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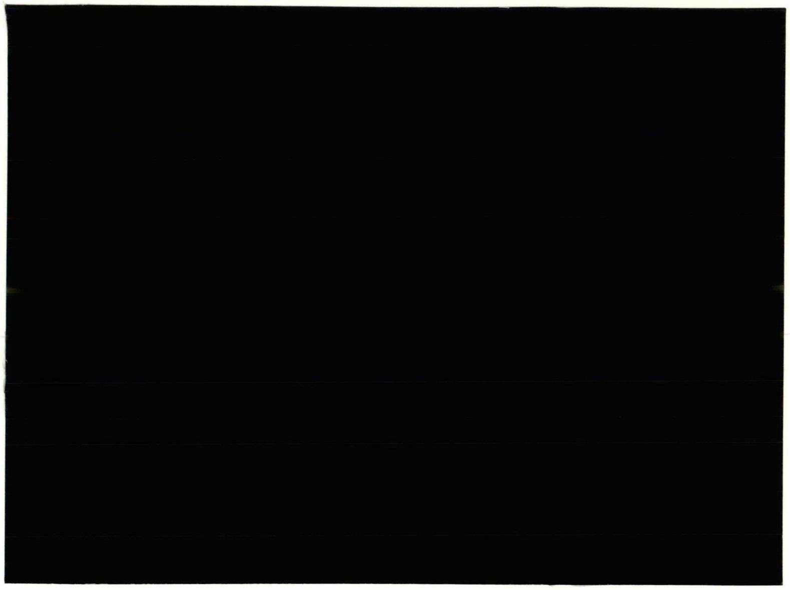

REVENUE TRACK GAGE WIDENING TESTS USING THE TRACK LOADING VEHICLE

REPORT NO. R-886

by
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Association of American Railroads
Transportation Technology Center
Pueblo, Colorado

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13. ABSTRACT

Gage widening tests were conducted using the TLV on portions of tracks of nine Class I railroads in North America. The measured unloaded gage and loaded gage, along with the computed delta gage (the difference between loaded and unloaded gages) and track compliance (delta gage per unit gage widening load) were used to determine the gage widening resistance. The data was sorted on a mile-by-mile basis, with respect to geometries from tangent to 10 degree curves, FRA track classes 2-6, concrete and wood tie track, and track with cut spikes and elastic fasteners. Each railroad was also analyzed without segmenting the aggregate data on a mile basis or a track type basis. Lastly, data from all railroads were combined for an overall assessment of gage widening resistance for the North American railroads tested.

More than 90% of the exceptions occurred due to the exceedence of the TLV loaded gage paint limit of 57.75". Wide gage (static gage in excess of 56.5") was concluded to be the onset of these exceptions. The total painted track length due to all the exceptions was about four-tenth of one percent of the total analyzed miles. Overall, the North American railroad track tested was in a very good condition.

Tracks through road crossings always indicated high gage widening resistance. Low gage widening resistance generally occurred on open-deck bridges, while ballasted-deck bridges showed high gage widening resistance. Elastic fasteners, whether on wood or concrete ties, provided higher gage widening resistance than did cut spikes. Unloaded gage and loaded gage increased, while delta gage decreased, at higher curvature track. A characteristic change with respect to track class was not as clear.

The averages of the lowest and highest values from all test sections showed that the mean value varied from 56.4" to 56.82" for unloaded gage, 56.8" to 57.25" for loaded gage, 0.3" to 0.6" for delta gage, and 0.0166"/kip to 0.033"/kip for track compliance. The combined results, on the other hand, showed that the mean unloaded gage was 56.58", the loaded gage 57.0", the delta gage 0.42" and the track compliance 0.0247"/kip.

14. SUBJECT TERMS Track Loading Vehicle, Gage Widening, Wood Ties, Concrete Ties, Cut Spikes, Elastic Fasteners, Lateral and Vertical Loads, Revenue Track, Delta Gage, Track Compliance, Loaded Gage, Unloaded Gage	**15. AVAILABILITY STATEMENT** Association of American Railroads Publication Order Processing COG, 5th Floor 50 F Street, NW Washington, D.C. 20001

EXECUTIVE SUMMARY

AAR has collected gage widening test data under constantly applied moving loads for the major North American railroads with the Track Loading Vehicle (TLV). The data provides good estimates for industry-wide unloaded wide gage and loaded gage widening occurrence rates, as well as mainline tie/fastener strength.

More than 3,500 miles of track was tested. The test data were segmented into various track classes, track types and geometries. The overall gage holding strength of North American track was found to be very good under current traffic conditions. Of the nine railroads surveyed using the TLV, four had computed delta gage 95-th percentile values of less than 0.6 inches (95% of the data is lower than this value) under 18 kips gage widening force. The other four had delta gage 95-th percentile values of about 0.8 inches or less. The loaded track gage 95-th percentile values, which are used to indicate wide gage conditions, was found to be less than 57.5 inches for all mainline track tested using the TLV.

Under normal operating conditions, this type of track (even at locations where static gage may already have been wide) is more than adequate to carry the lateral loads produced under most coal cars, which may range from 8,000 to 24,000 lbs under relatively severe curving conditions.

