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Fundamental Track Gage Widening Tests Using the Track Loading Vehicle

Report No. R-862

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13. ABSTRACT

In early 1991, a series of fundamental track gage widening tests were conducted at the Transportation Test Center. Tests, using the Track Loading Vehicle (TLV), were performed to provide fundamental knowledge about the manner in which wheel drop derailments occur, to establish data about current rail and track quality, to test and validate various derailment criteria, and to provide a means for the continued measurement of these criteria.

The track gage strength characterization tests showed that the initial lateral rail deflection comes in the form of rail translation, twist, and bending. When the lateral load applied at the rail head exceeds the frictional force, the rail slides on the tie plate until the rail base contacts the tie plate shoulder. The critical load levels needed to start rolling the rail are defined by the wheel-rail contact geometry. Resistance to this rail roll motion is obtained from the torsional resistance of the rail and the pullout resistance of the gage spikes.

Recent contributions to the prediction of gage widening derailment include the development of criteria and the formulation of indices to quantify the gage widening behavior of the track. A comprehensive series of tests was performed to validate various track gage widening derailment criteria such as rail rollover, lateral load severity, and projected loaded gage (gage reserve index), as well as to develop new criteria.

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EXECUTIVE SUMMARY

Recent studies conducted using AAR's Track Loading Vehicle (TLV) indicated that the concept of in-motion measurement of track strength is one of the most promising alternatives to traditional visual inspection of track for maintenance planning.

This report discusses the findings of the tests and analysis that were required to investigate the feasibility of moving from standards based on the physical condition of the tie/fastener system to standards based on the actual load carrying capacity of the track structure.

The report proposes a new method developed from track strength data obtained from controlled tests using the TLV. This methodology can be used in conjunction with automated track inspection systems to measure the performance and condition of ties and fasteners. The technique allows for the use of a variety of test loads and the assessment of the critical gage under severe loading conditions.

The report also presents a detailed description of the track gage widening tests conducted to investigate the relationship between physical characteristics of track and its response under heavy axle loads. The research which established the basic understanding between rail restraint and wheel loadings is also described.

Fundamental track gage widening tests, which were conducted at TTC, consisted of track strength characterization tests and rail restraint criteria tests. Both static and dynamic TLV tests were conducted to measure and determine the shape of typical restraint curves for the track classes in present use, to investigate the effect of the lateral position of the contact patch between the wheel lateral to vertical load ratios (L/V) from 0.3 to 0.7) to gage widening than cut spikes. Similarly, Azobe hardwood ties with cut spikes provide greater resistance (up to 50%) to gage widening than conventional ties with cut spikes.

As the lateral load is increased, under a constant vertical load, the increase in both average track delta gage and the loaded track gage was largest in the case of conventional wood ties with cut spikes and least for conventional ties with Safelok fasteners, where delta gage is the difference in gage between loaded and unloaded track. Test results of premium fasteners on conventional wood ties indicated that they provided increased rail restraint under higher lateral loads (although to a lesser degree with elastic fasteners). The same appeared to be true for Azobe ties with cut spikes. The best tie and rail restraint conditions were provided by Safelok and Pandrol fasteners on wood ties. Elastic spikes on conventional wood ties and the Azobe ties with cut spikes also provided "good" tie and rail restraint, which was somewhat better than that of cut spikes with conventional wood ties.

Deflection of track having conventional wood ties with elastic spikes, shows gage holding characteristics under heavy axle loads similar to those of track having Azobe ties with cut spikes. Elastic spikes on conventional wood ties and cut spikes on Azobe ties resulted in track deflections between those with cut spikes and premium fasteners on conventional wood ties; hence there does not appear to be any gain in the gage holding capacity provided by premium fasteners when the conventional wood ties were replaced with Azobe ties. The increase in both average track delta gage and the loaded track gage was largest in the case of conventional wood ties with cut spikes, and least for conventional wood ties with Safelok fasteners. It can be concluded that under both typical and heavy axle loads, premium fasteners on wood ties provide much greater resistance to gage widening

Rail rollover tests were run at a variety of vertical and lateral loads to evaluate this limiting condition in which track failure can occur. The test results showed that the rail does begin to roll about its field side base corner when the lateral load overcomes the hold-down moment from the vertical load. However, beyond this point, the rail continues to roll under increasing lateral loads, but it does not completely rollover.

Rail rollover tests showed that a criterion solely based on the rail's propensity to rollover at L/V ratios near 0.6 is clearly inadequate to predict an incipient wheel drop derailment. A single lateral load (in combination with a vertical load of 33 or 39 kips), applied at a single point near the gage face of the rail, was not sufficient to cause an adequately fastened rail to overturn at L/V ratios up to 1.

The TLV test results imply that the actual failure mode associated with rail rollover appears to be dynamic gage widening, (the difference between loaded and unloaded gage) followed by one or more wheels dropping inside the gage and causing the rail to roll over. On track with good tie/fastener conditions, rail roll produced the majority of rail head deflection, rail translation produced no more than 20% of the rail head deflection.

The same L/V ratio does not produce the same amount of lateral rail head deflection; as the vertical load is increased the deflection increases as well. In fact, at higher L/V ratios this increase is much more pronounced.

The magnitude of the net lateral load, referred to as the Lateral Load Severity (LLS), at a given L/V ratio governs the rail head deflection. At an L/V ratio of 1, the total rail head deflection under a 39-kip wheel load was twice as much as that under a 20-kip wheel load. This is due to the unloaded track geometry.

The last gage widening derailment criterion examined in this study was developed by the Volpe National Transportation Systems Center (VNTSC) and is under current use with a split axle track gage strength measurement system referred to as the Gage Restraint Measurement System (GRMS). This system implements a new index called the Projected Loaded Gage (PLG), which predicts the maximum dynamic gage expected under extreme loads. The lateral loads applied to the track are measured, and the maximum gage under assumed maximum loads are estimated based on extrapolation of the load/deflection curve. Since the tests used to determine rail restraint must be carried out at a load level which does not damage the track, extrapolation factors are used to determine whether the track is strong enough to prevent wheel drop under extreme loading conditions.

Tests were also run to provide a means for continuous measurement of track gage widening strength. The concept of Projected Loaded Gage (PLG), which was developed by the Volpe National Transportation Systems Center, was rigorously tested. It was found that the PLG constitutes an acceptable means for the determination of the limiting value of track gage leading to a wheel-drop derailment.

A number of TLV tests were conducted to determine the applicability of this technique to various track classes and to enhance the use of the PLG concept in different load environments. First an analytical procedure was developed to calculate rail head deflections from an estimation of the rail strength parameters determined from static load/deflection data. Then a more general formulation of critical track gage (PLG) was developed.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge and appreciate the involvement of the Federal Railroad Administration in the program, through both funding of the major portion of the TLV test activities, and the support and acknowledgments by various personnel, in particular Messrs. W. Paxton, and R. Krick of the Federal Railroad Administration (FRA). Funding for TLV testing was provided by the FRA under Task Order 2, titled "Vehicle Track Interaction Project, Derailment Analysis," of Contract DTFR53-86-C-00011.

In addition, the authors sincerely acknowledge Messrs. Tom Madigan, Tom Goldblatt, Doug Compton, and Randy Thompson and other AAR personnel who were involved in the TLV tests. A project of such complexity requires many people with different skills and expertise working towards a common goal. Special thanks are extended to Dr. Albert Reinschmidt for his helpful guidance and technical input throughout the test program.

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1.0 INTRODUCTION

Since the turn of the century, improvements in the understanding of the interactions between vehicles and track has continued to provide benefits in both performance and safety. One of the most comprehensive studies into the behavior of track structure was undertaken by the Talbot committee of the AREA during the early 1900's. Experience gained during these investigations had shown early on that experimental investigations offered the most benefit to enhance the understanding of the fundamental behavior of track under load. This was true because of the complexity involved in the modeling of the track under load due to the variability of its support conditions. More recently, the industry's knowledge and understanding of the fundamental behavior of track and vehicle/track interaction has improved dramatically since the beginning of the Track Train Dynamics Program.

Under the auspices of the AAR's new Vehicle Track Systems Program, several research projects were initiated in 1985 to bring about a systems view to analyze vehicle and track interaction problems to reduce track and equipment costs, and to improve the safety of train operations. The quantification of the lateral strength characteristics of in-place railroad track and the determination of the load environment under various types of operating conditions are among the major elements of this research program.

In the late 1950's and early 1960's, with increasing competition from other modes of transportation, the railroads increased maximum axle loads from 25 to 33-tons. Now our industry is facing yet another major challenge: safe and economic operation of heavy axle load (up to 39-ton axle load) cars. In order to provide a track structure which is capable of supporting the increased vertical and lateral loads, the load carrying capacity of the track must controlled derailment scenarios over a range of track conditions and to provide a controlled load environment in which the dynamic response of the track could be quantified.

The TLV was built by the AAR in 1989 to be used as a major research tool to measure the strength of in-place track, to further enhance our understanding of derailments, and to help us determine the strength of railway track structures and bridges under heavy axle loads. A potential application of the results obtained from the TLV is to develop better track inspection techniques, to produce vehicles which impose less damage on the track, and to identify track segments requiring immediate maintenance.

The testing with the TLV is supported by the Federal Railroad Administration (FRA) under the auspices of the Track Train Interaction Derailment Analysis Project under Task Order 6 of Contract DTFR53-86-C-00011. This project began in 1985 as a joint AAR/FRA effort to further the understanding of the forces and reactions occurring at the wheel-rail interface region for a range of wheel loadings, speeds, track conditions, and other operational characteristics. The investigations conducted under the auspices of this program included both analytical and experimental studies aimed at the examination of track failure modes associated with track gage widening and rail rollover.

Previous activities under this project included the conduct of a series of demonstration tests to ascertain the capabilities of the TLV to maintain controlled loads over different operating and track conditions, and to assess lateral restraint characteristics of railroad track. Based on these results, the operational performance and track gage widening strength-testing capabilities of the TLV far exceeded the targeted performance requirements. The TLV is capable of applying vertical and lateral loads in excess of 39-tons on tangent and curved tracks

2.0 HISTORICAL REVIEW OF TRACK GAGE WIDENING STUDIES

The problem of track gage widening has been of considerable interest to the railroad industry since the early 1900's. AAR Report No. R-258 provides a comprehensive historical review of this problem.[3] A summary of this work is presented herein along with updates to include the most recent studies of track gage widening.

Early investigations of rail roll encompassed limited experimental and analytical studies. One of the first attempts made was by E. Winkler in 1875 to measure the gage widening of track with various spikes[4]. In 1909, E. Stetson introduced the concept of the critical L/V ratio at which the rail section became unstable[5]. He concluded that "good" track under the stabilizing effect of the vertical load would provide more than sufficient resistance to rail overturning (this concept postulated in 1909 was verified once more with the TLV tests).

In 1918, the Talbot committee of the AREA examined rail roll under loaded cars at speeds up to 40 mph[6]. The committee recommended the use of unsymmetrical tie plates with larger bearing areas on the field side of the rail to prevent rail roll. Further investigations of gage widening performed by European railroads in 1927-1930 led to the introduction of various types of fastener systems designed to increase resistance to rail roll[7]. To study the effect of lateral loads generated by new locomotives on sharper curves, a more comprehensive set of track gage widening tests were run by the AAR Research Staff on the Santa Fe Railroad in 1951[8]. The 1966 tests run by the AAR on the Delaware & Hudson Railroad[9] and the Southern Pacific Railroad[10] investigated gage widening derailments due to locomotive loadings. Following these investigations, a set of laboratory tests taken to failure, were also run by the AAR in 1967 to determine the overturning resistance of a rail segment fastened to a wood or

In 1975, AAR researchers presented the results of an investigation of wide gage in terms of probability histograms and distribution curves[18]. This study concluded that dynamic gage widening under the passing trains did not cause any permanent damage. It was also noted that more significant rail roll occurred during winter months due to larger lateral loads.

The effect of rail longitudinal forces on rail roll was examined by a group of AAR researchers in 1976[19]. These tests found that the axial forces in the rail caused substantial increases in the resulting gage widening. The results from these tests confirmed Stetson's findings that a lateral load at a single point is not sufficient to overturn adequately fastened rail.

The Track Strength Characterization Program was initiated in 1977, as part of the Track Train Dynamics Program, with the objective of further enhancing the understanding of track strength. The early investigations conducted under the auspices of this program included both analytical and experimental studies aimed at the examination of track failure modes associated with track gage widening and rail rollover.

The feasibility of a continuous measurement of track gage widening was first demonstrated by A. Zarembski in a series of tests at the AAR Chicago Technical Center in 1978[20]. A test device designed and built earlier by the AAR was mounted on the B-end truck of a flatcar. The rail spreader apparatus utilized a hydraulic ram and the test was conducted at a speed of 3 mph. These initial tests demonstrated that it was possible to measure track strength and identify ties and fasteners in poor condition without significant damage to the track structure.

Battelle. Field evaluation of the Decarotor in 1980 showed that the system could continuously measure the strength of track at speeds up to 7 mph and successfully and repeatedly identify weaknesses in the track[23].

The Decarotor was used to characterize the lateral strength of mainline quality track in 1980[24] through 1983. Unloaded track gage was compared with loaded gage to determine the dynamic gage strength of the track. The vehicle was utilized to evaluate the general condition of mainline track and to identify its weak spots[25]. The Decarotor demonstrated the concept of in-motion measurement of track strength non-destructively but was rather limited in performance. Since it could not test at speeds faster than 7 mph and was not designed to test long stretches of track, it was taken out of service in 1983.

A recent field and laboratory test program conducted by the Volpe National Transportation System Center (VNTSC) beginning in 1980 was designed to investigate the minimum rail restraint characteristics of typical track. These studies focused on the rail restraint characteristics as influenced by vertical and lateral loads under special conditions such as missing ties and weakened rail joints. The test results, which were published in 1984, showed that gage widening mechanism of "poor" track is highly lateral load dependent[26]. The net rail base movement could account for 30 to 90% of the rail head movement, depending on the lateral load level, and tie and fastener condition. A large variation was noted in the strength characteristics of track components. Data were presented to show spike pullout strength and the tie plate vertical and lateral stiffness behavior of various track conditions. The data collected during these tests were later used in the development of suggested criteria and rail strength capacity limits for the prevention of excessive gage widening.

twist and roll about the longitudinal axis of the rail section. Timoshenko further suggested that the lateral bending and twist of the rail under a constant lateral load were of localized character and not affected substantially by the lateral loads from adjacent wheels. A similar investigation conducted in 1945 concluded that pure torsion is resisted by the entire rail section.

In 1969, and in 1974, M. Srinivasan[31] and Y. Sato[32] respectively presented improved formulations of rail roll which confirmed Timoshenko's findings. Also in 1974, A. Kish developed a comprehensive set of equations of non-linear bending and torsion of railroad track, but his formulation was not applied to the problem of rail roll[33]. Another attempt was made by F. Arbabi in 1976 to investigate the rail roll under a combination of vertical, lateral, and longitudinal loads[34]. The rail was represented as a beam constrained by linear and torsional springs.

A model study of track gage widening was made by A. Zarembski in 1978 to examine the deformation mechanisms of rail fastener/tie systems[35]. Zarembski concluded that gage widening of the track system is composed of rail translation and rail roll and cannot be separated in any analysis. For loads normally encountered under service conditions, rail rollover was not an instability problem.

In 1978, Bhatti of the Illinois Institute of Technology (IIT) developed the equations of motion of the rail subjected to time dependent lateral, vertical, and axial forces[36]. More recently, Chu utilized a finite element formulation to the track gage widening problem with nonlinear fastener stiffness characteristics[37]. His model predicted lateral and vertical rail displacements and rail roll due to external forces. These results were compared with those obtained through tests. Moderate agreement was achieved. Furthermore, Chu's study showed interaction problems to reduce track and equipment costs, and to improve the safety of train operations. The quantification of the lateral strength characteristics of in-place railroad track and the determination of the load environment under various types of operating conditions are among the major elements of this research program.

The Track Train Interaction Derailment Analysis Project began in 1985 as a joint AAR/FRA effort to further the understanding of the forces and reactions occurring at the wheel-rail interface region for a range of wheel loadings, speeds, track conditions, and other operational characteristics. The concept of the Track Loading Vehicle (TLV) was developed as a result of the industry's need for a multi-purpose research tool which could be utilized in a variety of comprehensive vehicle track interaction tests[40]. This new vehicle would simulate controlled derailment scenarios over a range of track conditions and provide a controlled load environment in which the dynamic response of the track could be quantified.

The TLV was built by the AAR in 1989 to be used as a major research tool to measure track strength and investigate various derailment mechanisms[41]. The capabilities of this vehicle to measure track strength were demonstrated in a series of in-motion track tests in 1990[42]. These tests showed that the TLV could apply lateral and vertical loads in excess of 39 tons on tangent and curved tracks up to 10 degrees at speeds up to 35 mph. The vehicle was found to be capable of measuring dynamic gage widening strength of track and of identifying weak track locations under simulated axle loads without causing permanent track damage[43].

A comprehensive series of static gage widening tests were conducted by the AAR's Track Loading Vehicle in 1990, to obtain fundamental knowledge about track gage widening derailments, and to test and validate various derailment criteria under critical load levels under

3.0 DESCRIPTION OF THE TRACK LOADING VEHICLE

The TLV is designed to simulate controlled derailment scenarios and provide controlled load environments to quantify the dynamic response characteristics of track. The vehicle applies computer controlled loads to the track and measures the track response while either stationary or moving.

The design of the TLV is based on an extensive list of functional requirements selected to enhance and further the understanding of the processes that take place at the wheel/rail interface. The vehicle was designed to perform extensive measurement and data collection tasks over a diverse range of applications. Typical applications include tests of vertical and lateral track strength, track panel shift, gage widening, flange climb derailments, wheel/rail force/creepage relationships, wheel/rail wear, and rail corrugations.

The TLV consists of a loading platform, adapted from an SD45X locomotive underframe, carried by two-axle locomotive trucks. A fifth wheelset is mounted in a load bogie underneath the center of the vehicle. A new superstructure, providing the required strength and stiffness, was constructed over the underframe. The superstructure is a welded structure which is constructed with various structural frames and I-beams welded to channel sections extending the length of the vehicle. A special load frame was constructed at the center of the vehicle and is used for supporting the vertical actuators. For stiffness, the sides and the top of the vehicle are completely covered with 1/4 inch sheet plates. Exhibit 1 is a photo of the TLV.

The load bogie is attached to the car frame to apply loads using the vertical actuators suspended from the car body and to measure responses. It is equipped with two servovalve controlled hydraulic actuators and associated load application mechanism, a stub axle

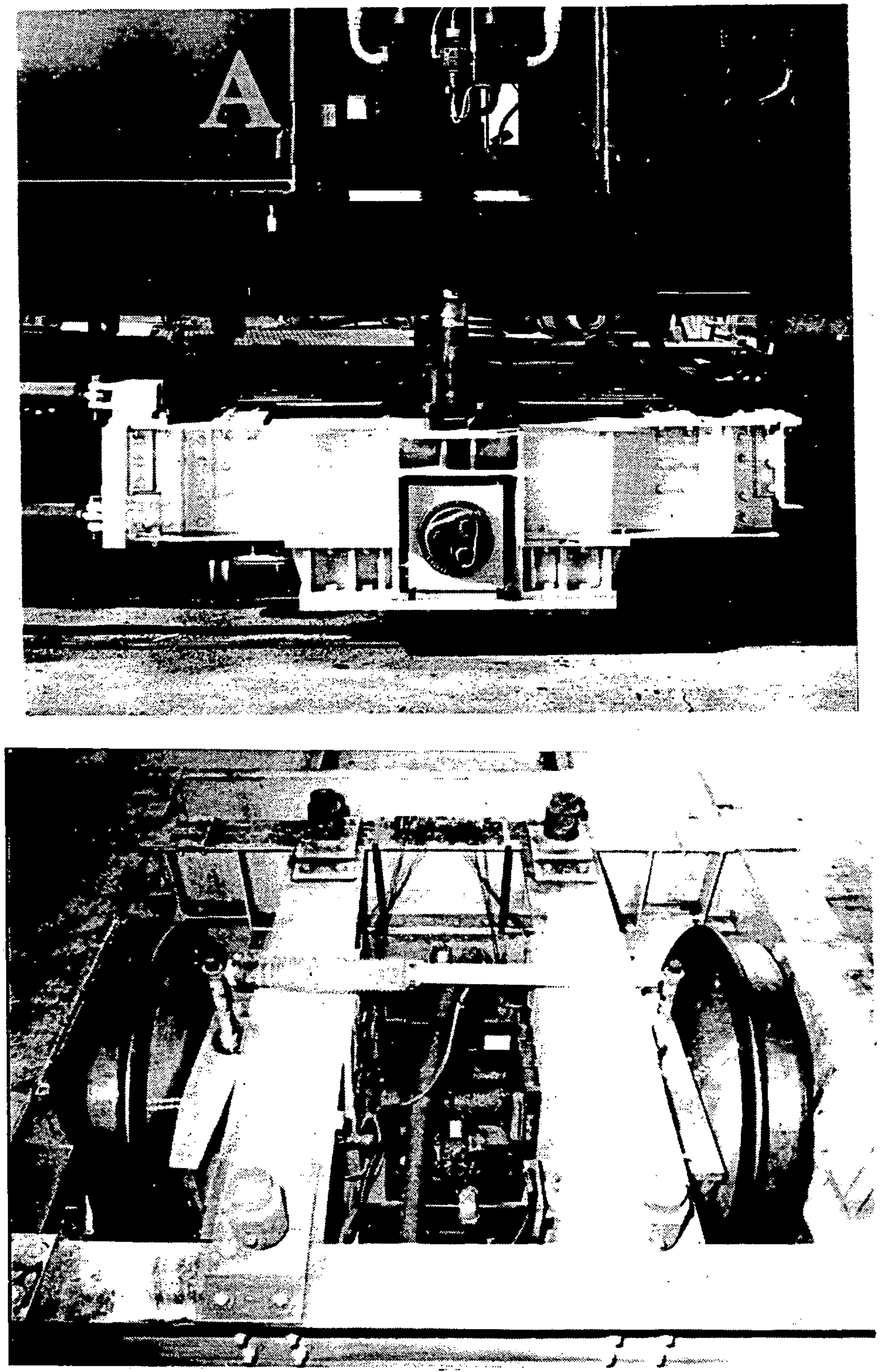


Exhibit 2. Track Loading Vehicle Load Bogie with Split Axle and Gage Widening Load Application Mechanisms.

