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AUTOMATED MEASUREMENTS OF LATERAL TRACK PANEL STRENGTH AND EXAMINATIONS OF TRACK MAINTENANCE EFFECTS USING AAR'S TRACK LOADING VEHICLE

REPORT NO. R-918

by

Dingqing Li and William Shust

Submitted in fulfillment of Task Order No. 4
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Transportation Technology Center, Inc.
A subsidiary of the Association of American Railroads
Pueblo, Colorado

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Norfolk Southern Railroad provided revenue track test sites.

13. Abstract

This report summarizes test results and findings under the project "TLV Track Panel Shift and Lateral Track Strength Tests." The project was jointly funded by AAR and FRA. These tests were performed primarily off-site on Norfolk Southern revenue tracks, but a significant portion of tests was conducted on TTC's test tracks.

The study was conducted to complement previous testing done by AAR for developing a prototype technique for automated track strength measurement and for studying the effects of track maintenance operations. Major results from this study included (1) the successful development and demonstration of a prototype TLV technique for automated lateral track strength measurements, (2) quantitative examination of the effects on lateral strength of wood tie tracks of surfacing and tamping, dynamic ballast stabilization and accumulative traffic, and (3) survey of Class 1 railroad slow orders and quantitative comparisons with TLV track strength test results.

14. Subject Terms

Lateral track strength, Track panel shift, Track strength inspection, Stationary and in-motion tests, Track Loading Vehicle, Train slow-orders

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EXECUTIVE SUMMARY

This report summarizes test results and findings from phase 3 of project "TLV Track Panel Shift and Lateral Track Strength Tests." Results and findings from phases 1 and 2 were published in an earlier report (R-917).[1] The project was jointly funded by Association of American Railroads (AAR) and the Federal Railroad Administration under contract DTFR53-93-R-00058. Phase 3 tests were performed primarily off-site on Norfolk Southern (NS) revenue tracks, but a significant portion was conducted at the Transportation Technology Center (TTC). Major results from this study included (1) the successful development and demonstration of a prototype TLV technique for automated lateral track strength measurements, (2) quantitative examination of the effects on lateral strength of wood tie tracks of surfacing and tamping, dynamic ballast stabilization and accumulative traffic, and (3) survey of Class 1 railroad slow orders and quantitative comparisons with TLV track strength test results.

The study was conducted to complement previous testing done by AAR to develop a prototype technique for automated track strength measurement and for studying the effects of track maintenance operations.[1] Phase 3 was performed to demonstrate the automated TLV technique, to study the effect of dynamic ballast stabilization, and to compare TLV test results with current slow-order policies. As found in the previous study, track lateral strength is quite variable, even in locations of consistent ballast shoulder and tie conditions. With this in mind, the main conclusions from this study are as follows.

Prototype TLV technique for automated track strength measurement

A prototype technique has been developed for automated measurement of lateral track panel strength at the tie-ballast interface, using AAR's Track Loading Vehicle (TLV). This technique has been applied successfully to identify weak spots continuously along the track and to examine the effects of track maintenance practices on lateral track strength. Further refinement and full applications of this technique will enable

railroads to identify and maintain weak spots for mitigating conditions leading to track buckling and panel shifting.

This prototype TLV technique involves in-motion application of vertical and lateral loads to the track and measurements of unloaded and loaded lateral track profiles. Higher deflections correspond to weaker track. A tangent wood-tie track is considered strong with a deflection of 0.04 inch or less, and weak with a deflection more than 0.1 inch (under 18 kip lateral axle load and 20 kip vertical axle load). However, more revenue track tests are needed to document effects of curvature and rail longitudinal force, and to establish thresholds dividing strong and weak tracks. A weaker track shows not only higher average deflections, but also higher variations along the track.

TTC on-site tests of track maintenance effects

Track lateral strength was reduced significantly by ballast tamping operations even if the rail lift was relatively small (0.5 to 1 inch). Dynamic ballast stabilizers accelerated ballast consolidation and strength recovery on wood-tie track. Test results on TTC wood-tie track with granite ballast indicated that use of a dynamic stabilizer following tamping produced ballast consolidation resulting in a recovery approximately equivalent in the range of 0.1 to 0.3 MGT of heavy axle load traffic at the Facility for Accelerated Service Testing.

Various tie types affected initial track lateral strength more than they affected consolidated track strength. Following tie installation and surfacing operations, both concrete and steel ties (inverted trough types) showed significantly greater initial strength than wood ties. However, this difference in track strength (as measured using the TLV) decreased as the ballast became more consolidated.

1997 Norfolk Southern tests of track maintenance effects

The tie-replacement (20 to 25 percent) and ballast-tamping process led to a lateral strength reduction of almost 50 percent. This magnitude agreed with previous TTC tests. However, the TTC tests included only minimum lifting (0.5–1″) and tamping, but no tie changes.

Following tamping, 0.1 MGT of traffic recovered approximately 15 percent of the track strength loss (to 65 percent) of the original strength.

Use of a dynamic ballast stabilizer following NS tie replacement and ballast tamping improved track strength equivalent to the effect of 0.1 MGT.

1998 Norfolk Southern tests of track maintenance effects

TLV tests showed that NS's dynamic ballast stabilizer could be operated as expected over a frequency range of 30 to 35 Hz and a vertical pressure range of 70 to 90 bar (a relative measure used by the operator, 1 bar = 14.5 psi). The few occasions where the stabilizer did not work effectively were mostly associated with lower vibrating frequency (25 Hz) and lower vertical pressure (50 bar).

After surfacing near Pell City, Alabama, the track lateral strength was reduced to approximately 62 percent of the pre-maintenance condition. Dynamic track stabilization returned this to 74 percent of the original strength (12 percent). After timber and surfacing gang operations near Poplarville, Mississippi, the baseline track strength was reduced to 65 percent (range 57 to 69%). Dynamic track stabilization returned this to 81 percent (range 73 to 88%) of the original value.

Limited TLV testing indicates, tie replacement percentages within the range of 13-30 percent, appear to have a minor effect on post-maintenance strength.

Slow-order policies

Dynamic ballast stabilization has been found, from several on- and off-site TLV tests, to be equivalent to at least 90,000 gross tons of revenue freight traffic. When dynamic ballast stabilization is used, railroads shorten the durations of post-maintenance train speed restrictions. However, a technical comparison of slow-orders with and without stabilization show inconsistencies between the two alternatives for some railroads.

Without dynamic ballast stabilization, the Class I railroads prescribe train operations of 25 mph or higher after 90,000 gross tons of vehicle traffic. Since a stabilizer is equivalent to at least this much traffic — based on limited wood tie TLV tests — it follows that 25 mph may be a suitable minimum initial speed for freight train operations following stabilizer use (subject to normal operating speeds).

Because of infrastructure, environmental, and train operation differences across the continent, as well as seasonal changes throughout the year, no single slow-order policy should be suggested for all railroads. If a minimum strength is specified, the TLV can help determine track strength as related to slow-order policy. As mentioned above, the TLV revenue service track strength tests were conducted at three sites over mainline quality track. Each test was run over 1,000 to 1,500 foot long track at 20 to 25 locations. The track lateral strength was measured using a special technique developed for the TLV. Based on these limited number of tests, it was found that approximately 100,000 tons of slowed traffic can achieve an average of 70 percent strength retention after surfacing maintenance. Tests also showed that a dynamic ballast stabilizer can achieve the equivalent of at least 90,000 tons.

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1.0 INTRODUCTION

"Lateral Track Strength and Panel Shift Test" is a jointly funded project by the Association of American Railroads (AAR) and the Federal Railroad Administration (FRA) under contract DTFR53-93-R-00058. The project addresses lateral track strength and panel shift characteristics as influenced by track infrastructure types and maintenance operations, as well as the techniques for automated measurements of lateral track strength. The project has the following three objectives:

1. Develop performance-based recommendations to optimize slow-order policies for reduced train speeds soon after tamping or similar maintenance operations and to optimize maintenance approaches to ensure adequate track strength.
2. Improve or develop panel shift safety criteria for preventing track misalignment growth and derailments due to excessive and rapid track panel shifting.
3. Develop performance-based test techniques to effectively measure available lateral track strength at the tie-ballast interface and to identify weak spots continuously.

Using AAR's Track Loading Vehicle (TLV), three types of lateral track strength and panel shift tests have been developed to advance the above objectives. The first type of test is a stationary test, under which the track is pushed laterally under constant vertical but increasing lateral axle loads. The other two types of tests are in-motion test modes. One of these requires repeated passing of the TLV over the same track section to determine characteristics of misalignment growth (panel shift) and critical lateral load. The second in-motion test mode is referred to as a stiffness profile (or deflection profile) test and is developed to measure lateral track strength variations along a track under constant but moving vertical and lateral axle loads.

The test program consists of three phases: (1) demonstration tests, (2) fundamental tests, and (3) off-site tests. The first two phases of tests were conducted on test tracks at the FRA's Transportation Technology Center (TTC), Pueblo, Colorado. Test results and findings from these two phases were published in earlier reports and papers.[1-6] The demonstration and fundamental tests focused on the checkout of TLV instrumentation and control for conducting stationary and in-motion types of tests as well as on the studies of the effects of various test parameters on lateral strength and panel shift characteristics. These test parameters included lateral and vertical axle loads, ballast consolidation level, rail longitudinal forces, ballast type, and tie type. During the first two phases, the concept of using the TLV for automated measurements of lateral track strength was developed and shown to be feasible.[1]

Further development of the automated TLV technique for lateral strength measurements, allowing the technique to be applied to revenue tracks, was the focus of phase 3. Effects on track strength of maintenance operations such as tie replacement, ballast tamping, and dynamic stabilization were examined. Phase 3 tests were primarily conducted off-site on revenue tracks. Some additional tests were performed on TTC test tracks. Some of the preliminary test results and findings from phase 3 have been published.[7-9] Test results from all phases have been used as the basis to develop limited recommendations for slow-order policies as implemented following track maintenance work and to optimize maintenance practices for adequate strength. However, because of infrastructure, environmental, and train operation differences across the continent, as well as seasonal changes throughout the year, no single slow-order policy should be suggested for all railroads.

This report documents various tasks and results of Phase 3 of the TLV lateral track strength project. Section 2.0 discusses the TLV methods developed and employed for the project. Section 3.0 describes the development of the prototype technique for automated strength measurements. Section 4.0 covers the effects of track maintenance operations on track strength. And Section 5.0 summarizes the conclusions.

2.0 APPROACHES

This section gives a brief description of the TLV in its application to testing lateral track strength. An earlier AAR research report, R-917, has a more detailed discussion of the TLV electro-hydraulic control system, peripheral load and deflection transducers, and the data acquisition system.[1] The description of several test approaches used for this project and the three types of TLV test methods used are discussed in the following subsections.

2.1 USE OF TLV IN LATERAL TRACK STRENGTH TEST

Exhibit 1 shows the TLV, which was designed and constructed to perform a wide range of tests to enhance and further the understanding of vehicle/track interactions. It consists of a high stiffness load structure (car body) supported by two locomotive trucks and is equipped with a fifth wheel set (load bogie) that is mounted underneath the vehicle center. The load bogie is suspended from the car body and operated by computer servo-controlled hydraulic actuators.

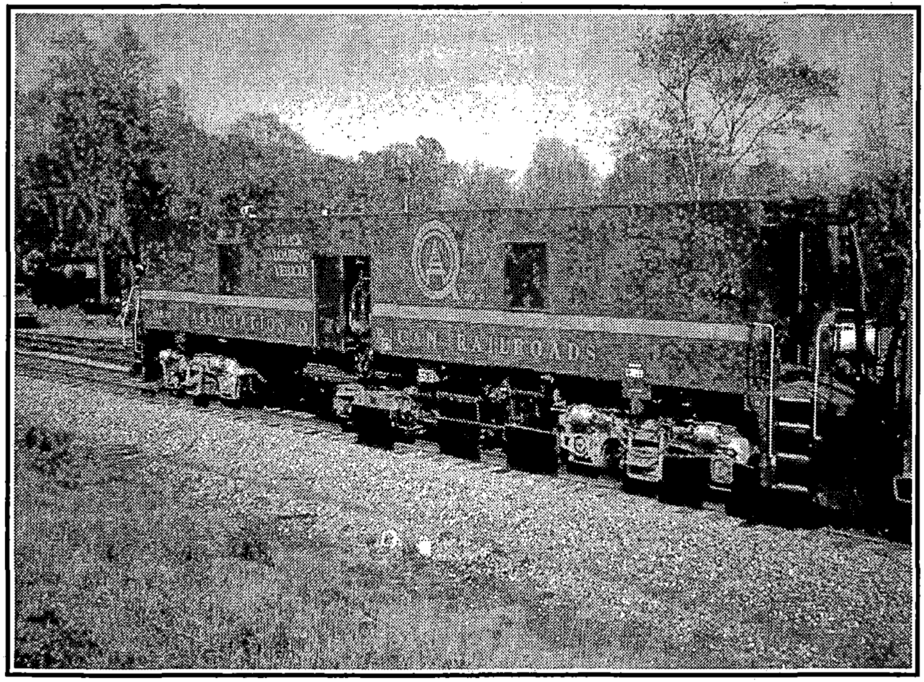


Exhibit 1. AAR's Track Loading Vehicle

To achieve the objectives outlined previously requires the use of the TLV to apply panel shift loads to an actual track, both stationary and in-motion. Exhibit 2 shows the wheel/rail interaction during a lateral track strength or panel shift test. As shown, lateral axle load is applied in one direction in order to generate lateral track deflection (or lateral tie deflection) with respect to the ballast.

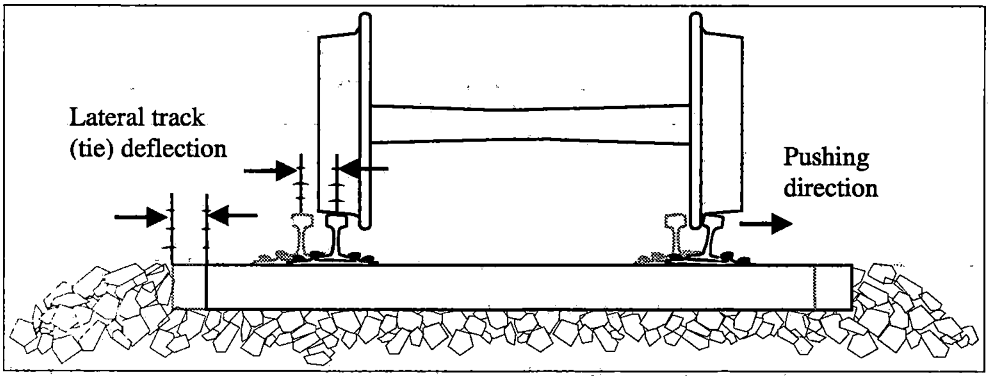


Exhibit 2. Panel Shift Load and Lateral Track Deflection during Lateral Track Strength/Panel Shift Test

Vertical and lateral loads are applied to the track through the bogie frame and a single wheel set by four hydraulic actuators. The main hydraulic system includes two 55-kip vertical and two 39-kip lateral actuators. The vertical and lateral axle loads applied to the track are determined based on the force equilibrium of the load bogie. As a result of the geometric arrangement of the four actuators, the maximum vertical and lateral axle loads, which can be applied to the rails, are approximately two-thirds of the above values.

As shown in Exhibit 2, the lateral axle load is primarily reacted by the pushed rail (the flanged rail), with a small portion of it being shared on the non-flanged rail due to the friction between the wheel and rail. As a result of the lateral axle load distribution between the two rails, the flanged rail will move with respect to the tie as a result of rail bending, roll, and possible translation. However, the non-flanged rail will have insignificant rail to tie movement due to the small lateral but large vertical wheel load applied, as confirmed from tests during phases 1 and 2.[1] Thus, during a lateral track strength or panel shift test, the non-flanged rail will experience lateral deflections similar to those of cross ties.

2.2 TLV STATIONARY TEST

In a stationary test, the following sequence of applying vertical and lateral axle loads is used:

1. Increase vertical axle load to a predetermined magnitude and hold constant (20 kips during all the phase 3 tests).
2. Increase lateral axle load until 0.5-inch lateral track deflection (or 35 kip lateral axle load) is reached.
3. Decrease lateral axle load to zero.
4. Decrease vertical axle load to zero.

Lateral track deflections are defined as lateral tie deflection relative to the ballast and are measured using wayside deflection transducers; i.e., Linear Variable Differential Transformer (LVDTs). Exhibit 3 shows a wayside deflection transducer and fixture. The LVDT is mounted on a steel plate, which is placed on the ballast. A small level is fixed to the plate to ensure that the LVDT is properly oriented. Wayside transducers are always placed on the tie end opposite to the panel shift direction. Because ballast cannot transmit tensile force, the ground (ballast) reference for tie deflections is not changed by track panel movements. All the wayside transducers are portable and are easily set up on the track. Wayside LVDTs are connected to the onboard data acquisition system, thus real time load-deflection curves can be displayed on the computer screen as a test progresses.

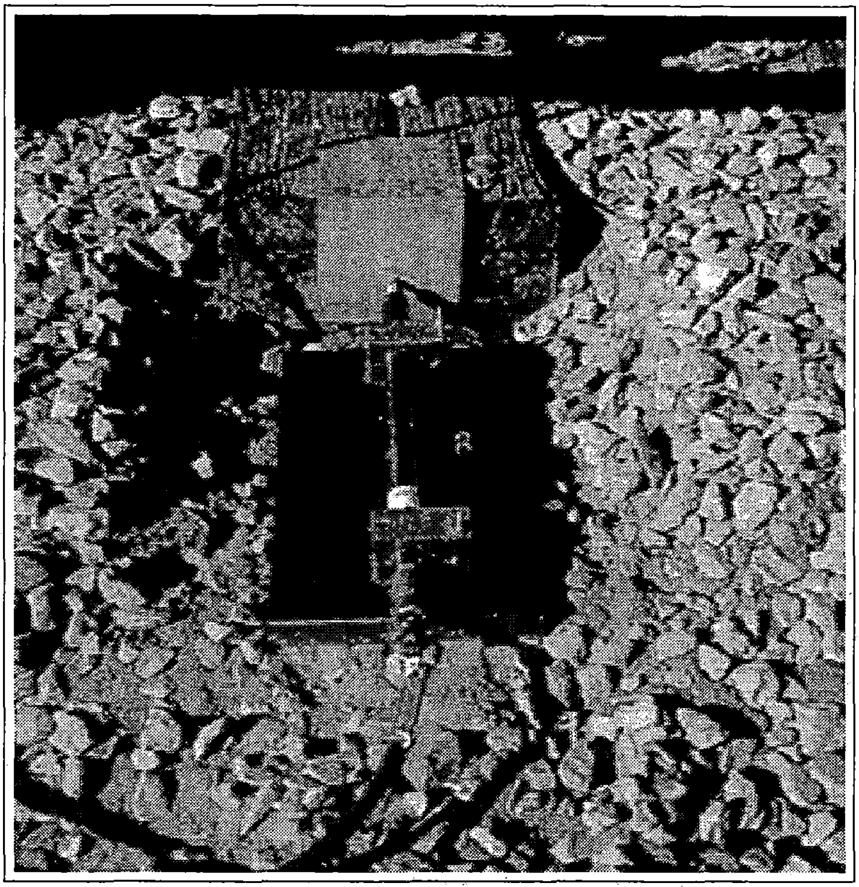


Exhibit 3. Wayside Transducer for Lateral Tie Deflection (Direction of push is into the page)

A stationary test will produce a complete load-deflection relationship, as Exhibit 4 shows. As shown, load-deflection relationships are non-linear. Therefore, they are characterized by using several strength and stiffness parameters.[1] *Stationary track strength* is defined as the lateral load required to produce a given lateral deflection. Effects of various load and track parameters on stationary load-deflection characteristics were studied during phases 1 and 2 tests and were reported previously.[1] Based on the findings from the previous tests, the strength defined at 0.1-inch deflection, $L_{0.1}$, has been used mostly during phase 3 tests as an objective indication of track strength.

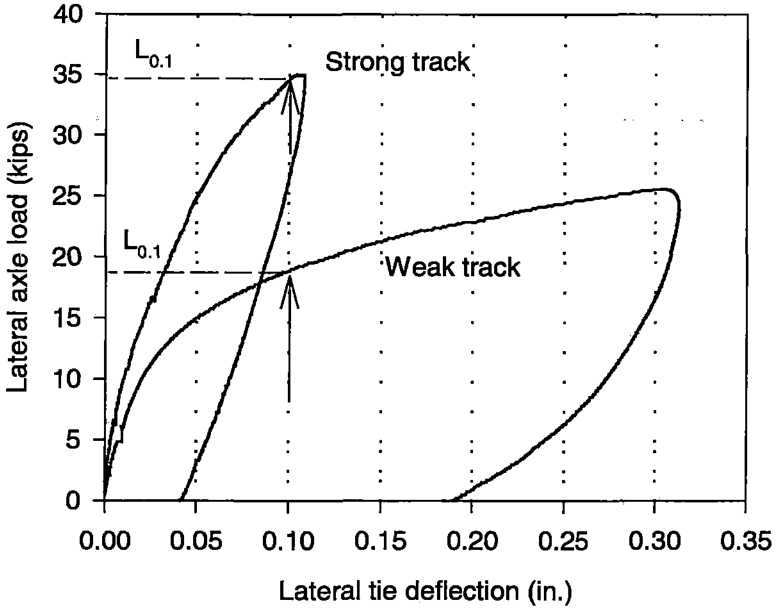


Exhibit 4. TLV Stationary Load-Deflection Relationships

2.3 TLV IN-MOTION STIFFNESS PROFILE (DEFLECTION PROFILE) TEST

Track stiffness profile (deflection profile) testing is designed to obtain the results, as Exhibit 5 illustrates. The approach is to measure the resulting track lateral deflection at a constant ratio of lateral to vertical axle loads (i.e., constant lateral and vertical loads) while the TLV travels. If other conditions are similar throughout a section of track, then any location where the track deflects less will possess higher track strength. In other words, soft spots in tracks will manifest themselves in the form of larger lateral deflections on the deflection profiles.

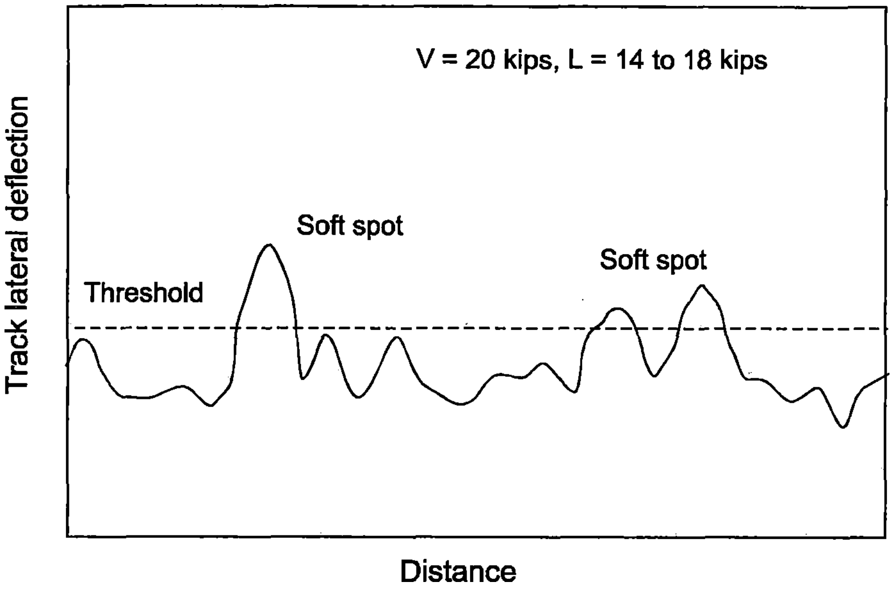


Exhibit 5. In-Motion Lateral Track Deflection Profile

By examining relative magnitudes of deflections along the track, track strength variation can then be estimated. Defining whether a track is "soft" or "strong" requires a comparison of the measured deflection profile to a predetermined "threshold" deflection value. This threshold deflection value must be determined based upon many test results.

