4	-1/4	-1/4	-1/4	-1/4	-1/4	-1/4	-3/16	+3/32
3	-5/16	-13/32	-3/32	-11/32	-3/8	-5/16	-11/32	-5/16	-11/32	-3/8	-3/8	-3/8	-5/16	0
4	-3/32	-1/8	-1/16	-1/32	-1/16	-1/32	-1/32	-1/32	-1/16	-1/32	-1/16	-1/32	-1/32	+1/16
5	-1/32	-3/32	-1/32	-1/16	-3/32	-1/32	-1/32	-1/32	-1/16	-1/16	-1/16	-1/32	-1/32	0
6	+1/4	+1/4	+11/32	+11/32	+5/16	+3/8	+3/8	+3/8	+13/32	+3/8	+11/32	+3/8	+3/8	+1/8
7	-5/32	-9/32	-7/32	-7/32	-1/4	-3/16	-7/32	-3/16	-7/32	-7/32	-1/4	-7/32	-7/32	-1/16
8	-3/8	-15/32	-7/16	-13/32	-15/32	-7/16	-7/16	-13/32	-7/16	-15/32	-15/32	-15/32	-7/16	-1/16
9	-1/32	-1/8	-1/32	-1/32	-1/16	0	0	0	0	-1/32	-1/32	-1/32	0	+1/32
10	+3/32	+1/16	+1/8	+1/8	+3/32	+1/8	+1/8	+5/32	+1/8	+5/32	+1/8	+5/32	+5/32	+1/16
11	-5/32	-1/4	-7/32	-3/16	-1/4	-7/32	-3/16	-3/16	-1/4	-1/4	-1/4	-1/4	-1/4	-3/32
12	0	-1/16	+1/32	+1/32	0	+1/16	+1/32	+1/16	+1/16	+1/16	+1/32	+1/16	+3/32	+3/32
13	-1/4	-3/8	-9/32	-9/32	-11/32	-9/32	-5/16	-5/16	-5/16	-5/16	-5/16	-5/16	-5/16	-1/16
14	-3/16	-7/32	-3/16	-3/16	-7/32	-3/16	-5/32	-5/32	-5/32	-3/16	-3/16	-3/16	-3/16	0
15	+1/16	+1/16	+1/8	+1/8	+3/32	+1/8	+1/8	+5/32	+5/32	+5/32	+1/8	+5/32	+3/16	+1/8
16	+1/8	+1/16	+1/8	+1/8	+1/16	+1/8	+3/32	+1/8	+3/32	+3/32	+3/32	+1/8	+1/8	0
17	+3-1/4	+3-7/32	+3-5/16	+3-5/16	+3-5/16	+3-11/32	+3-5/16	+3-11/32	+3-5/16	+3-5/16	+3-5/16	+3-9/32	+3-5/16	+1/16
18	+3-3/8	+3-3/8	+3-13/32	+3-7/16	+3-13/32	+3-7/16	+3-7/16	+3-7/16	+3-13/32	+3-7/16	+3-7/16	+3-7/16	+3-7/16	+1/16
19	+3-7/16	+3-3/8	+3-7/16	+3-15/32	+3-7/16	+3-7/16	+3-15/32	+3-15/32	+3-15/32	+3-15/32	+3-15/32	+3-15/32	+3-1/2	+1/16
20	+3-5/8	+3-9/16	+3-21/32	+3-21/32	+3-5/8	+3/21-32	+3-21/32	+3-11/16	+3-21/32	+3-21/32	+3-21/32	+3-21/32	+3-21/32	+1/32
21	+3-3/8	+3-3/8	+3-7/16	+3-7/16	+3-7/16	+3-7/16	+3-15/32	+3-15/32	+3-7/16	+3-7/16	+3-7/16	+3-7/16	+3-15/32	+3/32
22	+3-7/16	+3-13/32	+3-15/32	+3-15/32	+3-7/16	+3-1/2	+3-15/32	+3-15/32	+3-15/32	+3-1/2	+3-15/32	+3-15/32	+3-15/32	+1/32
23	+3-21/32	+3-5/8	+3-11/16	+3-23/32	+3-11/16	+3-23/32	+3-23/32	+3-23/32	+3-23/32	+3-23/32	+3-23/32	+3-11/16	+3-29/32	+1/4
24	+3-1/2	+3-9/16	+3-9/16	+3-9/16	+3-19/32	+3-19/32	+3-19/32	+3-19/32	+3-19/32	+3-19/32	+3-19/32	+3/19/32	+3-19/32	+3/32

Crosslevel was measured to 1/32 inch and converted to decimals to the nearest 0.03 inch.

South rail is reference rail; + indicates north rail is higher, and - indicates south rail is higher.