Analysis of over 2,000 miles of mainline quality track shows that there is little or no difference in gage widening performance between FRA Class 3 and Class 4 track. In most sharp curves, the

speed is governed by curvature, not track class. As expected, track gage increases as a function of curvature: both the unloaded and loaded track gage increase with curvature. However, track strength is not greatly affected by track curvature as the effect on delta gage or gage widening stiffness was found to be minimal. In general, delta gage decreased with an increase in track curvature.

This suggests that rail wear and the practice of (purposely) laying the curves wide account for a significant portion of the 0.7 inch difference seen between tangent (0-2 degrees) and sharp (6-10 degrees) curves. Permanent deformation of the tie plate area and spike hole also account for some of the wide (unloaded) gage. It is important to note that the wide gage areas had gage widening resistances comparable to the rest of the track. Railroad maintenance policy and inspection methods are undoubtedly finding and removing most of the weakest spots (i.e. unloaded wide gage and low gage widening resistance).

Weak track locations where the pre-set threshold gage levels were exceeded accounted for about four-tenth of one percent of the total analyzed miles. More than 90% of the time, exceptions occurred due to the exceedence of the TLV loaded gage paint limit of 57.75". Wide gage was concluded to be the onset of these exceptions, as the computed delta gage values did not imply laterally weak track.

Wide gage and gage widening do occur on tangent track as well as on curves. The occurrence of loaded wide gage (57.75 inches) in

TLV tests was a function of unloaded gage, discrete defects, special structures and clusters of bad ties. Unloaded gage was a major factor. It is speculated that some of the unloaded wide gage is the result of permanent lateral deformation of the tie/fastener system. Gage widening strength, as measured by lateral stiffness under 33 kip vertical and 18 kip lateral wheel loads, is uniformly good; even at the unloaded wide gage locations.

Examination of wide gage spots found by the TLV revealed that many are at special structures in track, such as: bridges/approaches, road crossings, rail joints and plug rails. These are all areas that are difficult to maintain with mechanized gangs. In the case of plug rails, they are "temporary" repairs that are often made under less than ideal conditions. The wide gage areas are also encountered in stiffness transition zones, which traditionally do not receive enough design attention, where dynamic loading will be greatest.

Other wide gage spots were found to be associated with clusters of bad ties. The plate areas of these ties were usually in poor condition, with loose "high" spikes, plate cutting, and displayed evidence of plate movement. These wide gage spots were generally short (e.g. 4-12 ties), and needed regaging or respiking, or at best a few new ties.

The effect of traffic density is not clear. On a tonnage basis, it is not clear that there is a traffic density effect. On a time basis, higher tonnage lines will have problems more often. If the problem of wide gage is affected by environmental factors, such as decay, iron degradation, etc, then on a per MGT basis lower tonnage lines have higher maintenance costs. Determining the effect from track performance data is difficult because the railroads have already factored it into their maintenance policies. The TLV test data has not been sorted by traffic density, due partly to lack of current information on traffic densities.

The TLV tests were conducted at an average speed of 20 mph. A 33-ton split-axle load and an 18-kip gage widening load were applied to the track.

Measurements taken by the TLV include unloaded gage, loaded gage, the amount of gage widening due to the loads exerted on the track by the TLV, and the lateral and vertical loads exerted on each rail. Exceedence limits for maintenance purposes of 57.75" on the loaded gage and 1.25" on the delta gage were used to define exceptions during testing. When a weak spot is detected, the TLV marks it with paint.

Data produced by the TLV include: distance history plots of unloaded gage; loaded gage; dynamic gage widening; applied vertical and lateral loads; milepost information; and the location of special track features such as bridges and road crossings. A summary table listing weak track locations is computed and printed out immediately after each test run, to provide railroad personnel with quantitative information that corresponds to the painted locations along the track tested.

Test results indicated that higher gage widening resistance was always encountered at road crossings. Based on limited test data, it was found that lower gage widening resistance, as compared with that of the preceding open track, generally occurred on open-deck bridges, while ballasted-deck bridges showed significantly higher gage widening resistance than the adjacent track.

A significant amount of data was collected on a wide variety of track types, including conventional track at various maintenance levels, wood tie track with a variety of premium fasteners, and concrete ties. The test results show that concrete ties with elastic fasteners provide much greater, more uniform rail restraint capability than cut spikes.

The results also show that, under heavy axle loads, premium fasteners on wood ties provide much greater resistance to gage widening than do cut spikes. These results imply that an alternative method of controlling track gage widening degradation on sharper curves may be to utilize premium fasteners on conventional wood ties.

Data from all test sections on each railroad were combined and analyzed to obtain a statistical description of track strength, represented by an average of 250 miles of track tested on each railroad. The statistical analysis of the combined data implies that the average unloaded gage for North American track is the standard gage of 56.5 inches. Only five percent of the total trackage tested had wide gage approaching the value of 57 inches. The loaded gage, measured under a 33-ton axle load and 18-kip lateral load, averages around 57 inches, and in only five percent of the trackage does the loaded gage approaches a value of 57.5

inches. The loaded track gage used to paint the track is 57.75 inches. The delta gage, or gage widening, reaches a maximum of 0.75 inches, only five percent of the time. The delta gage threshold value used during testing to mark the track was 1.25 inches. Similarly, the results show that the overall deflection rate remains under the value of 3/64 inch per one thousand pounds of applied lateral load for 95% of the track tested using the TLV. Note that either the delta gage, or the deflection rate parameter, is a direct measurement of track strength and can be used in maintenance planning activities.