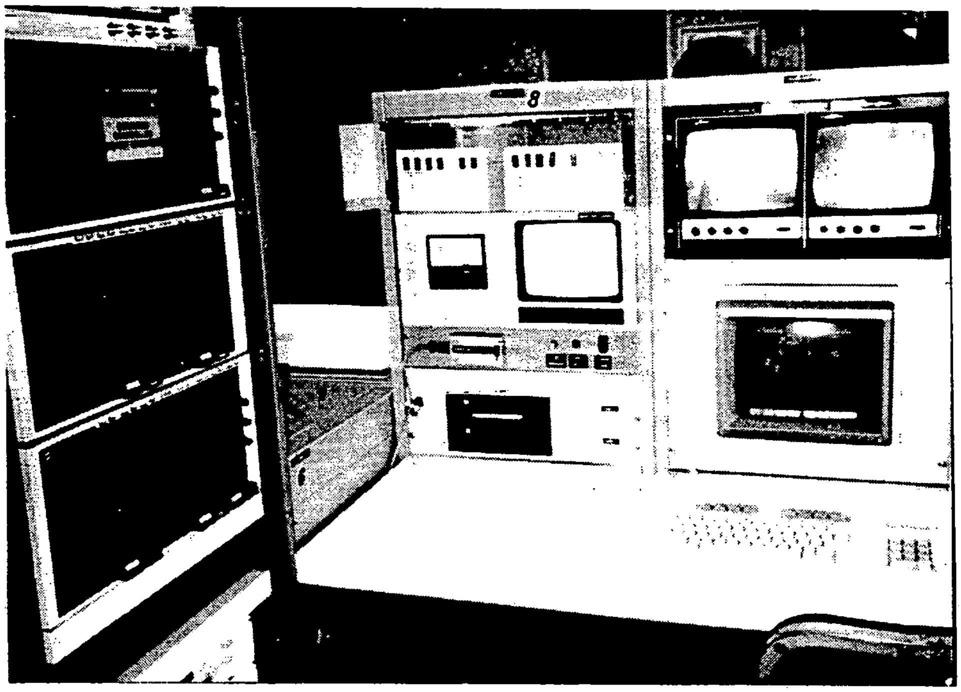


Exhibit 3. TLV Computer and Instrumentation Command Center.

during the transition from tangent to curves. Various failsafe modes have been built into the TLV system in case of load bogie derailment or in the event of hydraulic power or computer failure.

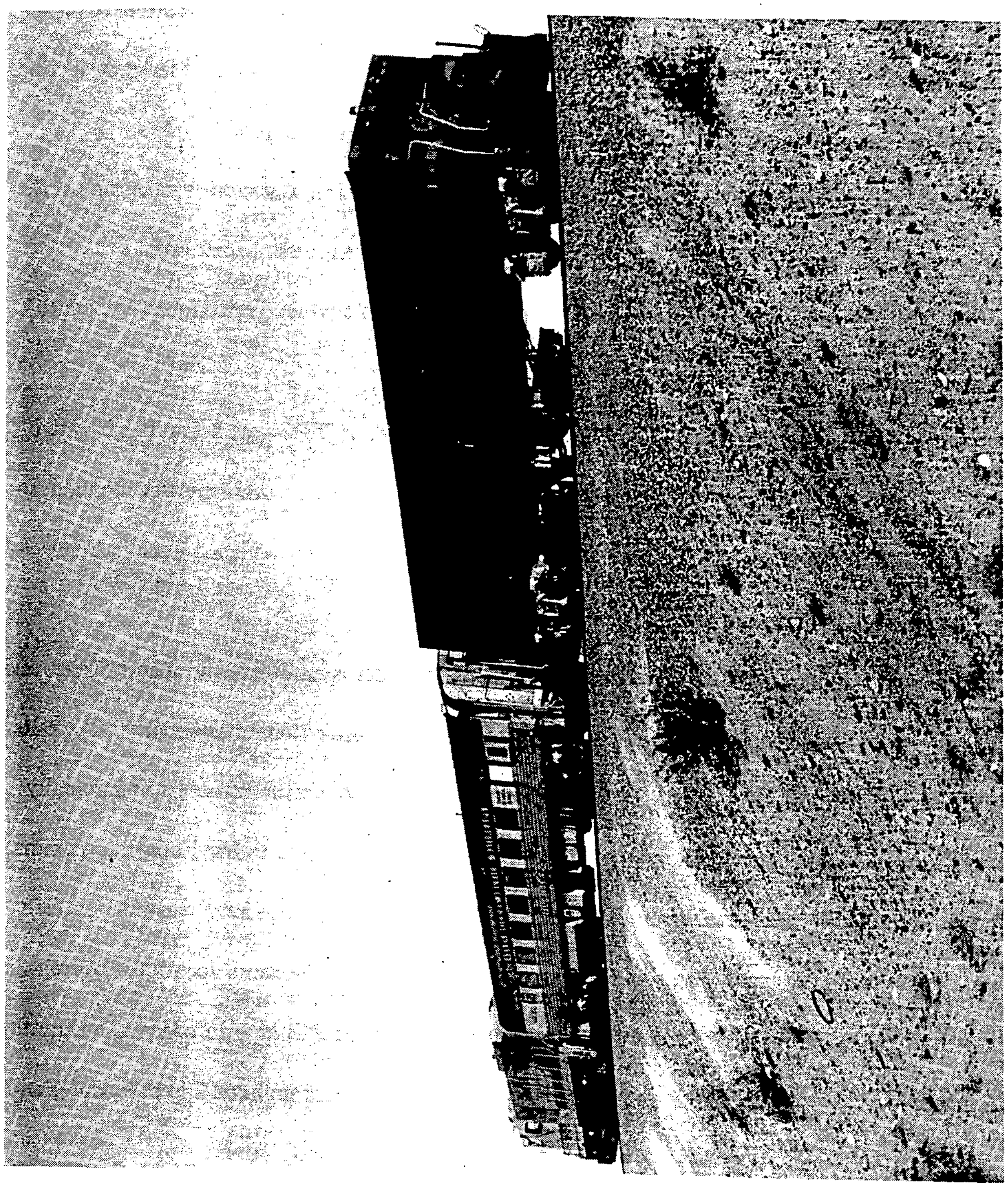


Exhibit 4. TLV Test Consist.

Exhibit 5. Hand Held Track Gage.

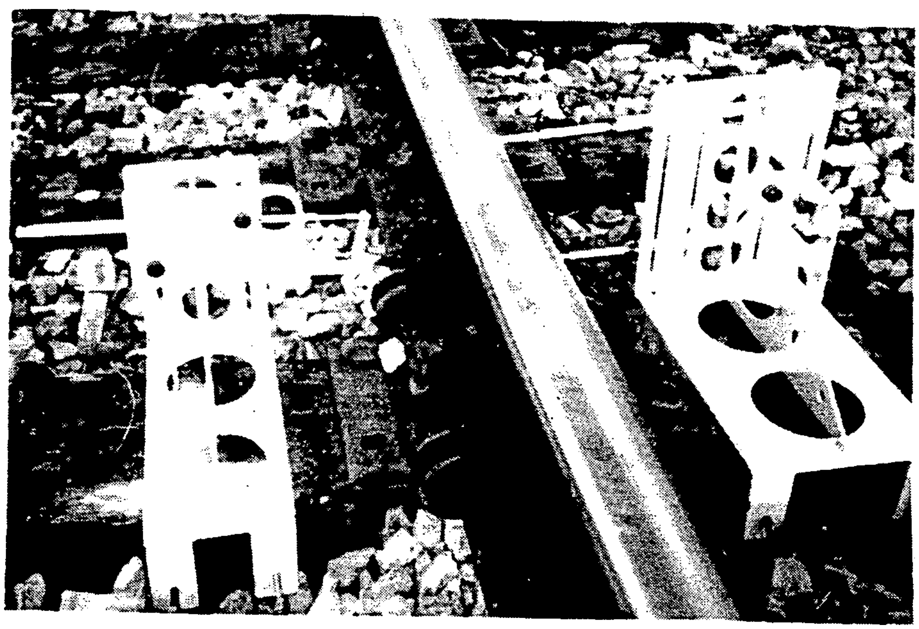


Exhibit 6. Wayside Instrumentation.

as four on a 5-degree curve. The track consists of 136 pound CWR on 7″ x 9″ x 9′ softwood ties on slag ballast. The tie plates were 17.74″ x 14″, with 4 spikes per tie on tangent track, and 5 spikes per tie on curved track. The additional spike on curved track is on the gage side. Shown in Exhibits 7 and 8 are examples of test locations. The tests that were done on the Heavy Tonnage Loop included a variety of fasteners, such as spikes, Pandrol clips, Safelok fasteners, and double elastic fasteners. The HTL rail is 132 or 136 CWR, with 7″ x 9″ x 8′6″ ties on slag ballast at 19.5″ centers. Ties tested include Azobe tropical hardwood, glue-laminated, Cedrite, and typical North American wood ties. Other test sites include the RTT (Class 6) and the TDT (Class 5), which have the same type of track construction.

In this set of tests, a variety of vertical and lateral load combinations were applied to the rail, and the resulting deflection was measured. The vertical load varied from 8 kips to a maximum of 39 kips. The lateral load was increased up to 26 kips, depending on the vertical load being applied. The L/V ratio was kept under 0.8 to prevent potential wheel climb and damage to the instrumented wheelset. The matrix of load combinations is shown in Exhibit 9.

4.1.2 Artificially Weakened Track

As part of these tests, it was desirable to look at track of varying quality. However, the track conditions at TTC are for the most part very good, and there are no sections of track that can be considered particularly weak. Since locating weak tie conditions is of great importance to the railroad industry, and is a major factor in the prevention of wheel-drop

V=8	10	17	21	27	33	39
Lateral Loads (kips)						
5	5	5	5	5	5	5
	8	8	8	8	8	8
		13	13	13	13	13
			15	15	15	15
				18	18	18
				22	22	22
					24	24
						26

Exhibit 9. Vertical and Lateral Load Combinations for Fundamental Gage Widening Test.

derailments, weak track conditions were artificially created on both tangent and curved track. Two sections of track (one on tangent track, and one on a 5-degree curve) were artificially weakened by removing, in order, the gage spikes, the plate spikes, and the tie plates from three consecutive ties. This was in an effort to see what contribution each individual component made to the gage-holding capabilities of the system. A complete series of static tests as outlined in the above matrix was run at each interval in order to determine the contribution to gage widening of each stage of track deterioration. The ties were also saturated with water in order to test their performance under wet conditions. Under these weakened conditions, however, no dynamic tests were performed. The various stages of "deterioration" are shown in Exhibits 10 - 13.

Exhibit 12. Third Stage of Artificially Weakened Track.

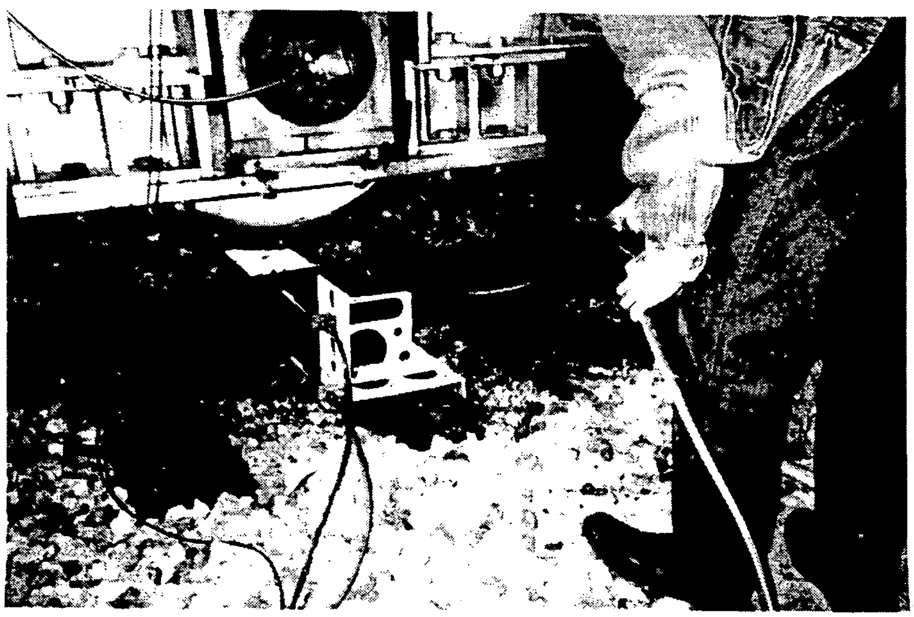


Exhibit 13. Fourth Stage of Artificially Weakened Track.

Based on this information, additional test data is necessary to understand the mechanism of rail rollover as well as to validate or develop new criteria. These tests included studies of the effect of the location of the contact patch on rollover tendency.

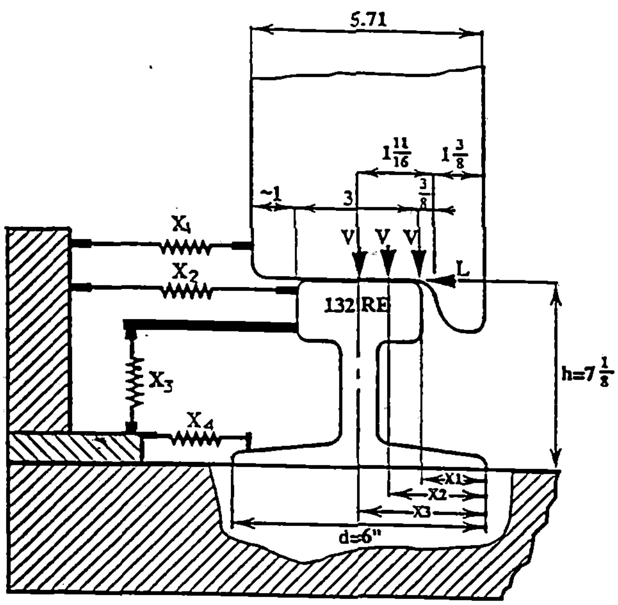


Exhibit 14. Illustration of Wheel Contact Geometry.

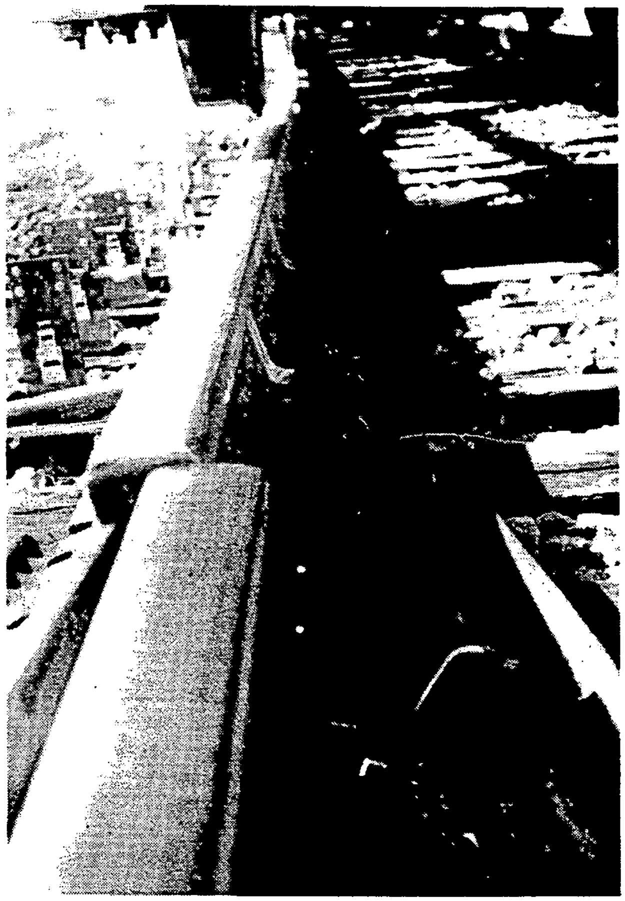


Exhibit 16. Example of Rail Roll.

A series of tests were also scheduled to study the effect of contact patch location on rail roll tendencies. A system was set up that fit over the rail, and a rod was inserted at varying positions. However, there was a problem with slippage, between the rail and the device used to alter the postiion of wheel/rail contact point and the lateral load could not be increased over 12 kips before slippage occurred. Various methods were tried in order to increase the coefficient of friction between the brace and the rail, but to no avail. Further work will have to be done in this area to determine a more appropriate way to vary the contact patch. Exhibit 17 and 18 illustrate the apparatus used for this test.

Additional tests were performed to check the reaction of the rail under extreme loading conditions, including rail roll and wheel lift, and to quantify the reaction of the rail/fastener system under continuously increasing lateral loads. This set of tests was performed on tangent track, with 4 spikes per plate, and involved taking the TLV to its physical limits in an effort to roll the rail. In the first test, only the bogie weight (6.7 kips) was applied vertically. Here the lateral loads were increased incrementally to 33 kips. A second series of tests was done with a vertical force of 50 kips being applied to the rail. At this heavier load, the lateral load could be increased up to 38 kips before the TLV ran out of stroke.

During all of the tests performed at TTC, it should be noted that the TLV itself does provide some resistance to rail rollover, as the TLV trucks exert a substantial vertical force on nearby rail, thereby restricting the rail rollover ability at the point of the gage widening force. It was desirable therefore to try to determine what effect this restraining force has on gage widening and to understand the mechanism of rail rollover taking into account the factor of rail torsional rigidity. The mere fact that the rail is a continuous beam provides restraint to rail rollover. In an effort to remove both of these outside factors, two additional sets of test were performed.

A section of a shallow (1.5-degrees) curved track which happened to have a set of parallel rail joints, was chosen for these tests. The first test was on a section of track which had parallel joints 19 feet apart, placing all of the joints within the truck spacing of the TLV. To determine a base line, or control condition, an initial set of tests with a vertical load of 33 kips and a lateral load of 33 kips on each rail was performed at these locations with the joint bars in place. The bars were then removed, and another set of tests were performed. The configuration

The second test, with one set of joint within the truck spacing was then performed. In this test, the TLV was centered over the track so that one of the parallel joints would fall between the load bogie and the inboard axles of the leading truck (the distance between the inboard axles of the TLV is about 37 feet). Both these tests were done by monitoring the displacement of the rail head, rather than the force applied, which had been the standard up to this point. This was done in order to ensure better control over the lateral movement of the rail, and to avoid any rapid rail roll. It was found to be impractical to control the movement of both rails simultaneously, so the test was done pushing one rail out at a time. Exhibit 20 illustrates the test location where the joint bars would be removed, while Exhibit 21 illustrates the configuration of the joints at this location.

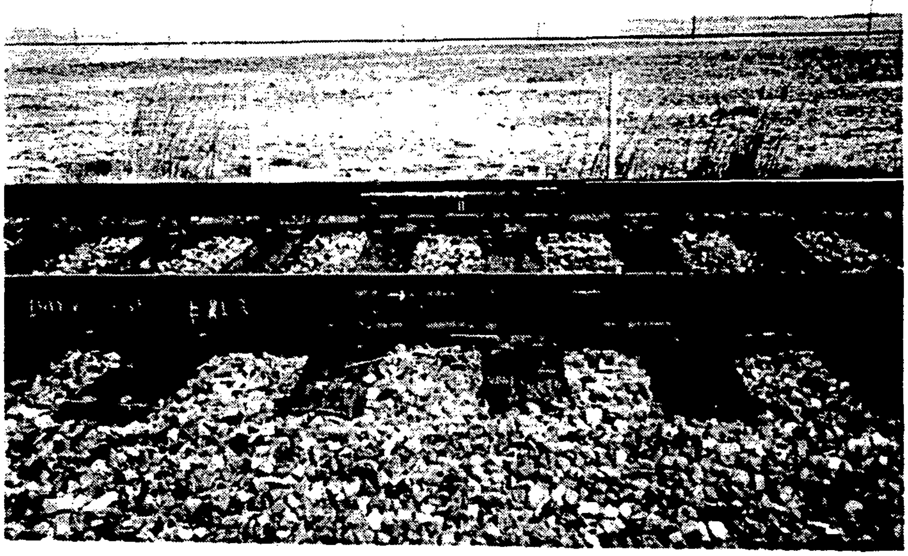


Exhibit 20. Example of Extreme Loading Test Location.

a) Determine the relationship between lateral load severity and track gage widening.
b) Investigate the effect of L/V ratio on load severity.

To complete objective b) a series of tests in which, the lateral and vertical loads were varied such that several combinations equivalent to L/V ratios of 0.5 through 0.8 were tested.

A second set of test was done under moving conditions. The vehicle was run at 20 mph over both tangent and curved sections. The loading matrices are shown in Exhibits 22 and 23.

V	Lateral Load			
	L/V=0.5	0.6	0.7	0.8
15	8	9	11	12
20	10	12	14	16
25	13	15	18	20
29	15	17	20	23
33	17	20	23	26
39	19	23	27	31

Exhibit 22. Stationary Lateral Load Severity Test Matrix.

The relationship between load severity and track gage widening for constant L/V ratios were investigated to develop load severity/gage widening curves for the use of the TLV to characterize the track strength characteristics of revenue track, and investigate the effect of equivalent load severity on the gage widening characteristics of track.

16 kips laterally on low rail for FRA Class 2 track, and 32 kips vertically and 32 kips laterally on high rail and 32 kips vertically and 16 kips laterally on low rail for Class 3 track. The reasoning behind testing at loads below the extreme load conditions is to prevent derailment of the test vehicle and minimize the amount of damage to the track.

The purpose of the minimum gage restraint tests, using the TLV, was to determine the feasibility of using an extrapolation factor, determine the appropriate test loads, and develop more realistic extrapolation factors. Exhibit 24 shows a summary of the minimum gage restraint tests performed at TTC. Exhibit 25 shows the test loading sequence.

Test Site	Class	Geometry	No. of Locations
Balloon Loop	4	Tangent	5
Balloon Loop	4	5 Degree Curve	5
Train Dynamics Track	5	Tangent	10
Railroad Test Track	6	Tangent	10
On Board Measurements : Applied Lateral and Vertical Loads Wayside Measurements : Lateral Rail Head and Base Displacements			

Exhibit 24. Summary of Minimum Gage Restraint Tests.

Vertical Load (kips)	Lateral Load (kips)	Type of Test
33	0 - 33	Static
33	0 - 33	Dynamic @ 0.1 HZ
39	0 - 39	Static
39	0 - 39	Dynamic @ 0.1 HZ

Exhibit 25. Load Sequence for Minimum Gage Restraint Tests.

5.0 FUNDAMENTAL TRACK GAGE WIDENING TEST RESULTS

5.1 TRACK GAGE STRENGTH CHARACTERISTICS

5.1.1 Conventional Track

The main purpose of the Fundamental Gage Widening tests was to provide an understanding and comparison of track lateral response under a variety of vertical and lateral wheel loads (up to an L/V ratio of about 0.7). Sections tested included those having different types of ties and fasteners, and were subjected to static and dynamic applications of lateral loads. By determining the relationship between the load applied to the rail head and its lateral displacement (gage widening), a comparison of different tie and fastener types was to be made to ascertain the advantages or disadvantages of one over the other. Tie types included in this test were of Douglas Fir, Oak, Azobe, Pine and Cedrite ties, while fastener types were cut spikes, Pandrol clips, Safeloks and double elastic fasteners.

During the first set of tests, lateral loads were applied to the rail by using the TLV split-axle wheelset in increments of 2 kips, from 2 to 24 kips under a 33-kip wheel load, and from 2 to 26 kips under a 39-kip wheel load. A second series of tests were performed to determine what the effect of increasing the vertical load from 33 kips to 39 kips (while holding the L/V constant) has on the amount of lateral deflection (gage widening). For these tests, lateral loads giving L/V ratios of 0.3 to 0.7 for both the vertical load cases were used. The highest lateral loads used were thus about 23 kips for the 33-kip wheel load case, and about 27 kips for the 39-kip wheel load case. Tests were performed on the Balloon Loop, which is used primarily to turn trains around, as well as various sections on the Heavy Tonnage Loop (HTL).