The first requirement for this type of test is the application of constant vertical and lateral loads to the track while the TLV is moving. However, a tougher requirement is a feasible and reliable onboard track lateral deflection measurement system. During phases 1 and 2, the feasibility of in-motion strength measurements was successfully demonstrated using a rail-contacting measurement system.[1] However, as will be discussed in the next section, a laser and camera measurement system is more suitable for railroad implementation.

2.4 TLV REPEATED PASSING TEST

Track panel shift, as defined in the earlier report, represents the lateral residual deformation growth (or misalignment growth), as a result of repeated axle passes.[1] With repeated load applications, the accumulation of misalignment can stabilize or it may continue to increase, depending whether a critical lateral axle load is exceeded. When the *critical load* is exceeded, excessive and rapid track panel shift will occur, impacting the safety of train operations.

Repeated passing tests (or in-motion track panel shift tests) yield results, as Exhibit 6 illustrates. Exhibit 6(a) shows the accumulation of residual deformation versus the number of repeated lateral loads; Exhibit 6(b) shows the incremental deformations due to each axle pass. The physical meanings of "incremental" and "cumulative" deformations are illustrated in Exhibit 6(c).

The critical load is defined in Exhibits 6(a) and 6(b). In Exhibit 6(a), the critical load is the load level at which the cumulative residual deformation increases at a constant rate. In Exhibit 6(b), this same critical load is the load level at which the incremental residual deformation is constant as the incremental total deformation increases, during each successive pass. For a stable track, the cumulative deformation becomes constant or increases very slowly, while the increment of residual deformation tends toward zero and the increment of total deformation becomes constant.

In-motion track panel shift testing requires repeated runs of the TLV over the same track zone at constant lateral and vertical axle loads throughout each test series (or groups). Between different test series, however, the combination of lateral and vertical axle loads are changed. This determines the effects of axle loads on panel shift and critical lateral axle load. Lateral track (tie) deflections are measured at selected track locations during and after the load bogie passes. Again, the wayside transducer fixture, as shown in Exhibit 3, is used for lateral deflection measurements. However, unlike a stationary test, wayside measurements are not recorded by the TLV's onboard data acquisition system. Instead, a wayside data acquisition system is used. During phases 1 and 2, extensive repeated passing tests were conducted to study critical lateral axle loads and panel shifts as influenced by test loads and track conditions.[1] No further tests were conducted during phase 3.

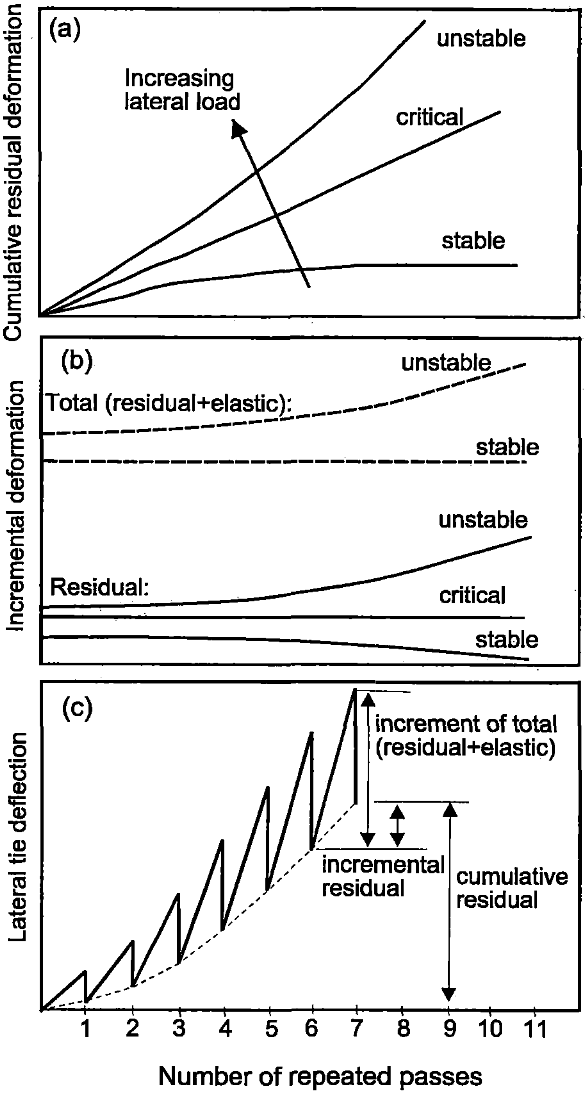


Exhibit 6. Panel Shift and Critical Lateral Load

2.5 SINGLE TIE PUSH TEST

Single Tie Push Tests (STPT) were used simultaneously with some TLV tests for relative comparisons. A STPT measures the ballast resistance to lateral displacement of one tie, which is free of restraint from rails and fasteners, and under zero vertical and longitudinal loads. Unlike TLV test results, STPT results do not include the effects of the entire track panel (rail size, fasteners, longitudinal forces, etc.), nor the effects of vertical axle load on lateral track strength.

3.0 PROTOTYPE TECHNIQUE FOR AUTOMATED STRENGTH MEASUREMENTS

Sufficient lateral track strength at the tie-ballast interface is essential to safe train operation. With low track strength, track misalignment may grow under vehicle loads. A misaligned track with low strength may buckle under high-rail compressive forces, or may shift gradually but excessively due to high lateral loads. To plan and implement early prevention of track buckling and excessive panel shifting, automated inspection techniques are needed to locate weak spots on revenue tracks. An automated inspection technique is also important to optimize track maintenance practices. For example, any track maintenance disturbing the tie-ballast interface will reduce track strength greatly, thus requiring a subsequent speed restriction (slow order). Therefore optimization of specific slow-order policies requires measurements of track strength variations due to track maintenance, dynamic ballast stabilization, and traffic consolidation, as well as theoretical assessments of resulting safety margins.

A significant outcome of this project is the development of a prototype technique using the TLV for automated measurements of track panel strength at the tie-ballast interface. This technique has been applied successfully to identify weak spots continuously along the track and to examine the effects of track maintenance practices on track strength. Tests have been conducted on tracks at the TTC as well as on revenue tracks.

The prototype technique involves in-motion application of vertical and lateral loads to the track and measurement of lateral track deflection profile, as stated in Section 2.3. The following subsections describe the development of the technique as well as its applications to test tracks at the TTC and to revenue tracks.

3.1 FEASIBILITY STUDY DURING PHASES 1 AND 2

The first step toward an automated technique for measurements of lateral track strengths was the concept development and feasibility study. To this end, several test techniques using the TLV were attempted during phases 1 and 2.[1] The stiffness profile test technique was proven capable of measuring track strength variation along the track while the TLV traveled at a given speed. The following is a brief summary of the early development during phases 1 and 2.

During phases 1 and 2, rail contact transducers (LVDT) were used and mounted to the TLV car body for lateral track deflection measurements. Two transducers were installed at the TLV ends, which were used for quantifying car body movements with respect to the non-moving (non-flanged) rail under the TLV ends. The other three LVDTs were installed under the TLV load bogie, where they measured lateral deflection of the non-flanged rail with respect to the car body. Exhibit 7a-b shows these onboard transducers.

Lateral track deflections have always been measured via the non-flanged rail. This allows separation of lateral track (tie) deflection from other possible lateral deflections (due to rail roll, bending, translation, etc.) as experienced by the flanged rail. During the early phases of development, the TLV car body served as the frame of reference for the onboard measurements. Exhibit 8 shows the LVDT mounting frame rigidly attached to the car body. The three transducers at the load bogie measured movements of the non-flanged rail with respect to this rigid reference frame.

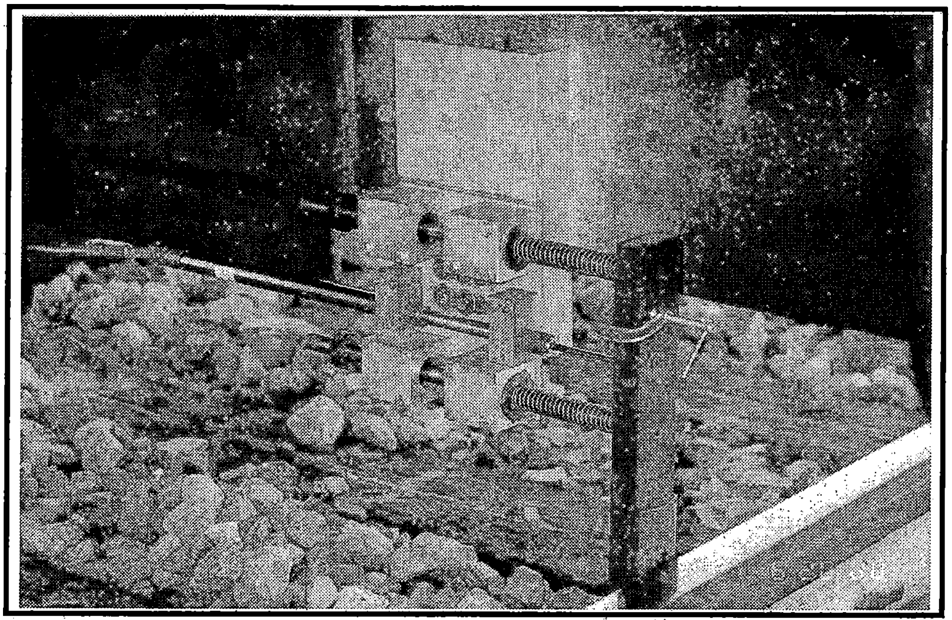


Exhibit 7a. LVDT Fixture at TLV Ends

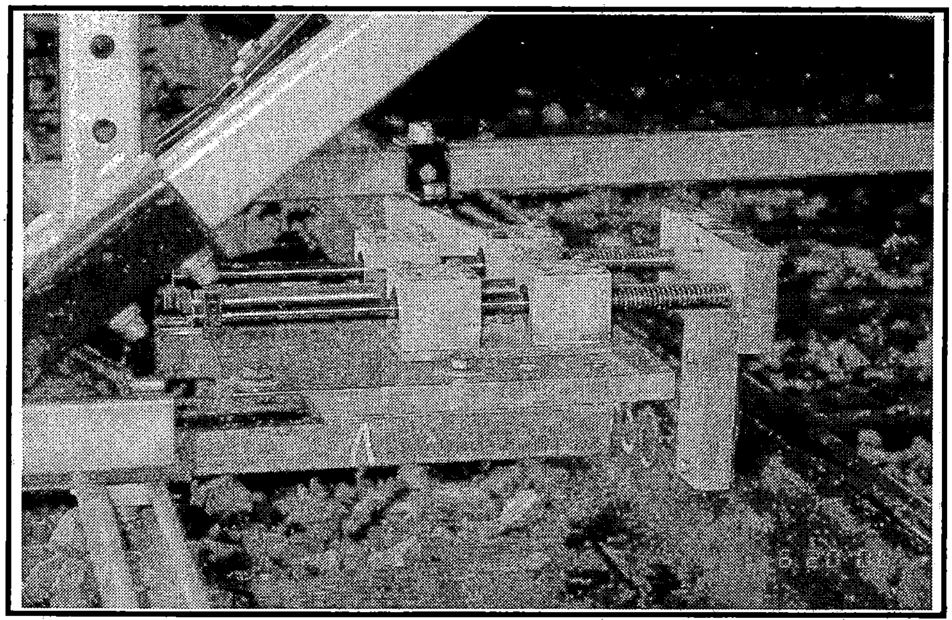


Exhibit 7b. LVDT Fixture at TLV Bogie

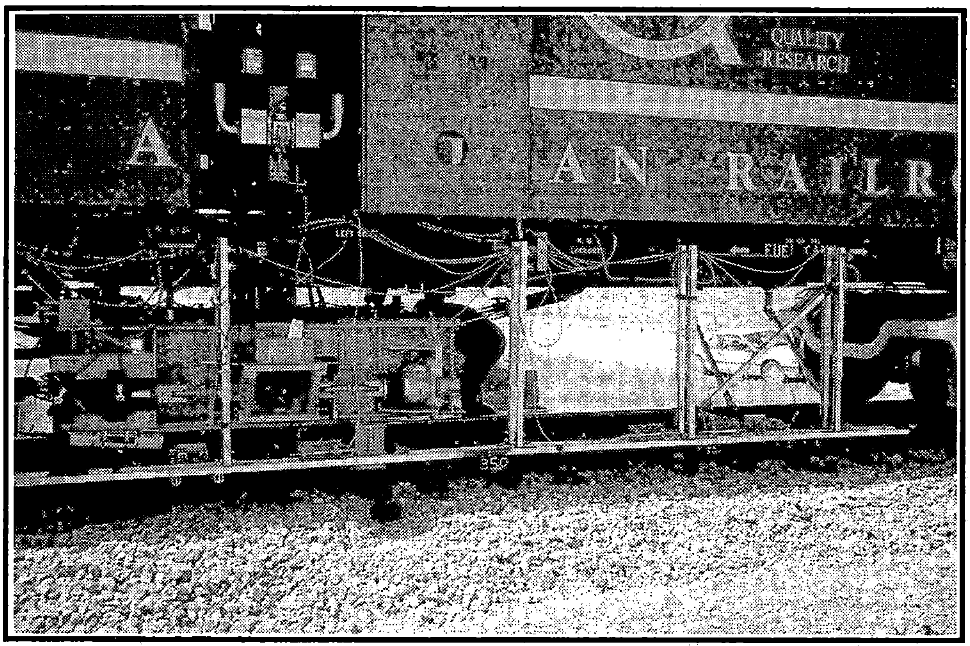


Exhibit 8. TLV Reference Frame Used during Early Phases

Deflection transducers at both ends of the TLV were used to quantify the reference movement. Since the rail under both ends of the TLV does not move in response to the TLV test loads exerted at the center, it was used as a separate reference to quantify the car body movement. Once the car body movements at the front and rear ends of the TLV were defined, the reference frame movements at the TLV load bogie could be determined. The total measurement, seen by the three onboard transducers installed at the TLV load bogie included three components: (1) reference movement, (2) track lateral deflection due to loads, and (3) track initial misalignment. The sum of the last two components — track lateral deflection and initial misalignment — was determined by subtracting the reference movements from the total measurements in real time.

Furthermore, in order to determine the track lateral deflection due only to the TLV lateral load, the initial unloaded track misalignment also needed to be quantified.

To do so, two TLV runs over the same section of track were made. The first run was made without applying lateral load but with the desired vertical axle load. During this no-load first pass, the outputs of the three onboard transducers at the bogie include only two components: (1) reference movement and (2) track initial misalignment. Again, the reference movement was determined by means of the two transducers installed at both ends of the TLV. Therefore, its effects were removed in real-time, leaving a record of initial misalignment only.

The second TLV run was then made using both lateral and vertical test loads. This measurement gave the results of both track deflection and track initial misalignment. By subtracting the initial misalignments determined in the first run from the results determined in the second run, the track lateral deflections due only to test loads were finally be obtained.

As previously reported, this technique was successfully used to measure variations of track strength along a track and to detect created soft zones.[1] Even though the early phase research proved the concept and showed feasibility of using stiffness profile tests to measure track strengths along the track, this contacting deflection measurement method was not suitable for revenue track testing. This method showed difficulties running through track discontinuities such as joints and crossings as well as sharp curves. Further, the requirement of two TLV passes for the same track segment was also not realistic as a strength inspection method on revenue tracks.

3.2 DEVELOPMENT OF LASER MEASUREMENT METHOD

One objective of phase 3 was to improve the method for onboard deflection measurements so that the technique can be applied to revenue tracks. To do so, non-contact laser/camera measurement systems replaced rail contact deflection transducers. Instead of using the TLV car body as the reference, two independent reference frames with similar laser positions were mounted to the lead TLV truck and to the center load bogie, thus avoiding the two-pass requirement during earlier phases. These frame positions also reduced the problems caused by a large car-body reference offsets while traveling in a curve.

The entire system is comprised of six laser/camera sensors. The system was acquired from E. H. Reeves and Associates, Inc., which also provided a VME computer chassis and software for collecting and processing video signals as well as for performing real time calculations of lateral rail movements relative to the sensors.

Exhibit 9 shows one sensor consisting of a laser and camera pair mounted on a reference frame prior to installation on the TLV. Exhibit 10 shows a sensor after the installation. The laser projects a thin beam of light to the rail, which is then covered by laser lines. The camera is used to record the position of laser lines. The video data is then converted to x-y (lateral and vertical) distances measured between the sensor and the rail gage face 5/8 inch from the rail top. The sensor sampling rate is 60 Hz.

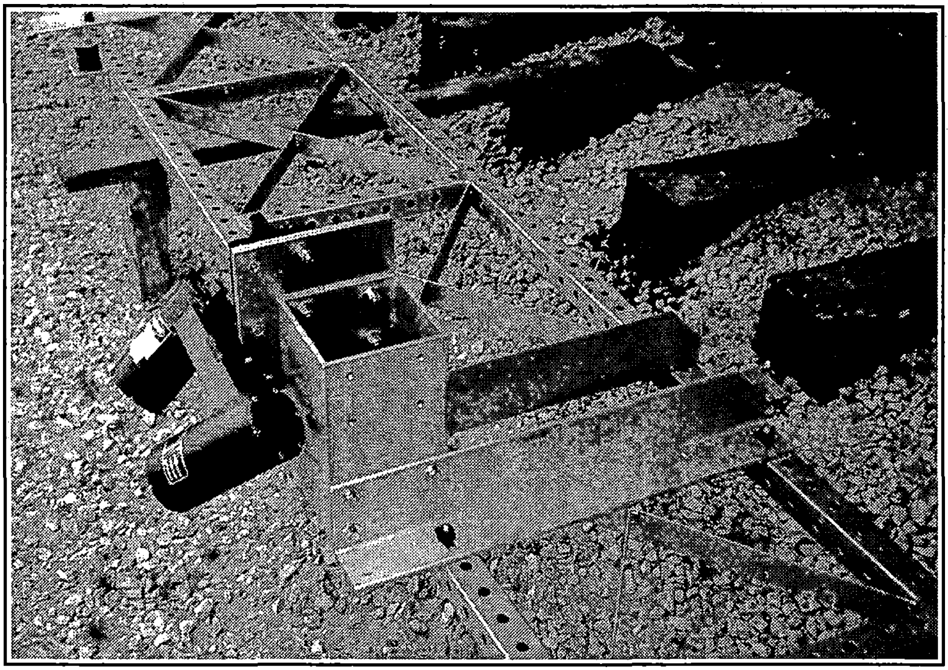


Exhibit 9. Laser/Camera Sensor

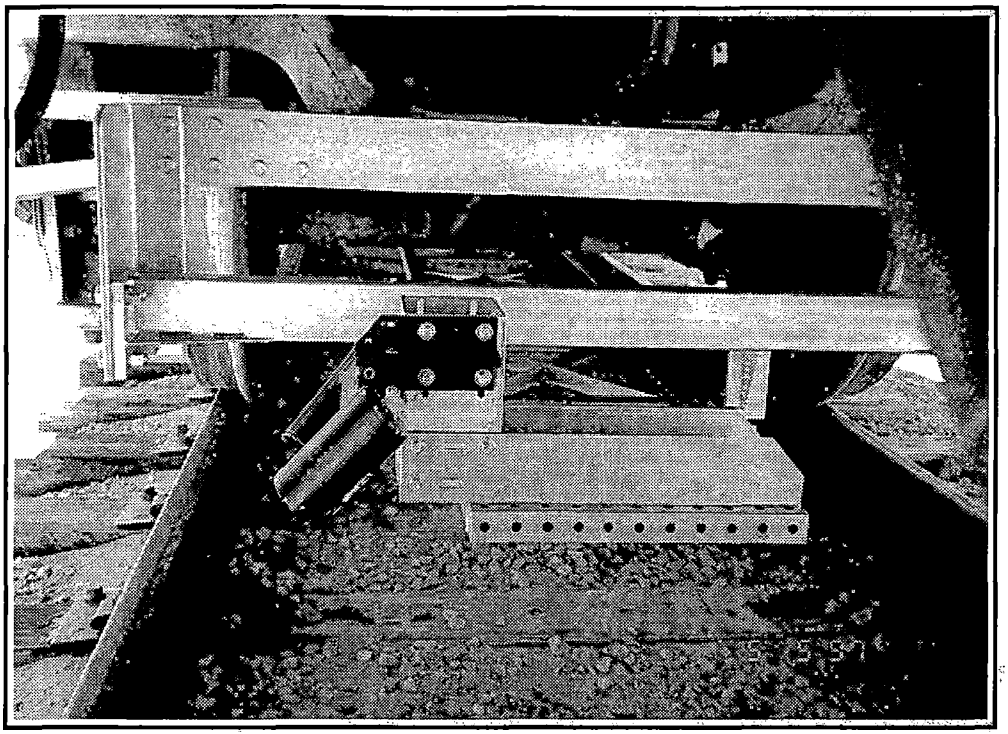


Exhibit 10. Laser/Camera Sensor after Installation

Each reference frame is rigid and equipped with three laser/camera sensors. Exhibit 11 shows one reference frame with three sensors before being mounted to the TLV. Exhibit 12 shows the general arrangement between a reference frame with its three sensors and the TLV load bogie (or the TLV lead truck). The sensors are oriented such that they measure the movements of the non-flanged rail. As discussed, during lateral track movements caused by a lateral test load, the non-flanged rail will move almost the same as the tie directly below.[1] Thus, the lateral movement of the non-flanged rail, as measured by the laser sensors, will represent the lateral track movement.

Each of the two rigid reference frames is resiliently attached to the lead TLV truck or the center load bogie, instead of the car body. This arrangement reduces the sensor range required to cover the distance changes between the rail and the car body.

The three distance measurements between the non-flanged rail and the reference will yield a chordal offset, illustrated in Exhibit 13. The offset equation based on three distance measurements (L_1, L_2, L_3) is also given in this exhibit.

