Association of
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INVESTIGATION OF LATERAL TRACK STRENGTH AND TRACK PANEL SHIFT USING AAR'S TRACK LOADING VEHICLE

REPORT NO. R-917

by
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Pueblo, Colorado

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13. Abstract

The Association of American Railroads (AAR) is conducting extensive lateral track strength (track panel shift) tests using the AAR's Track Loading Vehicle (TLV). The entire test program consists of three phases: (1) demonstration tests, (2) fundamental tests, and (3) off-site tests and is a joint research effort with the Federal Railroad Administration under its Vehicle Track Systems Program. This report covers the first two phases of tests that were conducted on test tracks at the Transportation Technology Center (TTC), Pueblo, Colorado. The main conclusions are given below based on three different types of TLV tests.

Stationary TLV panel shift tests have shown that lateral track strength can be measured on intact track with maximum track deflections of 0.3 inch. Among a number of load and track variables examined, vertical axle load and ballast consolidation were shown to have the most significant influence on lateral track strength. Single tie push tests were also performed and support trends as identified by TLV tests.

In-motion TLV panel shift tests were conducted using repeated TLV passes over a given test zone. These were used to identify lateral force levels that cause constant deformation growth per vehicle pass, and are defined as the critical lateral load. Critical lateral loads and misalignment growths were determined as a function of vertical axle load, tie type (wood versus concrete) and rail temperature

A technique known as stiffness profile testing has been developed for in-motion track strength measurements. This technique used rail-contacting sensors and two-pass TLV tests to examine strength variation along a track. Weaker locations in track were identified. This technique will be improved in the future, with the goal of single-pass continuous measurement using non-contacting sensors.

14. Subject Terms

Lateral Track Strength, Track Panel Shift, Track Strength Inspection, Stationary and In-Motion Tests, Track Loading Vehicle (TLV)

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EXECUTIVE SUMMARY

The Association of American Railroads (AAR) is conducting extensive lateral track strength (track panel shift) tests using the AAR's Track Loading Vehicle (TLV). The entire test program consists of three phases: (1) demonstration tests, (2) fundamental tests, and (3) off-site tests and is a joint research effort with the Federal Railroad Administration under its Vehicle Track Systems Program. This report covers the first two phases of tests that were conducted on test tracks at the Transportation Technology Center (TTC), Pueblo, Colorado. Phase 3 tests include off-site tests currently being pursued. The main conclusions drawn from the first two test phases are given below based on three different types of tests:

Stationary tests:

- The TLV stationary tests can provide quantitative information on lateral track strength and stiffness. A maximum panel push of 0.3 to 0.5 inches will provide sufficient information to quantify available static track strength and stiffness.

- Vertical axle load has a major effect on the resistance of a track panel to lateral deflection. Therefore, lateral track strength and stiffness measurements should be defined for a given vertical axle load. To generate a given lateral track deflection, the required L/V ratio will be lower if a higher vertical axle load is applied on the track.

- Lateral load-deflection relationships are non-linear. Lateral track strength measurements should be defined at specific deflection levels. Once a track panel is pushed past a certaiin deflection (e.g, 0.1 to 0.2 inches under a vertical axle load of 20 kips), the track will possess much lower lateral stiffness.

- Ballast consolidation presented a significant effect on lateral track strength. Ballast tamping (skin lift) reduced tie-ballast resistance considerably, and up to 9 MGT of traffic were required to fully restore original strength. Use of a ballast crib and shoulder compactor following tamping restored ballast resistance moderately (10 percent).

- Ballast type showed little effect on lateral track strength for fully consolidated conditions. Limited tests showed that use of concrete ties provided moderate benefit in improving lateral track strength (5 to 20 percent) defined at small lateral deflections and in reducing the strength variability along the track. An average 125-kip change from tension to compression forces in the tangent rails only slightly reduced lateral track strength (less than 10 percent).

- It is commonly known that Single Tie Push Tests (STPTs) do not measure all factors which contribute to lateral track panel strength. However, similar trends were observed by TLV stationary tests and by STPTs regarding ballast consolidation level, ballast type, and ballast shoulder width on lateral track resistance.

In-motion track panel shift tests (repeated passing tests):

- For a given tack condition, the accumulation rate of panel shift depends on the magnitudes of lateral and vertical axle loads. There exists a critical lateral load level above which the panel shift increases rapidly with each lateral load pass. Critical lateral load is defined as the level at which a track become unstable. The critical lateral load increases in proportion to the vertical axle load. An increase in vertical axle load also leads to a decrease in track misalignment growth. The critical lateral load results obtained from TLV tests on TTC tracks were higher than the limiting lateral loads predicted by the existing Prud'homme criteria (ref. 9).

- Sudden large panel shifts (with amplitudes of up to 6 inches) were observed on several occasions. These occurred at axle L/V ratios near or equal to one during controlled in-motion TLV tests. Sudden and excessive panel shift occurred in both warm and cold weather.

- Effects of rail compressive force were not apparent during tests with lateral force of 5 kips on tangent. However, larger lateral force (15 kips) tests showed that at 15 kip lateral axle load (and a 20 kip vertical axle load), the test track panel experienced much higher cumulative deformations when the rails were in compression (25 to 60 kips) than in tension (-60 to -100 kips).

- With other conditions being similar, in-motion track panel shift tests showed that concrete tie track exhibited higher (15 to 30 percent) critical lateral axle loads than wood tie track.

- The critical lateral load is empirically related to the static lateral track strength. The static lateral track strength is defined as the load necessary to cause a specific level of lateral track deflection from a TLV stationary test. For a similar track, static track strength defined at 0.05 inch and above is higher than the critical lateral load determined during repeated axle load passes.

- With all things equal, a track panel will shift more due to a moving load than a stationary load.

In-motion track strength tests:

- The stiffness profile test technique was capable of measuring lateral track strength variation along the track. The weaker locations within the test tracks exhibited larger deflections under constant vertical and lateral loads. For tests conducted on the TTC test tracks, repeatability of track strength measurements using the TLV has been satisfactory, and weak spots in tracks have been consistently identified.

- The variations of track strength shown by the stiffness profile testing were consistent with trends shown by limited wayside measurements and STPTs. These stiffness profile tests can show lateral track strength variation over short distances (several feet).

- The optimum lateral axle loads for detecting variation of lateral track strength (with a vertical axle load of 14 or 20 kips) appear to be 15 and 18 kips, respectively. Higher lateral axle load gives more distinctive profiles corresponding to variable track strength, but may result in a sudden shift of weak track.

- Significant enhancement is required to apply this technique for production use. The deflection profile results to-date have used transducers in contact with the non-flanged rail. These are not practical for off-site tests because a reference frame was needed on the side of the TLV body. This frame would be damaged by typical switch stands and other obstacles. Furthermore, since the car body cuts a mid-chord path through a rail curve, the contacting transducers are quickly pushed beyond their 3-inch operating range on curved tracks. The required improvement lies primarily in the development of a non-contact onboard deflection measurement system. An array of laser systems to be mounted on the bogies and between wheels is being considered as a better solution.

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1.0 INTRODUCTION

Adequate lateral track strength and stiffness is essential to track lateral stability under high longitudinal rail forces and/or vehicle loads. Track maintenance operations and unfavorable track conditions, such as fouled ballast and reduced ballast quality, often significantly reduce lateral track resistance. Heavier axle loads and higher train speeds have increased the influence of vehicle induced forces on the track lateral stability, and concern is growing about maintaining adequate lateral strength of the track structure.

In a program jointly supported by the Association of American Railroads (AAR's) Transportation Technology Center in Pueblo, Colorado, and the Federal Railroad Administration (FRA) we have conducted extensive lateral track strength or track panel shift tests using its Track Loading Vehicle (TLV). The project has the following objectives:

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

The TLV, designed and constructed by the AAR, is a unique test vehicle for performance-based testing and inspection of track. The TLV has been used previously in tests concerning gage widening strength, flange climb derailments, and bridge strength. The TLV can generate a load environment on revenue track similar to that under train traffic. Using the TLV, the AAR has developed three types of lateral track strength tests to achieve the above objectives. The first type 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 the relationship between misalignment growth (panel shift) and critical lateral load. The second in-motion test mode is a first step for a future track strength inspection vehicle. It involves measurements of lateral track strength under constant but moving vertical and lateral axle loads.

The entire 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 TTC. Demonstration tests consisted of checkout of TLV instrumentation and control for conducting stationary and in-motion types of tests. Under the fundamental test phase, tests were conducted under a variety of controlled load and track conditions. The effects of various load and track parameters on lateral track strength and stiffness were studied. These test parameters included lateral and vertical axle loads, ballast consolidation level, rail longitudinal forces, ballast type, and tie type. Phase 3 tests are primarily off-site tests with limited additional tests to be conducted on test tracks at TTC.

This report describes the three TLV panel shift test methodologies as well as test results from the first two test phases. Phase 3 testing is currently in progress. A final report will give Phase 3 test results and will incorporate findings and conclusions from all three phases of tests.

2.0 BACKGROUND AND BRIEF LITERATURE REVIEW

2.1 TERMINOLOGY AND BACKGROUND

Track panel shift, as illustrated in Exhibit 1, is defined as the cumulative residual lateral deformation of the *track panel* (the panel of two rails, affected ties and fasteners) over the ballast. This may result from one or more of the following: high lateral wheel/rail forces, high longitudinal rail compressive forces, in combination with low lateral track stiffness and strength. Track panel shift is a phenomenon different from that of rail lateral movement with respect to the ties, as in rail gage widening and rail roll.[1-3] Track panel shift is primarily a lateral rail misalignment affecting the ride quality and safety of train operation. The resulting misalignment, in conjunction with other adverse conditions, may lead to *track buckling,* which is a large amplitude, catastrophic event.[4] If a track panel shifts significantly or rapidly, derailments can occur.

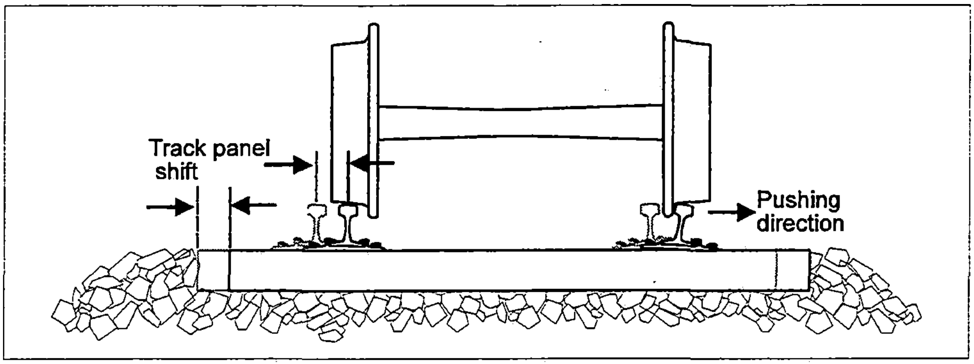


Exhibit 1. Track Panel Shift

The capacity of track panel in resisting lateral movement can be represented by lateral track strength and stiffness. These two terms are often used interchangeably, but they represent different physical meanings. In a stationary test, *lateral track strength* represents the required force to produce a certain amount of lateral track deflection, while *lateral track stiffness* is defined as the slope of the load-deflection relationship. Another term, used in conjuction with repeated passing tests, the *critical lateral load,* is the lateral load level, above which the lateral track deformation increases rapidly with each additional lateral load application. Lateral track strength and stiffness, as well as critical lateral load, are dependent upon track conditions as well as upon the vertical axle loads applied on the track. As discussed later in this report, they should be defined corresponding to specific levels of lateral track deflection. *Lateral track resistance* is often synonymous to lateral track strength, but is used in this report as a strength parameter mainly defined by track conditions (i.e., not including the effect of vehicle loads). In other words, lateral resistance of the track panel includes:

- Friction resistance between the bottom of ties and the ballast
- Friction resistance between the sides of ties and the ballast

- Internal friction among the interlocked ballast particles
- Resistance of ballast shoulder to displacement
- Rotational resistance of tie plates/fasteners
- Resistance of rails to lateral bending

Lateral track movement is comprised of both elastic and plastic (or residual) components. T*rack misalignment* or track panel shift represents only the track plastic deformation. Revenue service track panel shift occurs gradually as a result of repeated load applications. The accumulation of plastic deformation due to repeated load applications depends upon the magnitude of the lateral and vertical axle loads, and other factors. As previously defined, when the critical lateral load is exceeded, the lateral track misalignment will increase rapidly with each additional load application. This must be avoided. For loading levels below the critical level, the accumulation of lateral plastic deformation is relatively slow, with a large number of axle passes required before significant plastic deformation is produced.

Track panel shift is not only a result of vehicle-track interaction in the lateral direction, but is significantly influenced by the vertical vehicle-track interaction. Vertical axle load, for example, has a significant stiffening effect on the track panel. However, at a short distance (e.g. 8-10 feet) from the vertical load, the track panel may be subjected to uplifting, which can locally reduce lateral track resistance. Also vertical track stiffness, or *track modulus*, may influence lateral track behavior.

Although track buckling caused by longitudinal thermal rail force has a different mechanism from that of a track panel shift, they are both linked to a common strength parameter, lateral track resistance. Adequate lateral track resistance is required to resist both track panel shift and track buckling. Track maintenance operations, such as ballast tamping and cleaning, reduce lateral track resistance considerably. Thus, railroads may implement slow order policies following track maintenance. Depending on durations, these slow orders disturb traffic flows resulting in higher operation costs and lower economic returns for railroads.

In order to shorten slow order durations, railroads have used ballast consolidation machines such as ballast stabilizers and compactors to restore ballast lateral resistance following track maintenance. However, better test techniques are needed for inspecting the recovery of lateral track resistance and to verify the effectiveness of such machines. With a thorough understanding of ballast resistance restoration as influenced by maintenance, traffic, and ballast consolidation machines, more economical slow order policies can then be developed while ensuring safe train operations.

With the growing trends of railroads towards heavier axle loads and higher train speeds, railroads need to quantify the effects of various load and track factors on lateral track strength. Higher lateral loads with increased axle loads or higher train speeds will inevitably increase the potential for significant track panel shift. As higher speed operations are introduced in the United States, the European high-speed train safety criteria should be evaluated for applicability to limiting lateral axle loads under North American track conditions.

Extensive tests and modeling work have been carried out to understand the fundamental behavior of track buckling phenomenon.[5-7] However, there is limited knowledge of track panel shift mechanisms resulting from vehicle/track interactions. Although European railroads have performed some tests to characterize track panel shift, full-scale measurements of track panel shift in the field have never been attempted in North America.

This project is designed to improve the fundamental understanding of track panel shift and to address concerns of lateral track strength. With these common interests, this project is a joint effort between the AAR and the Federal Railroad Administration (FRA). Extensive tests have been conducted to measure lateral track strength as well as track panel shift, as influenced by various load and track conditions. It is expected that the information gathered will be used to develop performance-based track measurement techniques for determining lateral track strength and detecting weak zones in tracks. The test data will also be used to develop performance-based slow order guidelines for more effective track maintenance operations. Finally, the lateral load limiting criteria used by European railroads for preventing excessive track panel shift will be evaluated.

2.2 BRIEF LITERATURE REVIEW

The following is a brief review of past studies on track panel shift and lateral track resistance. For a comprehensive literature review, readers can refer to documents prepared by Kish and Mui and by Samavedam et al., respectively.[4,8]

In 1967, Prud'homme reported extensive measurements of track panel shift from tests conducted by the French National Railways (SNCF) using a "derailer wagon" car and a "Wagon Tombereau" car.[9] Variable vertical and lateral axle loads were applied to the rails under different track conditions. The measurements of track lateral shifting showed that a critical lateral load existed such that the track deformation increased rapidly for loads exceeding the limit. The critical lateral load, L_c, was expressed in the following form:

$$L_c = A(V + V_0) \tag{1}$$

where V is the vertical axle load (ton); V_0 is a constant independent of track conditions, and varies between 4 and 7; and A is a track structure dependent coefficient varying between 0.3 to 0.6.

Mainly based on the SNCF test results, several different lateral force limiting criteria have been developed by railroads for preventing excessive lateral track shifting. For example, the following criterion is used by European railways.[8]

$$L_c = 0.85(2.25 + 0.33V) \quad (kips) \tag{2}$$

Using the derailer wagon car, the SNCF later conducted track panel shift tests on its Train de Grande Vitesse (TGV) line.[8] These tests were particularly significant in the development of a resistance characterization methodology because a specific criterion was defined for the limiting lateral load. Constant vertical and lateral loads were applied to the track through a single center axle for three vehicle passes. After each set of three passes, the lateral load was increased for the next set of three passes. The incremental change in track displacement due to each vehicle pass was then calculated. If the change in displacement decreased with successive passes at a given lateral load, the SNCF assumed that additional passes would eventually cause no increase in deflection. However, if the change in displacement increased throughout one set of three passes, then any additional passes could be expected to further displace the track leading to excessive panel shift. The critical load was then deduced from the trend of the change in displacement with each pass within a set. However, as will be shown in Section 6.0, only three vehicle passes may not be sufficient to show a trend for defining a critical lateral load.

In practice, the following criteria are applied to the TGV dual block concrete tie track for limiting lateral axle load:[8]

$$L_c = 5.4 + 0.41V \quad (kips) \quad (unconsolidated) \tag{3}$$

$$L_c = 8.5 + 0.63V \quad (kips) \quad (consolidated) \tag{4}$$

AAR investigated the stationary track panel shift phenomenon under laboratory conditions in the early Track Strength Characterization Program.[10] The results from this study showed a "stiffening" influence of vertical axle loads on lateral load-deflection relationships and the need to define a "limiting deflection" for the onset of track shift.

Some U.S. "perturbed track" measurements showed L/V ratios of about 0.6 just prior to track shift.[11] Boyd et al.also studied the panel shift safety criterion as influenced by various factors.[12] The results from that study showed the critical lateral forces to be twice as high as those based on the SNCF criterion in Equation 2.

Lichtberger reported the use of a dynamic track stabilizer with measurement of the energy required for stabilization of track after tamping.[13] The indication of lateral track resistance was obtained by the magnitude of the energy expended by the oscillation unit of the stabilizer, based on the principle that this energy is approximately proportional to the lateral track resistance.

Using a modified switch tamper, CONRAIL conducted lateral track resistance measurements to determine a slow order policy for tracks restored with a stabilizer.[14] CONRAIL found that the ballast stabilizer was effective in restoring ballast resistance following tamping.

Single Tie Push Testing (STPT) has been used extensively for measuring lateral tie-ballast resistance. Extensive test results can be found in studies on continuous welded rail (CWR) track buckling.[6,7] AAR also used this test method to study the effect of traffic and a stabilizer on ballast resistance recovery following tamping.[15] The referenced study also found that the ballast stabilizer was an effective method of achieving lateral track stability on a newly tamped track.

3.0 TEST METHODOLOGIES

3.1 USE OF TLV IN TRACK PANEL SHIFT TESTING

Exhibit 2 depicts the TLV and its instrumentation car. The TLV was designed and constructed to perform a wide range of tests to enhance and further the understanding of vehicle/track interactions. Typical applications include tests of vertical, lateral, and longitudinal track strength, gage widening strength, flange climb derailments, and bridge strength [16-18]. The TLV consists of a high stiffness load structure (car body) supported by two locomotive trucks. It is equipped with a fifth wheel set (load bogie) mounted underneath the vehicle center. The load bogie is suspended from the car body and operated by servo-controlled hydraulic actuators.

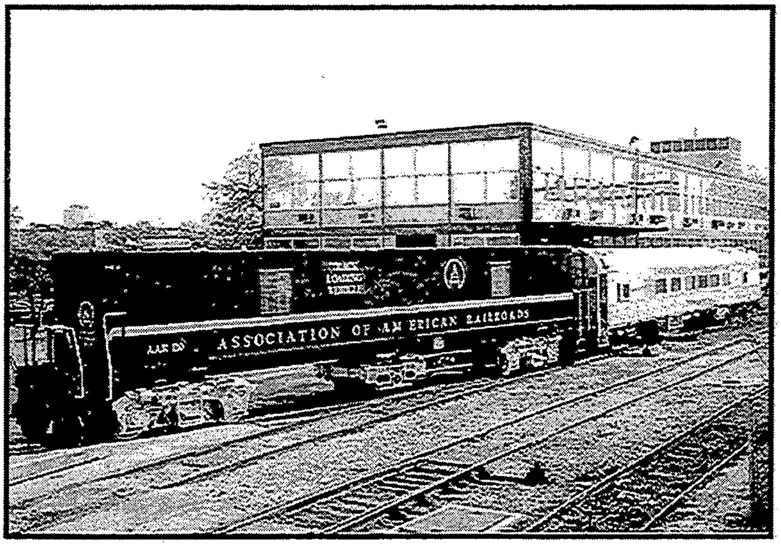


Exhibit 2. TLV and its Instrumentation Car

To achieve the objectives outlined previously, the use of the TLV to apply panel shift loads to an actual track, both stationary and in-motion, is a major requirement. In the track panel shift test mode, lateral axle load is applied in one direction to generate the track panel displacement with respect to the ballast.

Vertical and lateral loads are applied to the track through the bogie frame and a single wheel set by four hydraulic actuators. This bogie was originally referred to as the "yaw bogie" during previous AAR wheel climb tests. The main hydraulic system includes two 55-kip vertical and two 39-kip lateral actuators. Exhibit 3 shows how the track panel shift loads are applied to the track through these actuators. Load cells are installed on the four actuators to measure the force levels. 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 80 and 45 kips, respectively. As an alternative to the actuator load cells, an instrumented wheel set can be used to directly measure applied wheel/rail loads.

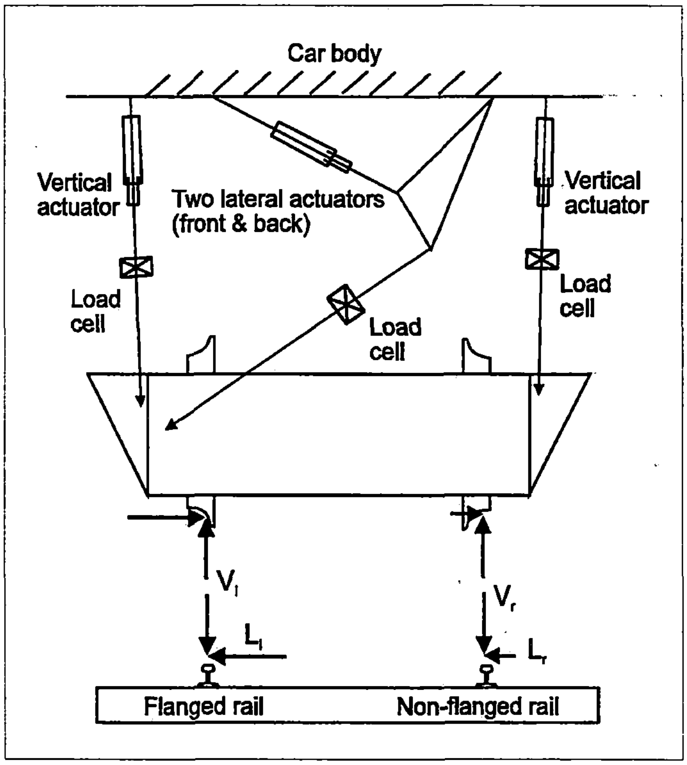


Exhibit 3. Panel Shift Loads Applied through TLV Load Bogie

In this report, the *track panel shift loads* are defined by lateral and vertical axle loads applied to the rail. As shown in Exhibit 3, the lateral axle load, *L*, and vertical axle load, *V*, are determined by summing reactions on the left and right rails as:

$$L = L_l + L_r \tag{5}$$

$$V = V_l + V_r \tag{6}$$

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 generally move with respect to the tie as a result of rail bending, roll, and possible translation. However, the non-flanged rail will exhibit insignificant rail to tie movement due to the small lateral wheel load applied, as shown in Section 4.0.

The TLV is operated from the adjacent AAR-100 Instrumentation Car, which is equipped with an electro-hydraulic control system and a data acquisition system. Comprehensive control software is used to provide interactive control over the hydraulic system. The acquisition software performs data collection, analysis, and storage tasks. Each of the load-controlled inputs along with any peripheral measurements, such as those from deflection transducers, are recorded by the data acquisition system.

3.2 STATIONARY TRACK PANEL SHIFT TESTING

In a stationary track panel shift test, the TLV does not move while applying panel shift loads to the track. This type of testing measures static lateral track strength and stiffness.

During a stationary track panel shift test, the following sequence is used for applying vertical and lateral axle loads:

(1) Increase vertical axle load to a predetermined magnitude and hold constant.
(2) Increase lateral axle load until a target lateral track deflection (or the

(1) Increase vertical axle load to a predetermined magnitude and hold constant.

(2) Increase lateral axle load until a target lateral track deflection (or the maximum possible TLV lateral axle load) is reached.

(3) Decrease lateral axle load to zero.

(4) Decrease vertical axle load to zero.

The lateral track deflection is defined as lateral tie deflection relative to the ballast. The two terms *"lateral track deflection"* and *"lateral tie deflection"* are used interchangeably in this report. Wayside deflection transducers (i.e., LVDTs) are used for lateral tie deflection measurements. Exhibit 4 shows a wayside deflection transducer and fixture.

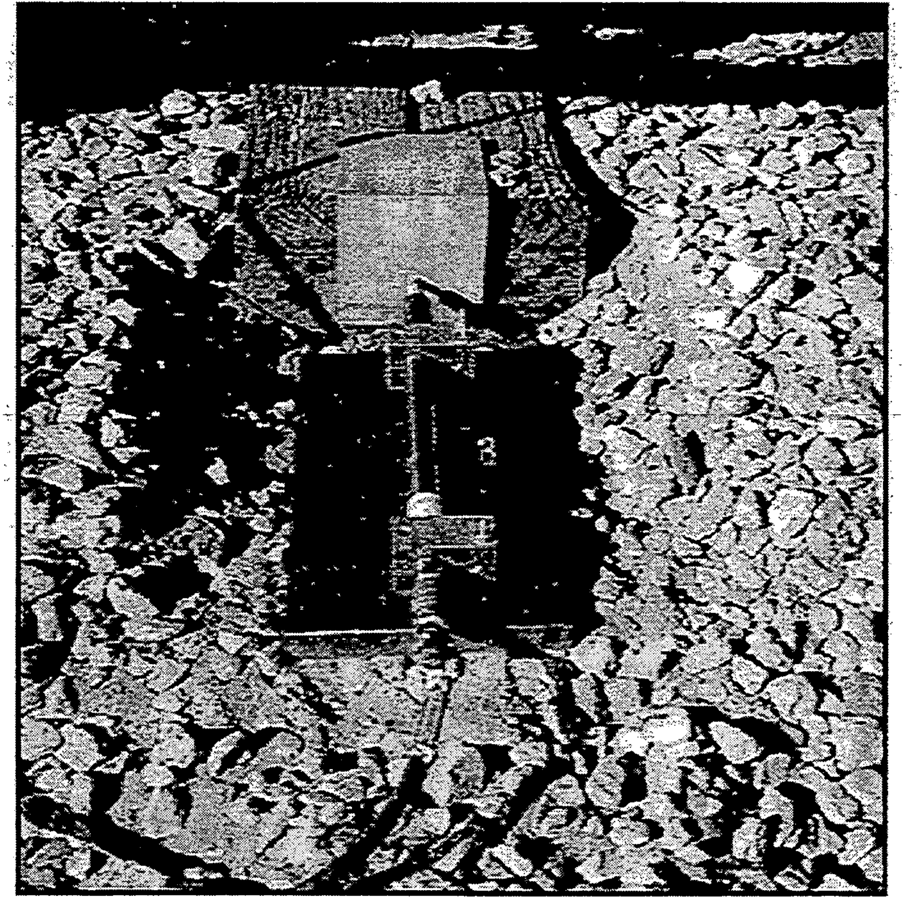


Exhibit 4. Wayside Transducer for Lateral Tie Deflection (direction of push is into the page)

The Linear Variable Differential Transformer (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. l the wayside transducers are portable and are set up easily 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.

A special fixture is used to measure rail-to-tie deflections for the flanged rail, as shown in Exhibit 5. This fixture is secured to a tie. In this way, the displacements of the railhead and base with respect to the tie are measured. Lateral rail-to-tie deflections, as well as rail roll, can be determined from these two measurements.

Exhibit 5. Wayside Transducer for Lateral Rail to Tie Displacements

Outputs of a stationary test include the load-deflection relationship and lateral tie deflection distribution along the track. Exhibit 6 shows a typical stationary test result. The lateral load-deflection curve (both loading and unloading) was obtained under a vertical axle load of 20 kips. As illustrated, the loading curve consists primarily of two regions with distinctive slopes. In the first region, before the lateral deflection reaches a certain magnitude, the track exhibits much higher stiffness. In the second region, however, the track has lower stiffness. That is, a small increase in lateral load will lead to a rapid increase in lateral track deflection. Note that the dividing point between these two regions for the load-deflection curve is subjective.

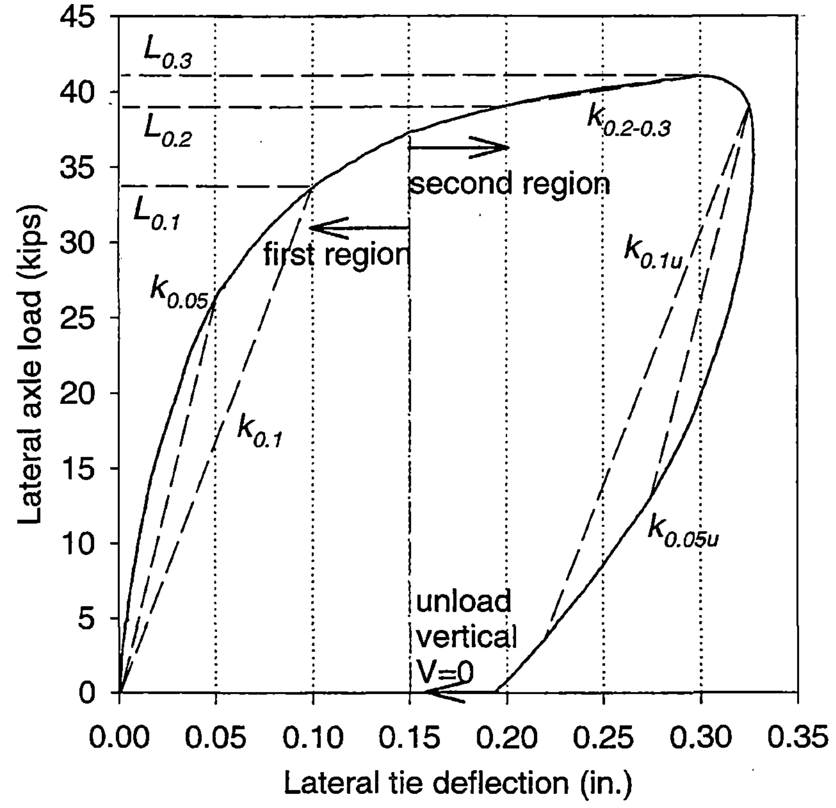


Exhibit 6. Stationary Load-Deflection Relationship

Exhibit 6 also indicates a non-linear load-deflection relationship, particularly in the initial stiffer region under loading as well as for the unloading portion. It is difficult to compare entire shapes such as this plot, and such evaluations would be subjective at best. To objectively analyze and compare load-deflection relationships influenced by different load and track variables, several strength and stiffness parameters have been defined. As shown in Exhibit 6, $k_{0.05}$ and $k_{0.1}$ are used to define the stiffness in the first stiffer region; $k_{0.2\text{-}0.3}$ is used to define the stiffness in the second softer region; $k_{0.05u}$ and $k_{0.1u}$ are used to define the slopes for the unloading curve. In addition to stiffness parameters, the strength parameters (i.e., the lateral load required to produce a desired deflection); $L_{0.1}$, $L_{0.2}$ and $L_{0.3}$ are also defined.

Exhibit 7 shows lateral track stiffness (slope of load-deflection curve) versus lateral tie deflection. Note that the stiffness is the first spatial derivative of the load-deflection data. As stated above, the lateral track stiffness is much higher in the first region than in the second.

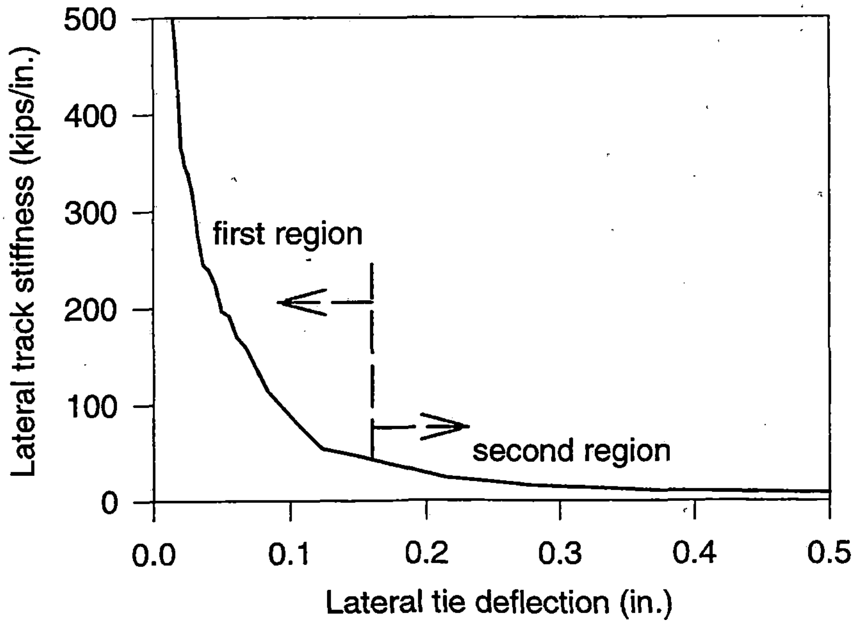


Exhibit 7. Lateral Track Stiffness versus Lateral Deflection Level

3.3 IN-MOTION TRACK PANEL SHIFT TESTING

As defined previously, track panel shift represents the lateral residual deformation growth (or misalignment growth), as a result of repeated axle passes. The accumulation of misalignment can stabilize or it may continue to increase with repeated load applications. This depends upon whether a critical lateral axle load is exceeded. When the critical load is exceeded, excessive and rapid track panel shift will occur.

In-motion track panel shift tests (also known as repeated passing tests) yield the results in Exhibit 8(a), 8(b), and 8(c). Exhibit 8(a) shows the accumulation of residual deformation versus the number of repeated lateral loads, while Exhibit 8(b) shows the incremental residual and total deformations due to each axle pass. The physical meanings of "incremental" and "cumulative" deformations are illustrated in Exhibit 8(c).

The critical load is defined in Exhibits 8(a) and 8(b). In Exhibit 8(a), the critical load is the load level at which the cumulative residual deformation increases at a constant rate. In Exhibit 8(b), this same critical load is the load level at which the incremental residual deformation is constant while the incremental total deformation increases, during each successive pass. For a stable track, the cumulative deformation should become constant or increase very slowly, while the incremental residual deformation should tend toward zero and the incremental total deformation should remain constant.

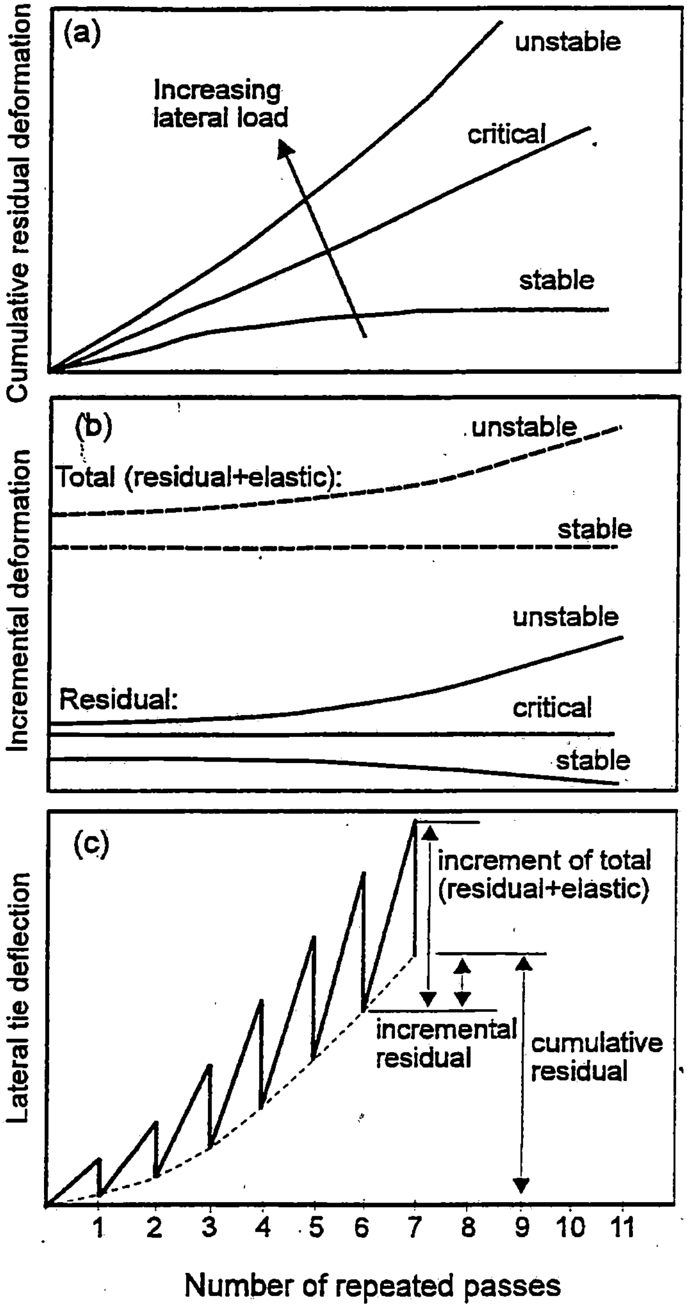


Exhibit 8. In-motion Panel Shift Test Results

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 4, is used for lateral deflection measurements. However, unlike a stationary test, wayside measurements are not recorded by the TLV onboard data acquisition system. Instead, a wayside data acquisition system is used. Exhibit 9 shows the wayside data acquisition system.

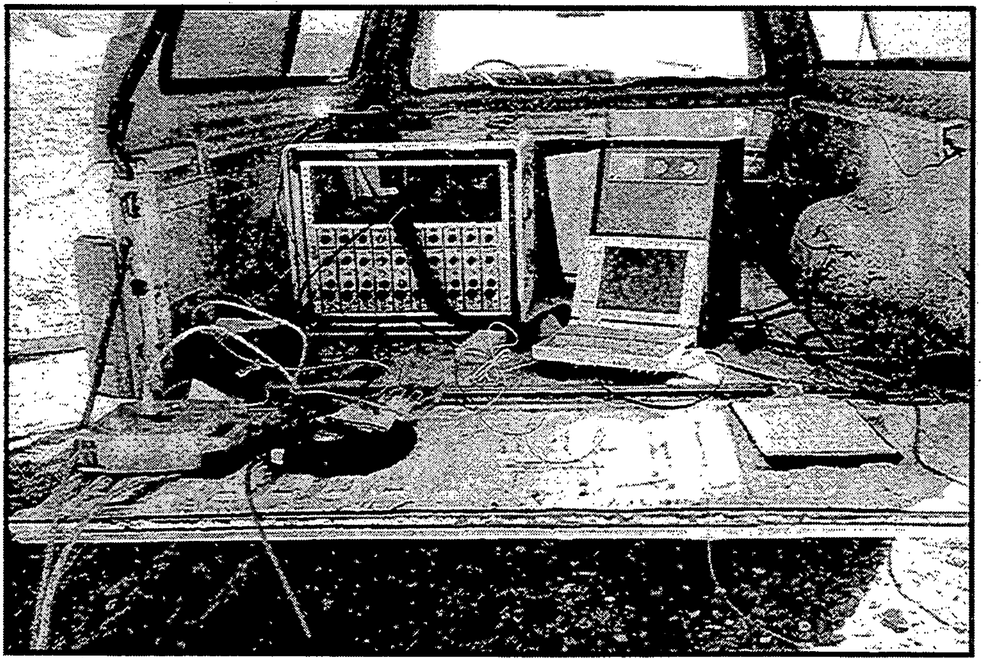


Exhibit 9. Wayside Data Acquisition System

Exhibit 10 shows the test zone setup for in-motion track panel shift testing. As illustrated, the test zone consists of three segments. The first and last segments allow the TLV to ramp panel shift loads to constant values and to ramp down, respectively. Data is acquired in the middle segment where both lateral and vertical axle loads are kept constant. To measure track panel shift behavior in one test zone, three wayside deflection transducers are located about the center location and are arranged three ties apart. Since panel shift loads can influence track up to 15 feet away, a minimum length of 40 feet, as shown in Exhibit 10, is required for the middle segment.

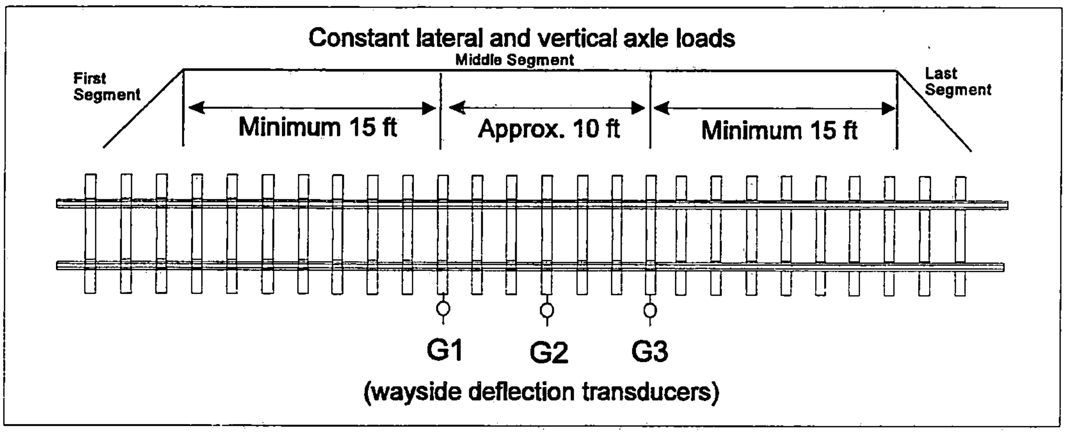


Exhibit 10. Test Zone Needed for In-Motion Track Panel Shift Testing

Only one vertical axle load is used in each test zone. However, for each zone, several series (or groups) of repeated TLV runs are conducted each with different lateral axle loads. Test series are arranged such that the lateral axle load is lowest during the first series and highest during the final series.

As stated previously, throughout each series (each group), both lateral and vertical axle loads are maintained constant during several repeated TLV passes. At each load level, a minimum of five TLV runs is required. A maximum of 20 passes for a load level is used. The minimum number of passes is used even if additional deflection ceases. The maximum number of passes is not exceeded even if the additional deflections continue to grow.

The TLV operating speed for these tests is between 2 and 4 mph. The sequence of applying panel shift loads for a test zone is as follows:

(1) Increase vertical axle load to a predetermined magnitude while the TLV is stationary.
(2) Pull the TLV at slow speed and increase lateral axle load to the desired value.
(3) Maintain constant lateral and vertical axle loads throughout the test zone.
(4) Decrease lateral axle load to zero after passing through the test zone.
(5) Decrease vertical axle load to zero and move the TLV back to the starting point.
(6) Repeat steps 1 to 5 for a minimum 5 passes and a maximum 20 passes.
(7) Increase lateral axle load for the next series.

3.4 IN-MOTION LATERAL TRACK STRENGTH TESTING

In-motion lateral track strength testing is designed to continuously measure lateral track strength and to detect soft zones along the track. This type of testing is more difficult than the stationary track panel shift tests since this involves in-motion measurements of lateral track deflection. In-motion testing of the tie-ballast strength has not been attempted before.

This first step toward a future track strength inspection vehicle explores the feasibility of measuring lateral track strength at the tie-ballast interface using continuous TLV loading. To this end, several test techniques using the TLV have been attempted. The following describes two techniques. One is referred to as in-motion stiffness profile testing; the other is referred to as curvature coefficient "a" method. Both test techniques require constant TLV vertical and lateral axle loads while moving forward. Several rail contacting transducers have been mounted to the TLV car body for track deflection measurements.

3.4.1 Track Stiffness Profile

Track stiffness profile (deflection profile) testing is designed to obtain the results, as illustrated in Exhibit 11. 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 conditions other than the tie-ballast interface are similar throughout a section of track, then any location where the track shifts less will possess higher track strength and stiffness. In other words, soft zones in tracks will manifest themselves in the form of larger deflections on the obtained profiles, as illustrated in Exhibit 11.

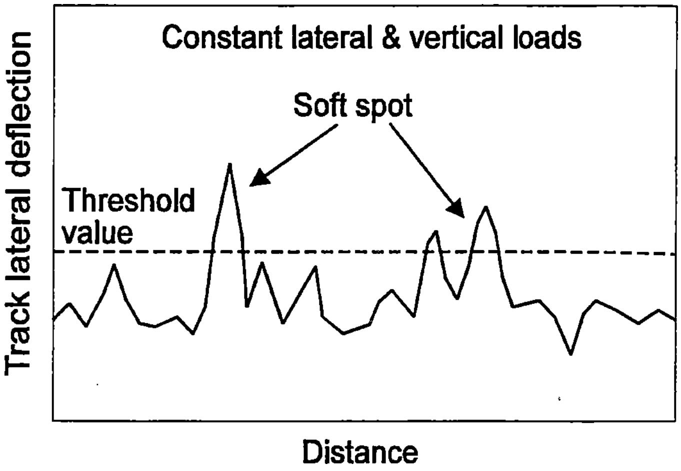


Exhibit 11. In-Motion Stiffness Profile Testing

By examining relative magnitudes of deflections along the track, track strength variation can then be determined. Determining 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.

Obviously, the first requirement for this testing is TLV application of constant vertical and lateral loads to the track while moving. A tougher requirement is a feasible and reliable onboard track lateral deflection measurement system. This first step for exploring the feasibility of such in-motion strength measurements used a rail-contacting LVDT measurement system. However, as will be discussed later, a laser measurement system must be pursued for revenue service implementation.

Exhibit 12 shows the locations of the five onboard deflection transducers (LVDT) installed on the TLV. Two transducers are installed at the TLV ends, which are used for quantifying car body movements with respect to the non-pushed rail under the TLV ends. The other three are installed under the TLV load bogie. These measure deflection of the non-flanged rail with respect to the car body. Exhibit 13 shows the LVDT fixture installed at the front and rear ends of the TLV. Exhibit 14 shows one LVDT fixture installed at the load bogie. As shown in these two pictures, steel shoes are spring-loaded against the non-flanged railhead. The maximum displacement capacity using these LVDTs is 2 to 3 inches.