TEST MM-151

Gage Measurements at Bolted Joints, in Inches

Test Joint Nos.	Date Day in July 1975													Change
	17	20	21	22	23	24	25	26	27	28	29	30	31	
1	56.84	56.81	56.81	56.81	56.81	56.81	56.81	56.84	56.81	56.81	56.81	56.81	56.81	-0.03
2	56.75	56.72	56.72	56.72	56.72	56.72	56.75	56.75	56.75	56.72	56.72	56.72	56.72	-0.03
3	56.88	56.84	56.81	56.81	56.81	56.88	56.81	56.84	56.81	56.81	56.81	56.81	56.81	-0.07
4	57.03	57.06	57.06	57.06	57.06	57.03	57.06	57.06	57.06	57.06	57.06	57.06	57.06	+0.03
5	56.88	56.88	56.88	56.88	56.88	56.88	56.88	56.88	56.88	56.88	56.88	56.88	56.88	0
6	56.81	56.78	56.75	56.75	56.75	56.75	56.75	56.72	56.75	56.75	56.75	56.75	56.75	-0.06
7	56.94	56.94	56.97	56.97	56.94	56.97	56.97	56.97	56.94	56.94	56.94	56.97	56.97	+0.03
8	56.75	56.69	56.75	56.75	56.72	56.75	56.75	56.75	56.75	56.78	56.75	56.78	56.75	0
9	56.69	56.69	56.69	56.69	56.69	56.69	56.69	56.69	56.69	56.69	56.69	56.69	56.69	0
10	56.75	56.72	56.69	56.69	56.69	56.69	56.72	56.72	56.69	56.72	56.69	56.69	56.72	-0.03
11	56.47	56.44	56.47	56.47	56.47	56.47	56.50	56.50	56.50	56.50	56.50	56.50	56.50	+0.03
12	56.66	56.59	56.63	56.63	56.59	56.63	56.63	56.59	56.56	56.56	56.52	56.56	56.56	-0.10
13	57.00	57.00	57.00	57.03	57.00	57.03	57.03	57.03	57.00	57.00	57.00	57.00	57.00	0
14	57.00	57.00	57.00	57.00	57.00	57.00	57.00	57.00	57.00	57.00	57.00	57.00	57.00	0
15	56.69	56.69	56.69	56.69	56.69	56.69	56.69	56.69	56.69	56.69	56.69	56.69	56.69	0
16	56.91	56.84	56.91	56.88	56.91	56.91	56.88	56.88	56.88	56.88	56.88	56.88	56.91	0
17	56.78	56.78	56.81	56.81	56.81	56.81	56.78	56.81	56.81	56.81	56.81	56.81	56.81	+0.03
18	56.84	56.81	56.84	56.81	56.81	56.81	56.81	56.84	56.84	56.84	56.81	56.81	56.84	0
19	56.94	56.94	56.94	56.94	56.94	56.94	56.94	56.94	56.94	56.94	56.94	56.94	56.94	0
20	57.00	56.97	56.97	56.94	56.97	56.94	56.94	56.97	56.97	56.94	56.97	56.97	56.97	-0.03
21	57.00	45.97	57.00	56.97	57.00	57.00	57.00	57.00	57.00	56.97	56.97	56.97	56.97	-0.03
22	56.81	56.78	56.88	56.81	56.78	56.81	56.78	56.81	56.78	56.78	56.78	56.78	56.78	-0.03
23	56.94	56.91	56.94	56.88	56.88	56.88	56.91	56.94	56.91	56.88	56.88	56.88	56.88	-0.06
24	56.69	56.69	56.75	56.69	56.69	56.69	56.69	56.75	56.72	56.72	56.72	56.72	56.69	0

Gage was measured to 1/32 inch and converted to decimals to the nearest 0.03 inch.

APPENDIX E

Data From Test MM-219
Lateral Resistance of Panels of Tracks on Consolidated and Unconsolidated Ballast

TEST MM-219
Chessie System April 1975
Lateral Stability of Track Panels
Panel 1, Wood Ties, Unconsolidated Ballast

Force 10^3lbs	Displacement In Inches Under Transducer Numbers										
	1	2	3	4	5	6	7	8	9	10	11
2.5	.001	0	.001	.010	0	0	0	0	-.005	0	.001
3.0	.001	0	.001	.025	0	.010	0	0	-.005	0	.002
4.0	.001	0	.001	.030	.005	.020	0	.010	-.005	0	.003
5.0	.001	0	.003	.050	.020	.050	0	.020	0	0	.005
5.5	.001	0	.009	.070	.030	.060	.001	.030	0	0	.007
6.0	.001	0	.014	.080	.060	.090	.030	.050	0	0	.009
6.5	.001	0	.026	.12	.080	.11	.050	.070	0	0	.011
7.0	.001	0	.031	.14	.11	.14	.070	.090	0	0	.014
7.5	.001	0	.033	.18	.15	.18	.11	.12	.010	0	.018
8.0	.001	0	.043	.23	.21	.23	.16	.16	.050	0	.023
8.5	.001	0	.088	.31	.29	.33	.24	.24	.11	0	.031
9.0	.001	0	.17	.38	.36	.39	.31	.30	.16	0	.038
9.5	.001	.007	.18	.42	.43	.47	.38	.36	.21	0	(4)
10.0	.001	.055	.28	.58	.59	.63	(4)	(4)	.32	0	.60
10.5	.001	.14	.47	.78	.80	.82	(4)	.68	.46	.01	.79
11.0	.001	.23	.57	.93	.97	1.01	.88	.84	.60	.03	.96
11.5	.001	.35	.87	1.18	1.23	1.25	1.13	1.06	.80	.09	1.19
12.0	.002	.58	1.14	1.63	1.74	1.74	1.61	1.52	1.20	.22	1.65
12.25(1)	.002	1.070	(3)	2.52	2.44	2.29	2.52	2.81	2.42	.57	(5)
(2)	.002	-.041	-	-.38	-.41	-.46	-.39	-.74	-.64	+.01	-

Panel 2, Wood Ties, Unconsolidated Ballast

4.55	0	0	0	.020	.020	0	0	0	0	0	0
5.0	0	0	0	.030	.030	.020	0	.010	0	0	0
5.5	0	0	0	.040	.040	.030	0	.020	.01	0	0
6.0	0	0	0	.060	.060	.050	.010	.030	.02	0	0
6.5	0	0	0	.080	.080	.070	.020	.050	.03	0	0
7.0	0	0	0	.11	.12	.11	.040	.070	.05	0	0
7.5	0	0	0	.13	.14	.13	.060	.090	.07	0	0
8.0	0	0	0	.16	.16	.16	.080	.11	.08	0	0
8.5	0	0	0	.19	.19	.19	.11	.13	.10	0	0
9.0	0	0	.010	.21	.22	.22	.13	.16	.12	0	0
9.5	0	0	.030	.25	.27	.27	.17	.19	.15	0	0
10.0	0	0	.050	.29	.31	.30	.20	.22	.17	0	0
10.5	0	0	.070	.33	.35	.35	.23	.26	.20	0	0
11.0	0	.009	.10	.38	.40	.40	.28	.29	.23	0	0
11.5	0	.040	.20	.44	.49	.48	.31	.37	.30	0	0
12.0	0	.085	.28	.55	.60	.59	.45	.47	.38	.010	0
12.5	0	.13	.32	.69	.75	.74	.60	.61	.49	.040	0
13.0	0	.17	.41	.81	.90	.88	.74	.75	.62	.080	0
13.5	0	.27	.63	1.06	1.17	1.15	1.00	1.00	.84	.16	0
14.0	-.005	.42	.90	1.43	1.55	1.53	1.17	1.37	1.18	.28	0
14.4(1)	-	(4)	(4)	(4)	(4)	(4)	2.66	2.51	2.25	(4)	(5)
(2)	(4)	.88	.25	1.91	2.06	1.99	-.60	-.96	-.43	.34	0