The results of the revenue tests indicated that the TLV can consistently find weak spots in the track. The application of these results can be utilized to increase the efficiency of track maintenance. Although the TLV itself has too many capabilities to be utilized as a production track inspection tool, and it is intended as a research tool, application of this approach to a track measuring system could produce an innovative track inspection vehicle.

In the past, track strength assessment has been subjective and dependent on the judgement of track maintenance personnel. Railroads currently use track geometry cars to identify weak spots. However, most track geometry cars measure the gage variation in track, not track strength. Moreover, given the differences in vehicle dynamics between the typical track geometry car and the average unit coal car or double stack vehicle, it is unlikely that a track geometry car will locate all of the weak spots in the track. Unlike track geometry cars, the TLV is capable of applying and maintaining peak vertical and lateral loads to continuously measure track strength.

TLV revenue track test results have shown that automated inspection methods can effectively measure available track strength, identify weak spots before further degradation occurs and increased maintenance is needed. Substantial savings could be realized by the industry if positive identification of defective ties can be improved using test devices like the TLV.

The TLV is also capable of quantifying the relative strength differences between tracks which may be in different stages of their maintenance cycles. This information can be used in conjunction with traffic requirements to efficiently prioritize timbering and/or fastener maintenance activities.

Moreover, based on the specific load environment seen over the track, economic decisions can be made as to when and to what level the track should be maintained. The statistical track strength information obtained by the TLV can be segmented by region, traffic type, track geometry, and by mile-by-mile to improve track strength where traffic volume and/or axle loads are expected to increase.

In another area of endeavor, the TLV can be utilized to reduce track maintenance requirements by helping to reduce the track damage caused by vehicle operation. Prior knowledge of the load carrying capacity of the track can be implemented as an aid to vehicle and truck designs. The measured track strength values can be used as a guide in the design of rolling stock with a subsequent reduction in the amount of track maintenance required.

Future research plans include developing track quality indices to minimize gage widening derailments in North America.

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The author wishes to give credit where it is due, and if he has missed contributors, it is unintentional.

1.0 BACKGROUND AND INTRODUCTION

The moving vehicle/track interaction can manifest itself as: 1) inadequate lateral restraint of the rail leading to its lateral translation and/or rollover, 2) track panel shift across the ballast due to large lateral forces or 3) climb of wheel over the rail due to excessive lateral and frictional forces. The most recent derailment statistics indicate that more than twenty percent of all track-caused derailments resulted due to high vertical and lateral forces causing excessive gage widening due to inadequate rail restraint [1][1]. To eliminate the high risk of a gage-widening derailment, an accurate and continuous gage widening measurement under dynamic vertical and lateral wheel/rail forces, similar to those encountered under operating conditions, is an important aspect of determining current revenue track maintenance condition and performance capability.

The problem of track gage widening has been of considerable interest to the railroad industry since the early 1900's. Association of American Railroads (AAR) Report No. R-258 [2] provides a comprehensive historical review of this problem. Railroads utilize several approaches to reduce the gage widening problem. These include use of improved train handling techniques, redesigning of locomotive and vehicle suspension systems to reduce L/V ratios, increased torsional resistance of track structure by improved spiking patterns, use of more efficient fasteners, and stronger cross tie components, including concrete cross ties. The

[1] Numbers in brackets refer to References listed in Section 8.0

need for further study to fully characterize the nature of the gage widening problem and to effect more permanent solutions remains. To supplement the still prevailing subjective visual inspection, new objective inspection methods based on actual tie and fastener performance are required. Studies should be directed toward automated tie/fastener performance inspections and practical ways to improve both the safety of operations and of maintenance efficiency and planning.

Automated, continuous and objective tie/fastener performance inspection is the requirement. The feasibility of such an inspection method was first demonstrated by A. Zarembski in a series of tests at the AAR Chicago Technical Center in 1978 [3]. A test device designed and built earlier by the AAR was mounted on the trailing 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 lateral track strength and identify poor tie and fastener conditions without damaging the track structure.

AAR, in its study of the automated inspection goal, reviewed the results of gage widening tests conducted at the AAR's Track Laboratory in 1979 [4]. These tests suggested that although gage widening was more severe under truck loading, the concept of a truck L/V ratio was not suitable for use in studying the gage widening behavior of track.

Follow up on these preliminary studies resulted in the construction of a prototype track strength test vehicle referred to as the Decarotor. This work was done by the AAR, with full support and cooperation from Southern Railway, Federal Railroad Administration (FRA) and Battelle Institute. Field evaluation of the Decarotor in 1980 demonstrated that it could continuously measure the lateral strength of track at speeds up to 7 mph, and successfully and repeatedly identify weaknesses in the track [5]. The Decarotor was used to characterize the gage widening resistance of mainline track during tests in 1980 through 1983 [6,7]. It also demonstrated the viability of the concept of in-motion nondestructive measurement of track strength, but was limited in performance. Since the Decarotor was restricted to test speeds not greater than 7 mph, and was not designed to test long stretches of track, it was taken out of service in 1983.