Results from these tests are divided into three broad categories, namely the lateral track

Track strength data from typical curved track on the Balloon Loop and the HTL are given in Exhibit 27. This graph shows the average (four locations for each tie/fastener type) gage widening magnitudes resulting from the application of lateral loads corresponding to the L/V ratios of 0.3, 0.5, 0.6 and 0.7, for each condition under a 33-kip wheel load. Similarly, Exhibit 28 shows these results under a 39-kip wheel load.

The fastener types shown in these plots are from typical Hard & Softwood ties with four cut spikes, glue laminated ties with four cut spikes, Pandrol fasteners, and Douglas Fir with Safelok fasteners[47]. It can be seen from these plots that at low L/V ratios the difference in the gage widening between the cut spikes and the premium fasteners is rather small, since the fasteners don't provide any resistance to rail roll until an L/V of about 0.65. Until then, resistance to gage widening is provided by the geometry of the rail section and resistance to translation from the fasteners. This difference increases substantially, however, as the L/V ratio is increased. This theory is explained in more detail in a later section.

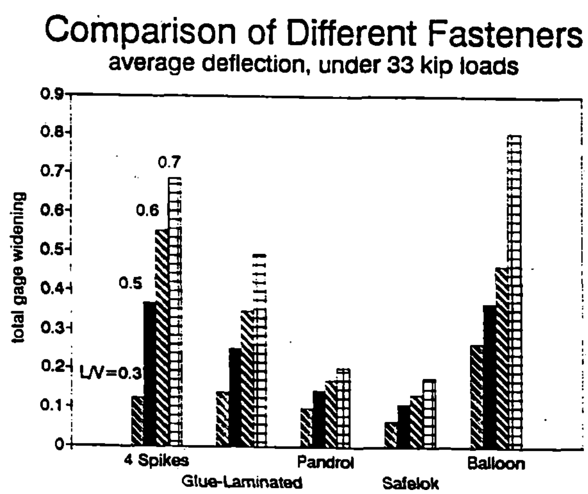


Exhibit 27. Total Gage Widening Under a 33 kip Wheel Load.

It is apparent from these graphs that the curved section on the Balloon Loop is weaker than the four cut spike section on the HTL. This is at least partially due to the fact that the HTL is a dedicated test track, therefore a high maintenance area, and the track is kept in very good condition. The Balloon Loop, on the other hand, is used more often to turn consists around than to perform tests. The quality from a maintenance point of view therefore, would not be quite as high. Moreover, the HTL was rebuilt in 1988 while the Balloon Loop ties were installed at a much earlier date.

A series of tests was done on the HTL on Section 25 (a 6 degree curve) to compare the lateral rail restraint responses of different wood types. Exhibits 29 and 30 show the comparison of the lateral restraint, in terms of the gage widening, for the various tie types with four cut spikes under different lateral loads. Two samples were taken of each tie type.

The results in Exhibit 29 correspond to a vertical load of 33 kips on each rail, and a gage widening load of 18 kips. On the other hand, Exhibit 30 results correspond to a gage widening load of 22 kips under 39-kip wheel loads. There is not any significant difference in the lateral restraint afforded by the different wood types, except for the Red Maple ties with end wear plates. For the test loads used in Section 25, the total gage widening for Red Maple wood ties with end wear plates is approximately half of each of the other gage widening magnitudes from other wood types. Exhibits 31 and 32 show an overall comparison of tie types at various lateral loads, including the Balloon loop, Azobe tie, section and selected ties in Section 25.

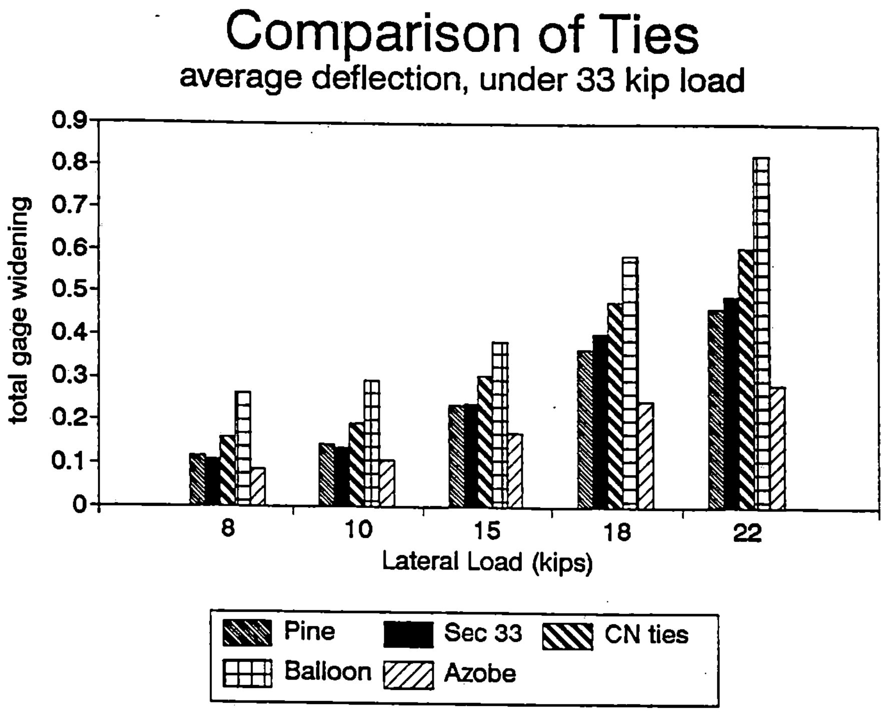


Exhibit 31. Overall Comparison of Gage Restraint by Tie Type Under 33 kip Wheel Load.

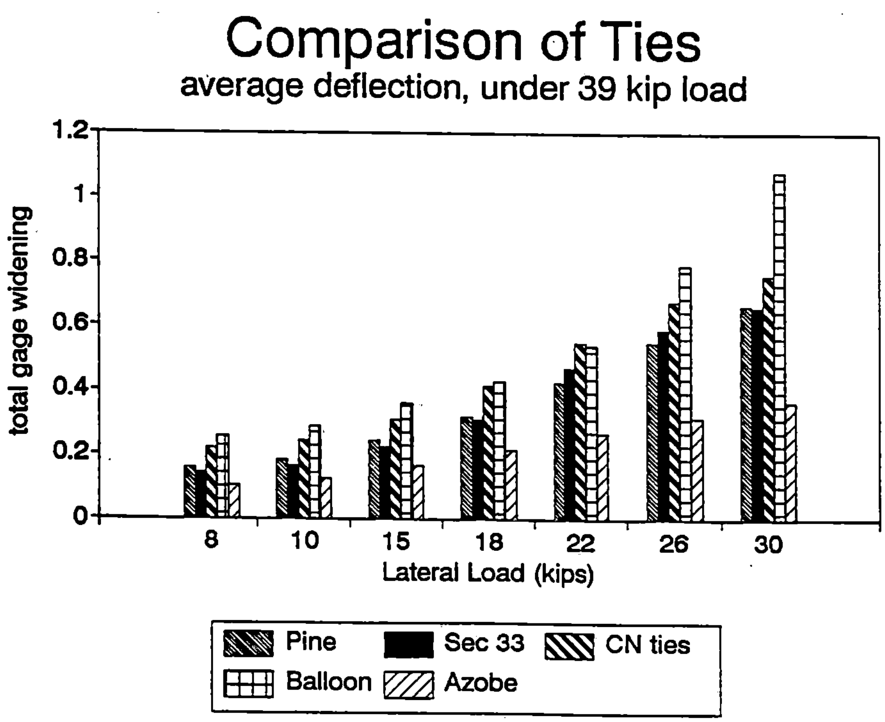


Exhibit 32. Overall Comparison of Gage Restraint by Tie Type Under 39 kip Wheel Load.

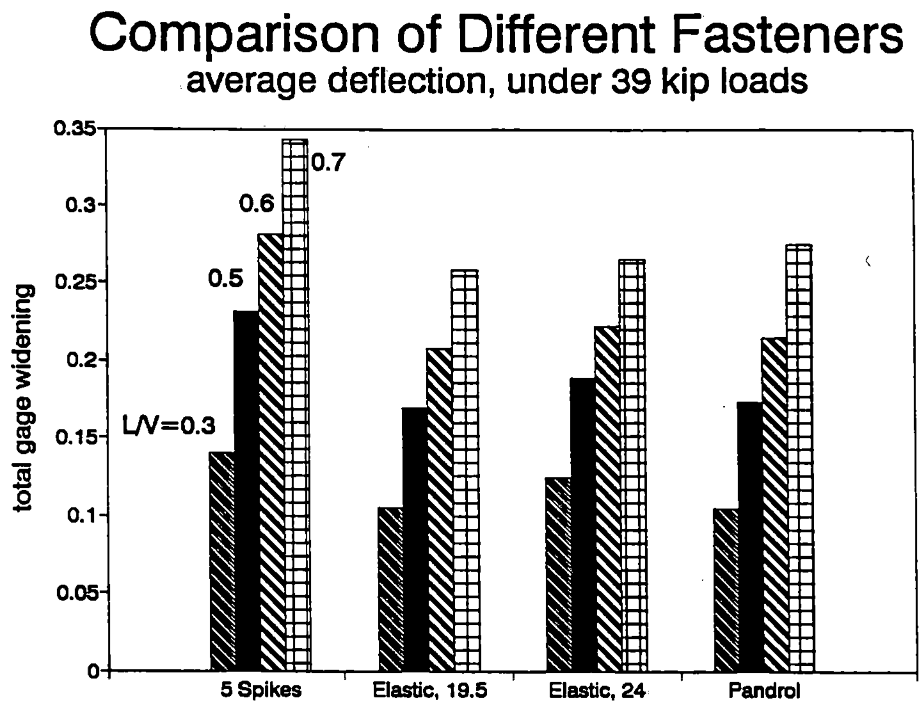


Exhibit 34. Gage Widening Results on Section 31 under a 39 kip Wheel Load.

A comparison with results of the typical North American wood ties with four cut spikes in Exhibits 27 and 28 reveals that the lateral rail restraint response of Azobe ties with five cut spikes is significantly higher than that for typical North American hardwood ties, especially for L/V ratios of 0.5 and above. The total gage widening for Azobe ties with five cut spikes is approximately reduced in half from that of the typical North American wood ties with four cut spikes. Azobe ties with five cut spikes provide quite a comparable lateral resistance to that from Pandrol fasteners and elastic spikes. Further, with respect to Exhibits 27 and 28, responses

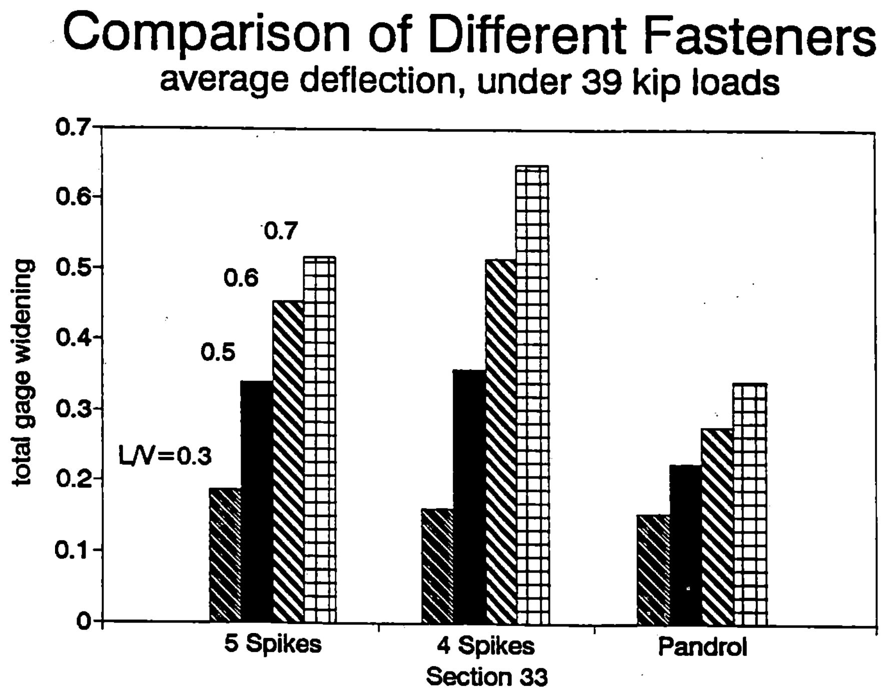


Exhibit 36. Gage Widening on Section 31 Under a 39 kip Wheel Load.

A study of the bar graphs in these exhibits reveals that there are only marginal improvements, and these occur only at high L/V ratios, from the use of five instead of four cut spikes on typical North American wood ties. A comparison of responses of five spikes on typical wood ties in these exhibits with five cut spikes on the Azobe ties in Exhibits 33 and 34 clearly brings out the much superior lateral restraint provided by cut spikes on Azobe ties over that of typical North American ties. The Pandrol fastener responses on the other hand are comparable to similar responses on other sections of the HTL.

As can be seen from these exhibits, an increasing L/V ratio results in comparatively drastic increases in the gage widening for typical North American ties with four cut spikes, while for the premium fasteners such as Pandrol and Safelok, the L/V ratio effects are not as pronounced. Five cut spikes on Azobe ties improve the lateral restraint response significantly compared to such a response from four cut spikes on typical ties. Overall, Safelok fasteners seem to give the best lateral restraint from the analyses of these test results.

To test the effect of increasing the axle load from 33 tons to 39 tons on lateral restraint from various fasteners, a series of tests to determine gage widening under a 39-kip wheel load was also conducted. Tests of gage widening under each 33 and 39 kip wheel loads were made to result in the same L/V ratios, and were conducted at the same locations. This would provide a direct comparison of the gage widening under the different loadings.

Comparisons of corresponding gage widening between 33- and 39-kip wheel loads show that, for each L/V ratio, the lateral deflection that occurs is greater under 39-kip wheel load, and increases with the L/V ratio. The corresponding test results, in terms of total gage widening, at L/V ratios of 0.3, 0.5, 0.6 and 0.7, are given in Exhibits 39 through 42. As can be seen from these plots, the gage widening taking place is always greater under the 39-kip wheel load.

The gage widening loads, corresponding to the L/V ratio of 0.7, are about 23 kips for 33-kip wheel load, and about 27 kips for 39-kip wheel load. Though the stabilizing holddown moment from 39-kip wheel load is higher than 33-kip wheel load, the overall rollover moment from a combination of lateral and vertical loads, resulting in the same L/V ratio, is more for 39-kip wheel load case than 33-kip wheel load case.

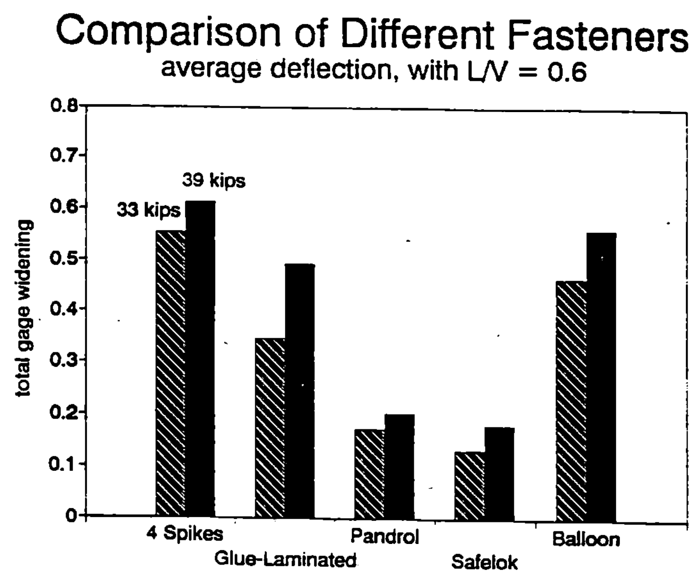


Exhibit 41. Gage Widening at an L/V Ratio of 0.6 Under 33 and 39 kip Wheel Loads.

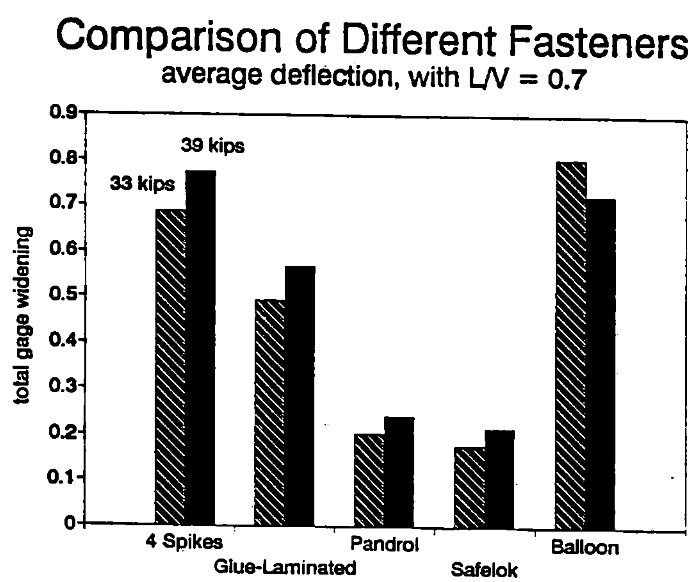


Exhibit 42. Gage Widening at an L/V Ratio of 0.7 under 33 and 39 kip Wheel Loads.

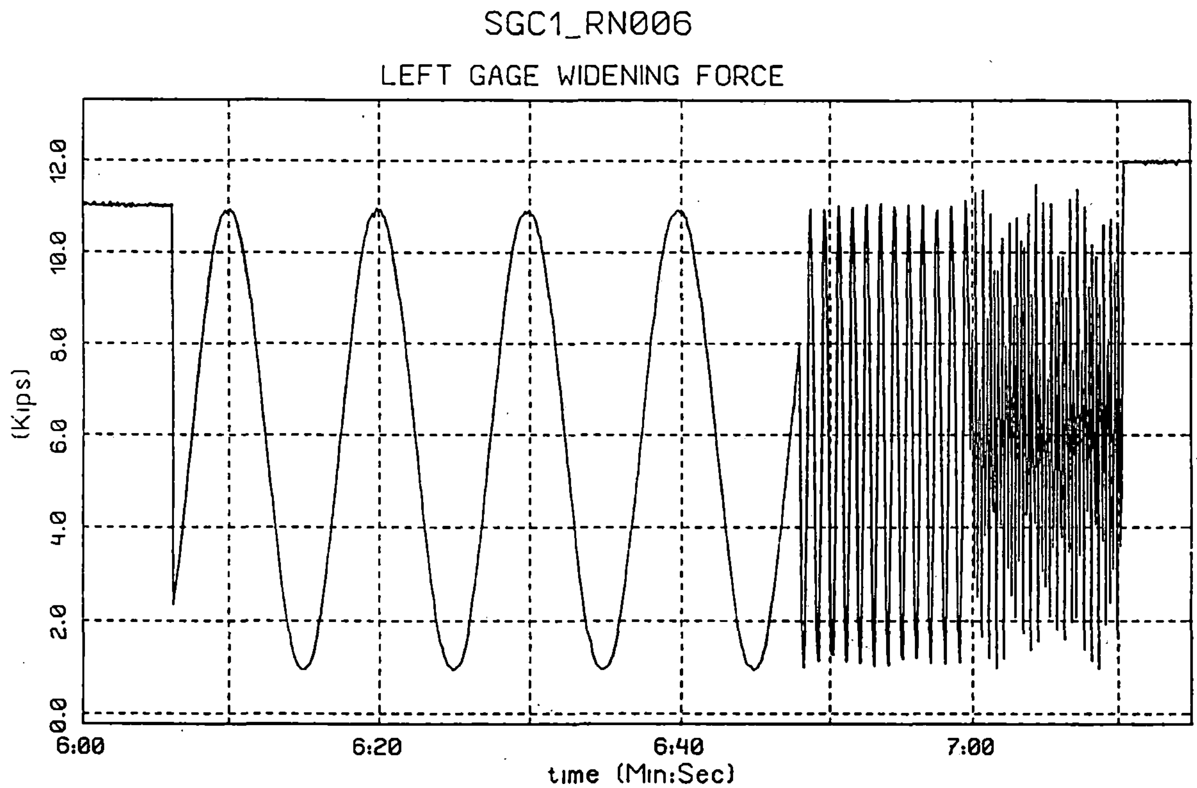


Exhibit 43. Applied Dynamic Force.

During the first few dynamic tests, it was noticed that the TLV's force levels at 6 Hz were not consistently at the desired load level due partly to high-load/large dynamic stroke requirements. This can be seen in Exhibit 43. In order to alleviate the possibility of excessive strain on the loading system, the 6 Hz tests were eliminated from the test matrix. Using the remaining data from the 0.1 and 1 Hz frequencies, there does not seem to be any difference in the gage widening that occurs from that of the statically applied loads.

5.1.2 Artificially Weakened Track

Artificially weakened track tests were performed on the Balloon Loop at TTC. Tests were performed to see the effect of localized weaknesses on the rail head deflection, which were produced by removing components of the rail-fastener system. Two tie locations were tested, one on tangent track and one on curved track. The procedure was as follows:

The track was first tested at various vertical and lateral loads in its normal condition. The spikes were pulled from three consecutive ties on both rails, and then the section was tested under the same loads. Finally, the tie plates were removed from the ties with no spikes, and the test was repeated. The applied loads and the rail head and base deflections were measured.

Exhibit 46 shows the lateral base load-deflection curves for the left rail on the tangent track section. Notice that the rail in its normal condition has a very stiff response, deflecting to approximately 0.12 inches under 33 kips vertically and 24 kips laterally. When the spikes were removed, the rail exhibited a much softer stiffness, deflecting to over 0.37 inches. The load deflection curve for the rail when the spikes were removed tends to show a non-linear response at lower lateral loads. This is due to the fact that before the vertical load of 33 kips is applied, the test under 27 kips vertically was performed. Under 27 kips vertically, a lateral load up to 22 kips was applied, deflecting the rail to over 0.4 inches. The lateral load was then removed but the vertical load remained, with friction between the tie plate and the rail base holding the rail out. When the vertical load was increased to 33 kips, the rail exhibited a non-linear response as the lateral load was increased, initially due to the rail being held out by friction. When the tie plates were removed, the rail could not be held out by the friction force, so the curve exhibited a linear response, showing a modest increase in weakening by deflecting to approximately 0.42 inches.