Notes: (1) Max Displacement
(2) Force Removed
(3) Transducer Limit
(4) Off Scale of Strip Chart
(5) Transducer Disconnected

TEST MM-219
Chessie System April 1975
Lateral Stability of Track Panels
Panel 3, Concrete Ties, Unconsolidated Ballast

Force 10^3 lbs	Displacement In Inches Under Transducer Numbers										
	1	2	3	4	5	6	7	8	9	10	11
2.5	0	0	0	0	0	0	0	0	0	0	0
3.0	0	0	0	.015	.015	.005	0	0	0	0	0
3.5	0	0	0	.020	.02	.005	.005	0	0	0	0
4.0	0	0	.005	.030	.03	.015	.010	0	0	0	0
4.5	0	0	.005	.040	.04	.030	.020	0	0	0	0
5.0	0	0	.025	.050	.05	.040	.030	0	0	0	0
5.5	0	0	.030	.060	.070	.050	.035	0	0	0	0
6.0	0	0	.040	.080	.080	.060	.040	.010	0	0	0
6.5	0	0	.047	.090	.095	.070	.050	.012	0	0	0
8.0	-.004	-	-	-	-	-	.58	.46	.31	.084	.057
9.5	-.004	-	-	-	-	-	.58	.46	.31	.084	.057
10.0	-.004	-	-	-	-	-	.58	.46	.31	.084	.057
11.0	-.004	-	-	-	.73	-	.59	.46	.31	.084	.057
11.5	-.004	-	-	.67	.75	.68	.60	.46	.32	.084	.057
12.0	-.004	.24	.50	.69	.76	.70	.62	.47	.33	.084	.057
12.5	-.004	.25	.57	.75	.84	.76	.68	.52	.36	.093	.057
13.0	-.004	.27	.62	.80	.89	.82	.73	.56	.40	.11	.057
13.5	-.004	.46	.76	.95	1.07	.99	.89	.70	.51	.16	.056
14.0	-.004	.53	.88	1.09	1.24	1.15	1.05	.85	.62	.22	.056
14.5	-.004	.62	1.03	1.27	1.43	1.35	1.24	1.02	.78	.30	.057
15.0	-.005	.88	1.24	1.96	1.96	1.88	1.75	1.50	1.18	.55	.11
15.0(1)	-.005	.89	1.62	2.00	2.20	2.12	1.99	1.73	1.38	.68	.13
(2)	.007	.87	1.38	1.65	2.05	-	1.68	1.55	1.30	.72	.11

Panel 4, Wood Ties, Consolidated Ballast

2.0	0	0	0	0	0	.010	0	0	0	0	0
3.0	0	0	0	0	0	.020	.010	.010	0	0	0
4.0	0	0	0	0	0	.030	.020	.030	0	0	0
5.0	0	0	0	.010	.020	.050	.030	.040	.020	0	0
6.0	0	0	0	.010	.030	.060	.040	.060	.020	0	0
7.0	0	0	0	.020	.040	.070	.050	.070	.020	0	0
7.5	0	0	.040	.020	.050	.080	.070	.080	.030	0	0
8.0	0	0	.010	.030	.070	.10	.080	.10	.040	0	0
9.0	0	.003	.024	.060	.10	.12	.11	.14	.060	0	0
9.5	0	.006	.036	.080	.13	.16	.13	.15	.070	0	0
10.0	0	.011	.051	.11	.15	.19	.16	.16	.090	0	0
10.5	0	.018	.070	.14	.19	.22	.20	.20	.12	0	0
11.0	0	.030	.098	.19	.25	.28	.25	.22	.16	0	0
11.5	0	.037	.11	.22	.28	.32	.28	.24	.17	0	0
12.0	0	.051	.14	.26	.33	.36	.33	.26	.21	0	0
12.5	-.002	.078	.19	.33	.41	.44	.40	.32	.27	0	0
13.0	-.007	.10	(4)	.43	.53	.56	.52	.43	.36	0	0
13.5	-.010	.15	(4)	.50	.60	.63	.58	.50	.41	0	0
14.3(1)	.061	1.12	(3)	2.20	2.37	2.37	2.30	1.92	1.89	.529	.010
(2)	.061	1.06	.46	1.77	1.95	1.83	1.83	1.55	1.56	.529	.010

Notes:
(1) Max Displacement
(2) Force Removed
(3) Transducer Limit
(4) Off Scale of Strip Chart

TEST MM-219
Chessie System April 1975
Lateral Stability of Track Profile
Panel 5, Wood Ties, Consolidated Track