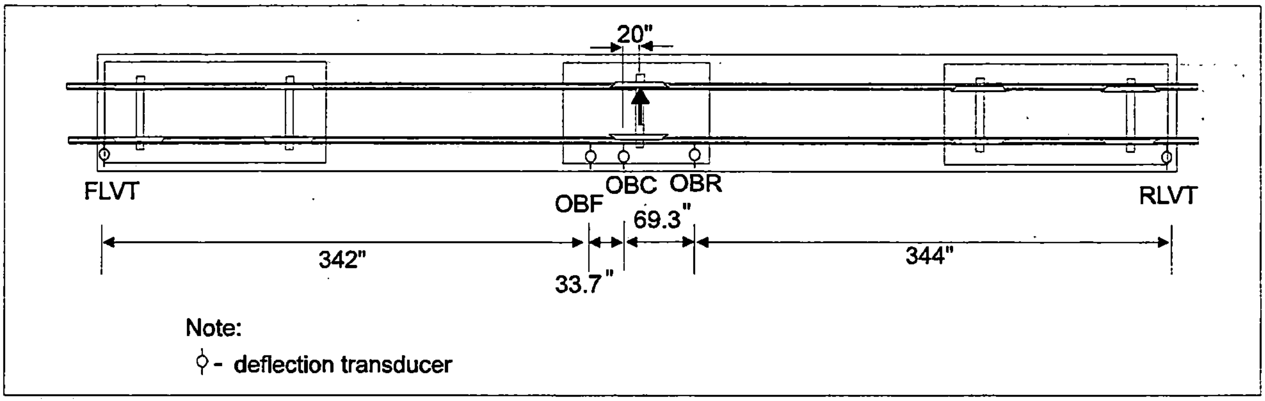


Exhibit 12. Onboard LVDT Locations

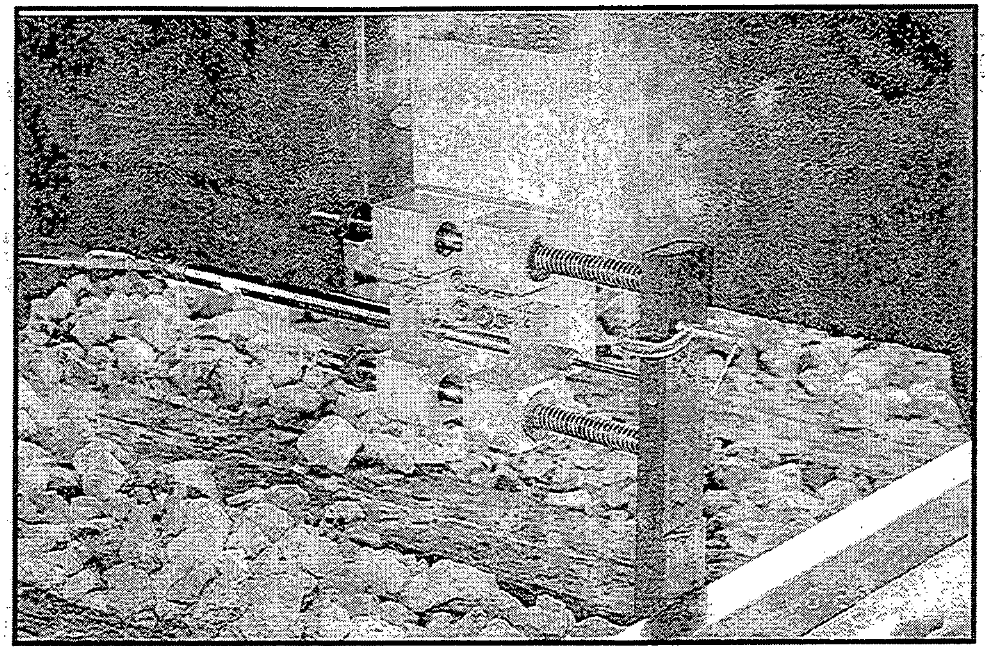


Exhibit 13. LVDT Fixture at TLV Ends

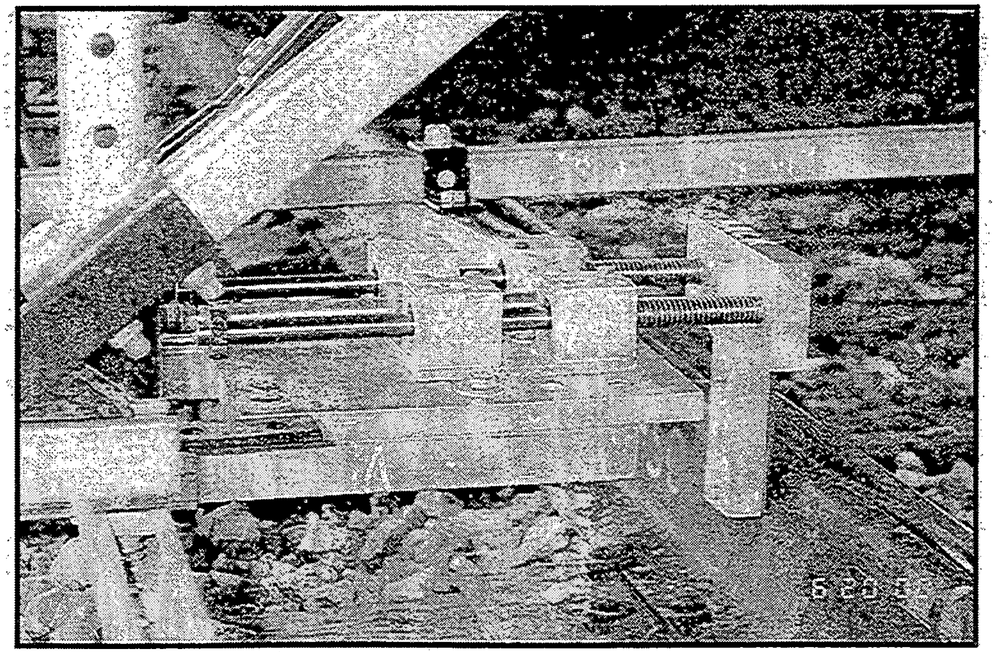


Exhibit 14. LVDT Fixture at TLV Bogie

Lateral track deflections were measured from the non-flanged rail. This allows separation of the track panel shift from other possible lateral deflections (due to rail roll, bending, translation, etc.) experienced by the flanged rail. The frame of reference for the onboard measurements is the TLV car body, which has high stiffness. Exhibit 15 shows the LVDT mounting frame rigidly attached to the car body. The three transducers at the load bogie measure movements of the non-flanged rail with respect to this reference frame. Inevitably, this frame moves rigidly with car body because the car body acts as a reaction to the applied panel shift loads. To quantify the reference movement, deflection transducers at both ends of the TLV (designated as FLVT and RLVT in Exhibit 12) were used. Because the rail under the TLV ends does not move in response to the TLV panel shift loads, it is used as a separate reference to quantify the car body movement.

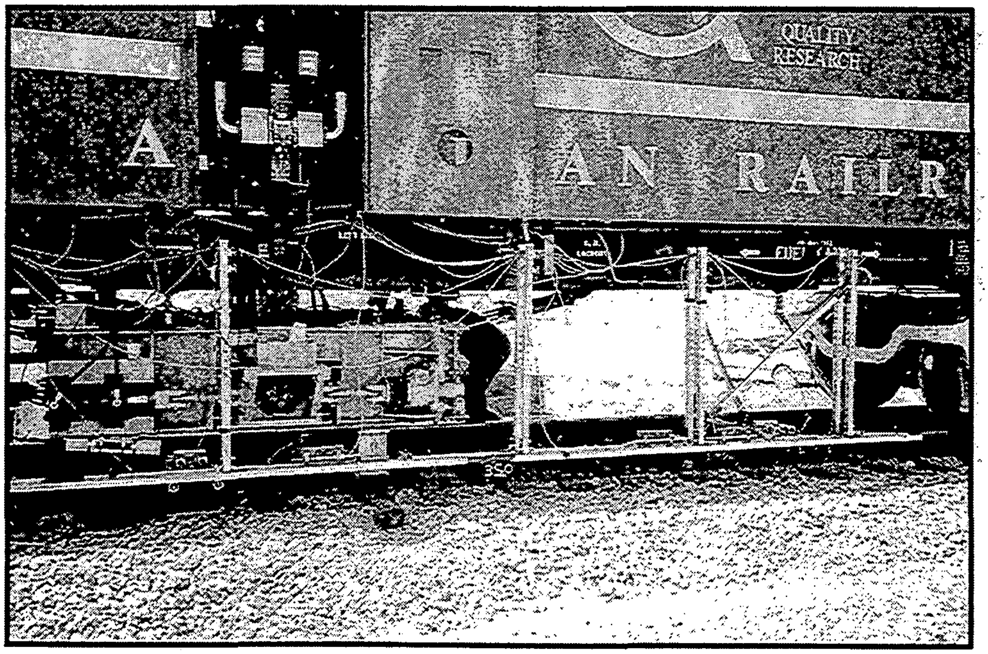
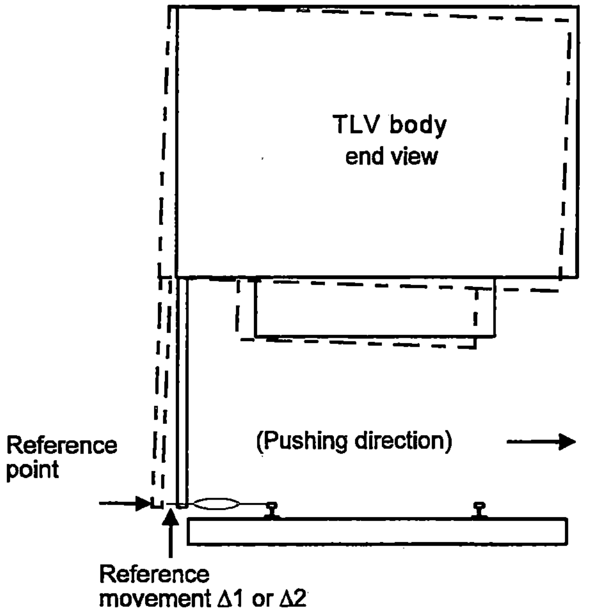


Exhibit 15. TLV Reference Frame

Exhibit 16(a) shows how the reference (from the car body) moves with respect to the unshifted rail due to TLV panel shift loads applied at the load bogie. The two deflection transducers at the TLV ends measure the reference movement outside of the panel shift influence length. Once the reference movements at the TLV front and rear ends are defined, the reference movements at the TLV load bogie locations can be determined. Exhibit 16(b) shows the determination of the reference movement at the TLV center based on the reference movements at the TLV ends.

(a) Reference movement with respect to unshifted rail



(b) Calculation of reference movement at TLV center

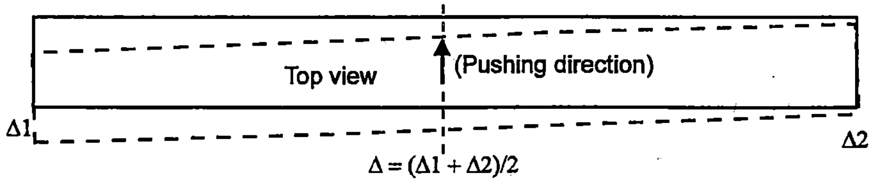


Exhibit 16. Reference Movements

Given the actual locations of the three onboard transducers (designated as OBF, OBC and OBR in Exhibit 12), the reference movements are determined by the following equations:

$$\begin{aligned} Z_f &= RLVT + 0.567(FLVT - RLVT) \\ Z_c &= RLVT + 0.524(FLVT - RLVT) \\ Z_r &= RLVT + 0.436(FLVT - RLVT) \end{aligned} \tag{7}$$

where

Z_f, Z_c, Z_r = reference movements at the locations of the three onboard LVDTs at the load bogie,

FLVT, *RLVT* = reference movements at the TLV front and rear ends.

The total measurement, *OB*, seen by the three onboard transducers installed at the TLV load bogie includes three components: reference movement, *Z*, track lateral deflection due to loads, δ, and track initial misalignment, *G*, i.e., the total measurement output is:

$$OB_x = Z_x + \delta_x + G_x \tag{8}$$

The reference movement, *Z*, is determined using Equation 7. In other words, the sum (δ + *G*) of track lateral deflection and initial misalignment for the three onboard transducers at the bogie is as follows:

$$\begin{aligned} (\delta + G)_f &= OB_f - Z_f \\ (\delta + G)_c &= OB_c - Z_c \\ (\delta + G)_r &= OB_r - Z_r \end{aligned} \tag{9}$$

In order to determine the track lateral deflection due only to the lateral load, the initial unloaded track misalignment also needs to be quantified. To do so, two TLV runs over the same section of track are required. The first run is made without applying lateral load but with the desired vertical axle load. During this first pass, the outputs of the three onboard transducers at the bogie include only two components: reference movement, Z_0, and track initial misalignment, G, i.e.:

$$OB_0 = Z_0 + G \tag{10}$$

Again, the reference movement, Z, can be determined using Equation 7 by means of the two transducers installed at the TLV ends. Therefore, its effects are removed in real-time, only leaving a record of misalignment.

The second TLV run is then made using track panel shift loading and gives the results of both track deflection, δ, and track initial misalignment, G. By subtracting G determined in the first run from $(\delta + G)$ determined in the second run, the track lateral deflections due only to track panel shift loads can finally be obtained.

3.4.2 Curvature Coefficient "A" Parameter Method

This section describes an alternative method that is designed to find weak track using relative (not absolute) track behavior.

Any method to detect panel shift behavior must sort weaker track from stronger track, therefore it must be an objective measure. It does not have to be an absolute measure however. Such a method must also be possible from a moving frame of reference (i.e. a vehicle). Unfortunately, as a vehicle rolls on a track, its suspended body may displace or rotate relative to the rails. Therefore, during a panel shift test, any measure of lateral rail to car body displacement will contain both car body motion as well as rail movement. Further, a parameter is needed which is insensitive to car body movement upon the vehicle suspension, but sensitive to track movement within the road bed.

One method of identifying panel shift activity is to record the absolute position of a rail before loading, and to record any change of position under load, as in Section 3.4.1. Another method of determining panel shift activity is to look at rail curvature before and during a lateral load.

To displace any portion of a track laterally, a change in the rail curvature must be made. Consider the hypothetical track center line as shown in Exhibit 17; path 1 has no curvature at all, while path 2 has a distinct shift at point A.

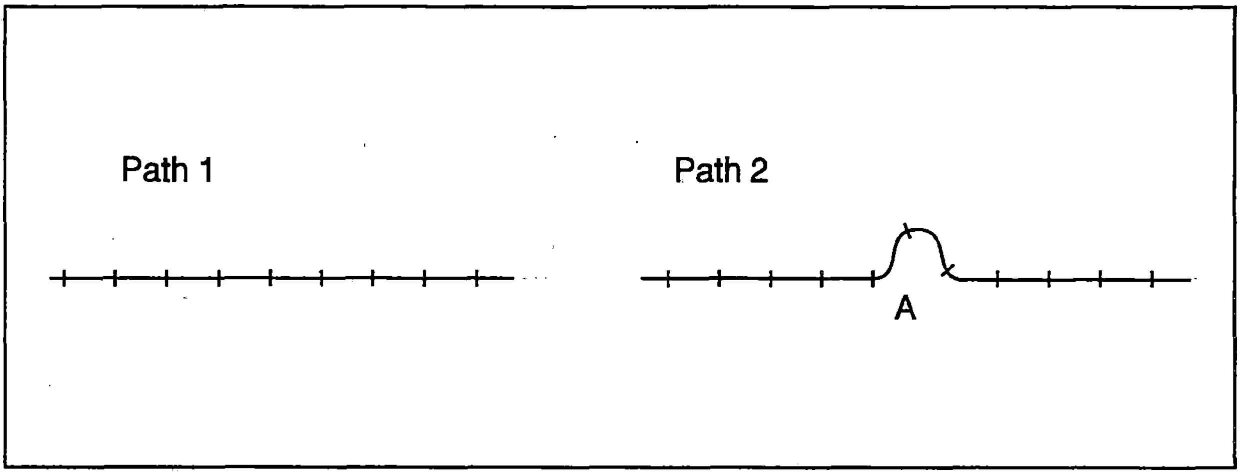


Exhibit 17: Two Paths of Track Alignment
A lateral shift at "A" would require a change in curvature.

A measure of curvature of each of these paths could locate point A just as an absolute location method would. However, it will be shown that the curvature measurement can be made insensitive to car body motion (unlike the absolute location method).

Given three displacement measurements between car body and a rail, a quadratic equation could be fit to them. This measurement array is shown in Exhibit 18.

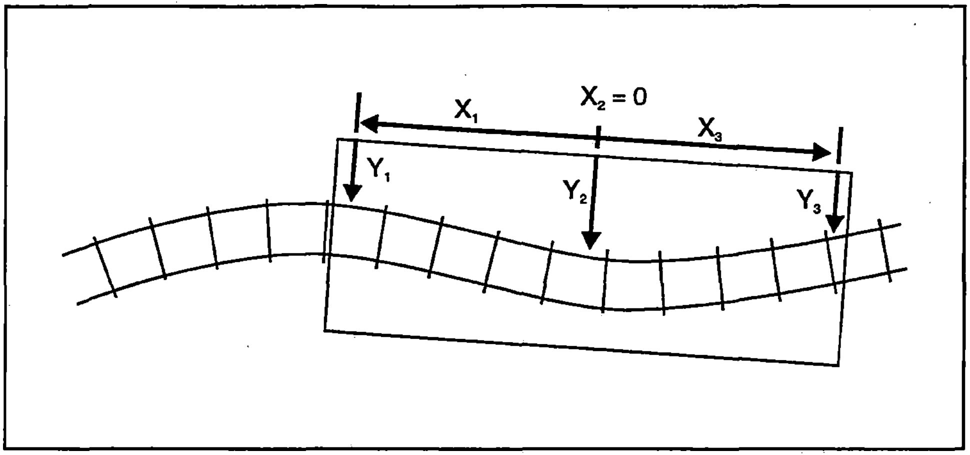


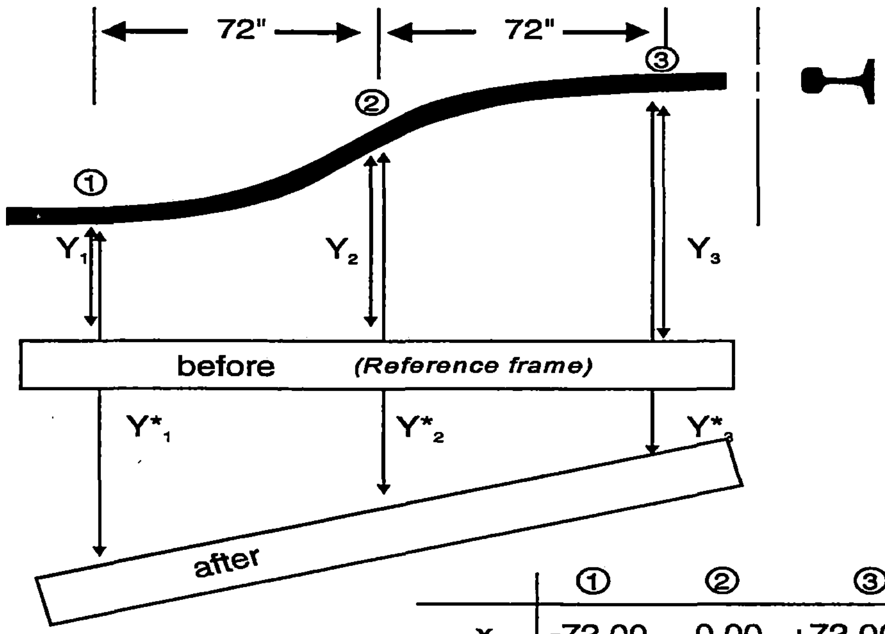
Exhibit 18: Approximation of Track Curvature via a Quadratic Equation Fit to Three Displacements

This curve would be approximated by the following equation:

$$v = ax^2 + bx + c \qquad (11)$$

Here, the *c* coefficient reflects the lateral offset at the location x=0. It will change as the car body moves closer or further from the rail. The *b* coefficient reflects the overall angle that the car body makes relative to the rail. It will change as the car body yaws. Coefficient *a* is a measure of the rail curvature. It will not change due to lateral car body displacement or car body yaw.

For verification, two hypothetical measures of the same rail are shown in Exhibit 19. Imagine that these two measurements were made at different times (perhaps when the beginning and end of an inspection device passed over a given track segment). Therefore, due to the suspension of the inspection device, the reference frame has been translated and rotated between the two sets of three lateral transducer outputs.



	①	②	③
x	-72.00	0.00	+72.00
Y	0.53	0.89	1.16
Y*	1.53	1.64	1.66

Simple curve-fit

$a \quad x^2 \quad + b\,x \quad + c \quad = y$

(before) $-8.68 \times 10^{-6} x^2 + 0.004x + 0.89 = y$

(after) $-8.68 \times 10^{-6} x^2 + 9.03 \times 10^{-4} x + 1.64 = y$

Exhibit 19: The Same Track Curvature Measured at Two Different Times. Note that coefficient "a" does not change even though the reference frame has moved and rotated.

The curve-fits to these two data sets are also shown. Note that the coefficients *b* and *c* have changed, but the coefficient *a* is the same for both the first and second snapshot in time.

Therefore, the second-order coefficient of a quadratic curve-fit can be used as a relative measure of rail curvature. It is insensitive to both rotation and lateral displacement of the reference frame.

This quadratic method will not work under one very unlikely scenario (Exhibit 20). This could happen if the amount of lateral shift created by the measurement device was constant for all track segments.

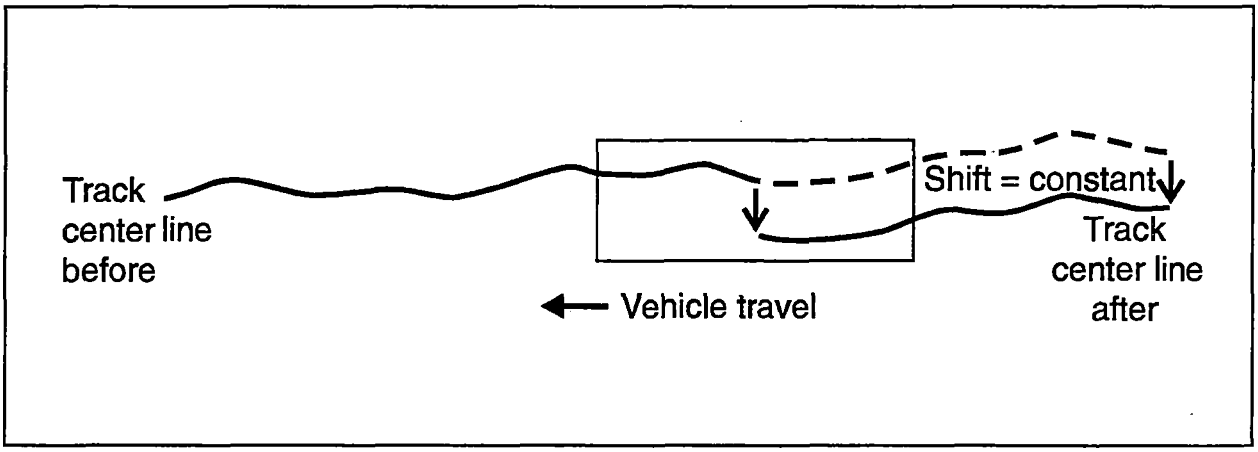


Exhibit 20: A Constant Shift Does Not Change Curvature.
The "A" Coefficient Will Not Reflect This Activity.

This ever-constant shift due to the lateral load is not likely. Rather, the inspection device will encounter track resistance changes as it travels. These changes will result in an continuous variation of the curvature parameter *a*. With experience, a tolerance could be identified which would bound "good" track, and therefore exceptions could be found for "not so good" track.

Ideally, three such arrays (each with three transducers) would be installed on an inspection device. The front array would document the curvature parameter for the original track geometry. The middle array would show the curvature during the panel shifting load. The rear array would record the curvature that is left behind. In this way, both elastic and plastic shifting behavior could be examined.

3.5 SINUSOIDAL LOADING OF TRACK IN-MOTION

A third method of in-motion track strength testing has been tried, which involves pulsing the track with a lateral load. Such a load would result in a sinusoidal deflection record, with a zero-load reference point once per cycle.

By examining the overall envelope of such a deflection wave shape, the weaker spots could be found. These would manifest themselves as larger deflections resulting from the constant amplitude sine wave force.

Such trials were attempted at loading frequencies of 2 - 8 hertz. However, the TLV does not lend itself to proper control of a dynamic forcing function. Thus far, such tests have been inconclusive.

3.6 SINGLE TIE PUSH TESTING

Single Tie Push Testing (STPT) has been used as a method to measure single tie lateral ballast resistance. STPT results have historically been used with respect to stability or buckling analysis of continuous welded rails.[5-7] 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.

Although STPT results can be related to track panel strength results with a given track type, more general correlations between STPT and TLV test results are not expected. This is because, unlike TLV test results, STPT results do not include the effects of the entire track panel (rail size, fasteners, and longitudinal forces) as well as the effects of vertical axle load on lateral track strength.

STPT was conducted simultaneously with some TLV tests for comparisons. Therefore the effects of some track variables (such as ballast consolidation level and ballast type) on tie-ballast resistance will be shown using both STPT and TLV methods.

4.0 DEMONSTRATION TESTS

The objectives of demonstration tests were to check out TLV capabilities of simulating and measuring track panel shift loadings as well as to develop lateral track deflection measurement systems. Demonstration tests were conducted in both the stationary and in-motion test modes.

Section 3.0 discussed how the TLV applies track panel shift loads to the track through the load bogie. It was also mentioned that the lateral and vertical axle loads applied are determined based on the force equilibrium of the load bogie. Verification of such a load determination method was performed, and comparison results are given in this section.

Section 3.0 also described the wayside and onboard track deflection measurement systems developed for stationary and in-motion types of tests. LVDTs are the primary deflection transducers used. Their applications in all three types of TLV tests are shown by test results given in this section as well as in the next three sections.

Demonstration tests were performed for all three types of tests: stationary, in-motion track panel shift, and in-motion stiffness profile. Some demonstration test results, however, will be discussed in conjunction with test results obtained under the fundamental test phase (Sections 5.0 to 7.0). Demonstration test results presented in this section include the distribution of the TLV panel shift loads, influence length of track panel shift load, deflections and roll of the flanged and non-flanged rails, effects of lateral loading rate, as well as cyclic stationary test results. A summary of findings from demonstration tests critical to implementing the fundamental test phase is also given.

4.1 VERIFICATION TESTS OF PANEL SHIFT LOAD DETERMINATION

To ensure correct TLV load control system functions, several load cases were verified using the instrumented rail cribs in the Rail Dynamics Laboratory (RDL) at TTC. Although these load cells in the RDL exhibit some lateral-to-vertical force cross talk, the cribs are the most accurate on site.

(1) Lateral axle load checkout:

Lateral axle load at various load bogie locations relative to the car body, was checked against a calibrated load cell. To do this, the load bogie was held above the rails using the vertical actuators in displacement control. Then a column load cell was placed between the load bogie and a reaction mass. Force control was used to ramp the applied lateral axle force from 0 to 35 kips. This was repeated with the load bogie at all extremes of its displacement envelope, both with and without a bogie roll angle.

In all cases, the TLV computed loads and the reference load cell output agreed to within 730 pounds at a load of 35 kips (2 percent). The worst case was with the bogie level, while ramping the axle load to the right. Exhibits 21 and 22 show a typical correlation between the two signals for both even and uneven vertical displacements.

(2) Vertical load checkout:

Vertical load at various wheel lateral positions was also checked on the instrumented rail sections. These cases were performed for both equal vertical load on both wheels and for unbalanced vertical loads.

Results for all cases showed the TLV computed loads and the instrumented rails had a maximum vertical force disagreement of 1100 pounds at a load of 50 kips on the right side (2 percent). This is not as good as the lateral-only study, due to cross talk in the instrumented rails. These are TTC's best instrumented rails with the least cross talk of any available. Exhibits 23 and 24 show a typical correlation during this check of both left and right vertical wheel loads.

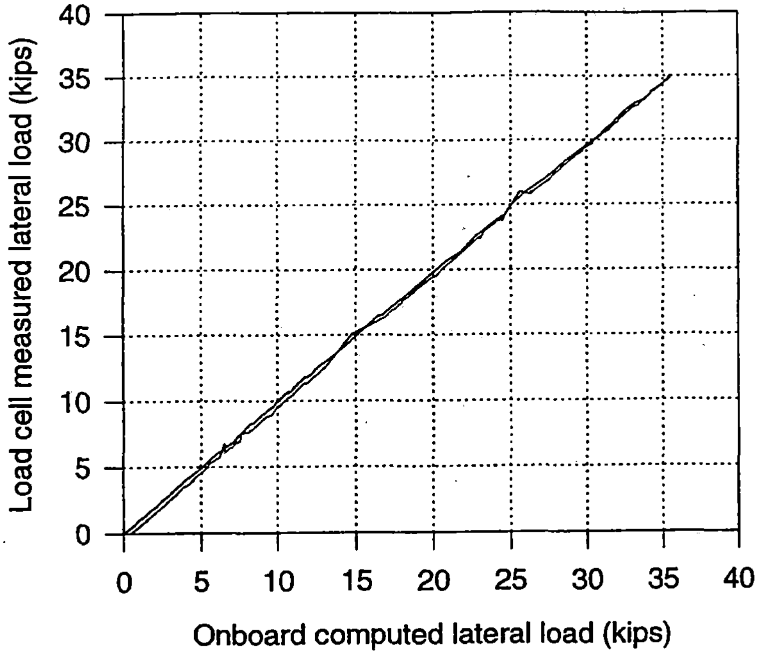


Exhibit 21: TLV Lateral Force Checkout (Even Vertical Displacements Above Rails)

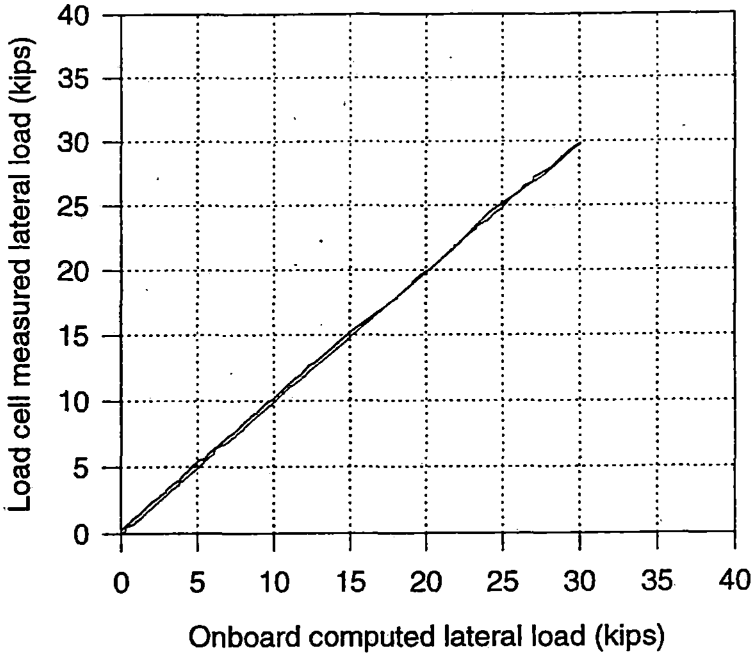


Exhibit 22: TLV Lateral Force Checkout (Uneven Vertical Displacements Above Rails)

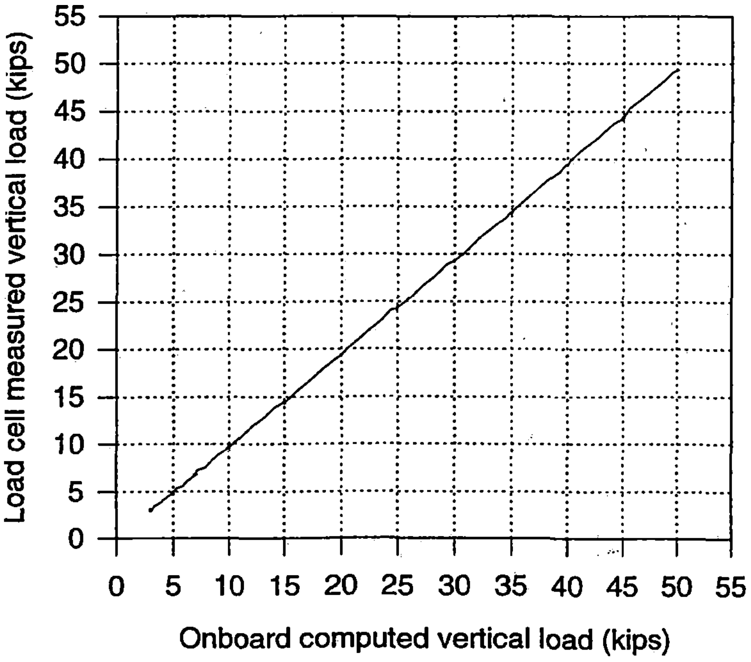


Exhibit 23: TLV Vertical Force Checkout (Left Rail)

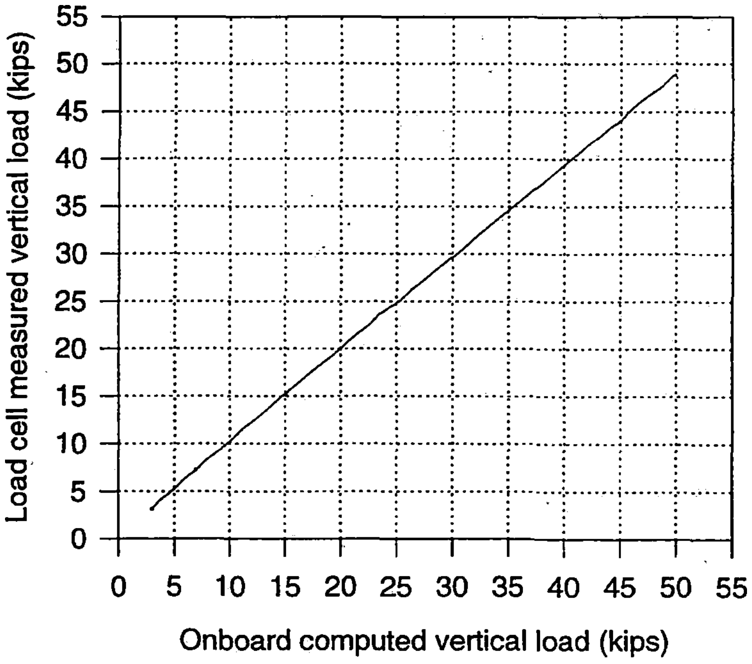


Exhibit 24: TLV Vertical Force Checkout (Right Rail)

(3) Combined lateral and vertical load checkout:

Combination load cases of both lateral and vertical forces; i.e., axle L/V ratio, were also performed. They showed a maximum disagreement on net lateral force of 3.4 kips at a lateral axle load of 32 kips and a vertical wheel load of 10 kips. Because we have already shown 2 percent disagreement when using either load case by themselves, this near 11 percent discrepancy is attributed to lateral to vertical cross talk in the RDL instrumented rail section. Original calibrations of the mini-shaker load bars (performed between 1988 and 1990) also showed similar crosstalk in the lateral force circuits when vertical forces were present. Exhibits 25 and 26 show a typical correlation during both left and right lateral ramps while using a 10 kip vertical load on both wheels.

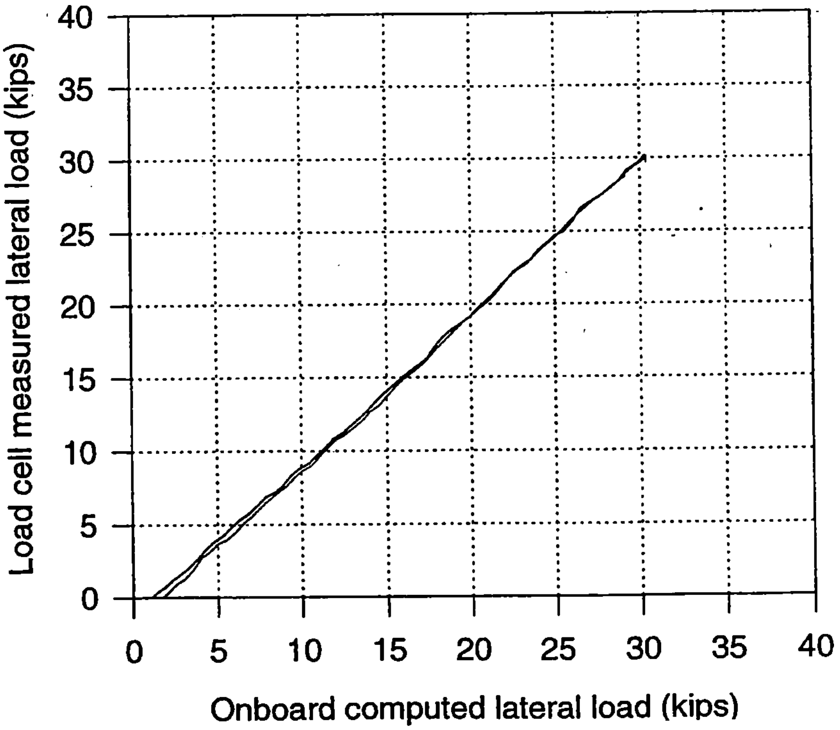


Exhibit 25: TLV Lateral Force Checkout (20 Kip Vertical Axle Load, Push To Left)

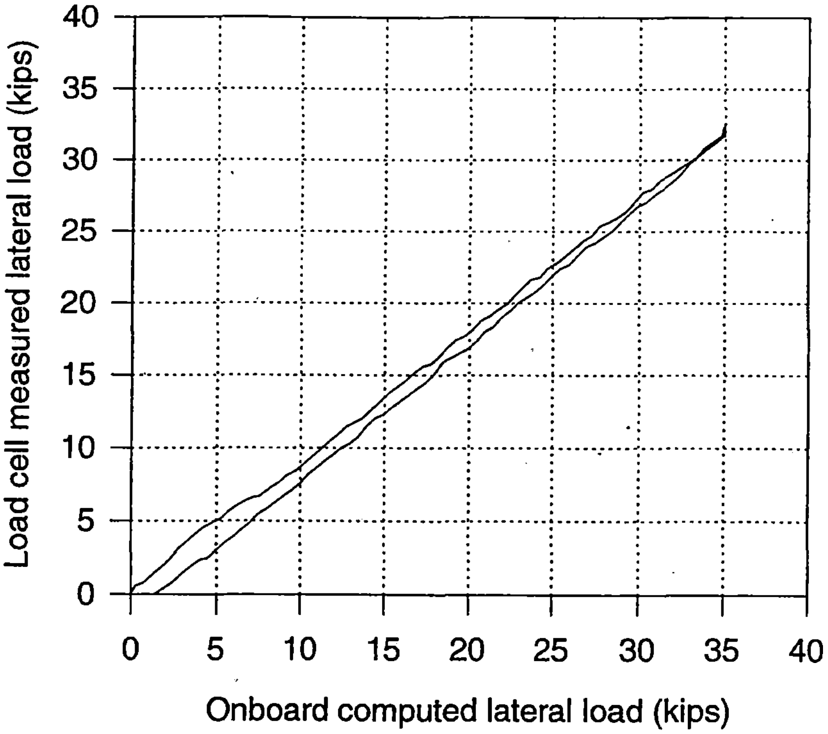


Exhibit 26: TLV Lateral Force Checkout
(20 Kip Vertical Axle Load, Push To Right)

4.2 DISTRIBUTION OF PANEL SHIFT LOADS

When the TLV loading axle applies lateral and vertical forces to the track, they are reacted by the car body. The reaction forces on the car body are in turn balanced by the wheel/rail forces under the front and rear trucks of the TLV. The lateral axle loads under these two adjacent trucks act on the track in an opposite direction to that of the lateral track panel shift load. Exhibit 27 shows the directions of the lateral axle loads under all axles of the TLV as a result of the lateral panel shift load applied.

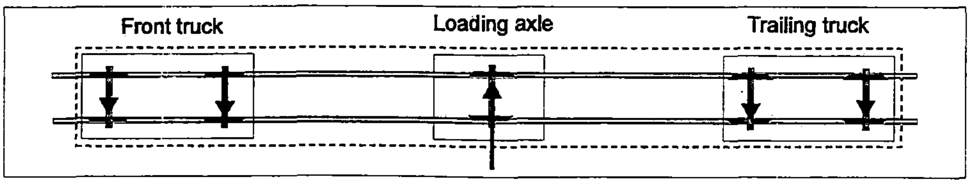


Exhibit 27. Directions of Lateral Axle Loads under TLV

During an in-motion track panel shift test run, each location on the track is pushed by the center loading axle, but it is also subjected to opposite pushes when the TLV end trucks pass over the same location. A checkout was conducted to determine whether the lateral axle reactions under either the TLV leading or trailing trucks might be large enough to negate the cumulative deformation caused by the track panel shift test.

Tests were conducted in a tangent track (Section 33 of the HTL) to measure lateral and vertical wheel forces caused by each axle when the TLV moved past the measurement location. Four strain gage circuits were installed on the two rails to measure vertical and lateral wheel loads. The track panel shift loads applied by the load bogie were 40 kips vertical and 24 kips lateral. The TLV speed was approximately 2 mph.

Exhibit 28 gives the measured vertical and lateral wheel loads using the strain gages on both the rails. Exhibit 28(a) shows the vertical wheel load results. As illustrated, the maximum vertical wheel load under the trucks was approximately 33 kips (similar to the wheel loads for a 100-ton cars). The measured vertical wheel loads from the loading axle reflected the applied vertical wheel loads; i.e., 20 kips.

Exhibit 28(b) shows the measured lateral wheel loads. A positive output represents a direction of lateral wheel load pointing outward from the track center line, whereas, a negative output represents a direction of load pointing inward (towards the center of the track). As illustrated, for an applied lateral axle load of 24 kips, the measured lateral wheel loads on the flanged and non-flanged rails were approximately 18 kips and 2.5 kips, respectively. The net lateral axle load measured using the strain gages was therefore 20.5 kips. Thus, a relative error of 3.5 kips existed between the TLV measurement and rail strain-gage measurement.

Under the trailing axles, the lateral wheel loads were 2.5 and 4 kips, respectively, on the non-flanged rail, and were approximately 1 kip negative on the flanged rails. Therefore, using the sign rules mentioned previously, the lateral axle loads were determined to be approximately 3.5 and 5 kips for two trailing axles, respectively, acting in an opposite direction to that of the lateral loading by the load bogie.

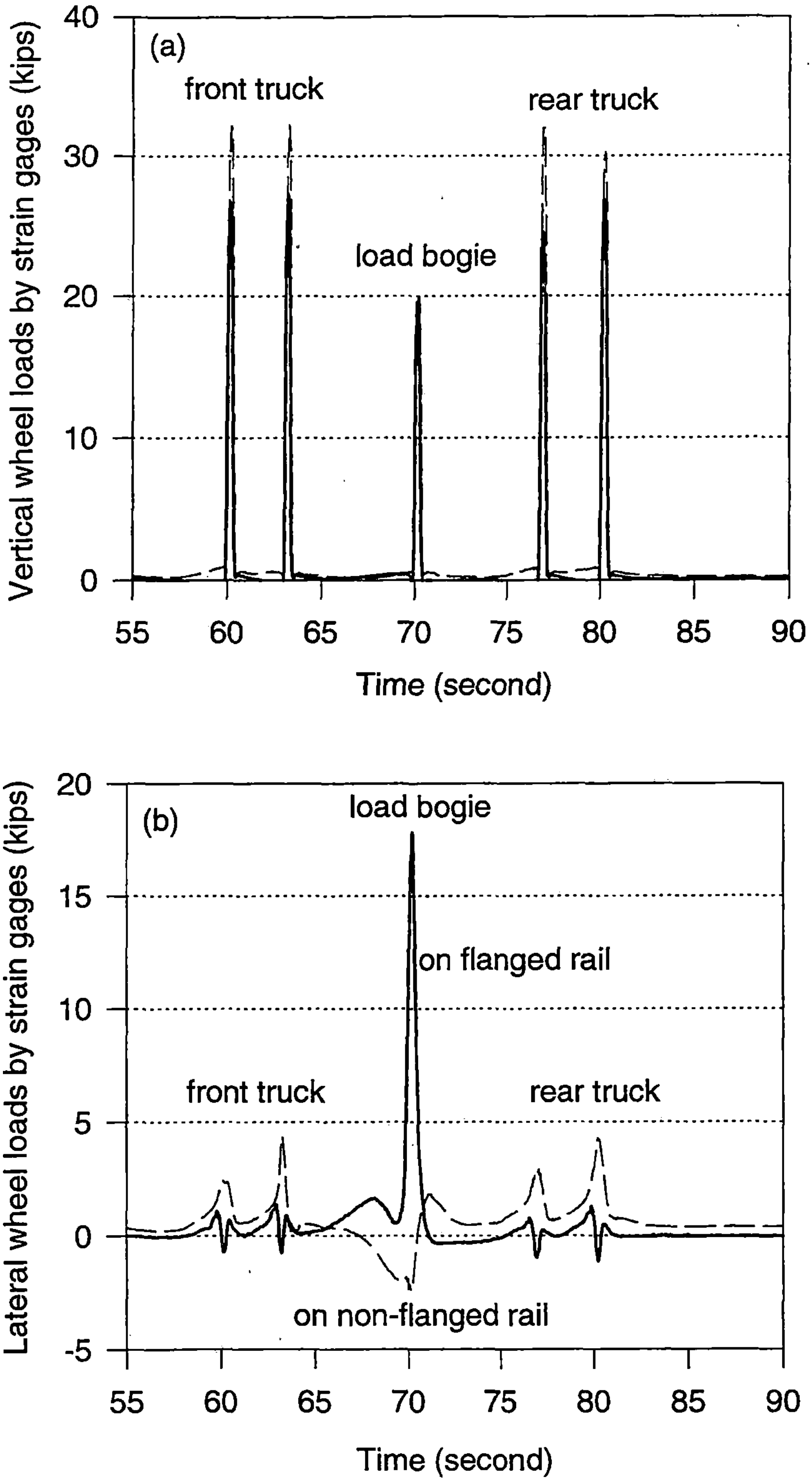


Exhibit 28: In-Motion Track Panel Shift Load Distribution (V=40 Kips, L=24 Kips)

Considering the magnitudes of both lateral and vertical axle loads for both the loading axle and trailing axles, the effects of the lateral axle loads under the trailing axles were insignificant. This is because not only the lateral axle loads under the trailing axles are small compared to the lateral axle loading under the loading axle (3.5 and 5 kips compared to 20.5 kips), but also the high vertical axle loads under the trailing axles have a large stiffening effects. Based on the results shown in Exhibit 28, the axle L/V ratio was 0.5 for the loading axle, as compared to the maximum axle L/V ratio of 0.08 for the trailing axles.

The results illustrated in Exhibit 28(b) also show that for the lateral axle load of 20.5 kips measured for the loading axle, the major portion (18 kips) was applied on the flanged rail, as opposed to only 2.5 kips being shared on the non-flanged rail.

4.3 INFLUENCE LENGTH OF TRACK PANEL SHIFT LOADS

Influence length is the track distance over which a track panel shift load has influence. Three reasons for examining this influence length are as follows:

- To ensure that the track panel under the TLV ends will not move due to the panel shift loads applied by the center loading axle. Given this, the car body movements can be determined with respect to the undeformed rail under the TLV ends for in-motion lateral track strength testing.

- The tie-ballast interface will be locally disturbed as a result of a panel shift test. We need to determine the appropriate length for a test zone allowed for a stationary push. This is particularly important for tests conducted on TTC test tracks since the available tracks are limited. Careful planning of test track usage must be based on the influence length information.

- Although not studied under this project, there is a general need to compare the influence lengths due to vertical and lateral axle loads, respectively. Vertical loads have a stiffening effect on the track panel, but may also uplift the track panel at a certain distance from the load application point. Any influence of lateral load in this track uplifting zone may contribute to loss of track stability, especially under thermal rail compression.

Stationary tests were conducted on the PTT (Precision Test Track) and Balloon Track. Exhibit 29 is a summary of track components for these two tracks:

Exhibit 29: Track Components for PTT and Balloon Test Tracks

Test Track	Rail	Tie	Fastener	Ballast
PTT	119	wood	cut spike	crushed stone
Balloon	136	wood	cut spike	slag

To measure lateral track deflections, the wayside transducers, as shown in Exhibit 4, were placed at selected tie locations along the track. Exhibit 30 shows two examples of test results of lateral track deflection along the track. Exhibit 30(a) shows the results for a test location at the 7.5-degree curve of the Balloon Track, while Exhibit 30(b) shows the results for a tangent test location at the PTT track. Zero distance corresponds to the application point of the panel shift loads. Lateral track deflection distributions along the track are plotted at various magnitudes of the maximum lateral track deflection (i.e., at various intervals through the push).

To better define the influence length based on the test results shown in Exhibit 30, lateral track deflections at various locations have been normalized by the maximum track deflection at the load application point. These normalized results are shown in Exhibit 31. The influence lengths are defined as the distance of significant lateral track deflection.