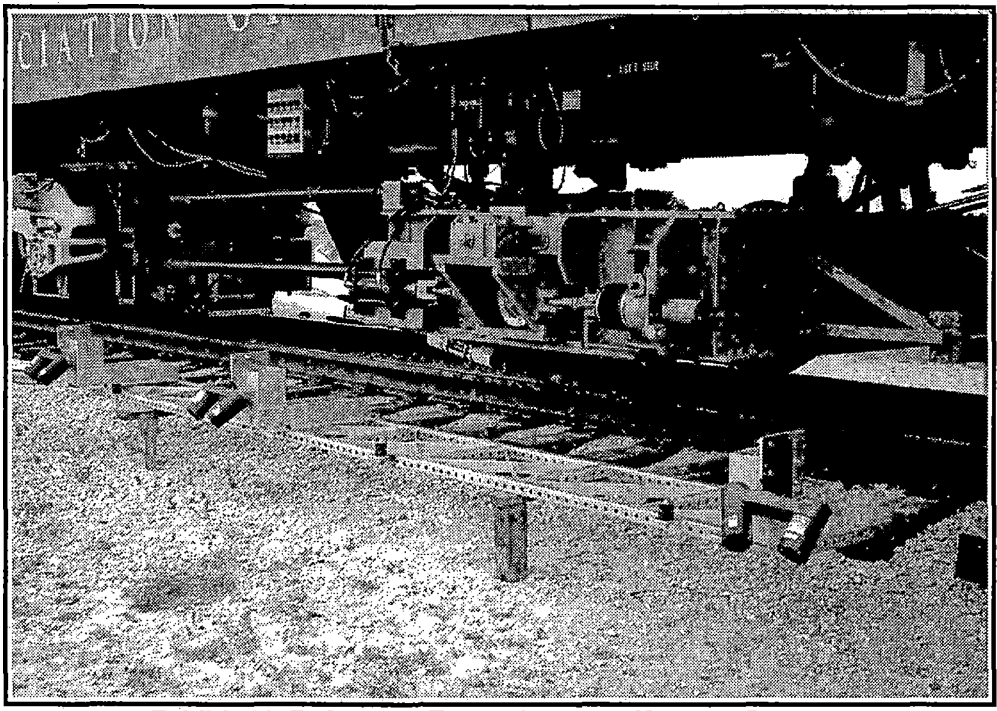


Exhibit 11. Reference Frame for Laser/Camera Sensors

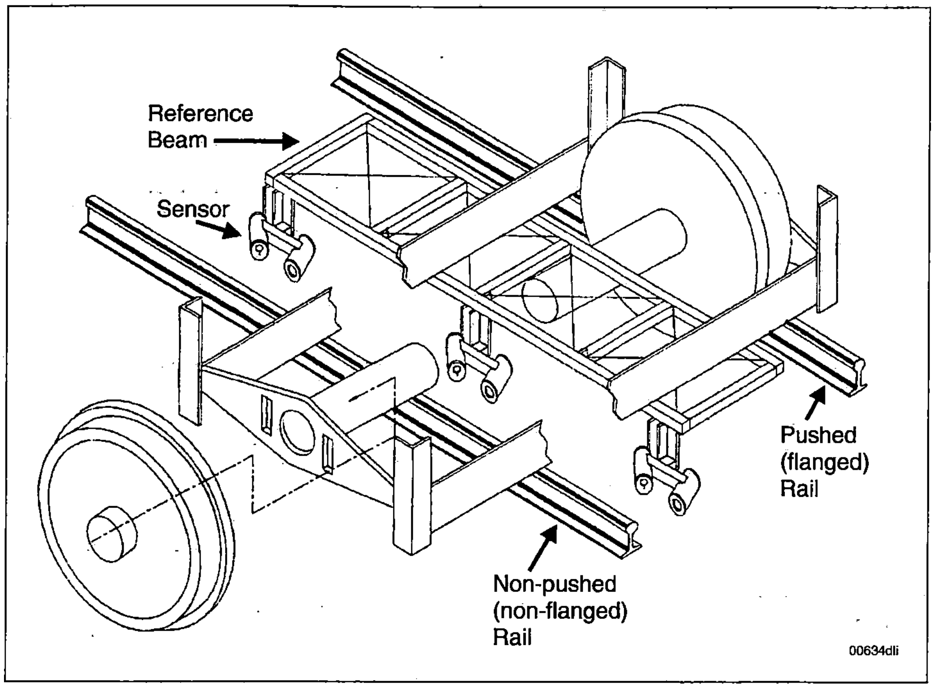
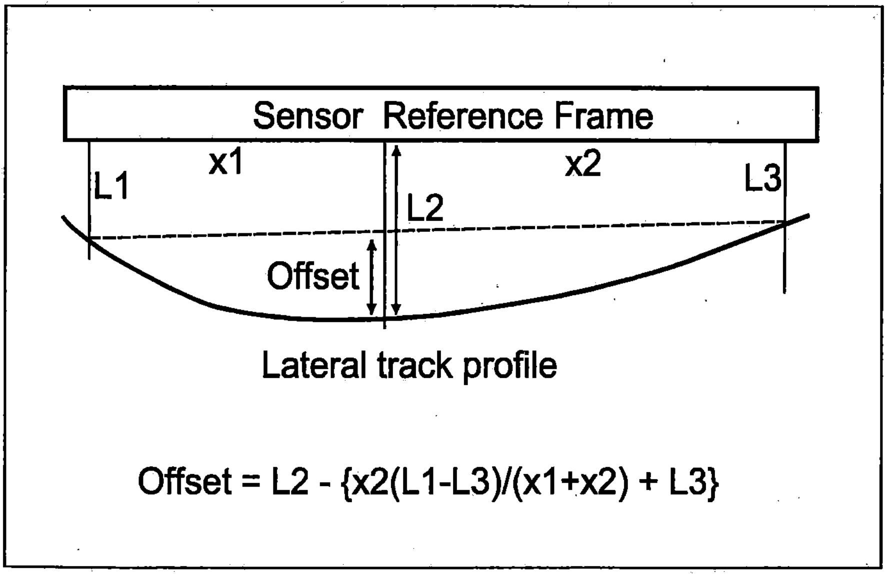


Exhibit 12. General Location of a Reference Frame



$$\text{Offset} = L2 - \{x2(L1-L3)/(x1+x2) + L3\}$$

Exhibit 13. Offset Determination

Exhibit 14 illustrates the offset measurements of the unloaded and loaded track. The front offset measurement system, installed with the lead TLV truck, yields initial misalignment or unloaded lateral track profile. The rear offset system, installed with the TLV load bogie, yields loaded lateral track profile. A synchronized subtraction of offset A from offset B is thus the lateral track deflection due to the TLV test loads. For the constant, but moving, lateral and vertical axle loads, larger track deflections will correspond to lower track strength at the tie-ballast interface.

Notice that offset B corresponds to a point 20 inches ahead of the load axle, thus should always measure smaller value than the one which would correspond to the load axle.

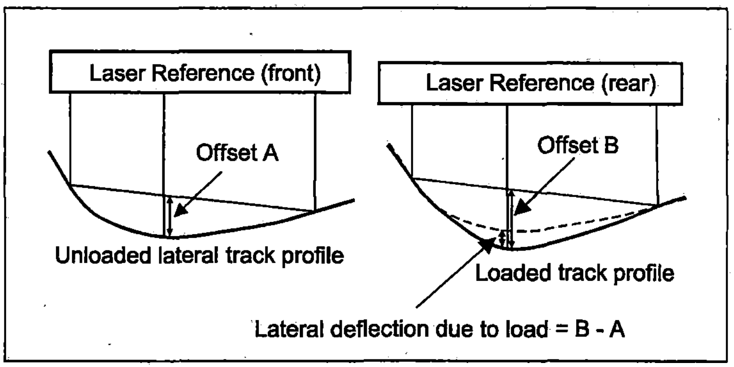


Exhibit 14. In-Motion Non-Contact Deflection Measurement Method

3.3 CHECK-OUT TESTS

After installation of the new laser/camera systems, the following system check-out tests were done:

- Individual sensor checkout
- Three sensor offset output checkout
- Checkout tests during stationary load mode
- In-motion checkout with zero lateral load (offset A versus offset B)
- Loaded in-motion checkout (wayside versus onboard deflections)

Individual Sensor Checkout

The expected (bench) accuracy of the laser sensors is 0.1 millimeter (0.004 inch). For confirmation, each of the six sensors was checked for its distance output by changing the distance between a sensor and a target on the rail. The distance change was recorded via a laser/camera sensor and was also measured manually.

Exhibit 15 shows comparisons between applied distance changes and those measured via sensors for a maximum 2-inch range. The distance increment was 0.25 inch. As illustrated, the 1:1 correlation lines indicate good performance of these six sensors

Exhibit 16 shows comparisons for smaller distance changes of approximately 0.01-inch increments. As illustrated, the correlations between the manually increments and the sensor outputs were not as close to 1:1 as for the larger increments in Exhibit 16. However, all the sensors still showed relatively valid measurements for the 0.01-inch increment distance changes. Notice that the applied distance changes used conventional methods (e.g., shims) and may have introduced some errors by themselves (this is difficult to quantify, however). Therefore, the sensors may be considered to have an accuracy at least 0.01 inch, if not 0.004 inch, as specified. The 0.01-inch accuracy is sufficient for measurements of unloaded and loaded lateral track profiles. The common range of the lateral track deflection generated under the TLV test loads is between 0.02 to 0.2 inch, which is much smaller than both offsets A and B.

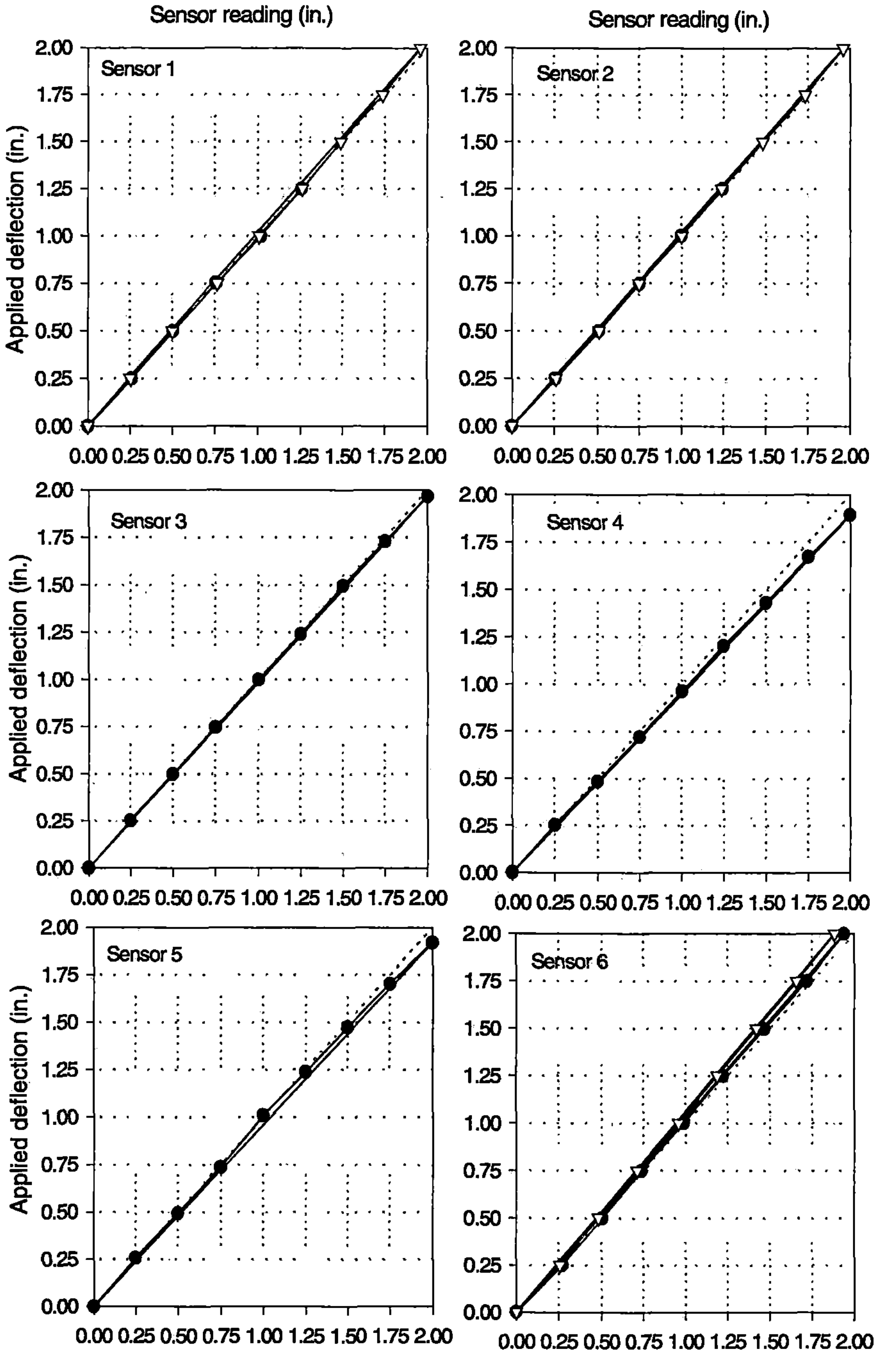


Exhibit 15. Individual Sensor Checkout (0-2-inch range)

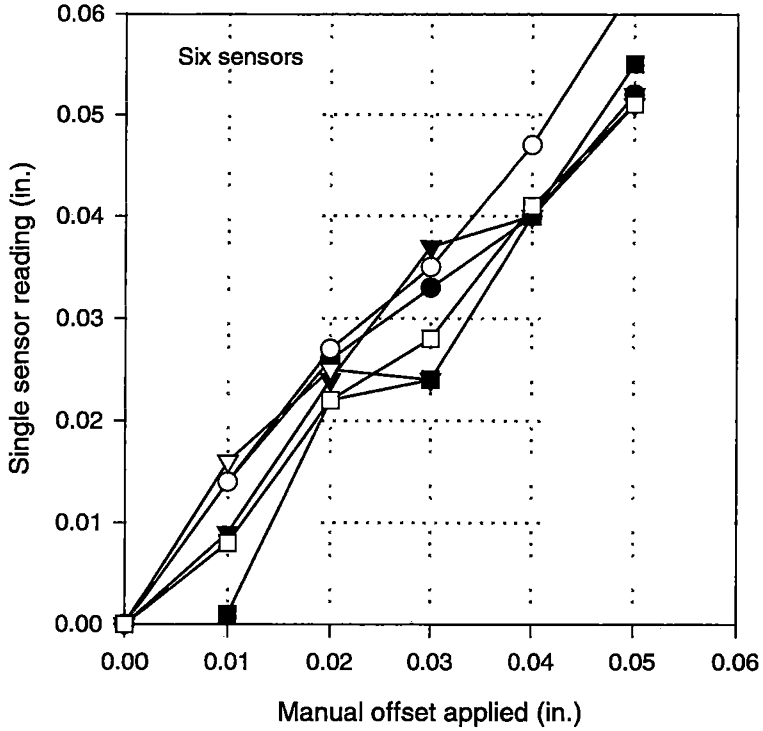


Exhibit 16. Six Individual Sensor Checkout (0-0.05-inch range)

System offset checkout

The offset outputs A and B were checked. Exhibit 13 has shown the calculation of offsets based on three sensor measurements. By using combinations of various shims, various offsets were created for both the front and the rear laser/camera systems. The total range of the simulated offset was approximately 1.0 inch. Changes of offsets varied from 0.1 to 0.2 inch, depending on the combination of shim sizes. Exhibit 17 shows the comparisons between the three sensor outputs and the simulated offsets. The comparison is satisfactory, as shown.

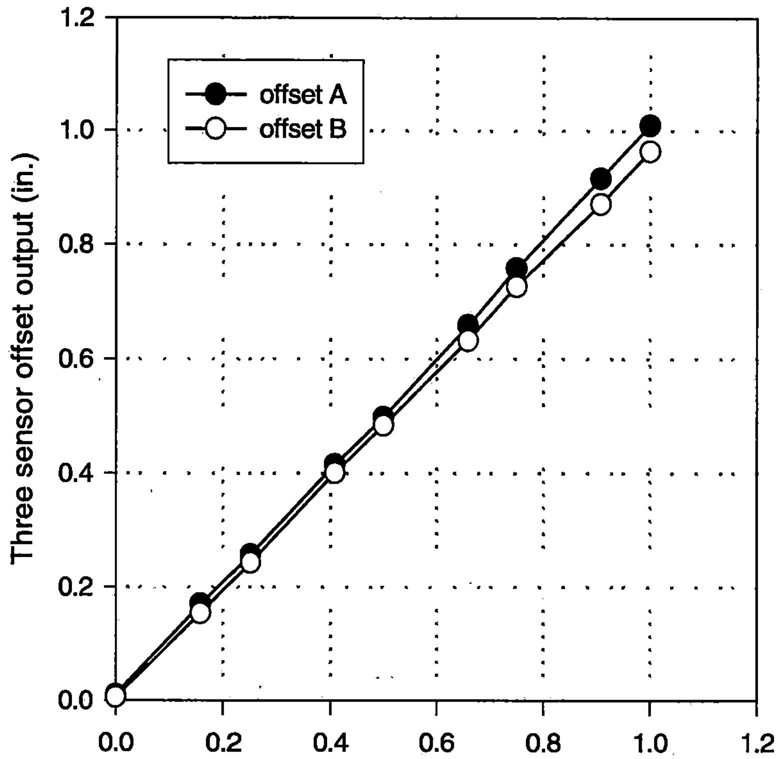


Exhibit 17. Three Sensor Offset Checkout

Checkout tests during stationary load mode

To compare non-contact offset measurements with wayside deflection measurements, checkout tests were run during stationary tests. Measurements included offset B and wayside lateral tie deflections. During these tests, three wayside LVDTs were placed at the tie locations close to the three laser sensors. During the stationary load checkout, any initial misalignment offset was zeroed prior to lateral load application. Under a constant vertical axle load of 20 kips, lateral axle load was increased to produce a desired lateral track deflection of 0.2 to 0.4 inch. For these desired lateral deflections, the two outside LVDTs detected insignificant lateral tie movements. Thus, the three sensor offset B should show actual lateral track deflection.

Exhibit 18 shows a comparison of time histories of onboard offset B and wayside deflection results. As shown, the wayside LVDTs placed near the two onboard end sensors measured deflections less than 0.005 inch. Thus, offset B represented actual crosstie lateral track deflection. The wayside LVDT lateral tie deflection near the middle onboard sensor was acceptably close to the offset B results. The time history signal of onboard offset B, however, was not as smooth as that of the wayside LVDT. The possible reasons may include (1) onboard sensors look at railhead while wayside looks at the tie, therefore as the TLV wheel slides across the rail the onboard system may get jerked somewhat, (2) the railhead is not damped much against lateral vibration or transients, while tie is heavily damped, and (3) onboard offsets are calculated based on three sensor measurements, while wayside is direct output from one LVDT.

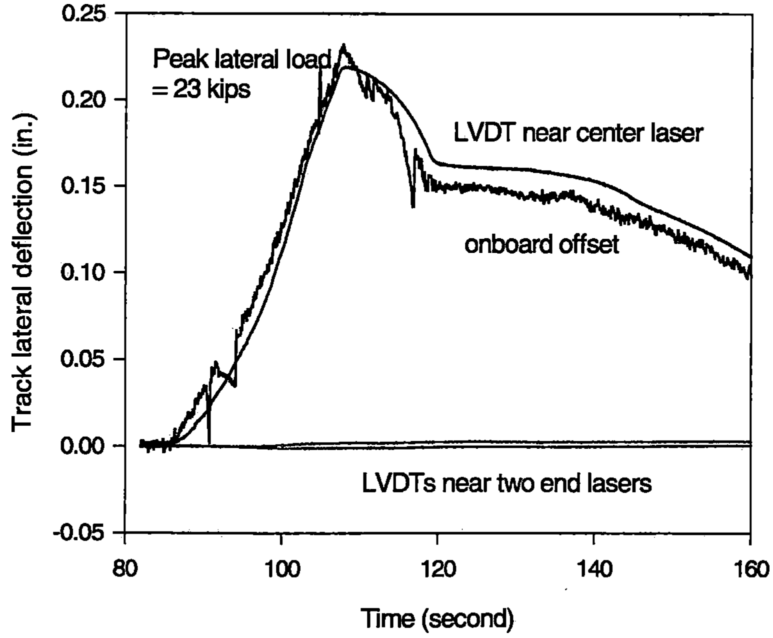


Exhibit 18. Comparisons between Onboard and Wayside Measurements

In-motion checkout with zero lateral load (offset A versus offset B)

Moving checkout tests were conducted to examine if both offsets measure the same unloaded lateral track profiles. Exhibit 19 shows comparisons of the offset A and offset B measurements at speeds of 5 mph and 20 mph, respectively. Both tests were performed through the same track section. As shown, with no external lateral load, offset A was consistent with offset B. Furthermore, the offsets measured at 5 mph and 20 mph were quite consistent. Therefore, during tests with an applied lateral axle load, the difference between offsets B and A should reflect the lateral track deflection due only to the constant lateral test load.

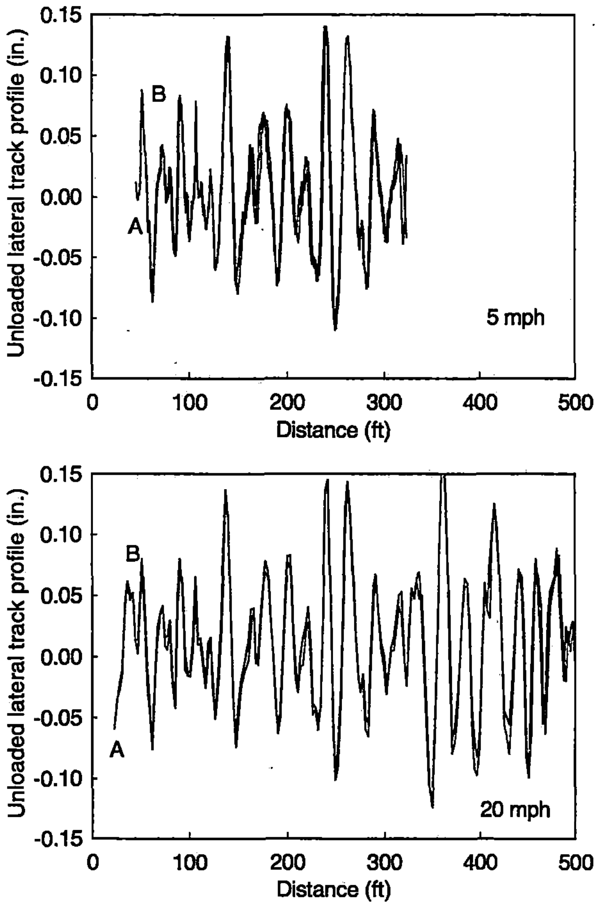


Exhibit 19. Unloaded Lateral Offsets as Measured by Front and Rear Laser Systems (V=20 kips, L=0)

Loaded in-motion checkout (wayside deflection versus onboard deflection)

Final checkout tests were performed to compare the onboard lateral track deflections (offset B minus offset A) with wayside lateral tie deflections under a given lateral axle load. Exhibit 20 shows the test results. The TLV speed was 5 to 8 mph. For an 80-foot test zone, 10 wayside LVDTs were placed on the track. The deflection as measured by each of these LVDTs was compared with onboard deflection profile, at the instant when the center onboard sensor of the rear system passed. As shown in this exhibit, the onboard laser/camera arrays measured similar lateral track deflections to the wayside tie deflections.

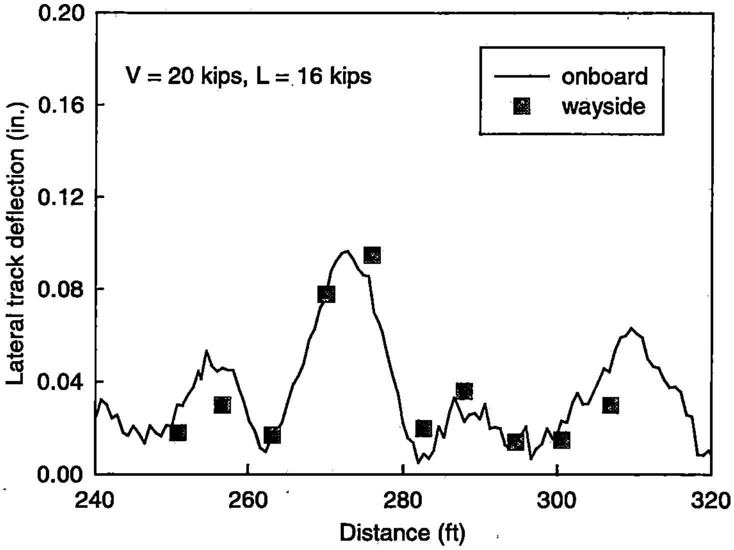


Exhibit 20. Comparison of 10 Wayside LVDTs and Onboard (continuous laser-based) Test Results

3.4 ON-SITE AUTOMATED TRACK STRENGTH TESTS

Tests were conducted on tracks at TTC to examine how well this technique could detect weak spots while the TLV traveled at a given speed. For all the tests, the applied vertical axle load was 20 kips, and the TLV traveling speed was between 5 and 10 mph. To create weak spots on a test track, consecutive ties in several zones were pulled laterally and then pushed back using a speed swing machine. This disturbed tie-ballast interfaces and reduced lateral strengths.