Beginning in 1980, the Volpe National Transportation System Center (VNTSC), in cooperation with the AAR, conducted track-safety research to determine the restraining capacity of ties and fasteners. It was determined that track geometry variations, slack action, or poorly performing cars, could produce peak lateral wheel loads of 24 kips under a vertical load of 33 kips. Test results showed that gage widening resistance of "poor" track was highly lateral load dependent [8]. Also, a large variation was noted in the strength characteristics of track components. Results also dealt with spike pullout strength and the tie plate vertical and lateral resistance behavior under various track conditions.

These track-safety research results led to the development of the Gage Restraint Measurement System (GRMS) [1]. The system was developed through a joint effort by the FRA, VNTSC, AAR and American Railway Engineering Association (AREA). The gage spreading split axle assembly formed the lead axle on the trailing truck under a half-loaded, 100-ton hopper car [9]. The GRMS, by measuring unloaded gage, applying a gage widening load and measuring the resultant loaded gage, predicted gage strength as the rails deflected laterally under dynamic lateral and vertical loads, at speeds up to 25 mph. The testing by GRMS was done under nominal loads of 17 kips vertical and 14 kips lateral. The results under these nominal loads were then used to estimate the projected loaded gage under a severe loading condition defined as the minimum rail-restraint criteria. This severe loading condition was defined as a 24 kip lateral load on the high rail, 16 kip lateral load on the low rail, and 33 kip vertical load on both the high and low rails. Approximately 4,000 miles of revenue track on several railroads was tested by using the GRMS under FRA's Track Safety Performance Standards Program.

Under the auspices of the AAR's new Vehicle Track Systems Program and the joint AAR/FRA effort in the Track Train Interaction Derailment Analysis Project, several research projects were launched in 1985. This endeavor incorporated a systems view in analyzing vehicle and track interaction problems to reduce track and equipment costs, and to improve the safety of train operations. The quantification of lateral strength characteristics of in-place railroad track and the determination of the load environment under various types of operating conditions were among the major elements of this research program.

Pursuant to these goals, the Track Loading Vehicle (TLV) was built in 1989. It was used as a major multi-purpose research tool to measure track strength and to investigate derailment mechanisms [10,11,12]. Based on a series of demonstration tests [13], the TLV was found capable of applying controlled lateral and vertical loads to the track similar to those existing under heavy axle load environment [14], and of measuring track response to moving loads [15]. Lateral and vertical wheel loads in excess of 39 kips, on tangent track and on curved track up to 10 degrees, could be applied by the TLV at speeds up to 35 mph. The wheel drop derailment tests [16], heavy axle load track gage widening tests [17], and bridge tests [18], using the TLV, all provided an introductory knowledge of the expected gage widening resistance to be found in TLV revenue track tests of rail restraint, and instilled confidence in the integrity of the TLV gage widening mechanism.

The TLV participation in the test program was jointly funded by the FRA and the AAR. The FRA support in the testing of the TLV was provided through the Track Train Interaction Derailment Analysis Project under Task Order 6 of Contract DTFR53-86-C-00011. The various elements of this Task Order are:

- Sub-task 6a) Testing and Validation of Current Rail Restraint Criteria.
- Sub-task 6b) Track Lateral Strength Tests.
- Sub-task 6c) Demonstration of the TLV as a Bridge Test Loading Machine.
- Sub-task 6d) Rail Uplift Tests for Rail Longitudinal Force Measurement.

This report presents results of the TLV revenue track gage widening tests conducted in 1991 and 1992 under Sub-task 6b of the Task Order 6.

The results of these TLV tests are deemed useful in determining better methods of controlling gage degradation and thereby, in the long run, providing for economic operation of the heavy axle loads. As railroads continue to automate and mechanize their work force, it will become increasingly difficult to implement maintenance procedures required under heavier axle loads. It is, therefore, important to develop and implement automated and objective inspection methods, such as is available using the TLV, to effectively measure track strength, and thus to identify and repair weak locations before further track degradation occurs and the need arises for increased track maintenance.

In summary, Section 1.0 identifies the industry's need for a multi-purpose research tool, ready for utilization in a variety of comprehensive vehicle track interaction tests.

The TLV was designed to 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. A short description of the TLV, including its design and test capabilities, is included in Section 2.0.

The purpose of and test procedures for gage widening resistance measurement of tracks of selected railroads in North America is set forth in Sections 3.0, 4.0, and 5.0 of the report. Test results are segmented by mile post and track type. The measurements of unloaded gage, loaded gage and gage widening force, and the corresponding evaluation of delta gage and track compliance lead to an identification of weak and strong tie/fastener condition statistics and an evaluation of track segments tested. Analysis and summary of these statistical results is presented in Section 6.0. Conclusions are set forth in Section 7.0.