Force 10^3lbs	Displacement In Inches Under Transducer Numbers										
	1	2	3	4	5	6	7	8	9	10	11
2.0	0	0	0	0	0	0	0	0	0	0	0
2.5	0	0	0	0	0	0	.010	0	0	0	0
3.0	0	0	0	0	0	0	.020	0	0	0	0
3.5	0	0	0	0	0	0	.020	0	0	0	0
4.0	0	0	0	0	0	0	.020	0	0	0	0
4.5	0	-.001	0	0	0	.010	.020	0	0	0	0
5.0	0	-.001	0	0	.010	.010	.030	0	0	0	0
5.5	0	-.001	0	0	.010	.020	.040	.010	.010	0	0
6.0	0	-.001	0	0	.010	.020	.040	.010	.010	0	0
6.5	0	-.002	0	0	.020	.030	.050	.020	.010	0	0
7.0	0	-.001	0	0	.030	.040	.060	.030	.020	0	0
7.5	0	-.001	0	0	.040	.050	.070	.040	.030	0	0
8.0	0	-.001	0	.010	.050	.070	.080	.050	.040	0	0
8.5	0	-.001	0	.020	.070	.080	.10	.060	.050	0	0
9.0	0	-.001	0	.030	.080	.10	.12	.090	.070	0	0
9.5	0	-.001	.002	.060	.12	.14	.17	.13	.10	0	0
10.0	0	-.001	.003	.070	.13	.15	.18	.14	.11	0	0
10.5	0	-.001	.004	.080	.15	.17	.20	.16	.13	0	0
11.0	0	-.001	.007	.10	.18	.20	.24	.19	.16	0	-.001
11.5	-.001	-.002	.013	.13	.22	.25	.28	.23	.19	.003	-.001
12.0	-.001	-.002	.023	.17	.26	.29	.33	.28	.24	.011	-.001
12.5	-.001	0	.040	.22	.32	.36	.40	.34	.30	.022	-.001
13.0	-.002	.007	.067	.27	.38	.42	.46	.43	.36	.037	-.001
13.5	-.003	.017	.097	.33	.45	.49	.54	.49	.41	.054	-.002
14.0	-.004	.034	.13	.39	.52	.56	.60	.56	.47	.071	-.002
14.5	-.004	.082	.23	.54	.71	.77	.81	.75	.67	.14	-.003
15.0	-.007	.12	.31	.69	.87	.94	.99	.94	.83	.20	-.007
15.2(1)	-.009	.16	.38	.78	1.00	1.07	1.14	1.08	.96	.26	-.013
(2)	-.024	-	.39	.73	.82	.88	-	-	.84	.34	-.080

Notes: (1) Max Displacement
(2) Force Removed

TEST MM-219
Chessie System April 1975
Lateral Stability of Track Panels
Panel 6, Concrete Ties, Consolidated Ballast

Force 10^3 lbs	Displacement In Inches Under Transducer Numbers										
	1	2	3	4	5	6	7	8	9	10	11
3.5	0	0	0	0	0	0	0	0	0	0	0
4.0	0	0	0	0	0	0	0	0	0	0	0
4.5	0	0	0	0	0	0	0	0	0	0	0
5.0	0	0	0	0	.010	0	.010	0	0	0	0
5.5	0	0	0	.010	.010	0	.010	0	0	0	0
6.0	0	0	0	.010	.010	0	.010	.010	0	0	0
6.5	0	0	0	.010	.010	.010	.010	.010	0	0	0
7.0	0	0	0	.010	.020	.010	.020	.010	0	0	0
7.5	0	0	0	.010	.030	.020	.030	.010	0	0	0
8.0	0	0	0	.020	.030	.020	.030	.020	0	0	0
8.5	0	0	.001	.020	.040	.020	.040	.020	0	0	-.001
9.0	0	-.001	.004	.030	.050	.030	.050	.030	.010	0	-.002
9.5	0	-.001	.008	.040	.060	.040	.060	.040	.020	0	-.002
10.0	0	-.001	.011	.050	.070	.070	.070	.050	.020	0	-.002
10.5	0	-.001	.014	.050	.080	.080	.090	.060	.020	0	-.002
11.0	0	-.001	.018	.060	.10	.090	.10	.070	.020	0	-.002
11.5	0	-.001	.024	.070	.11	.11	.12	.080	.040	0	-.002
12.0	0	-.001	.030	.090	.13	.12	.13	.090	.040	0	-.002
12.5	0	-.001	.041	.10	.15	.15	.15	.11	.050	0	-.002
13.0	0	-.001	.052	.12	.17	.17	.17	.12	.060	0	-.002
13.5	0	-.001	.068	.15	.21	.20	.20	.15	.070	0	-.002
14.0	0	-.001	.083	.17	.24	.23	.24	.17	.10	.002	-.002
14.5	.001	0	.10	.20	.24	.27	.27	.20	.12	.007	-.002
15.0	.001	.005	.13	.25	.28	.33	.32	.25	.16	.014	-.002
15.5	.001	.010	.16	.29	.33	.37	.36	.28	.18	.019	-.002
16.0	.001	.024	.21	.36	.38	.46	.43	.34	.22	.030	-.003
16.5	-.001	.035	.25	.41	.45	.53	.51	.40	.27	.042	-.003
17.0	0	.064	.34	.54	.52	.69	.66	.53	.36	.070	-.005
17.5	0	.077	.38	.59	.63	.74	.71	.58	.40	.079	-.005
18.0	-.001	.11	.47	.70	.86	.86	.82	.67	.46	.11	-.006
18.5	-.002	.16	.58	.84	1.03	1.02	.97	.80	.57	.15	-.009
19.0	-.002	.25	.78	1.09	1.29	1.29	1.22	1.04	.75	.23	-.014
19.5	-.002	.35	.97	1.32	1.55	1.55	1.47	1.27	.92	.31	-.017
20.0	-.002	.48	1.19	1.58	1.83	1.84	1.74	1.52	1.14	.42	-.020
20.25(1)	.005	.58	1.50	1.77	-	2.05	1.95	1.72	1.30	.52	-.026
(2)	.005	.66	1.22	1.53	2.08	1.69	1.60	1.46	1.20	.56	-.027