Exhibit 21a illustrates in-motion strength test results from a 350-foot test zone (tangent wood ties). Two weak areas were created in this test zone. As shown, under a lateral axle load of 18 kips, the automated TLV technique easily revealed the two weak areas, which showed much higher deflections than the rest of the test track. To further confirm these in-motion test results, three stationary TLV load versus deflection tests were conducted at selected locations: one corresponding to strong track, the other two corresponding to weak spots. These stationary force versus deflection results are shown in Exhibit 21b. As shown, the stationary test results were consistent with the in-motion test results; that is, locations D and E showed lower strength than location C.

A comparison between the in-motion and stationary test results as shown in Exhibit 21a and Exhibit 21b indicates that the variation of in-motion test deflections are greater than the track strength differences as exhibited from stationary tests. In other words, the in-motion test can better differentiate track strength variation along the track. This is because the magnitude of the generated deflection is non-linearly related to strength, and small differences in strength generally correspond to larger differences in deflection.

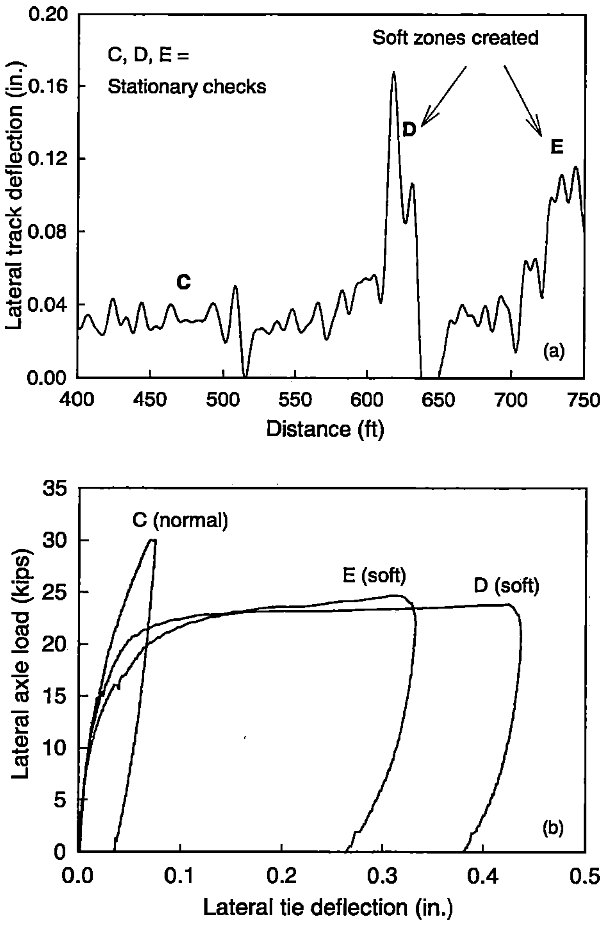


Exhibit 21a&b. In-Motion Test Detection "Soft Zones" (L=18 kips) and Stationary Test Checks

Exhibit 22 gives the in-motion test results with three lateral axle loads (14, 16, and 18 kips) for the same test zone. As shown, all load levels were able to reveal the created soft zones with relatively larger deflections than those yielded in the undisturbed zones. However, for larger lateral axle load runs, the test better differentiated different track strengths.

Exhibit 23 shows more in-motion tests in detecting artificially created "soft zones." The tests were conducted on another test track at TTC. Again, both lateral load levels of 16 and 18 kips were able to show larger deflections in the soft zones.

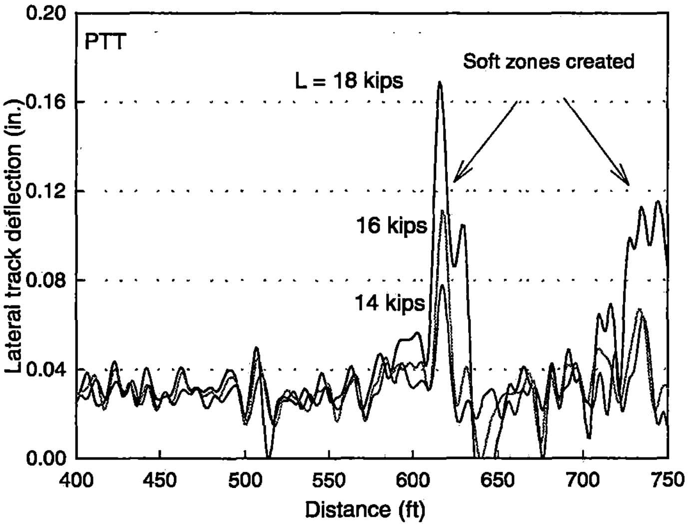


Exhibit 22. In-Motion Tests Deflecting "Soft Zones" (V=20 kips, L=14, 16, 18 kips)

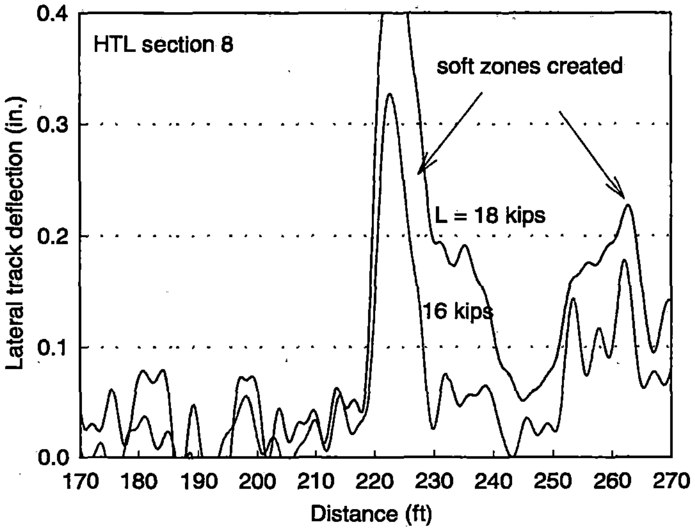


Exhibit 23. In-Motion Tests Deflection "Soft Zones"

3.5 OFF-SITE AUTOMATED TRACK STRENGTH TESTS

The automated TLV strength measurement technique was recently applied to Norfolk Southern (NS) railroad tracks to examine the effects of track maintenance practices on lateral strength. During this revenue track testing, continuous measurements of track strengths were conducted at 5 to 8 mph through various track features including left and right hand curves, road crossings, turnouts, and bridges. The test vertical axle load was always 20 kips. The technique detected weak zones along the track and also quantified the effects of various maintenance practices on track strength. This section gives some examples of track strength variations shown via in-motion TLV tests. More examples will be given in the next section, in conjunction with the discussion on the effects of track maintenance practices.

Exhibit 24 gives an example of deflection profiles (18 kip lateral test load) collected over a track length of roughly 1,200 ft. The first 400 ft (600 to 1000 ft) of this test zone was newly tamped, representing weakened track conditions, while the final 800 ft (1000 to 1800 ft) was tamped and stabilized using a dynamic ballast stabilizer, representing improved track strengths. As shown, the weakened track zone showed higher deflections (or lower strengths) than the stabilized track (0.08 inch average deflection for the non-stabilized track versus 0.03 inch average deflection for the stabilized track).

Exhibits 25 gives another example of deflection profile obtained on a track with as-is condition. As compared to the test results shown in Exhibit 24, the as-is track exhibited lower track deflections (or higher track strengths), except for the zone from 4,000 ft to 4,800 ft, where the track seemed to be much weaker, as shown in larger deflection magnitudes. However, no further investigation was conducted to confirm this weaker zone because there was no track time available.

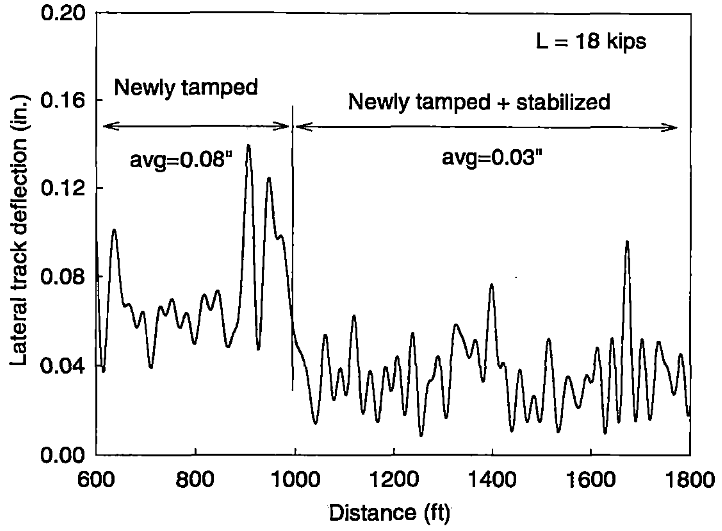


Exhibit 24. Example of Deflection Profiles over Revenue Track

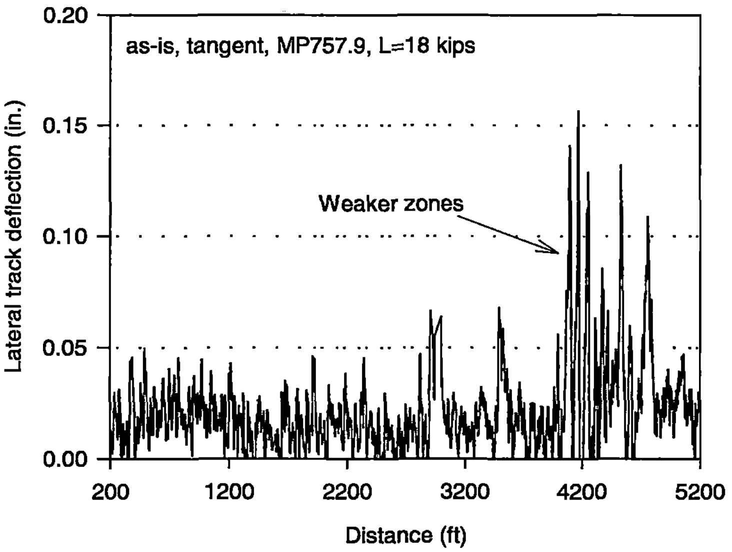


Exhibit 25. Example of Deflection Profiles over Revenue Track

3.6 SUITABLE IN-MOTION TEST LOADS

During various in-motion tests, lateral axle load applied on the track was varied between 14 and 20 kip, with a constant 20 kip vertical axle load. Each of these force levels yielded data capable of differentiating strength variations due to different track conditions. However larger lateral loads resulted in greater differentiation. Based on the tests conducted to date, under a vertical axle load of 20 kip, the test lateral axle load should be between 14 and 18 kip, with 18 kip most suitable for most Class 4 (or better) tracks. However, if anticipating extreme track conditions such as broken rails and welds, lower lateral axle loads of 14 or 16 kip should be used to avoid the potential of generating excessive panel shift.

For continuous welded rail tracks weakened only by ballast tamping, even 20 kip lateral axle load has not generated excessive track shifting during testing, unless this lateral load was applied to the same weak zone more than once. This high lateral load may further weaken a weak track, thus repeated TLV passes over a weak track with a high lateral test load may generate excessive panel shift.

Exhibit 26 shows a second test run pass on NS track using a 20 kip lateral axle load. This section of track had a soft spot near the end of the test zone, which was further weakened by a previous test run using a 20 kip lateral axle load. For this next test, the TLV ran through this soft spot again at 20 kip lateral axle load, causing the track panel to shift several inches. This required immediate maintenance and speed restrictions on trains. The result shown in Exhibit 26 was however obtained before the point of maximum track shift. As illustrated, the measured lateral track deflections had reached 0.4 inch (TLV measurement limit) approaching the spot where the track shifted.

Exhibit 27 shows another large deflection test result during a short NS test, over (unexpected) atypical track conditions. This was performed using 18 kip lateral test load, after tie replacement and surfacing operations, and use of dynamic ballast stabilizer. In addition, a short segment of the non-flanged rail had been replaced by the gang due to a rail break. This segment was inserted into the track using joint bars at either end. In this section of the track, the rail-replacing machinery also caused significant destruction of the (formerly regulated) ballast shoulder. In two areas near the resulting joint bars, 1 to 3 ties were left with less than one-half of their ends covered with ballast. During the test, the TLV pushed against the intact flanged rail, which tends to react most of the lateral load. However, this repaired zone proved to be significantly weaker than other zones. The plot shows that lateral deflection increased to unacceptable amplitudes (greater than 0.2 inch) beginning near the shoulder loss, several feet prior to the first joint bar. The test was aborted; however, a permanent shift was left by the TLV loads and required remedial attention.

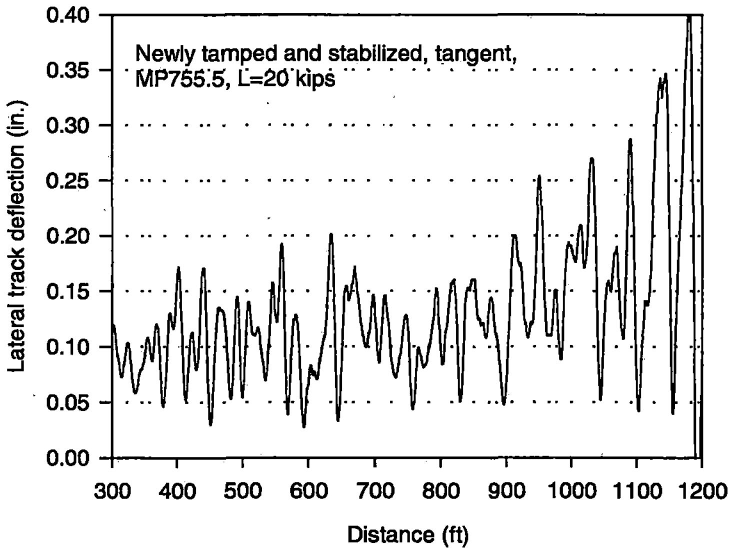


Exhibit 26. Excessive Panel Shift Generated during In-Motion Test

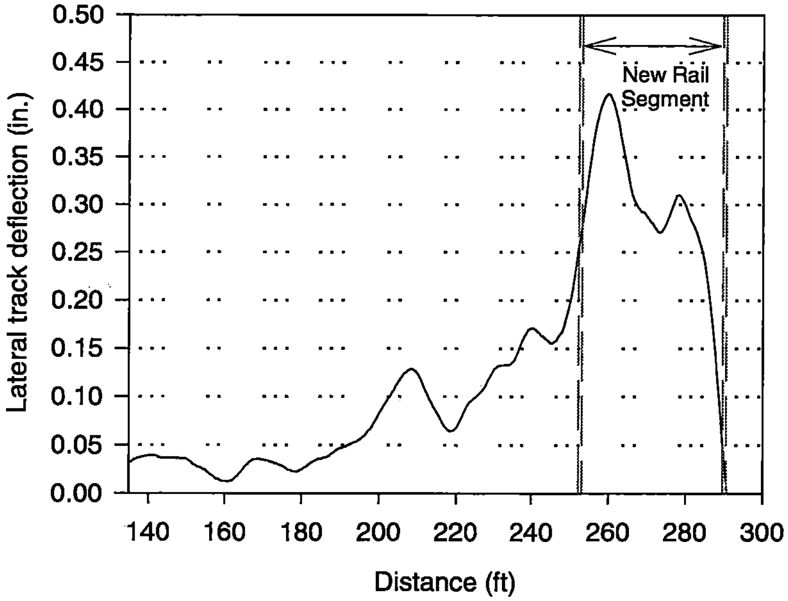


Exhibit 27. Large Track Lateral Deflection at a Location of Rail Repair

3.7 EFFECTS OF TRACK CURVATURE DURING IN-MOTION TESTS

TLV stationary tests have shown that track curvature was not a significant factor affecting *stationary* TLV test results.[1,8] However, during TLV in-motion tests, curvature was found to have significant effect on test results of deflection profiles due to constant but moving loads. This was consistent with the findings from the earlier phases of tests, which showed that a track panel would respond differently depending on whether the forces are stationary or moving.[1]

Exhibit 28a shows a deflection profile obtained on a varying section of NS track, which included two tangents, a 2.1-degree left-hand curve and a 3.1-degree right-hand curve. The track was newly tamped followed by stabilization via a dynamic stabilizer and by consolidation due to one night of traffic (less than 0.05 MGT). The track was therefore considered approximately uniform in its strength. As shown, the TLV-generated deflections were higher in right-hand curves (force toward high rail) than in tangents, and lower in left-hand curves (force toward low rail) than in tangents. At this time, it is not known whether curved track TLV deflections should be interpreted as-is (indicating the curve's net ability to withstand later force components (or whether such deflections should be normalized for curvature (therefore indicating an "equivalent" tangent track strength).

Exhibit 28b shows another test result obtained on NS track. This section of track was at as-is or pre-tamping condition and consisted of a 2.1-degree curve and a tangent. Again, the generated deflections were lower in the left-hand curve than in the tangent. Notice that there was a soft spot (roughly 50 ft long) near 1400 feet into the test zone, as shown by the large deflections. Again, no follow-up test was conducted to confirm this soft zone because of limited track time.

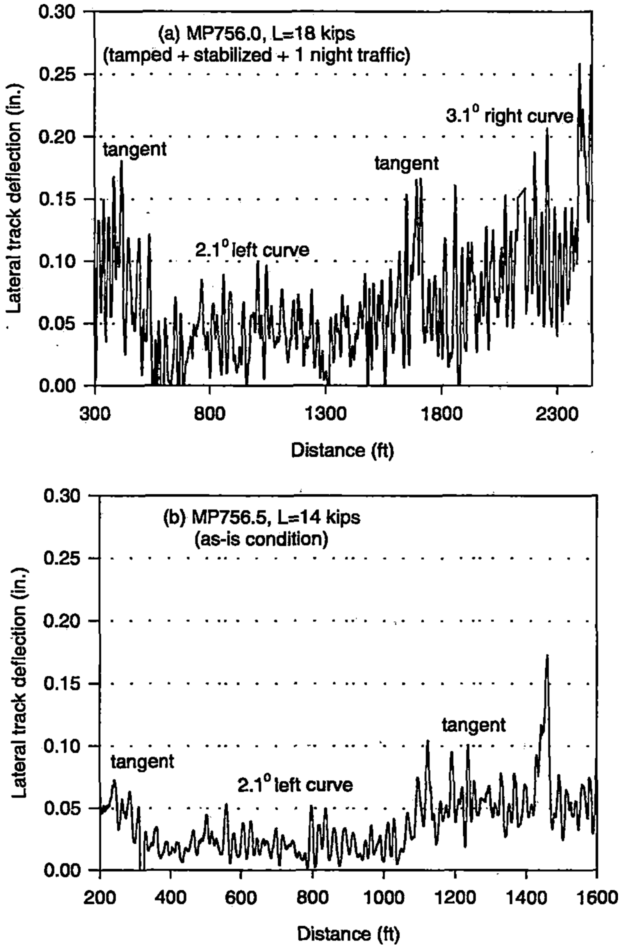


Exhibit 28. Effect of Track Curvature on In-Motion Test Results

3.8 RECOMMENDED FUTURE WORK

The revenue track test series has begun to generate data needed to set exception limits for in-motion TLV track strength tests. However, more revenue track tests are needed to document effects of curvature and rail longitudinal force and to establish thresholds dividing strong and weak tracks, and more data is needed before universal warning and exception reports can be drawn.

A major control system modification should be made to handle cases where the track is so weak or untypical that even 16 or 18 kip of lateral test force can cause unacceptable shift. This safety limit control scheme would immediately reduce lateral force levels if the track deflection appears to be too large.

In addition, several improvements to the laser/camera system are needed. These include better protection against interference from sunlight reflections, a better measurement algorithm to handle cases when a rail lip has formed on the interior gage face, and improved location of the laser/camera assemblies to ensure that the railhead stays within the field of view on curves. Also, the calibration technique should be improved to ensure that the subtraction of unloaded lateral track profile (initial track misalignments) from loaded lateral track profile results in a true zero when no lateral force is applied (currently performed in post-processing).

To date, satisfactory strength test results were obtained at 5 to 8 mph. Future tests will increase speed to 10 mph or above under loaded conditions, depending on the ability of the TLV to maintain constant test loads. As a first step, the laser/camera system showed consistent measurement at 20 mph with no lateral test load.

4.0 EFFECTS OF TRACK MAINTENANCE OPERATIONS

A major side effect of track maintenance operations, such as surfacing and ballast tamping, is the considerable reduction of lateral track strength due to weakened ballast and tie-ballast interface. Speed restrictions (slow-order policies) are implemented immediately following track maintenance to compensate for reduced track strength. These slow-order policies disrupt normal train operations and reduce railroad efficiency. To minimize speed restrictions and return train operation to track speed quickly and efficiently, track maintenance equipment such as dynamic ballast stabilizers are often used to accelerate ballast consolidation.

Many studies have been conducted to quantify the effect of track maintenance operations on lateral track strength.[10-14] However, many questions still remain as to appropriate track strength measurement techniques (e.g., stationary versus in-motion) and the effects of various track parameters on lateral strength. To meet these needs, a major part of phase 3 studied the effects of track maintenance practices on lateral track strength. Extensive tests were conducted to quantify track strength loss due to ballast tamping and strength recovery under traffic or machine-induced ballast consolidation. These test results were then used to develop limited performance based guidelines to improve train slow orders and maintenance techniques while ensuring adequate track strength.

Tests were conducted on test tracks at TTC during the first quarter of 1997. To include revenue-service conditions, extensive tests were conducted on NS tracks, first near Oakvale, West Virginia, in June 1997, then near Birmingham, Alabama, in February, 1998, and finally near Poplarvillie, Mississippi, in March 1998.

The TLV stationary and in-motion techniques described previously were used for these tests. In addition, some STPTs were performed.

4.1 ON-SITE TESTS AT TTC

Data collected between January and March 1997 on TTC's Heavy Tonnage Loop was used to determine the effect a dynamic ballast stabilizer has following ballast tamping. Lateral track strengths with different tie types at newly tamped and consolidated ballast conditions also were examined.

The single pass TLV in-motion test technique was used during the on-site tests. The constant lateral and vertical axle loads were 16 and 20 kips, respectively, while the TLV traveled at 2 to 5 mph. Since the onboard laser measurement technique was not ready at that time, 12 lateral track deflections were measured using wayside LVDTs spaced throughout zones approximately 150 feet long. Within each test zone, wayside deflection transducers were placed at 12 tie locations separated by 6- to 10-tie intervals. The averages of the 12 resulting peak deflections were then used as indications of lateral track strength. As discussed earlier, a strong track would deflect less than a weak track.