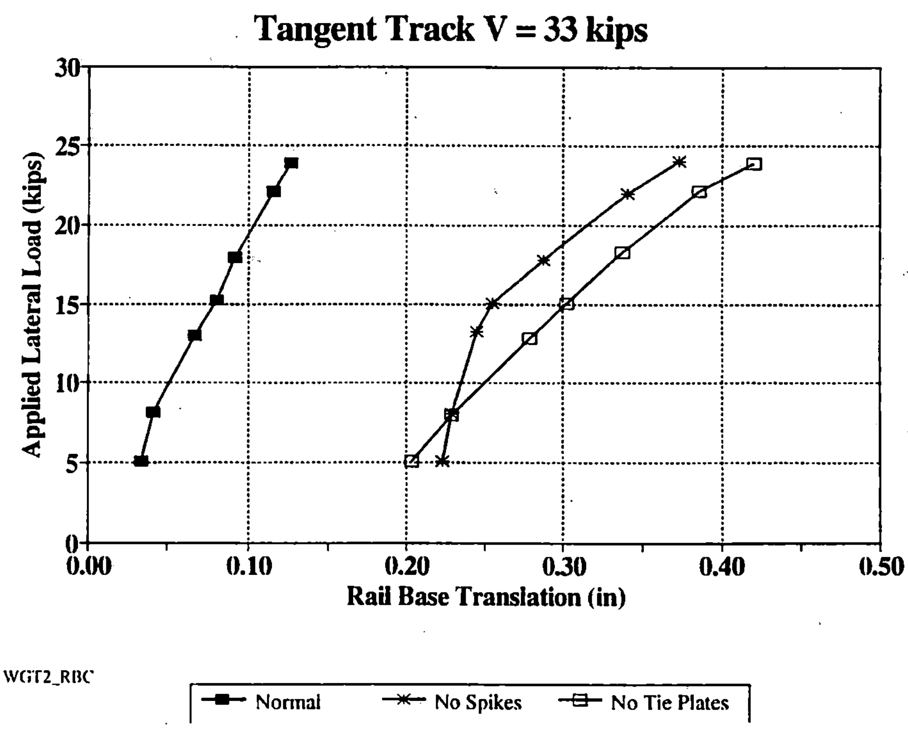


Exhibit 46. Rail Base Load-Deflection Curve on Tangent Track, Artificially Weakened.

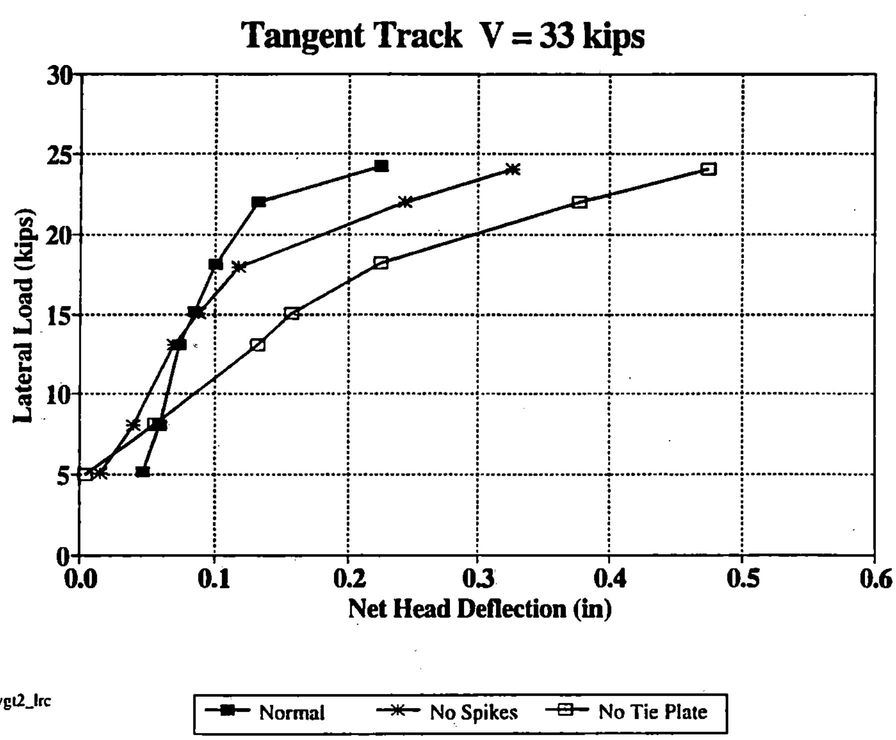


Exhibit 47. Net Head Load-Deflection Curve on Tangent Track, Artificially Weakened.

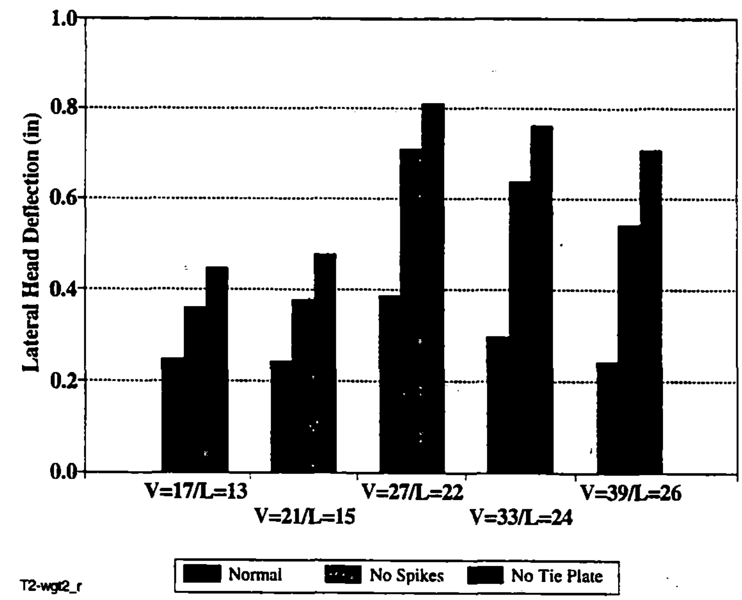


Exhibit 48. Rail Head Deflections on Tangent Track, Artificially Weakened.

	V = 17 L = 13	V = 21 L = 15	V = 27 L = 22	V = 33 L = 24	V = 39 L = 26
No Spikes	46%	45%	83%	114%	123%
No Tie Plate	81%	97%	108%	157%	191%

Exhibit 49. Increase in Head Deflection on Artificially Weakened Tangent Track.

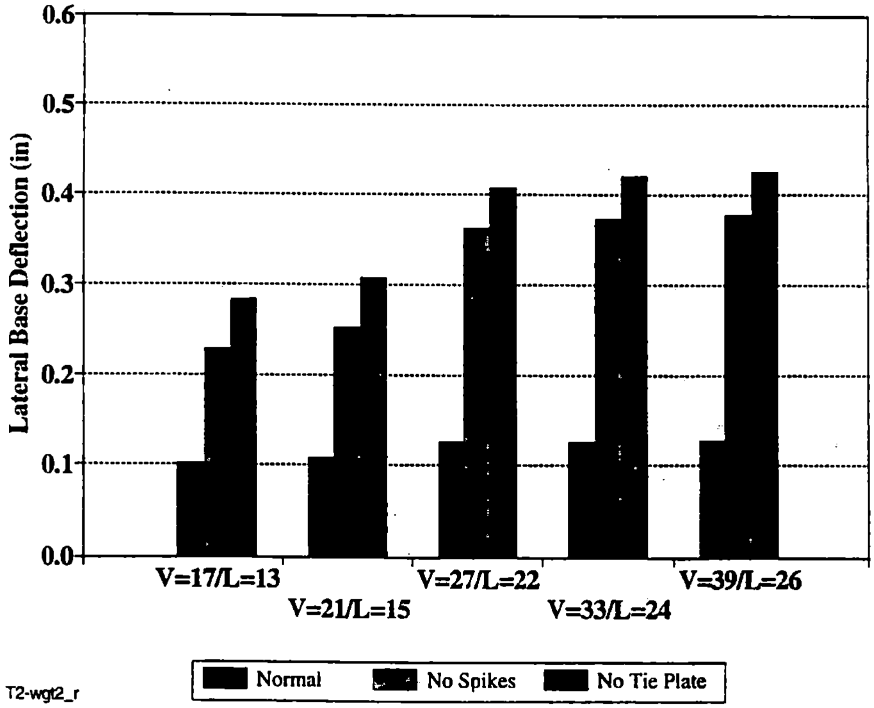


Exhibit 50. Rail Base Deflections on Tangent Track, Artificially Weakened.

	V = 17 L = 13	V = 21 L = 15	V = 27 L = 22	V = 33 L = 24	V = 39 L = 26
No Spikes	122%	132%	188%	194%	123%
No Tie Plate	176%	183%	223%	232%	191%

Exhibit 51. Increase in Base Deflection on Artificially Weakened Tangent Track.

deflections is more dramatic than it is on rail roll.

In Exhibit 50, the lateral base deflection slightly exceeds 0.1 inches under the five test loads with nominal tie/fastener conditions. When the spikes are removed, the lateral translation of rail with respect to the tie more than doubles. The relative magnitude of this deformation appears to depend on the magnitude of the applied lateral load, since the effect of the vertical load on lateral rail translation would be negligible at L/V ratios greater than the coefficient of friction at the rail base/tie plate interface. After the initial sliding across the tie plate, the unsupported rail segment between the three ties deflects laterally as a simply supported beam, and resistance to rail translation comes from the fasteners on adjacent ties. As seen in Exhibit 50, the resulting base deflection increases with lateral load from about 0.2 inches at 13 kips to almost 0.4 inches at 26-kip lateral load. Further deflection of the rail base would be followed by more spike pullout on adjacent tie fasteners.

The effect of spike removal is more subtle on rail roll than it is on rail translation. Theoretically, for unrestrained rail, rail rotation begins when the vector resultant of L and V falls outside the base of the rail. As mentioned above, this condition requires a L/V > 0.65, for 136 lb rail. All five test load combinations were run at L/V ratios greater than 0.65, so that the relative magnitude of the net rail head deflection, indicating rail roll, could also be assessed. Resistance to rail roll is obtained from the geometric section properties of the rail and from the pullout resistance of the gage side fasteners. Under nominal conditions, the rail head lateral translation due to roll, increases with increasing L/V ratios. However, when the spikes are removed, resistance to roll from the fasteners disappears.

As the critical L/V ratio is exceeded, resistance to rail roll comes only from the

5.2 RAIL RESTRAINT CRITERIA TESTS RESULTS

Recent contributions to the prediction of gage widening derailments include the development of criteria to aid in the understanding of lateral rail head deflection. The most commonly used criteria are: rail rollover, lateral load severity, and the Projected Loaded Gage.

5.2.1 Rail Rollover Criterion Test Results

The rail rollover criterion, as used previously by many researchers, implies that derailment occurs as soon as the roll moment about the field side of the rail base changes sign and encourages rail roll. This assumes that no resistance to rail roll is provided by the rail section's torsional rigidity, the fastener system and hold down moments from adjacent axles. Exhibit 54 is an illustration of where the vertical and lateral loads, from the wheel, are applied to the rail. The point of application of these loads produces moments which tend to either push the rail base against the tie plate and tie, or roll the rail about its base corner (field side), depending on the sign of the moment. The roll moment about the base corner is given by,

$$M = L \cdot h - V \cdot d \qquad (1)$$

Where h is the vertical distance and d is the horizontal distance, from the point of application of loads, on the rail head, to the rail base corner. When M has a negative sign, the moment tends to hold down the rail against tie and if M is positive, the moment tries to roll the rail about its base corner. The point at which the rail begins to roll, M is equal to zero and the equation simplifies to,

$$L/V = d/h \qquad (2)$$

to the coefficient of friction, about 0.3, times the vertical load. The magnitude of the applied lateral load, before slip occurred, decreased as the point of application was moved from the center of the rail toward the field side. Several attempts were made to clean the rail head and to increase the coefficient of friction, but they all failed. Therefore, these tests were not pursued any further, and the remaining tests were run with the loads applied at the gage corner of the rail.

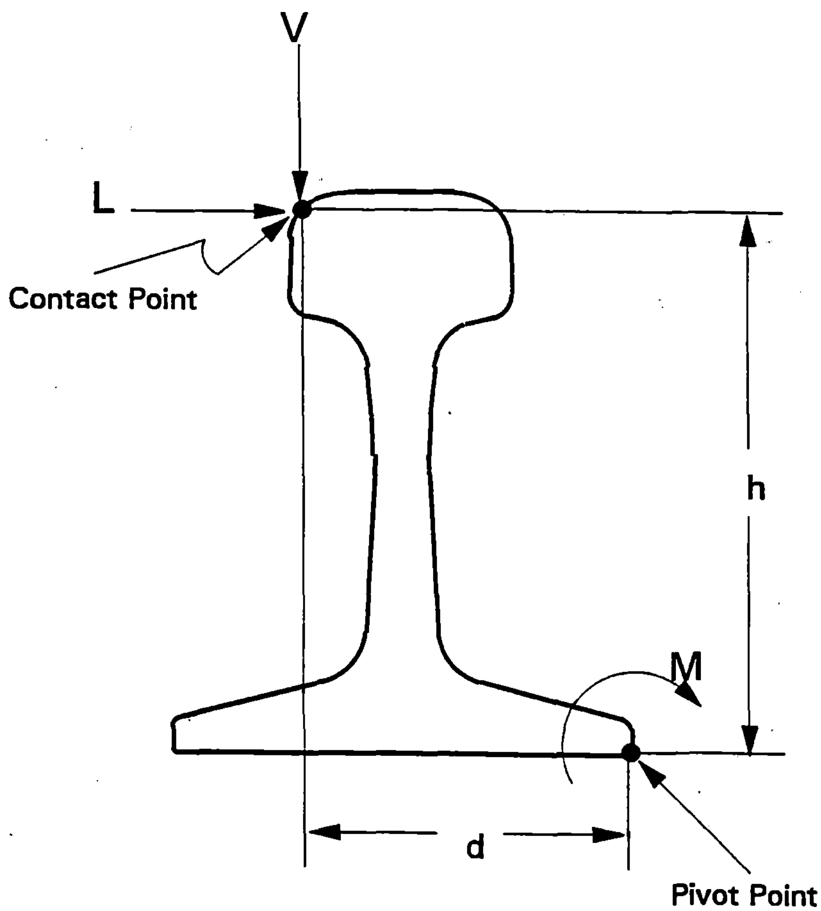


Exhibit 54. Rail Section with Wheel Load Contact Points.

In reality, it is very difficult to roll a properly restrained rail over completely. During the rail rollover tests, L/V ratios were increased to over 1.3, with no failures observed. Exhibit 57 shows the measured rail head deflection, on tangent track, at vertical loads of 20, 27, 33 and 39 kips with L/V ratios of 1.0. Exhibit 58 shows the measured rail head deflection, on curved track, at vertical loads of 20, 27, 33 and 39 kips with L/V ratios of 1.0. Three tangent and three curved track sections were tested, with each rail instrumented, giving a total of 12 rails. Notice that equivalent L/V ratios of 1.0, do not produce the same amount of deflection. At a L/V ratio of one, lower vertical loads produced much less deflection than higher vertical loads, perhaps showing the importance of the magnitude of the lateral load, not the L/V ratio. Also, tangent track showed significantly more deflection than curved track. Lateral head deflections of more than 1.4 inches were measured under 39 kips vertically and 39 kips laterally.

Exhibit 59 shows an example of the load-deflection curves for the lateral rail head, base and vertical base, under a vertical load of 39 kips. At a vertical load of 39 kips, and assuming a d/h ratio of 0.65, the lateral load at which the rail should begin to roll is 25 kips. This lateral load at which the rail begins to roll will be defined as L_0, which is a function of the wheel-rail contact geometry (d/h) and the applied vertical load. In this exhibit, the lateral rail head deflection curve exhibited a dramatic slope change at a lateral load of approximately 26 kips. The rail head has very little deflection up to this lateral load, and then the rail deflection increases dramatically, to over 1.4 inches at a lateral load of 43 kips. The vertical base deflection, a direct measurement of rail roll, indicated about 1.2 inches of spike pullout. The rail base, however, showed very little lateral translation, only 0.1 inches at a lateral load of 43 kips. This type of rail response was found to be typical of others tested at TTC, in which the rail began to roll dramatically at a L/V ratio approximately equal to d/h, but it did not completely roll over, even up to a L/V of 1.10, under 39 kips vertically.

Lateral rail head deflection is produced by two mechanisms: rail roll and lateral rail translation. The contribution to lateral rail head deflection from rail roll is not directly measured: the vertical base deflection does not directly measure the amount of rail head roll that takes place. To determine the contribution of rail roll to the total rail head deflection, the lateral base deflection is subtracted from the lateral head deflection to produce the net head deflection, a synthetic measurement of rail head roll.

Exhibit 60 shows the net head (roll) load-deflection curves for one rail under the vertical loads of 20, 27, 33 and 39 kips, on tangent track. The lateral loads at which the rail should begin to roll L_0, using a d/h ratio of 0.65 and vertical loads of 20, 27, 33 and 39 kips, are 13, 17.5, 21.5 and 25.4 kips, respectively. In this exhibit, the approximate lateral loads at which roll begins, are 13, 17, 20 and 24 kips for vertical loads of 20, 27, 33 and 39 kips vertically, respectively. Again, the rail does not rollover, even up to L/V ratios over one, for vertical loads of 20, 27, 33 and 39 kips. All four curves exhibit a bi-linear relationship up to 0.8 inches of roll. All four curves showed very little roll up to the lateral load L_0. This is due to the fact that the roll moment is negative and therefore the rail is being pushed against a foundation (tie plate and tie) with very high stiffness. Under all four vertical loads, the rail exhibited the same stiffness in the first portion of the bi-linear curve. After L_0, the stiffnesses dropped dramatically, the roll moment became positive and the rail began to roll about its field side base corner. It is believed that during this portion of the load-deflection curve, resistance to roll is provided by the torsional rigidity of the rail and the pull out resistance of the fasteners. When the 20 kip vertical case was run first, the rail rolled to about 0.8 inches. The 27 kip vertical case was run next with the rail rolling more than 0.8 inches at which point a slight increase in rail stiffness was noted. It is believed that this increase resulted from the residual spike pull-out effects introduced from the previous series of tests. In the 33 kip case, the rail rolled to over 0.8 inches, and then the stiffness again increased due to engaging the spikes, and leveled off to produce over 1.2 inches deflection at a lateral load of 43 kips. The last vertical load case, 39 kips, did not induce any stiffening until the rail had rolled to the point of the 33 kip vertical case. The lateral load of 43 kips under 39 kips vertically produced almost the same amount of roll as under 33 kips vertically, almost 1.3 inches.

On curved track, the rail exhibited a little different behavior, although the general trend was similar. Exhibit 61 shows the net head load-deflection curves for the vertical loads of 20, 27, 33 and 39 kips, on curved track. Notice that the initial stiffness (hold-down stiffness) is high, but not as high as the tangent track. The lateral loads at which the rail began to roll L_0, were 10, 15, 19 and 23 kips. These loads were on average lower than those on tangent track, this could be due to different wear on curves, and therefore a different point of contact on the rail head. The second stiffness appears to be stronger on curved track, notice also that the second stiffness of each curve are very comparable up to the point at which the rail engages the spikes again. This second stiffness is probably stronger on curved track because of an additional gage side spike or from an incease in torsional stiffness due to the rail being curved.

Some general observations on the net head load deflection curves, the first stiffness, which will be defined as the hold-down stiffness, does not seem to be a function of vertical load. The rail does not begin full rigid body roll until the roll moment becomes positive or the L/V is greater than d/h. The second stiffness, defined as the roll stiffness, also appears not to be a function of the vertical load as long as the same fastener conditions apply for both. The roll stiffness exhibits an increase when the rail engages the gage side spikes and then returns to a level similar to the one before. Based on these observations, knowing the two stiffnesses and L_0, the net head deflection can be calculated.

The behavior of the lateral translation of the rail, on tangent and curved track, was very similar. Exhibit 62 shows an example of a lateral base load-deflection curve. Notice that the 20 kip vertical case, which was run first, shows a very weak response initially until it reaches 0.08 inches of deflection. This initial response is due to the lateral load overcoming the friction force and the rail base shifting laterally. The friction force, under 20 kips vertically and a coefficient of friction of 0.4, is equal to 8 kips. Then the rail system exhibits a very stiff response, probably due to the rail engaging the tie plate-fastener system. The three other vertical load cases did not exhibit this initial weakness because they were run after the 20 kip case. The vertical load was not removed after the 20 kip vertical case, therefore the rail was held out from its equilibrium position by friction forces generated by the vertical force. The three curves for the 27, 33 and 39 kip vertical load exhibit the same stiff response as the 20 kip case when they engage the tie plate-fastener system.

Attempts to roll the rail were not successful, with L/V ratios exceeding 1.3. Additional tests were conducted under the most severe load combinations in an attempt to roll the rail over.

the linear portion of the load/deflection curve at about 12 kips per inch. Reduction in this stiffness may be attributed largely to the reduction of fastener torsional resistance from spike pullout experienced during previous tests. Increased unloading at the TLV trucks, when the rail loads at the center bogie were increased from 7 to 50 kips, could also have played a role.

Under a load combination of 7-kip vertical and 33-kip lateral, a total of 2.6 inches of lateral rail head deflection was produced. The test was repeated under a 50 kip vertical load, and the same level of lateral deflection was produced when the lateral load reached 44 kips per rail. In either case, under the most severe load combination imposed on the rail, the rail did not overturn or fail dramatically, if one inch spike pullout is not construed as a track failure condition. It is concluded from these tests that a lateral load at a single point, even in the absence of vertical loads on adjacent axles, would not be sufficient to overturn adequately fastened rail, unless there is a local weakness in the rail restraint capacity of the track.

Another series of tests was conducted to investigate the effect of vertical loads from adjacent trucks on gage widening resistance. A section of a shallow (1.5-degrees) curved track, on the TDT, was chosen as site for the test. This track consisted of 136 lb. rail spiked with four spikes per tie to fairly good hardwood ties at 19-inch spacing. The track had originally been constructed for special tests with 39-foot parallel rail joints. The TLV was centered over the test track so only one of the parallel joints would fall between the load bogie and the inboard axle of the leading truck (the distance between the inboard axles of the TLV is about 37 feet). The other pair of rail joints fell under the trailing truck of the TLV.

The rail joints, which were outside the influence zone of the weight on the leading truck, were taken out so that the rail could be rolled. Obviously, this would not only remove the effect of the TLV trucks but also would decrease the torsional resistance from the continuous beam effect of the rail and its spike resistance.

Tests were run with and without the joint bars, in order to quantify the degree of reduction in the resistance of the rail to overturn. Under a 33-kip vertical load, the lateral loads were continuously increased until the rail deflections, measured using wayside instrumentation, became sufficiently large to indicate the reduction in rail restraint.

Exhibits 65 and 66 respectively show the lateral rail head and base deflections for the low and high rails with and without the rail joints in place. With the rail joints, both the left and the right rails exhibit a strong rail restraint response. The left rail, low rail, translates laterally slightly more than 1/8", whereas the right rail translates slightly less than 1/4". Elastic rail twisting and rigid body roll motions along with the lateral rail translation combine to produce 2.15 inches of gage widening at lateral loads in excess of 35 kips. The vertical lift on both rails, as measured on the rail base, was about 5/8", which amounted to a minimal amount of spike pullout.