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2.0 THE TRACK LOADING VEHICLE

The TLV is designed to provide production testing by simulating controlled derailment scenarios and controlled load environments to quantify the dynamic response characteristics of track [11,12,13]. The vehicle applies computer controlled loads to the track and measures the track response either while 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 phenomena which 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 forces, 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. New superstructure was constructed over the underframe. It is a welded structure which is mainly 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" sheet plates. Exhibit 1 shows a photo of the TLV.

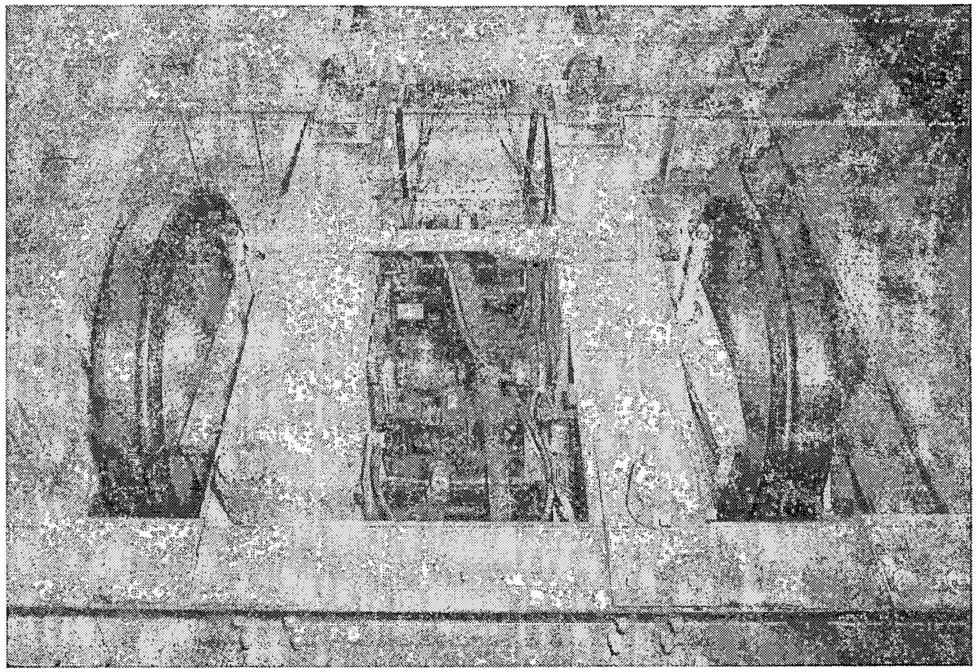
Exhibit 1. A Photo of the Track Loading Vehicle with the Load Bogie Underneath the Center of the Vehicle.

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 mechanisms, a stub axle wheelset, a loaded gage measurement system, and other support equipment. A close-up photo in Exhibit 2 shows the stub axles and bearing arrangements, and the load application linkage mechanisms utilized in the gage widening load bogie.

Planned test scenarios necessitate the use of an active hydraulic control system. The hydraulic system consists of a hydraulic power supply, two 55-kip vertical, two 39-kip lateral, and two 39-kip gage widening actuators, servovalves, hydraulic service manifolds, and electronic control components. A six channel customized electro-hydraulic control system, MTS 458.10 series, is used to control the servovalves, hydraulic pressure and interlocks, and to accommodate computerized control sequences. All actuator channels are equipped with both force and stroke feedback.

A hydraulic pump with maximum flow capacity of 70 GPM is used to supply oil at 3,000 psi to the actuators. Electrical power for the vehicle is obtained from an on-board 250 KW diesel generator. This power supply provides energy for the hydraulic pump and for auxiliary uses such as lighting, heating, power tools, etc.

The TLV is operated from the AAR-100 Research Car, which is equipped with electro-hydraulic control and data acquisition systems. The digital data collection software is configured to perform data collection, and transfer and storage tasks. Comprehensive control software is used to provide supervisory