Newly tamped or installed ballast with different ties

Exhibit 29 shows the results of lateral track deflections generated during in-motion TLV tests for three ballast consolidation conditions. The track structure consisted of wood ties, cut spikes, and granite ballast on this portion of the HTL. An average maximum deflection of 0.05 inch was measured for the well consolidated ballast. The largest average deflection of roughly 0.19 inch was measured for the newly installed ballast. This variation indicates a significant difference in track strength between the well consolidated and the newly installed ballast. The third ballast condition resulted from ballast tamping with a rail lift of 0.5 to 1 inch. As shown, the loss of track strength was also significant, as indicated by a deflection magnitude of 0.15 inch, which was nearly as much as for the newly installed ballast. In other words, the track strength loss due to a 0.5- to 1-inch rail-lift tamping was close to the loss due to complete ballast replacement.

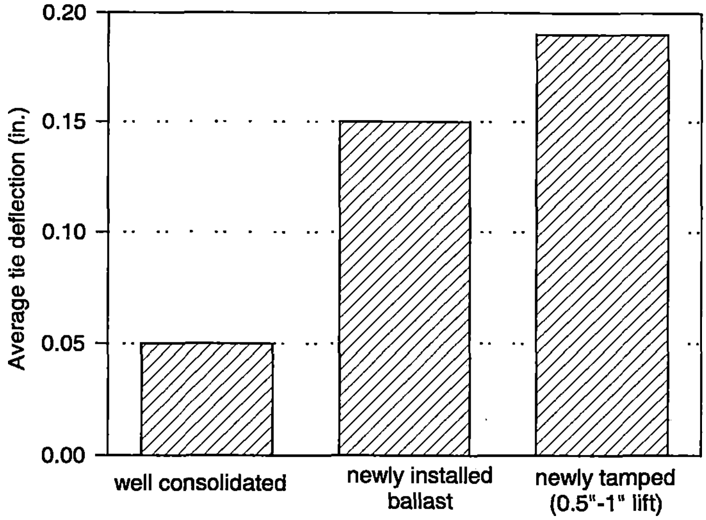


Exhibit 29. Effects of Ballast Tamping on Average Lateral Track Deflection due to One-Pass Constant Moving Lateral and Vertical Loads (Wood Ties, Cut Spikes and Granite Ballast)

Using a baseline track with well consolidated ballast and wood ties, lateral track strengths for five other cross-tie types are compared in Exhibit 30. These five sections of tracks all had newly installed granite ballast, but different tie types (19.5-inch tie spacing for wood and steel ties and 24-inch tie spacing for concrete ties). Except for the section where T-shaped steel ties were intermixed with wood ties (steel ties installed at every third tie locations), the other four sections had ties installed out-of-face. For each section, the average of peak deflections measured through 12 LVDTs was obtained under constant one-pass moving lateral and vertical TLV test loads. As shown in this exhibit, the wood-tie section had the largest lateral deflection due to the moving load; i.e., the lowest track strength. Other sections with concrete and steel ties (inverted trough types) showed much lower track deflections; i.e., higher lateral track strength. However, the section with intermixed T-cross section steel and wood ties showed deflections almost as much as the wood tie section.

Exhibit 31 shows the companion test results performed using single tie push testing. As illustrated, these STPT results(averages of six STPTs for each section) are consistent with TLV test results shown in Exhibit 30.

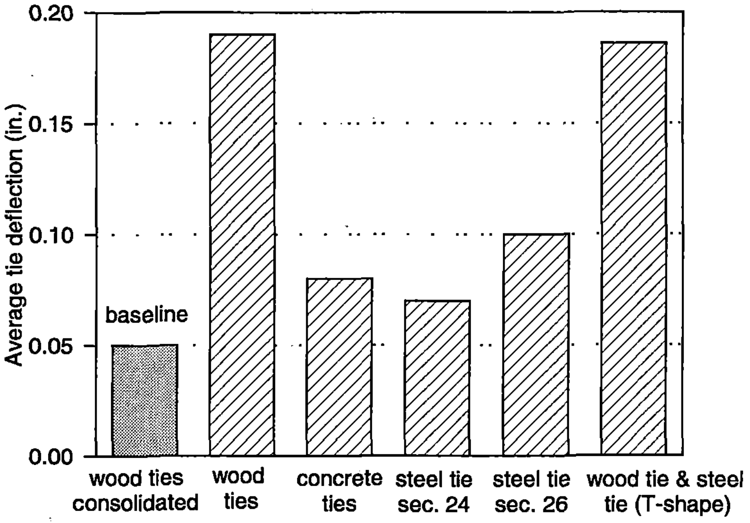


Exhibit 30. Comparison of Lateral Track Deflections due to Constant Moving Lateral and Vertical Loads for Newly Installed Tracks with Different Tie Types

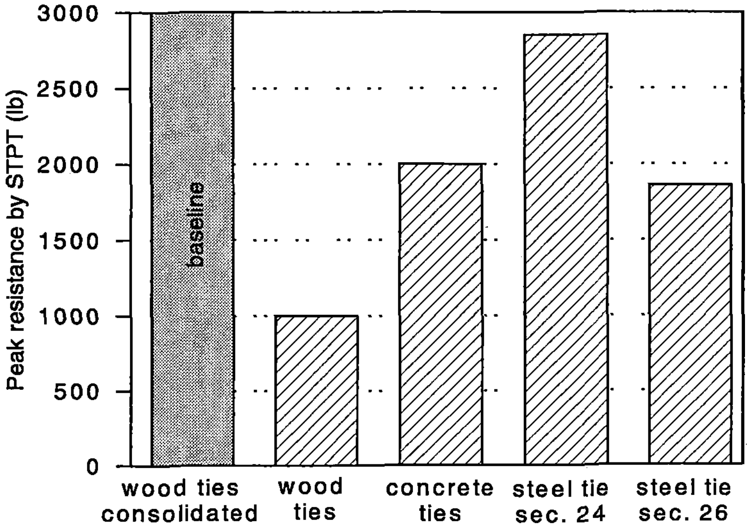


Exhibit 31. Comparison of STPT Results for Several Newly Installed Tie Types

Traffic and stabilizer induced-ballast consolidation

Exhibit 32 shows restoration of track strength induced by train traffic following ballast tamping or installation (dash line). It shows that the newly installed ballast suffered a large strength loss (i.e., a large increase in deflection) relative to the fully consolidated condition. Of that loss, most was recovered with 0.5 MGT of heavy-tonnage traffic on the HTL. However, previous TLV tests on a different type of ballast (with a similar track structure) showed that up to 4 MGT was required for a similar degree of strength recovery (and up to 9 MGT was required to fully develop the lateral track strength).[1] In other words, traffic induced strength recovery depended on ballast type and characteristics. One possible explanation is that ballast with different gradation, shape, and unit weight may settle differently and consequently consolidate differently under traffic.

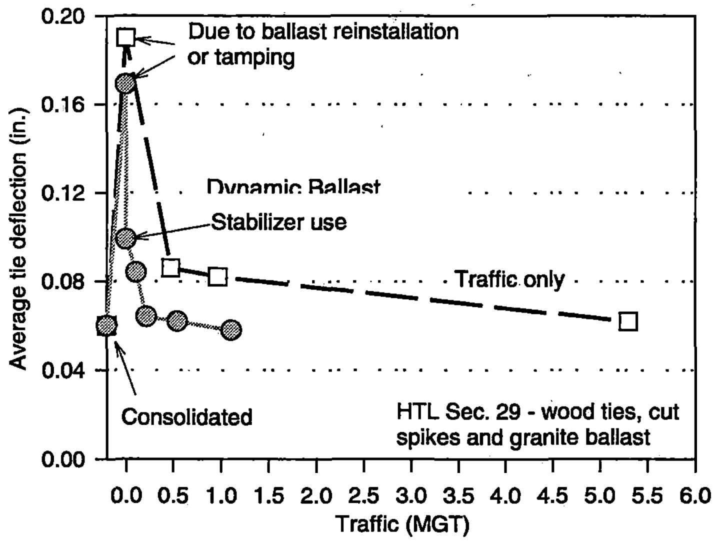


Exhibit 32. Effects of Ballast Tamping, Traffic- and Stabilizer-Induced Ballast Consolidation on Lateral Track Deflections due to Constant Moving Lateral and Vertical Loads

The effect of a dynamic ballast stabilizer on track strength was studied. The stabilizer was loaned to TTCI from Union Pacific Railroad and is a Plasser type PTS-62. The stabilizer was operated by Union Pacific staff in cooperation with Plasser American Corporation representatives.

Exhibit 33 gives the results obtained from tests conducted on the HTL (wood ties and mixed granite/traprock ballasts). Average deflection results obtained on the tangent track and a 5-degree curve track are compared with well consolidated, newly tamped (5-degree curve, skin-lifted) or newly installed (tangent), and tamped and stabilized ballast conditions, respectively. Again, for both the tangent and curve tracks, tamping or new installation caused significant track strength reductions. This was exhibited by significant increases in lateral track deflection under the constant but moving vertical and lateral axle loads applied by the TLV. Use of the stabilizer on both the tangent and curved tracks led to a significant stabilizing effect on the ballast weakened by tamping. This effect is shown by smaller measured track deflections following stabilizer use than those measured on newly tamped or newly installed tracks.

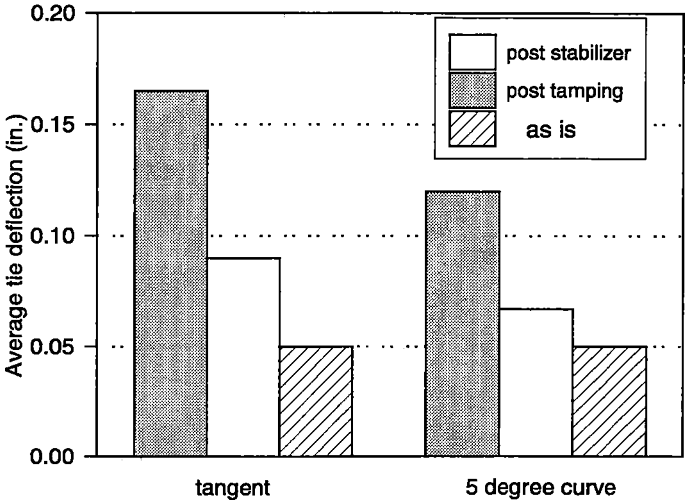


Exhibit 33. Effect of Dynamic Ballast stabilizer on Lateral Track Deflection due to Constant Moving Lateral and Vertical Loads (Wood Ties, Cut Spikes and Mixed Granite/Traprock Ballast)

The equivalent effect of the stabilizer action due to train traffic was estimated based on the test results obtained on Section 29 of the HTL (Exhibit 32, solid line). Use of the stabilizer on the newly tamped granite track led to a strength recovery roughly in the range of 0.1 to 0.3 MGT of traffic. Furthermore, with an additional 0.2 MGT of subsequent traffic following use of the stabilizer, the track was almost fully restored to its pre-tamping strength.

However, benefits of a dynamic stabilizer may be compromised if the stabilizer does not function to its specifications. An assumption that proper stabilization will occur whenever ballast is visibly shaken is unfounded. Some preliminary tests conducted on the HTL following initial use of an improperly adjusted but "still-vibrating" stabilizer demonstrated this.

Also, our limited tests concerning the stabilizer application on a newly tamped concrete-tie track suggested that more tests are required before sound conclusions can be drawn.

Exhibits 30 and 31 showed the comparison of track strength results for sections of various tie types under newly installed ballast conditions. These results showed that different tie types led to different initial track strength. However, as ballast becomes consolidated, the difference in track strength due to different tie types will be lessened. This is shown by the test results in Exhibits 34 and 35 (TLV and STPT results). As can be seen, for three indicated tie types, the post-traffic differences shown are generally much smaller than those shown in Exhibits 30 and 31.

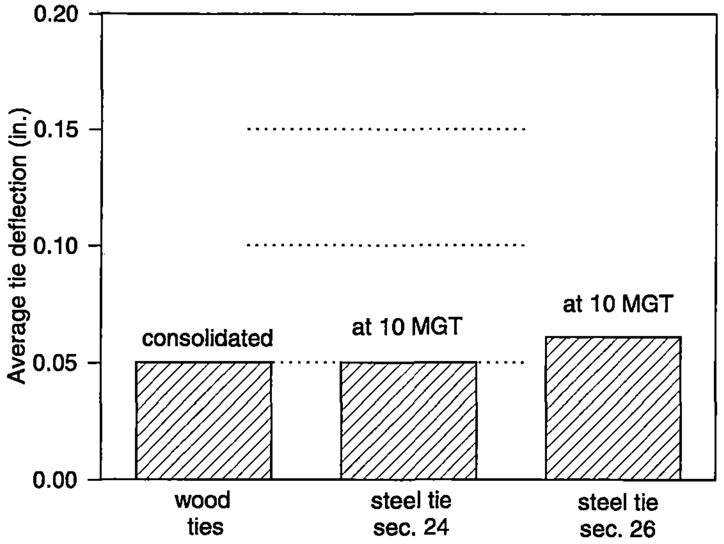


Exhibit 34. Comparison of Lateral Track Deflections due to Constant Moving Lateral and Vertical Loads for Consolidated Ballast with Different Tie Types

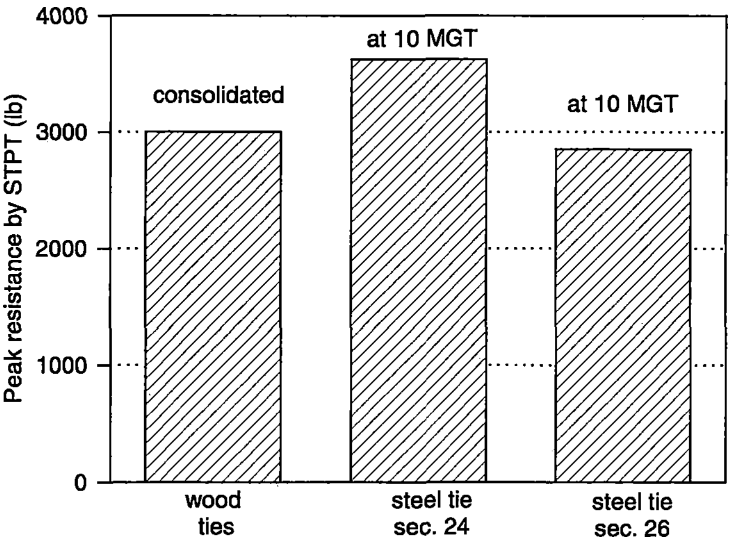


Exhibit 35. Comparison of STPT Results for Consolidated Ballast with Different Tie Types

Summary of TTC on-site test results

Track lateral strength was reduced significantly by ballast tamping operations even if the rail lift was relatively small (0.5 to 1 inch). The traffic induced strength recovery following tamping depended upon ballast type and its characteristics. Tests on TTC's granite ballasted track showed that most of the strength loss was restored within 0.5 million gross tons (MGT). However, previous tests on a different type of ballast showed that approximately 4 MGT was required for a similar degree of strength recovery.[1]

Dynamic ballast stabilizers significantly accelerated ballast consolidation and strength recovery on wood-tie track. Test results on wood-tie track with granite ballast indicated that use of a dynamic stabilizer following tamping produced ballast consolidation resulting in a strength recovery roughly in the range of 0.1 to 0.3 of heavy axle load traffic at TTC. As reported below, revenue track results indicated lower values for equivalent traffic than at TTC.

Various tie types affected initial track lateral strength more than they affected consolidated track strength. With newly installed ballast, both concrete and steel ties (inverted trough types) showed significantly greater initial strength than wood ties. However, this difference decreased as the ballast became consolidated.

4.2 NORFOLK SOUTHERN 1997 TESTS (OAKVALE, WEST VIRGINIA)

To expand the database obtained on TTC tracks, further TLV tests included revenue-service conditions. The first revenue track strength testing was conducted in June 1997. NS hosted this test series, in conjunction with a regular NS track maintenance (tie-replacement and surfacing) operation. Although current NS T&S operation does not normally include a dynamic ballast stabilizer for the purposes of this project, NS added this in certain test zones.

TLV tests were conducted on NS tracks immediately before and after tie replacement (20 to 25 percent) and ballast tamping, as well as immediately following ballast consolidation via traffic and via a dynamic ballast stabilizer.

Track maintenance and TLV tests

During the period June 9–12, 1997, stationary TLV tests were conducted on Class 4 NS mainline tracks near Oakvale, West Virginia. Tests were scheduled in conjunction with the NS tie-replacement and ballast-tamping operations. Of existing ties, 20 to 25 percent (higher percentage for the curves but lower for the tangents) were being replaced with new hardwood ties. Exhibit 36 shows the TLV on the NS revenue track with new ties ready at wayside.

Exhibit 36 TLV Track Strength Testing in Conjunction with Track Maintenance in NS track

TLV track strength tests were performed between Mile Posts (MP) N345 and N350. This track consisted of 136-pound, continuous-welded rails, granite ballast, wood ties with cut spikes (two spikes per plate on the tangent versus five per plate on the curve), both before and after the maintenance. A pair of rail-anchors was used for every other tie on the tangent, and for every tie on the curve. NS specifies a ballast shoulder minimum width of 6 inches for tangent track and 12 inches for curves, respectively. Tests were conducted immediately before and following tie replacement and ballast tamping (June 9 and 10, respectively). Although its use was not part of the scheduled maintenance operations, a dynamic ballast stabilizer (Plasser PTS-62) was applied immediately following tamping in several track zones for TLV strength tests on June 11. The stabilizer was operated by NS personnel and examined by Plasser personnel immediately prior to the test. In addition, TLV tests were conducted at post-gang traffic accumulations of 0.04 and 0.1 MGT (June 11 and 12, respectively).

TLV tests were conducted on both tangent and curved (5- to 9-degree) tracks, for four tie-ballast interface conditions: (1) consolidated (prior to tie replacement), (2) weakened due to tamping, (3) stabilized, and (4) traffic-consolidated. At curves, the lateral TLV load was always applied toward the outside direction. For each tie-ballast condition, a total of 15 to 25 stationary tests were completed. The minimum distance between two adjacent test locations was 50 feet. During a stationary test, the TLV load bogie maintained a constant vertical axle load of 20,000 pounds on the track, and applied an increasing lateral load to push the track panel relative to the ballast. The track panel displacement was measured as tie deflection relative to the ballast using transducers placed at three consecutive tie-ends nearest the load axle.

Exhibit 37 shows examples of TLV stationary test results (load-deflection curves) obtained following replacement of approximately 25 percent of ties and ballast tamping. For most TLV tests, the track panel was pushed to 0.3-inch maximum deflection. TLV stationary strength values are defined as the lateral axle load necessary to achieve certain magnitudes of lateral track deflection such as $L_{0.05}$ (0.05-inch deflection) and $L_{0.1}$ (0.1-inch deflection). To account for measured strength variations at different test locations, mean and standard deviation values have also been analyzed.

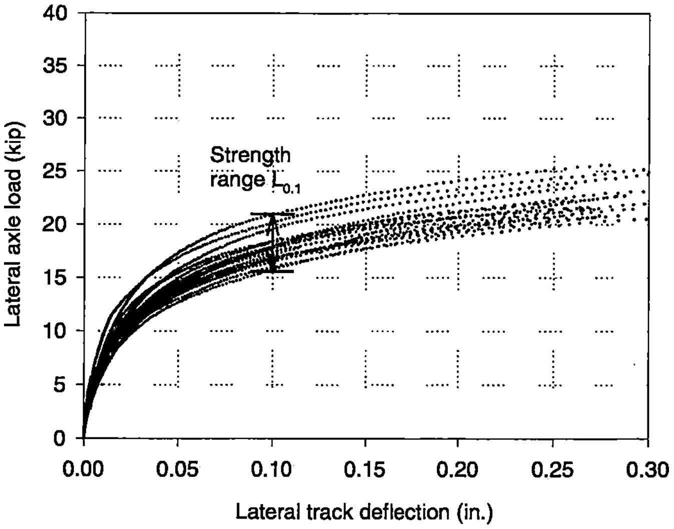


Exhibit 37. Examples of 20 TLV Stationary Test Results following Replacement of Approximately 25% of Crossties and Ballast Tamping

Test result and analysis

Test results were first compared between tangent and curved tracks. Exhibit 38 shows mean strength ($L_{0.1}$) values obtained for both the tangents and curves at three post-tamping tie-ballast conditions: newly tamped, machine-stabilized, and 0.1 MGT following tamping. As shown, no obviously higher strength can be seen for tangents than for curves at these three tie-ballast conditions. This may seem counter-intuitive, but TLV stationary track strength primarily depends on the tie-ballast interface. Rail-bending stiffness and rail/tie-fastener rotational stiffness also contribute to track panel strength. In a curve, lower panel-bending stiffness is often compensated for by higher rotational fastener stiffness (due to more fasteners in the curve). As to longitudinal rail forces, their effects on panel shift during a TLV stationary test are not considered to be significantly larger on curves than at tangents. This is likely due to the 20 kip vertical load applied by the TLV test axle at the point of shift (eliminating vertical uplift of the track). It is also conjectured that due to the longitudinal restraints from the four vertical axle loads (roughly 60 kips each) under the two TLV trucks, rail longitudinal forces will not generate significant lateral panel deflection under a non-moving test vehicle, regardless of curvature. Therefore, further stationary test results were grouped only in terms of tie-ballast conditions, not curvature.

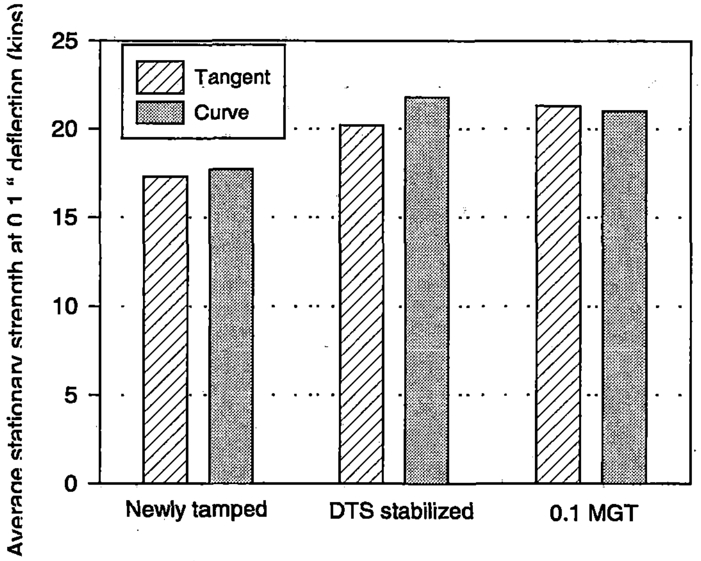


Exhibit 38. Comparison of Mean Test Results for Tangent and Curve (5° to 9°) Tracks following Tamping and Consolidation Via Dynamic Ballast Stabilizer or Traffic

Exhibit 39 shows load-deflection relationships for four tie-ballast conditions: baseline prior to tie replacement (consolidated), newly tamped following 0.1 MGT and machine-stabilized following tamping. The solid lines are the mean values of all the tests conducted for each condition. The data variations are reflected using bands of plus and minus one standard deviation, and are shown by shading.

Under the three conditions following tamping, track panels were pushed up to 0.3 inch. However, before tie replacement, the preset TLV maximum lateral load of 30,000 pounds did not push the panel this far (the force limit was a precaution by the TTCI test crew to prevent possible excessive shifting of the revenue track.) Extrapolation of the baseline test results above 30,000 pounds for the condition before tie replacement is shown by a dashed line in Exhibit 39. This extrapolation uses a lateral load-deflection equation[15] {$L=a\delta+\delta/(b+c\delta)$, where L = load, δ = deflection, a, b, c =

fit coefficients} to estimate results up to 0.3 inch. The different strength characteristics (as measured by TLV) due to the four test conditions are quite obvious, as Exhibit 39 shows.