The hold down stiffness was unaffected by the removal of the rail joints, as expected. However, both the low and high rail's roll stiffness decreased dramatically when the rail joints had been removed, as seen from the load/deflection curves. With the rail joints in place, the slopes of the load deflection curves from the linear segments of the roll zones were computed for linear stiffnesses at approximately 37 kips per inch. Without the rail joints, this stiffness was reduced from 37 to about 19 kips per inch on the low rail within a rail head deflection range from 0.2 to 0.85 inches. Resistance to rail roll was reduced more dramatically on the

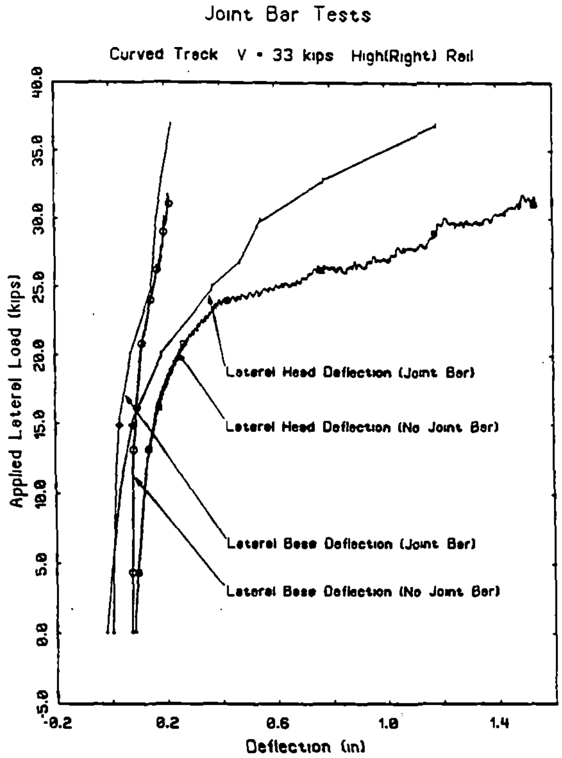


Exhibit 65. Joint Bar Tests and Effect of Loads on Adjacent Axles on Wheel Drop Derailment, Low Rail.

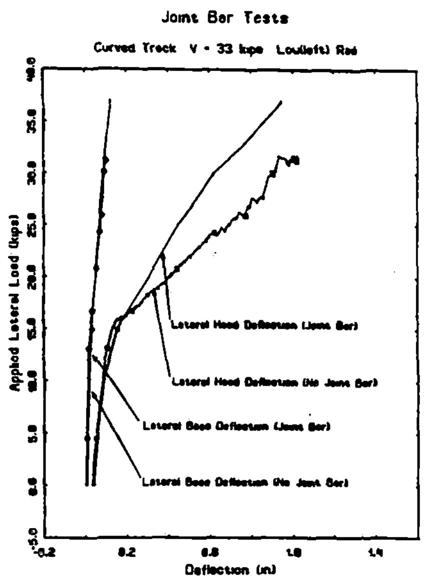


Exhibit 66. Joint Bar Tests and Effect of Loads on Adjacent Axles on Wheel Drop Derailment, High Rail.

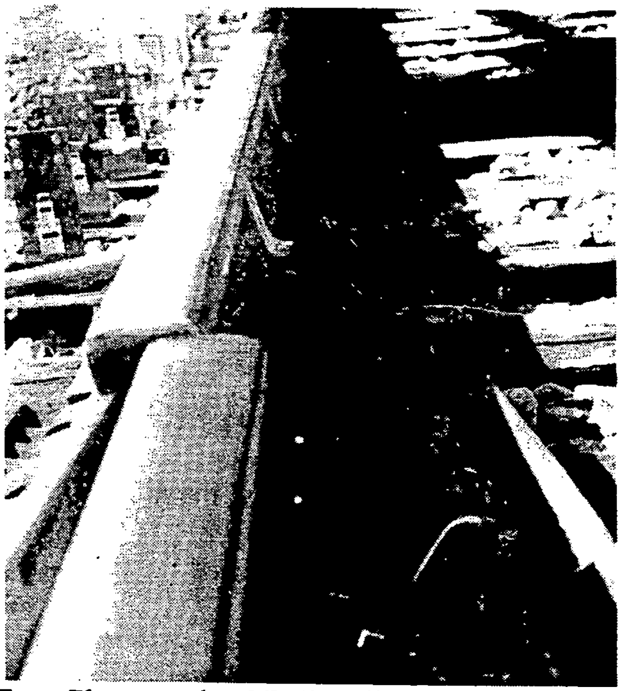


Exhibit 67. Photograph of Rail Rollover During Joint Bar Removal Tests.

Exhibit 68. Photograph of Low Quality Track Location.

While the lateral rail strength may change as the point of load application is moved away from the instrumentation and the effect of the TLV leading and trailing trucks is not known, these tests do show the localized nature of gage widening.

As described in the section on rail rollover criterion, the rail does begin to roll about its field side base corner, when the lateral load overcomes the hold-down moment from the vertical load, but it does not completely rollover. A single lateral load, (in combination with a vertical load) applied at a single point in the track, is very unlikely to cause a rail to overturn. Test results showed that long lengths of rigidly connected rail fastened to conventional ties in a conventional manner, together with the vertical loads applied by adjacent trucks, appears to provide adequate rail restraint capability at load levels over and beyond those loads which can be expected in revenue service. Tests carried out to failure showed that in order to overturn the rail, it is necessary to disconnect either or both ends of the rails between the trucks, pullout all the gage spikes between the disconnected ends of the rail, and apply positive overturning moments to the rail.

Derailments due to rail overturning are commonly reported by the railroads. In recent years, a number of serious derailments characterized by rail rollover have taken place on several major railroads. Investigations into the cause of these derailments pointed to rail overturning due to lateral loading. However, it is not clear whether or not these derailments occur due to dynamic gage widening followed by rail overturning. The TLV results indicate that rail overturning is very unlikely to occur, even at L/V ratios well beyond the levels proposed under the "rail rollover criterion". In fact, this criterion only addresses the geometrical properties of the rail section as affected by the hold-down mechanism provided by the vertical force. Rail overturning is a limiting case of rail roll, and it occurs when the

5.2.2 Lateral Load Severity Criterion Tests

In a study previously undertaken by the AAR, controlled tests were carried out to assess what effect the vertical and lateral loads have on rail deflection[20]. The theory was to try and simplify the relationship between rail deflection and the vertical and lateral loads applied to the rail. It was hypothesized, for significant lateral rail deflections and a fixed point of contact between the wheel and the rail, the effective lateral load available for deflection of the rail is the applied lateral load reduced by an amount proportional to the vertical load,

$$S = L - c \cdot V \qquad (3)$$

where,

S = Lateral Load Severity

L = Applied Lateral Load

V = Applied Vertical Load

c = Coefficient of Friction

An explanation of this behavior is that the lateral load severity is less than the applied lateral load by an amount due to friction at the rail-tie plate and tie interface. Data was taken from five sets of field and laboratory static tests to validate this concept. Data was analyzed by plotting points of constant deflection as a function of the applied vertical and lateral loads. Linear regression through these points showed that indeed this concept did exist, with the slopes of these lines being equivalent to the coefficient of friction. Moving tests were performed as well, measuring the combined deflection of both rails, termed gage widening. Results showed a linear relationship between gage widening and the load severity, using an

Exhibit 71 shows the measured lateral head deflection on a typical tie, for L/V ratios from 0.5 to 0.8. Notice that the same L/V ratio does not produce the same amount of deflection, as the vertical load is increased the deflection increases as well. In fact, at higher L/V ratios this increase is much more pronounced.

Exhibit 72 shows a lateral head load-deflection curve for a typical tie, which was on tangent track. At each vertical load, the slope of each curve seems to be decreasing initially and then it levels out. The initial slopes do not appear to be parallel, after the curves level out, the slopes on each curve seem to be parallel.

The load severity concept is based on an estimated coefficient of friction (c). Since the coefficient of friction is hard to measure accurately, to calculate the load severity (S), a trial and error process was used to estimate the coefficient of friction. The lateral head load severity deflection curves were produced with values of c ranging from 0.1 to 0.6.

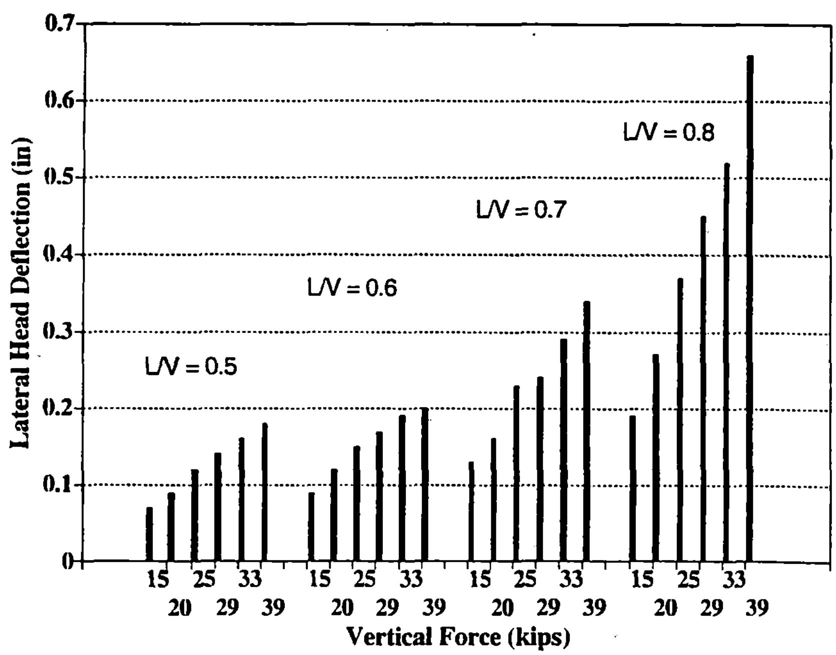


Exhibit 71. Typical Measured Lateral Head Deflections at Various L/V Ratios.

non-linearities observed in the first portion of the curve cannot be explained using the lateral load severity concept.

Exhibit 74 shows the lateral base load-deflection curves for a typical tie during these tests. Notice that in this plot, the base deflection does not seem to be a function of vertical load at all, only the lateral load. Note, this may be due to the fact that the vertical load was not removed altogether before increasing it to the next test load level. This could cause the rail to be held out by the friction forces and change its load-deflection characteristics. Also, the tie conditions observed at TTC were excellent, resulting in the rail not sliding but engaging the tie plate-fastener system instantaneously, which was found to be very stiff. If the rail base translation is not a function of load severity, and the constant (c) is not the coefficient of friction, then what is causing the linear relationship between load severity and the head deflection?

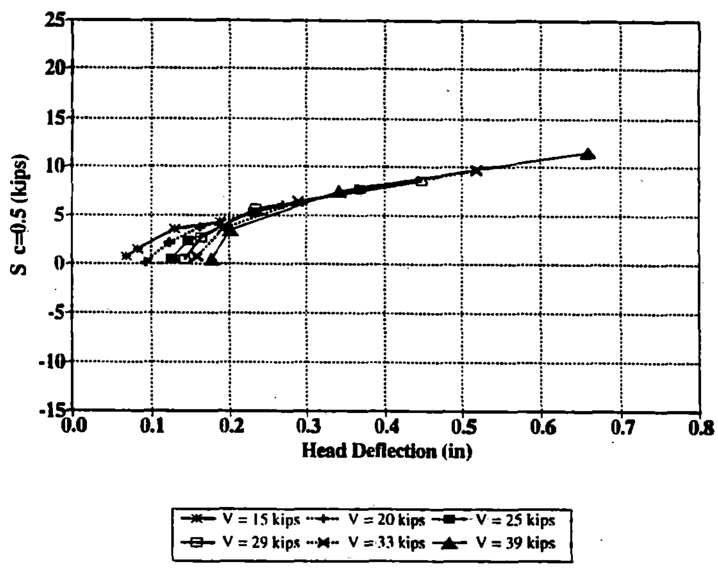


Exhibit 73. Typical Lateral Head Load Severity Load-Deflection Curve (c=0.5).

lines of constant net head deflection (roll), for a typical tie. Notice that for the deflection of 0.1 inches, the line appears non-linear and the slope (which represents the constant c) is very shallow. For deflections from 0.2 to 0.7 inches, the lines are fairly parallel. Once the deflection is increased to 0.8 inches and above, the lines of constant deflection have slopes which are negative. The reason that the slopes become negative may be due to the fact that during tests with high vertical loads, the 33 kip vertical load case was run first, thereby pulling the gage side spikes out a certain amount. Then, when the 39 kip vertical load case was run, it took less lateral load to produce the same amount of deflection because the rail did not engage the spikes.

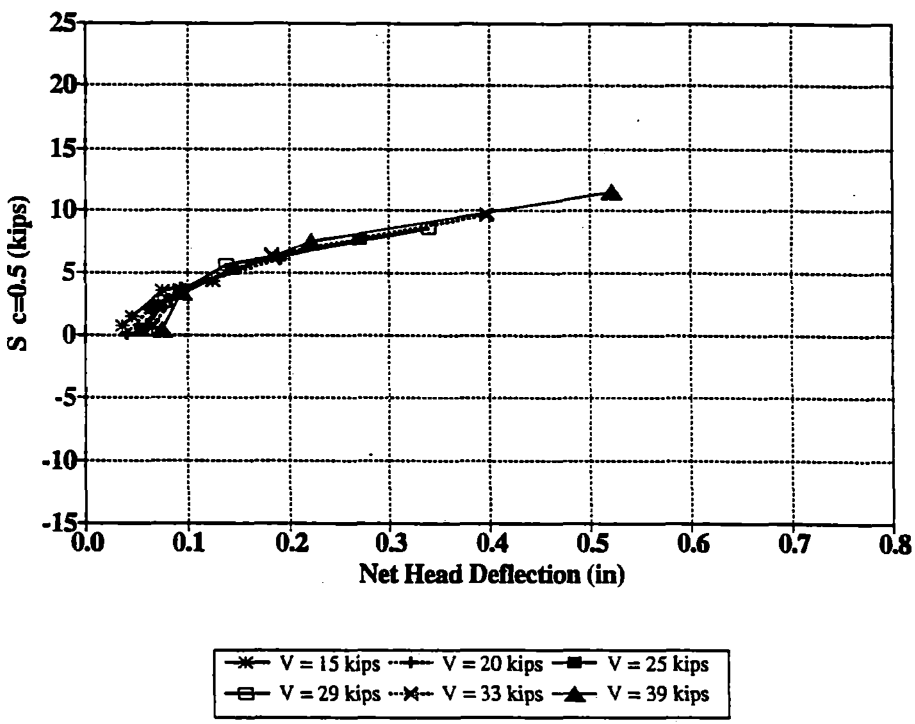


Exhibit 75. Typical Net Head Load Severity-Deflection Curve (c=0.5).

All of the analysis discussed so far has been on the topic of the deflection of an individual rail. Gage widening, which is the combined deflection of both rails, and its relationship with load severity was explored as well during these tests. A series of moving tests were conducted on a four hundred foot long tangent section of the Balloon Loop, on which the static tests were performed as well. A series of lateral loads were applied to the track under vertical loads of 15, 20, 25, 29, 33 and 39 kips, representing L/V ratios of 0.5, 0.6 and 0.7. The TLV conducted these tests by applying these various vertical and lateral loads to the track, while travelling at a speed of 20 mph, and measuring loaded and unloaded gage.

Delta gage was calculated continuously along the test section by subtracting unloaded from loaded gage. Delta gage is a combined measurement of each rail's lateral head deflection. With this type of measurement, it is impossible to determine each individual rail's contribution to delta gage or the contribution from rail translation and roll to the rail head deflection. Exhibit 78 shows the mean delta gage, over the 400 foot long tangent section, measured under vertical loads from 15 to 39 kips, with L/V ratios from 0.5 to 0.7. Notice that lines appear linear and parallel. Since rail head deflection appeared to be a linear function of the load severity during static tests, would delta gage, the combined deflection of both rails during moving tests, be as well? Exhibit 79 shows delta gage vs. load severity for the same moving tests, and an assumed coefficient (c) of 0.5. Notice that the parallel lines now fall on top of each other, and the delta gage appears to be a linear function of the load severity.

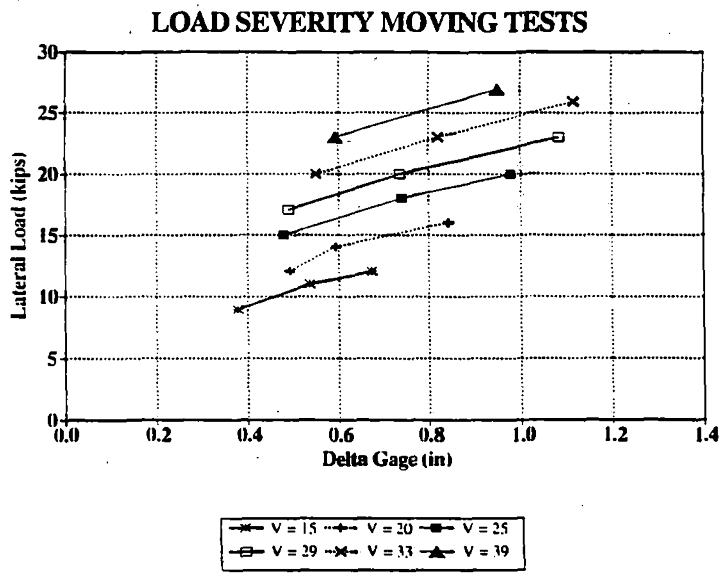


Exhibit 78. Lateral Load vs Delta Gage Curve for Moving Tests on Tangent Track.

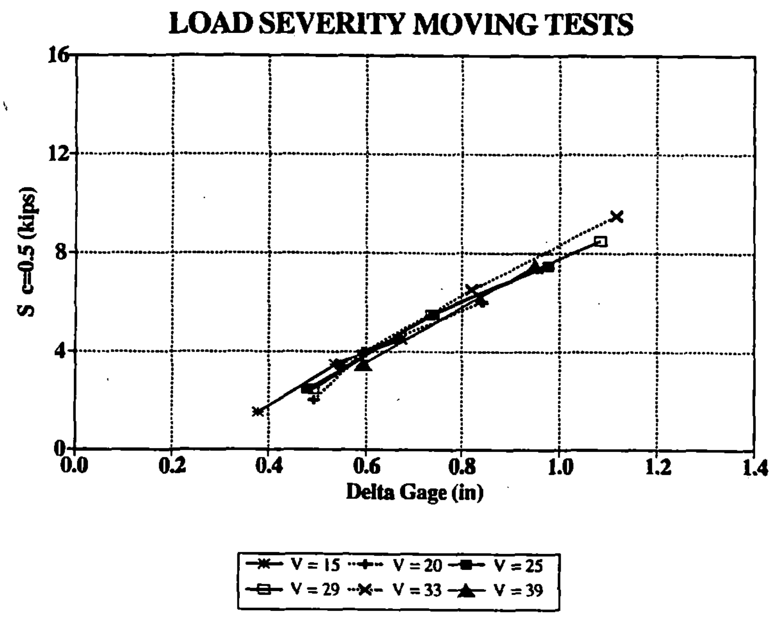


Exhibit 79. Load Severity (c=0.50) vs Delta Gage Curve for Moving Tests on Tangent Track.

and were developed from the lines of constant rail head deflection. These equations give the extrapolation factor for test loads of 17 kips vertically and a lateral load (L) to the extreme loading conditions of 32 kips vertically with 24 kips laterally (A_{24}) and 32 kips laterally (A_{33}).

$$A_{24} = (0.574 - 3.40/L + 254/L^2) \tag{5}$$

$$A_{33} = (1.1 - 11.4/L + 440/L^2) \tag{6}$$

The GRMS currently applies loads of 17 kips vertically and 13 kips laterally, which would coincide with extrapolation factors of:

$$A_{24} = 1.82$$

$$A_{33} = 2.83$$

The extrapolation factors given in Equations 5 and 6 are currently in use by the GRMS to predict a potential wheel drop condition under assumed worst case revenue service loads. During testing, the lateral loads applied at the wheel/rail interface are measured using instrumented wheels and the extrapolation factor is computed continuously along the track at a test speed of 25 mph. Currently, the applied vertical loads are not measured by the GRMS, and not used in the computation of the extrapolation factors. Therefore, Equations 5 and 6 are only valid for an average vertical load of 17 kips.

The primary purpose of the GRMS is to demonstrate the use of an automated track inspection technique to measure the performance of tie/fastener systems as the basis for an alternative to the current Track Safety Standards on gage widening. The proposed concept of "Projected Loaded Gage" as the limiting value of track gage leading to wheel drop derailment is the most promising derailment criterion currently available. However, the determination of the adequacy of the lateral restraint of the rail using the PLG requires further consideration.

fastened to 7″ x 9″ x 9′ softwood ties, spaced at 19″, on slag ballast. All three tangent sections had 4 cut spikes per tie plate.