Notes: (1) Max Displacement
(2) Force Removed

TEST MM-219
Chessie System August 1975
Lateral Stability of Track Panels
Panel 1, Wood Ties, Unconsolidated Ballast

Force 10^3 lbs	Displacement In Inches Under Transducer Numbers										
	1	2	3	4	5	6	7	8	9	10	11
2.5	0	0	0	0	0	.040	0	.010	0	0	0
3.75	0	0	0	.020	0	.050	0	.010	0	0	0
5.0	0	0	0	.040	0	.060	0	.010	0	0	0
6.25	0	0	0	.050	0	.070	.010	.020	0	0	0
7.50	0	0	0	.070	.020	.11	.030	.030	0	0	0
8.75	0	0	0	.090	.030	.13	.050	.040	0	0	0
10.0	0	0	0	.090	.040	.14	.060	.040	0	0	0
11.25	0	0	.011	.11	.070	.17	.090	.050	0	0	0
12.5	0	0	.030	.15	.11	.22	.13	.070	0	0	0
15.0	0	0	.22	.36	.35	.47	.37	.15	.090	.015	0
15.25(1)	0	.004	.42	.64	.65	.77	.64	.25	.23	.058	0

Note: Panel continued to move with no increase in force.

Panel 2, Wood Ties, Unconsolidated Ballast

2.0	0	0	0	0	0	.020	0	0	0	0	0
4.0	0	0	0	.020	.010	.050	0	0	0	0	0
5.0	0	0	0	.030	.020	.060	0	0	0	0	0
5.5	0	0	0	.040	.030	.070	0	0	0	0	0
6.0	0	0	0	.040	.030	.070	0	0	0	0	0
6.5	0	0	0	.040	.030	.080	0	0	0	0	0
7.0	0	0	0	.050	.040	.090	.010	0	0	0	0
7.5	0	0	0	.050	.050	.10	.010	0	0	0	0
8.0	0	0	0	.060	.050	.10	.010	0	0	0	0
8.5	0	0	0	.080	.060	.11	.020	0	0	0	0
9.0	0	0	0	.090	.070	.12	.020	.025	0	0	0
9.5	0	0	0	.090	.080	.14	.030	.025	.010	0	0
10.0	0	0	0	.10	.090	.14	.040	.025	.010	0	0
10.5	0	0	0	.11	.10	.15	.040	.025	.010	0	0
11.0	0	0	0	.12	.11	.16	.050	.050	.020	0	0
11.5	0	0	0	.13	.12	.17	.050	.050	.030	0	0
12.0	0	0	0	.15	.14	.19	.060	.050	.030	0	0
12.5	0	0	0	.15	.15	.20	.070	.075	.040	0	0
13.0	0	0	0	.17	.17	.22	.090	.075	.050	0	0
13.5	0	0	.008	.20	.19	.25	.10	.11	.060	0	0
14.0	0	0	.017	.22	.22	.28	.12	.10	.070	0	0
14.5	0	0	.025	.24	.25	.31	.15	.13	.090	0	0
15.0	0	0	.040	.28	.28	.35	.17	.15	.11	0	0
15.5	0	0	.075	.35	.36	.42	.24	.23	.15	0	0
16.0	0	.016	.13	.46	.50	.55	.32	.28	.21	0	0
16.5	0	.075	.23	.65	.74	.75	.52	.47	.34	0	0
17.0(1)	-.005	.12	.32	.77	.84	.87	.67	.60	.44	0	0

Notes: (1) Max Displacement
Panel continued to move with decreasing load

TEST MM-219
Chessie System August 1975
Lateral Stability of Track Panels
Panel 3, Concrete Ties, Unconsolidated Ballast

Force 10^3lbs	Displacement In Inches Under Transducer Numbers										
	1	2	3	4	5	6	7	8	9	10	11
2.0	0	0	0	0	0	0	0	0	0	0	0
2.5	0	0	0	0	0	0	0	0	0	0	0
3.0	0	0	0	0	0	0	0	0	0	0	0
3.5	0	0	0	0	0	0	0	0	0	0	0
4.0	0	0	0	0	0	0	0	0	0	0	0
4.5	0	0	0	0	.020	0	0	0	0	0	0
6.0	0	0	0	0	.020	.010	0	0	0	0	0
7.0	0	0	0	0	.030	.010	0	0	0	0	0
8.0	0	0	0	.020	.030	.010	0	0	0	0	0
9.0	0	0	0	.040	.050	.030	.010	0	0	0	0
9.5	0	0	0	.050	.060	.030	.010	0	0	0	0
10.0	0	0	.005	.050	.060	.040	.010	0	0	0	0
10.5	0	0	.010	.060	.070	.040	.015	.005	0	0	0
11.0	0	0	.016	.070	.080	.050	.020	.005	0	0	0
11.5	0	0	.021	.070	.080	.050	.020	.010	0	0	0
12.0	0	0	.029	.080	.090	.060	.025	.010	.010	0	0
12.5	0	0	.040	.10	.11	.080	.030	.010	.010	0	0
13.0	0	0	.055	.12	.13	.090	.035	.015	.010	0	0
13.5	0	0	.073	.15	.15	.12	.045	.020	.020	0	0
14.0	0	0	.085	.16	.17	.14	.050	.020	.020	0	0
14.5	0	.005	.12	.21	.23	.18	.060	.040	.030	0	0
15.0	0	.010	.13	.22	.24	.20	.080	.040	.050	-.001	-.001
15.5	0	.015	.15	.25	.27	.24	.090	.045	.060	-.001	-.002
16.0	0	.026	.19	.30	.33	.29	.12	.060	.090	-.001	-.002
16.5	0	.045	.24	.37	.41	.38	.15	.090	.14	.013	-.004
17.0	0	.095	.36	.53	.59	.58	.25	.16	.27	.053	-.006
17.5	0	.16	.51	.73	.83	.82	.37	.25	.46	.13	-.005
18.0	0	.24	.67	1.08	1.08	1.09	.68	.38	.61	.21	-.010
18.5	0	.31	.81	1.12	1.27	1.29	1.01	.67	.88	.33	-.019
19.0	0	.64	1.33	1.71	1.88	1.90	1.55	1.13	1.27	.57	--
19.6(1)	0	.72	1.43	1.90	2.10	2.13	1.81	1.45	1.45	.69	--

Notes: (1) Max Displacement

Panel continued to move with decreasing load.