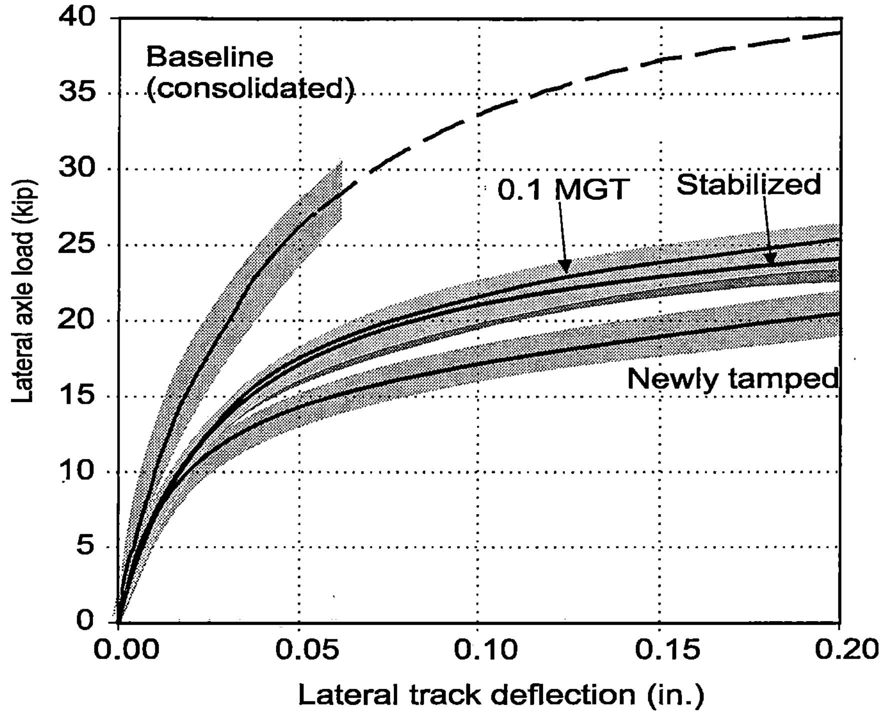


Exhibit 39. Comparison of Test Results for Consolidated, Newly Tamped, following 0.1 MGT and DTS Stabilized (Line is Mean Data, Shading is +/-1 Standard Deviation)

A quantitative comparison of various track strengths is presented in Exhibit 40, which shows the $L_{0.05}$ and $L_{0.1}$ strength parameters. As shown, the tie replacement and tamping caused a strength loss of almost 50 percent. Traffic following tamping gradually recovered the lost strength. Of the loss due to tamping, roughly 30 percent was restored (or 65 percent of the original strength was achieved) via 0.1 MGT of traffic. Similarly the stabilizer application following tamping recovered roughly 65 percent of the original baseline strength, indicating that for this site the stabilizer was equivalent to the effect of 0.1 MGT of revenue traffic.

Results shown in Exhibit 40 are consistent with what was found from tests conducted on a similar TTC track, as discussed previously. However, the moving test method was used on tests performed at TTC. Tests showed that ballast tamping or reinstallation led to a large track-strength loss, and most of this loss was recovered via 0.5 MGT of traffic. However, use of a dynamic ballast stabilizer was found to be more effective on the TTC track than at NS, recovering a portion of the lost strength equivalent to the effect of roughly 0.1 - 0.3 MGT. Several factors may account for this difference in dynamic stabilizer performance, such as variation in stabilizer operations and in slow-order policies, and skin-lift tamping on the TTC test. Also, on the revenue track 20 to 25 percent of the existing ties were replaced, and it is postulated that a dynamic ballast stabilizer may be more effective with used ties having rougher surfaces.

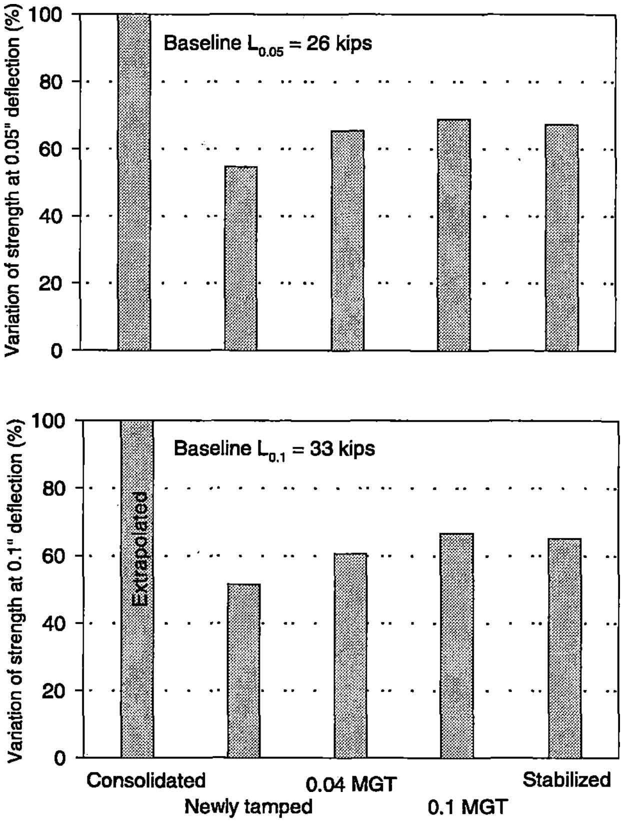


Exhibit 40. Lateral Track Strength Before and After Various Maintenance and Traffic

Summary of 1997 Norfolk Southern test results

The tie-replacement (20 to 25 percent) and ballast-tamping process led to a lateral strength reduction of almost 50 percent. This magnitude agreed with the significant strength reduction due to ballast tamping or ballast installation, which was observed during previous TTC tests.

Following tamping, 0.1 million gross tons (MGT) of traffic recovered roughly 30 percent of the track strength loss (to roughly 65 percent of the original strength). This rate of traffic-induced strength recovery was considered consistent with the previous TTC tests on a similar track structure, which showed that more than 0.5 MGT was required to restore most of the lost strength.

Use of a dynamic ballast stabilizer following tie replacement and ballast tamping improved track strength equivalent to the effect of roughly 0.1 MGT. This was less than the effect of a similar stabilizer equivalent between 0.1 and 0.3 MGTs as found in tests conducted at TTC. However, the TTC tests included skin-lift tamping, but no tie changes. In addition, the test method was different. The revenue tests used the stationary method, while the TTC tests used the in-motion method.

TLV stationary tests on 5- to 9-degree curves did not exhibit lower track strength than on tangents under the post-maintenance ballast conditions: newly tamped, machine-stabilized, and up to 0.1 MGT traffic.

4.3 NORFOLK SOUTHERN 1998 Tests

The 1998 NS tests in Alabama and Mississippi were performed to find better methods to maintain railroad track, with both rail network efficiency and safety in mind. NS tests in 1997 near Oakvale, West Virginia, showed that the timber and surfacing (T&S) operation reduced the stationary track lateral strength by approximately 50 percent, and that subsequent stabilization returned the strength to approximately 65 percent of the original. At that time, the TLV in-motion lateral measurement system was not yet functional. Since then, a continuous TLV in-motion capability has been developed by TTCI, and NS invited TTCI to re-examine the lateral strength effects of stabilizing newly surfaced tracks (including zones with planned tie replacements) using the in-motion technique.

NS initiated these revenue track tests in order to better understand the process of dynamic ballast stabilization (NS's Plasser PTS-62 Dynamic ballast stabilizer was used during testing). They desired to measure the variability in stabilizer effectiveness under different operating parameters. In addition, they desired to verify stabilization effectiveness when the ties were replaced by T&S gang operations.

TTCI was interested in performing this series of tests to gather revenue track experience with the new TLV in-motion track strength measurement technique. In addition, if post-maintenance traffic could be documented, and track access was available, TTCI was interested in the rate of strength recovery versus traffic. This final goal was part of an ongoing effort to better understand the objective criteria which might be used to develop and/or terminate slow-orders.

These tests were performed on NS Class 4 mainline track in the vicinities of Pell City, Alabama, and Poplarville, Mississippi. The annual traffic near Pell City is about 45 MGT (25 MGT east direction and 20 MGT west direction). The rails before replacement were 132 lb/yd. The new rails are 136 lb/yd. The annual traffic near Poplarville is about 22 MGT (10 MGT southbound, and 12 MGT north) over 132 lb/yd rail. In addition, several Amtrak trains operate over these tracks daily. In both locations, the ballast is primarily granite. During the scheduled maintenance, new granite ballast was added to the track. The ties are mixed hardwood with cut spikes. Daily access to track for test purposes ranged from a low of 1 1/2 hours to a maximum of 7 hours.

Throughout these tests, the TLV remained behind the NS maintenance gangs. In this manner, the TLV tests did not affect gang operations significantly. In this post-gang test operation, a significant block of track time is very important. For a meaningful test, the gang must be able to prepare a suitable test length of track (at least 1500 ft) and move further ahead. The stabilizer is then operated, and then TLV tests (in-motion and/or stationary) are done. Finally, when the track access window is about to close, the TLV often must clear the track (sometimes several miles away) before the gang can back up to clear as well.

In addition to the in-motion technique, TLV stationary test technique was used for these tests. A constant vertical axle load of 20 kips was always applied on the track during tests. For in-motion TLV tests, the lateral axle load applied varied between 14 and 20 kips. For stationary tests, the lateral axle load was increased from zero to up to 35 kips.

4.3.1 Tests Near Pell City, Alabama

NS tracks near Pell City, Alabama, were tested before and after surfacing gang operations during February 9 through 19, 1998. These tests were planned to examine the various operating adjustments that could be made with a dynamic ballast stabilizer. In these tests, the operating frequency and the steady downward pressure exerted by the stabilizer were varied. Typically, the operating frequency on such a unit can be varied from 25 to 45 cycles per second (Hz). Also, the pressure in the stabilizer's steady downward actuators can be varied from 50 to 100 bar. Each of these settings were varied during the test matrix. Subsequently, the TLV applied lateral and vertical forces to the track (either while stationary or in-motion) and lateral track deflections were measured.

In general, tracks appeared in fair conditions after surfacing. The ballast was found moderately fouled in some locations. Mud pumping locations were found in several grade crossings. Ballast shoulder width was found somewhat inconsistent for some tangent portions of tracks.

TLV stationary tests

Exhibit 41 shows various TLV stationary strength data defined at 0.1-inch track deflection. These tests were conducted at four ballast conditions: (1) as-is condition prior to tie/rail replacement, (2) newly tamped condition, (3) stabilized, and (4) after some additional traffic (0.01 to 0.05 MGT).

For the as-is (baseline) conditions, tests were done on both mainline tracks and on a side track. As shown in Exhibit 41, the average strength for the mainline tracks was 31.8 kip, higher than the average strength of 27.3 kip for the siding.

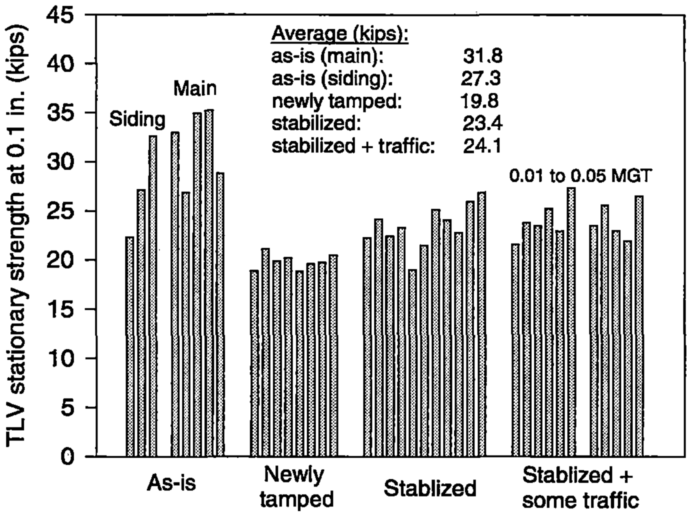


Exhibit 41. Track Strengths Found using TLV Stationary Tests near Pell City, Alabama

All other three conditions (newly tamped, stabilized, stabilized plus some traffic) were recorded only for the mainline tracks. As shown in this exhibit, tamping caused an average strength reduction from 31.8 to 19.8 kip. Therefore, the strength of the newly tamped track was approximately 62 percent of the original track strength.

Use of the stabilizer following tamping improved track lateral strength. Although stabilizer operating parameters were varied (31-35 Hz and 50-90 bar) in some stationary test locations, the test results (at all stabilizer operation parameters) have been grouped together because of the limited overall number of tests. As an average, for this site, the track strength following stabilization was 23.4 kip, or 74 percent of the original strength.

Tests were also conducted on tracks which were stabilized and subsequently consolidated by additional traffic (3 to 10 trains or 0.01 to 0.05 MGT). These test results are also shown at the far right of Exhibit 41. As can be seen, the average track strength for this condition was 24.1 kip, or 77 percent of the original strength.

TLV in-motion tests

A total of 36 TLV test runs were conducted. For each run, the test zone length varied between 200 to 6,000 feet. The applied lateral axle loads were varied between 14 and 20 kip (mostly 18 kip), and track conditions varied in curvature, ballast conditions (as-is, newly tamped, stabilized with various combinations of operation parameters, stabilized plus some traffic). However, five test runs did not generate meaningful results because one of the six lasers was out of focal range in some right hand curves.

In-motion data showed that post-tamped use of the stabilizer improved track strength, which was consistent with TLV stationary test results. This was shown by significant reductions of lateral track deflections in the stabilized zones as compared to the deflections generated for the newly tamped zones.

Exhibits 42 shows seven test zones during an in-motion test with lateral load equal to 18 kip. In these cases, the stabilizer vertical pressure was held at 90 bar, but the operating frequency was varied between 25 Hz and 39 Hz. Also, two zones without dynamic track stabilization (no DTS) were tested. Lateral deflections were significantly larger in zones without any stabilization, indicating laterally weaker track. Among the stabilized zones, the 30, 35, and 39 Hz operating frequencies all yielded similar deflection results. The lowest frequency zone (25 Hz stabilization) exhibits larger deflections, indicating somewhat lower effectiveness.

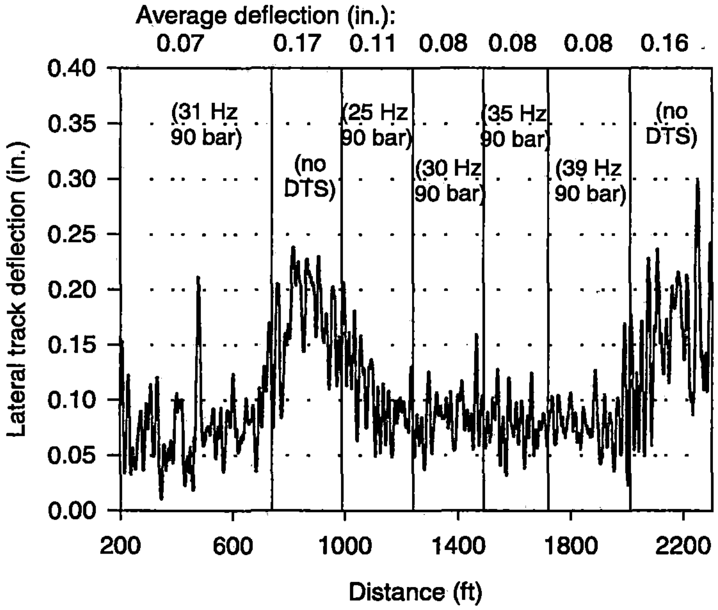


Exhibit 42. Track Lateral Deflections during TLV In-Motion Tests at Various Stabilizer Operation Parameters (tangent, MP757.5, L=18 kips)

Exhibit 43 shows data from an in-motion TLV test across four track zones. In this test, the dynamic stabilizer operating frequency was kept constant at 35 Hz, and the vertical pressure was varied from 50 bar to 90 bar. The first zone shows non-stabilized track, and again the lateral deflection resulting from the TLV forces are larger than for any stabilized zone. Also, the fourth zone (50 bar) shows larger deflections, indicating less effective stabilization.

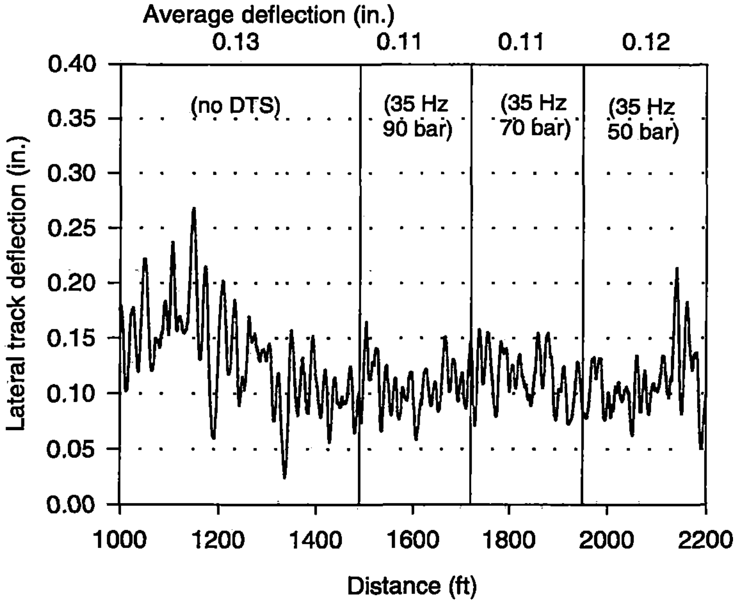


Exhibit 43. Track Lateral Deflections during TLV In-Motion Tests at Various Stabilizer Operating Parameters (tangent, MP760.6, L=18 kips)

Overall, under an 18 kip lateral axle load and for tangent tracks, the average generated deflections in the stabilized tracks ranged from 0.04 inch to 0.11 inch, as compared to the average deflections from 0.14 inch to 0.16 inch in the newly tamped tracks. The average deflections generated at 18 kip lateral axle load were usually less than 0.04 inch for the as-is track conditions of the main line tracks.

Exhibits 44 to 47 show more examples of TLV in-motion test results in the zones with various stabilizer operating parameters. In general, within the ranges of the operation parameters from 25 to 40 Hz (vibrating frequency) and 50 to 90 bar (downward pressure), the stabilizer was able to improve track strength to various degrees.

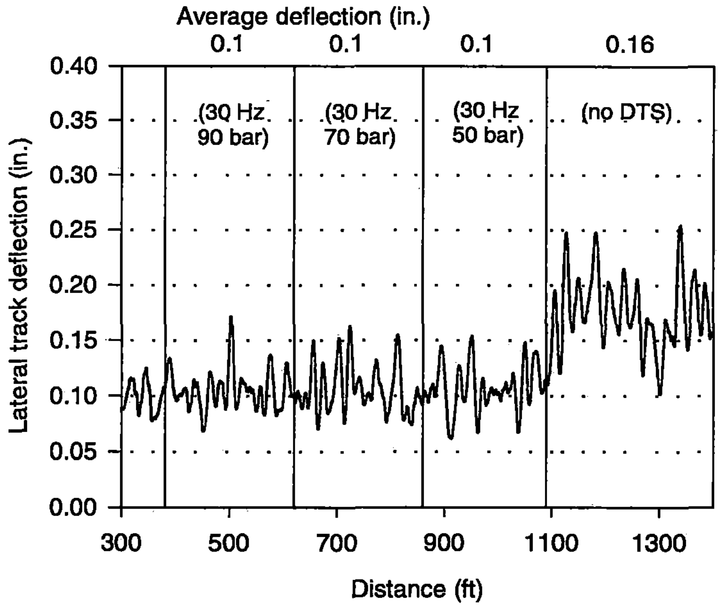


Exhibit 44. Example of TLV In-Motion Tests on Stabilizer Effects (tangent, MP759.6, L=18 kips)

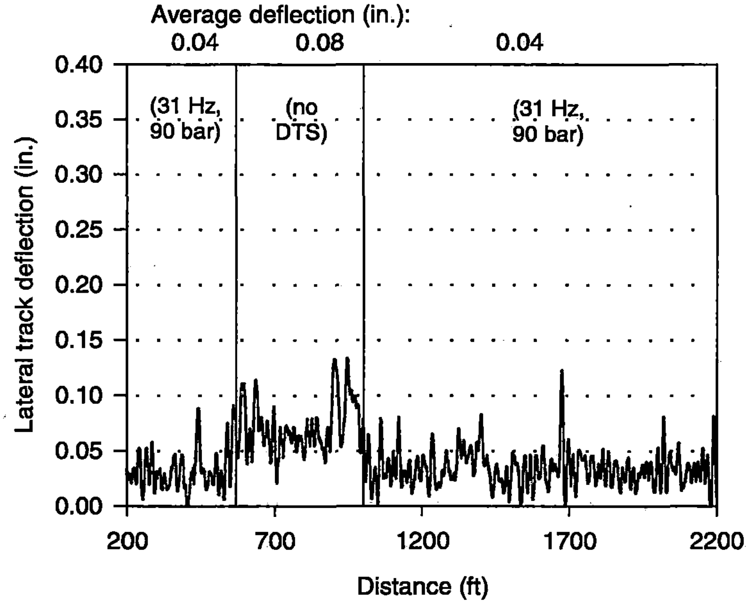


Exhibit 45. Example of TLV In-Motion Tests on Stabilizer Effects (tangent, MP764.0, L=18 kips)

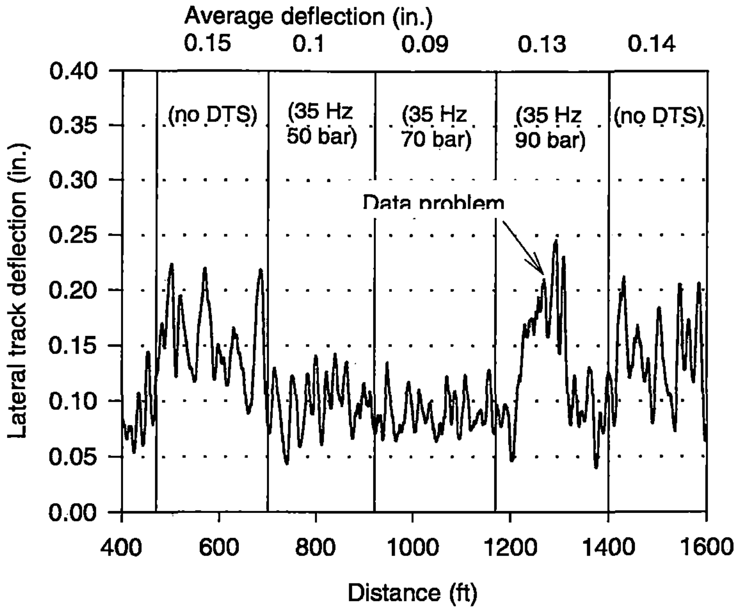


Exhibit 46. Example of TLV In-Motion Tests on Stabilizer Effects (tangent, MP755.9, L=18 kips)

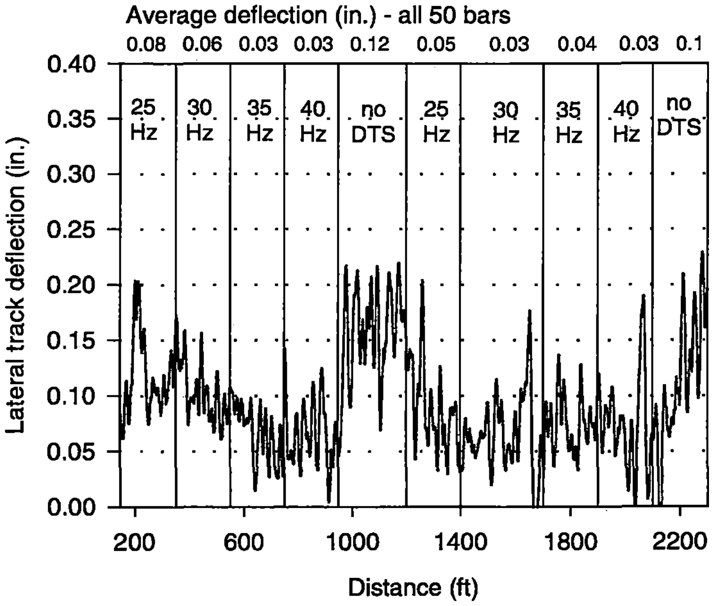


Exhibit 47. Example of TLV In-Motion Tests on Stabilizer Effects (reverse curve, MP762.7, L=18 kips)

Recommended stabilization technique

Stabilizer operation parameters with vibrating frequency from 30 Hz to 35 Hz and downward pressure between 70 and 90 bar generated more consistent strength improvements, and should be targeted for daily operation. This was found to be within current operating methods. However, wider operating ranges (from 25 Hz to 40 Hz and from 50 bar to 90 bar) were sometimes as effective. The few occasions where the stabilizer did not work effectively were mostly associated with the combinations with low vibrating frequency around 25 Hz, low pressure 50 bar, or high pressure 90 bar.