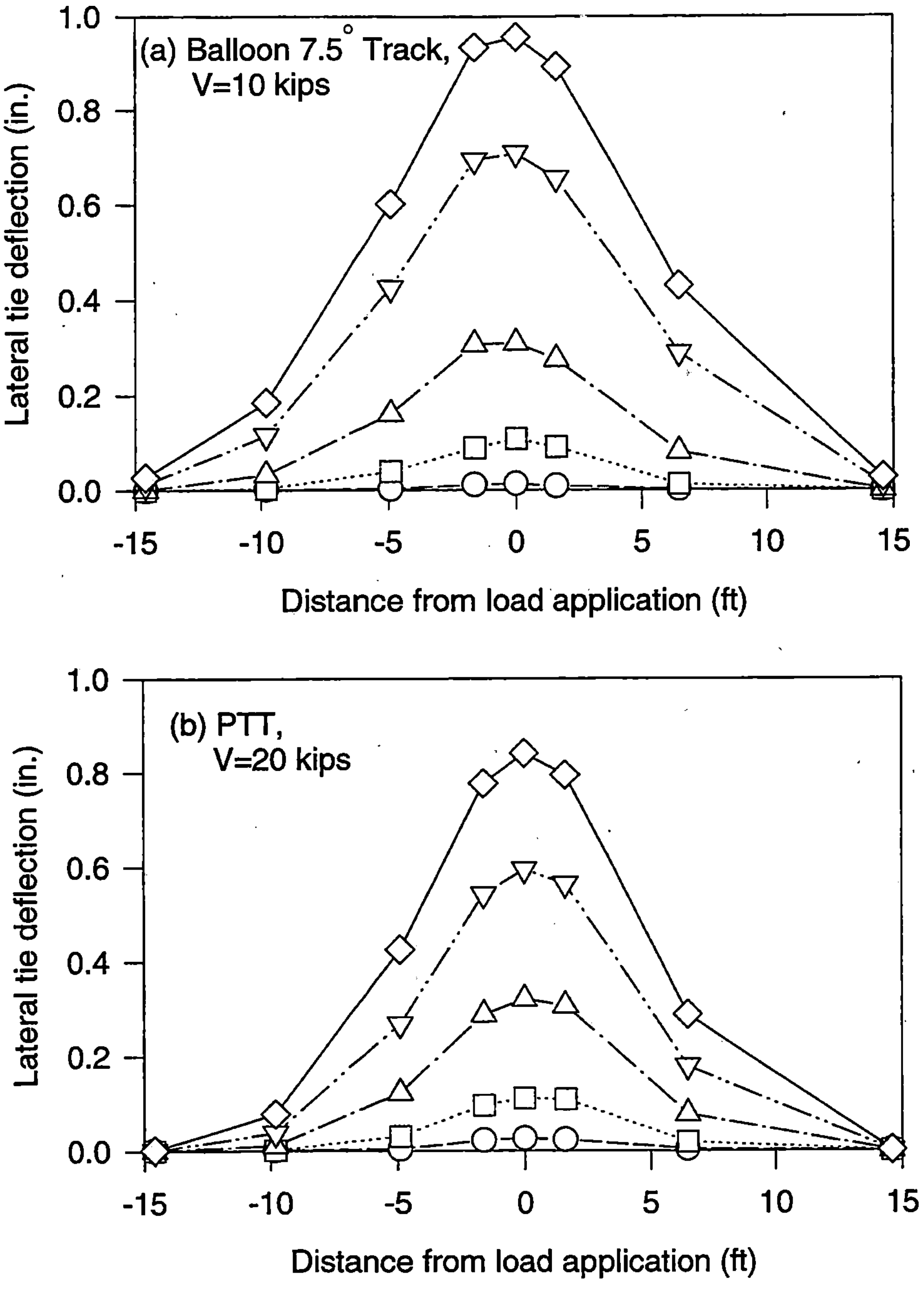


Exhibit 30. Distribution of Lateral Tie Deflection Along Track From Stationary Test
(Note that the same symbols between (a) and (b) do not indicate the same lateral loads)

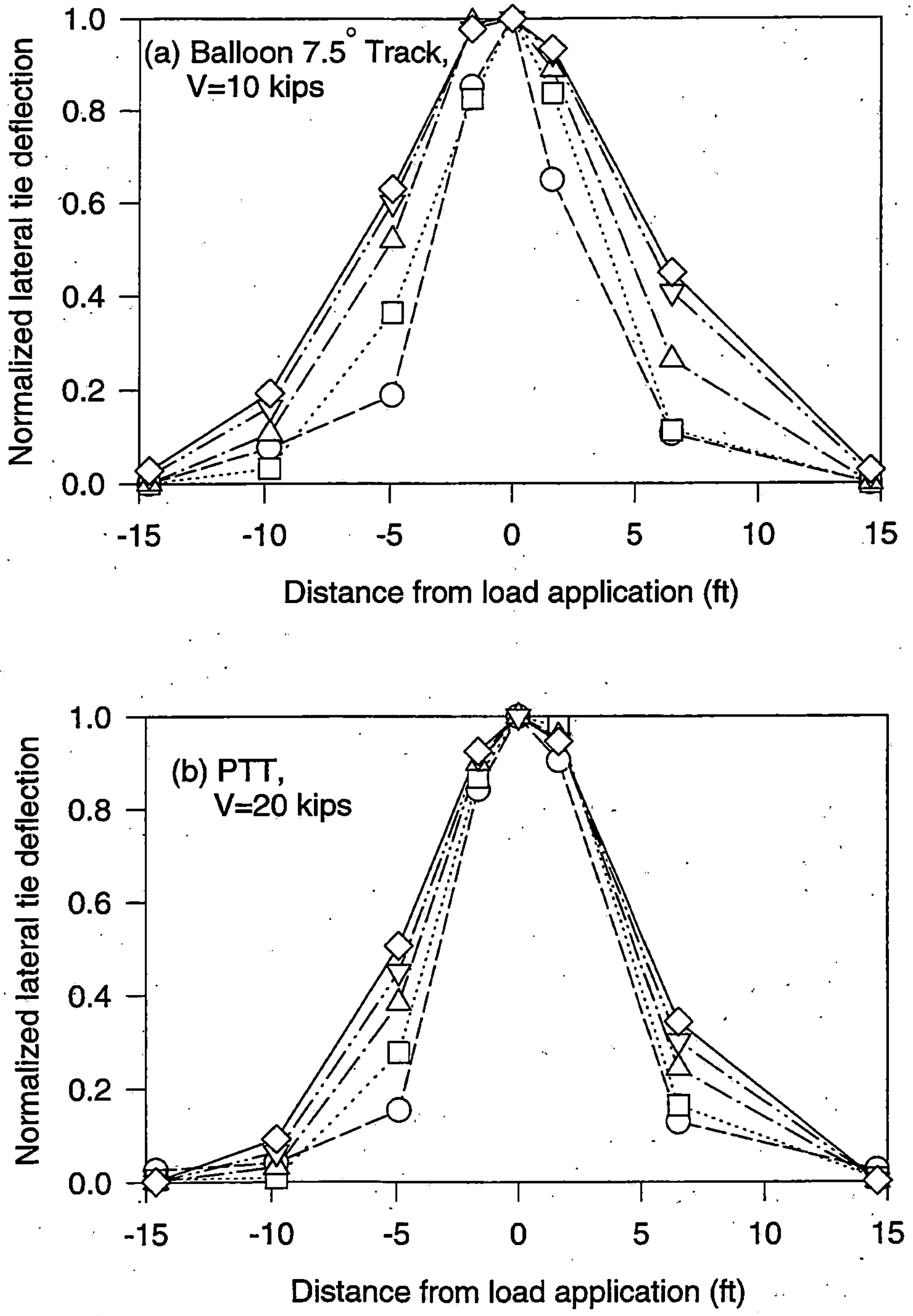


Exhibit 31. Influence Length From Stationary Test

As illustrated in Exhibit 31, regardless of track deflection magnitude, the track deflection at 15 feet is less than 5 percent of the deflection at the center of push; therefore, the influence length can be considered approximately 15 feet. This is true even at small lateral track deflections. In other words, the normalized influence length does not depend upon the maximum lateral track deflection.

Because the TLV ends are more than 30 feet from the loading axle, the track panel under the TLV ends will not move due to the panel shift loads. Also, based on the above test results, a test zone of 30 feet has been chosen for a stationary test in order to avoid influences of any previous test.

4.4 DEFLECTION AND ROLL OF FLANGED AND NON-FLANGED RAILS

For stationary and in-motion track panel shift tests, track deflections are measured in terms of lateral tie deflections. However, for in-motion lateral track strength testing, deflection profiles are measured in terms of non-flanged rail lateral deflections. It is assumed that the lateral deflection of non-flanged rail is equal to the tie deflection due to panel shift loads. This is because the non-flanged rail reacts only to a small portion of lateral axle load that is applied. Therefore the non-flanged rail should not move significantly relative to the ties.

To verify this assumption, tests were conducted on the PTT and Balloon Track. Exhibit 32 shows examples of test results. These results show relative deflections of tie to ballast, railhead to tie, and rail-base-to-tie, respectively. For measurements of tie to ballast lateral deflection, the transducer fixture shown in Exhibit 4 was used. For measurements of rail to tie lateral deflections, the wayside transducer fixture shown in Exhibit 5 was used.

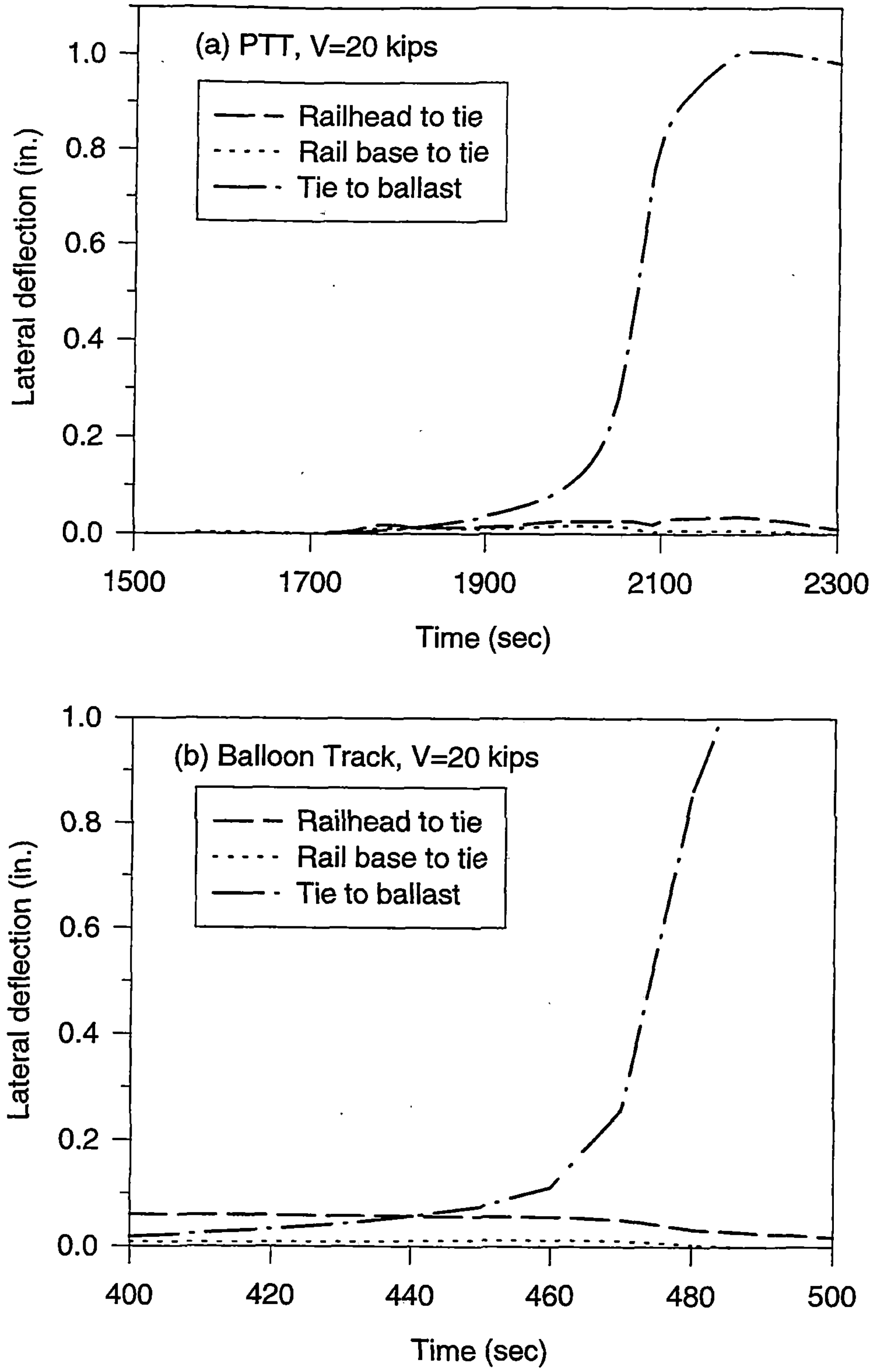


Exhibit 32: Relative Deflections of Non-Pushed Rail and Crosstie during Lateral Force Ramp.
(Note larger tie to ballast deflections and smaller rail to tie deflections.)

For a maximum tie lateral deflection approximately 1 inch, Exhibit 32 shows that the lateral deflections of the non-flanged railhead and base were almost zero with respect to the ties. Therefore, the lateral deflection of the non-flanged rail relative to the ballast can be considered the same as the lateral deflection of the tie relative to the ballast.

On the other hand, because the flanged rail reacts mainly to the lateral panel shift load, only this rail will move significantly relative to the ties. Response of the flanged rail was examined using displacement transducers (LVDTs) between the rails and ties. These transducers included lateral motion of the rail relative to the tie (at both the railhead and base), as well as uplift of the rail base at the inside foot. They were held either horizontally (lateral measurement) or vertically (uplift measurement) by a fixture rigidly attached to the tie. The vertical measurement indicates whether the rail fasteners were pulled upward due to rail rollover.

Tests were performed on wood ties with cut spike fasteners. The vertical force on each rail was constant and maintained at 10 kips. Exhibits 33 and 34 show results for one trial run.

As shown in Exhibit 33, the flanged rail base motion relative to the tie reaches a maximum of 0.07 inch at full-tie deflection of 0.23 inch. Because the flanged rail reacts to the majority of the lateral load, movement of the rail base will depend on initial clearances between rail, tie plate, and fasteners. The tie condition also will affect this movement due to spike holes in the tie and the resilience of the tie material surrounding such holes.

The flanged-rail motions shown here have not been investigated further because measurements for the balance of the project were made on the non-flanged rail or direct to the tie. While any propensity of the flanged rail to roll may alter the force path of lateral reactions, this effect is not expected to be significant.

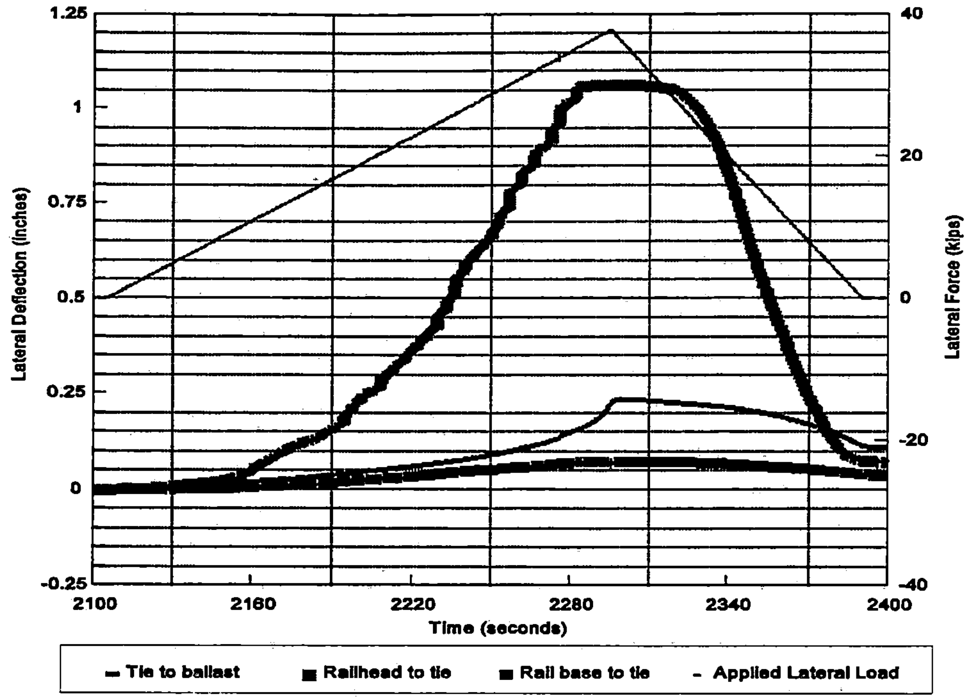


Exhibit 33: Deflection of Flanged Rail-to-tie and Tie-to-ballast (HTL Section 40, V=20 kips)

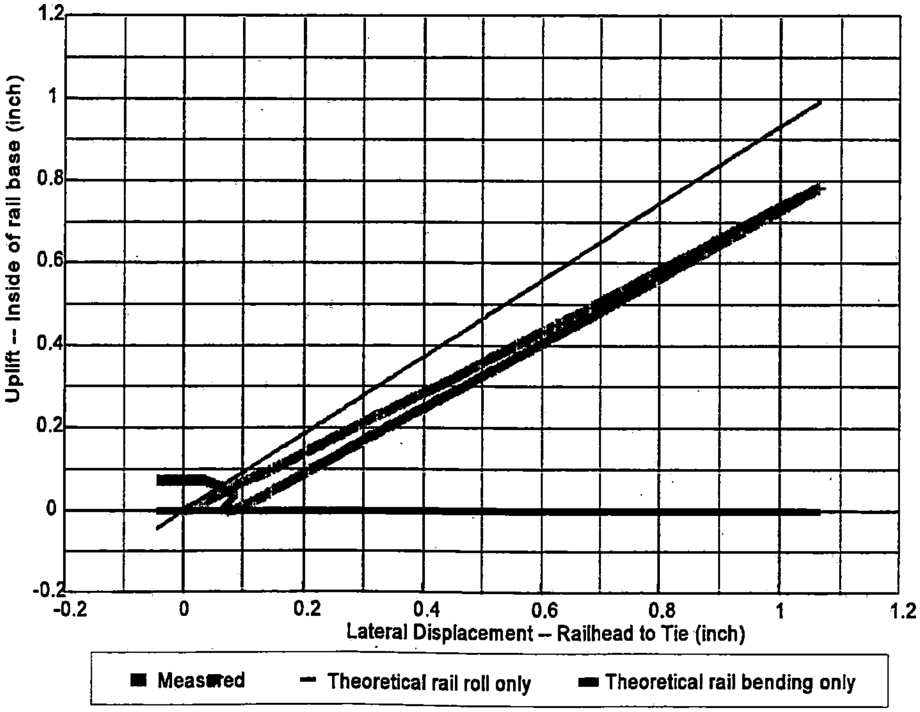


Exhibit 34: Flanged Rail Uplift versus Head Lateral Movement (HTL Section 40, V=20 kips)

The railhead motion of the flanged rail is significant and is also shown in Exhibit 33. More than 1 inch of railhead deflection was seen. It is interesting that this motion stabilizes near 2280 seconds **before** the lateral load applied by the TLV reaches a peak, which suggests that an upper limit of rail deflection exists under this loading method.

To examine the nature of this displacement, a cross-plot of the rail head movement and the rail base uplift movement is shown in Exhibit 34. Also shown on the plot are two lines of the theoretical responses of pure rolling action, or pure bending action. The measured data more closely reflects a rollover response of the rail, with little rail bending activity.

4.5 EFFECTS OF LATERAL LOADING RATE

Under the demonstration test phase, stationary tests with various loading rates were conducted to determine possible TLV loading rate effects on test results. The range of loading rates considered was from 0.05 to 1 kip per second, covering a slow push to a fast push. For the lowest loading rate, approximately 13 minutes are required to complete a 40 kips lateral loading, and for the highest loading rate, it would take 40 seconds to complete a 40 kips lateral loading.

Exhibit 35 shows lateral load-deflection relationships for four different loading rates. Tests were conducted on the PTT track with a vertical axle load of 20 kips. As illustrated, an increase in loading rate resulted in an increase of the required lateral load to produce the same amount of lateral track deflection. However, effect can be considered to be small within a lateral track deflection of 0.3 inch. Also note that the effect of loading rate is smaller for strength defined at smaller deflections (e.g., $L_{0.05}$ and $L_{0.1}$) than at larger deflections (e.g., $L_{0.2}$ and $L_{0.3}$).

To be consistent, the lateral loading rates were chosen between 0.2 to 0.4 kip per second. Within this range, the effect of loading rate is insignificant.

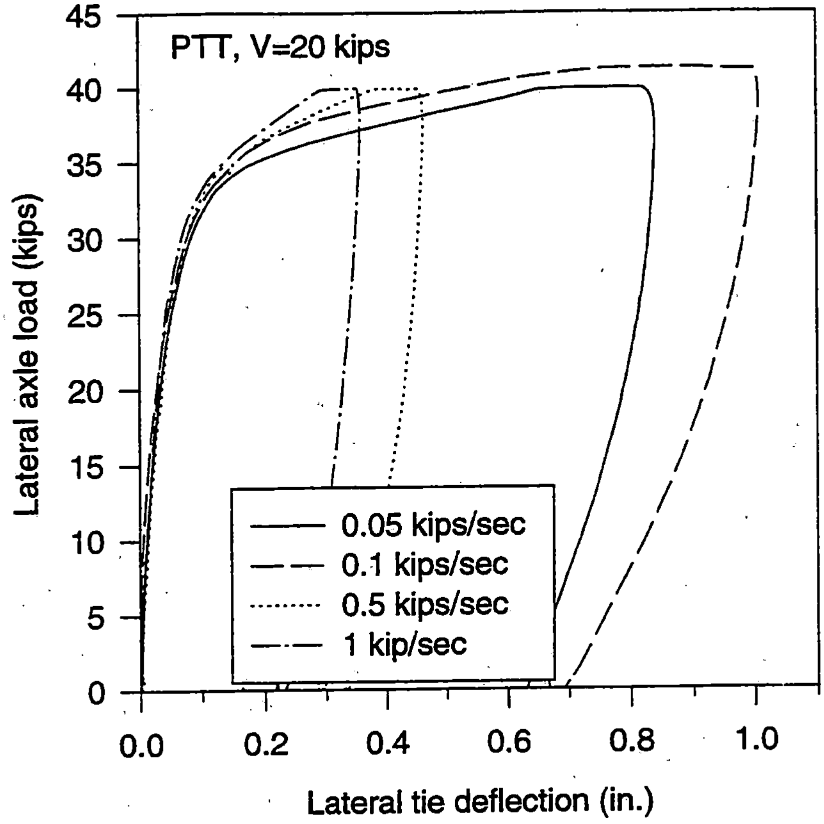


Exhibit 35. Lateral Load Rate Effect

4.6 CYCLIC STATIONARY TESTS

To examine the destructive effects of a stationary panel push on the available lateral track strength and stiffness, several cyclic stationary tests were conducted. In a cyclic stationary test, the sequence of applying vertical and lateral loads was repeated three times at the same test location. By examining slopes of load-deflection curves for three load cycles, the effect of a previous load cycle on the successive load cycles can be determined.

Exhibit 36(a) shows the load-deflection relationship obtained at a test location of the Balloon Track. During the first load cycle, the track panel was pushed to a maximum lateral deflection close to 0.04 inch, while during the second load cycle, the track panel was pushed to a maximum lateral deflection close to 0.07 inch. Given these values, the panel push for both the load cycles were well within the first stiffer region of load-deflection curve. Therefore, following each load cycle, even though a certain amount of plastic deformation was generated, the lateral track stiffness did not change. This is evident by the parallel load-deflection curves among all the three load cycles.

Exhibit 36(b) shows the load-deflection relationship obtained at the Facility for Accelerated Service Testing on the High Tonnage Loop. For the first load cycle, the maximum panel push was still very small. Compared to the first cyclic stationary test, during the second load cycle, the track panel was pushed further to approximately 0.12 inch. Nonetheless, the lateral track deflection during the first two load cycles was still within the first stiffer region of load-deflection curve. As illustrated, the lateral track stiffness for the second and third load-deflection relationships did not show reduced magnitudes following the previous load cycles.

The third cyclic stationary test was conducted at a test location of the Balloon Track. In this test, the track panel was pushed for a maximum deflection close to 0.5 inch during the second load cycle. In other words, the track panel was pushed far past the initial stiff region of load deflection curve and into the second softer region. Exhibit 36(c) shows the load-deflection relationship during the three load cycles. During the third load cycle, initially the track showed almost the same stiffness for a lateral loading up to 12 kips. However, above 12 kips, the slope of the transition curve to the second weaker region of the load-deflection curve is much lower.

The above test results indicate that a track panel push will not reduce the available lateral track strength and stiffness significantly if the lateral track deflection is kept within the first region of load-deflection curve. However, if the track is pushed much into the second region, the available track strength can be reduced significantly.

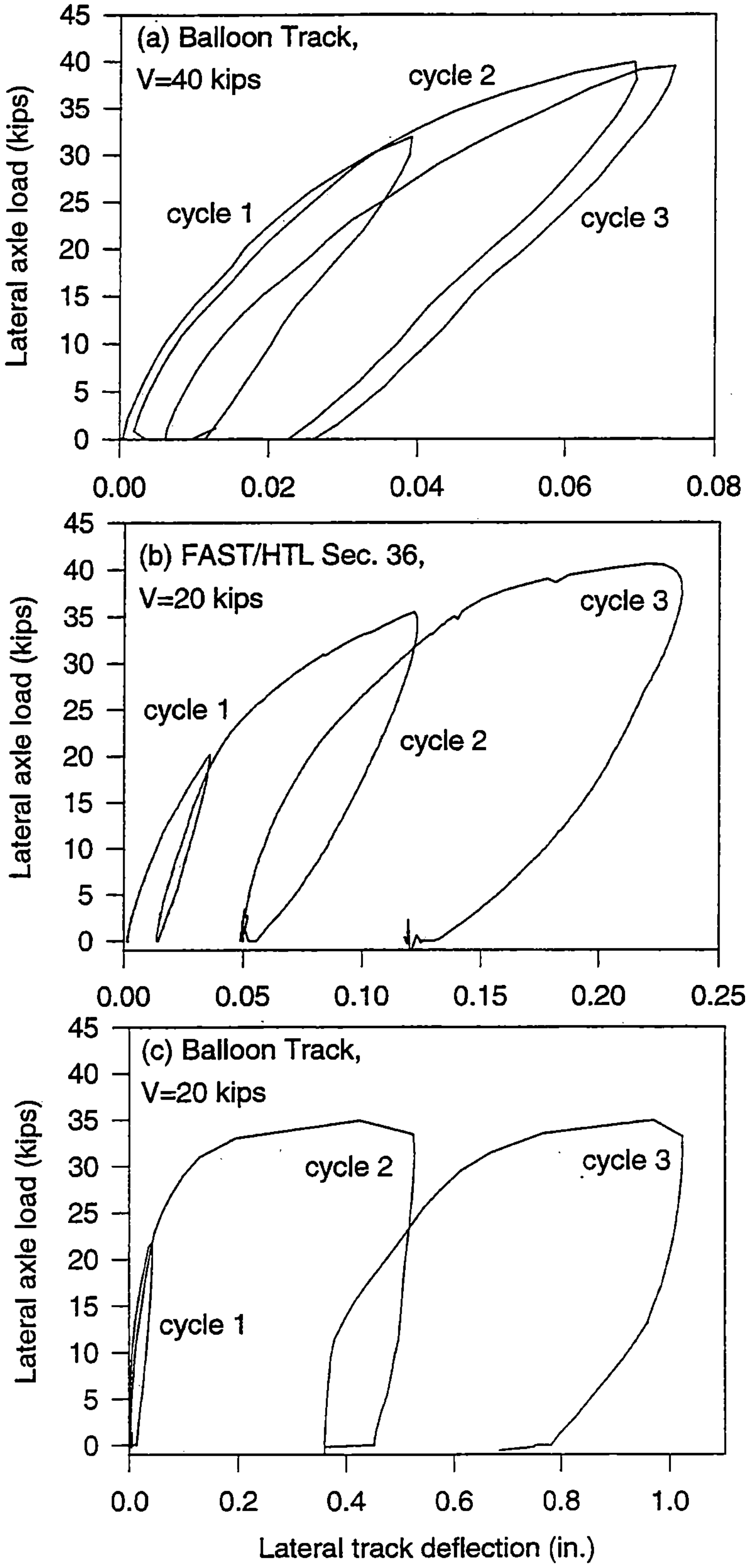


Exhibit 36. Cyclic Loading-Unloading Test Results

4.7 EFFECT OF UNBALANCED VERTICAL AXLE LOADS

Throughout this study (whether stationary or in-motion), equal vertical wheel loads were applied to both rails. However, limited stationary tests were conducted with constant vertical axle loads, but variable distributions between two wheels. This was done to check out possible effects of unbalanced vertical axle loads on test results.

For a constant vertical axle load of 20 kips, three combinations of vertical wheel loads were applied to the flanged and non-flanged rails. The combinations included equal loading on both rails, and left to right rail load ratios of 15:5 and 5:15 kips. For each combination, three tests were repeated to obtain more representative results. Exhibit 37 shows comparisons of values of the strength parameters as mentioned for the three vertical wheel load combinations.

No obvious trend can be seen from the results shown in Exhibit 37 in terms of the effects of the unbalanced vertical axle load. No further tests were attempted since the checkout test was considered to serve a secondary purpose.

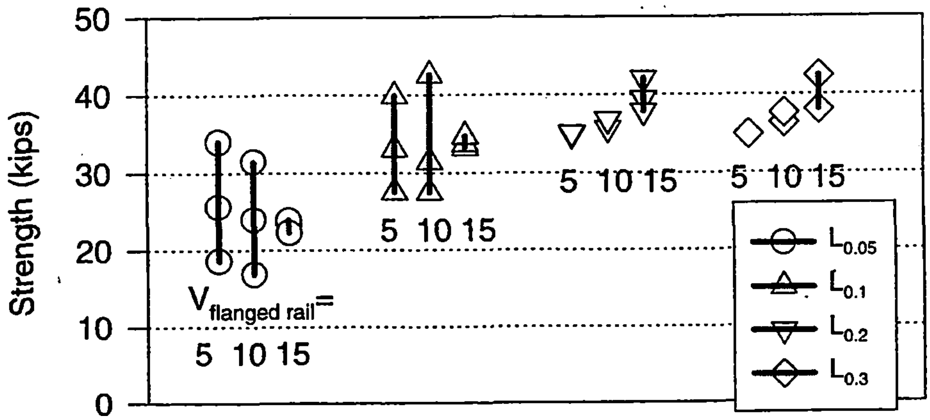


Exhibit 37: Effects of Unballanced Vertical Load

4.8 SUMMARY

To discuss lateral track strength and track panel shift results more coherently, some demonstration test results will be given in conjunction with fundamental test results in the next three sections. However, the following is a summary of findings from demonstration tests which were critical for implementing the fundamental test phase:

- All three types of TLV track panel shift tests described in Section 3 are feasable using the TLV.
- Track panel shift load determination based on the force equilibrium of the load bogie is accurate to within 2 percent.
- The lateral axle reactions under the trailing truck due to panel shift loads applied by the center load bogie will not influence in-motion track panel shift test results significantly.
- The influence length of track panel shift loads is approximately 15 feet each direction; therefore, 30 feet of track are needed for each stationary test. The track panel under the TLV ends will not move laterally due to applied panel shift loads.
- The lateral panel shift load is reacted primarily on the flanged rail. The flanged rail moves considerably relative to the ties under panel shift loads, mainly due largely to rail roll and partly bending and translation. Cut spikes (gage side only) may pull out as a result of the flanged rail movements. On the other hand, the non-flanged rail experiences little or no lateral deflection with respect to the ties, under applied panel shift loads.
- For a stationary test, depending upon track conditions and vertical axle load, the required lateral track deflection should be between 0.2 and 0.5 inch to adequately determine lateral track strength and stiffness. Beyond this deflection, sometimes large subsequent panel shift may occur quickly.
- An increase in lateral loading rate increases the measured lateral track strength and stiffness. However, for the range of 0.05 to 1 kips per second considered, the rate of applying lateral axle load under a stationary test is insignificant.
- A track panel push will not reduce the available track strength and stiffness significantly if the lateral track deflection is kept small within the first stiffer region of load-deflection curve. However, if the track is pushed into the second region, the available track strength can be reduced significantly.

5.0 FUNDAMENTAL STATIONARY TESTS

As discussed in Section 3.0, TLV stationary track panel shift tests measure static lateral track strength and stiffness. This type of TLV testing provides a simple and rational test method to study the fundamental characteristics of lateral track strength and stiffness influenced by different load and track variables.

This section gives test results and their analyses from stationary tests conducted under the fundamental test phase. For more comparative analysis, some stationary test results obtained under the demonstration test phase are also given.

In addition to lateral load-deflection relationships directly obtained under stationary tests, the strength and stiffness parameters defined in Section 3.0 are used to quantify stationary test results. As illustrated in Exhibit 6 of Section 3.0, the stiffness parameters include $k_{0.05}$, $k_{0.1}$, $k_{0.2\text{-}0.3}$, $k_{0.05u}$, and $k_{0.1u}$, and the strength parameters include $L_{0.05}$, $L_{0.1}$, $L_{0.2}$, and $L_{0.3}$. Note that the numeric subscripts used with these parameters represent deflection levels, and the subscript "u" represents the situation for lateral unloading.

It is known that lateral track strength and stiffness are influenced by various load and track variables. The load and track variables studied using TLV stationary tests include vertical axle load, ballast consolidation level affected by track maintenance and traffic, rail longitudinal forces, tie type, ballast type, track curvature, and ballast shoulder width.

Under the fundamental test phase, stationary tests were generally repeated three times each at a different location to represent one test condition. To avoid the influence of a previous test, each test location was at least 30 feet from another test location, based on the conclusions from demonstration tests.

Comparisons between TLV stationary test results and STPT test results are given for some track variables studied. Also, some analytical results using a theoretical model developed by Foster-Miller Inc. and VNTSC are compared with test results.

5.1 TEST TRACKS

Fundamental tests were conducted at FAST on the HTL. This test loop is 2.7 miles long and is a FRA Class 4 track. At this track, test variables included ballast type, tie type, and track curvature. Also, operations of the heavy axle load train consist on the HTL provided an excellent opportunity to study the effect of traffic on lateral track resistance recovery following ballast tamping.

Exhibit 38 shows the four sections of the HTL where various stationary tests were conducted. Section 03 is a 5-degree curve; Sections 33, 36 and 40 are all tangent tracks. Exhibit 39 summarizes the track component information as well as track variables studied for these four sections of tracks.

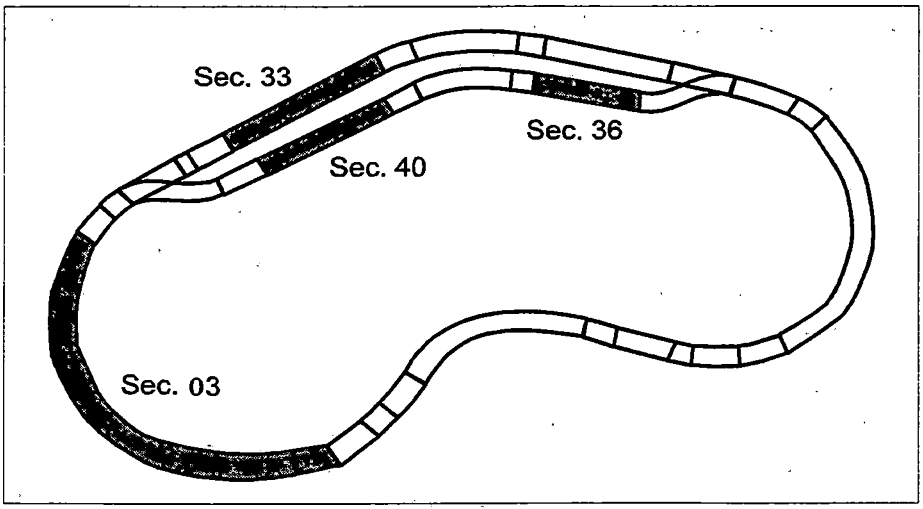


Exhibit 38: Test Sections at HTL/FAST

Under the demonstration test phase, stationary tests were conducted on the PTT and Balloon Track. The track component information for these two test tracks were given in Exhibit 29.

Exhibit 39: Test Track Information and Test Variables Studied

Sec.No.	Rail	Tie	Fastener	Ballast	Variables studied
03	133	wood/ concrete	cut spike/ Pandrol	granite, lime-stone, traprock	ballast and tie type, vertical load
33	133	wood/ concrete	cut spike/ Pandrol	granite	tie type, vertical load
36	132	wood	cut spike	slag	vertical load, ballast consolidation
40	132	wood	cut spike	slag	ballast consolidation

5.2 EFFECTS OF VERTICAL AXLE LOAD

To quantify the effects of vertical axle load on static lateral track strength and stiffness, tests were conducted on several test tracks with a wide range of vertical axle loads. Exhibit 40 summarizes vertical axle loads applied for tests conducted under different track conditions. Note that for all the vertical axle loads listed, wheels loads were distributed equally on both rails.

Exhibit 40: Test Matrix for Vertical Axle Load Effects

Test Track	V (kips)
Sec. 03 of HTL for concrete and wood tie segments	14, 20, 30, 40
Sec. 33 of HTL for wood tie segment	6, 20, 40, 60
Sec. 36 of HTL	6, 20, 40, 60
PTT	5, 10, 20, 30, 40
Balloon Track	10, 20, 30, 40, 60

Exhibits 41 and 42 show two examples of lateral load-deflection relationships influenced by the vertical axle load. As illustrated, the vertical axle load has a large stiffening effect on the track panel. The higher the applied vertical axle load is, the more difficult the track panel is to push. In fact, when the vertical axle load reached 60 kips, the track panel could hardly be pushed with the TLV maximum lateral load.

Also as illustrated in these two exhibits, different track strength and stiffness characteristics under various vertical axle loads can be discerned easily from TLV stationary tests with a maximum track panel deflection of 0.1 to 0.3 inch.

Thus, an increase in vertical axle load will increase lateral track strength and stiffness. By using the lateral track strength and stiffness parameters defined previously, the effects of vertical axle load can be quantified by plotting these parameters versus vertical axle loads. Exhibits 43 and 44 show two examples of correlations between these parameters and the vertical axle load.

Reasonable linear correlations between vertical axle load and lateral track strength as well as stiffness are reflected by their correlation coefficients close to and above 0.9 for most cases. In other words, the following two general equations can be used to quantify the effects of vertical axle load on lateral track strength and stiffness:

$$L_\delta = L_{\delta 0} + a_\delta V \qquad (12)$$

$$k_\delta = k_{\delta 0} + b_\delta V \qquad (13)$$

where L_δ, k_δ = lateral track strength and stiffness for a given deflection level, δ,

V = vertical axle load,

$L_{\delta 0}$, $k_{\delta 0}$ = intercepts, or lateral track strength and stiffness defined for a given deflection level, δ, corresponding to zero vertical load,

a_δ, b_δ = slopes, or stiffening coefficients of vertical axle load on strength and stiffness, respectively.

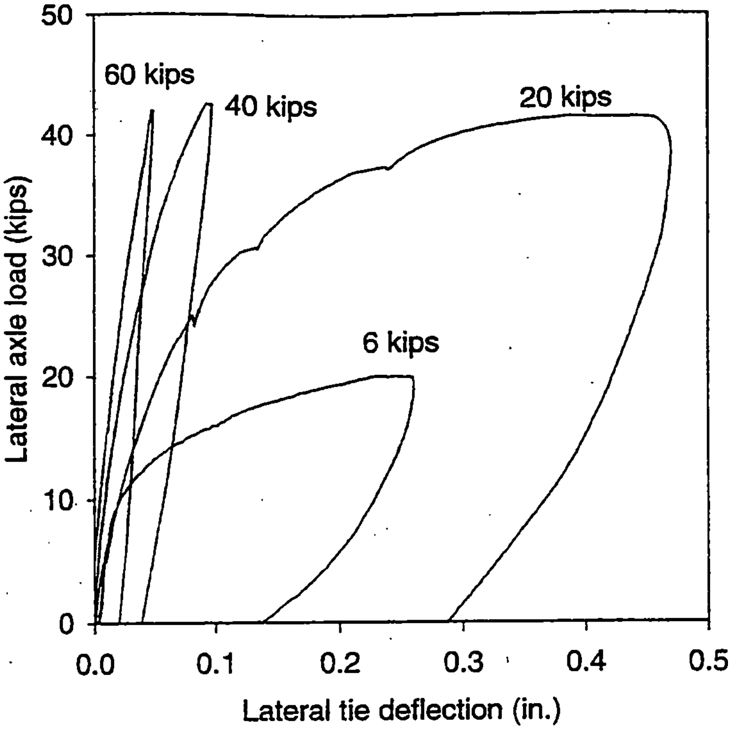


Exhibit 41. Lateral Load-Deflection Relationships Influenced by Verticle Axle Load (HTL Sec. 36)

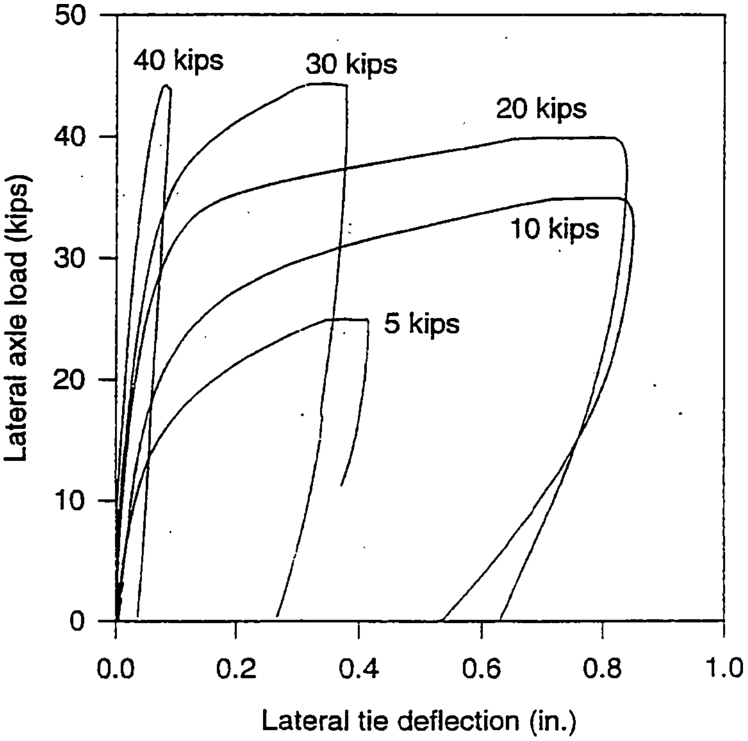


Exhibit 42. Lateral Load-Deflection Relationships Influenced by Vertical Axle Load (PTT Track)

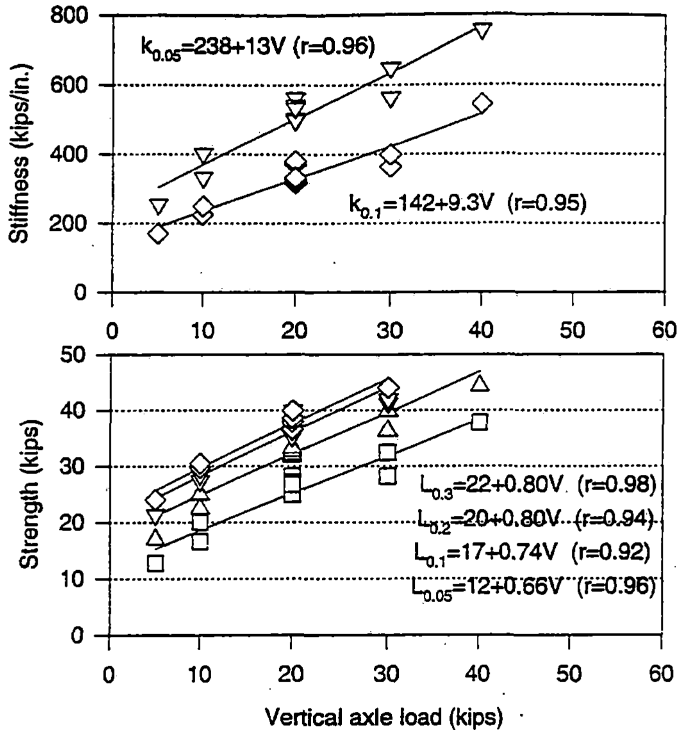


Exhibit 43. Correlations Between Strength and Stiffness Parameters and Vertical Axle Load (PTT Track)

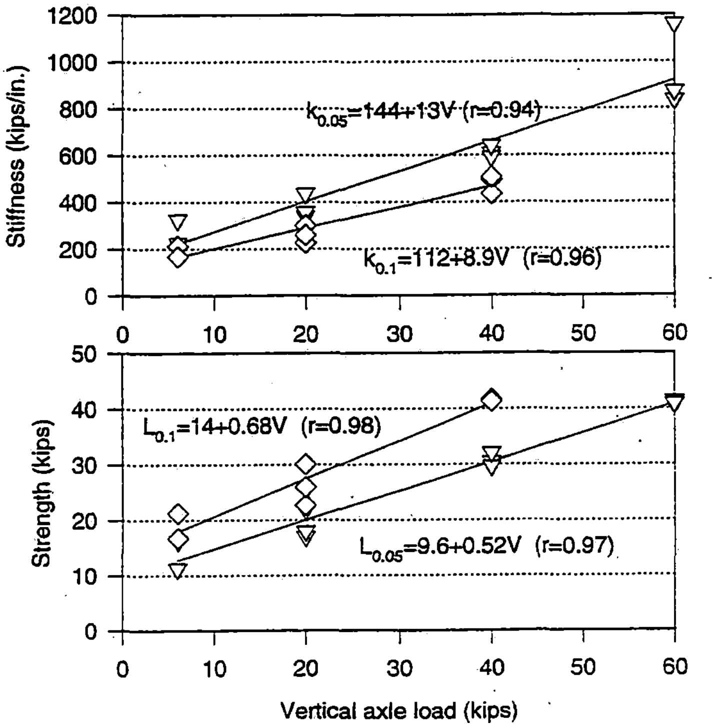


Exhibit 44. Correlations Between Strength and Stiffness Parameters and Vertical Axle Load (HTL Sec. 36, Wood Ties)

Exhibit 45 summarizes the values of the two coefficients; i.e., intercept and slope for strength parameters for results obtained from all the tests.

Exhibit 45: Summary of $L_{\delta 0}$ and a_{δ} values

δ (in.)	$L_{\delta 0}$ (kips)		a_{δ} (kip/kip)	
	average	range	average	range
0.05	13	10-16	0.47	0.32-0.66
0.1	15	13-17	0.69	0.54-0.79
0.2	21	18-20	0.64	0.42-0.80
0.3	22	-	0.80	-

It can be seen from the above table that these two coefficients depend upon the deflection magnitudes. The lateral track strength can be subsequently higher if higher lateral track deflection is allowed. Therefore, lateral track strength should be specified for a given lateral track deflection.

Exhibit 46 summarizes the values of the two coefficients — intercept and slope — for stiffness parameters defined at two deflection levels. Since available track deflections were small when the vertical axle load reached 40 kips, only stiffness parameter values defined at 0.05 and 0.1 inch are given in Exhibit 46.

Exhibit 46: Summary of $k_{\delta 0}$ and b_{δ} values

δ (in.)	$k_{\delta 0}$ (kips/in.)		b_{δ} (1/in.)	
	average	range	average	range
0.05	216	141-301	12	8.1-15
0.1	123	60-163	8.8	6.3-13

The results shown in the above table indicate that $k_{0.05}$ is larger than $k_{0.1}$; i.e., even at small lateral track deflections, lateral load-deflection relationships are non-linear. This is also evident by the results shown in Exhibits 41 and 42.

By rearranging Equation 12, the following equation is obtained to determine the required axle *L/V* ratio for generating a given deflection, δ:

$$\left(\frac{L}{V}\right)_{at\,a\,given\;\delta} \;'\; a_{\delta}\,\%\,\frac{L_{\delta 0}}{V} \qquad (14)$$

$L_{\delta 0}$ and a_{δ} are dependent only upon deflection level. Equation 14 means that the required *L/V* ratio to produce a given magnitude of lateral track deflection must be lower if a higher vertical axle load is applied to the track.

The strength and stiffness coefficients listed in Exhibits 45 and 46 at given deflection levels vary in a wide range. This variation is caused by variable track conditions. The influence of variable track conditions will be discussed in the following sections.

To study the effects of track variables on characteristics of lateral track strength and stiffness, a nominal vertical axle load was chosen to be 20 kips for majority of the TLV stationary tests. Selecting such a nominal vertical axle load not only represents an optimum operation condition for the TLV to perform track strength tests, but also provides an adequate vertical load level to eliminate any pre-existing vertical slack in the track.[19] Furthermore, if the vertical axle load is too low, the flanging wheel may climb the rail as lateral axle load is increased. Conversely, if the vertical axle load is very high, it will be very difficult to push the track.

As shown in Exhibit 6, a track panel does not need to be pushed more than a lateral deflection of 0.3 inches to obtain test results for defining these strength and stiffness parameters. Thus, for a majority of the stationary tests conducted under a vertical axle load of 20 kips, the track panel was only pushed to approximately 0.3 inch prior to unloading lateral axle load.

5.3 EFFECTS OF BALLAST CONSOLIDATION LEVEL

It is well known that ballast consolidation level influences lateral track resistance at the tie-ballast interface. It is also well known that track maintenance operations, such as ballast tamping and cleaning, reduce tie-ballast resistance significantly. Railroads implement slow order policies following track maintenance to ensure safe train operations. However, such slow order policies interfere with normal train schedules and result in an increase in operation costs. To restore lateral track resistance following track maintenance, machines such as ballast stabilizers and compactors have been used. Railroads hope that use of these machines will result in quick consolidation of ballast, resulting in shorter slow order durations.

To better understand lateral track strength influenced by ballast consolidation, TLV stationary tests were conducted in Sections 36 and 40. A continuous skin lift tamping (0.5-inch lifting as compared to a full lifting of 2 to 3 inches) was applied throughout Sections 36 and 40. To evaluate the effectiveness of a ballast shoulder and crib compactor, the ballast in Section 36 was compacted immediately following tamping, whereas the ballast in Section 40 was not compacted.

Baseline tests were conducted before tamping. Further tests were done immediately following tamping in Section 40 and following compaction by the compactor in Section 36, at traffic levels of approximately 0.05, 0.1, 0.2, 1, 4, and 9 million gross tons (MGT). For each ballast consolidation level, three stationary tests were conducted to achieve more representative measurements.

Exhibit 47 shows the results of lateral track strengths obtained from Sections 40 and 36. The strength values shown are defined at deflection levels of 0.05, 0.1, and 0.2 inch. Results immediately before tamping and at four different MGT levels (0, 1, 4 and 9 MGT) following tamping are shown.