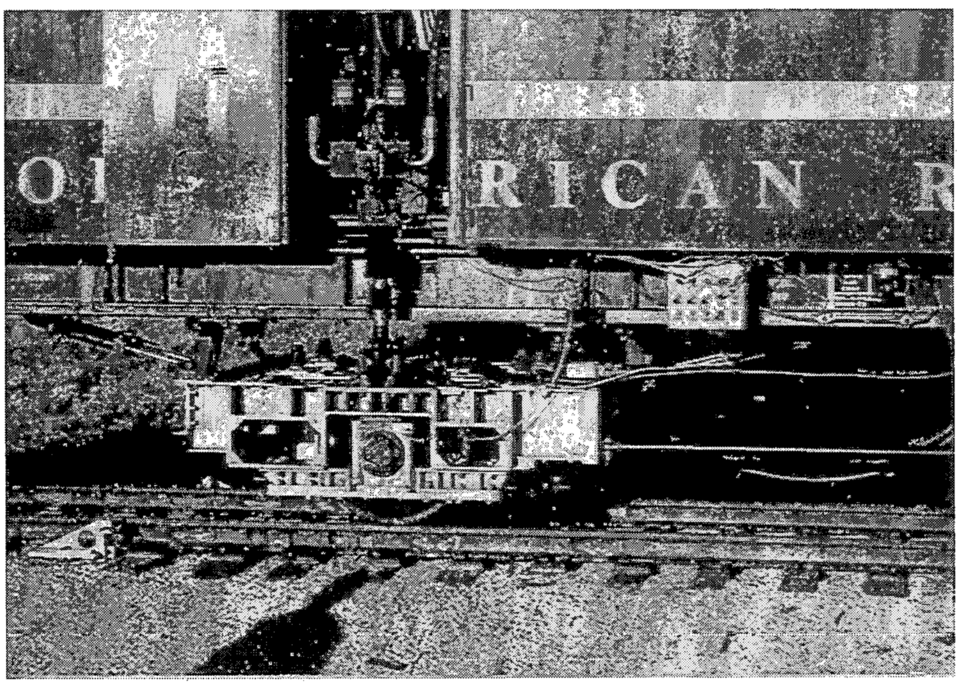


Exhibit 2. The Track Loading Vehicle Load Bogie with Split Axle and Gage Widening Load Application Mechanism.

control over the hydraulic system. Exhibit 3 shows a photo of the TLV computer system, which resides inside the AAR-100 Research Car.

Computer controlled vertical and gage spreading loads are applied to the track structure by hydraulic actuators through the load bogie and split-axle wheelset. The loaded and unloaded gage as well as the gage widening loads are measured. These measurements are used to determine the gage widening resistance of track. During operation, the TLV control system compensates for small irregularities in track vertical and lateral alignments. Active intervention by the computer is also required during the transition from tangent to curves. Various fail safe mechanisms have been built into the TLV system in case of hydraulic power or computer failure.

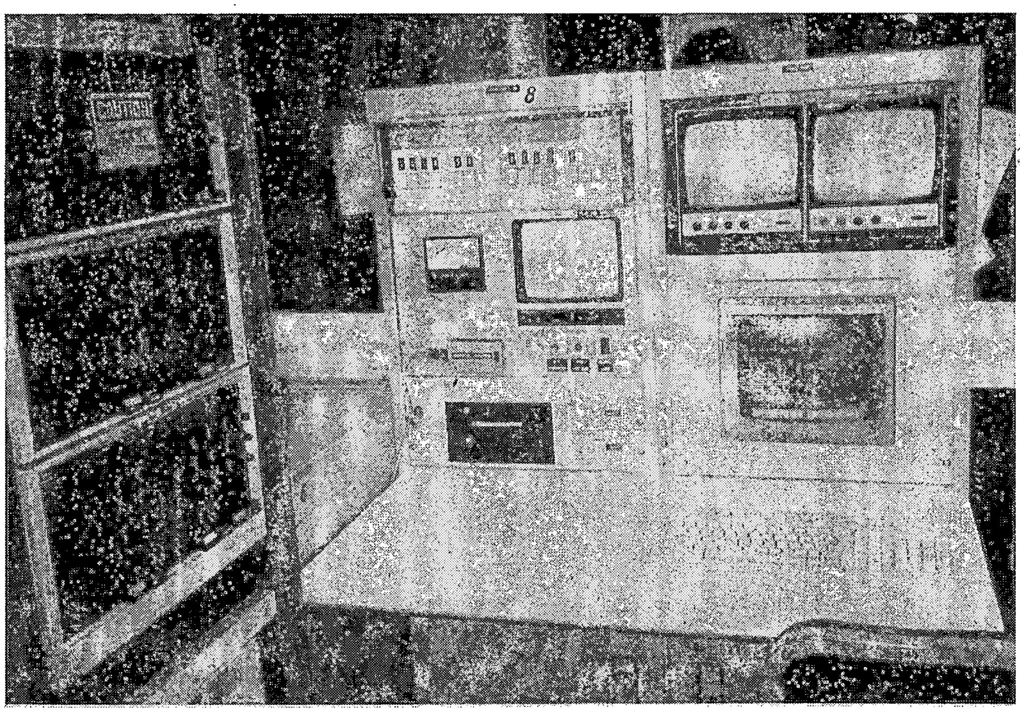


Exhibit 3. The TLV Computer and Instrumentation Command Center.

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3.0 TEST OBJECTIVE

The primary purpose of this study was to obtain a statistical description of the dynamic gage widening resistance of average revenue service track of selected Class I railroads in North America. The secondary purpose was to identify the laterally-weak track locations which require immediate maintenance, based on exceedence of threshold of 57.75" for loaded gage, or 1.25" for delta gage. The exception reports document the location and gage widening resistance data corresponding to painted locations on the track for each test. These were provided to the respective railroad personnel witnessing the TLV gage widening survey.

Loaded gage and delta gage measurements are important to the extent that they relate to the possible presence of tight or wide gage. It is true that an excessive loaded gage could result in a derailment. However, a large loaded gage may not imply weak track if wide gage existed before the loading. Similarly, a weak track as identified by large delta gage, may not cause derailment if the unloaded gage was tight. The statistical results presented in this report deal only with the evaluation and maintenance aspects of relative rail restraint provided by different track segments, not with whether or not a certain magnitude of delta gage or loaded gage will result in derailment. The prolonging of the life of ties which successfully maintain gage and the reduction of wide-gage derailments are emphasized by the results of these tests.