4.3.2 Tests Near Poplarville, Mississippi

A second series of TLV tests was done in conjunction with a T&S gang which replaced approximately 25 percent of the crossties near Poplarville, Mississippi. Since newly installed ties are typically smooth (without dimpled bottom surfaces), the effectiveness of ballast stabilizers on such track has periodically been questioned. As a result, several in-motion tests of nominal stabilization (30 Hz, 90 bar) were performed over a 2-day period. These nominal parameters were chosen based on results from tests near Pell city, Alabama.

Baseline track conditions and TLV stationary test results

The track near Poplarville, Mississippi, appeared to have significant tie degradation. This included tie end splitting, plate cutting, and some decay between the rail as well. However, many spikes were found to be 0.5 to 2 inches up from a full-driven position, and a significant portion of the existing tie plates could be moved under the rails, indicating small perturbations in vertical profile as well. After digging between tie centers in several places, the ballast was found to be free draining, although considerable aggregate was found to be smaller than typical (major dimension of ¾" to 1½"). In general, the track conditions near Poplarville were not as good as during earlier tests at Pell City, Alabama. Since a T&S gang had been scheduled for the area, this is to be expected. As an example, Exhibit 48 shows a poorer section of nearby track.

Exhibit 48. A Poorer Segment of Baseline Track near Milepost 118

To examine the baseline or pre-maintenance track lateral strength, TLV stationary tests were conducted behind the gang, but outside of the mileposts assigned for T&S work. However, this prevented tests at any one location both before- and after-maintenance.

Exhibit 49 shows results of several stationary tests performed during the mornings of March 10 and March 11. These tests were performed under 20,000-pound vertical TLV test axle loads, using a lateral force which ramped from zero to 35,000 pounds. As shown, the measurements were quite variable, with an average lateral force of 27.4 kips. This is somewhat lower than 1997 results in Oakvale, West Virginia (33 kip), or typical track lateral strength values at HTL (30 kip), but similar to the results at the side track near Pell City, Alabama (27.3). This may correlate with subjective opinions that the track near Poplarville exhibited more tie-plate cutting, more tie degradation, some finer ballast material within the aggregate, and significant moisture due to rains in Poplarville. Regardless, the 27.4 kip average baseline strength will be used as 100 percent for comparisons with other track conditions in this test series.

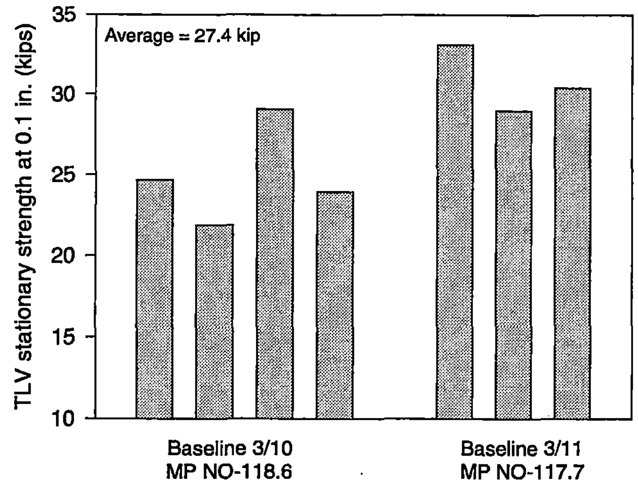


Exhibit 49. Baseline Stationary Track Lateral Strengths under Vertical Axle Load of 20 kip

All remaining data herein was obtained on track with (nominally) 25 percent new ties, and after production surfacing. Therefore, in locations where stabilized and non-stabilized tracks are compared, the timber replacement and surfacing was completed prior to stabilizing and/or TLV tests.

Effect of stabilization on track with 25-percent new ties

Exhibit 50 shows two zones tested in-motion using a TLV lateral force of 16,000 pounds. The vertical axis shows resulting lateral deflections, and the horizontal axis shows track position in feet. This allows a comparison of stabilized versus not-stabilized track after T&S operations, but before any additional traffic. Again, note that lower deflections indicate relatively stronger track.

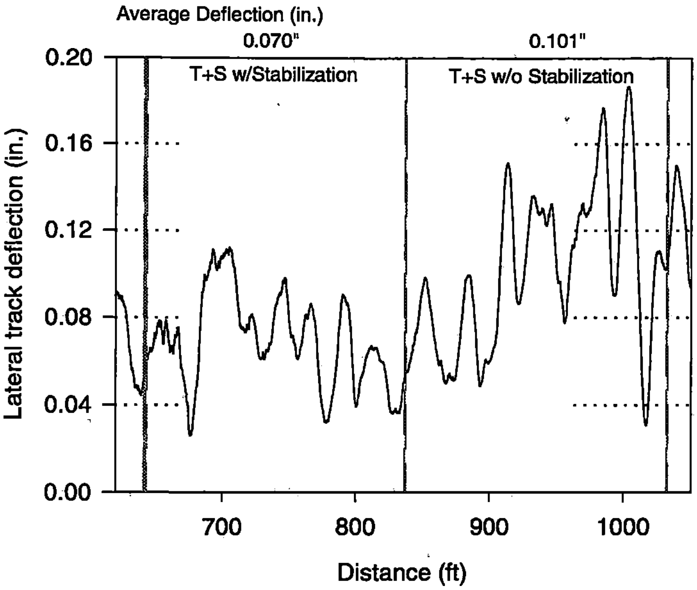


Exhibit 50. Two TLV Test Zones Showing Track Lateral Deflection after T+S Operations Both with and without Subsequent Stabilization

The first zone in Exhibit 50 included ballast stabilization and resulted in a mean track lateral deflection of 0.070 inch. The stabilizer was not operated in the second zone, where mean deflection was measured to be 0.101 inch, which is approximately 44 percent greater. Because track acts in a non-linear fashion between lateral shift loads and deflection behavior, numerical values of mean deflection tend to exaggerate track strength differences. Therefore, to document changes in *strength,* stationary TLV lateral pushes were performed and are shown in Exhibit 51. The stabilized strength averaged 21.2 kip (approximately 77% of baseline). The non-stabilized zone strength averaged 18.7 kip (68% of baseline).

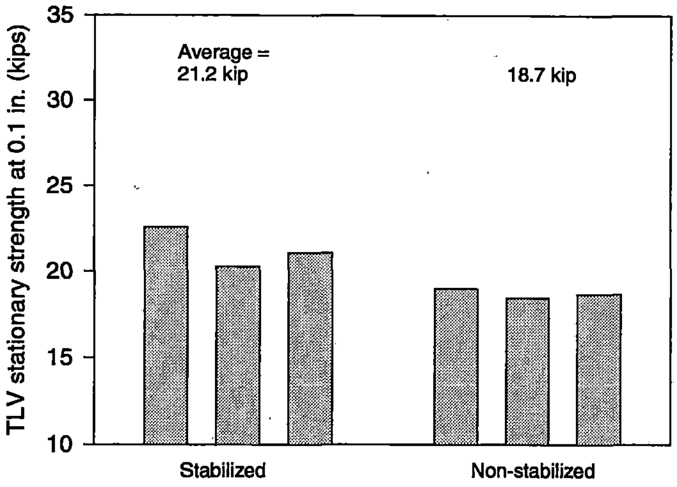


Exhibit 51. Track Lateral Strength for Stabilized and Non-Stabilized Zones Near Milepost No-124.8-9 (Measured using TLV Stationary Tests)

Another contributing factor to this difference may be that the non-stabilized test zone had experienced significantly more tie replacement (26% new ties) than the stabilized zone (20%). However, the effect of tie replacement density is believed to be less significant than the effect of ballast stabilization. This tie replacement effect has been examined and will be discussed.

Additional zones of stabilized versus non-stabilized track were tested between MP NO 125 and MP NO 126.1 on March 11. The ballast shoulders in this area generally ranged from 18 to 24 inches. But one test zone had a 12-inch shoulder width. These were again performed with a TLV lateral test load of 16,000 pounds. Exhibit 52 shows the results of TLV measurements over three stabilized zones, and four non-stabilized zones. A fourth stabilized zone (not shown) was measured as well and showed lower deflections (as with the first three stabilized zones). However lower deflections in this final zone may have resulted from pushing against the low rail in a spiral. Therefore, this data was discarded.

Data from the fifth zone of Exhibit 52 should be interpreted cautiously because the track condition is different than neighboring zones. The ballast shoulder in the fifth zone was approximately 12 inches; the shoulder ranged from 18 inches to 24 inches throughout the other 6 zones. This same fifth zone also experienced the largest percentage of replaced ties. Taken together, these factors resulted in a mean deflection of 0.147 inch, and therefore the weakest zone of the seven.

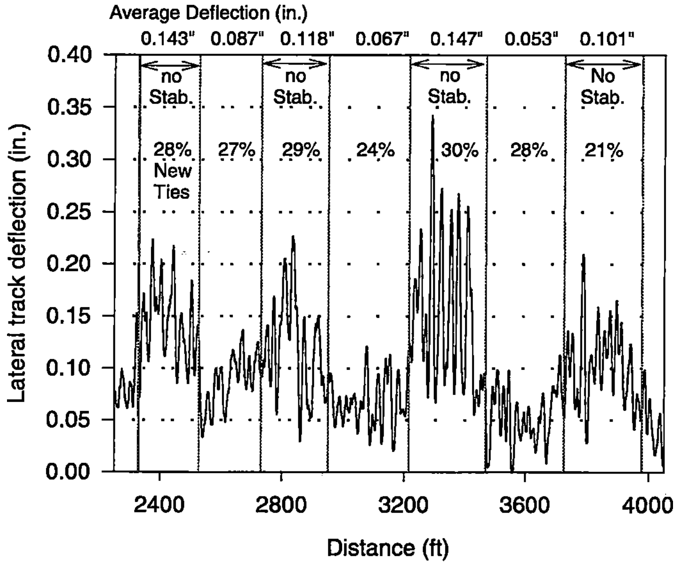


Exhibit 52. TLV In-Motion Lateral Shift Test Over Seven Track Zones Both With and Without Ballast Stabilization

The deflection averaged over other three non-stabilized zones was 0.121 inch and peaked at approximately 0.23 inch. The deflections averaged over the three stabilized zones was 0.069 inch, with an upper limit of 0.14 inch. Therefore, (given a nominal tie replacement rate of 26%) mean TLV-deflections on non-stabilized track were approximately 75 percent larger than for stabilized track. Again the percentage of increased deflection from these constant-load moving TLV tests tend to exaggerate strength differences (i.e. the 75% increase in deflection should not be interpreted as a 75% reduction in strength). Therefore, several stationary tests were performed in the first three of these zones to document the track differences in terms of strength, and will be discussed.

It is also worth noting that the variation of deflection in the stabilized zones is less than the variation found in non-stabilized zones, indicating that proper ballast stabilization results in more uniform track strength, as well as an increase in average strength.

In addition to computing mean deflection values through the zones, deflection histograms were created by grouping the four non-stabilized test zones and the three stabilized zones. The results were then normalized using the total number of data samples within each condition. Exhibit 53 shows the results of this analysis. Notice that the stabilized condition has significantly fewer counts at deflections of 0.11 inch and greater.

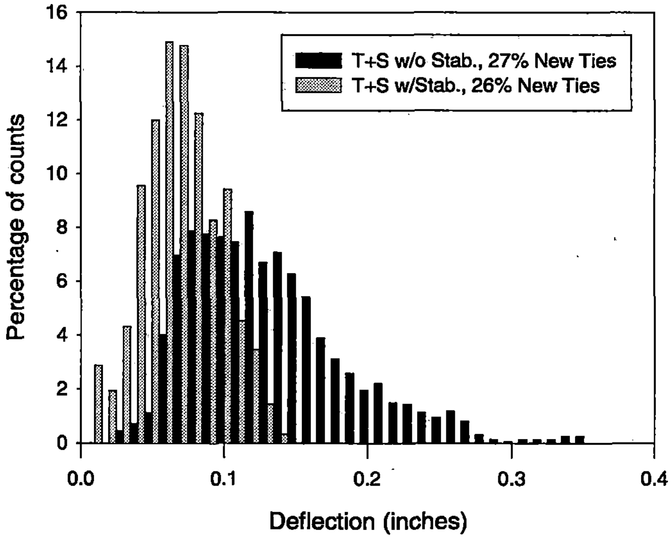


Exhibit 53. Stabilized Versus Non-Stabilized Histograms of TLV-Measured Lateral Deflections between Mileposts NO-125 and NO-126.1

Several stationary TLV tests were performed in the first three zones of this test as shown in Exhibit 54. These show that the stabilized strength was measured to be 23.4 kip (approximately 85% of baseline). The average non-stabilized strength was measured to be 17.3 kip (63% of baseline).

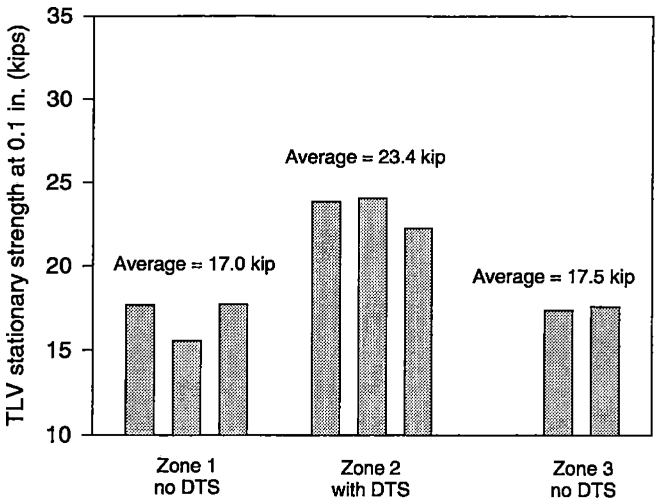


Exhibit 54. Lateral Strength Variation in Stabilized and Non-Stabilized Zones Between Mileposts NO-125 and NO-126.1 (Measured Using TLV Stationary Tests)

Effects of tie replacement on stabilizer effectiveness

Exhibit 55 shows the lateral track deflection versus distance near MP NO 121.8. This was performed on March 10, using a 16,000-pound lateral test axle load, after the T&S gang operations and subsequent dynamic track stabilization. As with the stabilized zones from Exhibit 52, this exhibit shows a fairly uniform deflection profile throughout the test.

The number of replaced ties were counted over five test zones; replacement rates are noted on the plot. Also the lateral deflection values were averaged over each zone, and the mean values are shown above the plot. Notice that the first zone had the most ties replaced (20%), and also showed the largest average lateral deflection of 0.067 inch. Only 13 percent of the ties were replaced in the third and fifth zones, and these exhibited the lowest average deflections (0.050" and 0.047"). Although the effect is rather small, the other zones are consistent with this trend. That is, greater tie replacement rates correspond to larger average deflections. This minor effect shown here may not represent the results for a new track with 100-percent new ties.

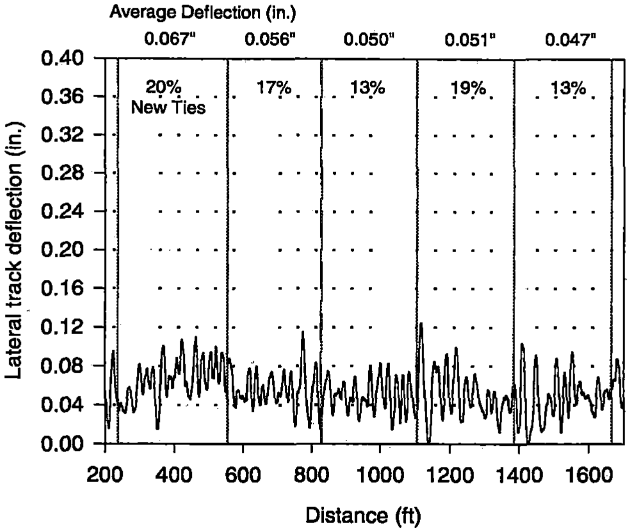


Exhibit 55. Effects of Tie Replacement on TLV In-Motion Track Lateral Deflection

Traffic effects

Exhibit 56 shows four zones near MP NO 122.3, tested March 11. The track had experienced approximately 50,000 gross tons of traffic (overnight) since the T&S operations and use of a dynamic stabilizer. This test was performed using a 16,000-pound TLV lateral test load. The new tie percentages are noted on the plot, as well as mean track lateral deflections as measured by the TLV. As in Exhibit 55, greater numbers of replaced ties correspond to greater mean deflections. In order to check for differences due to the traffic, these data may be compared with pre-traffic data from Exhibit 55 (due to similar test parameters). A comparison of the deflections for 19- and 21-percent tie replacement zones herein with similar zones from Exhibit 55 indicate approximately 15-percent lower deflections in the post-traffic zones.

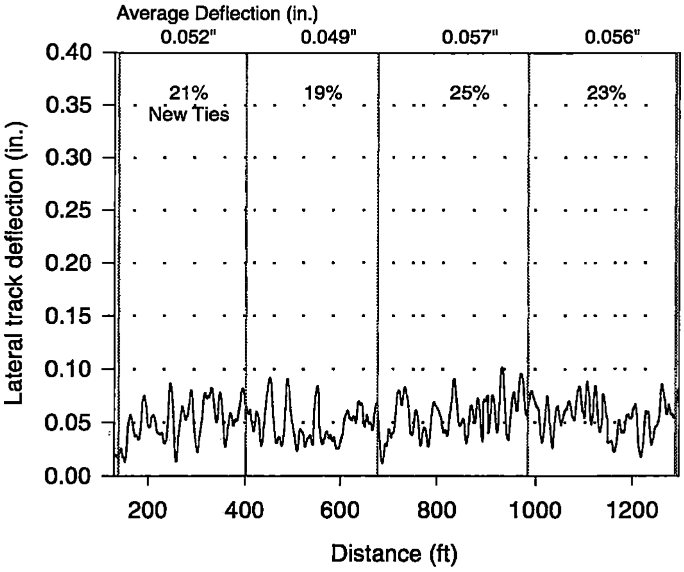


Exhibit 56. Post-Traffic (50,000 Gross Tons) In-Motion TLV Tests of Four Zones (Timber and surfacing operations and stabilization were performed the previous day.)

Stationary tests were also performed to examine these effects of traffic and stabilization as shown in Exhibit 57. Again the baseline strength of 27.4 kip was reduced to 17.8 kip by the T&S operation. This is approximately 65 percent of the original value. After overnight traffic of approximately 50,000 gross tons another set of strengths was obtained and averaged. The mean value was 19.8 kip, or approximately 72 percent of original.

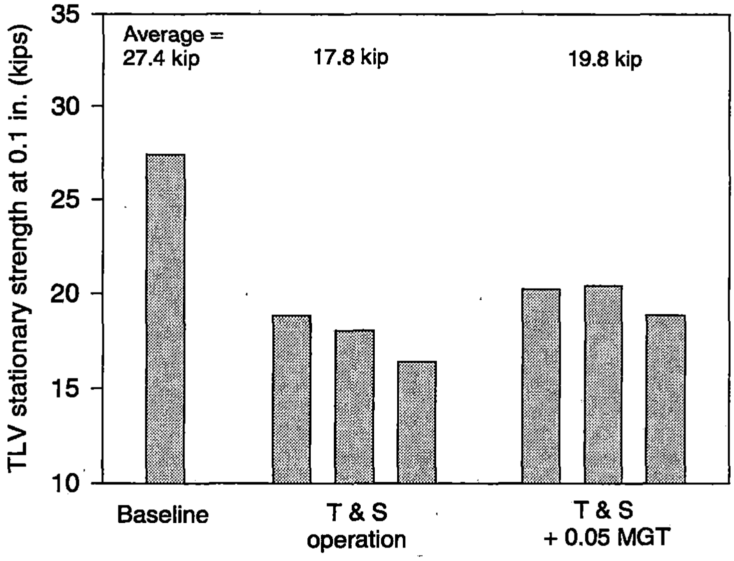


Exhibit 57. Comparison of Track Lateral Strengths Measured using TLV Stationary Tests

Summary of 1998 Norfolk Southern tests

NS's dynamic ballast stabilizer can be successfully operated over a frequency range of 30 to 35 Hz and a vertical pressure range of 70 to 90 bar. Properly used, the dynamic ballast stabilizer improves track lateral strength whether 25-percent new ties have been installed or not. The few occasions where the stabilizer did not work effectively were mostly associated with lower vibrating frequency (25 Hz), and lower vertical pressure (50 bar).

After surfacing near Pell City, Alabama, the TLV stationary strength was reduced to approximately 62 percent of the pre-maintenance condition. Dynamic track stabilization returned this to 74 percent of the original strength. After T&S operations near Poplarville, Mississippi, the baseline track strength was reduced to 65 percent (range from 57 to 69%). Dynamic track stabilization returned this to 81 percent (range from 73 to 88%) of the original value.

Pre-maintenance track lateral strength near Poplarville, Mississippi, was more variable than other locations which have been measured. This as-is strength was also somewhat lower (10-15%) than other locations, including NS track near Pell City, Alabama, and Oakvale, West Virginia, and TTC track.

Tie replacement percentages appear to have a minor effect on post-maintenance strength. Larger average track deflections (and hence lower strength) result from greater density of replaced ties. The weaker sections of NS track generally corresponded to areas of large fill above the surrounding grade. In these cases, the following characteristics were noted: (1) the ballast shoulder width (ballast even with top of tie extending beyond the outer edge of the tie) ranged from zero to 12 inches, and (2) the slope of the ballast edge was constant and appeared to be the natural angle of repose of the aggregate. The weakest track segment was found at a compromised ballast shoulder, near a rail repair. The necessary joint bar connection contributed to the weakness at this location.

4.4 EVALUATION OF EXISTING SLOW-ORDER POLICIES BASED ON TLV RESULTS

North American railroads ensure safe operations through significant investments in track inspection and regular maintenance, including ballast and tie replacement. However, track maintenance inadvertently weakens the tie/ballast interface. Whenever the interlocking ballast aggregate is disturbed, its ability to restrain the track from moving is compromised. For this reason, railroads commonly control their own operations with temporary train speed restrictions (known as slow-orders). This allows the ballast particles to settle and re-interlock, thus regaining strength gradually with traffic. Unfortunately slow-orders disrupt traffic flow.