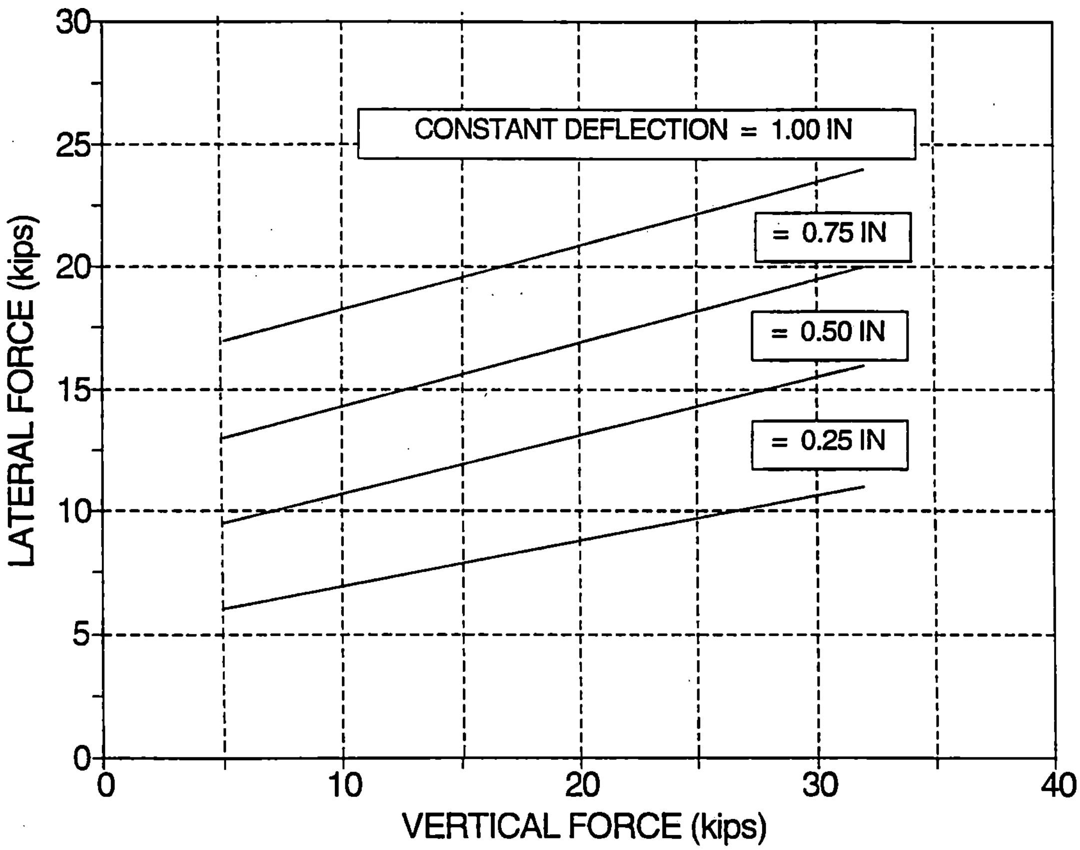
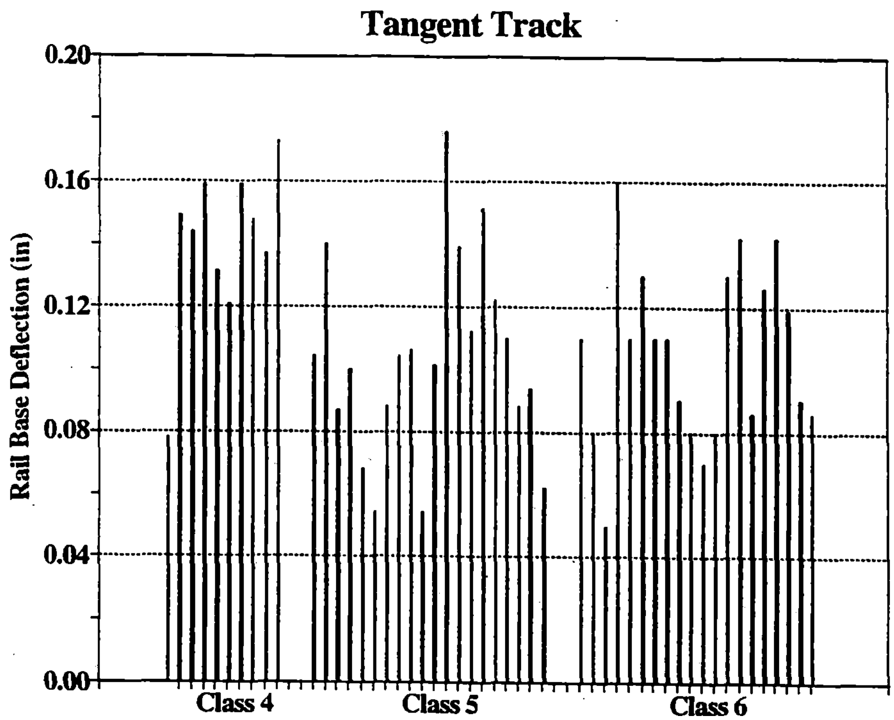


Exhibit 80. Lines of Constant Rail Head Deflection as a Function of Lateral and Vertical Load as Produced by VNTSC.

than 20% of the total rail head deflection. Exhibit 84 shows the calculated net rail head deflection and statistics as a function of track class, on tangent track. Net rail head deflection is calculated by subtracting the base from the head deflection which results in an indirect measurement of rail roll. Tests show that on good track, net head deflection or rail roll does contribute a significant amount to the total rail head deflection, (i.e. 80 to 90%). As seen in Exhibit 84, the deflection does vary significantly within each track class and between each track class due to varying tie and fastener conditions. On tangent track, net rail head deflection dropped significantly as the track class increased.



	TANGENT		
	CLASS 4	CLASS 5	CLASS 6
MEAN	.140 (in)	.103	.105
STD	.025	.031	.027
MAX	.173	.176	.160
MIN	.078	.054	.050

Exhibit 83. Measured Rail Base Deflection and Statistics-Tangent; V = 33, L = 33.

As described earlier, lateral rail head deflection can result from two different mechanisms: roll (indirectly measured as net rail head deflection) and rail base translation. To gain a better understanding of these two mechanisms, a general discussion will follow on some of the test results. Exhibit 85 shows an example of an individual rail's net head load-deflection curve, on Class 5 track. This curve exhibits a bi-linear shape, the first portion of this curve exhibits a very stiff response, resulting from rail twisting and bending on its foundation (tie plate and tie), which is referred to as the rail "hold down" stiffness. Once the lateral load overcomes the hold down moment from the vertical load, the rail exhibits a much weaker response, and this is observed in the second portion of the curve. This second stiffness, or "roll" stiffness, is a result of the torsional stiffness of the rail and the pullout resistance of the gage side spikes. As discussed earlier, although the magnitude of the vertical load determines the point of transition from the first stiffness to the second, on the bi-linear curve, it does not appear to affect the magnitude of these stiffnesses.

Because of this, the net rail head deflection can be predicted, at various lateral loads, for vertical loads below the test vertical loads of 33 and 39 kips.

Exhibit 86 shows two typical rail base load-deflection curves, on Class 5 track, under 33 kips vertically. Notice that initially both rails exhibit very stiff responses, almost no deflection occurs up to approximately 13 kips at which the lateral load overcomes the friction force developed at the rail-tie plate and tie plate-tie interface.

The rail then engages the tie plate-fastener system, after which the two curves exhibit very different responses, this is believed to be due to the differences in the lateral strength of the two different tie plate-fastener systems. The first rail's base deflects to 0.08 inches while the second rail deflects to over 0.160 inches. Exhibit 87 shows a lateral base load-deflection curve in which a lateral shift occurs when the lateral load overcomes the friction force, estimated at 13 kips. This amounts to almost 0.040 inches of deflection, and is believed to be due to a gap and/or slack in the tie plate-fastener system. Also, this shift does not always occur instantaneously. This type of shift was not experienced often on these tests because of the quality of track at TTC, but it has been experienced during other tests on track of lesser quality.

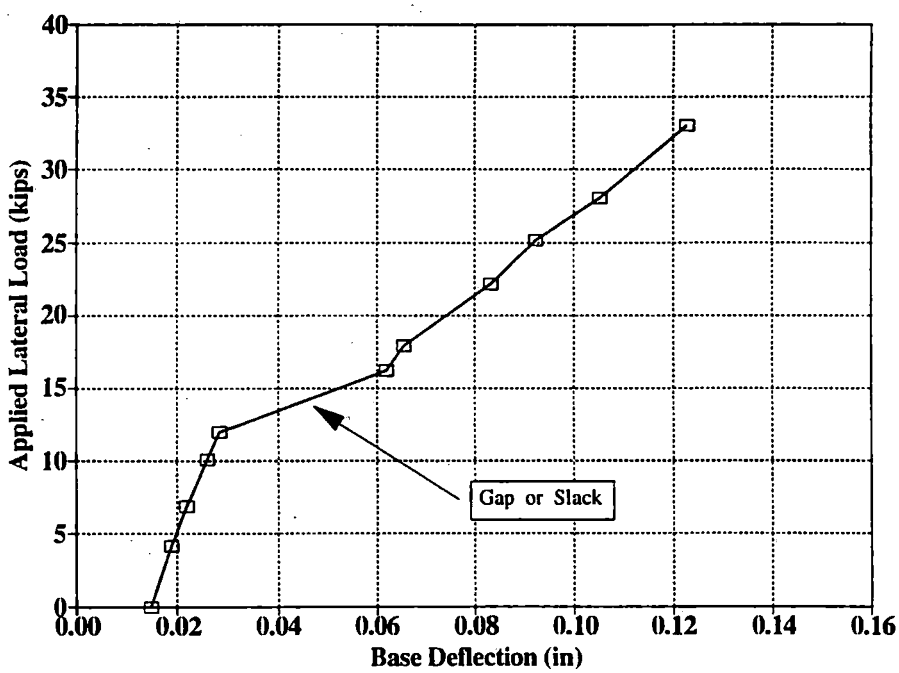


Exhibit 87. Example of Shift in the Rail Base Load-Deflection Curve.

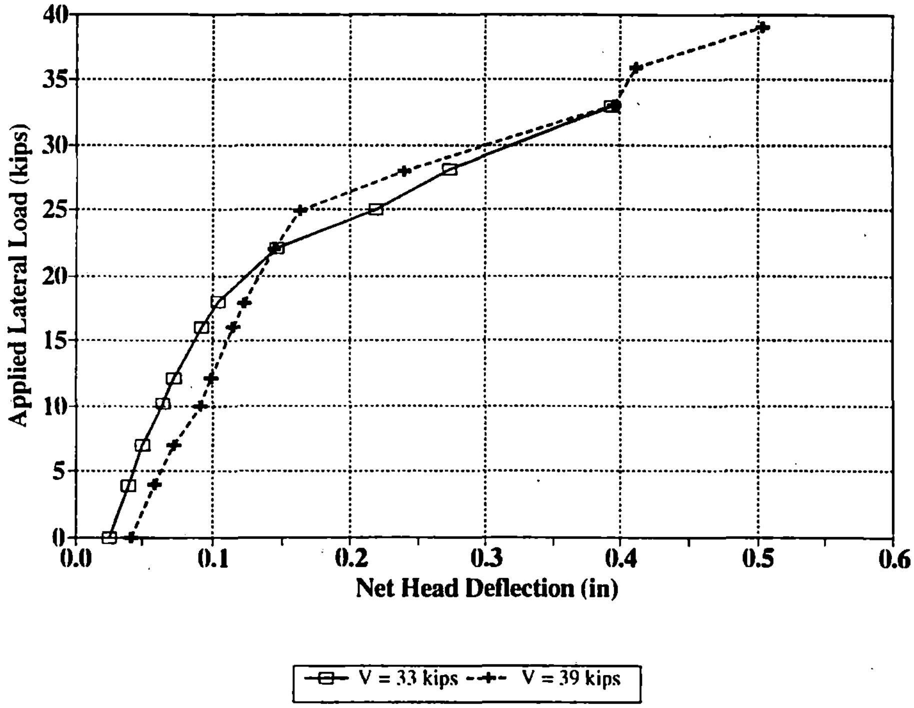


Exhibit 88. Example of the Static Net Rail Head Load-Deflection Curve Under 33 & 39 kips Vertically.

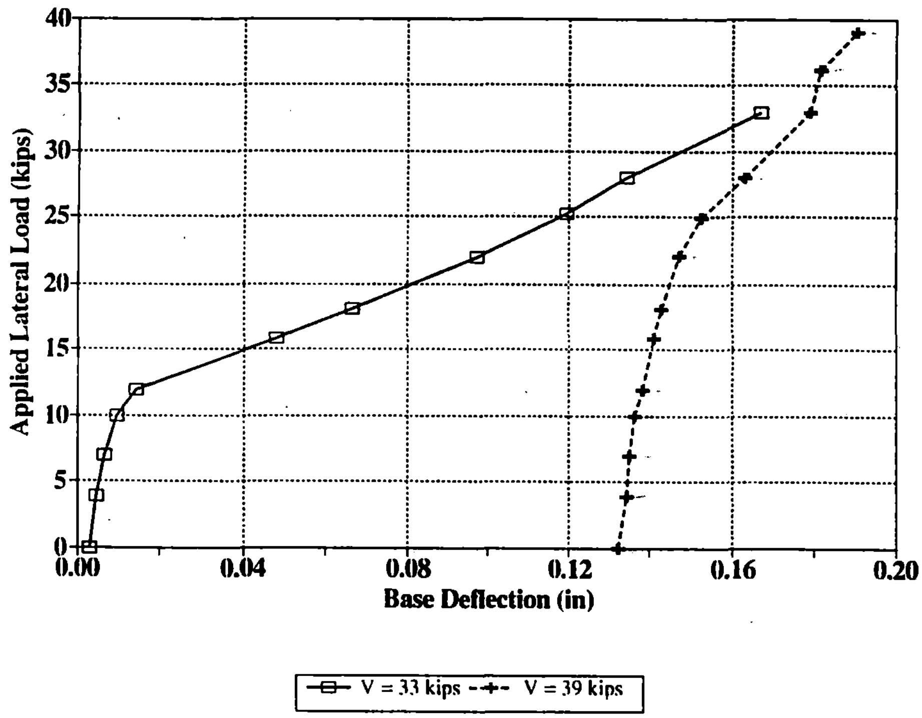


Exhibit 89. Example of the Static Rail Base Load-Deflection Curve Under 33 & 39 kips Vertically.

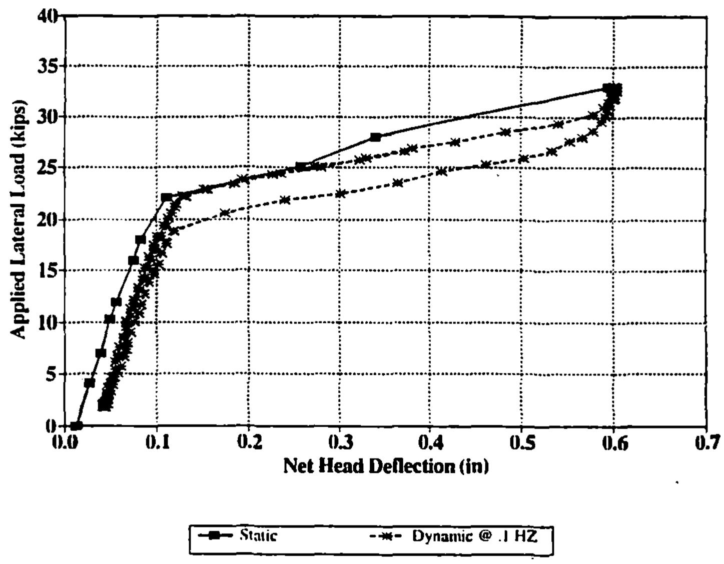


Exhibit 90. Example of the Static and Dynamic Net Rail Head Load-Deflection Curves Under V = 33 kips.

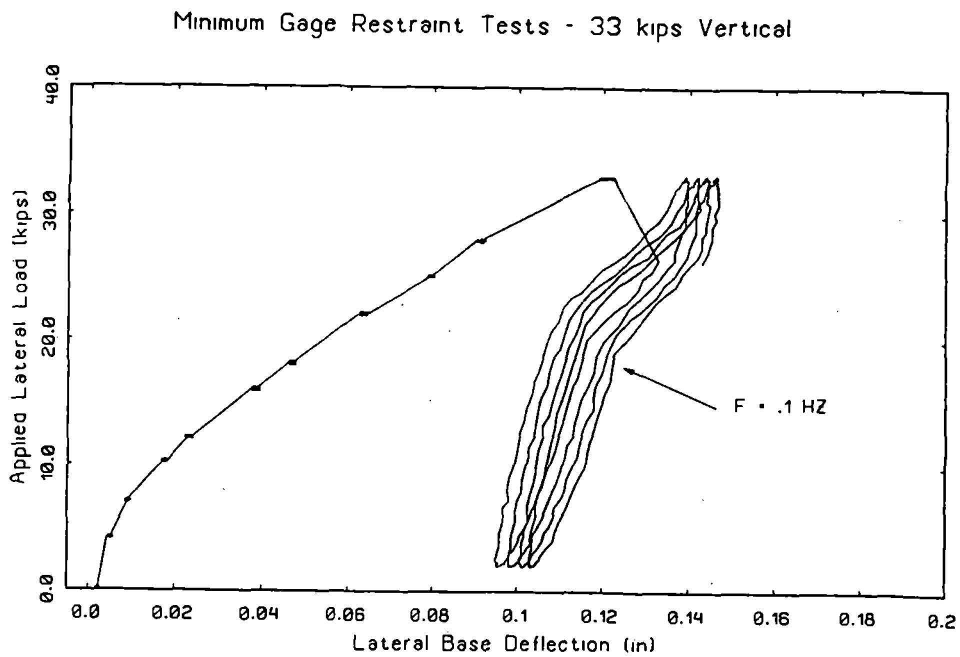


Exhibit 91. Example of Static and Dynamic Rail Base Load-Deflection Curves Under V = 33 kips.

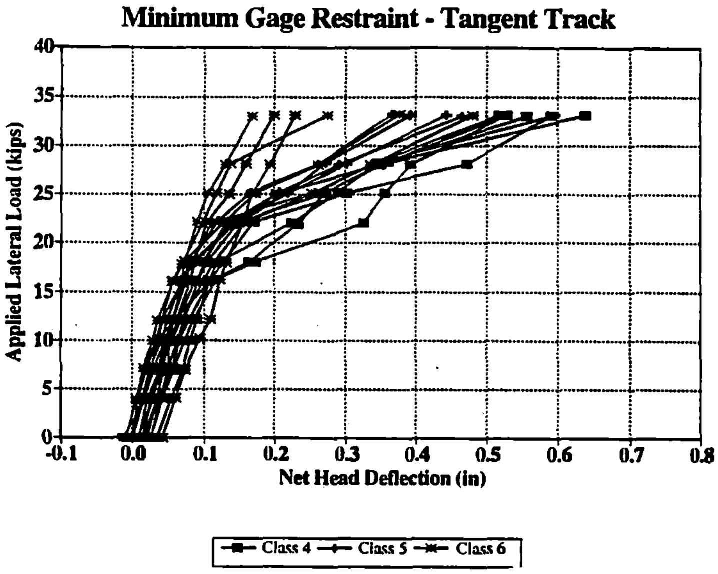


Exhibit 92. Static Net Rail Head Load-Deflection Curves for Tangent Track Minimum Gage Restraint Tests.

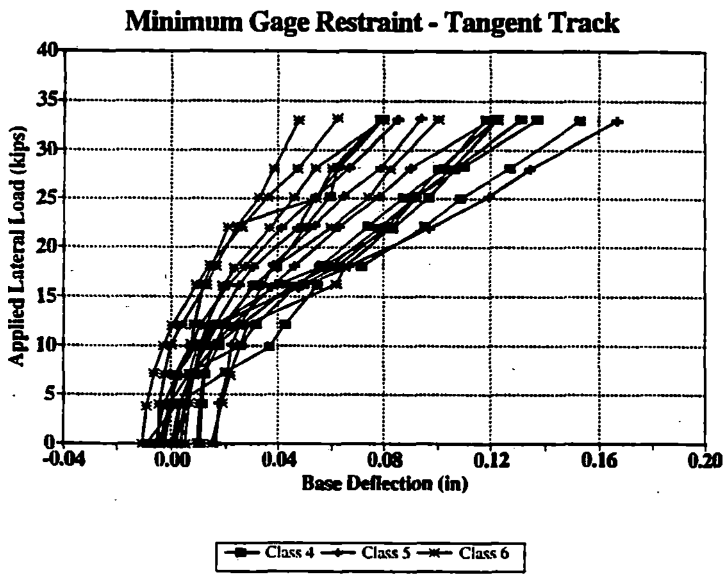
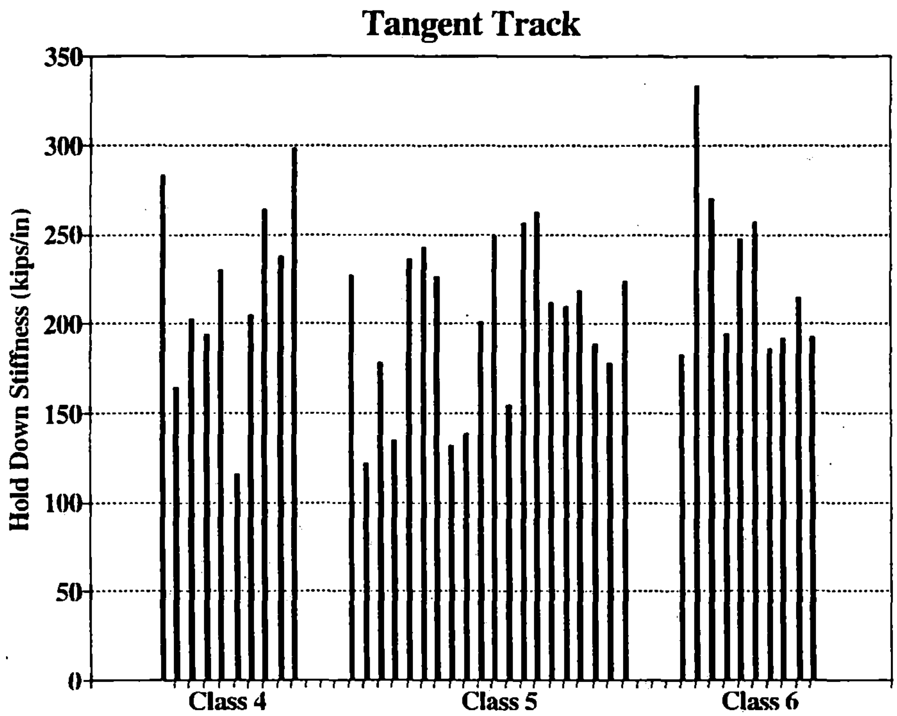


Exhibit 93. Static Rail Base Load-Deflection Curves for Tangent Track Minimum Gage Restraint Tests.



	TANGENT TRACK		
	CLASS 4	CLASS 5	CLASS 6
MEAN	219.1	199.3	226.6
STD	52.7	43.1	46.8
MAX	298.0	262.3	333.0
MIN	114.8	121.6	182.1

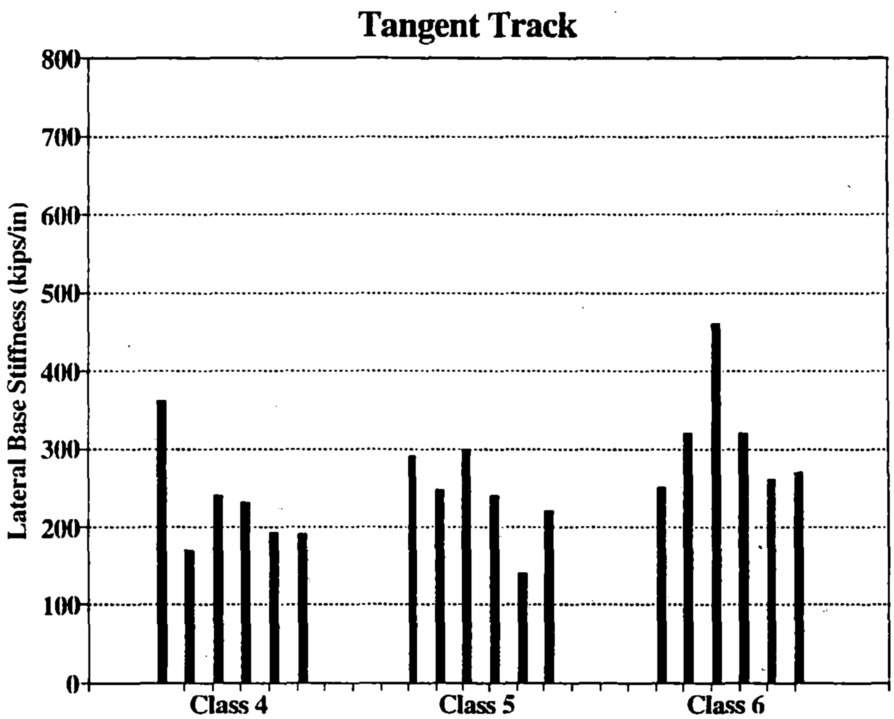
Exhibit 94. Calculated Hold Down Stiffnesses and Statistics on Tangent Track.

track the average lateral load at which rigid body roll begins (L_0) appears to increase as a function of track class. The mean L_0, as measured on each tangent section was 19.6, 21.8 and 22.4 kips on Class 4, 5 and 6 track, respectively.

Exhibit 97 shows the lateral base stiffness and statistics, as computed from the lateral base load-deflection curve, at each rail and tie location for the three classes of tangent track. The Class 6 location had relatively higher stiffnesses than Class 4 and 5 track. The mean lateral base stiffnesses were 230.5,239.4 and 313.3 kips/in on Class 4, 5 and 6 tangent track, respectively.