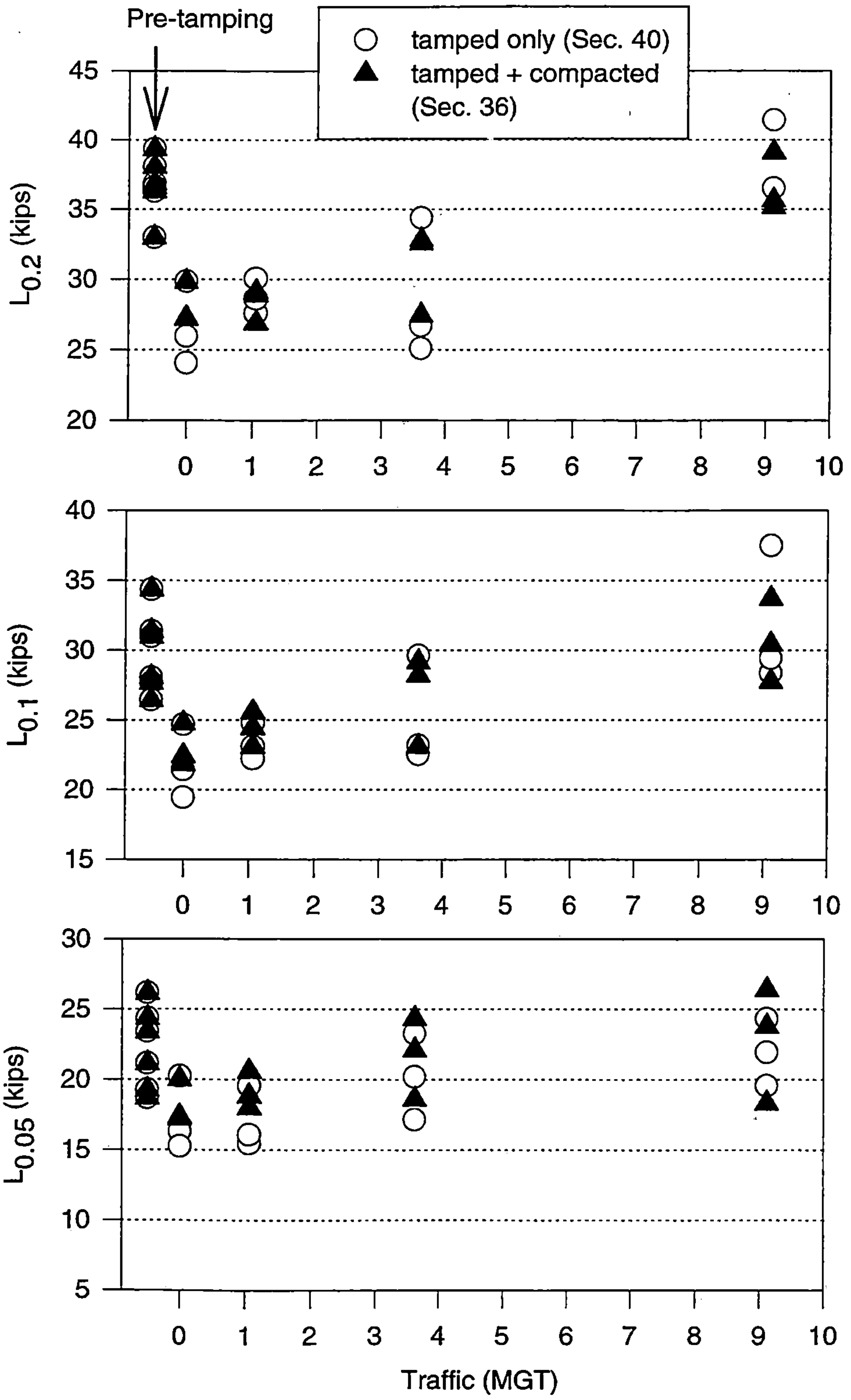


Exhibit 47. Effect of Ballast Consolidation on Track Strengths

Exhibit 48 gives results representing averages of individual results shown at each MGT level in Exhibit 47. The strength values are normalized such that the pre-tamping strength values are 100 percent.

As illustrated in Exhibit 48, ballast tamping (skin lift) caused significant decreases in lateral track strengths by 20 to 30 percent. (Note that the decrease in strength could be even higher if a regular tamping with 2- to 3-inch panel lifting was applied to the ballast). The subsequent traffic gradually restored lateral track strength as ballast particles became more compacted and interlocked under traffic. However, it took about 8 to 9 MGT of traffic for track strength to recover completely to its original level. It can be seen that approximately 4 to 6 MGT were needed to restore 90 percent of the lost strength.

Use of the compactor following tamping only moderately improved track strengths (returned approximately 10 percent of the lost strength at 0 MGT); roughly 4 MGT were needed to restore 90 percent of the lost strength when the compactor was used following tamping.

Use of the ballast compactor immediately following ballast tamping has also reduced the variability of lateral track strength along the track in Section 36. This is evident by the results shown in Exhibit 47. As illustrated, the variation of strength results at each MGT level is smaller for tests conducted in Section 36 with use of the compactor (shown by smaller ranges of triangle symbols at each MGT level measured) than for tests conducted in Section 40 without use of the compactor (circular symbols). The less variation of track strength in Section 36 was a result of ballast compaction by the compactor in this section.

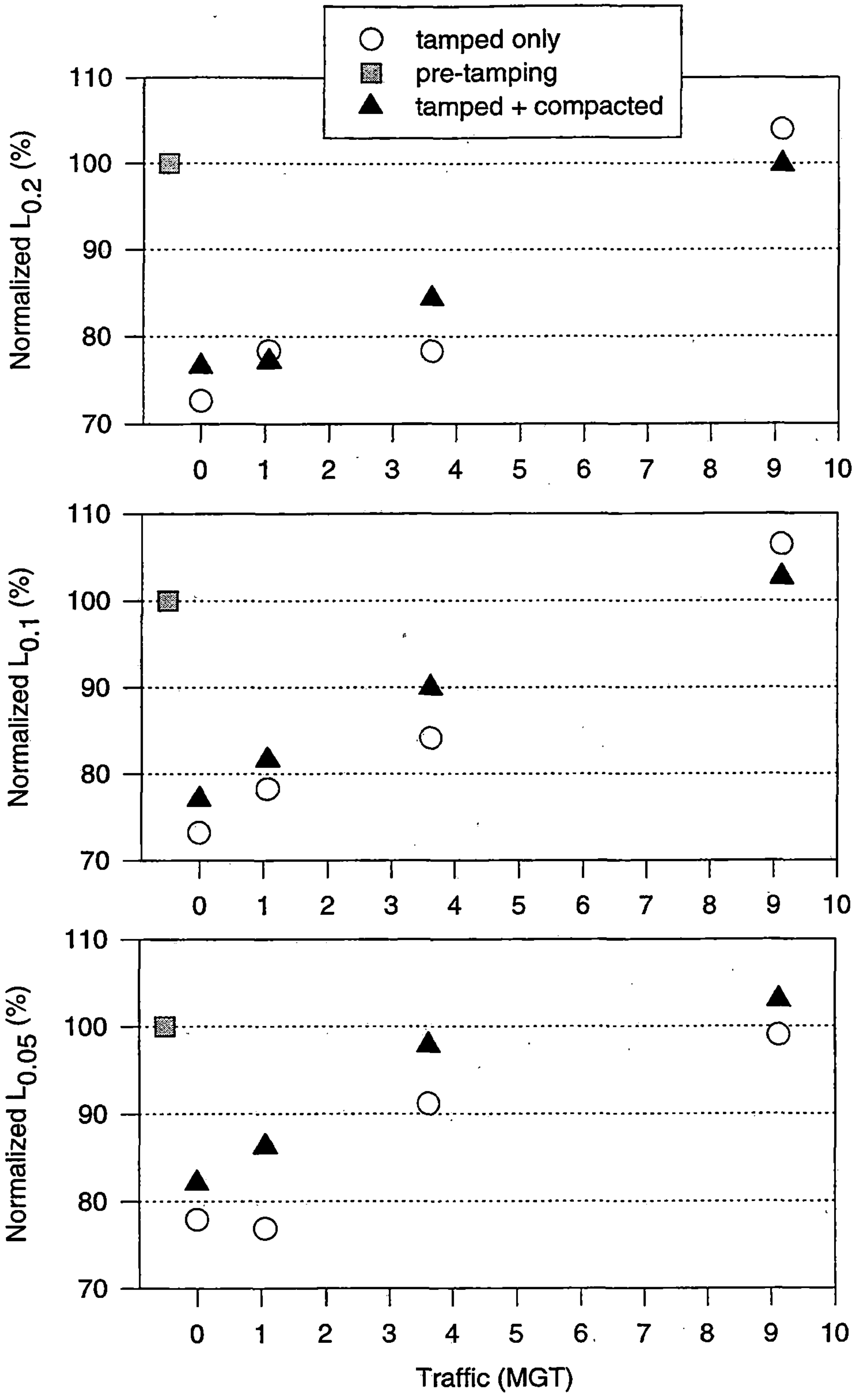


Exhibit 48. Effect of Ballast Consolidation on Normalized Track Strengths (Each Symbol Representing an Avarage of Results Shown in Exhibit 47)

As mentioned previously, measurements were also taken between 0 and 1 MGT. Exhibit 49 shows values of three stiffness parameters with traffic for tests conducted in Section 40. As can be seen, the ballast did not consolidate much due to less than 1 MGT traffic. Similar trends were also found for tests conducted in Section 36 and for all strength parameters.

Exhibit 49 also shows that the stiffness parameter, $k_{0.2\text{-}0.3}$, is essentially independent of ballast consolidation level. As defined previously, this stiffness parameter, $k_{0.2\text{-}0.3}$, represents the track panel stiffness after the track panel is pushed more than 0.2 inch. These test results showed that ballast tamping and subsequent traffic did not influence the magnitude of this stiffness parameter. Thus, once the track panel is pushed more than 0.2 inch, the remaining lateral track strength and stiffness is not affected by the ballast consolidation level.

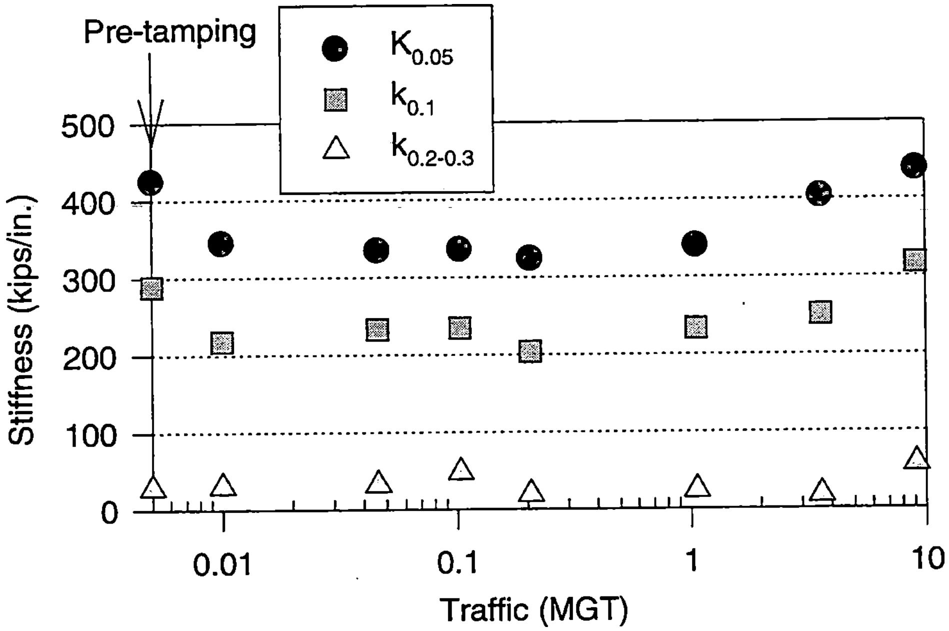


Exhibit 49. Effects of Ballast Tamping and Traffic on Stiffness Results (Sec. 40, No Compactor)

Exhibit 50 gives comparison of two lateral load-deflection curves at 0 and 9 MGT, respectively. As illustrated, the TLV stationary testing can measure the difference in track strength and stiffness at lateral track deflections of 0.2 to 0.3 inch.

5.4 EFFECTS OF RAIL LONGITUDINAL FORCES

Tests were conducted in Section 36 from late May to early June 1996 to study the effects of rail longitudinal forces on stationary test results. To measure rail longitudinal forces, strain gage circuits were installed on both the rails. A total of 10 circuits were installed over a 350-foot test zone with 5 circuits on each rail. The four adjacent strain gage circuits surrounding a test location were used to give an average longitudinal force. Rail longitudinal force change was primarily due to rail temperature change from its neutral temperature. (All strain data has been converted to longitudinal force for the balance of this report.)

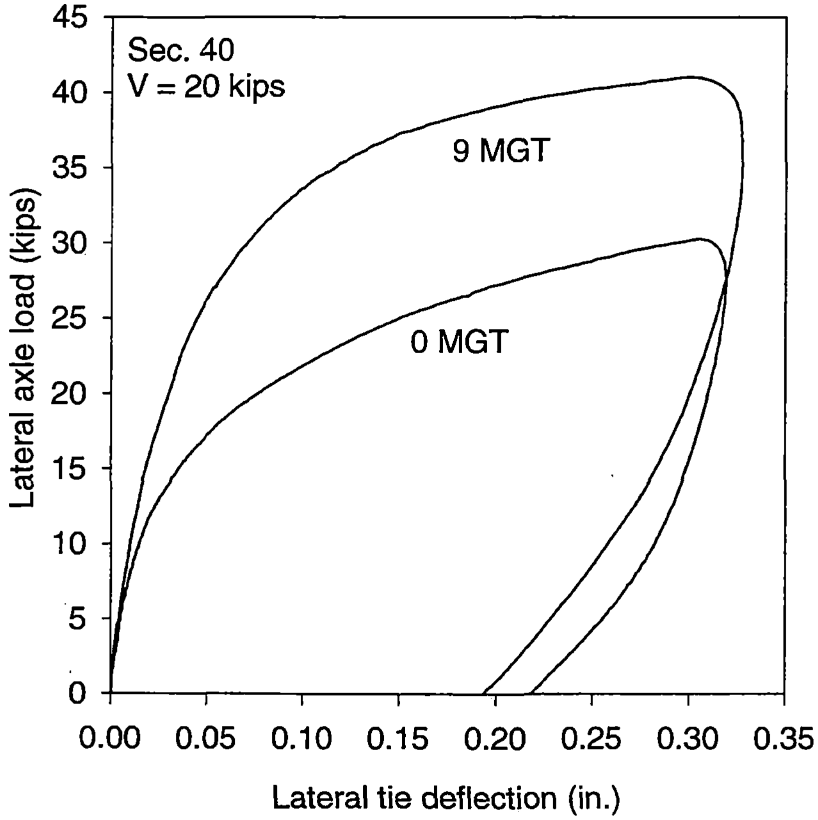


Exhibit 50: Effect of Ballast Consolidation on Load-Deflection Relationship

To establish a neutral rail temperature, the rails in Section 36 were first de-stressed. This was accomplished by cutting the rails at one end of Section 36, loosening all the fastening between the rails and ties, and putting the rails on rollers for a day. Rails were then anchored back onto the ties and welded. Unfortunately, the resulting average neutral rail temperature of both rails for the test zone was approximately 90° F, higher than the planned 70° F.

TLV tests were then conducted at the lowest and highest rail temperatures possible. However, testing was delayed several days to inclement weather. Three stationary tests were conducted in one early morning, with the rail temperature between 50° to 60° F. Also four stationary tests were conducted during one afternoon, with the rail temperature ranging between 100° to 110° F. The following equation is used to calculate the longitudinal thermal rail force:

$$P = AE\alpha\Delta T \tag{15}$$

where P = thermal rail force (lbs),

A = cross section area of rail (12.95 square inches for 132 lb rail),

E = Young's modulus of rail (30E6 psi),

α = linear expansion coefficient of rail (6.5 E-6), and

ΔT = rail temperature change from its neutral temperature (Fahrenheit).

Exhibit 51 shows the effects of rail longitudinal forces on lateral track strength and stiffness determined from these stationary tests. In this exhibit, the lateral axis gives the rail temperature change from its neutral temperature, which is directly proportional to rail longitudinal force. A positive change indicates a compressive force, whereas a negative change indicates a tension in the rail. From Equation 15, the average tension force in the rail at the low rail temperature was approximately 100 kips, and the average rail compressive force at the high rail temperature was approximately 25 kips.

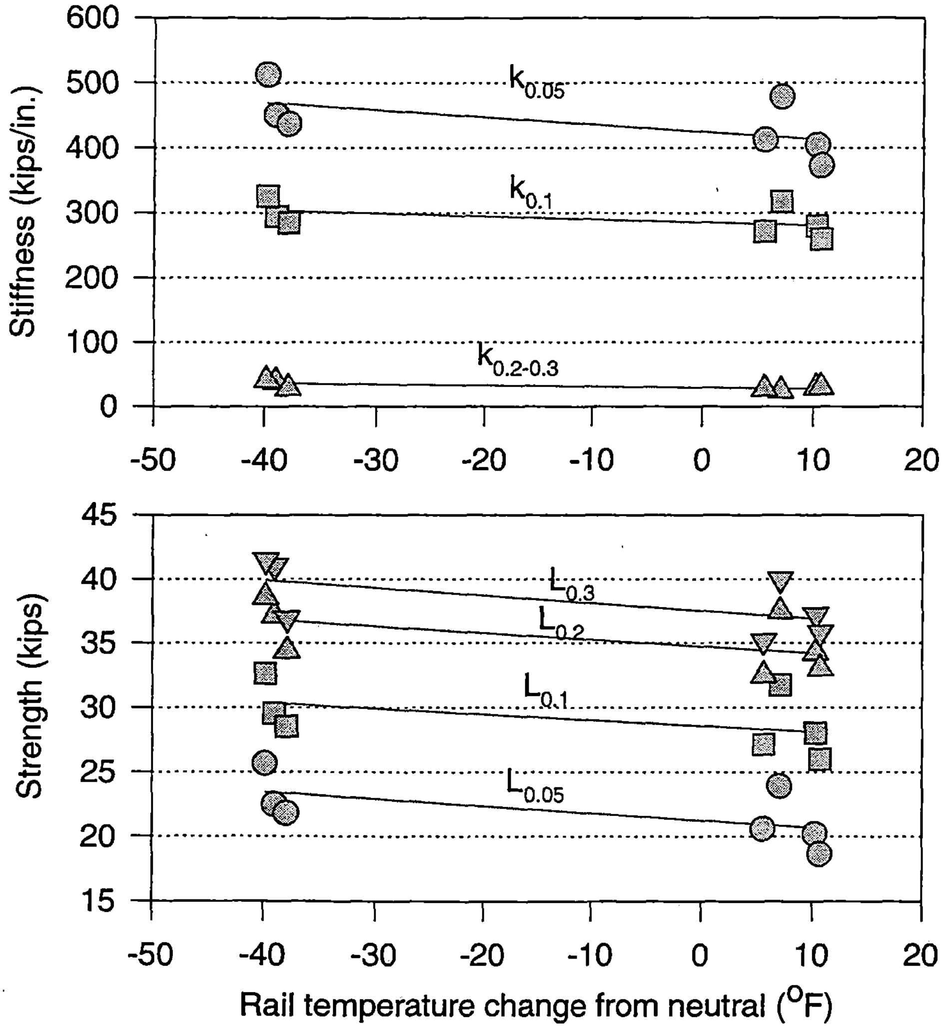


Exhibit 51. Effects of Rail Longitudinal Forces

For this tangent track test zone, an average change of 125 kips in the rail longitudinal forces (or approximately 50 degree in rail temperature change), caused less than 10-percent changes in values of the strength and stiffness parameters.

This phenomenon was supported using VNTSC stationary track model. As will be shown in Section 5.10, a +50° F rail temperature change resulted in only 5- to 8-percent strength reduction.

5.5 EFFECTS OF TIE TYPE

Stationary tests were conducted in Sections 03 and 33 to compare test results between the track segments with concrete ties and wood ties, respectively. In Section 03, comparison tests were conducted with a range of vertical axle loads from 14 kips to 40 kips. In Section 33, comparison tests were conducted only with one vertical axle load of 20 kips. For test locations in both Sections 03 and 33, track conditions were similar except for the tie and fastener types.

Exhibit 52 gives comparisons of results of three strength parameters (defined at deflections of 0.05, 0.1 and 0.2 inch, respectively) for two track segments in Section 03 (other conditions were considered similar except tie type). Four vertical axle load levels were applied. As shown, at the low deflection level of 0.05 inch, measured lateral track strength was approximately 20 percent higher in the concrete tie segment than in the wood tie segment. At deflection level of 0.1 inch, the concrete tie segment showed higher strength ranging from 0 to 15 percent, depending on the vertical axle load applied. At deflections more than 0.2 inch, no obvious trend of results can be found between the concrete-tie segment and the wood-tie segment.

However, regardless of strength, lateral track deflection and vertical load levels, the results from the concrete tie segment showed consistently lower variability than the results from the wood-tie segment (see Exhibit 52). At each deflection level, variation ranges of strength values from three repeated tests are consistently lower for the concrete tie segment than for the wood tie segment.

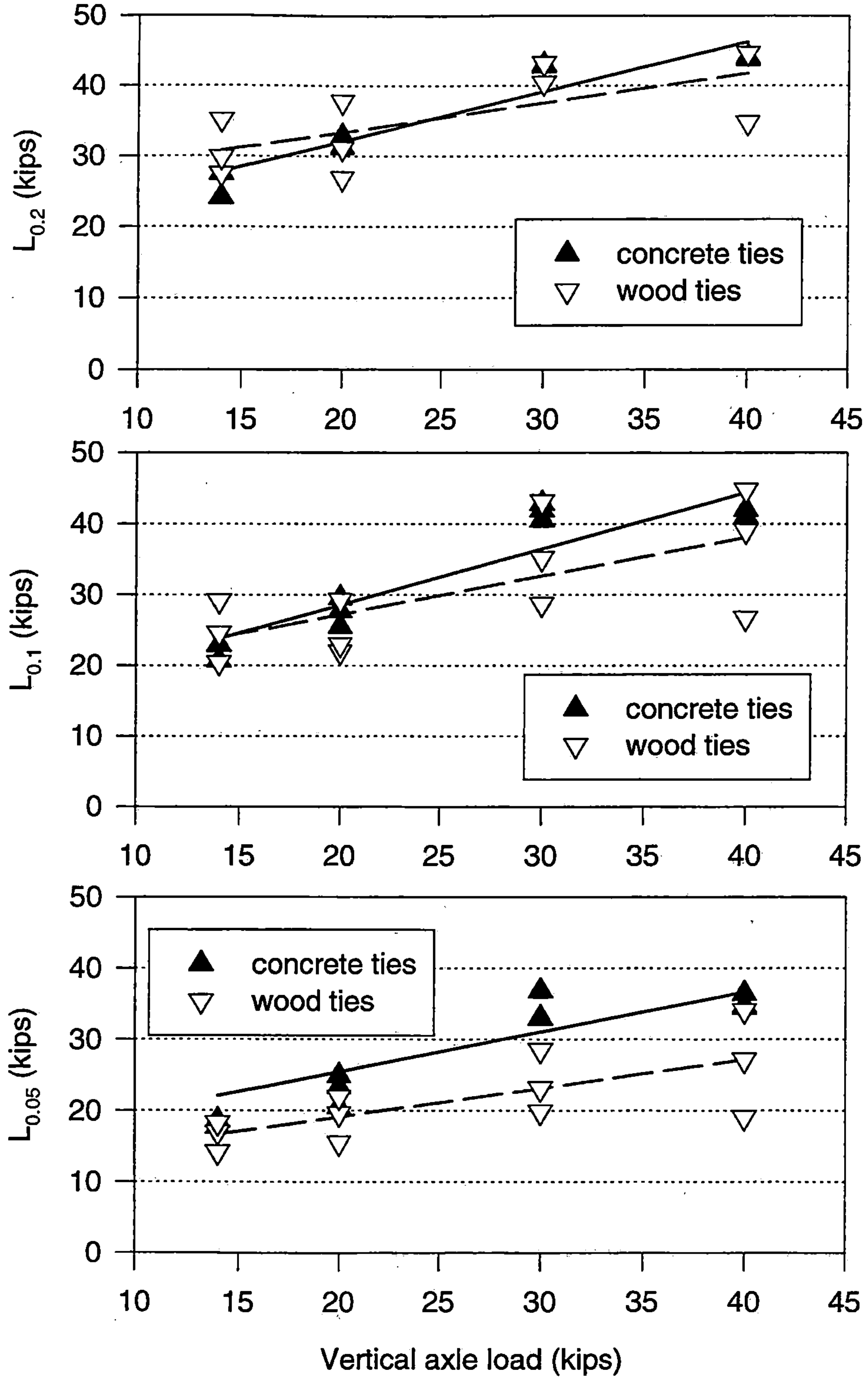


Exhibit 52. Comparisons of Test Results Between Concrete and Wood Tie Tracks (HTL Sec. 3) (with other conditions being similar)

Exhibit 53 shows comparisons of test results obtained from Section 33. Only one vertical axle load (20 kips) was used. Again, only at lower deflection levels (0.05- and 0.1-inch deflections) can the average strength values seen to be slightly higher (5 to 10 percent) for the concrete tie segment than for the wood tie segment. On the other hand, the variabilities of these strength values for three repeated tests are consistently lower for the concrete-tie segment than for the wood-tie segment.

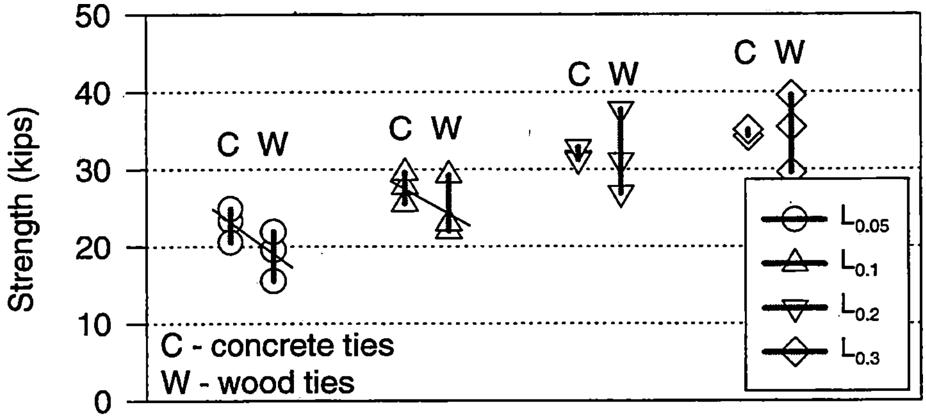


Exhibit 53. Variabilities of Test Results between Concrete- and Wood-tie Tracks (HTL Sec. 33, V=20 kips) (thinner solid lines show average values)

5.6 EFFECTS OF BALLAST TYPE

HTL Section 03 has three track segments with three different types of ballast. They are traprock, granite and limestone. Generally, traprock and granite ballasts are considered good quality ballasts in terms of their durability in resisting ballast breakdown due to various factors. To examine whether ballast type is an important factor in providing lateral track resistance, stationary tests were conducted in Section 03 to compare different ballasts.

Exhibit 54 shows the results of lateral track strength and stiffness parameters influenced by ballast type (wood tie tracks). Again, three repeated tests at each segment were conducted to represent each ballast type. The other track conditions were chosen similar except for the ballast type. The vertical axle loads for all the tests were 20 kips. As illustrated in this exhibit, limestone ballast segment showed slightly (5 percent) higher strength and stiffness values on the average. However, no obvious trend can be seen between the traprock and granite ballasts.

As discussed previously, $k_{0.2\text{-}0.3}$ is a stiffness parameter defined in the second region of the load-deflection curve while $k_{0.05}$ and $k_{0.1}$ are stiffness parameters defined in the first region. Exhibit 54 shows that $k_{0.2\text{-}0.3}$ is much smaller than $k_{0.05}$ and $k_{0.1}$. This indicates that it is very important to control lateral axle load so that the lateral track deflection generated does not advance into the second region where a track possesses much lower stiffness. Also, the stiffness values defined at 0.1-inch deflection, $k_{0.1}$, are significantly smaller than the stiffness values defined at 0.05-inch deflection, $k_{0.05}$. This indicates that at small deflections (from 0 to 0.1 inch), the load deflection relationships are non-linear.

5.7 EFFECTS OF TRACK CURVATURE

Exhibit 55 shows comparisons of test results between a tangent track segment and a track segment of 7.5 degree in the Balloon Track. Between these two segments, other track conditions were considered similar except for track curvature. The vertical axle

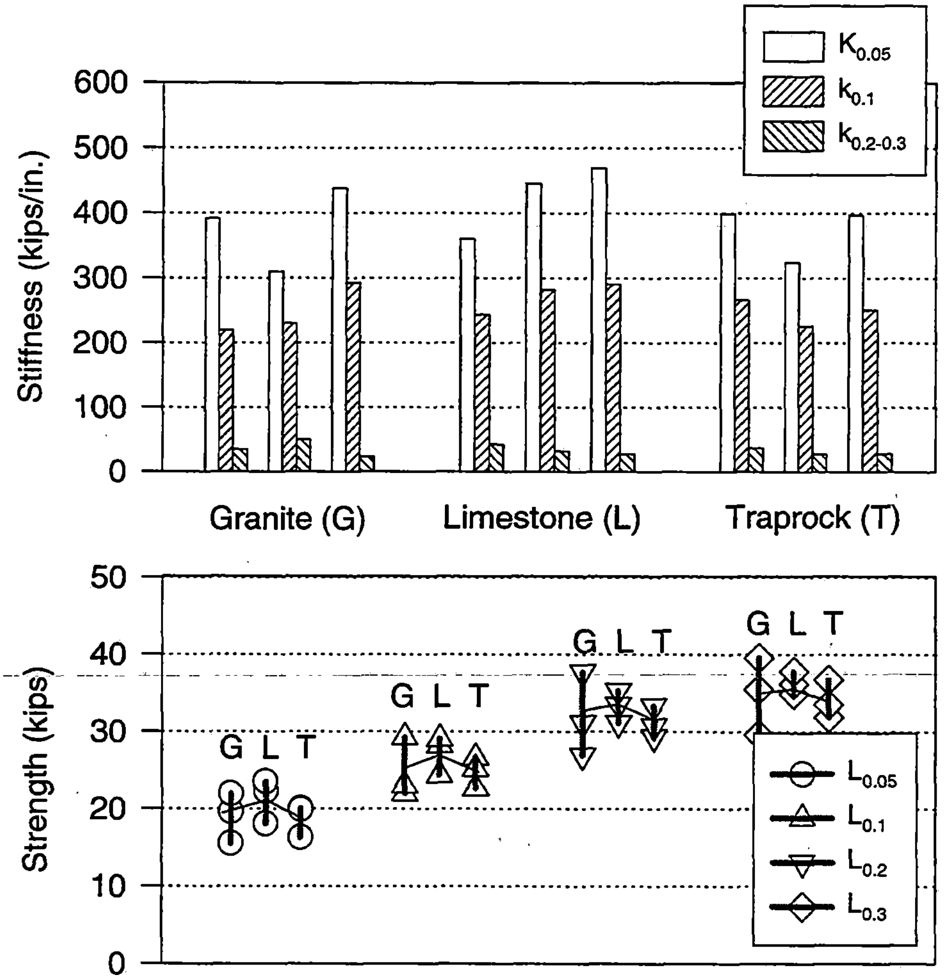


Exhibit 54. Effects of Ballast Type on Test Results (HTL Sec. 03, wood ties V=20 kips)

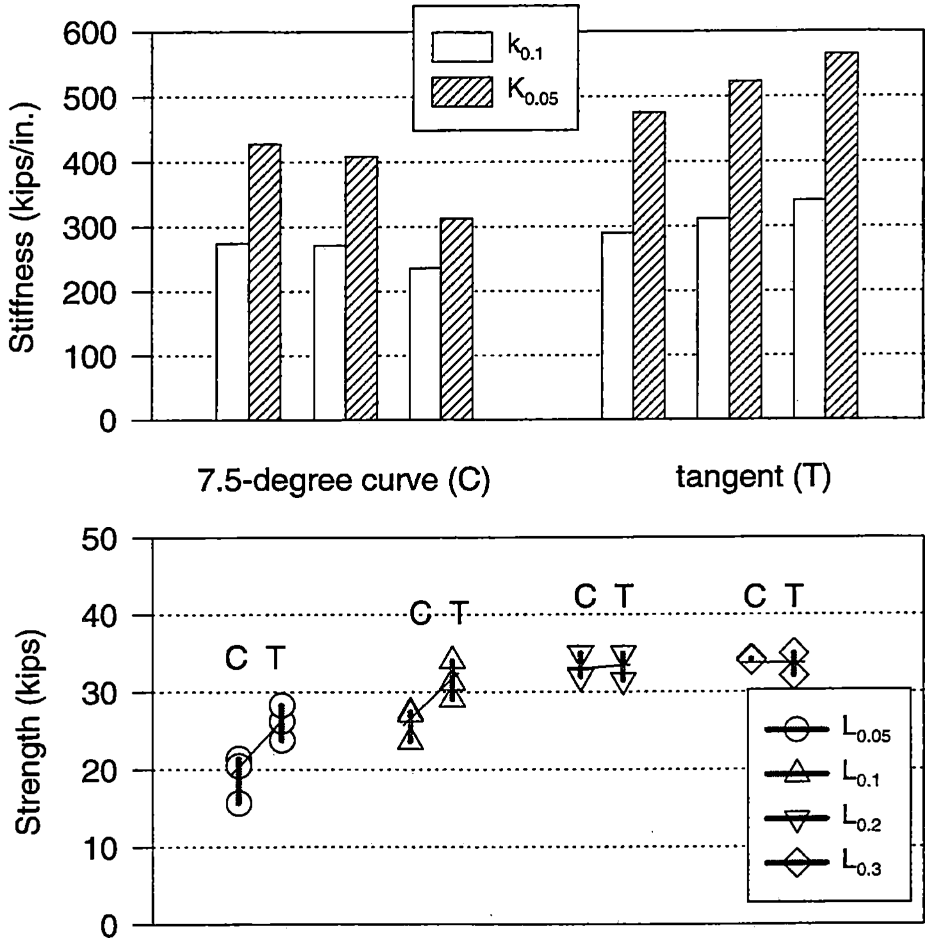


Exhibit 55. Effects of Track Curvature on Test Results (Balloon Track, V=20 kips)

loads applied were 20 kips. The track panel was pushed towards the curve outside in each test. As illustrated in Exhibit 55, the strength and stiffness parameters defined at 0.05 and 0.1 inch exhibited higher values for the tangent track than for the 7.5-degree curve. For example, the average values of $L_{0.05}$ and $L_{0.1}$ are 40 percent and 20 percent higher respectively for the tangent track than for the 7.5-degree track. At higher deflection levels of 0.2 and 0.3 inch, the measured lateral track strength did not seem to be affected by the track curvature.

Exhibit 56 compares test results between a segment in Section 03 and a segment in Section 33 of the HTL. Section 03 is in a 5-degree curve; Section 33 is a tangent track. Between these two segments, other track conditions were similar. The results presented in this exhibit were obtained under a vertical axle load of 20 kips. As illustrated, the measured lateral track strength, $L_{0.05}$, $L_{0.1}$ and $L_{0.2}$ were only slightly higher (less than 10 percent) for the tangent track than for the 5-degree curve.

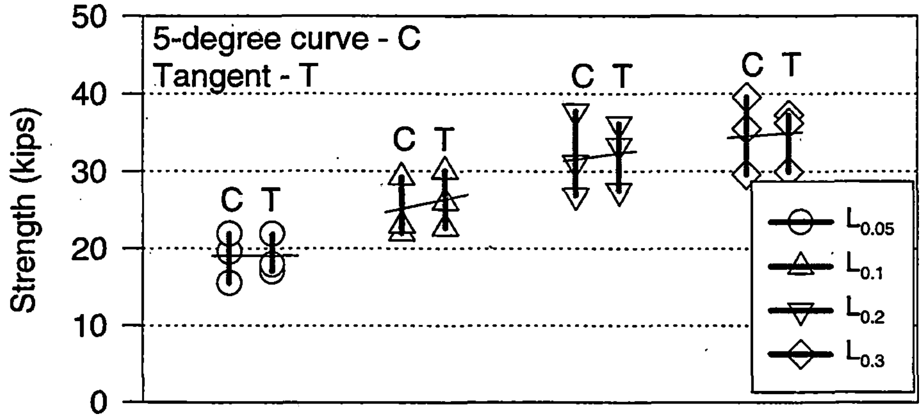


Exhibit 56. Effects of Track Curvature on Test Results (HTL track, V=20 kips)

5.8 EFFECTS OF BALLAST SHOULDER WIDTH

Exhibit 57 shows strength and stiffness results affected by ballast shoulder width. All the tests were conducted in Section 03 (5-degree curve) with vertical axle load equal to 20 kips. Three tests were conducted at three locations with normal shoulder widths (ranging from 15 to 20 inches). The other three tests were conducted at a segment where the ballast shoulder was completely cut to the tie bottom; i.e, no ballast shoulder was provided in this segment of track.

For three tests conducted at the segment without ballast shoulder, one test showed magnitudes of lateral track strength and stiffness parameters similar to the test results for the segment with normal ballast shoulder. However, the other two tests conducted at the segment without ballast shoulder showed much lower lateral track strength and stiffness than the tests conducted at the segment with normal shoulder width. Based on average values from three tests, the track with normal shoulder showed 15 to 30 percent higher strength than the track without a shoulder.

5.9 COMPARISON WITH SINGLE TIE PUSH TEST RESULTS

In conjunction with most TLV stationary tests, STPTs were also conducted to examine if both tests would lead to similar conclusions regarding the effects of some track variables on lateral track resistance. Lateral track strength determined from TLV stationary tests includes not only the components which also contribute to the STPT resistance, but also other components such as track panel lateral bending stiffness and tie-ballast frictions. Note that STPT resistance does not reflect the friction coefficient between ties and ballast.[20]

Exhibit 58 shows two examples of STPT results obtained at the HTL. For consolidated ballast, the STPT load-deflection curve typically shows a peak resistance, F_P, which is followed by a lower residual (limiting) resistance, F_L at much larger deflection.

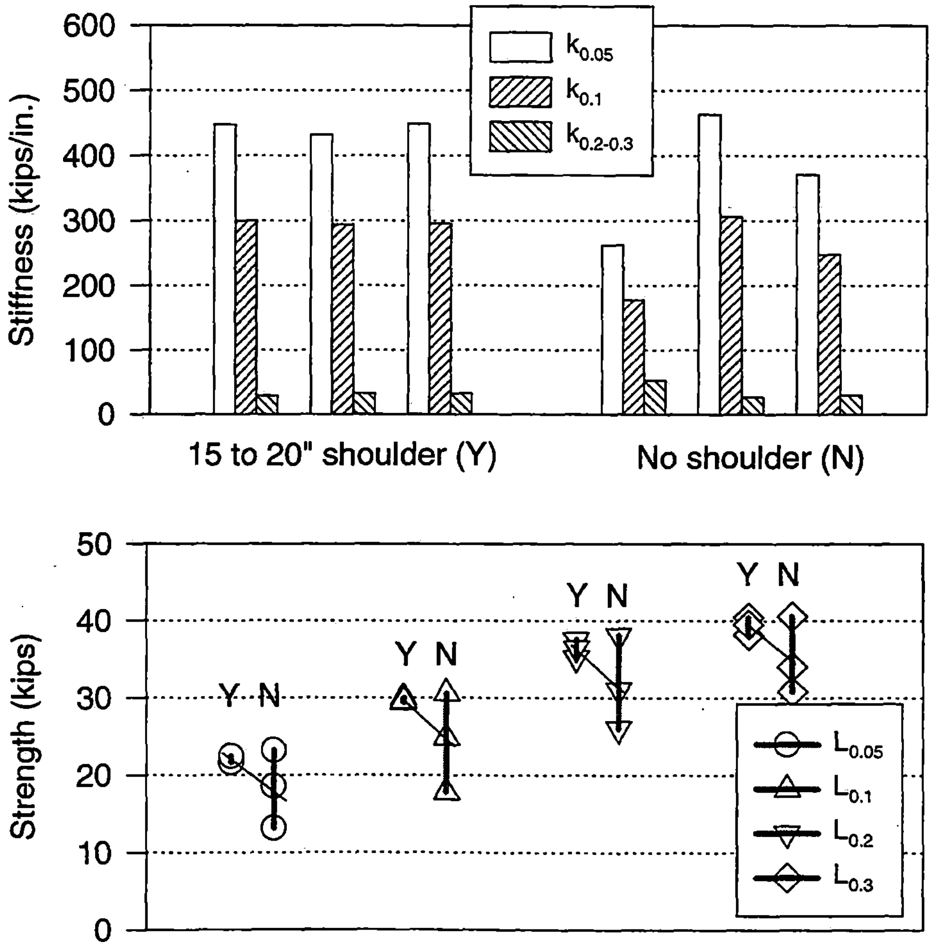


Exhibit 57. Effects of Ballast Shoulder Width on Test Results (HTL Sec. 3, V=20 kips)

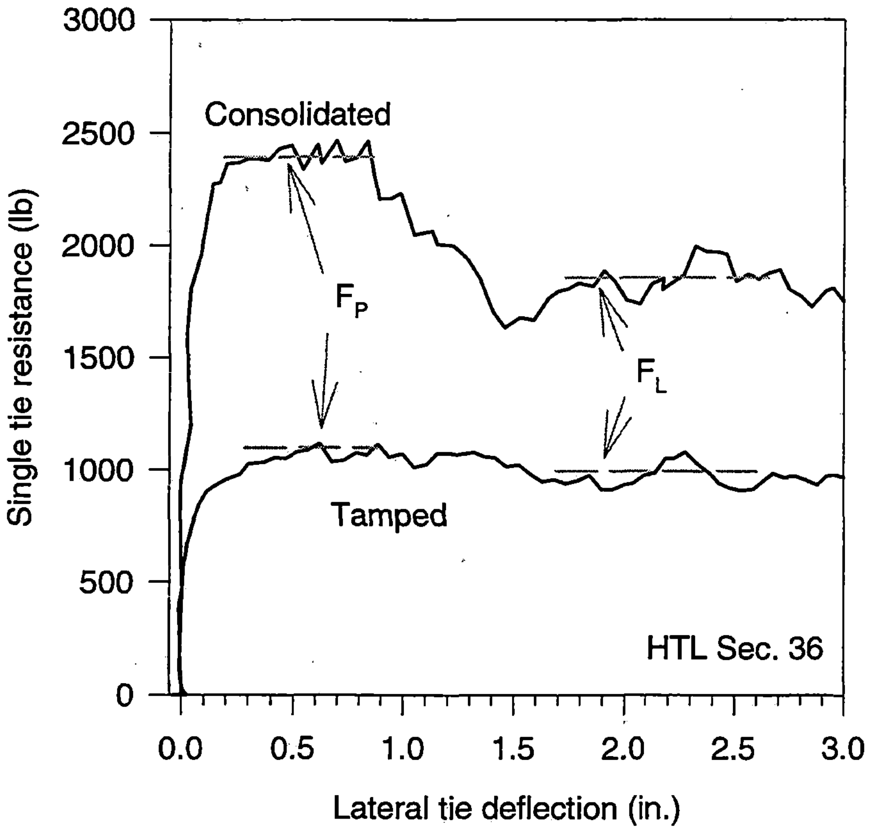


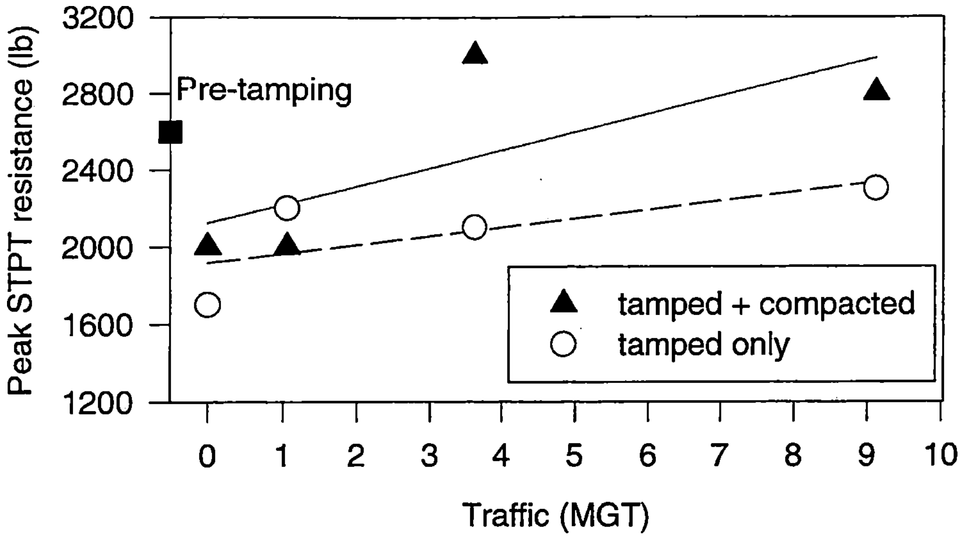
Exhibit 58. Typical STPT Tests

For newly tamped ballast, the resistance is much lower and the peak resistance is almost the same as the residual resistance. For a TLV test, the maximum track panel was rarely pushed more than 1 inch. Thus, only the STPT peak resistance, F_P, is compared to TLV stationary test results.

Exhibits 47 to 50 show the influence of ballast consolidation on lateral track strength, based on TLV stationary tests conducted in Sections 36 and 40. The difference between Sections 36 and 40 tests is that a ballast compactor was used following ballast tamping in Section 36, but was not for Section 40. To compare these TLV test results with STPT results, STPTs were conducted with TLV tests before tamping, immediately following tamping in Section 40 and following compaction by the compactor in Section 36, and at traffic levels of approximately 0.05, 0.1, 0.2, 1, 4, and 9 MGT. For each ballast consolidation level, six STPTs were conducted to obtain average values.

Exhibits 59 and 60 show the influence of ballast consolidation on STPT peak resistance for tests conducted in Sections 36 and 40. At each MGT level, results shown represent an average of six STPTs. Exhibit 59 shows the results immediately before tamping and at four MGT levels (0, 1, 4 and 9) following tamping. A comparison between Exhibits 47 and 59 shows similar trends between TLV stationary test results and STPT results; i.e., ballast tamping caused a significant decrease in lateral track resistance. The subsequent traffic gradually restored track resistance as ballast particles became more compacted and interlocked due to traffic. Use of the ballast compactor following tamping improved lateral track resistance. The decrease in STPT peak resistance due to tamping for the ballast in Section 40 was approximately 60 percent. Use of the ballast compactor following tamping restored 15 percent of the STPT peak resistance loss due to ballast tamping.

Exhibit 60 includes measurements between 0 and 1 MGT. Consistent with the results of TLV stationary tests, STPT results shown in this exhibit also indicate that ballast did not consolidate significantly with a traffic less than 1 MGT.



Exhibits 59. Comparison of STPT Results Between Sections 36 and 40 (Each Point Representing an Average of Six Measurements)

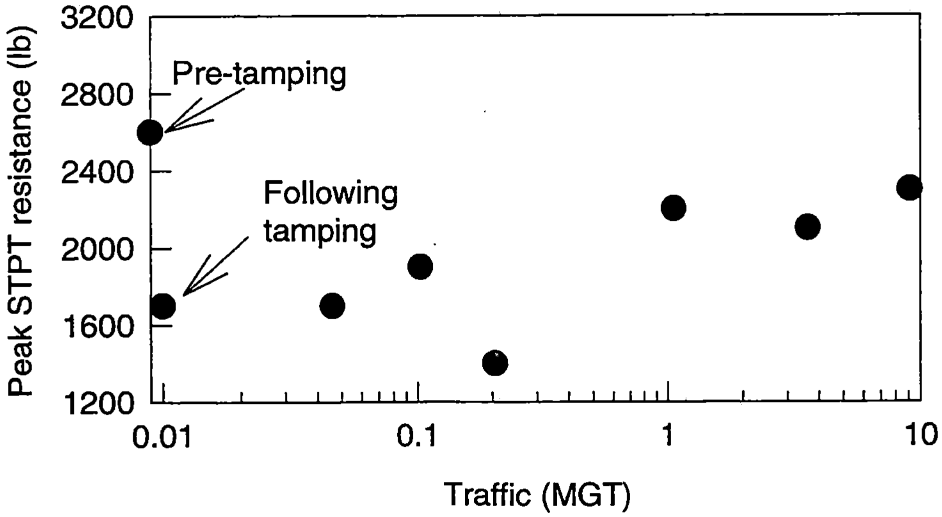


Exhibit 60. STPT Results Influenced by Ballast Tamping and Traffic (Sec. 40, Tamping Only, Each Point Representing Six Measurements)

Exhibit 61 gives the correlations between the TLV strength parameters defined at various deflection levels and STPT peak resistance. The results from TLV stationary tests and STPT tests were obtained from Sections 36 and 40 during the study of ballast consolidation on track strength. Thus, a wide range of track strength was available for correlating TLV and STPT test results. As illustrated, an increase in STPT peak resistance is seen to be accompanied with an increase in track strengths determined from TLV stationary tests. The correlations seem to be generally better between the STPT resistance and the lateral track strength determined at lower lateral track deflection levels. This is shown by the higher correlation coefficient for lower lateral track deflections.