A survey of current post-surfacing slow-order practices shows that prescribed baseline durations vary from 50,000 to over 400,000 gross tons of vehicle traffic, with initial speed restrictions varying from 10 mph to 30 mph. As of 1997, six railroads shorten train speed restrictions when performing dynamic ballast stabilization, slowing only 10,000 to 55,000 gross tons of cumulative traffic after maintenance.

Track lateral strength tests performed on site at TTC and elsewhere have shown that the use of dynamic ballast stabilization can reduce the required slow-order traffic after track maintenance for wood-tie tracks. After review of lateral strength tests, proper dynamic ballast stabilization can be conservatively considered equivalent to at least 90,000 gross tons of traffic. This equivalence has been used to examine current slow-order policies, leading to recommendations for more balanced speed restriction practices.

Because of infrastructure and environmental differences across the continent, no single slow-order policy should be suggested for all railroads. However, several current post-maintenance practices can be improved based on objective track strength measurements. If desired, detailed investigations of specific policy effects can be conducted through controlled field tests using the TLV.

4.4.1 Survey of Class 1 Railroad Slow-Orders

Many railroads implement speed restrictions after ballast disturbances such as tamping, ballast cleaning or tie replacement. Other times, slow-orders may be in effect due to rail flaws and/or maintenance, bridge and structure repair work, and environmental extremes. This report does not address speed restrictions other than related to ballast or tie maintenance.

Understanding current speed restrictions is important to properly interpret experimental strength tests. Therefore, TTCI surveyed North American Class I railroads regarding train slow-orders after large ballast disturbances such as out of face surfacing, undercutting, or tie replacement. In cases where various policies depend on track conditions, the slow orders chosen apply to continuously welded rail over wood ties when the rails are above targeted neutral temperature. Due to industry mergers, during the survey, there were more slow order policies than individual railroads.

Exhibit 58 shows various slow-orders in North America. In the plot, the prescribed train speed is shown versus cumulative traffic in thousands of gross tons. Some railroads specify the duration in hours, based on annual tonnage categories. In these cases, each tonnage category was assumed and the resulting slowed traffic was computed. The plotted slow-order policies show the cases which resulted in minimum traffic before returning full track speed. For railroads specifying duration in hours or in trains, but without tonnage categories, one tonnage train is commonly assumed to equal 5,000 tons, and 10 such trains were assumed per 24-hour period (18 MGT annually). As shown, current Class I slow-orders vary significantly. For example, the initial speed limit may range from 10 mph to 30 mph. Also the overall required traffic may vary from 50,000 to 400,000 tons.

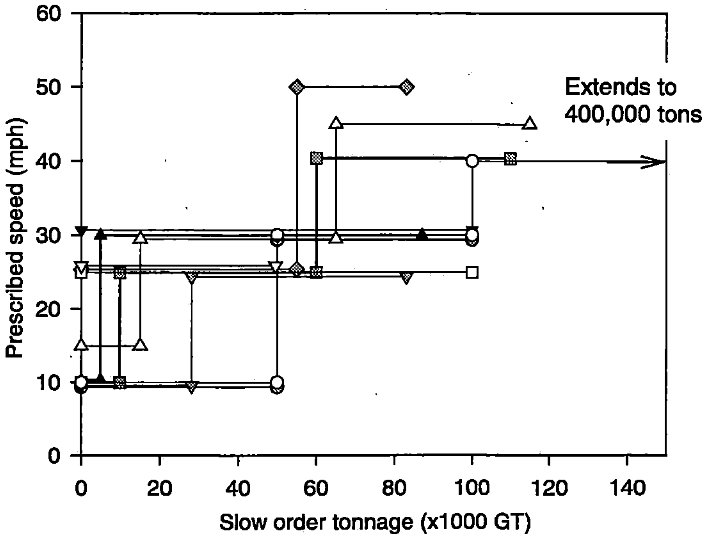


Exhibit 58. Baseline (traffic only) Class 1 Post-Maintenance Speeds Restrictions

Exhibit 59 reflects alternative policies employed by seven railroads when using dynamic ballast stabilization. When ballast stabilizers are used, slow-order durations are nominally much shorter than traffic-only operations. As shown, the initial prescribed speeds remain 10 to 30 mph; however, the required traffic decreases (10,000 to 55,000 tons). For five of seven railroads however, only one to three tonnage trains are slowed after stabilization.

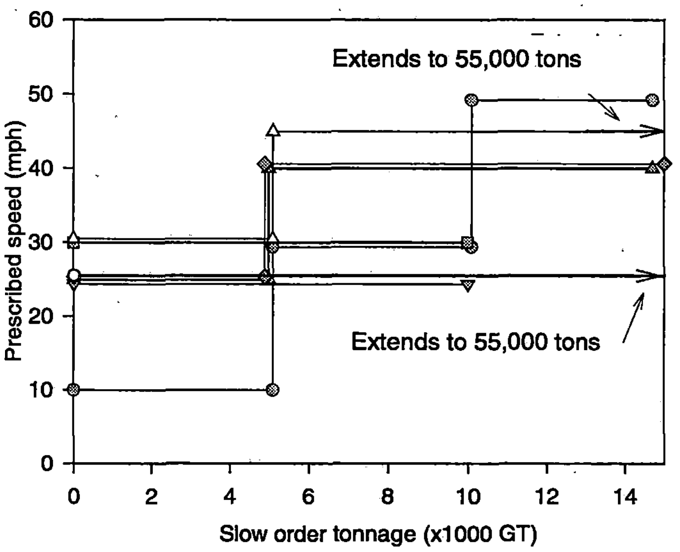


Exhibit 59. Shorter Speed Restrictions when using Dynamic Track Stablizer

4.4.2 Factors Affecting Slow-Orders

Several factors may affect slow-order policy, including class of track (speed), curvature, and rail temperature, which are briefly discussed here:

Force effects on reduced train speeds

On tangent track, wheel lateral forces typically increase as alignment perturbations increase. However, this relationship is commonly offset by reducing the allowable speeds over lower track geometry classes with larger perturbations. Therefore, in practice, the train lateral forces are somewhat constant over a speed range of 15 to 45 mph. Above this, vehicle hunting may result in significantly larger lateral wheel/rail forces. Therefore, greater ballast consolidation should be attained before allowing such speeds.

In curves, the lateral component of wheel/rail force is not necessarily less at lower vehicle speeds due to designed super-elevations. Unfortunately, the wide variety of system operating speeds and curvatures does not allow a practical method to match slow-order speeds to curvature.

Another undesired result of higher train speeds can be excessive longitudinal forces into the track during traction or braking. Therefore, such forces are usually minimized by slower train operations after track maintenance.

Resistance to thermal forces

Curvature also affects track stability via rail thermal forces. U.S. Department of Transportation documentation has shown that sustainable lateral forces are inversely related to temperature and track curvature.[16] To counter this, some slow-order policies include overnight requirements for thermal cycling. These longitudinal forces are especially important because of the rail uplift wave which precedes loaded wheels. Consequently, the lateral restraint offered by under-tie friction is temporarily unavailable, leaving the ballast shoulder and crib, and the rail bending inertia to resist lateral components of rail compressive force. This effect as well as in-train forces make speed restrictions more important in curves. As a result, several railroads use larger ballast shoulders on curves than tangents.

4.4.3 Track Strength Results and Comparison of Slow-Order Policies

Track strength results presented earlier will be summarized here as a basis for the discussion of slow-order policies.

Exhibit 60 shows the same results included in Exhibit 32 but focused on traffic below 0.6 MGT. Twelve wayside tie deflections were measured while the TLV passed through a test zone at various levels of consolidation. The dashed line showing "traffic only" recovery is a logarithmic curve fit including data at 5.3 MGT, although this fit is sensitive to minor data changes in the 0 to 0.3 MGT range where more data points would have been useful. With this type of test, larger resulting deflections indicate laterally weaker track. Prior to any track work, the average of resulting tie deflections was 0.06 inch. After ballast tamping, the average deflection was 0.19 inch. In one test case, the track was consolidated using traffic only. In another case, a loaned dynamic ballast stabilizer from Union Pacific was used to accelerate consolidation. The results showed that the ballast stabilizer reduced the average tie deflection to that expected after 100,000 to 300,000 gross tons of FAST traffic, depending on curve fitting. In the balance of this report, a more conservative result of 90,000 tons found during revenue tests is used.

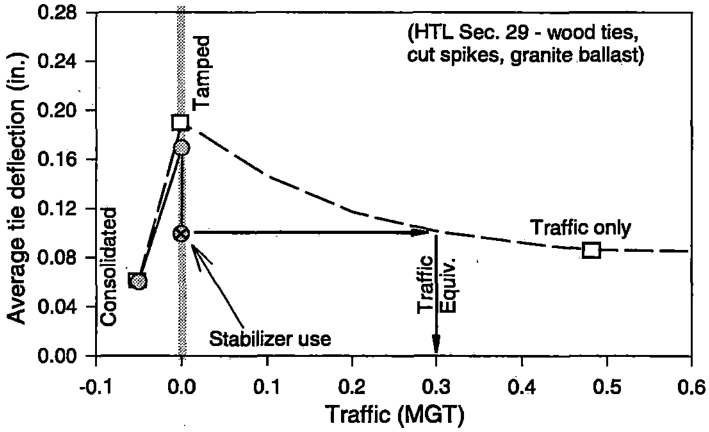


Exhibit 60. In-Motion TLV Tests at FAST Stabilizer on Loan from Union Pacific (Two more data points at 0.9MGT and 5.3 MGT are not shown here.)

Exhibit 61 summarizes track strength results obtained at NS during 1997 and 1998. These were stationary TLV tests and were repeated at discrete locations and therefore required significantly more track time than in-motion tests. Some in-motion TLV tests were also performed on revenue track. (However, because of non-linear force versus track deflection behavior, such comparisons tend to exaggerate differences between strong and weak track.)

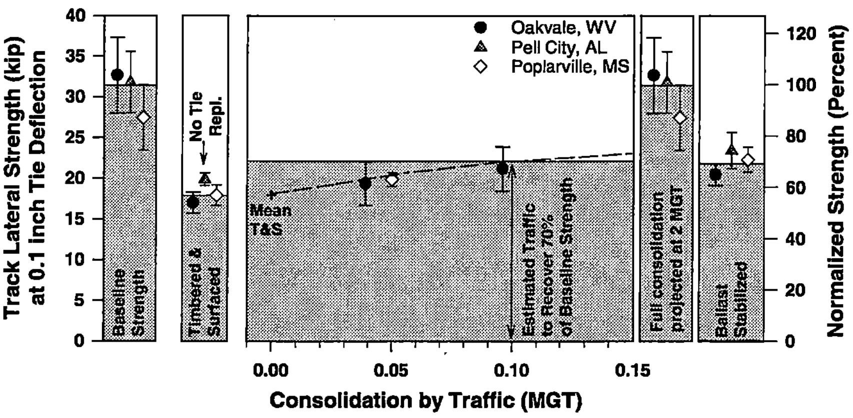


Exhibit 61. Combined Results from Three Series of TLV Field Tests at NS

In Oakvale, West Virginia, and Poplarville, Mississippi, track lateral strength was measured at 0.1 inch of tie deflection for various conditions ahead and behind a tie replacement and surfacing gang. In Pell City, Alabama, similar work was performed with only a surfacing gang. In Exhibit 61, the revenue track strength results are shown for pre- and post-maintenance conditions, at various traffic levels, and for ballast stabilizer operations. The data points show average strength found during each series, with vertical error bars showing a plus or minus one standard deviation band.

Overall, the average original strength at 0.1-inch tie deflection was 31,400 pounds. After maintenance, the strength was reduced to 17,900 pounds, or approximately 57 percent of the original. As the exhibit shows, approximately 100,000 tons of traffic is expected before a return to 70 percent of the original strength. On these tracks, use of the dynamic ballast stabilizer returned the strength to just under 70 percent of original, which was equivalent to 90,000 tons of traffic.

Seven Class I freight railroads use alternative speed restrictions to account for the benefits of dynamic ballast stabilization. Ideally, any railroad's pair of these policies (with stabilizer versus without) are balanced. In other words, consolidation yielded by a traffic-only slow-order policy should be similar to the results of an (alternative) policy which accounts for benefits of stabilization.

A properly applied stabilizer has been shown to provide the equivalent of at least 90,000 gross tons of traffic. Therefore, it follows that the train operations prescribed immediately after stabilization should be similar to operations prescribed after 90,000 tons of traffic only. All 10 railroads surveyed allow 25 mph or faster operation after 90,000 gross tons of traffic. Furthermore, since two of the railroads surveyed end their baseline slow-orders before 90,000 gross tons, test results herein indicate that proper ballast stabilization yields lateral strength similar to or greater than these two baseline policies.

To further check this balance, baseline (traffic-only) slow-order policies were compared with the traffic equivalence of a dynamic stabilizer plus the brief speed restrictions prescribed for post-stabilizer use. Therefore, Exhibit 62 compares the total equivalent traffic during either the baseline or stabilized slow-order policies.

If balanced, these alternatives should prescribe similar equivalent tonnage levels. However, this is not reflected from the survey. All of the seven railroads with modified policies when using ballast stabilizers allow full-track speed after an equivalent of 100,000 to 145,000 gross tons (stabilization plus an additional 10,000 to 55,000 tons). However, the baseline (traffic-only) requirements for these roads range from 85,000 to 400,000 gross tons before removing speed restrictions. Therefore, some railroads' baseline (traffic-only) slow-orders (when compared to their own alternative (stabilized policies), differ by up to 260,000 equivalent tons. This difference shows the possibility of additional optimization of certain policy alternatives.

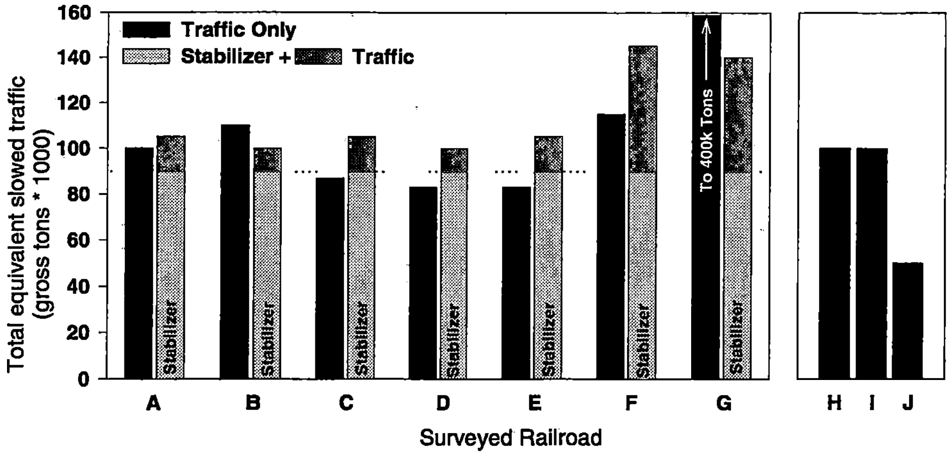


Exhibit 62. Slow-Order Comparison for 10 Class 1 Railroads (Baseline versus Stabilizer Equivalent Traffic)

4.4.4 Recommendations

Based on the survey, tests and analyses, several limited observations have been made regarding wood tie track strength and speed restrictions.

Dynamic ballast stabilization has been found to be equivalent to 90,000 gross tons of revenue freight traffic. A greater effect was found on the closed FAST loop at TTC. In analyses presented in this section, the conservative (90,000 ton) equivalence is assumed.

When dynamic ballast stabilization is used, railroads shorten the durations of post-maintenance train speed restrictions. However, a technical comparison of slow-orders with and without stabilization show inconsistencies between the two alternatives for some railroads.

Without dynamic ballast stabilization, all Class I railroads surveyed prescribe train operations of 25 mph or higher after 90,000 gross tons of vehicle traffic. Since a stabilizer is equivalent to at least this much traffic — based on limited TLV tests — it follows that 25 mph may be a suitable minimum initial speed for train operations immediately following stabilizer use.

The longest existing post-stablization slow-orders are lifted after at an additional 55,000 tons of traffic given the stabilizer traffic equivalence of at least 90,000 tons. This yields a lateral strength anticipated to equal that caused by 145,000 tons of traffic. For this reason, traffic only slow orders beyond 145,000 tons should be re-examined.

Over the past two decades, various North American railroads have shown a consistent decline in incidents related to lateral track instability. An important component of successful track maintenance strategies has been implementation of post-maintenance speed restriction policies. However, because of infrastructure, environmental, seasonal, and train operation differences across the continent, no single slow-order policy should be suggested for all railroads. If a minimum strength is specified, the TLV can help determine track strength as related to the proper slow-order policy. As mentioned, the TLV revenue service track strength tests were conducted at three sites over mainline quality track. Each test was run over 1,000 to 1,500 foot long track at 20 to 25 locations. The track lateral strength was measured using a special technique developed for the TLV. Based on these limited number of tests, it was found that approximately 100,000 tons of slowed traffic can achieve an average of 70 percent strength retention after surfacing maintenance. Tests also showed that a dynamic ballast stabilizer can achieve the equivalent of at least 90,000 tons.

5.0 SUMMARY AND CONCLUSIONS

This report summarizes test results and findings from phase 3 of project "TLV Track Panel Shift and Lateral Track Strength Tests." Test results and findings from phases 1 and 2 were published in an earlier report (R-917).[1] The project was jointly funded by AAR and FRA. These tests were conducted to complement phases 1 and 2 tests of the project for developing a prototype technique for automated track strength measurement and for studying the effects of track maintenance operations. The main conclusions from phase 3 study are given below:

Prototype TLV technique for automated track strength measurement

A prototype technique has been developed for automated measurement of lateral track panel strength at the tie-ballast interface, using AAR's Track Loading Vehicle (TLV). This technique has been applied successfully to identify weak spots continuously along the track and to examine the effects of track maintenance practices on lateral track strength. Further refinement and full applications of this technique will enable railroads to identify and maintain weak spots for mitigating conditions leading to track buckling and panel shifting.

This prototype TLV technique involves in-motion application of vertical and lateral loads to the track and measurements of unloaded and loaded lateral track profiles. Higher deflections correspond to weaker track. A tangent wood-tie track is considered strong with a deflection of 0.04 inch or less, and weak with a deflection more than 0.1 inch (under 18 kip lateral axle load and 20 kip vertical axle load). However, more revenue track tests are needed to document effects of curvature and rail longitudinal force, and to establish thresholds dividing strong and weak tracks. A weaker track shows not only higher average deflections, but also higher variations along the track.

TTC on-site tests of track maintenance effects

Track lateral strength was reduced significantly by ballast tamping operations even if the rail lift was relatively small (0.5 to 1 inch). Dynamic ballast stabilizers accelerated ballast consolidation and strength recovery on wood-tie track. Test results on TTC wood-tie track with granite ballast indicated that use of a dynamic stabilizer following tamping produced ballast consolidation resulting in a recovery approximately equivalent to the effect of 0.1 to 0.3 MGT of heavy axle load traffic at the Facility for Accelerated Service Testing.

Various tie types affected initial track lateral strength more than they affected consolidated track strength. Following tie installation and surfacing operations, both concrete and steel ties (inverted trough types) showed significantly greater initial strength than wood ties. However, this difference in track strength (as measured using the TLV) decreased as the ballast became more consolidated.

1997 Norfolk Southern tests of track maintenance effects

The tie-replacement (20 to 25 percent) and ballast-tamping process led to a lateral strength reduction of almost 50 percent. This magnitude agreed with previous TTC tests. However, the TTC tests included only minimum lifting (0.5–1″) and tamping, but no tie changes.

Following tamping, 0.1 MGT of traffic recovered approximately 15 percent of the track strength loss (to 65 percent) of the original strength.

Use of a dynamic ballast stabilizer following NS tie replacement and ballast tamping improved track strength equivalent to the effect of 0.1 MGT.

1998 Norfolk Southern tests of track maintenance effects

TLV tests showed that NS's dynamic ballast stabilizer could be operated as expected over a frequency range of 30 to 35 Hz and a vertical pressure range of 70 to 90 bar (a relative measure used by the operator, 1 bar = 14.5 psi). The few occasions where the stabilizer did not work effectively were mostly associated with lower vibrating frequency (25 Hz) and lower vertical pressure (50 bar).

After surfacing near Pell City, Alabama, the track lateral strength was reduced to approximately 62 percent of the pre-maintenance condition. Dynamic track stabilization returned this to 74 percent of the original strength (12 percent). After timber and surfacing gang operations near Poplarville, Mississippi, the baseline track strength was reduced to 65 percent (range 57 to 69%). Dynamic track stabilization returned this to 81 percent (range 73 to 88%) of the original value.

Limited TLV testing indicates, tie replacement percentages within the range of 13-30 percent, appear to have a minor effect on post-maintenance strength.

Slow-order policies

Dynamic ballast stabilization has been found, from several on- and off-site TLV tests, to be equivalent to at least 90,000 gross tons of revenue freight traffic. When dynamic ballast stabilization is used, railroads shorten the durations of post-maintenance train speed restrictions. However, a technical comparison of slow-orders with and without stabilization show inconsistencies between the two alternatives for some railroads.

Without dynamic ballast stabilization, the Class I railroads prescribe train operations of 25 mph or higher after 90,000 gross tons of vehicle traffic. Since a stabilizer is equivalent to at least this much traffic — based on limited wood tie TLV tests — it follows that 25 mph may be a suitable minimum initial speed for freight train operations immediately following stabilizer use (subject to normal operating speeds).

Because of infrastructure, environmental, and train operation differences across the continent, as well as seasonal changes throughout the year, no single slow-order policy should be suggested for all railroads. If a minimum strength is specified, the TLV can help determine track strength as related to slow-order policy. As previously mentioned, the TLV revenue service track strength tests were conducted at three sites over mainline quality track. Each test was run over 1,000 to 1,500 foot long track at 20 to 25 locations. The track lateral strength was measured using a special technique developed for the TLV. Based on these limited number of tests, it was found that approximately 100,000 tons of traffic can achieve an average of 70 percent strength retention after surfacing maintenance. Tests also showed that a dynamic ballast stabilizer can achieve the equivalent of at least 90,000 tons.

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Report Brief
AAR RESEARCH REPORT

Automated Measurements of Lateral Track Panel Strength and Examinations of Track Maintenance Effects Using AAR's Track Loading Vehicle

by Dingqing Li and William Shust

R-918
May 1999

This report summarizes test results and findings under the project "TLV Track Panel Shift and Lateral Track Strength Tests."

The project was jointly funded by AAR and FRA. These tests were performed primarily off-site on Norfolk Southern revenue tracks, but a significant portion of tests was conducted on TTC's test tracks.

The study was conducted to complement previous testing done by AAR for developing a prototype technique for automated track strength measurement and for studying the effects of track maintenance operations. Major results from this study included:

(1) The successful development and demonstration of a prototype TLV technique for automated lateral track strength measurements.
(2) Quantitative examination of the effects on lateral strength of wood tie tracks of surfacing and tamping, dynamic ballast stabilization and accumulative traffic.
(3) Survey of Class 1 railroad slow orders and quantitative comparisons with TLV track strength test results.

To order this report, contact Kathy Pacheco, P.O. Box 79780, Baltimore, MD 21279-780. Phone: 1-877-999-8824. Please make all checks payable to TTCI.

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