The main objective of these tests, therefore, was to develop a gage widening resistance statistical data base with respect to FRA track classes comprising a broad sample of North American track installations. These TLV tests present a step beyond an explanation of the fundamental gage widening principles, and earlier rudimentary gage widening measurement attempts. The tests document a practical and automated inspection method, which relates track lateral strength to track-safety by detecting laterally-weak locations in track. Overall assessment of the gage widening resistance of track and therefore, an illustration of the general condition of the Class I railroads in North America tested is discernible from the results of these tests.

The unloaded gage and gage widening resistance statistics were compiled by segmenting the test data on a mile-by-mile basis as well as track type basis. Mile-by-mile evaluation included all the relevant data in a test mile for analysis. For track type evaluation, each railroad division was analyzed separately by separating the data on the division based on track curvature and class, and also with respect to tie type and fastener type. It was, however, found that railroads in North America did not use the "division" classification uniformly. It, therefore, became necessary to use the generic term "test section" in this report, to consistently identify track section tested on the various railroads.

4.0 TEST METHODOLOGY

The TLV, by measuring unloaded gage, loaded gage and the gage widening load, provides the in-motion capabilities to identify wide gage and differentiate between weak and strong tie/fastener conditions. This made possible the use of statistical analysis to evaluate track by segmenting on a mile-by-mile basis as well as track type basis. Data from broad sample of North American track installations, including curvatures from tangent to 10 degrees, FRA track classes 2-6, concrete and wood ties, as well as cut spike and elastic fastener track, was gathered. In order to select test sites, representatives from the AAR member railroads were contacted to provide track charts of selected average main line tracks. The test length of the track on each individual railroad was then chosen, between 150 - 350 miles, containing both good and problem segments. A total of 2,135 miles of average main line track on nine Class I railroads in the United States, Canada, and Mexico was thus tested. Of these test miles, 1,939 miles of data was actually analyzed after eliminating the test data through switches and the transient data at the beginning and end of each test section. A summary of the tested and analyzed track miles on each railroad is given in Exhibit 4.

In order to provide a basis for comparison, the TLV test parameters were kept constant throughout the entire period of testing. The tests were conducted at an average speed of 20 mph (unless under a restricted slow order) while a 33-ton axle load and a gage widening load of 18 kips were applied to the track. These conditions were believed to simulate dynamically produced gage widening loads in revenue service, thus resulting in realistic dynamic gage widening characteristics of various track installations in the tests.

RAILROADS TESTED

RAILROAD	MILES TESTED	MILES ANALYZED
A	240	201.31
B	160	149.36
C	200	161.39
D	220	207.77
E	145	129.08
F	250	226.19
G	370	349.45
H	280	257.93
I	270	256.51
TOTAL MILES	**2135**	**1938.99**

Exhibit 4. Miles of Gage Widening Tests on North American Class I Railroads Tested.

5.0 TEST INSTRUMENTATION AND DATA COLLECTION

The TLV test consist comprised of a locomotive, the AAR-100 Research Car and the TLV, as seen in Exhibit 5. The TLV was operated from the AAR-100 Research Car. The computer controlled vertical and gage widening loads were applied to the track structure by hydraulic actuators through the load bogie and the split-axle wheelset.

All measurements taken during the tests were made by using the onboard instrumentation. The unloaded gage, gage widening loads and displacements, vertical actuator forces and displacements, together with split-axle wheelset lateral and vertical loads were measured continuously. These onboard measurements were used to determine the total gage widening under the application of a given combination of vertical and gage widening loads.

The loaded gage was measured at the wheel/rail interface by a set of transducers on the split-axle bogie of the TLV. The unloaded gage was measured using the onboard laser gage system. This laser gage system is located 16 feet in front of the load bogie, directly behind the trailing axle of the leading TLV truck. The system reads the unloaded gage at points 5/8" below the tops of the two rails. The spatial difference in the locations of unloaded and loaded gage measurements was compensated in the calculations by using the speed of the TLV at that instant.

The measurements were converted to digital format at a sample rate of 256 per second. The conditioned signals (time series) were anti-alias filtered to remove intentionally all frequency components higher than 100 Hz before beginning the analysis.

Quick-look programs were used to plot and analyze the track responses for physical integrity. The raw data were recorded on optical disks in binary format, then converted from the HP to VAX computer format and sent to the Chicago Technical Center for further processing.

The load and displacement channels were plotted, and hard copies were examined to check for offsets, transducer malfunction, analog-to-digital converter failure, and extraneous noise picked up in the test. Computer routines were used to determine the maxima, minima, rms, mean, standard deviation, and other statistical descriptors, such as probability distributions. Results of the tests are given in the following Sections.

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6.0 TEST RESULTS

Four basic factors contributing to gage widening resistance are: lateral bending and twisting resistances from the rail section, pull out resistance of gage side fasteners, translational resistance from field side fasteners, frictional resistances at rail/tie plate interface, and at tie plate/tie interface. Gage widening resistance is thus revealed by the loaded gage, indicated by the delta gage, and quantified by the compliance value.