TEST MM-219
Chessie System August 1975
Lateral Stability of Track Panels
Panel 4, Wood Ties, Consolidated Ballast

Force 10^3 lbs	In Inches Under Transducer Numbers										
	1	2	3	4	5	6	7	8	9	10	11
4.0	0	0	0	0	0	.045	.010	0	0	0	0
4.5	0	0	0	0	0	.050	.010	.010	0	0	0
5.0	0	0	0	0	0	.050	.010	.010	0	0	0
5.5	0	0	0	0	0	.055	.010	.010	0	0	0
6.0	0	0	0	.010	.010	.060	.010	.010	0	0	0
6.5	0	0	0	.010	.010	.060	.010	.010	0	0	0
7.0	0	0	0	.010	.010	.070	.010	.010	0	0	0
7.5	0	0	0	.015	.015	.070	.010	.010	0	0	0
8.0	0	0	0	.015	.020	.075	.010	.010	0	0	0
8.5	0	0	0	.020	.020	.080	.020	.010	0	0	0
9.0	0	0	0	.020	.025	.085	.020	.010	0	0	0
9.5	0	0	0	.025	.030	.090	.020	.010	.010	0	0
10.0	0	0	0	.030	.030	.090	.020	.020	.010	0	0
11.0	0	0	0	.035	.040	.10	.020	.020	.010	0	0
11.5	0	0	0	.040	.050	.11	.030	.020	.010	0	0
12.0	0	0	0	.040	.050	.11	.030	.020	.020	0	0
12.5	0	0	0	.050	.060	.13	.030	.030	.020	0	0
13.0	0	0	0	.050	.060	.13	.030	.030	.020	0	0
13.5	0	0	0	.060	.070	.14	.040	.030	.030	0	0
14.0	0	0	.001	.070	.080	.15	.040	.040	.040	0	0
14.5	0	0	.006	.080	.090	.17	.050	.040	.050	0	0
15.0	0	0									
15.5	0	0	.020	.11	.14	.22	.070	.060	.080	0	0
16.0	0	0	.026	.13	.16	.25	.090	.070	.090	0	0
16.3(1)							.20	.15	.25	0	0

Notes: (1) Max Displacement

Panel Continued to move with decreasing load.

TEST MM-219
Chessie System August 1975
Lateral Stability of Track Panels
Panel 5, Wood Ties, Consolidated Ballast

Force 10^3 lbs	In Inches Under Transducer Numbers										
	1	2	3	4	5	6	7	8	9	10	11
2.0	0	0	0	0	0	0	0	0	0	0	0
4.0	0	0	0	0	0	0	0	0	0	0	0
5.0	0	0	0	0	0	0	0	0	0	0	0
5.5	0	0	0	0	0	0	0	0	0	0	0
6.0	0	0	0	0	.010	.010	.010	0	0	0	0
6.5	0	0	0	0	.010	.010	.010	0	0	0	0
7.0	0	0	0	0	.010	.010	.010	0	0	0	0
7.5	0	0	0	0	.010	.010	.010	0	0	0	0
8.0	0	0	0	0	.010	.020	.010	0	0	0	0
8.5	0	0	0	.010	.020	.020	.010	0	0	0	0
9.0	0	0	0	.010	.020	.020	.020	.025	.010	0	0
9.5	0	0	0	.010	.020	.030	.020	.025	.010	0	0
10.0	0	0	0	.010	.030	.030	.020	.025	.010	0	0
10.5	0	0	0	.010	.030	.040	.020	.025	.020	0	0
11.0	0	0	0	.020	.040	.040	.030	.025	.020	0	0
11.5	0	0	0	.020	.040	.050	.030	.025	.030	0	0
12.0	0	0	0	.020	.050	.060	.040	.050	.030	0	0
13.0	0	0	0	.030	.060	.070	.040	.050	.040	0	0
13.5	0	0	0	.030	.060	.080	.050	.050	.050	0	0
14.0	0	0	0	.040	0.80	.090	.050	.075	.060	0	0
14.5	0	0	0	.040	.080	.10	.060	.075	.070	0	0
15.0	0	0	0	.050	.090	.11	.060	.10	.080	0	0
15.5	0	0	0	.060	.11	.14	.070	.13	.10	0	-.001
16.0	0	0	0	.070	.13	.16	.090	.15	.11	0	-.001
17.0	0	0	0	.12	.20	.25	.14	.23	.20	0	-.001
17.5	-.001	0	.023	.24	.35	.42	.22	.40	.35	.004	-.001

Note: Panel continued to move with decreasing load.

TEST MM-219
Chessie System August 1975
Lateral Stability of Track Panels
Panel 6, Concrete Ties, Consolidated Ballast