Exhibit 62 shows the effects of ballast type on the STPT peak resistance. Four ballast types are compared. All ballasts were consolidated. For each ballast type, three to six STPT tests were conducted. As illustrated, the results for each ballast type are more variables than TLV stationary tests, as shown in Exhibit 54. Therefore, as also illustrated in Exhibit 62, no significant conclusion can be drawn concerning the effect of ballast type on lateral track resistance. This is consistent with the results by TLV stationary tests.

In conjunction with TLV stationary tests to study the effects of ballast shoulder width, STPT tests were conducted in both the segments with and without ballast shoulder. Three STPT tests were conducted for each segment. Exhibit 63 shows comparison of STPT peak resistances from six tests conducted. As illustrated, one test in the segment with normal shoulder showed the same magnitude of peak resistance as the tests in the segment without shoulder. However, two other tests in the segment with normal ballast shoulder measured peak resistance approximately twice as high as the peak resistance obtained in segment without ballast shoulder. Compared to the TLV results presented in Exhibit 57, the effect of ballast shoulder width is much higher in STPT peak resistance than for lateral track strength measured by TLV stationary tests. This was considered reasonable since the ballast shoulder contribution to track strength is lower for the entire track panel loaded with vertical force than for a single tie free of vertical force.

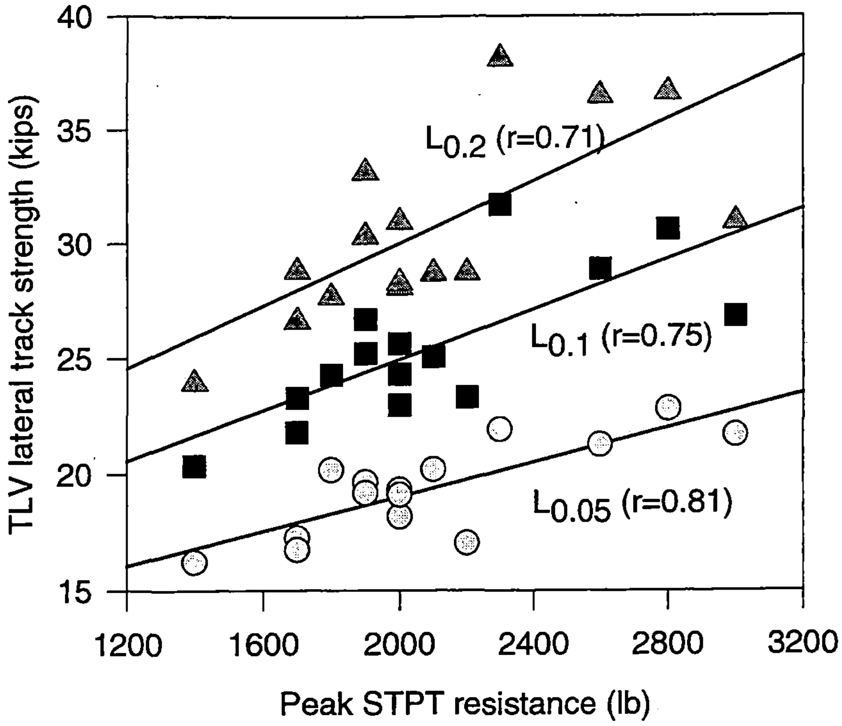


Exhibit 61. Correlations Between TLV Lateral Track Strengths and STPT Peak Resistance (HTL Track)

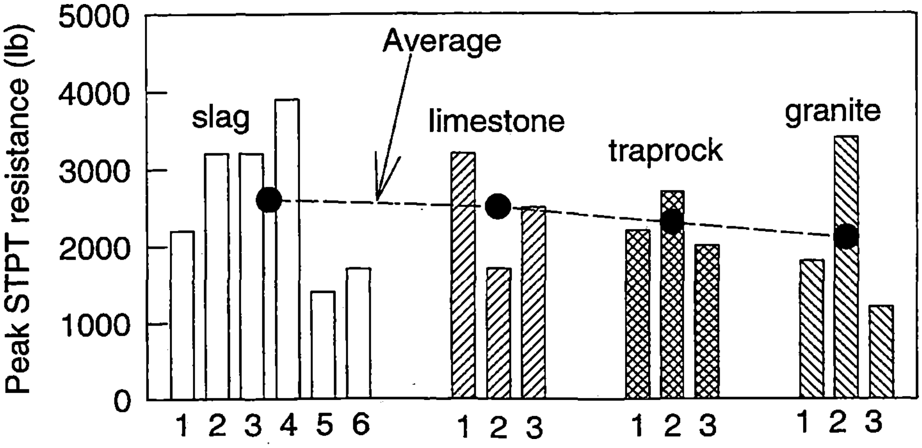


Exhibit 62. Effect of Ballast Type on STPT Results (HTL Sec. 3)

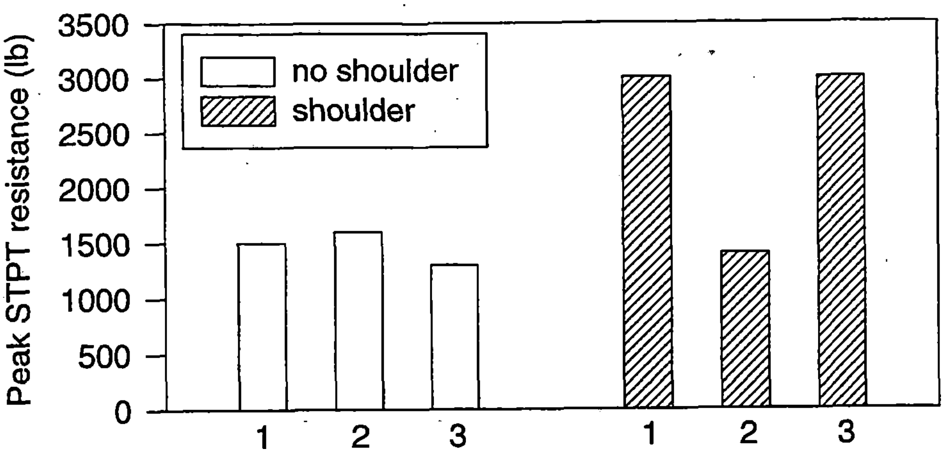


Exhibit 63. Six STPT Results for Segments With Shoulder and Without Shoulder (HTL Sec. 03)

5.10 COMPARISON WITH MODELING

The Volpe National Transportation Systems Center (VNTSC) and Foster-Miller, Inc. have jointly developed a model for predicting lateral track panel behavior under stationary loads.[20] The model is known as TPLRS (Track Panel Lateral Response under Stationary loads). The main parameters considered in this model include STPT values, tie-ballast friction coefficient, vertical track modulus, and rail temperature change from neutral.

A parametric study using this model was conducted to examine the effects of various track parameters on stationary load-deflection relationships. Exhibit 64 lists values of parameters studied. In this exhibit, case 1 represents a nominal situation, cases 2 and 3 represent the change of STPT parameters, cases 4 and 5 represent the change of tie-ballast friction coefficient, cases 6 and 7 represent the change of rail temperature from neutral, and cases 8 and 9 represent the change of vertical track modulus.

Exhibit 64. Input Parameters for Model Predictions

Case No.	STPT parameters				Rail temp. change from neutral ΔT (° F)	Vertical track modulus u (psi)	Tie ballast friction μ
	F_P (lb)	W_P (in.)	F_L (lb)	W_L (in.)			
1	2000	0.3	1000	5	0	6000	1.0
2	1000	0.3	1000	5	0	6000	1.0
3	5000	0.3	2000	5	0	6000	1.0
4	2000	0.3	1000	5	0	6000	0.6
5	2000	0.3	1000	5	0	6000	2.0
6	2000	0.3	1000	5	-20	6000	1.0
7	2000	0.3	1000	5	50	6000	1.0
8	2000	0.3	1000	5	0	3000	1.0
9	2000	0.3	1000	5	0	9000	1.0

Shaded areas highlight those parameters that differ from the nominal case.

Effect of STPT parameters: Exhibit 65 shows the effect of STPT parameters. The range of input parameters are representative of weak (F_P =1000 lb), normal (F_P =2000 lb), and strong track (F_P =5000 lb). The peak resistance was assumed to occur at 0.3-inch tie deflection (W_p)and the residual resistance (F_L) was assumed at a maximum 5-inch tie deflection (W_L).

As shown, the STPT resistance inputs cause a large change in predicted panel shift characteristics. Lowering the peak resistance (F_P) causes the panel deflection to become plastic at a lower lateral load. Note that the "weak" STPT simulation results in track deflection above 1.5 inches (off scale). Both the elastic and plastic tie deflection increased as a result of the weaker STPT results. The larger STPT resistance inputs resulted in a strong track, and predicted very little of both elastic and plastic deflection.

Effect of ballast friction coefficient: In cases 4 and 5, different tie/ballast friction coefficients were input to the model (see Exhibit 66). The effect is similar to that for the STPT resistance variation. The higher ballast friction coefficient resulted in minimal elastic and little plastic deflection. The low-friction case resulted in a large (off scale) plastic deflection of the track panel.

Results in Exhibits 65 and 66 indicate that the model considers ballast friction to be a factor independent from STPT data. This must result from the fact that a STPT test includes no vertical force acting on the tie. Friction is computed as a ratio of vertical force to lateral force; this requires data at more than one vertical force. Therefore, the unweighted STPT test cannot by definition measure friction, and its results are assumed independent of the friction value.

Effect of rail longitudinal force: The TPLRS model was run using assumed rail temperatures at 50 degrees higher and 20 degrees lower than the neutral. As illustrated in Exhibit 67, these produced little change in the predicted panel shift characteristics, especially at deflections below 0.3 inch.

These three predictions are in closest agreement during the initial linear portion of the load-deflection curve. For deflections between 0.1 and 0.3 inch, the model shows only a 5 to 8 percent reduction in strength due to the rail temperature rise from neutral to +50 degrees. The experimental TLV data also showed similar trend.

Effect of vertical track modulus: As shown in Exhibit 68, a change in vertical track modulus from 3,000 to 9,000 psi caused virtually no change in the panel shift prediction. The elastic deflection characteristics are similar in all three cases, particularly at deflection values below 0.3 inch.

Comparison with TLV test results: The model shows that STPT parameters and tie-ballast friction are significant influences, with rail temperatures and vertical track modulus being not as significant. Some of this agrees with TLV results. Experimental data shows that high STPT resistances correspond to large TLV track strength values. The experimental results also show that rail temperature is not a significant influence on TLV stationary test results.

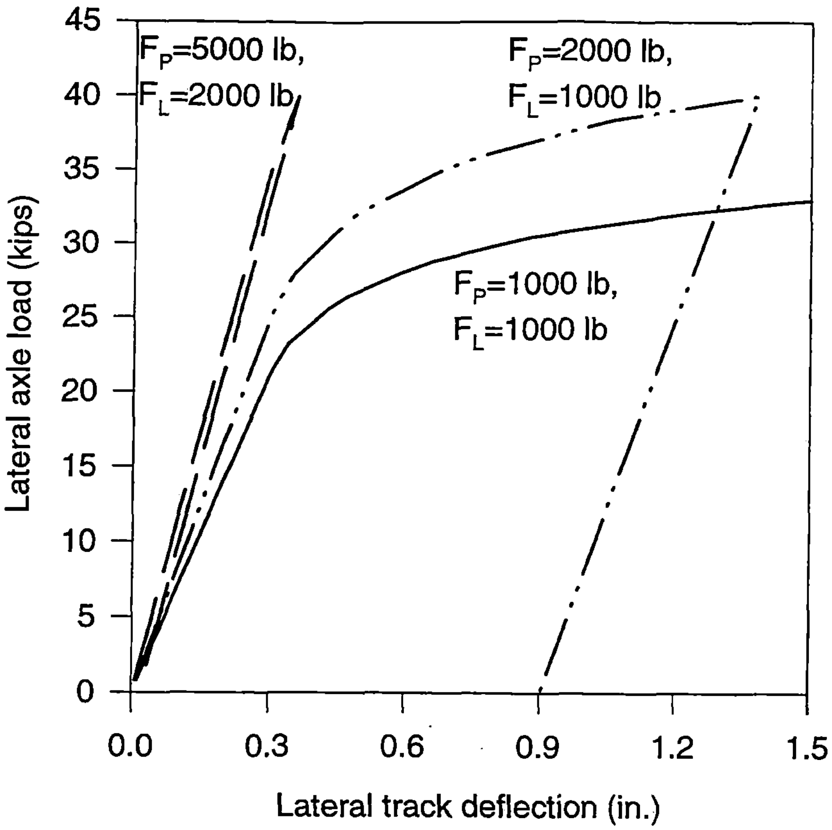


Exhibit 65. Model Results Due to Changes in STPT Resistance

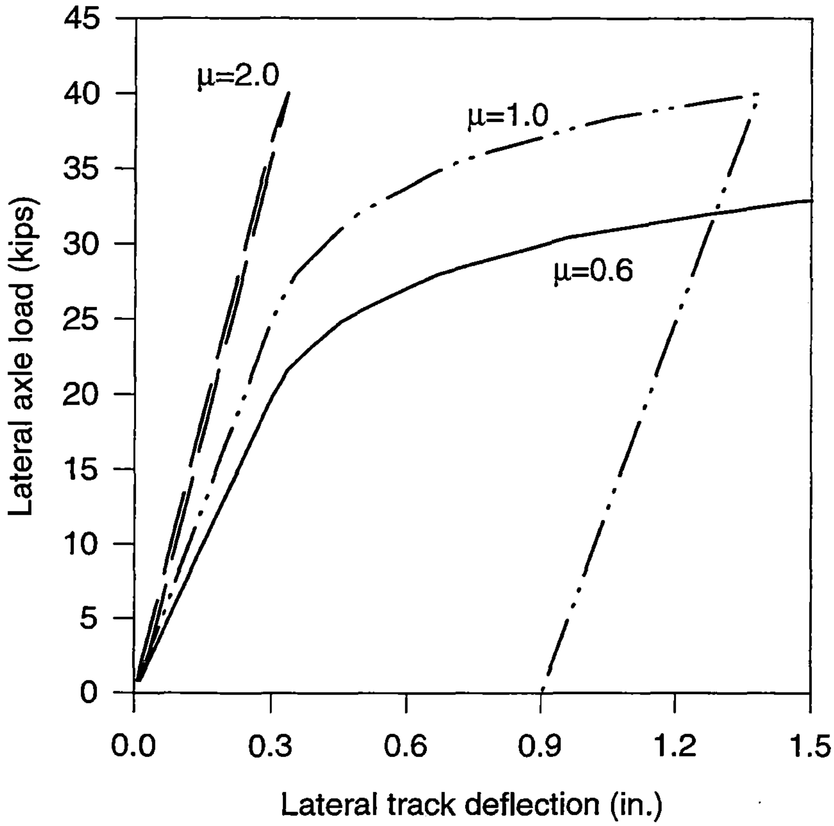


Exhibit 66. Model Results Due to Changes in Tie/Ballast Friction

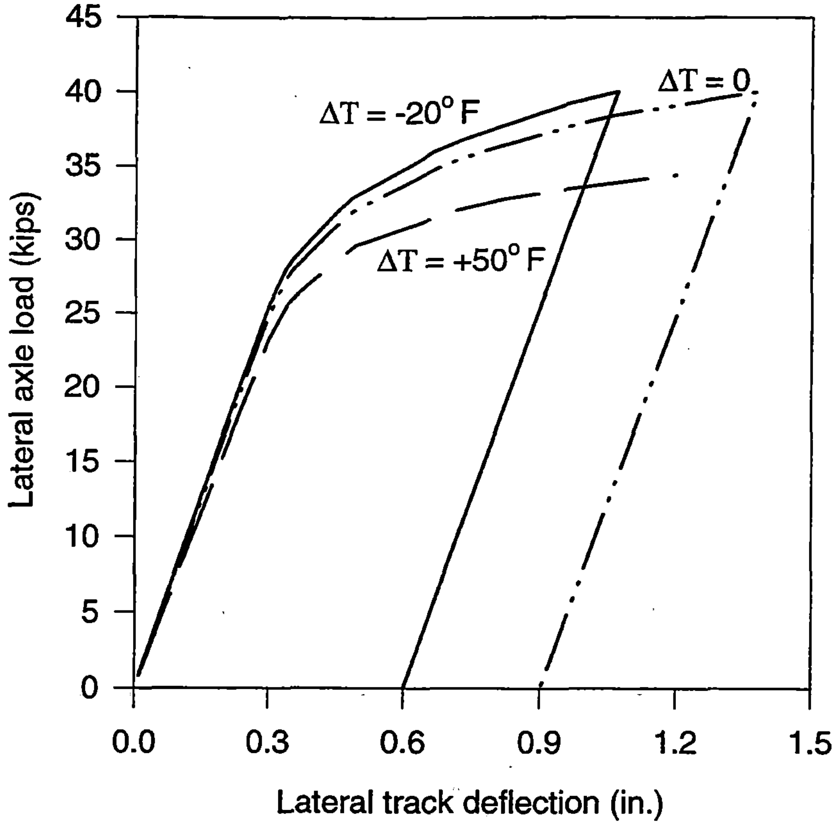


Exhibit 67. Model Results Due to Changes in Rail Temperature From Neutral

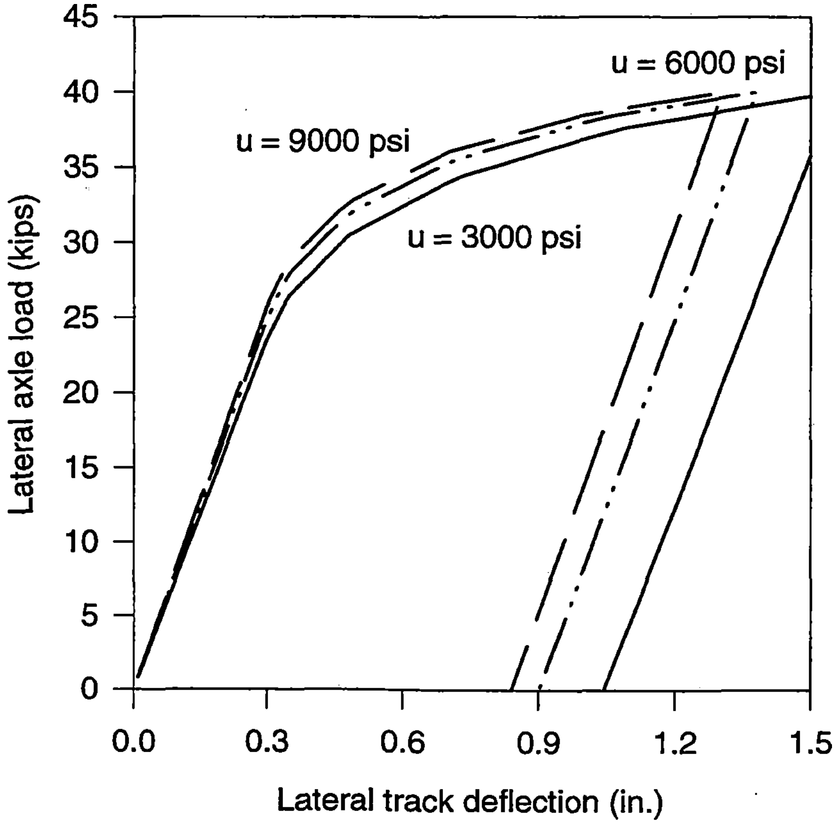


Exhibit 68. Model Results Due to Changes in Vertical Track Modulus

For a specific test/model comparison, several TLV stationary tests were performed over a newly tamped track at Section 36. The track response was then predicted using TLPRS. STPT and friction values for the model input were measured during one of the experimental trials. The rail neutral temperature and the applied vertical force were known for this run, and also used as inputs to the model. The vertical track modulus value is known for the HTL.

Various experimental load deflection curves were found to be consistent with each other. The curve with closest agreement to the model is reproduced in Exhibit 69. Also shown is the model prediction for these test parameters.

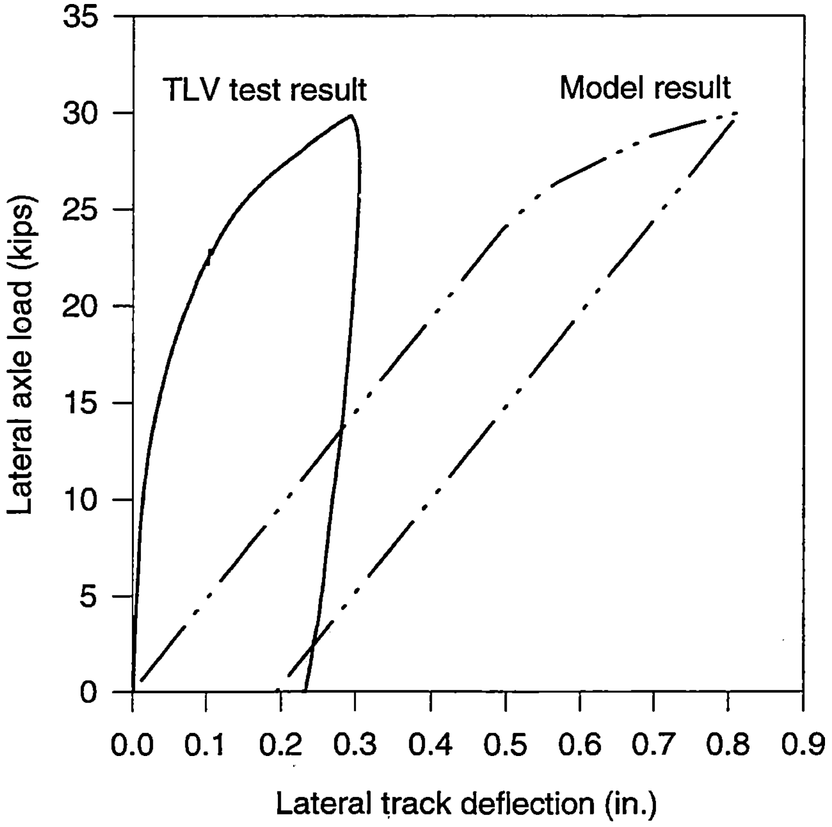


Exhibit 69. Compariosn of TLV Test Result with Model Predicted Results (V=20 kips, HTL Sec. 36)

The plot shows that the model predicts highly elastic response up to the maximum lateral force, followed by a linear return of the panel. However, the TLV data shows that a much higher initial stiffness was measured, and that the response is non-linear throughout.

Note that the TPLRS model does not account for vertical force caused by the TLV ends. These trucks restrain the track (with over 100,000 pounds each) at 30 feet before and after the loading point. This tends to restrain the panel longitudinally. If these weights were not on the rail, it would be more flexible, which may allow closer agreement between experimental and modeling results.

5.11 SUMMARY

The following summary and conclusions are based on TLV stationary test results conducted under the fundamental test phase:

- The TLV stationary tests can provide quantitative information on lateral track strength and stiffness. A maximum panel push of 0.3 inch will provide sufficient information to quantify available lateral track strength and stiffness.

- Vertical axle load has a large effect on the resistance of a track panel to lateral deflection. Lateral track strength and stiffness should therefore be defined at a given vertical axle load. For a given level of track deflection, the required L/V ratio will be lower if a higher vertical axle load is applied on the track.

- Lateral load-deflection relationships are non-linear. Lateral track strength and stiffness should be defined corresponding to given lateral track deflection levels. Once a track panel is pushed to a critical magnitude (e.g, 0.1 to 0.2 inch under a vertical axle load of 20 kips), the track will possess much lower lateral stiffness.

- Ballast consolidation level presents a significant effect on lateral track strength and stiffness. Ballast tamping reduces tie-ballast resistance considerably, and the reduced resistance required up to 9 MGT of traffic to be fully restored to its original level. A ballast compactor restored ballast resistance moderately (approximately 10 percent of the lost strength) and improved the uniformity of strength along the track.

- Ballast type has a less significant effect on lateral track strength and stiffness for consolidate conditions. Use of concrete ties presented a moderate benefit for lateral track strength (5 to 20 percent), and reduced variability of lateral strength along the track.

- For the range of rail longitudinal forces considered, a change from tension to compression in the tangent rail only slightly reduced lateral track strength and stiffness (less than 10 percent).

- A 7.5-degree track curvature significantly reduced measured track strength at small lateral deflections (under 0.1 inch). However, once the track panel was pushed more than 0.2 inch, the results showed little difference between a tangent track and the 7.5-degree track. For a track with a curvature 5 degrees or less, the difference in measured track strength due to curvature was not as significant (less than 10 percent).

- Effects of some variables such as ballast compaction, tie type and track curvature appear to be more significant on lateral track strength and stiffness defined at small lateral track deflection (0.1 inch and less), than at larger deflections.

- STPTs only measure one factor of lateral track panel strength. However, similar trends were observed by TLV stationary tests and by STPT tests regarding the effects of ballast consolidation levels, ballast type, and ballast shoulder width on lateral track resistance.

- A theoretical model, TPLRS, agreed with TLV results regarding the relative influences of parameters such as STPT resistance and rail temperature change on stationary panel behaviors. However, the model does not accurately compute the non-linear behavior at small tie deflections. In general, the model overpredicts tie deflections, when compared to stationary TLV results.

6.0 IN-MOTION TRACK PANEL SHIFT TESTS

Section 3.0 discussed how in-motion track panel shift tests (or repeated passing tests) are being used to measure growth of lateral residual deformation (panel shift or misalignment growth) caused by repeated axle loads. These tests also determine the critical lateral load which leads to excessive track panel shifting. Extensive in-motion track panel shift tests were conducted on the HTL under the fundamental test phase. Tests were conducted to study the cumulative effects of vertical and lateral axle loads, tie type, longitudinal rail forces, and ballast consolidation.

Test results and their analyses are presented for in-motion track panel shift tests. Comparisons are also made between in-motion and stationary panel shift test results.

6.1 TEST TRACKS AND CUMULATIVE LATERAL DEFORMATION MEASUREMENTS

In-motion panel shift tests under the fundamental test phase were conducted on the HTL. Exhibit 70 lists the three sections of the HTL where in-motion track panel shift tests were conducted. Also listed in this exhibit are the test variables studied. During the previous demonstration test phase, trial in-motion panel shift tests were conducted on the west tangent of the Balloon Track.

Exhibit 70: Test Sections and Test Variables at FAST/HTL

Section No.	Test Variables
03	axle loads, tie type
36	axle loads, rail longitudinal force
40	axle loads, ballast consolidation

To achieve uniform track conditions, a segment of track was either tamped uniformly or subjected to a traffic for more than 10 MGT. As described in Section 3.0, a test zone for in-motion track panel shift tests requires a minimum 40 feet of track, which is subjected to constant but moving axle loads. Additional lengths of track adjacent to this test zone are needed for the TLV to ramp the lateral axle load up and down. Three wayside transducers were generally installed over a distance of 10 feet in the middle of the test zone to obtain an average of track lateral deflection measurements.

Exhibit 71 gives two examples of lateral track deflections recorded by a wayside deflection transducer as the TLV passed a measurement location. For both examples, the vertical axle load was 20 kips. The example at the top shows the results for repeated passings of a 10 kip-lateral axle load, and the example at the bottom shows the results for repeated passings of a 15 kip-lateral load. Each trace in these two exhibits represents the lateral tie deflection experienced at one measurement location as the test consist passed. Each bump in the curves can be linked to a specific axle of either the instrumentation car or the TLV.

Several terms associated with repeated passing tests were defined in Section 3.0 (Exhibit 8). Their meanings can be further illustrated in Exhibit 72, which shows the deflection/time histories at the first and ninth TLV runs, from the bottom part of Exhibit 71. As illustrated, the "incremental residual deformation" is the lateral residual deformation change due to a single TLV pass. The incremental total deformation is the maximum elastic plus plastic lateral track deflection caused by a single TLV pass. The "cumulative residual deformation" is the overall lateral residual deformation as a result of repeated TLV passes, and is also referred to as "track panel shift" or "misalignment growth."

Referring back to Exhibit 71, cumulative residual deformation (panel shift) increased with the number of repeated passes, but the cumulative residual deformation was smaller at the lower lateral axle load (L=10 kips) than at the higher lateral axle load (L=15 kips). The cumulative residual deformation between run 1 and run 9 (at L=15 kips) are also shown in Exhibit 72. Obviously, the growth of cumulative residual deformation was a function of the applied lateral axle load. As expected, a higher lateral axle load led to a higher cumulative deformation.

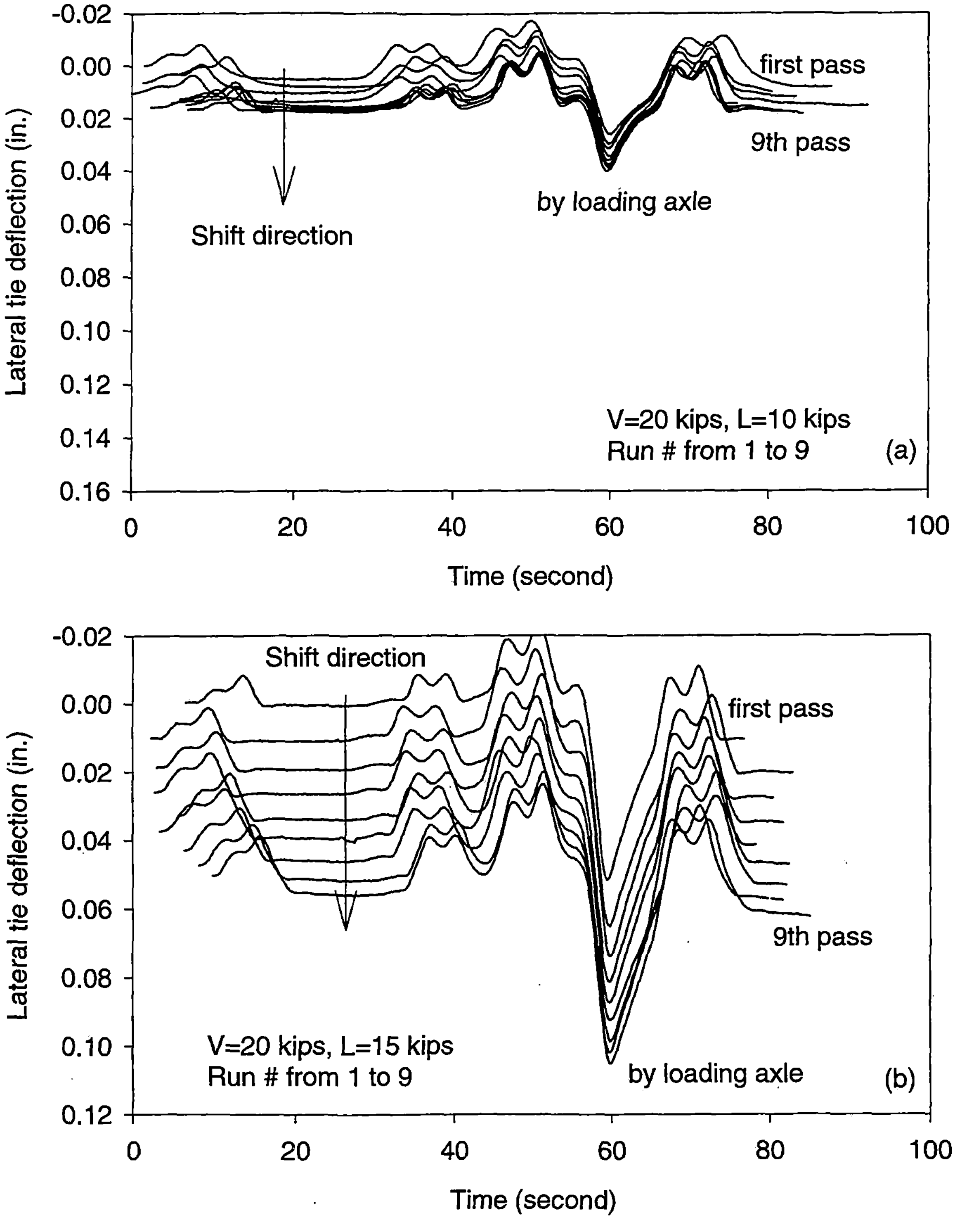


Exhibit 71. Lateral Track Deflection Measurements During Repeated Passes of Axle Loads (HTL, Sec. 40)

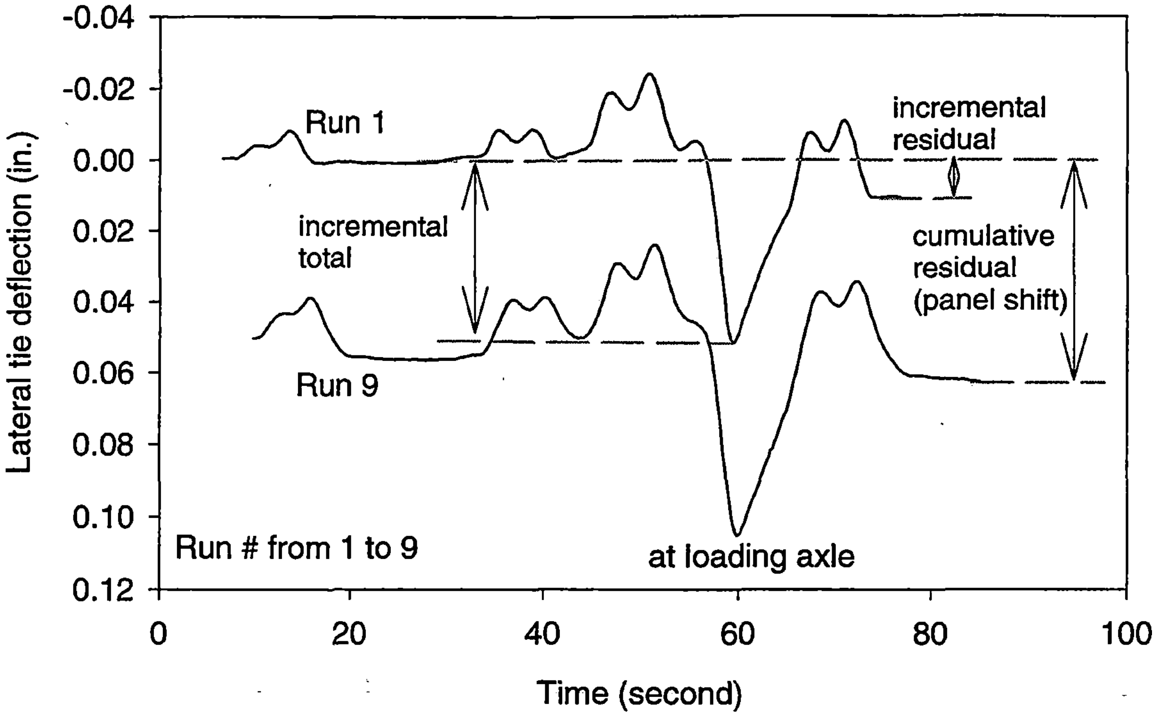


Exhibit 72. Definitions of Panel Shift Terminology
(HTL Sec. 40, V=20 kips, L=15 kips)

Exhibits 71 and 72 also show that incremental residual and total deformations are a function of the applied lateral axle load and are higher at the higher lateral axle load (15 kips). However, at both levels of lateral axle loads (10 and 15 kips), the incremental residual deformation decreased with each pass of axle loads, as evident by the decreasing spacing between successive passes.

When the lateral axle load was increased to 20 kips, however, both the incremental residual and total deformations increased with each pass of the axle loads. These results are shown in Exhibit 73. The track became unstable at this lateral axle load. In fact, the track panel suddenly shifted several inches at the sixth run, affecting roughly 50 feet of track. Exhibit 74 shows the shifted and distorted track.

In the following sections, track panel shift test results will be represented by the results of cumulative residual deformation (panel shift) as well as by incremental residual and total deformations. Full time histories of wayside deflections will not be shown.

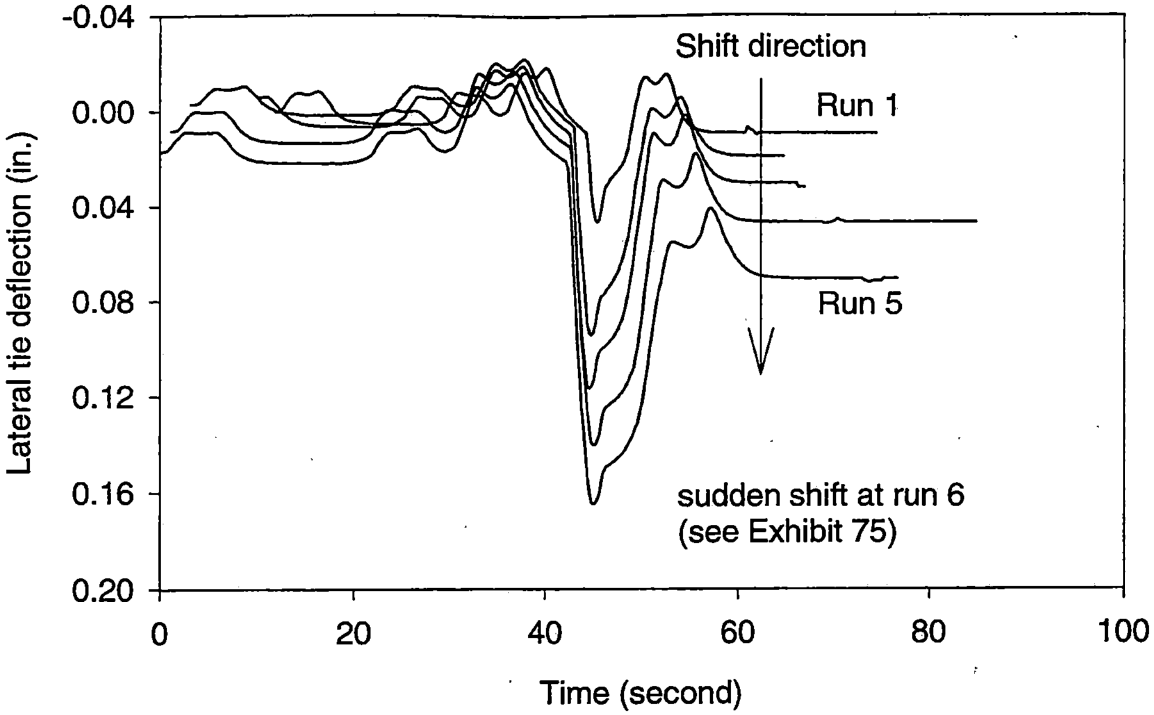


Exhibit 73. Unstable Panel Shift (HTL Sec. 40., V=L=20 kips)

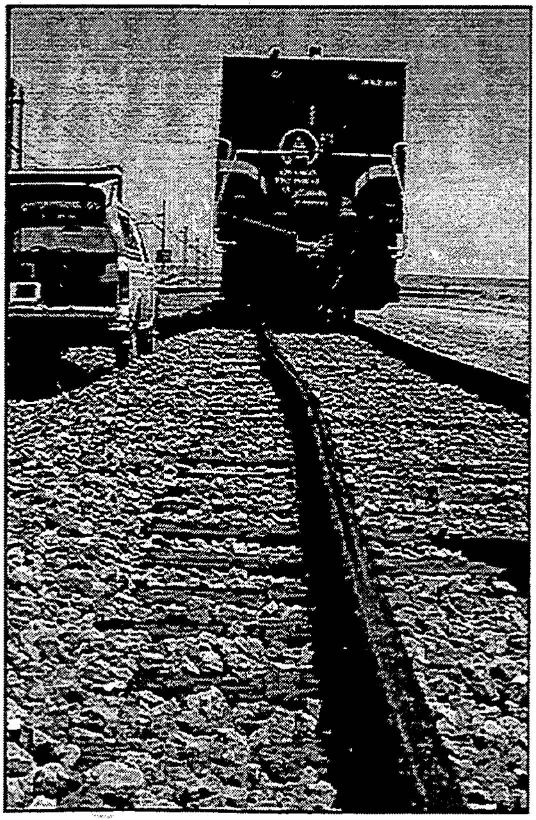


Exhibit 74. Large Panel Shift at 6thRun (see Exhibit 73, HTL Sec. 40, V=L=20 kips)

6.2 EFFECTS OF VERTICAL AND LATERAL AXLE LOADS

Exhibit 75 lists vertical and lateral axle loads applied during all the in-motion track panel shift tests. The range of vertical axle loads was from 20 kips to 40 kips, and the range of lateral axle loads was from 5 kips to 40 kips.

Exhibit 75: Matrix of Loads Applied for In-motion Track Panel Shift Tests

Track	Section 03		Section 36		Section 40				Balloon
Track Variable	Wood & Concrete		Thermal Force	Baseline	Baseline			Ballast Tamp	Baseline
Vertical Force (kips)	20	40	20	40	6	20	40	20	20
Lateral Force (kips)	10 15 20	20 30	5 15	24 30	5 10 15	10 15 20 25	15 20 25 30 35 40	10 15 20	10 15 20 25
L/V	0.5 -1.0	0.5 - 0.75	0.25 - 0.75	0.6 - 0.75	0.8 -2.5	0.5 - 1.25	0.38 -1.0	0.5 - 1.0	0.5 -1.25

6.2.1 Cumulative Residual Deformation (Panel Shift)

Exhibit 76 shows the results of cumulative residual deformation obtained on the west tangent of the Balloon Track. The vertical axle load was 20 kips for all the repeated passes. The applied lateral axle loads were 10, 15, 20, and 25 kips, respectively. Tests started with the lowest lateral axle load. As discussed in Section 3.0, a minimum five runs were required for any combination of lateral and vertical axle loads. If the cumulative residual deformation observed using a dial gage became constant for three consecutive runs, the lateral load was increased and a new series was started.

Exhibit 76 shows that at the lateral load level of 20 kips and lower, the accumulation of residual deformation with repeated passes of loads was small. However, when the lateral axle load reached 25 kips, cumulative residual deformation increased with each subsequent pass of the TLV. The increasing rate of cumulative deformation was so large during the last several runs that the track suddenly lost its stability, ending the series. Exhibit 77 shows the shifted and distorted track panel for a length approximately 80 to 100 feet with the maximum shift approximately 6 inches. Note that this trial test was conducted during early March 1996, with snow on the track.

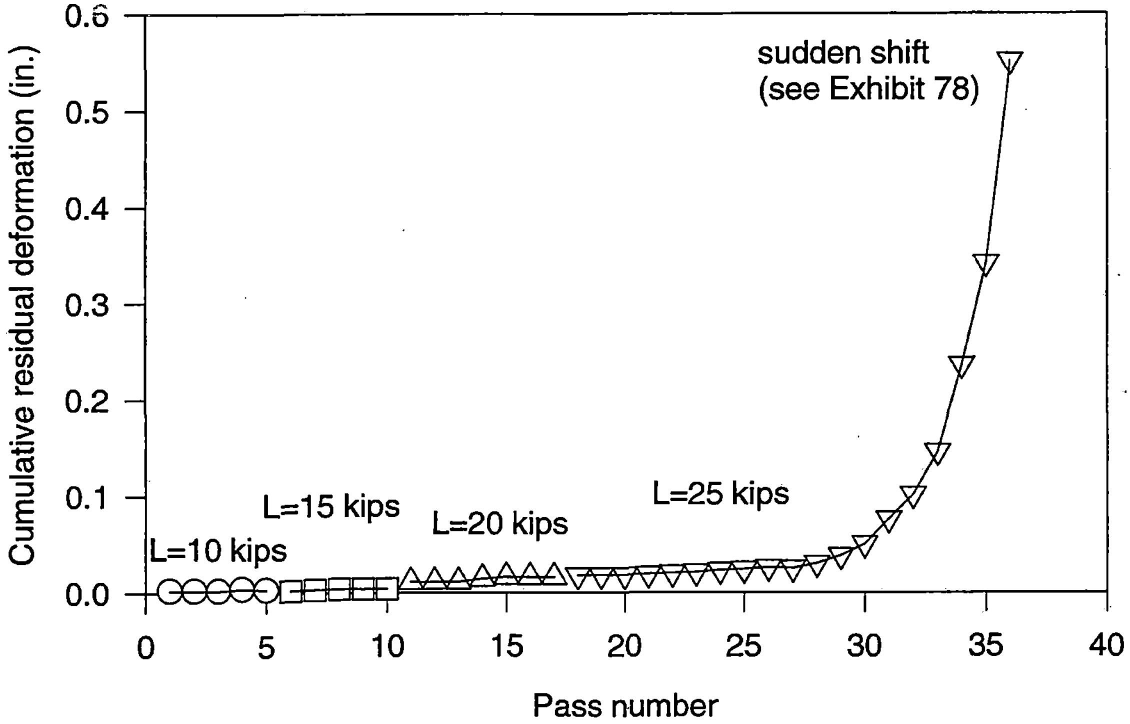


Exhibit 76. Cumulative Residual Deformation (panel shit) for Tests Conducted at West Tangent of Ballon Track

Exhibit 77. Sudden Panel Shift during Final Run from Tests shown in Exhibit 76 (Balloon Track)

Exhibit 78 shows cumulative residual deformation results measured in a newly tamped Section 36 of the HTL. The vertical axle load was 40 kips, while the lateral axle loads applied were 24 and 30 kips, respectively.

As illustrated in Exhibit 78, the cumulative residual deformation increased after each pass at either of the two lateral loads. However, a faster rate of cumulative residual deformation with each load pass is shown for the higher lateral axle load of 30 kips. It is obvious that the track was losing its stability at the lateral load level of 30 kips. At the lateral load level of 24 kips, it appeared that the track was approaching its critical state since the cumulative deformation continued to increase.

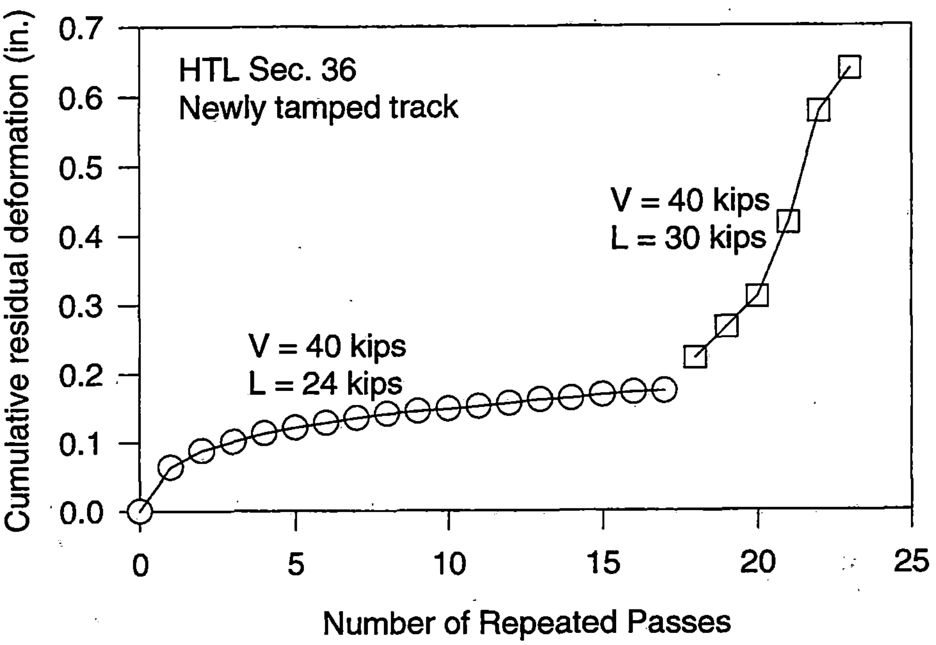


Exhibit 78. Cumulative Residual Deformation

The next several exhibits will show more results of cumulative residual deformation (panel shift) under various combinations of lateral and vertical axle loads. For some tests conducted at lower lateral axle loads, tests should have been conducted with more runs to obtain better indications of test trends. However, a dial gage was used to help determine whether the track panel shift had ceased. This malfunctioned without notice, thus additional runs at lower lateral axle loads were not performed. Nevertheless, a minimum five runs with any load combination were always accomplished.

The critical lateral loads will be determined based on results of incremental deformation per pass in the next section. Although the critical lateral load is defined as the load level at which the slope of the cumulative residual deformation becomes constant, it is easier to use trends of the incremental deformation to characterize the critical lateral axle loads.

Exhibit 79 shows results of cumulative residual deformation obtained in Section 40 of the HTL. Three series were done, each with a different vertical axle load. For each vertical axle load, various lateral axle loads were applied, as shown in this exhibit. Comparisons of results due to these various load combinations will be given in Section 6.2.2.

Exhibits 80 and 81 give more results of cumulative residual deformation obtained in Section 03 of the HTL. Exhibit 80 shows results from the track segment with wood ties, while Exhibit 81 shows results from the track segment with concrete ties. Again, comparisons of test results between the wood tie segment and concrete tie segment will be discussed later in Section 6.3.