Exhibit 98 shows the break friction forces (L_f) and statistics, as computed from the lateral rail base load deflection curve, at each rail and tie location for the three classes of tangent track. The mean, which increased as a function of track class, was measured to be 8.5, 12.8 and 14.3 kips on Class 4, 5 and 6 tangent track, respectively.

On Class 4 tangent track, two rails showed rail base shift of 0.01 inches, while the rest showed relatively no shift. On Class 5 track, only one rail showed a shift, with a magnitude of 0.05 inches, the maximum on tangent track. On Class 6 track, two rails showed shift, with magnitudes of 0.04 and 0.02 inches. Most of the rails tested showed relatively no lateral base shift, perhaps due to the quality of the track. On tangent track, the mean amount of lateral shift taking place was calculated to be the same on all three classes of track, 0.01 inches.



	TANGENT TRACK		
	CLASS 4	CLASS 5	CLASS 6
MEAN	230.5	239.4	313.3
STD	62.7	52.5	71.1
MAX	360	300	460
MIN	170	140	250

Exhibit 97. Measured Lateral Base Stiffnesses and Statistics on Tangent Track.

Based upon the preceding measured parameters, an analytical expression can be used to calculate the mean lateral rail head deflection for the three classes of tangent track. The total rail head deflection can be calculated using:

$$\delta_H = \delta_N + \delta_B \tag{7}$$

where,

δ_H = Lateral Rail Head Translation

δ_N = Net Rail Head Deflection (Roll)

δ_B = Lateral Base Deflection

Net head deflection for lateral loads above L_0 can be calculated using:

$$\delta_N = L_0/k_H + (L - L_0)/k_R \text{ , for } L \geq L_0 \tag{8}$$

where,

L = Applied Lateral Load

V = Applied Vertical Load

k_H = Hold Down Stiffness

k_R = Roll Stiffness

$L_0 = (d/h) * V$

From Exhibit 54 and the rail rollover criteria test results section, L_0 is defined as the lateral load needed to overcome the hold down moment from the vertical load, d is the horizontal distance and h is the vertical distance from the field side rail base corner to the point of contact between the rail and the wheel.

Lateral base deflection for lateral loads above L_F can be calculated using:

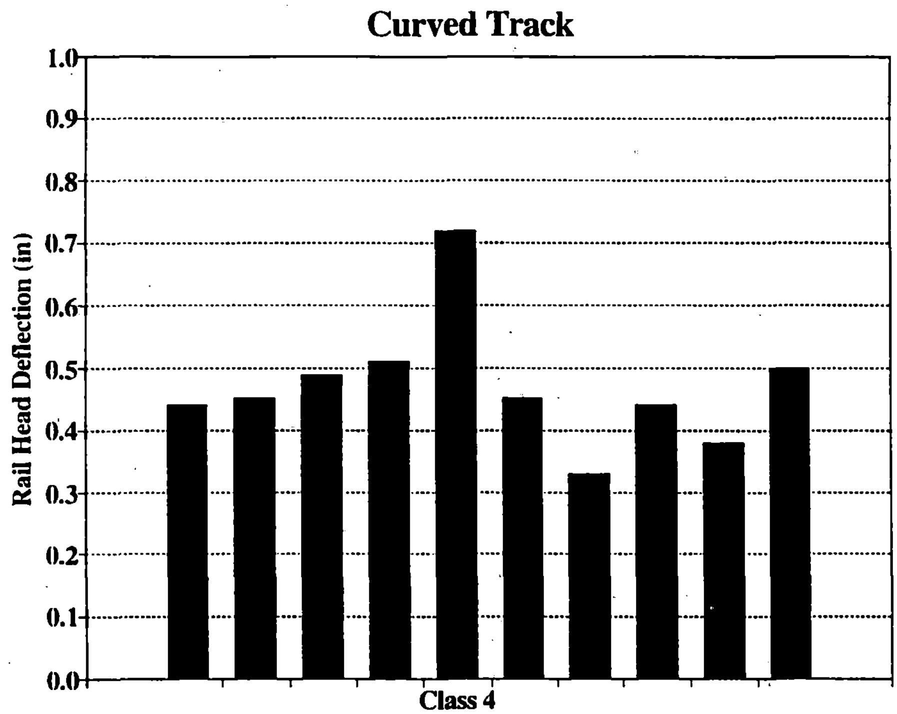
$$\delta_B = \text{Shift} + (L - L_F)/k_B \text{ , for } L \geq L_F \tag{9}$$

the data points. Similarly, mean +/- two standard deviations would cover 95% of all the data points.

CLASS 4	δ_H (in) V=17,L=13	δ_H (in) V=33,L=24	δ_H (in) V=33,L=33	A_{24}	A_{33}
Mean - STD	0.122	0.198	0.482	1.62	3.94
Mean	0.194	0.319	0.669	1.64	3.45
Mean + STD	0.320	0.537	1.105	1.68	3.17
CLASS 5					
Mean - STD	0.084	0.136	0.335	1.62	3.98
Mean	0.140	0.225	0.502	1.60	3.58
Mean + STD	0.260	0.414	0.876	1.59	3.37
CLASS 6					
Mean - STD	0.063	0.105	0.229	1.67	3.65
Mean	0.106	0.169	0.364	1.60	3.44
Mean + STD	0.230	0.350	0.851	1.52	3.70

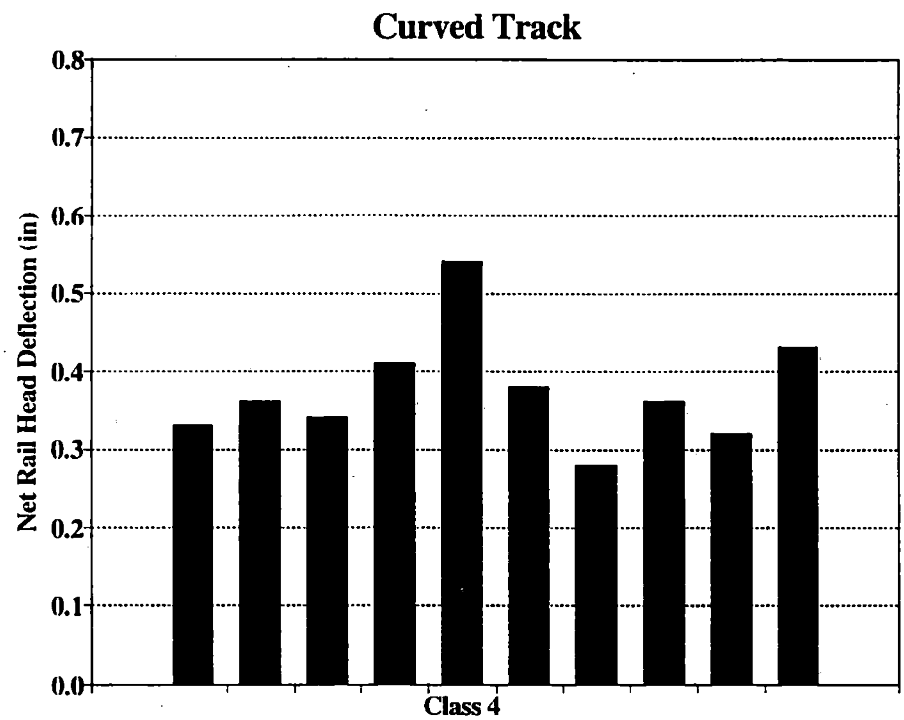
Exhibit 99. Calculated Rail Head Deflections and Extrapolation Factors for Tangent Track.

Using Equations (5) and (6) the GRMS extrapolation factors, A_{24} and A_{33}, can be computed as 1.82 and 2.83, respectively. The GRMS extrapolation factor A_{24} is higher than those predicted by the TLV tests while the GRMS extrapolation factor A_{33} is lower on average than those given in Exhibit 99. The extrapolation factor A_{24} did not vary much on tangent track, from 1.52 to 1.68, while A_{33}, varied between 3.17 and 3.98 (See Exhbit 99). Therefore, on these tangent track sections, it is more accurate to use extrapolation factors to calculate deflections at 24 kips laterally than 33 kips laterally, under 33 kips vertically.



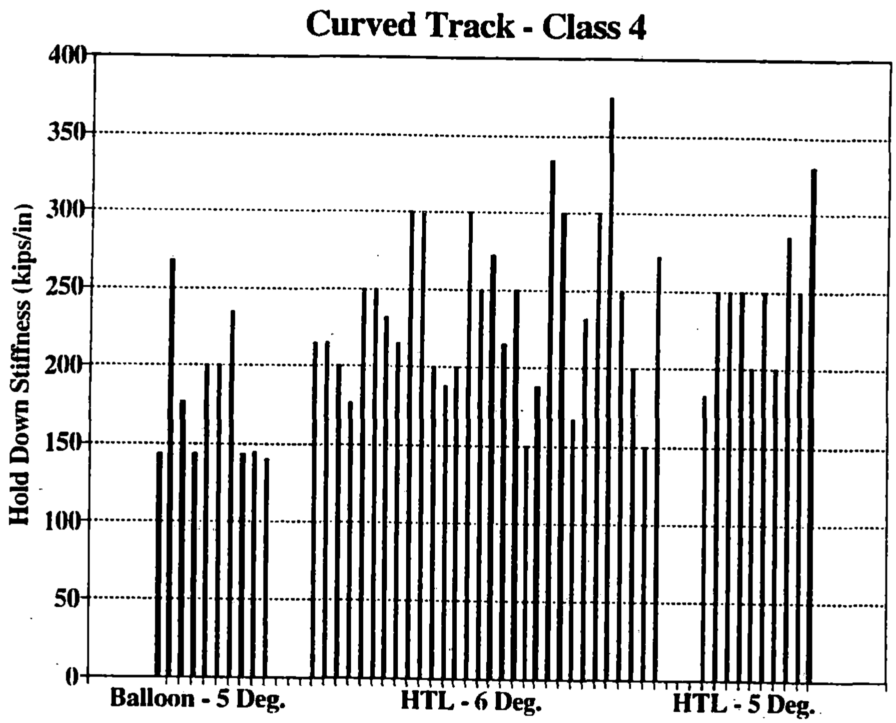
CURVED TRACK CLASS 4	
MEAN	0.471 (in)
STD	0.098
MAX	0.720
MIN	0.330

Exhibit 100. Measured Lateral Rail Head Deflection and Statistics- Curved ; V=33, L=33.



CURVED TRACK CLASS 4	
MEAN	0.375 (in)
STD	0.069
MAX	0.540
MIN	0.280

Exhibit 102. Calculated Net Rail Head Deflection and Statistics- Curved; V = 33, L = 33.



	CLASS 4 CURVED TRACK		
	BALLOON-5 DEG.	HTL - 6 DEG.	HTL - 5 DEG.
MEAN	179.1	238.0	244.7
STD	42.9	54.1	41.2
MAX	267.0	375.0	330.0
MIN	140.0	150.0	182.0

Exhibit 103. Calculated Hold Down Stiffnesses and Statistics on Class 4 Curved Track.

stiffnesses were 58.2, 66.2 and 61.1 kips/in, on the Balloon Loop, HTL - 6 degree curve and HTL - 5 degree curve, respectively.

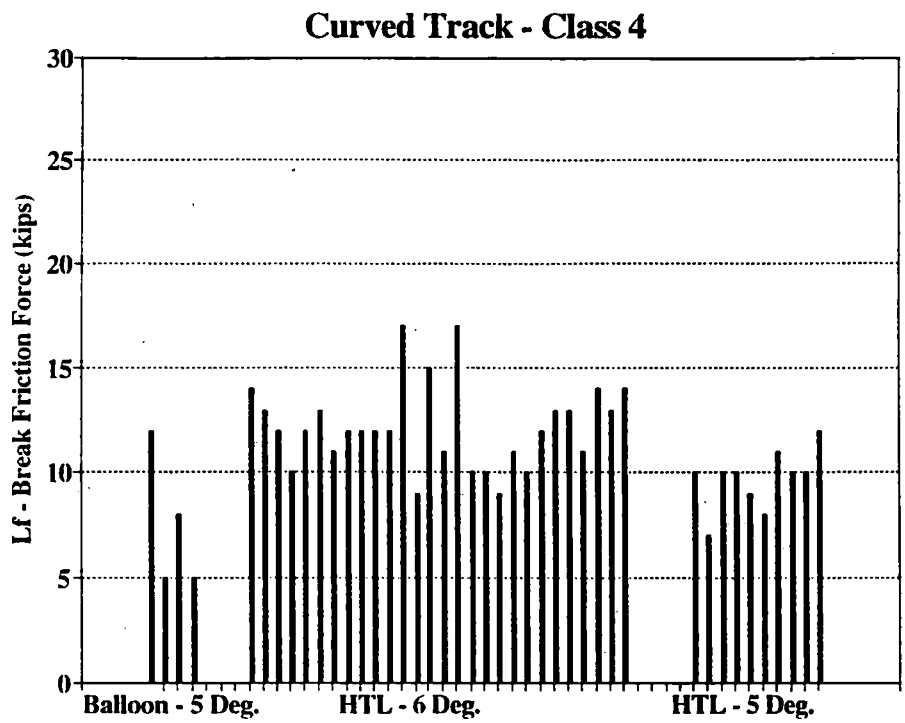
Exhibit 105 shows the roll point (L_0) and the statistics for the three curved track locations. The roll point was lower on the two HTL test sections compared to the Balloon Loop test section. The mean roll point as calculated was 18.6, 15.2 and 15.8 kips on the Balloon Loop, the HTL - 6 degree curve and the HTL - 5 degree curve, respectively. The significantly lower roll point (L_0) on the HTL could be due to the type of traffic, heavy tonnage, that the track experiences and subsequently the wear on the rail. The normal wear on the Balloon 5 degree curve probably produces contact between the wheel and rail at the gage corner, while the HTL rail, with its worn profile, produces two point contact, which reduces the moment arm from the pivot point. By having contact towards the center of the rail, the lateral load needed to overcome the hold down moment from the vertical load (L_0), was less.

Exhibit 106 shows the lateral base stiffnesses and statistics for Class 4 curved track. The Balloon - 5 degree curve and the HTL - 6 degree test sections exhibited a much stiffer response than the HTL - 5 degree curved track test section. The mean lateral stiffnesses were 440.0, 438.5 and 343.0 kips/in, on the Balloon Loop, HTL - 6 degree curve and HTL - 5 degree curve, respectively.

Exhibit 107 shows the break friction forces (L_f) and statistics for Class 4 curved track. The mean frictional break out forces were 7.5, 12.2 and 9.7 kips, on the Balloon - 5 degree curve, HTL - 6 degree curve and HTL - 5 degree curve, respectively.

The mean values of measured shift were 0.05, 0.00 and 0.02 inches on the Balloon - 5 degree curve, the HTL - 6 degree curve and the HTL - 5 degree curve, respectively. The standard deviation on the Balloon - 5 deg., the HTL - 6 deg. and the HTL - 5 deg. was 0.05, 0.00 and 0.03, respectively. The Balloon - 5 degree test section experienced the most lateral rail base shift out of all the tests, with two rails experiencing 0.05 and 0.10 inches shift. The HTL - 6 degree curve section had no shift at any of the tie locations. The HTL - 5 degree curve section had two locations where base shift were 0.06 and 0.10 inches.

Using equations (10), (11), and (12) and the rail deflection parameters just discussed, deflections and extrapolation factors were calculated. Exhibit 108 is a table of calculated deflections and extrapolation factors for the test loads that the GRMS currently uses, V = 17 kips and L = 13 kips and the assumed extreme load levels.



	CLASS 4 CURVED TRACK		
	BALLOON-5 DEG.	HTL - 6 DEG.	HTL - 5 DEG.
MEAN	7.5	12.2	9.7
STD	2.9	2.0	1.4
MAX	12	17	12
MIN	5	9	7

Exhibit 107. L_f (Break Friction Force) and Statistics on Class 4 Curved Track.

Low Quality Track

To augment the amount of understanding gained through the minimum gage restraint tests, additional tests were performed at the Chicago Technical Center (CTC). The two ties tested were on access track and were considered low quality. The vertical load of 17 kips was applied first, then the lateral load was gradually increased to 17 kips, or L/V of 1, and then gradually decreased back to zero. The same procedure was repeated for vertical loads of 27, 33 and 39 kips vertically with lateral loads gradually increased to a L/V ratio of one, for each vertical load, and then decreased back to zero. In these tests, the vertical load was completely removed before the next vertical load was applied. Exhibit 109 shows an example of the vertical and lateral load time histories for these tests. The two tangent tie locations were constructed using 100 lb jointed rail, with 7 1/2" x 10" tie plates, fastened to 7" x 8" x 8 1/2' ties, spaced at 21 inches, with two cut spikes per tie plate.

For simplification purposes, only the 17 and 33 kips vertical load results will be discussed. Exhibit 110 shows an example of the net head load-deflection curves from vertical loads of 17 and 33 kips. The first stiffness, hold-down stiffness, was very close on both vertical load cases, 333 kips/in. The roll point (L_0), on the 17 kip vertical curve, was approximately 12 kips, while the 33 kip case had a roll point of 23 kips. The roll stiffnesses on both curves were very similar, 21 kips/in, up to the point the 33 kip vertical case seems to stiffen, perhaps due to the rail engaging the gage side spikes.

Exhibit 111 shows an example of the lateral rail base load-deflection curves for the two vertical loads. There was an initial offset on both curves due to the vertical load being applied and the rail moving outward. The first segment of the load deflection curve represents the frictional resistance L_F (7 kips for the 17 kip vertical and 14 kips for the 33 kip vertical case), between the base of the rail and the tie plate. This resistance is overcome and the rail slides across the tie plate until it contacts the shoulder of the tie plate. Beyond this, resistance comes from the tie plate-fastener system, with a lateral base stiffnesses equal to 235 kips/in.

Exhibit 112 shows the rail strength parameters for the low quality track tests, where L_{017} is the roll point for the vertical load of 17 kips, and L_{033} is the roll point for the vertical load of 33 kips. L_{F17} is the friction break force for the vertical load of 17 kips and L_{F33} is the friction break force for the vertical load of 33 kips. Notice that the parameters for rail roll, k_H, k_R and L_0, are comparable to the results obtained at TTC, implying that the effect of rail weight and section are negligible. The rail base characteristics however, are very different; the lateral rail base stiffnesses on tie 2 are 91 and 77 kips/in, much below those experienced at TTC. More significantly, the amount of rail base shift measured was much different; the rail base shift ranged from 0.05 to 0.23 inches on the rails tested at CTC.

Exhibit 113 shows the deflections, for the test and extreme loads, and extrapolation factors for the low quality track tests. Notice that the lateral head deflections measured were more than those measured at TTC on average. But more importantly, the extrapolation factors are much lower than those at TTC, and also lower than the GRMS extrapolation factors. This difference is most evident on the right rail of tie 1, where its extrapolation factors, A_{24} and A_{33}, are equal to 1.25 and 2.11, respectively, compared to 1.82 and 2.83, used by the GRMS. This difference may be due to the amount of lateral base shift taking place.

Artificially Weakened Track

The artificially weakened track test results discussed earlier gave a good indication of how much different components of the lateral rail restraint system contributed to restraining the rail. These tests could also be used to see how the different track components affect the extrapolation factor. These tests were run only up to 26 kips laterally, so only A_{24} can be analyzed. Recapping the test procedure, one rail was tested under various vertical and lateral loads including, 17 kips vertically and 13 kips laterally (GRMS test load levels), and 33 kips vertically and 24 kips laterally. The rail was first tested in its normal condition, then it was tested with all the spikes removed from three consecutive ties and finally it was tested with the tie plates removed from the three consecutive ties. Two tie locations were tested, one on a tangent section and on a 5 degree curve.

	δ_H (in) V=17,L=13	δ_H (in) V=33,L=24	δ_H (in) V=33,L=33	A_{24}	A_{33}
Tie 1 Left Rail	0.134	0.177	0.355	1.32	2.65
Tie 1 Right Rail	0.323	0.403	0.681	1.25	2.11
Tie 2 Right Rail	0.301	0.458	0.803	1.53	2.67

Exhibit 113. Measured Deflections and Extrapolation Factors for Low Quality Track Tests.

Left Rail	δ_H (in) V=17,L=13	δ_H (in) V=33,L=24	A_{24}
Normal	0.169	0.281	1.66
No Spikes	0.433	0.699	1.61
No Tie plate	0.434	0.695	1.60
Right Rail			
Normal	0.246	0.297	1.21
No Spikes	0.360	0.637	1.77
No Tie Plate	0.446	0.762	1.71

Exhibit 114. Measured Deflections and Extrapolation Factors for Weakened Track Tests on Tangent Track.

Left Rail	δ_H (in) V=17,L=13	δ_H (in) V=33,L=24	A_{24}
Normal	0.261	0.358	1.37
No Spikes	0.408	0.629	1.54
No Tie plate	0.500	0.763	1.52
Right Rail			
Normal	0.117	0.201	1.72
No Spikes	0.242	0.432	1.78
No Tie Plate	0.341	0.614	1.80

Exhibit 115. Measured Deflections and Extrapolation Factors for Weakened Track Tests on Curved Track.

foundation (tie plate and tie), averaged 219.1 kips/in on Class 4 tangent track. Extrapolation factors were computed, as a function of lateral load under 17 kips vertically (the vertical load currently used by (VNTSC), using Equations (10), (11) and (12) with k_H values of 150, 219.1 and 300 kips/in, representing low, moderate and high quality track. Extrapolation factors were also calculated using Equations (5) and (6), which were developed by VNTSC. Exhibit 116 shows the extrapolation factor A_{24} as a function of lateral load, under 17 kips vertically. The four curves correspond to the three different hold down stiffness values and the VNTSC calculation. At a lateral load of 9 kips, the curves exhibit a discontinuity, the point at which the rail begins to roll about it's base corner. The three curves then converge together at a lateral load of 12 kips, and are fairly comparable to the VNTSC calculation at lateral loads above this point.

The roll stiffness (k_R), which is a result of the rail torsional stiffness and fastener torsional resistance, averaged 28.9 kips/in on Class 4 tangent track. Exhibit 117 shows the extrapolation factor A_{24} as a function of lateral load, under 17 kips vertically. Note that below a lateral load of 12 kips, a reduction in the roll stiffness causes an increase in the extrapolation factor. The three curves then converge together at a lateral load of 12 kips for A_{24}, and are comparable to the VNTSC curve.

The lateral base stiffness (k_B), which is a result of the rail bending stiffness and fastener lateral resistance, averaged 231 kips/in on Class 4 tangent track. Exhibit 118 shows the extrapolation factor A_{24} as a function of lateral load, under 17 kips vertically. Note that lateral base stiffness appears to have little effect on the extrapolation factor, and the three curves and the VNTSC calculation are comparable.

Next the effect of the wheel-rail contact geometry on the extrapolation factor A_{24} was investigated. The d/h ratio had an average value of approximately 0.6 on Class 4 tangent track. Exhibit 119 shows the extrapolation factor A_{24} as a function of the d/h ratio, under 17 kips vertically. Note that initially, a lower d/h ratio produces a higher extrapolation factor, until the rail rolls about it's base corner, then it actually produces a lower extrapolation factor.