Force 10^3lbs	In Inches Under Transducer Numbers										
	1	2	3	4	5	6	7	8	9	10	11
1.5	0	0	0	0	0	0	0	0	0	0	0
2.0	0	0	0	0	0	0	0	0	0	0	0
3.0	0	0	0	0	0	0	0	0	0	0	0
4.0	0	0	0	0	0	0	0	0	0	0	0
5.0	0	0	0	.010	.010	.010	.010	0	0	0	0
6.0	0	0	0	.020	.020	.020	.020	.025	.010	0	0
7.0	0	0	0	.020	.040	.050	.030	.050	.020	0	0
8.0	0	0	0	.040	.060	.060	.040	.050	.020	0	0
10.0	0	0	.016	.070	.10	.11	.060	.10	.060	0	0
11.0	0	0	.080	.17	.24	.26	.090	.13	.080	0	0
12.0	0	0	.089	.19	.26	.29	.14	.23	.15	.009	0
12.5	0	0	.11	.22	.30	.34	.16	.25	.17	.015	0
13.0	0	0	.16	.29	.39	.42	.20	.35	.22	.030	-.001
13.5	0	.006	.17	.31	.42	.45	.22	.38	.24	.035	-.002
14.0	0	.029	.25	.42	.57	.61	.30	.50	.35	.069	-.004
14.5	-.001	.072	.42	.59	.77	.81	.40	.70	.50	.13	-.007
15.0	-.009	.17	(2)	.82	1.04	1.10	.74	.95	.70	.21	-.011
15.4(1)	-.010	.18	.68	.98	1.22	1.28	1.24	1.73	.84	.27	-.016

Notes: (1) Max Displacement
(2) Off scale of Strip Chart

Panel continued to move with decreasing load.

TEST MM-219
Chessie System August 1975
Lateral Stability of Track Panels
Panel 7, Wood Ties, Undisturbed Ballast

Force 10^3 lbs	In Inches Under Transducer Numbers										
	1	2	3	4	5	6	7	8	9	10	11
2.0	0	0	0	0	0	0	.010	0	0	0	0
3.0	0	0	0	0	0	0	.010	0	0	0	0
4.0	0	0	0	0	0	0	.010	0	0	0	0
5.0	0	0	0	0	0	0	.010	0	0	0	0
6.0	0	0	0	0	0	0	.010	0	0	0	0
7.0	0	0	0	0	0	0	.020	0	0	0	0
8.0	0	0	0	0	0	.010	.020	0	.010	0	0
9.0	0	0	0	.010	.010	.010	.020	0	.010	0	0
10.0	0	0	0	.010	.010	.020	.030	0	.020	0	0
11.0	0	0	0	.010	.020	.030	.030	0	.020	0	0
12.0	0	0	0	.010	.020	.030	.030	0	.030	0	0
13.0	0	0	0	.010	.030	.040	.040	.025	.040	0	0
14.0	0	0	0	.020	.030	.050	.040	.025	.040	0	0
15.0	0	0	0	.020	.040	.050	.040	.025	.050	0	0
16.0	0	0	0	.030	.040	.060	.050	.025	.060	0	0
17.0	0	0	0	.030	.050	.070	.050	.025	.070	0	0
18.0	0	0	.001	.040	.060	.080	.060	.050	.070	0	0
19.0	0	0	.006	.050	.070	.10	.070	.050	.090	0	0
20.0	0	0	.009	.060	.090	.12	.080	.075	.10	0	0
21.0	0	0	.013	.060	.10	.14	.070	.075	.12	0	0
22.0	0	0	.017	.080	.12	.15	.080	.10	.14	0	0
23.0	0	0	.019	.080	.13	.17				0	-.001
24.0	0	0		.011	.17	.22	.11	.18	.19	0	-.001
25.0	0	0	.041	.14	.20	.25	.14	.18	.22	0	-.001
26.0	0	0	.059	.17	.25	.32	.16	.25	.27	0	-.001
26.5	0	0	.080	.22	.32	.39	.20	.33	.33	.006	-.001
27.0	0	0	.11	.30	.40	.48	.24	.33	.41	.020	-.001

Note: Test ended to protect wire rope.

TEST MM-219
Chessie System August 1975
Lateral Stability of Track Panels
Panel 8, Wood Ties, Undisturbed Ballast

Force 10^3lbs	In Inches Under Transducer Numbers										
	1	2	3	4	5	6	7	8	9	10	11
2.7	0	0	0	.010	.010	.040	.010	0	0	0	0
4.0	0	0	0	.020	.010	.040	.010	0	0	0	0
5.0	0	0	0	.020	.020	.040	.010	0	0	0	0
6.0	0	0	0	.020	.020	.040	.010	.025	0	0	0
7.0	0	0	0	.030	.030	.060	.010	.025	0	0	0
8.0	0	0	0	.030	.030	.060	.010	.025	0	0	0
9.0	0	0	0	.040	.040	.070	.020	.025	0	0	0
10.0	0	0	0	.040	.040	.080	.020	.025	0	0	0
11.0	0	0	.003	.050	.050	.080	.020	.050	0	0	0
12.0	0	0	.005	.050	.050	.090	.020	.050	0	0	0
13.0	0	0	.006	.060	.060	.100	.030	.050	0	0	0
14.0	0	0	.008	.060	.070	.100	.030	.050	0	0	0
15.0	0	0	.010	.070	.070	.11	.030	.050	0	0	0
16.0	0	0	.011	.070	.080	.11	.030	.050	0	0	0
17.0	0	0	.014	.080	.090	.12	.040	.075	.010	0	0
18.0	0	0	.016	.090	.090	.13	.040	.075	.010	0	0
19.0	0	0	.017	.090	.10	.15	.050	.10	.010	0	0
20.0	0	0	.019	.10	.11	.15	.050	.10	.020	0	0
21.0	0	0	.022	.11	.11	.16	.050	.10	.020	0	0
22.0	0	0	.023	.11	.12	.17	.060	.13	.020	0	0
23.0	0	0	.027	.13	.14	.19	.070	.13	.020	0	0
24.0	0	0	.029	.13	.14	.20	.070	.13	.030	0	0
25.0	0	0	.031	.14	.15	.20	.070	.15	.030	0	0
25.0	0	0	.035	.15	.17	.22	.090	.15	.030	0	0

Note: Test ended to protect wire rope.