For results shown in Exhibits 79 to 81, at L/V ratios 0.5 and above, growth rates of cumulative residual deformation did not indicate trends characteristic of a stable track. The magnitudes of cumulative residual deformation shown in these exhibits may still fall within the FRA allowable alignment limits for Class 1 to 6 tracks. However, if many same direction lateral axle load applications were exerted, it can be expected that continued growth in misalignment would increase until the geometry exceeded the FRA safety limits.

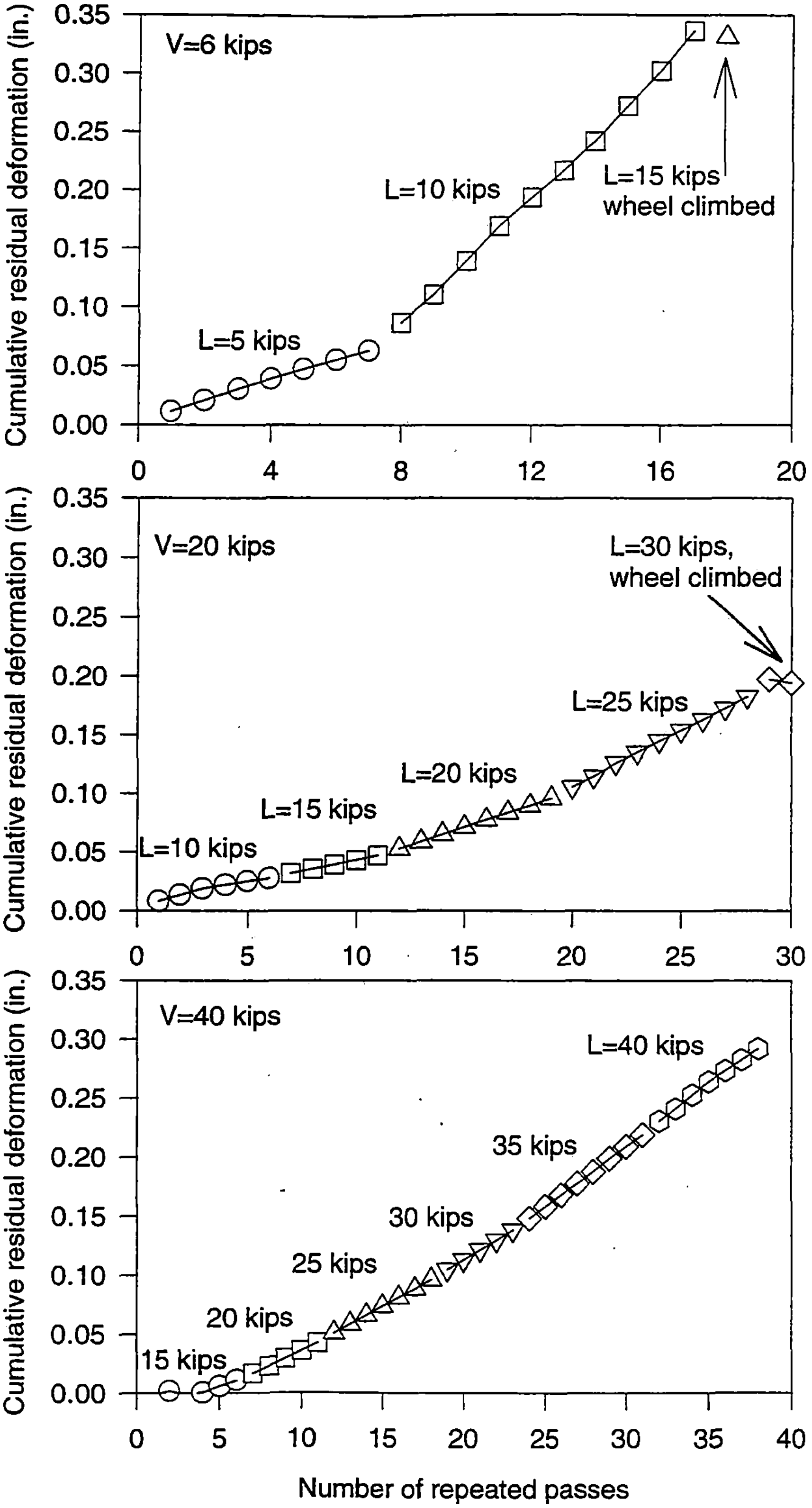


Exhibit 79. Cumulative Residual Deformation (Panel Shift) Under Various Loads (HTL Sec. 40)

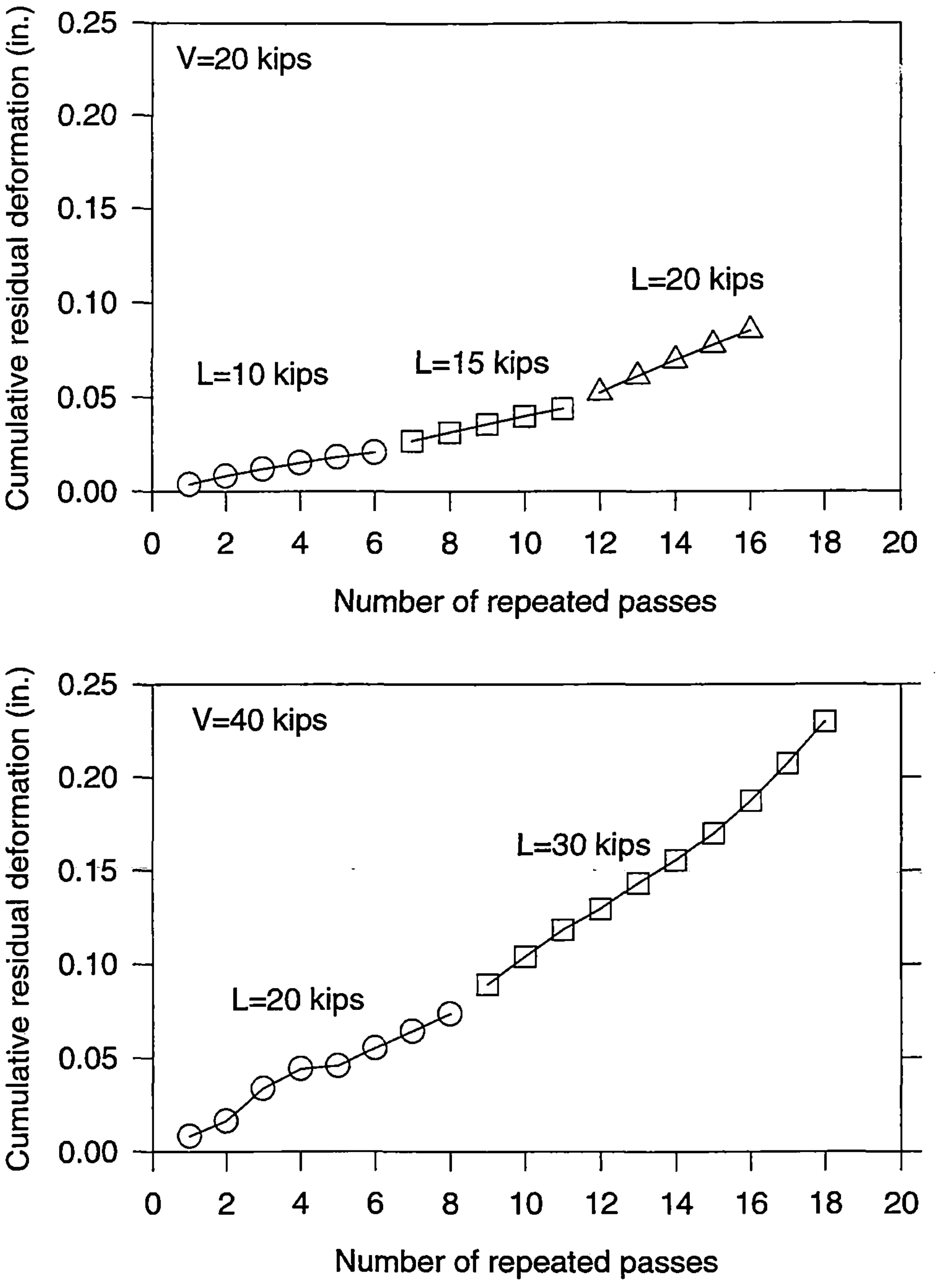


Exhibit 80. Cumulative Residual Deformation (HTL Sec. 3, Wood Ties)

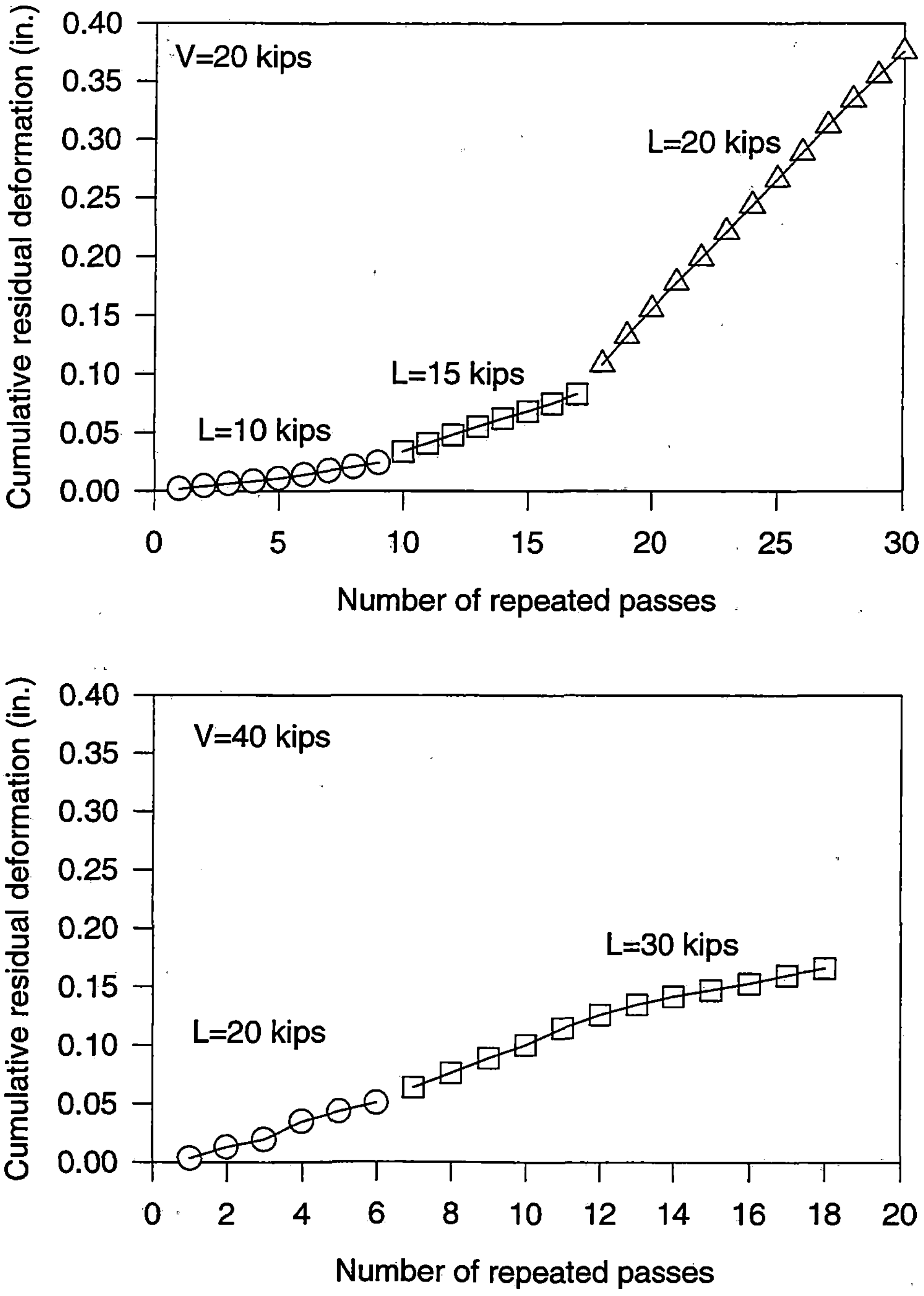


Exhibit 81. Cumulative Residual Deformation (HTL Sec.3, Concrete Ties)

6.2.2 Incremental Residual and Total Deformations

For a stable track, discussed in Section 3.0, incremental residual deformation should tend toward zero (or grow at a very small rate), and incremental total deformation should tend constant with the number of repeated load passes. The critical lateral load is defined as the load level causing constant incremental residual deformation and ever increasing incremental total deformation due to repeated load applications.

Incremental total deformation, due to each load pass, includes incremental residual deformation and instantaneous elastic deformation. At low-lateral load levels (i.e., a stable track), the instantaneous elastic deformation should remain constant with each axle load pass, while incremental residual deformation tends to become zero. However, when the lateral axle load is high, with each pass of axle loads not only does the incremental residual deformation increase, but also the instantaneous elastic deformation is higher. This higher instantaneous elastic deformation at critical load is due to the non-linear elastic behavior of the track structure. Refer to Exhibit 6 of Section 3.0, lateral track stiffness is lateral load-dependent and will decrease as the lateral axle load goes up. The decrease in lateral track stiffness will be even more significant when the lateral axle load approaches the second region of the load-deflection curve, where the track possesses much lower lateral stiffness.

Based upon the above discussion, when the track becomes unstable, we can assume that a track will behave in the softer second region (see Exhibit 6). Thus, the instantaneous elastic deformation will increase at lateral loads above critical. In other words, at the critical lateral load, the incremental residual deformation will become constant, while the incremental total deformation will start to increase, with each pass of axle loads.

Exhibits 82 to 84 show results of both incremental residual deformation and incremental total deformation for various in-motion track panel shift tests. A discussion of these exhibits follows.

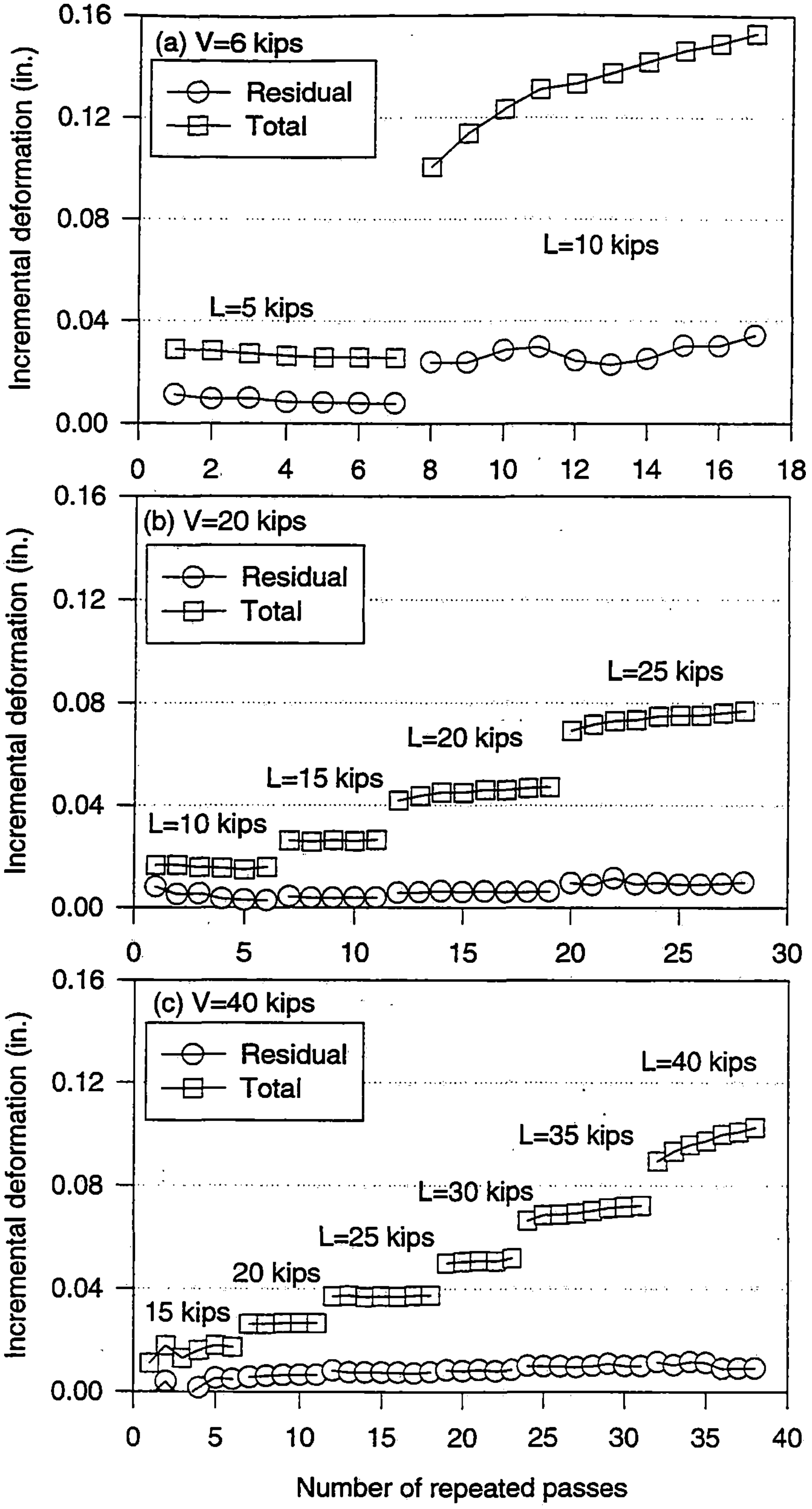


Exhibit 82. Incremental Deformations (HTL Sec. 40)

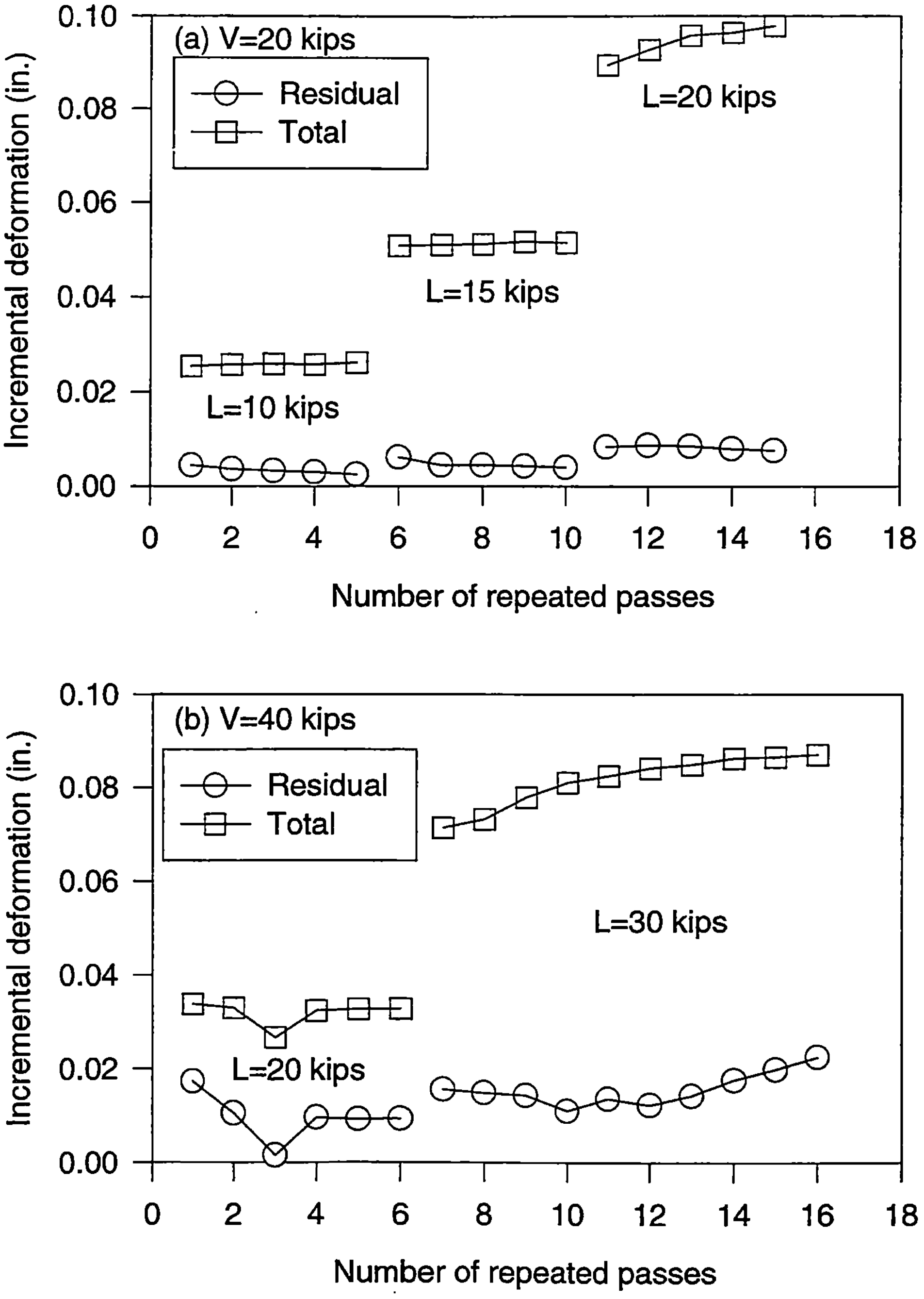


Exhibit 83. Incremental Deformations (HTL Sec. 3, Wood Ties)

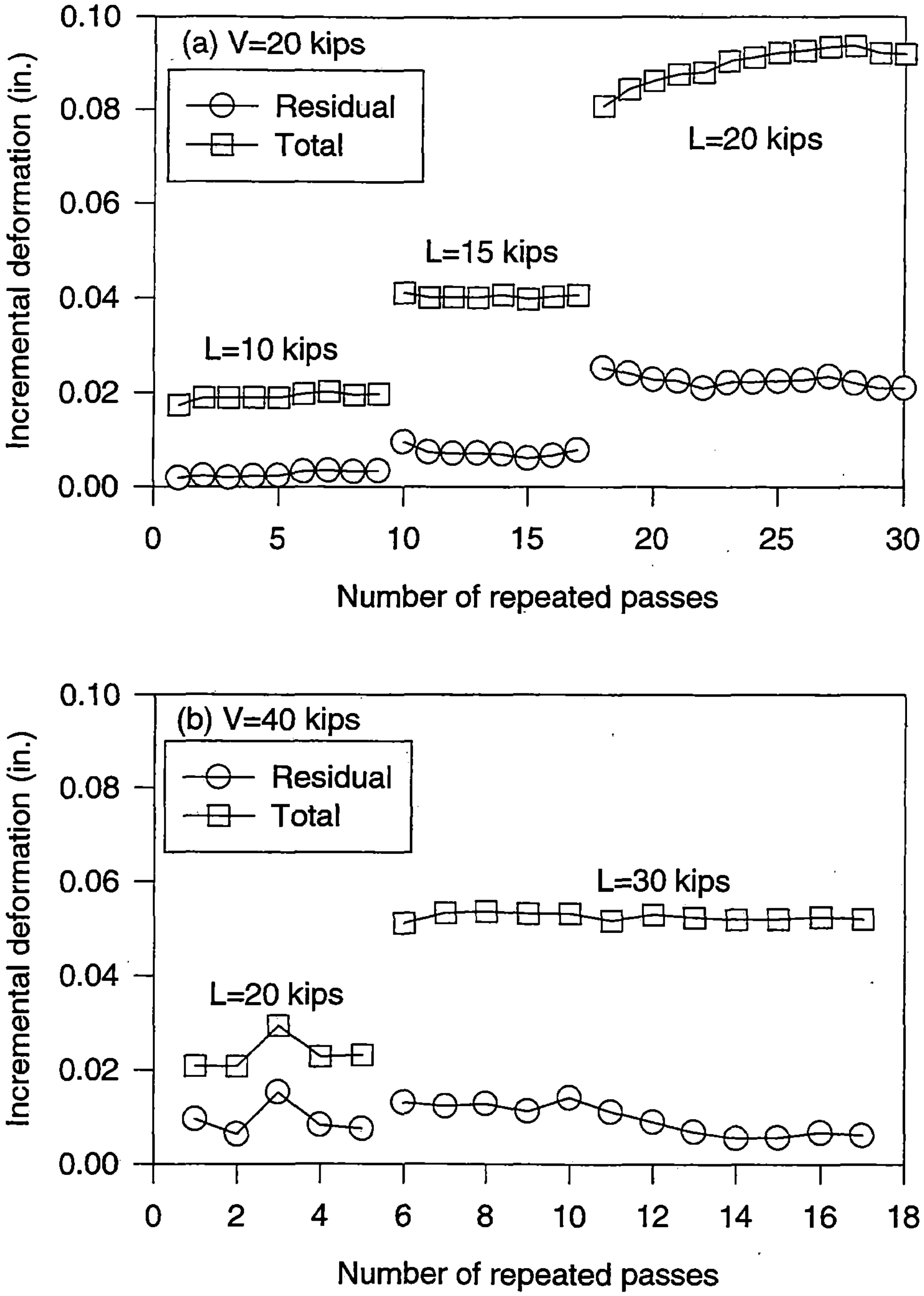


Exhibit 84. Incremental Deformations (HTL Sec. 3, Concrete Ties)

Exhibit 82(a) shows results obtained from HTL Section 40 under a vertical axle load of 6 kips. As illustrated, at the lateral axle load of 5 kips both incremental residual and total deformations decreased with the number of repeated passes. At the higher lateral load of 10 kips, however, incremental deformations became higher. The lateral axle load of 10 kips can be considered to be at (or above) the critical lateral load since the incremental residual deformation tended to become constant and the incremental total deformation increased, with the number of repeated passes.

Exhibit 82(b) shows results obtained from Section 40 under a vertical axle load of 20 kips. As illustrated, an increase in lateral axle load resulted in an increase of both incremental residual and total deformations. The critical lateral axle load can be seen to be between 15 to 20 kips at this test location.

Exhibit 82(c) shows results obtained from Section 40 under a vertical axle load of 40 kips. Again, an increase in lateral axle load resulted in an increase of both incremental residual and total deformations. The critical lateral axle load can be seen to be approximately between 25 to 30 kips at this test location.

Exhibits 83(a) and 83(b) show results obtained from Section 3 for the track segment with wood ties, under a vertical axle load of 20 and 40 kips, respectively. From these two exhibits, the critical lateral loads for this segment of track can be seen to be approximately 15 and less than 30 kips, corresponding to vertical axle loads of 20 and 40 kips, respectively.

Exhibits 84(a) and 84(b) show results obtained from Section 3 for the track segment with concrete ties, also under a vertical axle load of 20 and 40 kips, respectively. From these two exhibits, the critical axle loads for this segment of track can be seen to be approximately 20 and above 30 kips, corresponding to a vertical axle load of 20 and 40 kips, respectively. In other words, with other conditions being similar, the critical lateral loads appeared to be higher for the segment with concrete ties than the segment with wooden ties.

The results of critical lateral loads determined at various vertical axle loads are plotted in Exhibit 85. These limited results of the critical lateral loads determined under various vertical axle loads do not allow a statistically sound correlation between the critical lateral load and vertical axle load. However, the following equation is presented as an approximate relationship between the critical lateral load and vertical axle load for consolidated ballasts and wood ties, based on the test results from this study:

$$L_c = 6 + 0.5V \qquad (kips) \tag{16}$$

The limiting lateral loads predicted using the Prud'homme criterion (Equation 2 in Section 2.0) are also plotted in Exhibit 85 for comparison. As can be seen, the limiting lateral load determined from Equation 2 is lower than on the results obtained using TLV tests. Note that the Prud'homme criterion incorporates a safety factor of 0.85 and does not represent the critical lateral load.

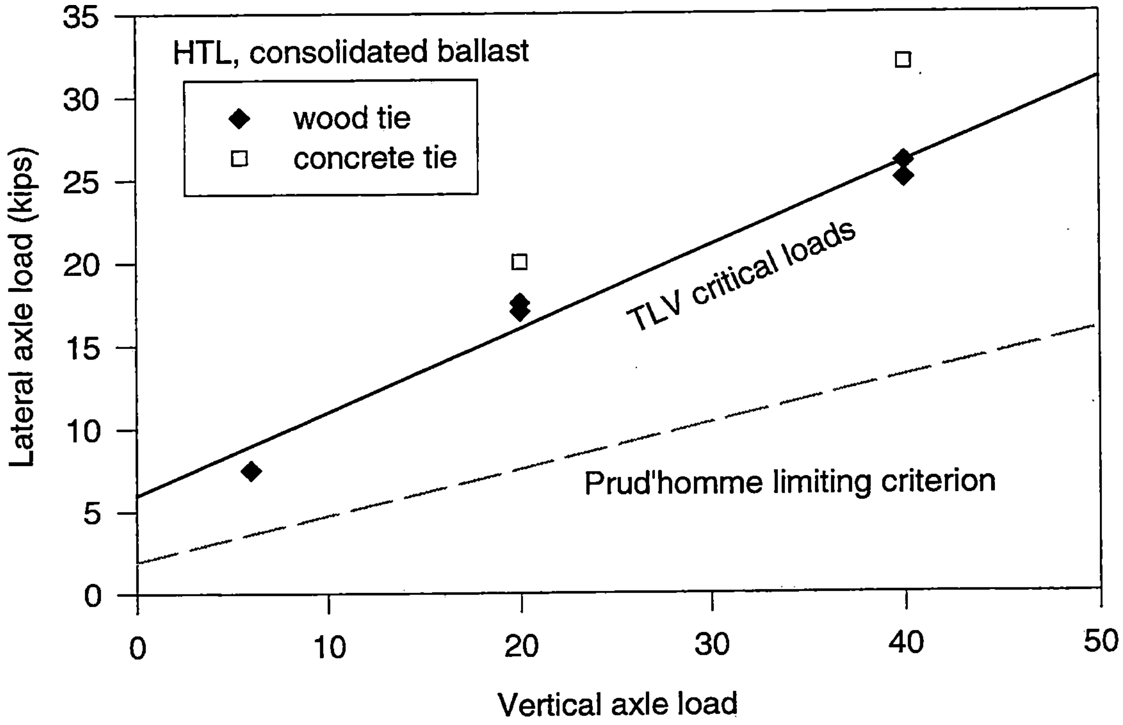


Exhibit 85. Critical Lateral Axle Loads for Tangent Track Tests and Prud'homme Limits

Equation 16 indicates that the vertical axle load has a significant effect in stiffening the track panel. An increase in the vertical axle load will result in an increase in the critical lateral load. The effects of vertical axle load on the magnitudes and rates of incremental deformations can be further seen in Exhibits 86 and 87.

Exhibit 86 shows that for a lateral axle load level of 10 kips, an increase in the vertical axle load from 6 kips to 20 kips not only reduced the magnitudes of incremental residual and total deformations considerably, but also reduced the change of incremental deformations for subsequent repeated passes.

Exhibit 87 shows the effects of vertical axle load on the incremental deformations for three lateral axle loads respectively. The effect of an increase in vertical axle load from 20 kips to 40 kips on the incremental residual deformation is insignificant until at the highest lateral axle load of 25 kips. However, as illustrated in Exhibit 87(b), the stiffening effect of vertical axle load on the incremental total deformation is obvious for all the three lateral load levels. That is, an increase in the vertical axle load from 20 kips to 40 kips not only reduced the magnitudes of incremental total deformation approximately by 50 percent, but also reduced the rates of incremental total deformations with the number of repeated passes.

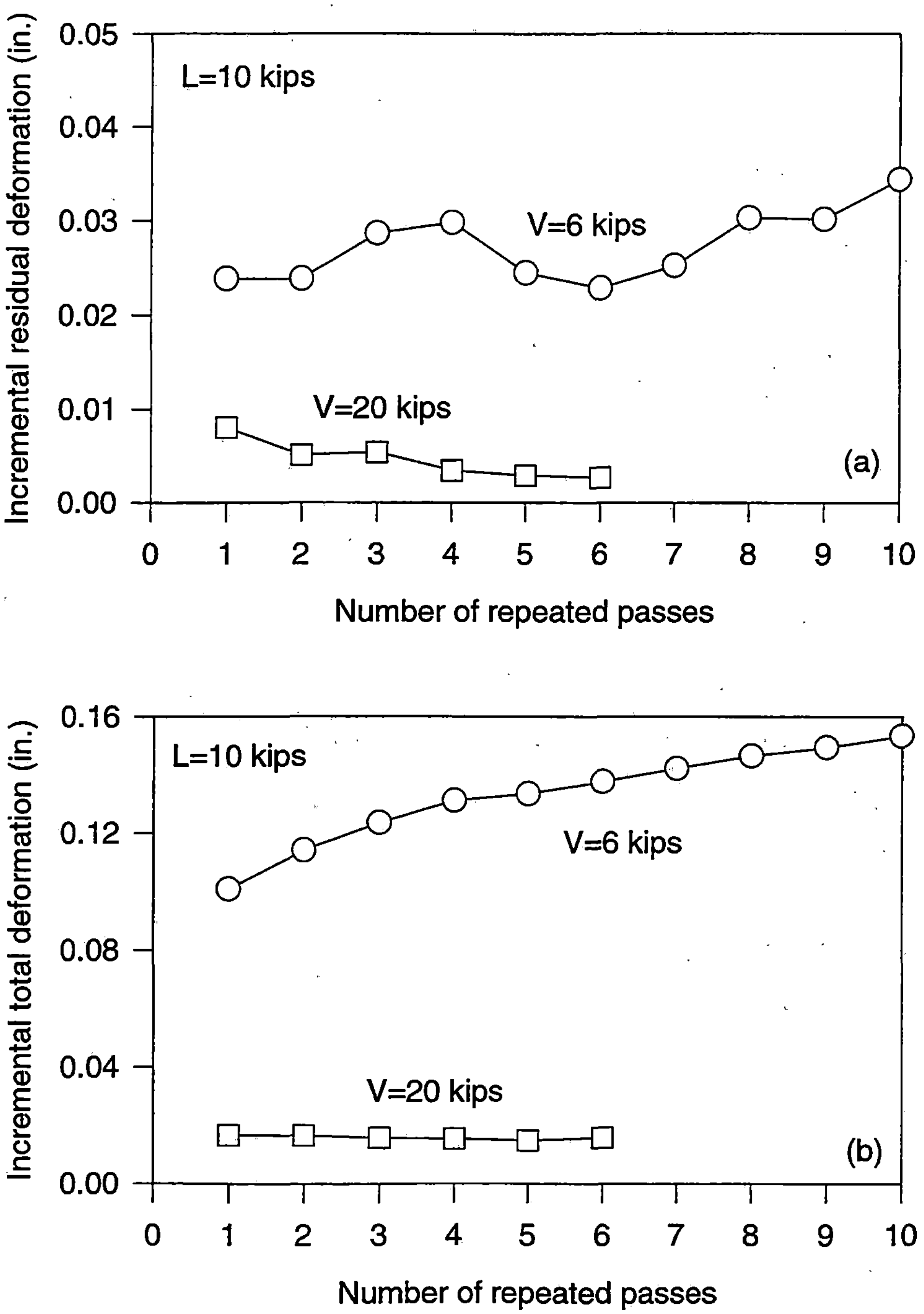


Exhibit 86. Effect of Vertical Axle Load (HTL Sec. 40)

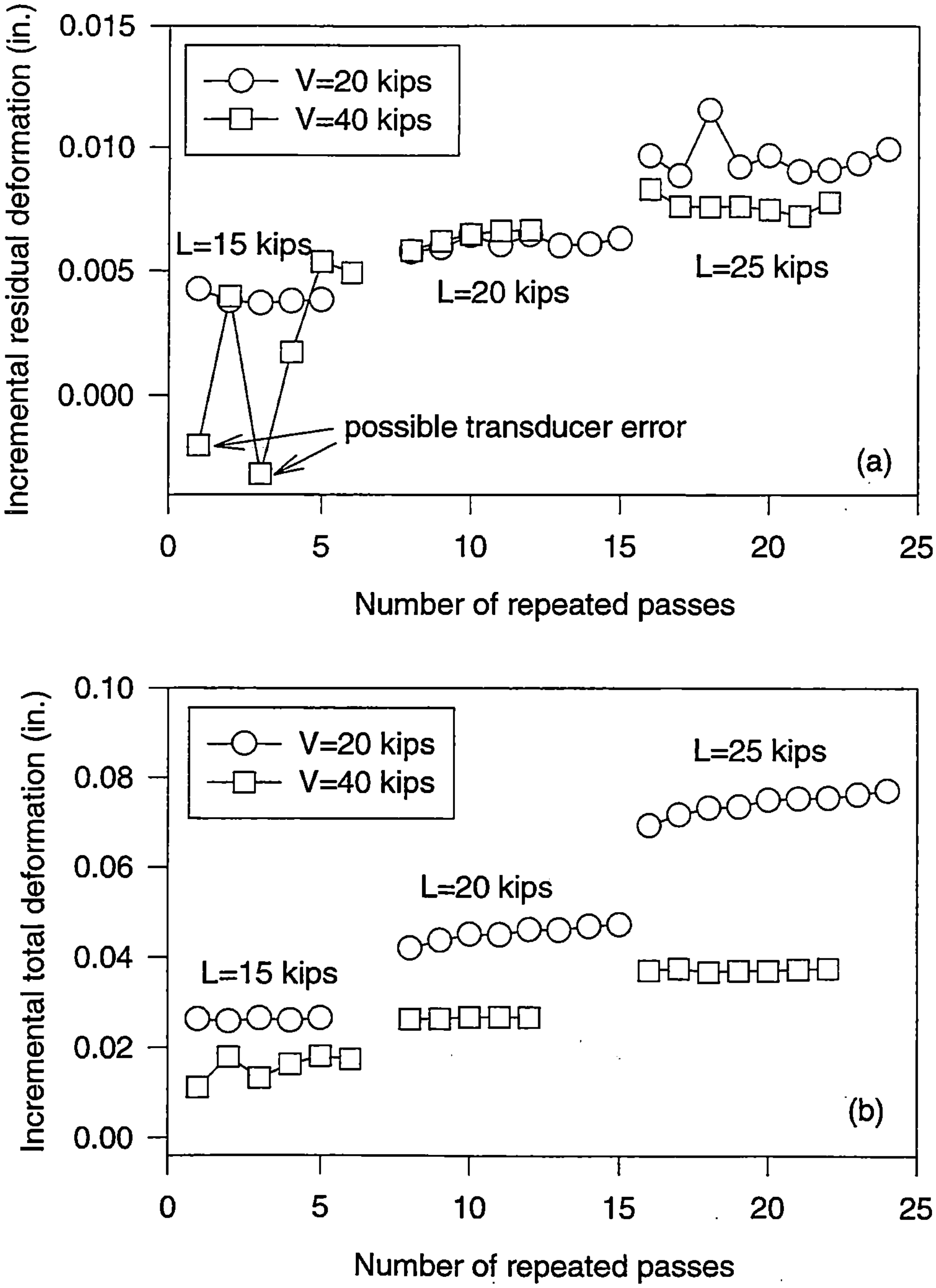


Exhibit 87. Effect of Verticle Axle Load (HTL Sec. 40)

6.3 EFFECTS OF TIE TYPE

Section 03 of the HTL has two segments with different types of ties. One track segment has wood ties and the other track segment has concrete ties. In-motion track panel shift tests were conducted in both the segments to compare test results between these two segments.

Exhibits 80 and 81 have already given the cumulative residual deformation results obtained from these two segments in Section 03. Direct comparisons of the magnitudes of cumulative residual deformations between wood and concrete ties were not made because the total numbers of repeated axle passes between these two segments did not match. However, comparisons can be made based on the incremental deformations.

Note that based on Exhibits 83 and 84, it was mentioned that the critical lateral loads determined at two lateral axle loads of 20 and 40 kips were higher for the track segment with concrete ties than the track segment with wood ties.

Exhibits 88 and 89 give comparisons of both incremental residual and total deformations between wood and concrete ties, for a vertical axle load of 20 and 40 kips, respectively. Exhibits 88(b) and 89(b) show that the magnitudes of incremental total deformations are lower for the track segment with concrete ties than the track segment with wood ties. However, the advantage of concrete ties cannot be seen in terms of the magnitudes of incremental residual deformations, as shown in Exhibits 88(a) and 89(a). In fact, at the 20 kip vertical axle load, the magnitudes of incremental residual deformation are higher for the concrete ties than the wood ties, for the two higher lateral axle loads of 15 and 20 kips, respectively. At the higher vertical axle load of 40 kips, Exhibit 89 shows that the difference in incremental residual deformation between these two types of ties is small until at the higher lateral axle load of 30 kips, when the incremental residual deformation for the segment of wood ties started to grow higher with each load pass following the sixth pass.

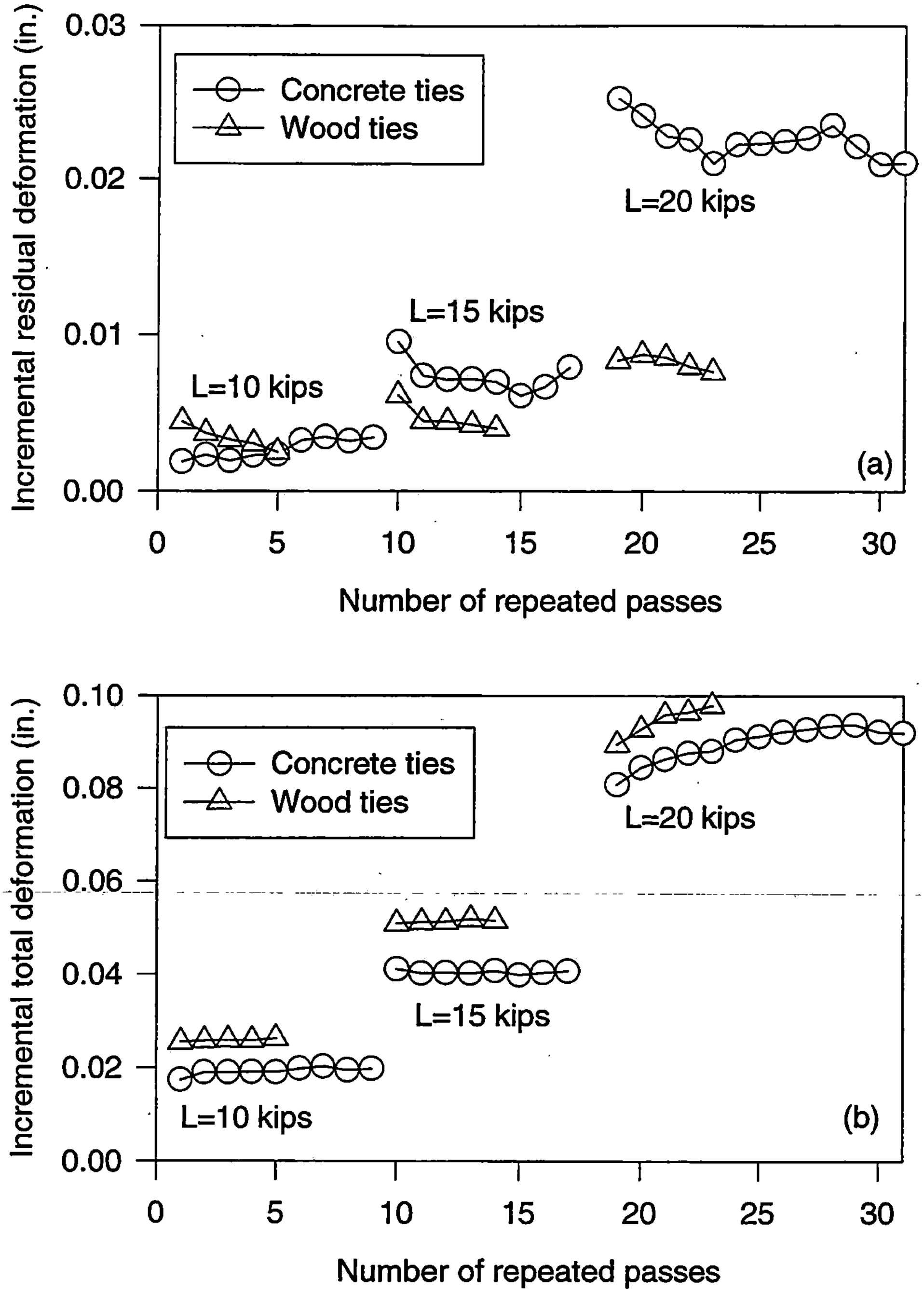


Exhibit 88. Concrete Ties vs. Wood Ties (HTL Sec. 3, V=20 kips)

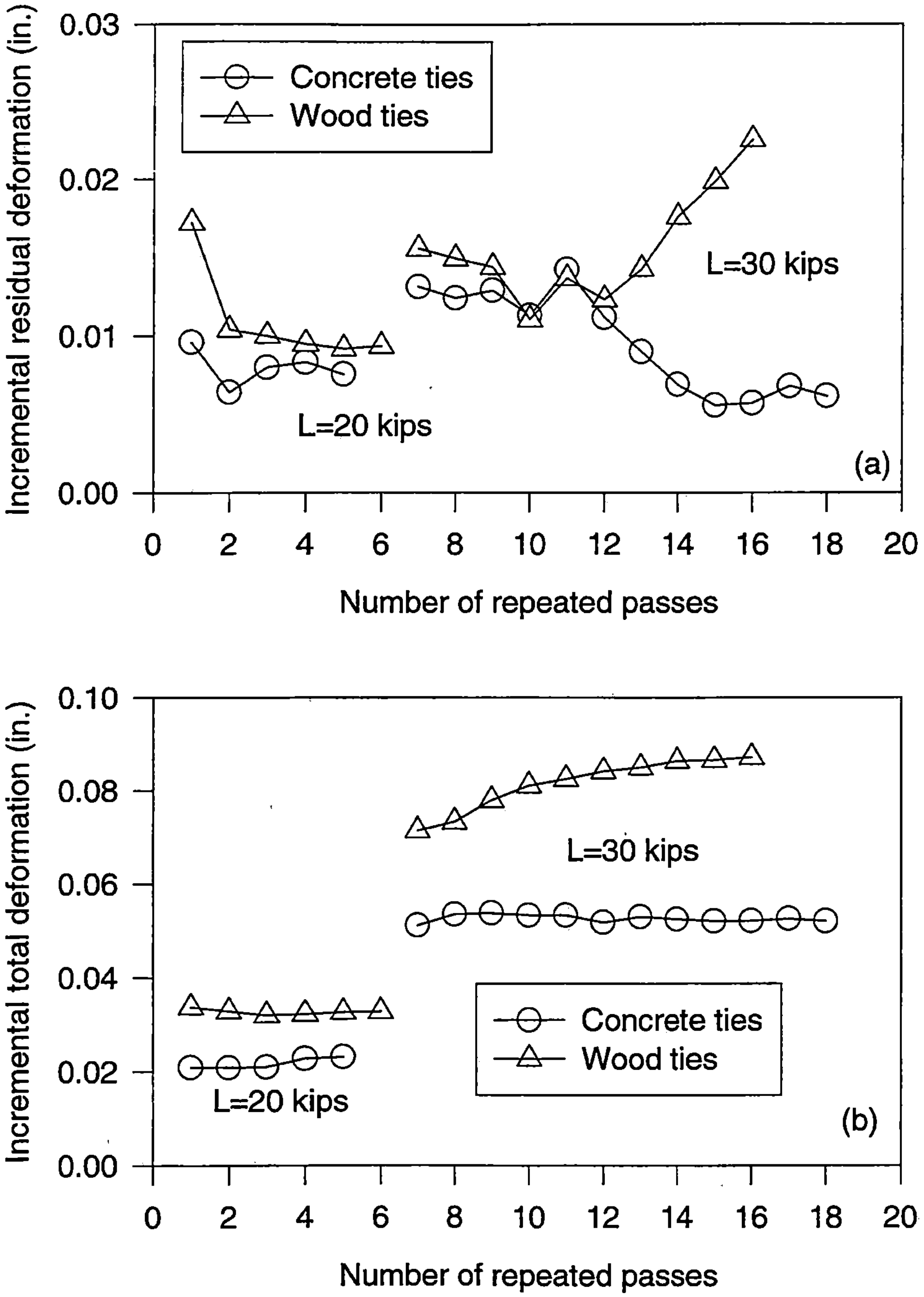


Exhibit 89. Concrete Ties vs. Wood Ties (HTL Sec. 3, V=40 kips)

Since the incremental total deformation includes the incremental residual deformation and instantaneous elastic deformation, the above results indicate that the instantaneous elastic deformations generated under various load combinations were smaller for the track segments with concrete ties than with wood ties; i.e., a concrete tie track may have a higher lateral track stiffness than a wood-tie track.

6.4 EFFECTS OF RAIL LONGITUDINAL FORCES

During late May to early June 1996, in-motion track panel shift tests were conducted in Section 36 of the HTL to compare test results influenced by different rail longitudinal forces. Rail longitudinal force change was primarily due to rail temperature change from its neutral temperature. Section 5.4 describes procedures for establishing neutral rail temperature and measuring rail longitudinal forces.