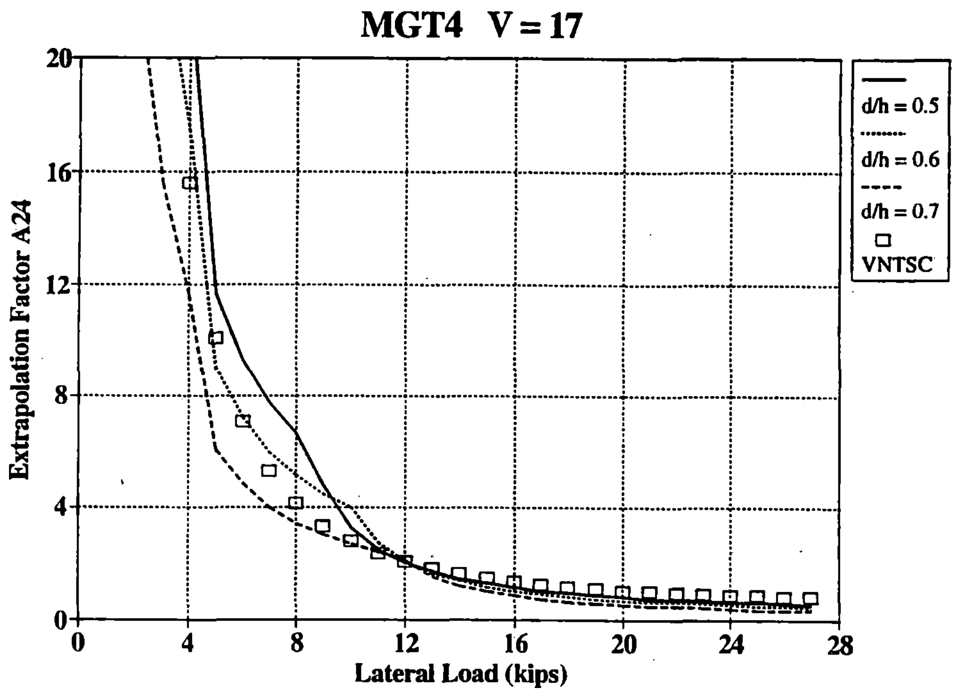


Exhibit 118. Extrapolation Factor (A_{24}) vs Lateral Load at Various Lateral Base Stiffnesses (k_B) Under 17 kips Vertically.

extrapolation factor. It is not until higher lateral loads that the curves merge together with the VNTSC calculation.

The TLV test results, show that on average the extrapolation factor A_{24}, was closer to the VNTSC calculation and showed less variation with track quality than the extrapolation factor A_{33}. The extrapolation factor A_{24} was lower on average than the VNTSC calculation of 1.82. But, the extrapolation factor A_{33} was actually larger than the VNTSC calculation. Low quality and artificially weakened tests showed that while rail head deflection may increase dramatically, this does not necessarily translate into a large change in the extrapolation factors. A parametric study of the effect of different track strength parameters on the

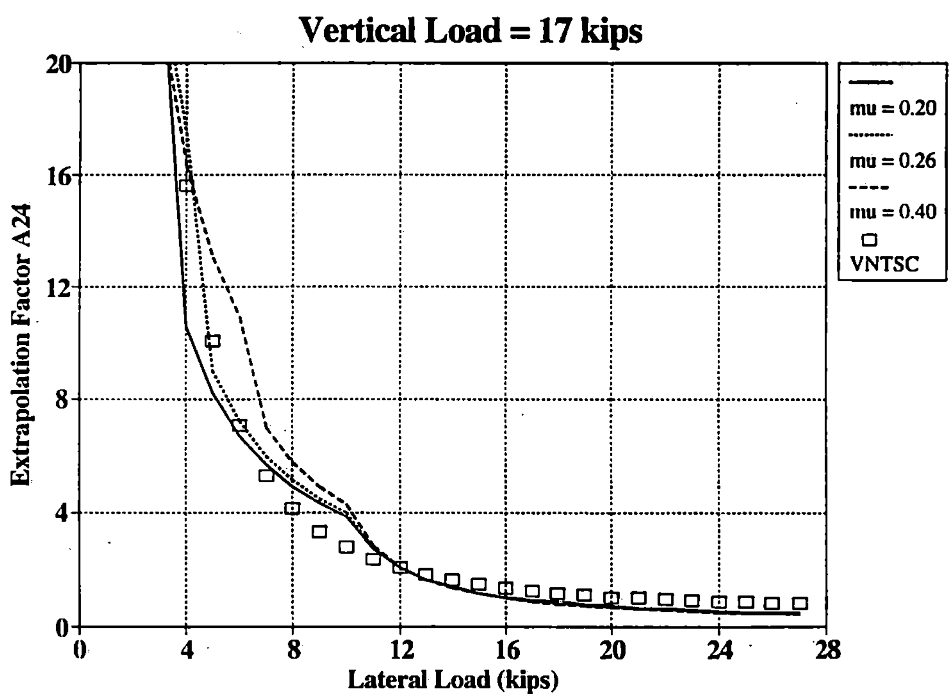


Exhibit 120. Extrapolation Factor (A_{24}) vs Lateral Load at Various Values of the Coefficient of Friction Under 17 kips Vertically.

Quality	k_H	k_R	k_B	d/h	μ	shift
Low	150	15	175	0.50	0.3	0.250
Moderate	225	30	225	0.55	0.3	0.125
High	300	45	275	0.60	0.3	0.062

Exhibit 122. Track Strength Parameters on Different Qualities of Track.

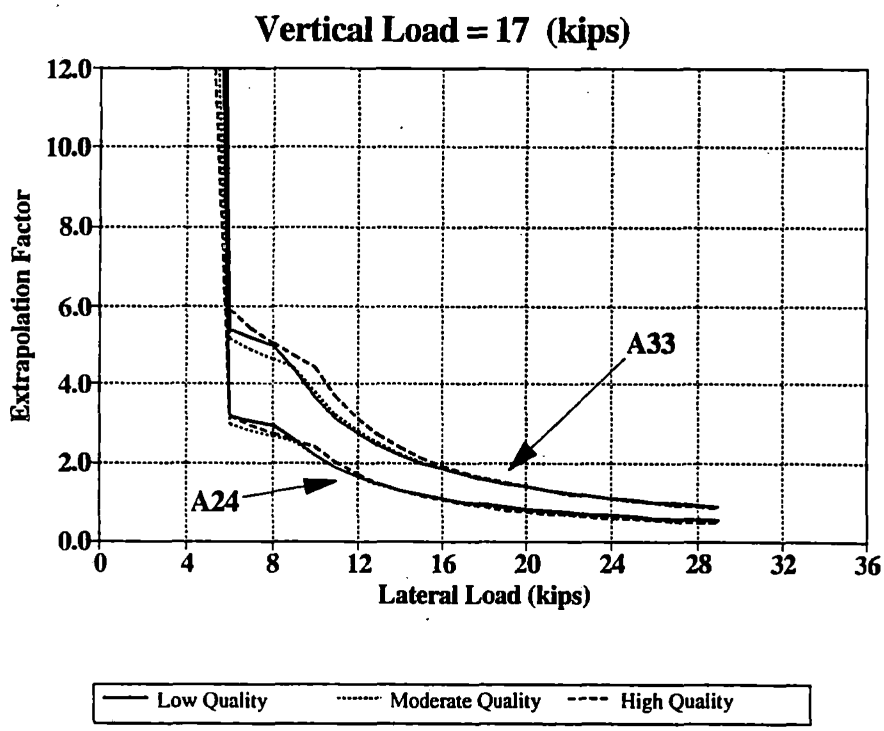


Exhibit 123. Extrapolation Factor (A_{24} and A_{33}) vs Lateral Load at Various Qualities of Track Under 17 kips Vertically.

track. This discontinuity in the curves is a result of the rail shifting over after the lateral load overcomes the frictional force. Exhibit 126 shows a curve fit of the two extrapolation factors after the rail has shifted over, and for extrapolation factors above one, and the resulting equations are as follows:

$$A_{24} = -533/L^2 + 106/L - 2.46 \qquad (13)$$

$$A_{33} = -726/L^2 + 155/L - 3.26 \qquad (14)$$

Using statistically defined qualities of track showed that the extrapolation factors show small variances due to changes in the track quality above a certain load level, namely above the frictional break out force.

Using the average rail strength parameters, k_H, k_R, k_B, d/h, μ and rail base lateral shift, for Class 4 tangent track (Exhibits 96-100) and for 6 degree, Class 4 curved track (Exhibits 105-109), rail head deflection and extrapolation factors were computed using Equation 10, for various vertical and lateral loads. Typically, the extrapolation factor goes to infinity as the lateral load goes to zero, and the extrapolation factor goes to zero as the lateral load goes to infinity. The extrapolation factor, between these two extremes, is a function of both the applied lateral and vertical load. But, it was found that if extrapolation factors were plotted as a function of load severity only, one could obtain a general formulation of a rail's load/deflection characteristics.

Exhibit 127 shows the extrapolation factors A_{24}, A_{28} and A_{33} as function of load severity, on tangent track, using a value of c = 0.5, at vertical loads from 17 to 39 kips. Notice that at a load severity of 0, the extrapolation factors range from 2.3 to over 10, and there is no functional relationship between the extrapolation factors and load severity. This has to do with the fact that the rail does not begin to roll about it's base corner until a load severity of 4 is reached, for the various vertical loads. Note that once a load severity of 4 is reached, the curves converge. Also, at a load severity of 7.5, A_{24} is equal to 1.0; at a load severity of 11.5, A_{28} is equal to 1.0; and at a load severity of 16.5, A_{33} is equal to 1.0. An extrapolation factor below one represents extrapolating backwards to a load condition less severe, which is not the subject of this study. Exhibit 128 shows the extrapolation factors A_{24}, A_{28} and A_{33} as function of load severity, on tangent track, above a load severity of 4, where there is a relationship between load severity and the extrapolation factor. A curve is fit through these points for each extrapolation factor, and the resulting equations are as follows:

$$A_{24} = -3.62/S^2 + 7.95/S + 0.001 \qquad (4 \le S \le 8) \qquad (15)$$

$$A_{28} = -5.60/S^2 + 11.9/S + 0.001 \qquad (4 \le S \le 12) \qquad (16)$$

$$A_{33} = -8.07/S^2 + 16.9/S + 0.001 \qquad (4 \le S \le 16) \qquad (17)$$

Exhibit 129 shows the extrapolation factors A_{24}, A_{28} and A_{33} as function of load severity, on curved track, using a value of c = 0.35, at vertical loads from 17 to 39 kips. Again, at a load severity of 0, there is no functional relationship between the extrapolation factors and load severity. Note, when a load severity of 4 is reached, the curves converge. Also, at a load severity of approximately 12, A_{24} is equal to 1.0; at a load severity of 16, A_{28} is equal to 1.0; and at a load severity of 20, A_{33} is equal to 1.0. Exhibit 130 shows the extrapolation factors A_{24}, A_{28} and A_{33} as function of load severity, on curved track, above a load severity of 4, where there is a relationship between load severity and the extrapolation factor. A curve is fit through these points for each extrapolation factor, and the resulting equations are as follows:

$$A_{24} = -5.32/S^2 + 13.2/S + 0.001 \qquad (4 \le S \le 12) \qquad (18)$$

$$A_{28} = -6.64/S^2 + 17.1/S + 0.001 \qquad (4 \le S \le 16) \qquad (19)$$

$$A_{33} = -8.39/S^2 + 22.1/S + 0.001 \qquad (4 \le S \le 20) \qquad (20)$$

This means, if the deflection for a certain rail is measured under a specific load combination, the deflection can be extrapolated to the extreme loading conditions of 33 kips vertically and 24, 28 and 33 kips laterally. For example, if a rail head deflected 0.3 inches on tangent track, under 27 kips vertically and 19 kips laterally, the deflection under 33 kips vertically and 24, 28 and 33 kips laterally could be extrapolated using Eequations 15, 16 and 17, respectively. Using the definition of load severity and the constant (c = 0.5) the load combination of 27 kips vertically and 19 kips laterally would be equal to a load severity of

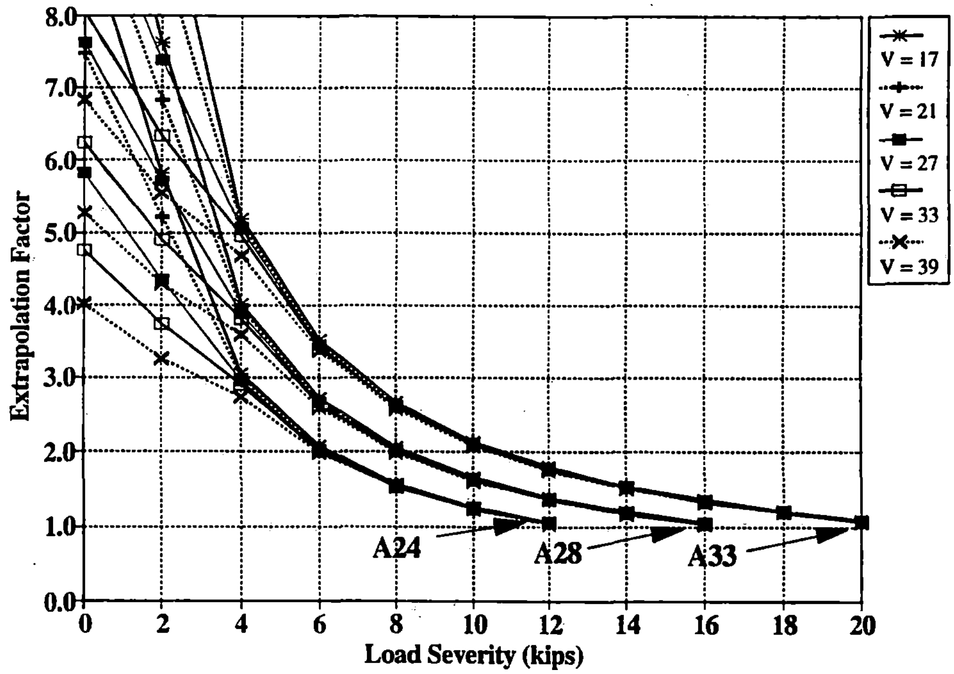


Exhibit 129. Extrapolation Factors (A_{24}, A_{28} and A_{33}) vs Load Severity Under Various Vertical Loads, On Curved Track.

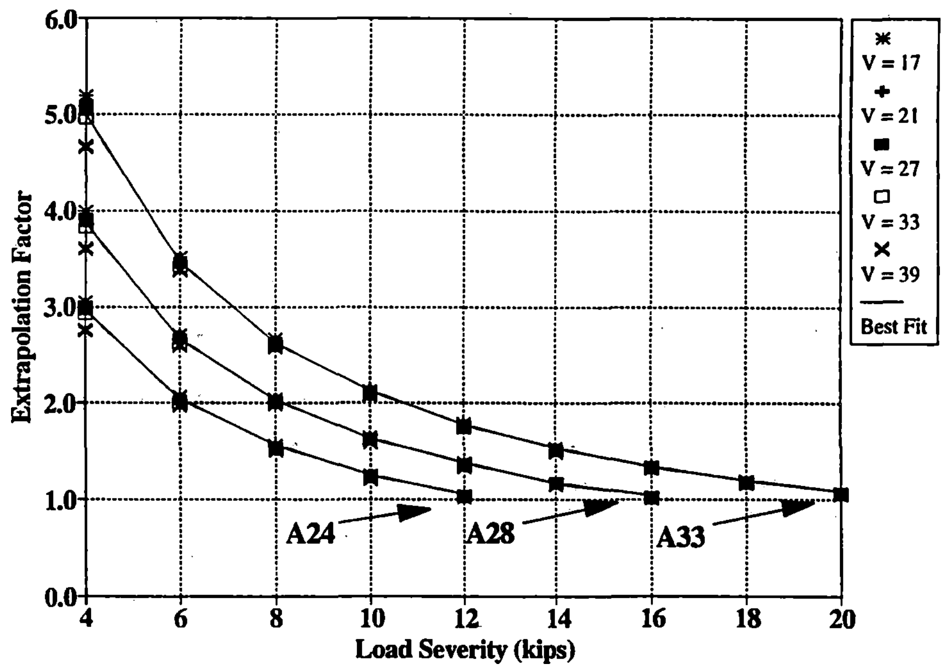


Exhibit 130. Curve Fit of Extrapolation Factors (A_{24}, A_{28} and A_{33}) vs Load Severity, On Curved Track.

comes from the frictional forces between the rail base and the tie plate, as well as from the base of the tie plate and the top surface of the tie.

When the lateral load applied at the rail head exceeds the frictional force, the rail slides on the tie plate until the rail base contacts the tie plate shoulder. Concurrently, the clearances due to the elongation of the spike holes are taken up, and the primary resistance to rail translation comes from the fastener/tie interface, where the spikes resist lateral tie plate movement. Rail twist and bending are resisted at the rail base by the tie plate/tie structure, and by the torsional rigidity of the rail.

The critical load levels needed to start rolling the rail are defined by the wheel-rail contact geometry. Beyond this load level, the rail starts rolling about the field corner on the tie plate. Resistance to this rail roll motion is obtained from the torsional resistance of the rail and the pullout resistance of the gage spikes.

The results from the track strength characterization tests on nominal track did not provide any real surprises. On average, premium fasteners provided a much greater rail restraint capability as compared with cut spikes on conventional wood ties.

As the lateral load is increased, under a constant vertical load, the increase in both average track delta gage and the loaded track gage was largest in the case of conventional wood ties with cut spikes and least for conventional ties with Safelok fasteners.

Average values of the track strength data indicated that for conventional wood ties with cut spikes and glue laminated ties with cut spikes, the track responded to the applied lateral loads in a somewhat linear fashion. On the other hand, test results on premium fasteners on conventional wood ties indicated that premium fasteners provided increased rail that, as the lateral load is applied to the rail, the rail's translation is resisted by the tie plate shoulder, which is resisted by the spikes. The net head deflection (roll) is influenced by both spike and the plate removal. The spikes tend to hold the tie plate in place, which helps prevent the tie plate from rocking, as well as resisting rail roll, with the gage side spikes. The tie plate provides a foundation, on which, the vertical load can hold the rail down, and resist rail roll. In general, local weaknesses appear to affect rail translation much more than rail roll.

Recent contributions to the prediction of gage widening derailment include the development of criteria and the formulation of indices to quantify the gage widening behavior of the track. The criteria are required as a measure of proximity to incipient wheel drop derailment from simulation and test data, and also to establish limits to variations in track quality for optimum operational safety and maintenance practices. A comprehensive series of tests was performed to validate various track gage widening derailment criteria such as rail rollover, lateral rail deflection, and projected loaded gage (gage reserve index), as well as to develop new criteria.

The rail rollover criterion, as used previously by many researchers, implies that derailment occurs as soon as the roll moment about the rail section corner changes sign and encourages rail roll. The ratio of lateral to vertical wheel loads, L/V, has been widely used by the railroad industry as the limiting parameter for rail rollover. For typical geometries, this ratio ranges from 0.5 to 0.65.

Rail rollover tests were run at a variety of vertical and lateral loads to evaluate this limiting condition in which track failure can occur. The test results showed that the rail does broken spikes and missing tie plates, etc.

In conclusion, the TLV test results imply that gage widening large enough to cause a wheel to drop inside the gage can occur; the actual failure mode associated with rail rollover appears to be dynamic gage widening followed by one or more wheels dropping inside the gage and causing the rail to rollover. The current rail rollover criterion is overly conservative to predict any derailments. It totally ignores gage widening due to lateral rail translation and the effect of the tie/fastener system, the effect of adjacent wheels, and the torsional resistance of the rail segment. Therefore, a criterion solely based on the rail's propensity to rollover at L/V ratios near 0.6 is clearly inadequate to predict an incipient wheel drop derailment. The critical L/V ratio concept should be used as an alarm level but not as the limit of the lateral forces that can be applied to the track.

On "good" track, rail roll produced the majority of rail head deflection, rail translation produced no more than 20% of the rail head deflection. The same L/V ratio does not produce the same amount of lateral rail head deflection; as the vertical load is increased the deflection increases as well. In fact, at higher L/V ratios this increase is much more pronounced.

The Lateral Load Severity Concept hypothesizes that, for significant lateral rail deflections and fixed point of vertical load application, the effective lateral load applied to the fasteners is the applied load reduced by an amount proportional to the vertical load.

Controlled static and dynamic tests were conducted to investigate the concept of Lateral Load Severity, how it affects track gage widening, and how it could be used in the prediction of wheel drop derailments. The principal finding from this study was that the friction force at the rail-tie plate and tie interface does have an important effect on the rail simultaneously. Furthermore, a general criterion must include the restraint due to rail fasteners and the effect of adjacent vertical loads, and unloaded track geometry.

The last gage widening derailment criterion examined in this study was developed by the VNTSC and is under current use with a split axle track gage strength measurement system referred to as the GRMS. This system implements a new index called the Projected Loaded gage, (PLG), which predicts the maximum dynamic gage expected under extreme loads. The lateral loads applied to the track are measured, and the maximum gage under assumed maximum loads are estimated based on extrapolation of the load/deflection curve. This estimate is compared to the gage under which wheel drop will occur. Since the tests used to determine rail restraint must be carried out at a load level which does not damage the track, extrapolation factors are used to determine whether the track is strong enough to prevent wheel drop under extreme loading conditions. Tests were conducted using the TLV to obtain a statistical description of the restraint curves for various track classes to enhance the use of the PLG in different types of load environments.

An analytical procedure has been developed for the estimation of the stiffness parameters from the static load/ deflection data obtained from the TLV tests. As mentioned above, lateral rail head deflection is produced by lateral base translation and rail roll (indirectly measured as net head deflection). Lateral base translation is characterized by the lateral load needed to overcome the friction force L_F, the amount of shift that can take place in the tie plate-fastener system, and the lateral stiffness of the rail and tie plate-fastener system k_B. Rail roll or the net head deflection is a function of the hold-down stiffness k_H (foundation stiffness and rail properties), the lateral load needed to overcome the hold down

A parametric study of the effect of rail strength parameters on the extrapolation factors showed that, above a minimum lateral load, variance of these parameters showed small effects on the extrapolation factors. One exception to this is rail base shift, which caused significant changes in the extrapolation factor. Using statistically defined qualities of track strength parameters, calculated extrapolation factors exhibit small variances due to changes in track quality above a certain load level, (i.e. the frictional break out force).

A general formulation of extrapolation factors was accomplished by considering the lateral load severity as well as rail roll for use under different types of test loads. It is proposed that utilizing the load severity concept to relate different loading conditions along with extrapolation to more severe loading conditions, one could predict the amount of gage widening that might occur or the loads that might produce a failure.

The concept of in-motion measurement of track gage strength, using split axle devices, and assessment of tie/fastener performance has been shown to be one of the most promising alternatives to traditional visual inspection of track for maintenance planning. Extrapolation factors developed from the TLV tests are expected to permit the use of any load combination with an automated gage strength measurement system.

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Fundamental Track Gage Widening Tests Using the Track Loading Vehicle, 1994
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