TEST MM-219
Chessie System August 1975
Lateral Stability of Track Panels
Panel 9, Wood Ties, Undisturbed Ballast

Force	In Inches Under Transducer Numbers										
10^3lbs	1	2	3	4	5	6	7	8	9	10	11
4.0	0	0	0	0	0	0	.010	0	0	0	0
5.0	0	0	0	0	0	0	.010	0	0	0	0
6.0	0	0	0	0	0	0	.010	0	.010	0	0
7.0	0	0	0	0	0	0	.020	0	.010	0	0
8.0	0	0	0	0	.010	0	.020	0	.020	0	0
9.0	0	0	0	0	.010	.010	.030	0	.020	0	0
10.0	0	0	0	0	.020	.010	.030	0	.030	0	0
11.0	0	0	0	0	.020	.010	.030	0	.030	0	0
12.0	0	0	0	.010	.020	.020	.030	.025	.030	0	0
13.0	0	0	0	.010	.030	.020	.030	.025	.040	0	0
14.0	0	0	0	.010	.030	.020	.040	.025	.040	0	0
15.0	0	0	0	.010	.040	.030	.040	.025	.050	0	0
16.0	0	0	0	.010	.040	.030	.040	.025	.050	0	0
17.0	0	0	0	.010	.050	.040	.050	.025	.060	0	0
18.0	0	0	0	.010	.050	.040	.050	.025	.060	0	0
19.0	0	0	0	.010	.060	.050	.050	.050	.070	0	0
20.0	0	0	0	.010	.060	.050	.060	.050	.070	0	0
21.0	0	0	0	.010	.070	.060	.060	.050	.080	0	0
22.0	0	0	0	.010	.070	.060	.060	.050	.080	0	0
23.0	0	0	0	.020	.080	.070	.060	.050	.090	0	0
24.0	0	0	0	.020	.090	.080	.070	.075	.10	0	0
25.0	0	0	0	.020	.090	.090	.070	.075	.10	0	0
26.0	0	0	0	.020	.10	.10	.080	.10	.11	0	0

Note: Test ended to protect wire rope.

TEST MM-219
Chessie System August 1975
Lateral Stability of Track Panels
Panel 10, Wood Ties, Undisturbed Ballast

Force 10^3lbs	In Inches Under Transducer Numbers										
	1	2	3	4	5	6	7	8	9	10	11
4.0	0	0	0	0	.010	.030	0	0	0	0	0
5.0	0	0	0	0	.020	.030	0	0	0	0	0
6.0	0	0	0	.010	.020	.040	0	0	0	0	0
7.0	0	0	0	.010	.030	.050	.010	0	0	0	0
8.0	0	0	0	.020	.030	.050	.010	.010	0	0	0
9.0	0	0	0	.020	.040	.060	.010	.010	.010	0	0
10.0	0	0	0	.020	.050	.070	.010	.010	.010	0	0
11.0	0	0	0	.030	.050	.070	.020	.010	.020	0	0
12.0	0	0	0	.040	.060	.080	.020	.020	.020	0	0
13.0	0	0	0	.040	.060	.090	.020	.020	.020	0	0
14.0	0	0	0	.060	.070	.10	.030	.020	.030	0	0
15.0	0	0	0	.060	.080	.11	.030	.020	.030	0	0
16.0	0	0	0	.060	.090	.11	.030	.030	.040	0	-.001
17.0	0	0	0	.070	.090	.12	.040	.030	.040	0	-.002
18.0	0	0	0	.070	.11	.14	.040	.030	.040	0	-.002
19.0	0	0	0	.080	.11	.15	.050	.050	.050	0	-.002
20.0	0	0	0	.090	.12	.15	.050	.040	.050	0	-.003
21.0	0	0	0	.090	.13	.16	.060	.040	.050	0	-.003
22.0	0	0	0	.10	.15	.18	.060	.050	.060	0	-.003
23.0	0	0	0	.11	.15	.20	.070	.050	.070	0	-.004
24.0	0	0	0	.12	.17	.21	.080	.060	.080	0	-.004
25.0	0	0	0	.14	.19	.23	.080	.060	.080	0	-.004
26.0	0	0	0	.15	.20	.24	.090	.070	.090	0	-.004
27.0	0	0	0	.16	.22	.26	.10	.070	.10	0	-.005
28.0	0	0	0	.18	.24	.29	.11	.080	.11	0	-.005
28.5	0	0	0	.19	.26	.31	.12	.090	.12	0	-.005

Note: Test ended to protect wire rope.

Test MM-219 Lateral Track Stability
Rise and Rotation of Track Panels
Under Lateral Force in Inches and Degrees

The distances measured were from the tops of the rails to a horizontal, taut steel wire fastened to two steel posts. The rise is taken at the center of the track. A positive rotation angle indicates that the north rail rose higher, or depressed less, than the south rail.

Tests in April, 1975

Panel Number	South Rail	North Rail	South Rail	North Rail	Rise	Rotation
1	1.00	1.00	0.85	0.90	0.12	-0.05°
2	0.93	1.15	0.85	1.10	0.06	-0.03°
3	1.00	0.90	0.88	0.81	0.10	-0.03°
4	1.97	2.20	1.89	2.05	0.11	+0.07°
5	0.95	1.70	0.70	1.50	0.22	+0.05°
6	2.12	2.10	2.00	2.00	0.11	-0.02°

Tests in August, 1975

Panel Number	South Rail	North Rail	South Rail	North Rail	Rise	Rotation
1	1.62	1.38	1.38	1.00	0.31	+0.14°
2	1.25	1.38	0.75	0.75	0.565	+0.13°
3	0.75	0.75	0.50	0.50	0.25	0
4	3.00	3.50	2.63	3.25	0.31	-0.12°
5	2.88	2.63	2.38	2.00	0.56	+0.13°
6	2.25	2.00	2.50	2.13	-0.19	+0.13°
7	2.13	2.63	1.63	2.00	0.56	+0.13°
8	2.00	1.88	2.00	1.88	0	0
9	2.75	3.50	3.00	3.50	-0.12	+0.25°
10	1.88	2.25	1.88	2.25	0	0