The average neutral rail temperature for the two rails in Section 36 was approximately 90° F. Two zones in Section 36 were used to conduct in-motion track panel shift tests for the lowest and highest rail temperatures possible. In one zone, tests were conducted early in one morning, with the rail temperature ranging between 50° to 60° F. In another zone, tests were conducted during one afternoon, with the rail temperature ranging between 100° to 110° F. This was not as high as desired, but after several days of waiting for higher temperatures, this testing could not be delayed.

A vertical axle load of 20 kips was used for all the in-motion test runs. Two levels of lateral axle loads, 5 and 15 kips, were applied for tests conducted at both the lower rail temperature and the higher temperature.

Exhibit 90 shows the results of cumulative residual deformation versus the number of repeated axle passes, obtained at two ranges of different rail temperatures (i.e., two different rail longitudinal forces). A positive temperature change shown indicates a compressive force in the rails, whereas a negative change indicates a tension in the rails.

The range of tension force in the rail at the low-rail temperature was from -60 to -100 kips, and the range of rail compressive force at the high-rail temperature was approximately 25 to 65 kips. At both lower and higher ranges of longitudinal rail forces, the first 16 runs made were under a lateral axle load of 5 kips while the subsequent 20 runs were conducted under a lateral axle load of 15 kips. Results of cumulative residual deformation shown in this exhibit represent the average of measurements from three wayside deflection transducers installed over a distance of 10 ties. Like the other tests in this report, available track lengths limited the size of test zones.

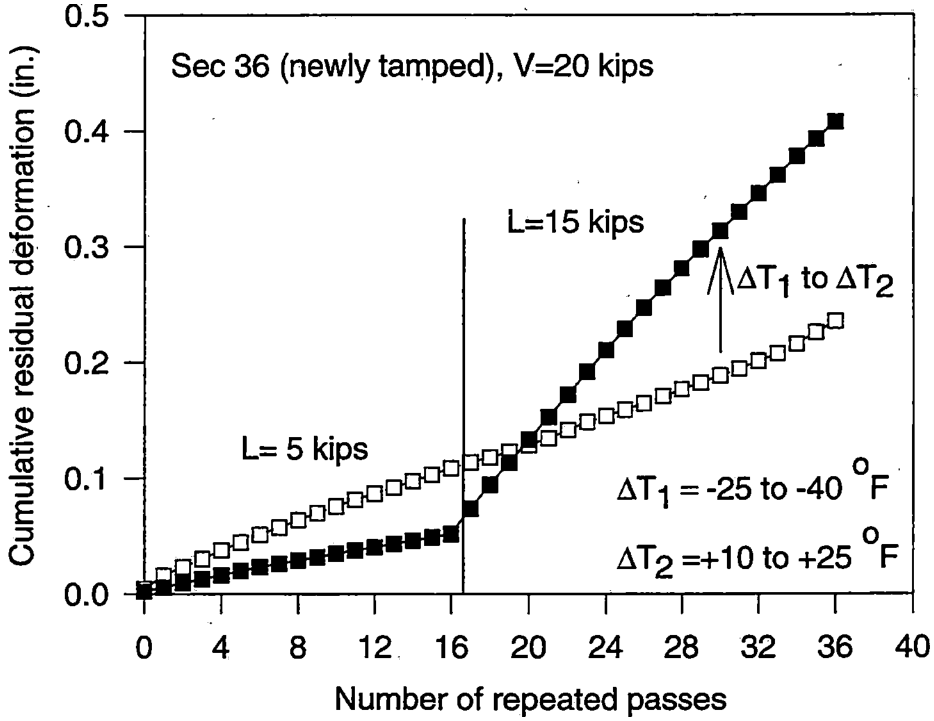


Exhibit 90. In-motion Track Panel Shift Tests Influenced by Rail Longitudinal Force

At the lower lateral axle load (5 kips), an increase in rail longitudinal force from tension to compression (in the range tested) did not cause a significant increase in the growth of cumulative residual deformation (panel shift). In fact, cumulative deformation was even higher at the lower rail temperature (we cannot explain this effect at this time). However, as the lateral axle load was increased to 15 kips, the growth of cumulative residual deformation was significantly higher at the higher rail temperature than at lower rail temperatures.

Exhibits 91 and 92 show the results of incremental residual and total deformations influenced by the longitudinal rail forces, for the two lateral axle loads, 5 and 15 kips, respectively. As shown in Exhibit 91, higher longitudinal rail forces in compression did not cause higher incremental deformations at the low lateral axle load of 5 kips. The magnitude of incremental residual deformation was actually higher at the lower range of rail temperature. The difference in the incremental total deformation was essentially indiscernible for the two ranges of rail temperatures considered. On the other hand, when the lateral axle load was at 15 kips, magnitudes of both incremental residual deformation and incremental total deformation were higher for tests conducted at higher rail temperatures, as illustrated in Exhibit 92.

Based upon the changes of both incremental residual and total deformations with the number of repeated passes, the lateral axle load of 15 kips seems to be close to the critical lateral axle load at the range of lower temperature. This is because both trends of incremental residual and total deformations increased with each pass of lateral load. However, this cannot be said for the tests conducted at the range of higher rail temperature; i.e., increasing incremental deformations were not the case at the range of higher rail temperature. An increase in rail temperature was not found to reduce the critical lateral axle load level for this track.

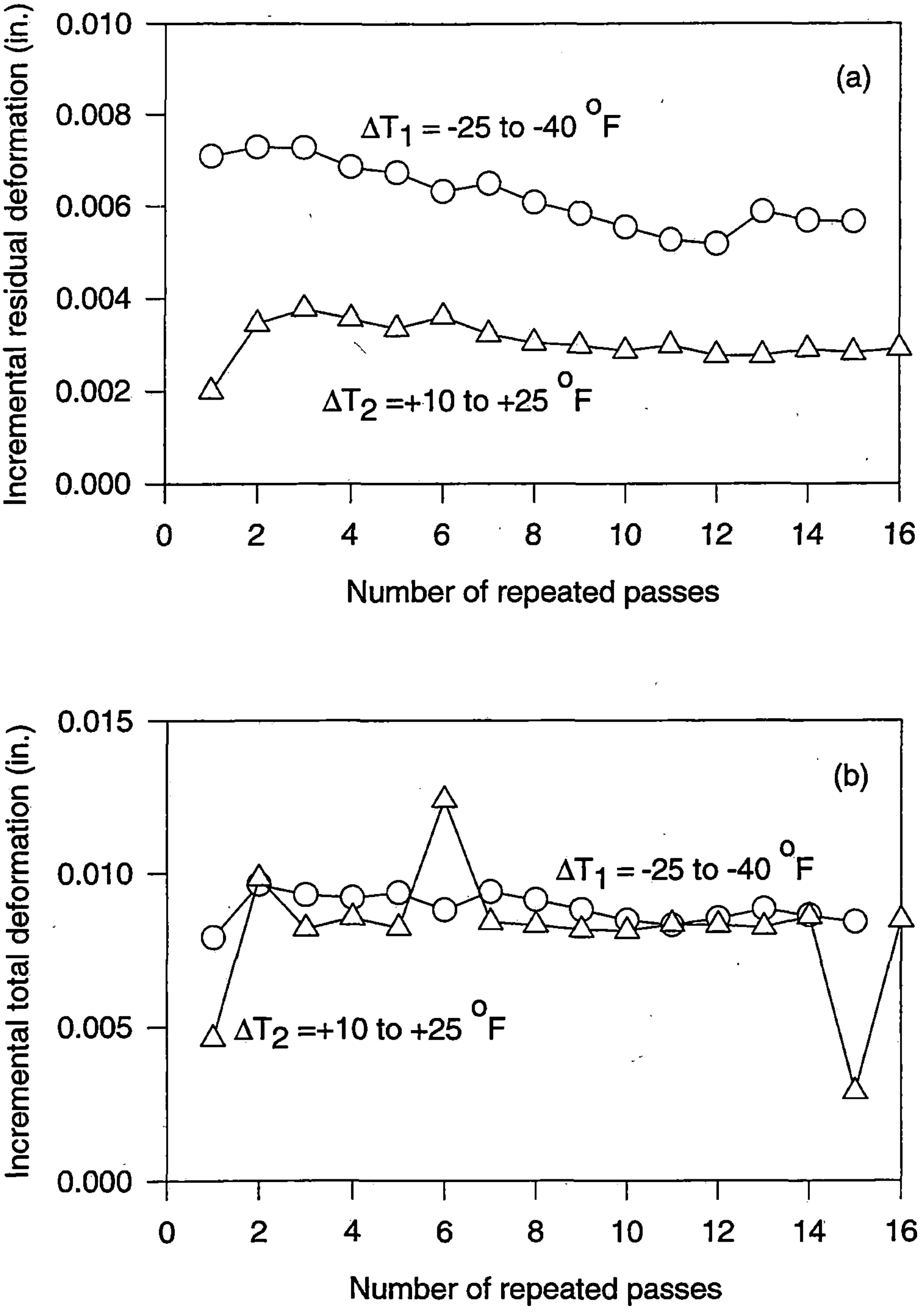


Exhibit 91. Effect of Rail Temperature on Incremental Deformations

(HTL Sec. 36, V=20 kips, L=5 kips)

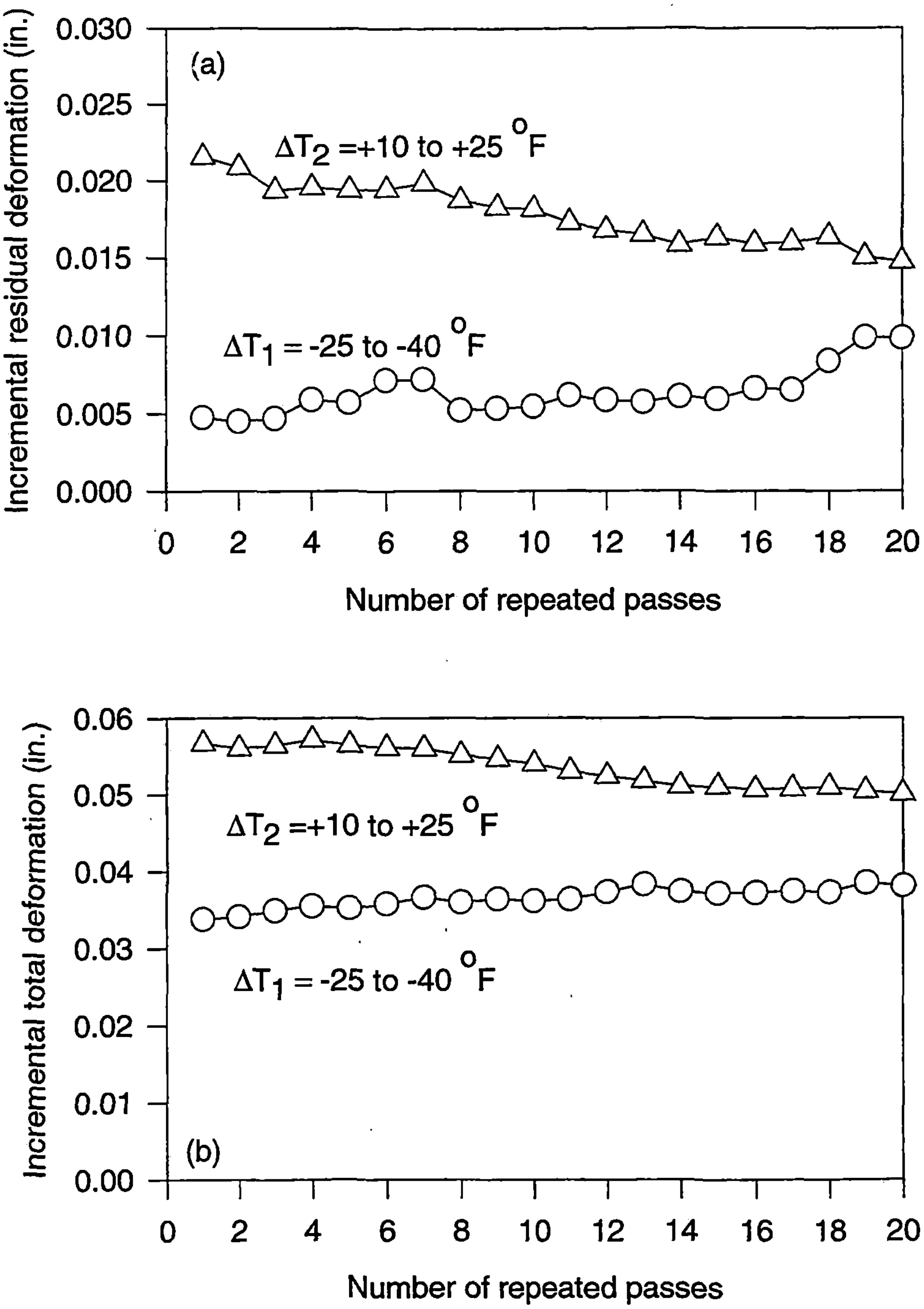


Exhibit 92. Effect of Rail Temperature on Incremental Deformations (HTL Sec. 36, V=20 kips, L=15 kips)

6.5 EFFECTS OF BALLAST CONSOLIDATION

In-motion track panel shift tests were conducted in Section 40 to study the effects of ballast tamping and subsequent traffic on test results. The entire Section 40 was divided into four zones for conducting in-motion track panel shift tests at four different MGT levels: 0, 1, 4 and 9 MGT. For all the in-motion track panel shift tests, the vertical axle load applied was 20 kips. The lateral axle loads included 10, 15 and 20 kips. For each MGT level, in-motion track panel shift tests were conducted with repeated passings at the lowest lateral load first and the highest lateral load last.

Exhibit 93(a) shows comparisons of cumulative residual deformations measured at four MGT levels following ballast tamping, at the lateral axle load of 10 kips. As illustrated, the growth of cumulative residual deformation was highest at the traffic level of 1 MGT. The newly tamped track showed the second highest growth of cumulative residual deformation. At 4 MGT, the measured growth of cumulative residual deformation was the smallest.

Exhibit 93(b) shows additional growth of cumulative residual deformation at lateral axle load level of 15 kips. As illustrated, the newly tamped track showed highest growth of cumulative residual deformation. However, significant difference was not observed between the results for the traffic levels at 1 and 4 MGTs.

Exhibit 93(c) shows additional growth of cumulative residual deformation at the lateral axle load level of 20 kips. As illustrated, no benefits of ballast consolidation caused by traffic can be observed, since the additional growth of cumulative residual deformation at this lateral load level was highest at the traffic level of 9 MGT.

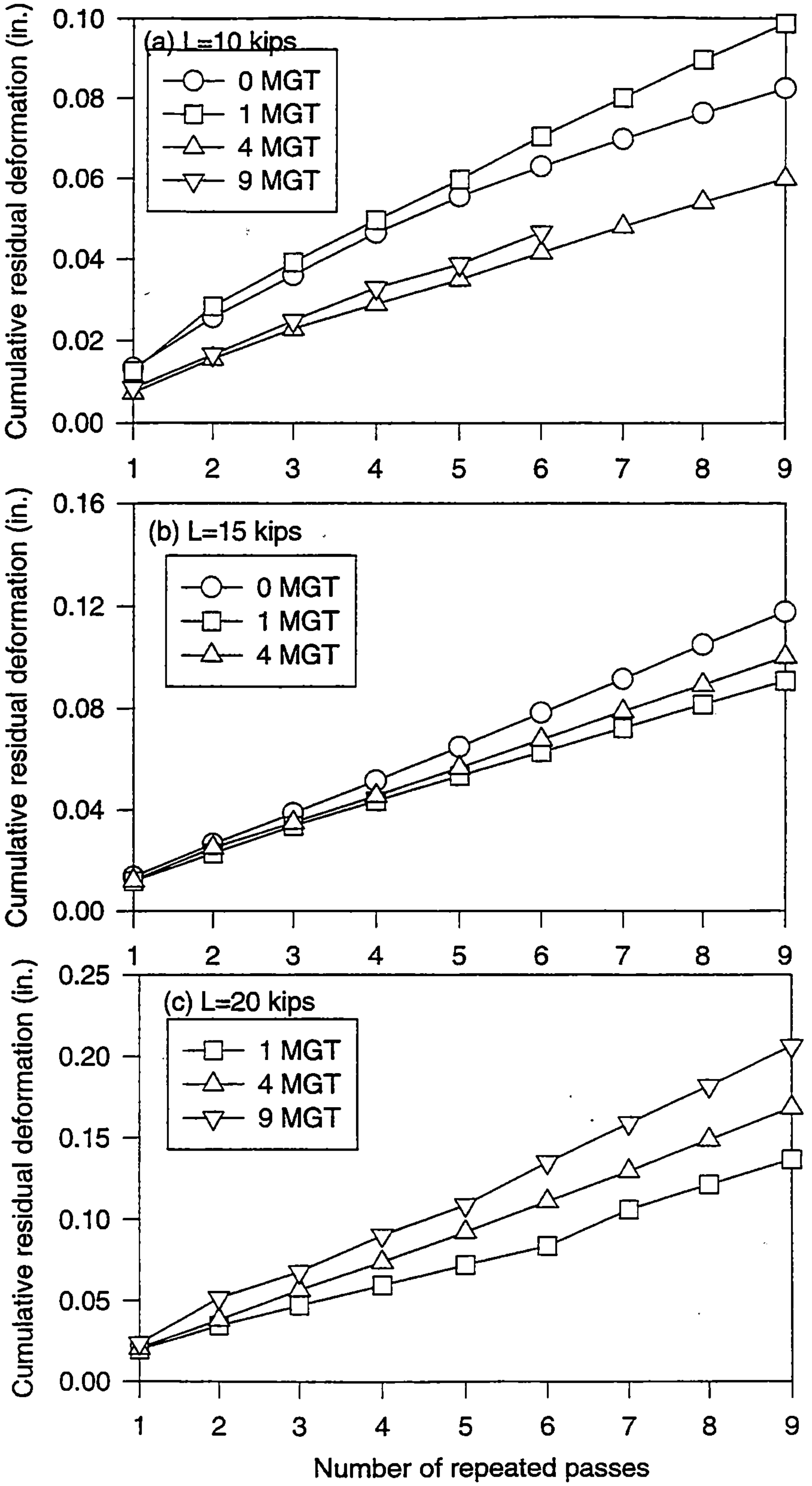


Exhibit 93. Effects of Ballast Consolidation Induced By Traffic (HTL Sec. 40, V=20 kips)

Overall, the results shown in Exhibit 93 indicate that in-motion track panel shift tests with high lateral loads may not give a valid representation of the effects of ballast consolidation on the lateral track strength and stiffness exhibited at small deflection levels. The pre-test ballast consolidation (caused by traffic) may be destroyed by the early lateral panel movements due to repeated large lateral axle loads. Thus, between the traffic levels 0 MGT and 9 MGT, the initial ballast consolidation levels may be irrelevant to the final cumulative residual deformations because of the tie-ballast disturbance due to repeated passes of high lateral axle loads.

6.6 COMPARISON WITH TLV STATIONARY TESTS

6.6.1 Static Lateral Track Strengths and Critical Lateral Load

The static lateral track strength determined from a TLV stationary test depends upon the allowable lateral track deformation and is given in Equation 12 of Section 5.0. The critical lateral load is given in Equation 16 in this section. Both the static lateral track strength and the critical lateral axle load are directly proportional to the vertical axle load applied.

To better illustrate comparisons of critical loads and static lateral track strengths as influenced by vertical axle load, calculations based on Equations 12 and 16 at various vertical loads were performed and are given in Exhibit 94. Note that calculations of static strengths were based on the averages given in Exhibit 45 of Section 5.0.

As can be seen, all the values of static lateral track strengths are higher than the corresponding critical lateral axle loads at any vertical axle load level. Therefore, any of the static lateral track strength parameters corresponding to the four given deflection levels should not be directly used as the critical lateral axle load.

Exhibit 94: Comparison of static lateral track strengths and critical lateral load
(All units are in kips)

V	L_c	$L_{0.05}$	$L_{0.1}$	$L_{0.2}$	$L_{0.3}$
10	11	18	22	27	30
20	16	22	29	34	38
40	26	32	43	47	54
60	36	41	56	59	70
80	46	51	70	72	86

However, the following equation was found to relate the static lateral track strengths to the critical lateral loads (wood tie tracks), based on the fact that both the static lateral track strength and critical lateral load are directly proportional to the vertical axle load:

$$L_c = cL_\delta - d \tag{17}$$

where c, d = two coefficients depending upon the magnitude of the lateral deflection level used to define the static lateral track strength. For example, the values of these two coefficients can be found to be {0.73, 5.2} and {0.78, 11} corresponding to the two lateral deflection levels of 0.1 and 0.2 inch, respectively.

6.6.2 Effects of Track Variables

The track variables such as tie type, rail longitudinal forces, and ballast consolidation were studied under both the stationary and in-motion panel shift tests. The following gives a general discussion of the test results between these two types of tests regarding the effects of these track variables.

The track with concrete ties showed higher (15 to 30 percent) critical lateralload and lateral track resistance to the incremental total deformation than the track with wood ties.

However, the difference between concrete- and wood-tie tracks was not quite obvious in terms of the magnitude of incremental residual deformation. During stationary tests, the track with concrete ties showed higher strength (5 to 20 percent) than the track with wood ties at small deflection level (i.e, 0.1 inch and less). When a track panel was pushed more (e.g. 0.2 inch), however, no significant difference in static track strength was observed between these two types of track structures.

For the range of rail longitudinal forces considered, a change from tension to compression in the rail only slightly reduced static lateral track strength and stiffness determined from stationary tests (less than 10 percent). The cumulative residual deformation was not higher due to higher rail temperature for a low lateral axle load. However, at a higher lateral axle load close to the critical, the magnitude of cumulative residual deformation was higher at higher rail temperature.

Ballast consolidation caused by tamping and subsequent traffic showed a significant influence on static lateral track strength determined from stationary tests. In-motion track panel shifts at lower lateral axle loads also showed higher cumulative residual deformation for a newly tamped track than a track exposed to a significant amount of traffic. However, this trend was not observed at high-lateral axle loads because the initial ballast consolidation was no longer relevant to the growth of cumulative residual deformation due to disturbance of the tie-ballast interface by repeated axle loads.

6.7 SUMMARY

The following summarizes the results from the track panel shift tests:

- Under repeated lateral loads, the track experiences cumulative lateral residual deformation (or panel shift) resulting in a misalignment. The growth of panel shift is significantly dependent on the magnitudes of lateral and vertical axle loads. There is a lateral load level at which the panel shift increases rapidly. This critical lateral load is a function of vertical load and is greatly influenced by track conditions. An increase in the vertical axle load will lead to a lower track misalignment growth and a higher critical lateral load.

- Llimiting lateral axle loads for preventing excessive panel shift as predicted by the Prud'homme criterion are lower than TLV critical load test results obtained on TTC tracks.

- The panel shift phenomenon is not only a concern of misalignment, but also a concern for safety. Sudden track panel shifting with up to 6-inch lateral movements were observed at several occasions with axle L/V ratios close to one during controlled in-motion TLV tests. Sudden and excessive lateral shift happened during tests in various weather including snowy conditions.

- In the tangent, the effort of rail longitudinal forces was higher when higher lateal axle laod was applied to the track. At the critical lateral load, with each pass of TLV axle loads, the incremental residual deformation will become constant, while the incremental total deformation will start to increase.

- A track with concrete ties had higher lateral track stiffness (i.e., lower incremental total deformation) and exhibited higher critical lateral axle load (15 to 30 percent) than a track with wood ties.

- At high-lateral axle loads (15 kip lateral and 20 kip vertical), track panels experienced much higher panel shift when the rail was in compression than in tension. On the other hand, when the lateral axle load was low (5 kip lateral to 20 kip vertical), this effect was not found.

- In-motion panel shift tests with repeated passes of high lateral load may significantly disturb the existing ballast consolidation;thus, this method may not give a good indication of ballast consolidation level versus track strength.

- For the same track, the static lateral track strength corresponding to a deflection level of 0.05 inch or higher, determined from a stationary test, is higher than the critical lateral load defined during repeated passes of lateral axle load.

- The controlled TLV tests showed that, for a given loading situation, a track panel will respond differently depending on whether the forces are stationary or moving. For example, a track panel will deflect more during in-motion TLV tests than during stationary tests at the same vertical and lateral loads.

- The effects of load and track variables on lateral track strength and stiffness found from stationary track panel shift tests were generally consistent with their effects on the critical lateral load and cumulative residual deformation found from in-motion track panel shift tests.

7.0 IN-MOTION LATERAL TRACK STRENGTH TESTS

Track geometry cars can continuously measure track space curves of both rails under light axle loads. However, such geometry measurements neither tell us actual track strength, nor predict track performance under realistic (much heavier) axle loads. Development and applications of in-motion track gage strength measurement techniques have improved significantly upon geometry measurements.[16, 17] These new techniques can measure track gage strength under actual load environments and can continuously detect soft spots at the rail/tie interface.

TLV stationary track panel shift tests measure static lateral track strength and stiffness. These parameters influence track misalignment growth and sudden track panel shift under traffic, as well as potential track buckling due to rail thermal force. However, the nature of such stationary testing prevents continuous measurements of lateral track strength. Such stationary tests are inevitably too slow to be practical as a production track strength inspection method. Rather the purpose of such TLV stationary testing is to provide a rational method for studying the effects of load and track variables.

The objective of in-motion track strength tests under this project is to study the feasibility of such a technique for the first time. This implies the ultimate goal of an inspection tool for continuously measuring lateral track strength and detecting soft spots at the tie/ballast interface.

Two TLV test techniques have been used to examine the feasibility of continuous measurement of lateral track strength. These two techniques were described in Section 3.0. The primary test technique is referred to as stiffness profile (or deflection profile) testing. The other technique is called curvature coefficient "a" testing. Both types of tests use the TLV to apply constant vertical and lateral loads to the track in motion. The rail contacting mechanism uses LVDTs for deflection measurements. Results of these tests obtained on TTC tracks are discussed below.

7.1 TEST TRACKS

A majority of the in-motion lateral track strength tests were conducted at FAST. Exhibit 95 shows the three sections (33, 36, and 40) where tests were conducted. All three sections are tangent tracks and have continuous welded rails. Section 33 was divided into two test zones. In addition, during the demonstration test phase, similar trials were conducted at the north tangent of the PTT track. Track details were given in Exhibits 30 and 40 of Sections 4.0 and 5.0.

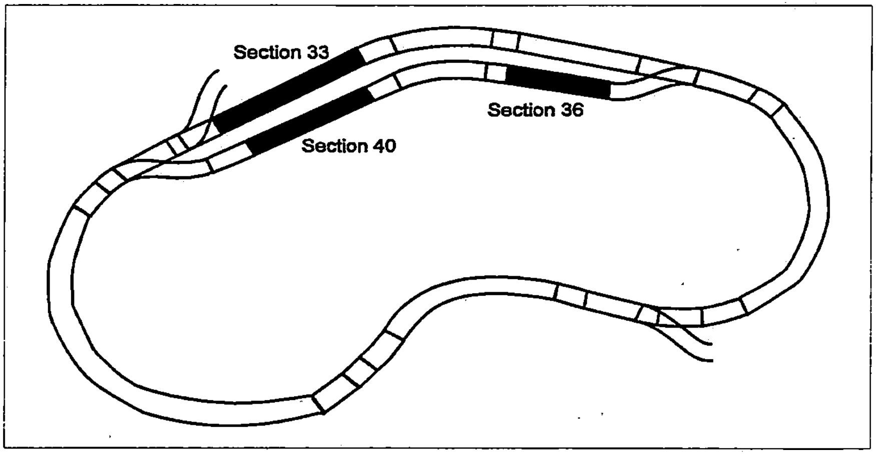


Exhibit 95. Test Sections at FAST on the HTL For In-motion Lateral Track Strength Tests

In various test locations, efforts were made to create "soft" zones in order to establish variable strengths along a track. Track maintenance machines were used to reduce the tie-ballast lateral resistance. The HTL was disturbed using a ballast tamping machine. A speed swing was used to disturb the tie/ballast interface while at the PTT. Ties were unfastened from the rails and pulled laterally several inches. These ties were then pushed back and anchored to the rails again.

However, the losses in track strength at the artificially created "soft" zones were not always as desired. This will be shown later by test results. In other words, the track surrounding the soft zones was already relatively weak due to previous panel shift tests. Therefore discrimination of the soft zone was not possible in every trial.

7.2 WAYSIDE INSTRUMENTATION

The objective of an in-motion lateral track strength test is to avoid use of wayside measurements. However, wayside deflections were included during in-motion stiffness profile tests to verify onboard measurements.

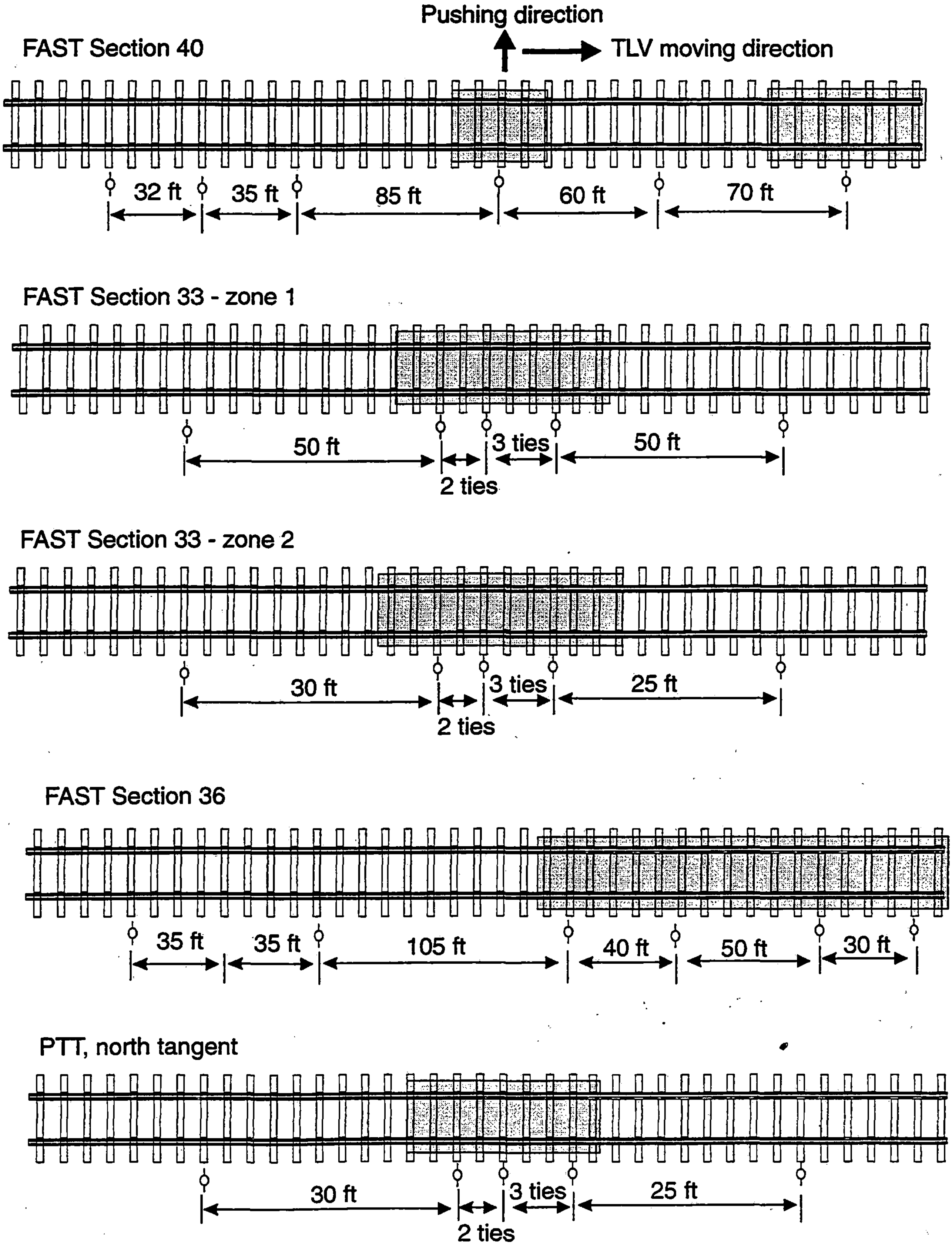
The LVDT wayside deflection transducers were also used in stationary and in-motion (repeated passing) track panel shift tests. Exhibit 96 shows wayside transducer locations for the five stiffness profile test zones. The wayside system recorded tie lateral deflections at selected locations as the TLV passed.

Automated location detector (ALD) reflectors were placed at each wayside transducer. The ALD signals allow synchronization of the wayside and onboard deflection measurements. The ALD signals were also used to transform time-based measurements to distance-based data. This step was needed to subtract the initial misalignment (obtained under the zero lateral load) from the measurement under the second run (with a test lateral load).

7.3 TEST LOADS

Exhibit 97 gives the test loads used for stiffness profile tests. As discussed above, a stiffness profile test requires two TLV runs. During the first run, a lateral axle load of 0 to 2,000 pounds was used to record initial track misalignment. For the second run, various constant lateral axle loads were applied from 5 to 25 kips. Only two vertical axle loads were used: 14,000 and 20,000 pounds. Throughout the test zones, both vertical and lateral axle loads were maintained constant for each TLV run. The TLV traveling speed was 2 to 3 mph.

Optimal TLV panel shift is achieved with 14 to 20 kips as the vertical axle load. This also provides a necessary minimum load level to eliminate any vertical track slack.



FAST Section 40

FAST Section 33 - zone 1

FAST Section 33 - zone 2

FAST Section 36

PTT, north tangent

Exhibit 96. Wayside Deflection Transducers for In-Motion Lateral Track Strength Tests (Newly Tamped Ballasts in Shaded Areas)

Exhibit 97. Test Loads for Stiffness Profile Tests

Test Section	Vertical axle load (lb)	Lateral axle load (lb)
HTL Sec. 40	20,000	20,000
HTL Sec. 33 - zone 1	20,000	5,000, 10,000, 15,000, 18,000, 20,000
HTL Sec. 33 - zone 2	20,000 14,000	15,000, 18,000, 20,000 10,000, 15,000, 18,000
HTL Sec. 36	20,000	15,000, 18,000, 20,000
PTT, north tangent	20,000	5,000, 10,000, 15,000, 20,000, 25,000

7.4 STIFFNESS PROFILE TEST RESULTS AND ANALYSIS

In this section, in-motion stiffness profile results and analyses are presented for tests conducted at FAST Sections 33, 36 and 40, as well as at the north tangent of the PTT.

7.4.1 FAST Section 40

These results are presented first to show the feasibility of measuring variable lateral track strength along the track, via stiffness profile tests.

In FAST Section 40, one stiffness profile test was conducted. The misalignment record was made with zero lateral axle load and the test run was made with a lateral axle load of 20,000 pounds. In both runs, the vertical axle loads were 20,000 pounds. Exhibit 98 shows the deflection profile obtained.

A close examination of the deflection profile shows deflections less than 0.1 inch until 220 feet. Then it shows lower lateral track strength (i.e., larger deflections) beyond 270 feet. In fact, the track at 460 feet was so weak that it suddenly shifted with an amplitude of 6 to 7 inches during testing. Exhibit 99 shows the view of the distorted track structure due to this sudden shift.

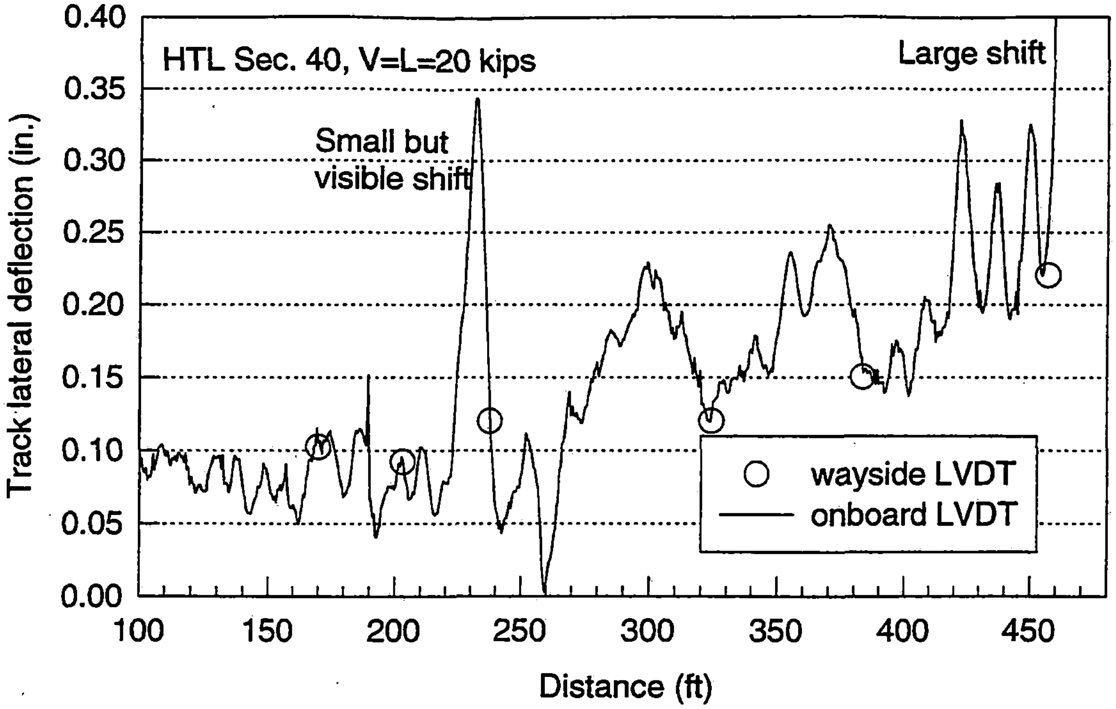


Exhibit 98. Stiffness Profile Test in Section 40

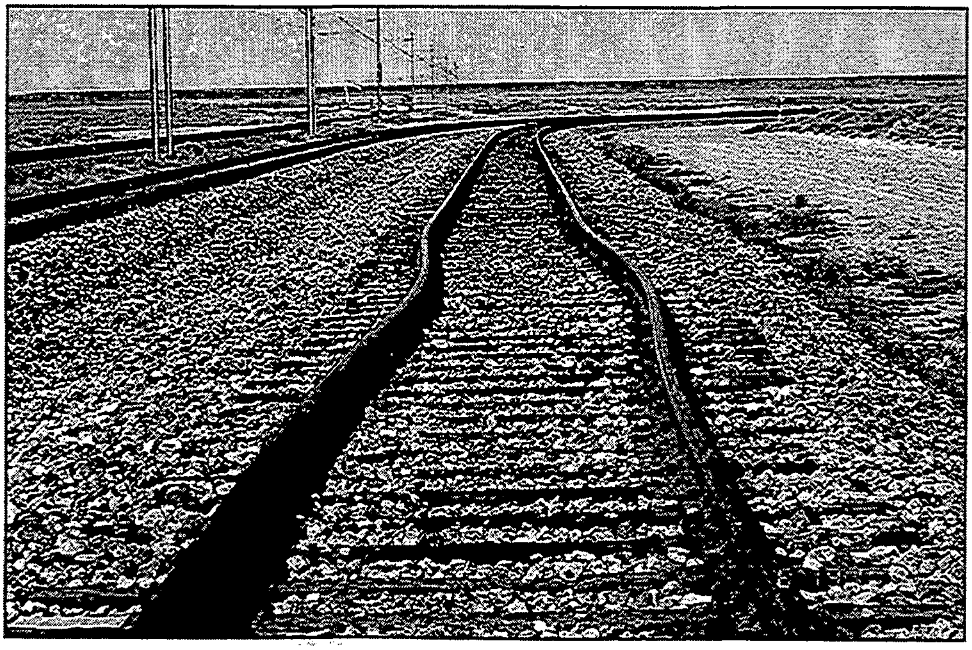


Exhibit 99. Large Shift during Stiffness Profile Test (HTL Sec. 40)

From 220 to 240 feet, the deflection profile exhibits a 0.34-inch peak. Visual observation after tests showed that a small but visible track shift was left in this region. This small but visible shift is believed to be a result of weaker ballast resistance. The stiffness profile test was able to reveal this soft zone.

The strength trend established using the stiffness profile test was consistent with results of four STPT tests conducted along the test zone and with six wayside tie deflections. STPT results are given in Exhibit 100, and wayside deflection measurements are plotted as circles in Exhibit 98. Both STPT and wayside deflection measurements indicated weaker track from 270 to 470 feet.

Exhibit 100: STPT Test Results

Distance	210 ft	320 ft	380 ft	450 ft
STPT peak resistance	2700 lb	2000 lb	1500 lb	1400 lb

Because the wayside deflection measurement system is directly referenced to ground, it gives more reliable deflection results than the onboard system. As will be discussed later (Section 7.4.2), the wayside LVDTs did not measure exactly the same track lateral deflection as the onboard LVDTs. However, as shown in Exhibit 98, six comparisons between wayside and onboard measurements were relatively consistent.

7.4.2 FAST Section 33

Section 33 was divided into two test zones. Stiffness profile tests with several lateral axle loads were conducted in each of these two test zones. The tie-ballast interface in each zone was disturbed for a length of approximately 35 feet using a tamping machine. Generally, the track in Section 33 was considered stronger than the track in Sections 40 and 36 because Section 33 was less disturbed by previous TLV tests.

Furthermore, within Section 33, more TLV tests were previously conducted in test zone 2 than in zone 1. Thus a greater disturbance of the tie/ballast interface was left by previous pushes in test zone 2 than zone 1.

Deflection profiles: Exhibit 101 shows deflection profiles obtained with various lateral axle loads (5 to 20 kips) for test zone 1. The vertical axle load was 20 kips. Track deflection increased as a function of the applied lateral axle load. As illustrated, the track between 62 feet to 97 feet was tamped (skin lift) prior to the tests. This tamped segment was assumed to have lower strength. However runs under lateral axle loads of 5 kips and 10 kips did not indicate larger deflections for this tamped zone. When the lateral axle load was increased to 15 kips, the deflection profile reflected larger deflections for the tamped zone. The larger deflection magnitudes were more obvious as the lateral axle load was increased to 18 kips and then 20 kips.

As shown by the deflection profiles, at the lateral axle load of 20 kips, the difference in lateral track strength between the tamped zone and non-tamped zone was about 30 percent. The wayside deflections at the same 20 kip lateral axle load show an average of 50 percent difference between the tamped and non-tamped zones.

A comparison of the Section 33 and Section 40 deflection profiles under 20 kips lateral axle load (Exhibits 98 and 101) shows that the track in Section 33 should be considered stronger than the track in Section 40. Note that the deflection magnitudes are smaller for Section 33 (less than 0.1 inch) than for Section 40 (most of them larger than 0.1 inches). The stiffness profile test results support the "previous-use" track condition hypothesis for the two sections, as discussed previously.

Exhibits 102 and 103 show the test results for zone 2 with various lateral loads and under two different vertical axle loads. Within test zone 2, the track from 110 to 150 feet was tamped (skin lift). However, both stiffness profile results and wayside tie deflection measurements indicate that this tamped zone was not the weakest segment. Note that deflections measured over the tamped zone were not the largest.

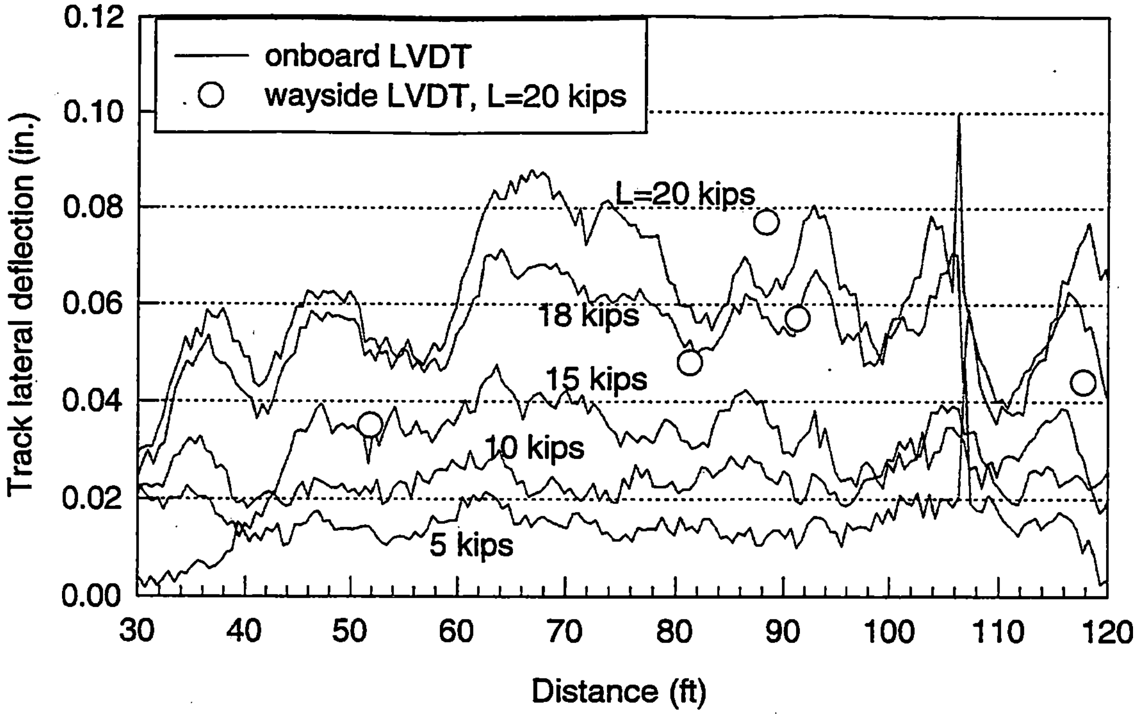


Exhibit 101. Stiffness Profile Tests (HTL Sec. 33, Test Zone 1, V=20 kips)

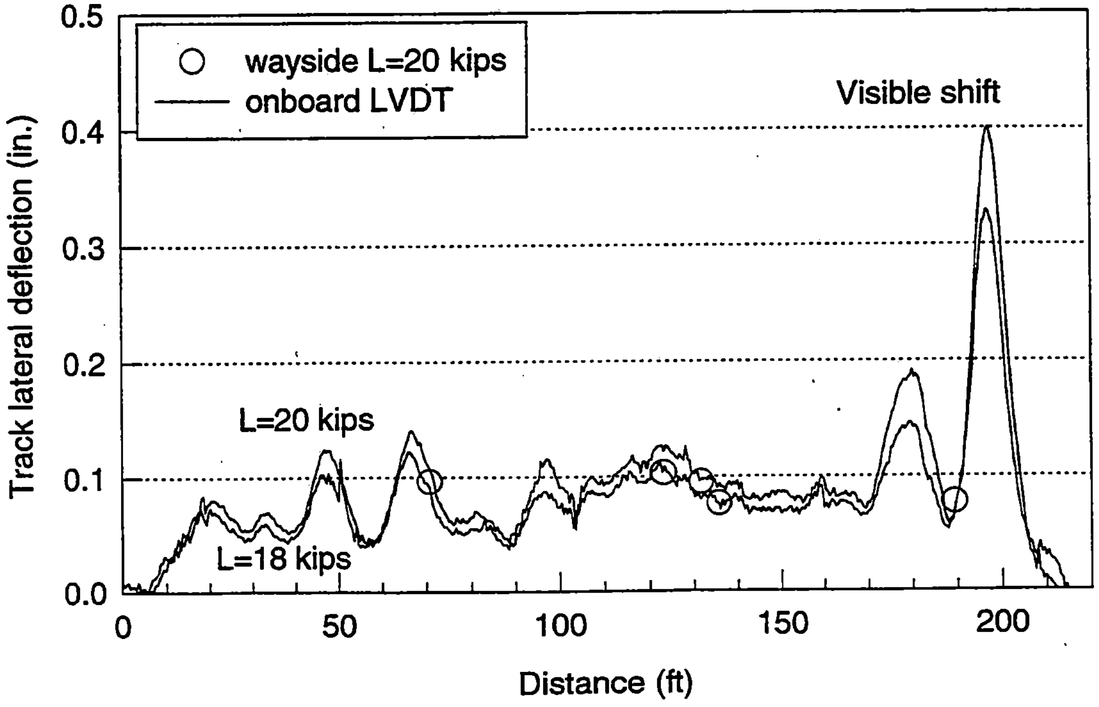


Exhibit 102. Stiffness Profile Test (HTL Sec. 33, Test Zone 2, V=20 kips)

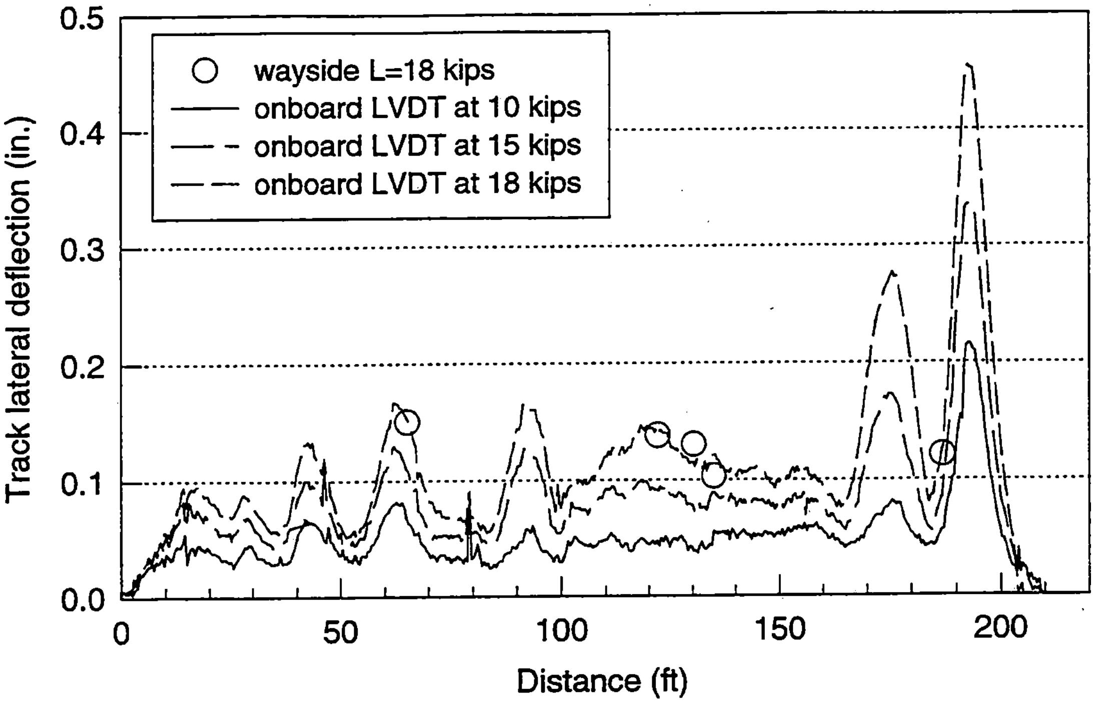


Exhibit 103. Stiffness Profile Test (HTL Sec. 33, Test Zone 2, V=14 kips)

Rather, Exhibits 102 and 103 show that the weakest location occurred between 170 and 206 feet since here the track exhibited large peak deflections. Subsequent observations of the track revealed a small but visible panel shift in this region.

Exhibit 103 shows a comparison of the deflection profiles as produced under different lateral loads. These profiles show that the lateral track deflection increases as a function of applied lateral load, and the responses of weaker locations are more easily identifiable at higher lateral loads. The optimum applied lateral load needed to identify this weakness appears to be 15 kips under a 14 kips vertical axle load.

A comparison of test results between Exhibits 102 and 103 shows consistent profiles of lateral track strength among all five runs with two different vertical axle loads of 14 kips and 20 kips, respectively. For a given lateral axle load of 18 kips, the magnitude of deflections were larger under a vertical axle load of 18 kips than under a vertical axle load of 20 kips.

Five wayside deflection transducers were used to measure track lateral deflections. The data is plotted as circles in Exhibits 102 and 103 as well. As illustrated, comparisons are consistent between onboard and wayside measurements.

Initial track misalignment: As stated, the current stiffness trials require two TLV runs. The first run is made without much lateral axle load in order to obtain the initial track misalignment. The results from the second TLV run include both the initial misalignment and the deflection due to lateral axle loading. To obtain deflection profiles, as illustrated in Exhibits 98 and 101, 102 and 103, a subtraction of the initial misalignment (determined under the first TLV run) from the second test run is required.

Exhibit 104 shows results covering 90 feet obtained from the first and second TLV runs for two stiffness profiles using two different lateral axle loads (5 kips and 20 kips, respectively). The profiles shown by the dash lines give the initial track alignment determined under zero lateral load. As illustrated, this test zone showed a track misalignment with a maximum peak to peak offset of approximately 0.5 inches. Note that this is obtained using a 66 feet chord, which is controlled by the TLV length. The profiles shown by the solid lines were obtained during the second TLV test runs. The shift of the second profile from the first profile indicates track lateral deflection. In other words, the difference between the second run and the first run gives lateral track deflection due only to the panel shift load. As shown by the comparison between Exhibit 104(a) and Exhibit 104(b), the track lateral deflection was obviously larger at the 20 kip lateral axle load than at the lateral axle load of 5 kips. Since the initial track misalignment is an order of magnitude greater than the change in profile due to panel shift, it is difficult to show variable lateral track strength along the track without subtracting initial misalignment results.

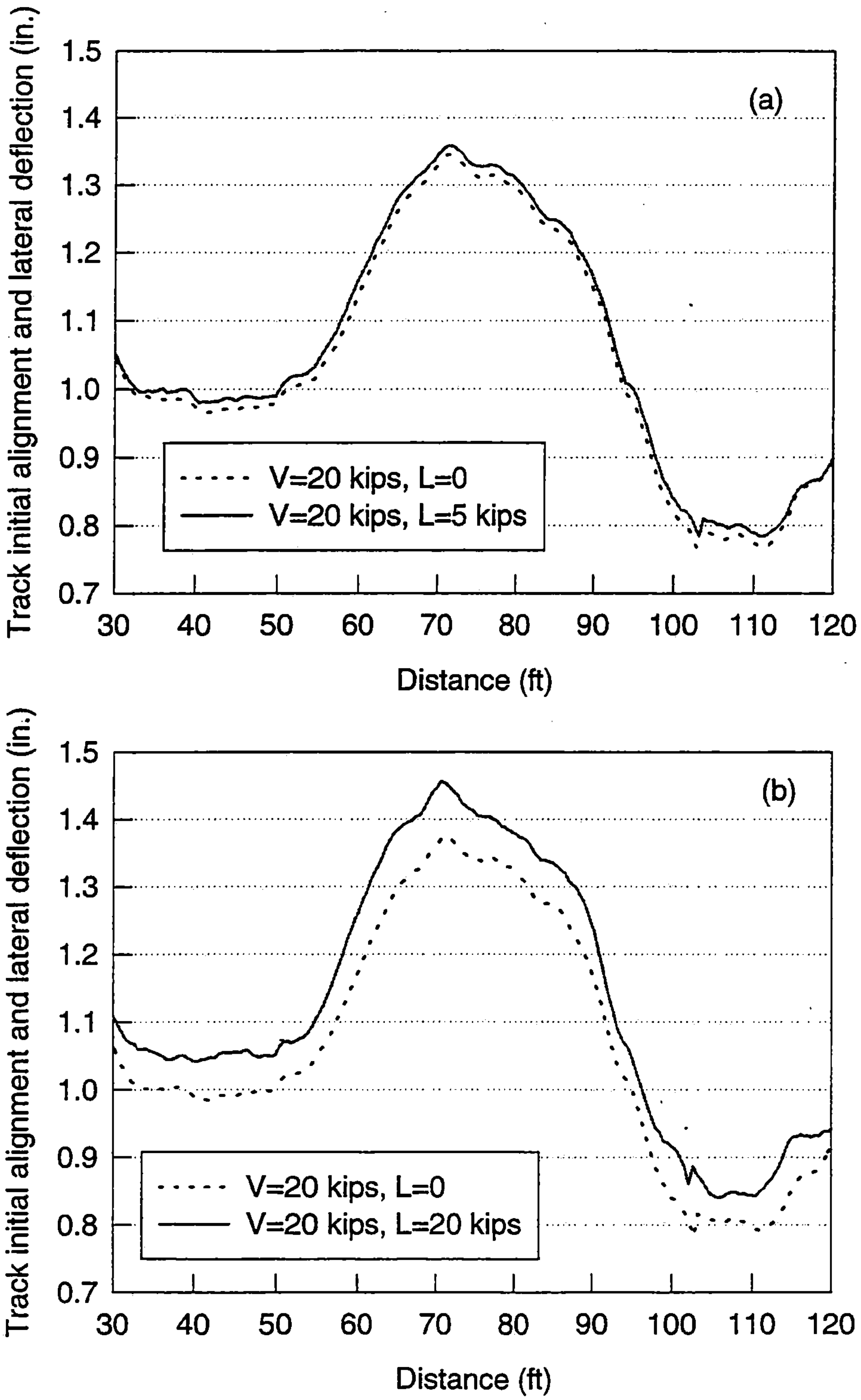


Exhibit 104. Sum of Track Initial Misalignment and Lateral Deflection (HTL Sec. 33, Test Zone 1)

Wayside deflection measurements: Exhibit 105 shows recordings of lateral tie deflections measured by the wayside transducers. Lateral tie deflections at five locations are plotted versus time for test zone 2 under a lateral axle load of 20 kips. The peak values represent the maximum tie deflections as the moving load bogie passed. These peak values have been compared with the non-flanged rail lateral deflections measured by the onboard transducers. The minor deviations within these time histories reflect the passing of other wheel sets in the consist.

Tie deflection results by the wayside transducers were also used to sample lateral track strength at several locations along the track. Under a given panel shift load, track that shifts less will possess higher lateral strength. For example, the results presented in Exhibit 105 indicate that the track at the locations G1 and G2 was weaker than the track at G4 and G5.

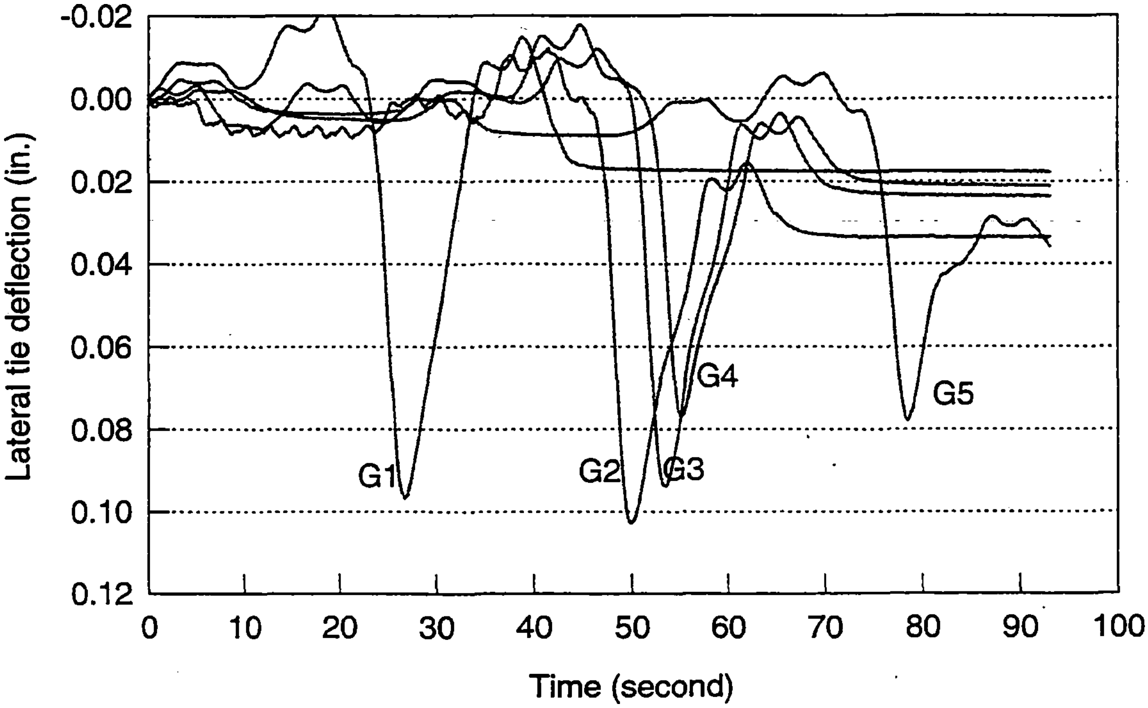
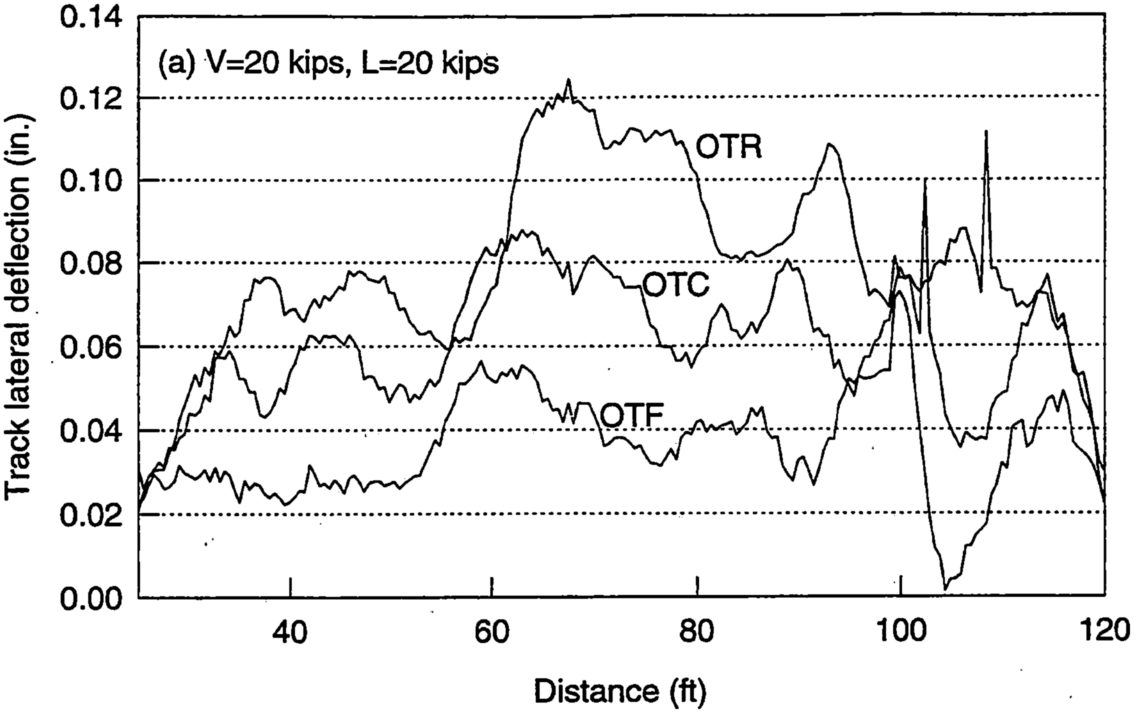


Exhibit 105. Example of Wayside Deflection Recordings
(HTL Sec. 33, Test Zone 2, V=20 kips, L= 20 kips)

Onboard deflection measurements: As described previously (Section 3.0), three onboard transducers (OTR, OTC, OTF) were installed at the load bogie for obtaining lateral deflection profiles of the non-flanged rail. Their locations relative to the load axle are shown in Exhibit 12. Because of space constraints, the central transducer was not installed exactly at the loading axle but at a distance of 34 inches ahead of the axle. Exhibit 106 gives examples of deflection profiles obtained from these three on-board transducers under two different lateral axle loads. As illustrated, all three on-board transducers give consistent deflection trends. However, these lateral deflections differ in magnitude. The front transducer consistently measures the smallest deflection while the rear transducer measures the largest.

This phenomenon is explained in Exhibit 107. Because a track is not a completely elastic structure, the lateral track deflection δ0 caused by the previous loading (t=0) does not disappear completely when the load bogie moves to location 1 (t=t1). Thus, the new deflection generated by the current loading (t=t1) will superimpose on the residual deflection left by the previous loading. Further, an unsymmetrical deflection wave shape will form under moving loads, and the maximum total track deflection relative to the original track may not occur at the point of the loading axle. Instead, the maximum deflection may occur at a point following the loading axle. Consequently, the front transducer measures the smallest lateral track deflection while the rear transducer measures the largest lateral track deflection. The difference in measurements between these three transducers will be larger at higher lateral axle load, due to increased residual deformation left by the higher load. This can be seen by comparing the results shown in Exhibit 106(a) and Exhibit 106(b). As illustrated, as the lateral axle load was increased from 18 to 20 kips, the difference in deflection magnitude between these three transducers increased as well.



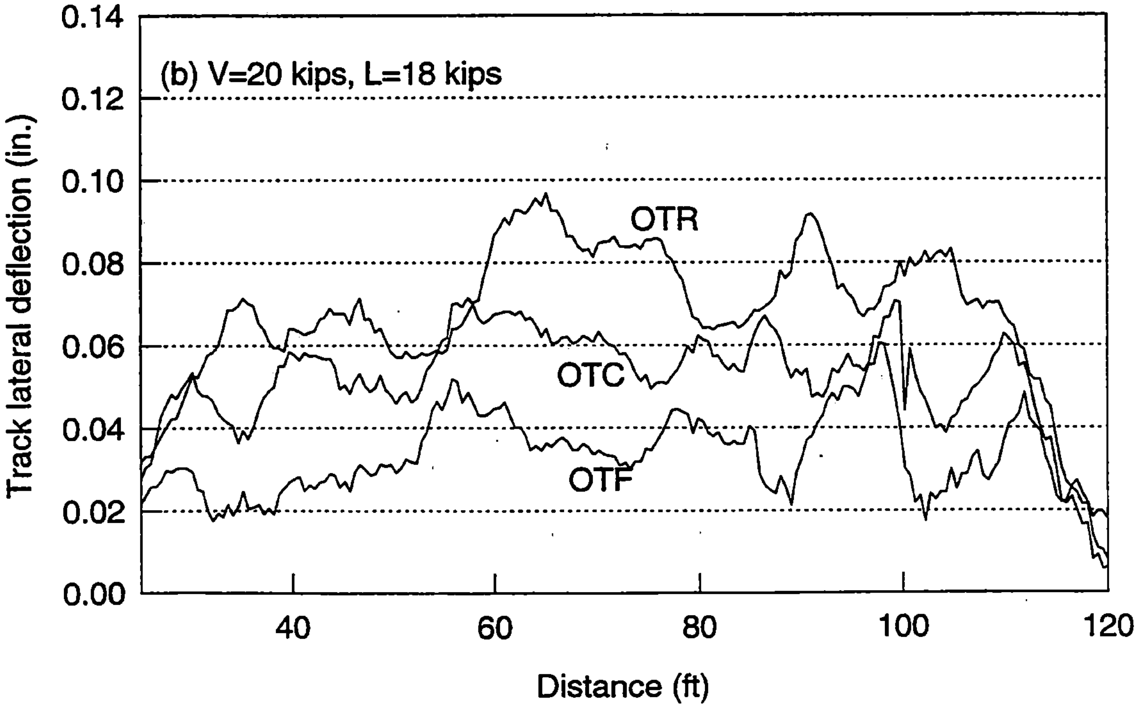


Exhibit 106. Comparisons of Three On-board Transducers (HTL Sec. 33, Test Zone 1)
OTR=Rear, OTC=Center, OTF=Front

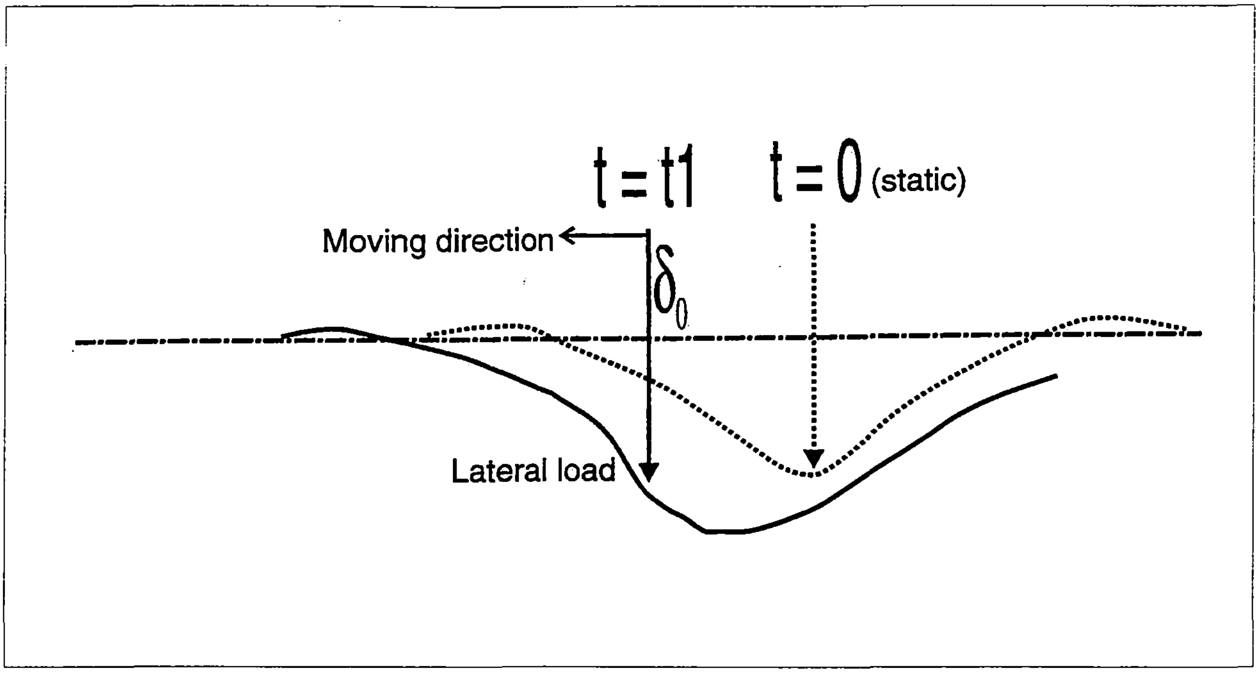


Exhibit 107. Deflection Wave Showing the Maximum Deflection Behind Loading Point

In Exhibits 98 and 101, 102, and 103, all deflection profiles shown were obtained by the central transducer (OTC). The deflections obtained from the wayside transducers at discrete locations were also plotted in these exhibits for comparison with onboard deflection profiles. The maximum tie deflections measured by the wayside deflection transducers coincided with the loading axle passes (i.e., they show deflections when the loading axle exactly passed the wayside transducer locations). On the other hand, the profiles obtained by the central transducer were the deflections 34 inches in front of the loading axle. As a result of these two factors — not measuring deflections at the same point between the onboard system and wayside system, and having different deflection values over the distance for the three onboard transducers — wayside deflections will not match onboard results. Nevertheless, comparisons from these results allow assessment of the deflection results obtained with the onboard system based on the deflection results obtained with the wayside system.

As already shown in Exhibits 98 and 101, 102 and 103, comparisons between onboard deflection profiles and wayside results indicate better agreement in some cases and some inconsistency in other cases.

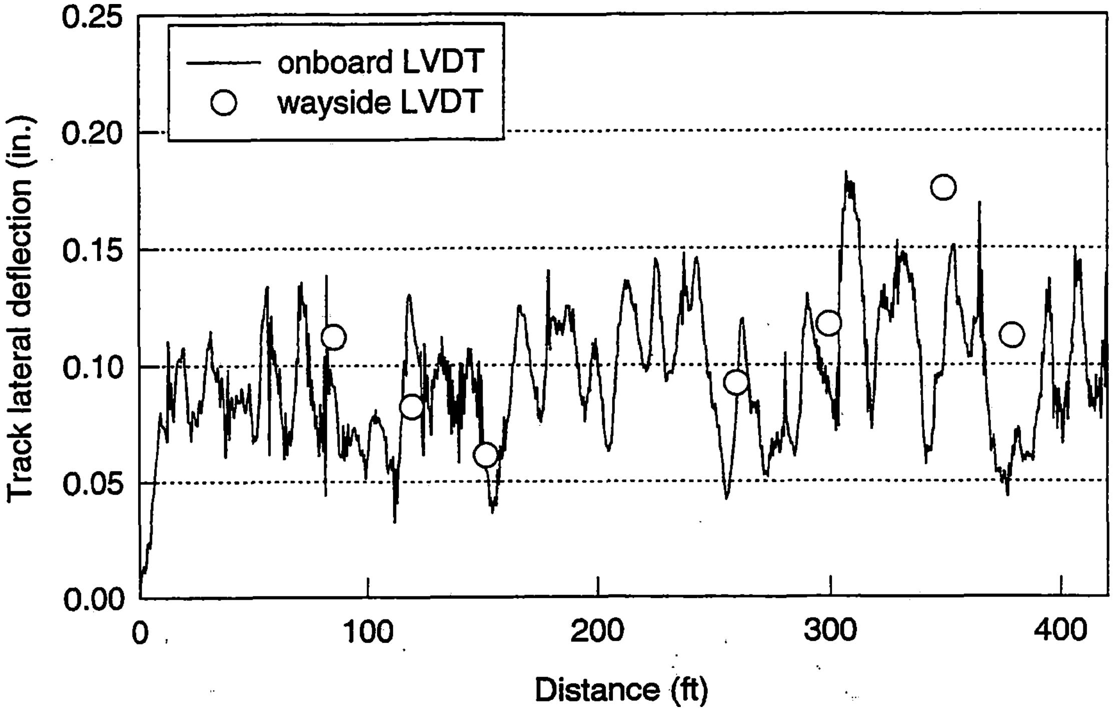


Exhibit 108. Stiffness Profile Test (HTL Sec. 36, V=20 kips, L=20 kips)

7.4.3 FAST Section 36

Stiffness profile tests were also conducted in Section 36. Exhibit 108 shows the onboard deflection profile and the tie lateral deflections from the wayside measurement system. A segment from 230 to 420 feet was tamped prior to the trial. Both the deflection profile and the tie deflection results showed larger deflection peaks (softer track) in the tamped zone. However, the difference in track strength between the tamped and non-tamped zones was not as large as expected. In retrospect, this was because the non-tamped zone was subjected to many previous TLV pushes, thus it was as nearly soft as the tamped zone.

7.4.4 Precision Test Track

Exhibits 109 and 110 show stiffness profile test results obtained on the PTT track during the demonstration test phase. The tests were performed at the north tangent. Eleven ties (a zone approximately 17 feet long) were disturbed using a speed swing. Again, the track for this test zone was not uniform due to many previous stationary demonstration pushes.

Exhibit 109 shows deflection profiles for two lateral axle loads (15 and 20 kips respectively) under a vertical axle load of 20 kips. For a third test under a 25-kip lateral load, the bogie wheel climbed shortly after start. Thus, only two deflection profiles were completed with lateral axle load of 15 kips and 20 kips. At lateral axle load of 15 kips, the deflection profile showed slightly higher magnitudes over the artificially created soft zone. When the lateral axle load was increased to 20 kips, the deflection profile showed even larger magnitudes over the soft zone.

To reduce the propensity for flange climbing, a negative angle of attack (0.01 radian) was set for the loading axle relative to the rails. Exhibit 110 shows the results of deflection profiles for three axle loads of 15, 20, 25 kips with this negative angle of attack. As can be seen, at 25 kips of lateral axle load, the wheel did not climb until past the soft zone where the track deflected more than 0.6 inch. Again, the deflection profile at a lateral axle load of 15 kips showed slightly higher magnitudes over the soft zone. At the two lateral axle loads of 20 and 25 kips, the magnitudes of deflection were much higher over the soft zone. The negative angle of attack was used in all fundamental phase tests.

Some measurements of maximum tie deflections obtained using the wayside deflection transducers are also plotted in these two exhibits for comparisons with deflection profiles. Again, comparisons are more consistent in some cases than in some other cases.

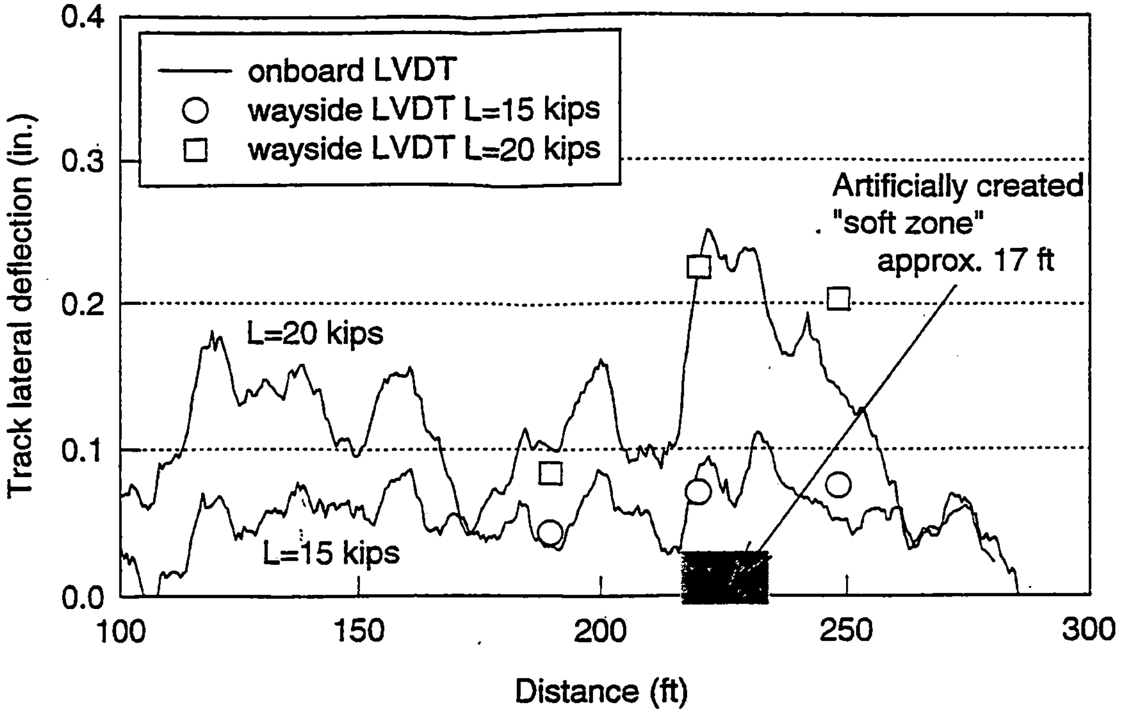


Exhibit 109. Stiffness Profile Tests, PTT, V=20 kips

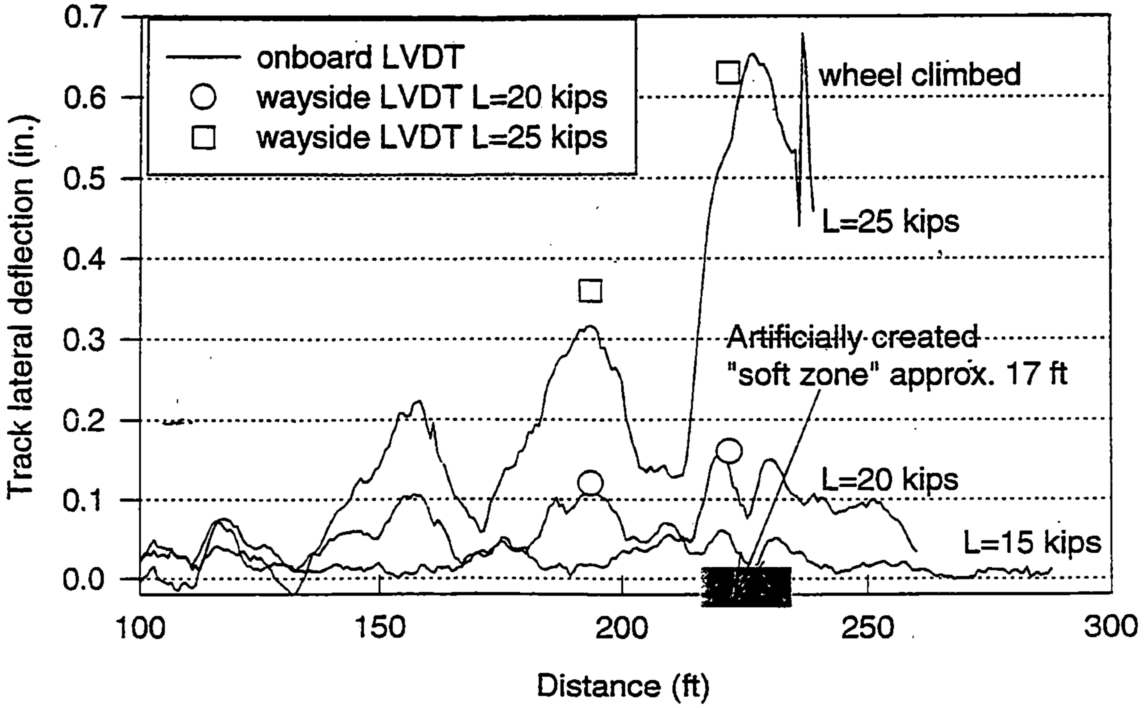


Exhibit 110. Stiffness Profile Tests, PTT, V=20 kips

7.5 CURVATURE COEFFICIENT "A" RESULTS

In Section 3.0, the method of using curvature coefficient "a" was described for detecting variable track strength along the track. Results from several stiffness profile tests are used to calculate the curvature coefficient "a" to examine this method.

Exhibit 111 shows results for test zone 2 of Section 33 of the HTL. The corresponding stiffness profile test results were shown in Exhibit 103. Note that the "a" parameter will change sign twice for a single lateral track movement. This is because it will show a concave (-) sign going into a kink, and a convex (+) sign at the kink, and finally a concave sign (-) again while leaving the kink.

As track lateral shift becomes more pronounced at higher lateral axle load, the standard deviation of the "a" parameter will increase due to this sign reversal. In Exhibit 111 this can be seen by the more extreme values taken on during larger lateral force runs. As shown, the deviation of the "a" parameter becomes larger at the soft zone from 170 ft to 206 feet. This is consistent with the stiffness profile test results shown in Exhibit 103.

Section 3.0 stated that this method has an advantage over a mid-chord offset technique in that it does not require that the end transducers be a constant distance from the rail head. Again, they can move relative to the rail without affecting "a." The only requirement is that the three transducers within any set be unchanging relative to each other (i.e. on a rigid frame). Also, this allows the "before" array and the "after" array to be completely independent of each other (on two rigid frames, not all attached to one frame). This method also has an advantage over the stiffness profile method, because the curvature parameter does not require that the entire car body be rigid. Only that a shorter lighter reference frame be rigid.

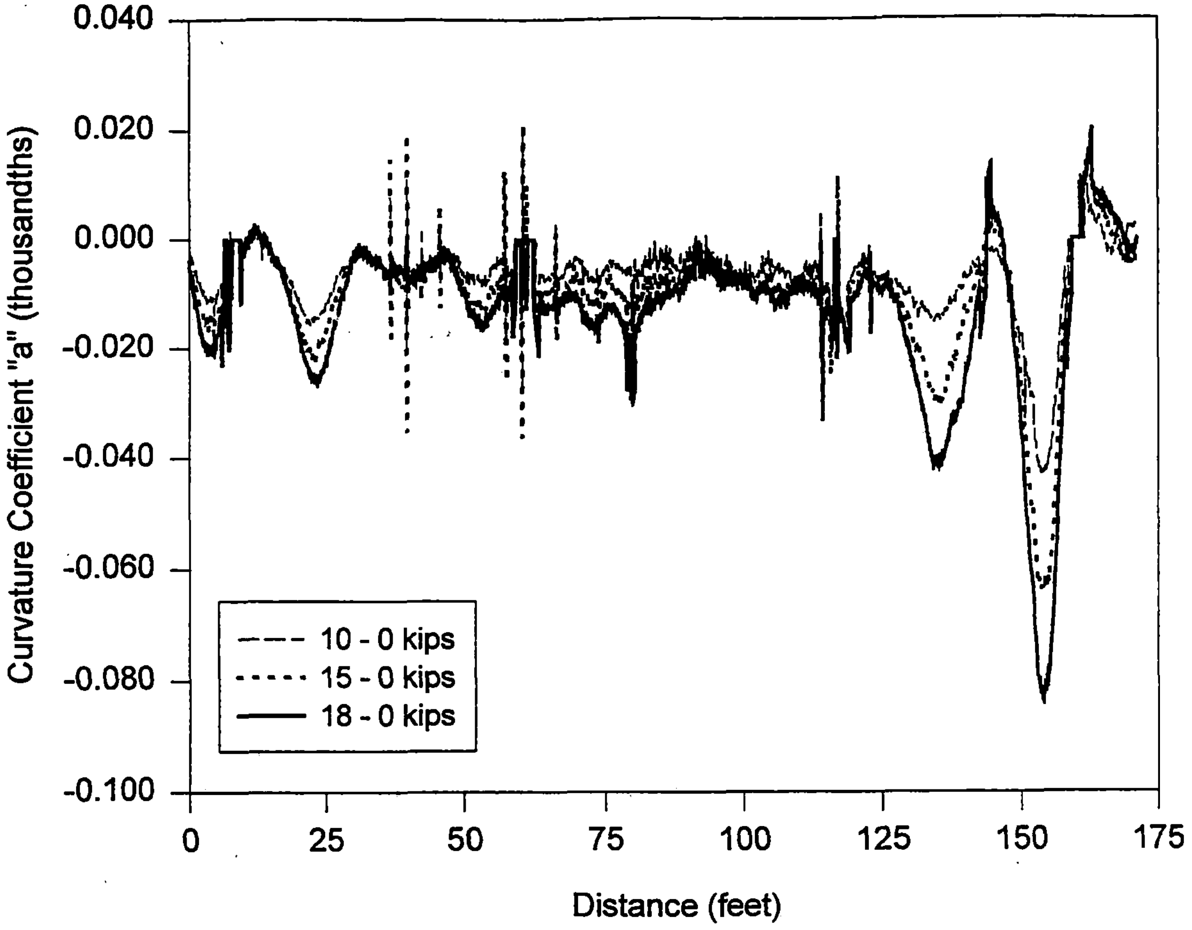


Exhibit 111. Curvature Coefficient "a" as Computed From Several Passes at Different Lateral Load Levels (HTL Sec. 40, V=14 kips)

7.6 SUMMARY

The stiffness profile testing technique was shown to be capable of measuring the lateral track strength variation at the tie/ballast interface. The weaker (softer) spots at the test tracks exhibited generally larger deflections under constant vertical and lateral track panel shift loads. Lateral track deflections consistently increased as a function of applied lateral axle load. Based upon tests conducted on the HTL and PTT, the optimum lateral axle load with a vertical axle load of 14 to 20 kips appeared to be between 15 to 20 kips for detecting variation of lateral track strength. Higher lateral axle loads yield more distinctive profiles corresponding to variable lateral track strength, but may result in a sudden track shift for soft or weak track. Also wheel climbing may occur at lateral axle loads above 20 kips.

The variation of lateral track strength shown by the stiffness profiles for tests conducted at FAST and on the PTT were relatively consistent with the trends shown by limited wayside deflection measurements and STPT results. The stiffness profile tests can show lateral track strength variation over a distance as small as several feet.

Due to the fact that ballast materials are not completely elastic, the track lateral deflection caused by a moving load is superimposed on the residual deflections caused by the panel shift loading applied at all previous locations. Thus, near the load bogie, the deflections measured by the rear onboard transducer were higher than the deflections measured by the front onboard transducer.

The results to date have been generated using LVDTs in contact with the non-flanged rail. They are not practical for commercial use because they mount to the Unistrut frame at the side of the TLV. The frame does not fit in the standard car clearance envelope and would be damaged by typical switch stands and other obstacles. And because the car body cuts a mid-chord path through a rail curve, the contacting sensors are easily pushed beyond their operating range on curved track.

Tests conducted on TTC tracks have proved the feasibility of using the TLV to profile lateral track strength and to detect weak spots in-motion. However, significant improvements are required in order to apply this technique for production track strength inspection. The limitations with the current system include difficulties in conducting tests through curves and through track discontinuities such as joint bars, turnouts, crossing, etc. Although the onboard contact transducers have recorded consistent measurements among themselves and with the wayside system — this has been done in a very specific and limited environment — it is not a general solution.

The recommended improvement lies primarily on the development of a non-contact onboard deflection measurement system. Non-contacting sensors must replace the contacting LVDTs. Laser/camera systems have been used on the TLV to measure gage-widening behavior in the past. An array of such transducers might be a better solution. With an onboard system which can directly measure track lateral deflection due to panel shift loading, a stiffness profile testing requiring only one TLV run will make this technique practical for production use.

8.0 CONCLUSIONS

In Sections 4.0 to 7.0, summary and conclusions were drawn based on test results and analyses discussed. The following is based on the summaries and conclusions given in those sections:

Demonstration tests:

- All three types of TLV track panel shift tests described in Section 3.0 are practical and for full use. Track panel shift load determination based on the force equilibrium of the load bogie is accurate to within 2 percent.

- The lateral axle reactions under the trailing truck due to panel shift loads applied by the center load bogie will not influence in-motion track panel shift test results significantly.

- The influence length of track panel shift loads is approximately 15 feet each direction. Therefore 30 feet of track are needed for each stationary test. The track panel under the TLV ends will not move laterally in reaction to applied panel shift loads.

- The lateral panel shift load is reacted primarily on the flanged rail. The flanged rail moves considerably relative to the ties under panel shift loads, due to its roll, bending, and translation. Cut spikes may pull up as a result of the flanged rail movements. On the other hand, the non-flanged rail experiences little lateral deflection with respect to the ties, under applied panel shift loads.

- For a stationary test, depending upon track conditions and vertical axle load, the required lateral track deflection should be between 0.2 and 0.5 inches to adequately determine lateral track strength and stiffness. Beyond this deflection, sometimes large subsequent panel shift may occur suddenly.

- An increase in lateral loading rate increases the measured lateral track strength and stiffness. However, for the range of 0.05 to 1 kips per second considered, the rate of applying lateral axle load under a stationary test can be considered to influence test results insignificantly.

- A track panel push will not reduce the available track strength and stiffness significantly if the lateral track deflection is small within the first stiffer region of load-deflection curve, e.g. 0.15 inch at a vertical axle load of 20 kips. However, if the track is pushed into the second region, the available track strength can be reduced to a significant extent.

Fundamental stationary tests:

- The TLV stationary tests can provide quantitative information on lateral track strength and stiffness to enhance development and implementation of optimum track maintenance. A maximum panel push of 0.3 inch will provide sufficient information to quantify available lateral track strength and stiffness.

- Vertical axle load has a large effect on the resistance of a track panel to lateral deflection. Lateral track strength and stiffness should be defined at a given vertical axle load. To generate given level of track deflection, the required L/V ratio will be lower if a higher vertical axle load is applied on the track.

- Lateral load-deflection relationships are non-linear. Lateral track strength and stiffness should be defined corresponding to given lateral track deflection levels. Once a track panel is pushed to a critical magnitude (e.g, 0.1 to 0.2 inch under a vertical axle load of 20 kips), the track will possess much smaller lateral stiffness.

- Ballast consolidation level presents a significant effect on lateral track strength and stiffness. Ballast tamping reduces tie-ballast resistance considerably, and the reduced resistance required up to 9 MGT of traffic to be fully restored to its original level. A ballast compactor restored ballast resistance moderately (approximately 10 percent of the lost strength) and improved the uniformity of track strength along the track.

- Ballast type has a less significant effect on lateral track strength and stiffness under consolidated conditions. Use of concrete ties presented moderate benefit in improving lateral track strength (5 to 20 percent), and in reducing variability of lateral track strength along the track.

- In the tangent track, for the range of rail longitudinal forces considered, a change from tension to compression in the rail only slightly reduced lateral track strength and stiffness (less than 10 percent).

- A 7.5-degree track curvature may reduce measured track strength at small lateral deflection (0.05 and 0.1 inch) significantly (20 to 40 percent). However, once the track panel is pushed more than 0.2 inch, the results showed little difference between a tangent track and the 7.5-degree track. For a track with a curvature of 5 degrees or less, the difference in measured track strength due to curvature was not significant (less than 10 percent).

- Effects of some variables, such as ballast compaction, tie type and track curvature appear to be more significant on lateral track strength and stiffness defined at small lateral track deflections (0.1 inch and less).

- STPT tests only measure one factor of lateral track panel strength. However, similar trends were observed by TLV stationary tests and by STPT tests regarding the effects of ballast consolidation level, ballast type, and ballast shoulder width on lateral track resistance.

- A theoretical model, TPLRS, predicted similar influence trends of parameters such as STPT resistance and rail temperature change on stationary panel behaviors. However, the model does not represent the non-linear behavior at small tie deflections and overpredicts tie deflections.

<u>In-motion Track Panel Shift Tests:</u>

- Under repeated lateral loads, the track experiences cumulative lateral residual deformation or panel shift resulting in a misalignment. The actual rate of panel shift is significantly dependent on the magnitudes of lateral and vertical axle loads. There is a critical lateral load level above which the panel shift increases rapidly. This critical lateral load is a function of vertical load and is greatly influenced by track conditions. An increase in the vertical axle load will lead to a lower track misalignment growth and a higher critical lateral load. However, the limiting lateral axle loads for preventing excessive panel shift predicted by the Prud'homme criterion are lower than TLV critical load test results obtained on TTC tracks.

- The panel shift phenomenon is not only a concern of misalignment, but also a concern for safety. Sudden track panel shifting with up to 6-inch lateral movement was observed at several occasions at axle L/V ratios close to one during controlled in-motion TLV tests. Sudden and excessive lateral shift happened during various weather including snowy conditions.

- At the critical lateral axle load, with each pass of TLV axle loads the incremental residual deformation will become constant, while the incremental total deformation will start to increase.

- A track with concrete ties had higher lateral track stiffness (i.e., lower incremental total deformation) and exhibited higher critical lateral axle load (15 to 30 percent) than a track with wood ties.

- In the tangent, the effect of rail longitudinal forces was higher when higher lateral axle load was applied to the track. At high lateral axle loads (15 kip lateral and 20 kip vertical), track panels experienced much higher panel shift when the rail was in compression than in tension. On the other hand, when the lateral axle load was low (5 kip lateral to 20 kip vertical), this effect was not found.

- In-motion panel shift tests with repeated passes of high lateral load may significantly disturb the prior ballast consolidation (established by traffic); thus, this method may not give a good indication of ballast consolidation level on track strength.

- For the same track, the static lateral track strength corresponding to a deflection level of 0.05 inch or higher, determined from a stationary test, is higher than the critical lateral load defined during repeated passes of lateral axle load.

- The controlled TLV tests showed that, for a given loading situation, a track panel will respond differently depending on whether the forces are stationary or moving. For example, a track panel will deflect more during in-motion TLV tests than during stationary tests at the same vertical and lateral loads.

- The effects of load and track variables on lateral track strength and stiffness found from stationary track panel shift tests were generally consistent with their effects on the critical lateral load and cumulative residual deformation found from in-motion track panel shift tests.

<u>In-motion Lateral Track Strength Tests:</u>

- The stiffness profile testing technique was shown to be capable of measuring lateral track strength variation at the tie/ballast interface along the track. The weaker zones within the test tracks exhibited larger deflections under constant vertical and lateral track panel shift loads. For tests conducted on the TTC test tracks, repeatability of track strength measurements using the TLV has been satisfactory, and weak spots in tracks have been consistently identified.

- Lateral track deflection increased as a function of applied lateral axle load. Based upon tests conducted on the HTL and PTT, the optimum lateral axle load with a vertical axle load of 14 to 20 kips appeared to be between 15 to 20 kips for detecting variation of lateral track strength. Higher lateral axle load yields more distinctive profiles corresponding to variable lateral track strength, but may result in a sudden track shift for soft or weak track. Wheel climbing may occur at lateral axle load above 20 kips.

- The variation of lateral track strength shown by the stiffness profile testing for tests conducted on the HTL and PTT were consistent with the trends shown by limited wayside deflection measurement results and STPT test results. It appears that the stiffness profile tests can show lateral track strength variation over distances as small as several feet.

- Due to the fact that ballast materials are not completely elastic, the track lateral deflection caused by a moving panel shift loads becomes superimposed on the residual deflections caused by the panel shift loading applied at the previous locations. Thus, over the load bogie length, the deflections measured by the rear onboard transducer were higher than the deflections measured by the front and center onboard transducer.

Recommendations:

With regard to the three objectives of the project (page 1), more research will be performed during Phase 3 to fully accomplish the first and third objectives. The work for the second objective is complete, although more tests, under a separate task in cooperation with VNTSC, will be conducted to study the effect of rail thermal force.

Based on the results obtained from the first two test phases, the following studies are recommended for Phase 3:

- Tests conducted to study the effects of track variables such as tie type and track curvature were limited. More tests on revenue tracks are needed to support the preliminary conclusions drawn regarding the effects of these track variables on lateral track strength and stiffness.

- To develop slow order guidelines, tests are needed to study the effect of a dynamic ballast stabilizer on recovery of lateral track strength following ballast tamping and cleaning operations. More tests are needed regarding the effect of traffic on restoring lateral track strength following track maintenance. A survey of lateral track strength and stiffness on revenue tracks will expand the database obtained from tests conducted on TTC test tracks.

- Additional tests are recommended to study the effects of compressive rail thermal force on lateral track strength and stiffness when the compressive forces in the rails are higher than what was considered in the fundamental test phase for both tangent and curved tracks.

- Although tests conducted at TTC proved the feasibility of using TLV to measure lateral track strength and detecting weak spots under in-motion test mode, significant improvements are required in order to apply this technique for production use as a track strength inspection tool. The results to date for in-motion lateral track strength tests have been generated using LVDTs in contact with the rail. These are not practical for use on commercial track because they attach to the Unistrut frame mounted at the side of the TLV. This frame does not fit in the standard car clearance envelope and would be damaged by typical switch stands and other obstacles. Because the car body cuts a mid-chord path through a rail curve, the contacting sensors are quickly pushed beyond their operating range on curved track.

- The recommended improvement focuses primarily on the development of a non-contact onboard deflection measurement system. Non-contacting sensors must replace the contacting LVDs. Laser/camera systems have been used on the TLV to measure gage-widening behavior in the past. An array of such transducers might be the solution.

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