Delta gage is the direct difference between loaded gage and the corresponding unloaded gage. Compliance or deflection-rate index normalizes delta gage measurement, and is the value of the quotient of delta gage and the corresponding gage widening load. It is stated as the increment in gage in inches per kip of gage widening load. Because the gage widening load was kept constant through the entire period of testing, a direct comparison of loaded gage and delta gage may be used to determine areas of weak and strong gage widening resistance in the track of North American railroads tested. However, unlike the constant gage widening load requirement for delta gage and loaded gage comparisons, the compliance is a direct, independent and quantitative measure of relative gage widening resistance at different locations.

Each railroad was examined individually, by performing statistical analyses of four primary variables describing gage holding capacity. As mentioned before, these variables were unloaded gage, loaded gage, delta gage and track compliance. Each variable was analyzed for mean value, standard deviation, L95 value, and a comparison with normal distribution by examining the data in two ways: by each mile tested and by each track type tested. L95 value defined the 95th-percentile rank such that 95% of data was below this value. As will be shown subsequently, the variables, in general, had asymmetrical distributions about the median so that a better representation of the overall gage holding capacity is given by the L95 values of these variables.

A comprehensive statistical analysis was performed on each mile tested and for each variable. However, to consolidate the amount of information obtained, the discussion in the following sections, based on mile-by-mile segmenting, examines only the mean and L95 of each variable on each mile tested. These analyses are presented in bar chart form to allow comparison between one mile of track and another, as well as between different test sections. Such a quantitative comparison allows for a ready determination of strong and weak sections of track, and thereby allows for a more economical and safe assignment of maintenance funds.

Track type analysis was performed by dividing the data by railroad, test section and track configuration. The track configuration was defined by tie and fastener type, track curvature and FRA track class. Tie types were divided into wood and concrete. Elastic fasteners and cut spikes were separated. Curves were divided into zero to two degree, two to four degree, four to six degree and six to ten degree ranges. Track classes were defined as from 2 to 6 by the FRA standard of maximum operating speeds. Similar to mile-by-mile analysis, the track type analysis also examines only mean value, standard deviation and L95 value, using bar charts for data comparison.

To avoid repetition in reporting results, only a few characteristic examples of gage widening at road crossings, bridges and through special track work (e.g., transition from concrete to wood ties) are reported in this section. The two exception reports, one pertaining to exceedence of the loaded gage paint threshold and the other pertaining to exceedence of the delta gage paint threshold, are included as examples in this section. A characteristic set of unloaded, loaded, and delta gage distributions, plotted on normal probability paper for comparison with normal distribution, are reported in this introductory section.

Exhibit 6 shows distance histories of unloaded, loaded and delta gage through a road crossing. Typically, unloaded gage was measured at 56.5" to 57.0" in this test, except at the road crossing where it dropped below 56.5". Added maintenance, track rigidity, and tighter gage control were probably responsible for the results. Loaded gage averaged 57.5", except through the road crossing where it dropped to 56.8". Due to track rigidity and enhanced maintenance, delta gage was found to drop from 0.7" elsewhere, to 0.4" at the road crossing. This is an example of a well maintained road crossing with tight-gage.

On the other hand, Exhibit 7 shows an example of a wide-gage road crossing. Both unloaded and loaded gage showed a dramatic increase through the road crossing. Unloaded gage increased from 56.5" to 57.5", while loaded gage increased from 57.2" to 58.3". Because loaded gage exceeded the 58.25" safety limit, the auto-pause was triggered. An auto-pause occurs when the vertical and

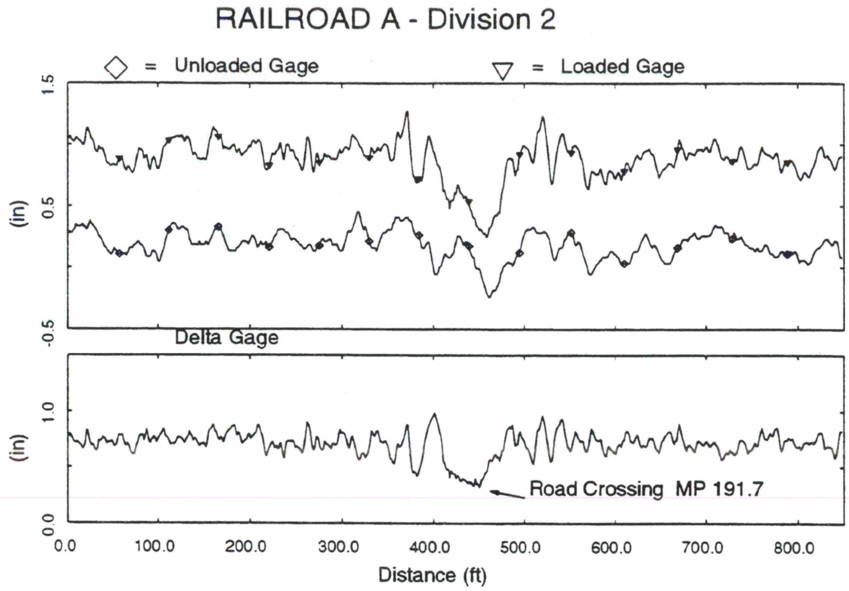

Exhibit 6. Unloaded, Loaded and Delta Gage Distance Histories over a Tight-Gage Road Crossing.

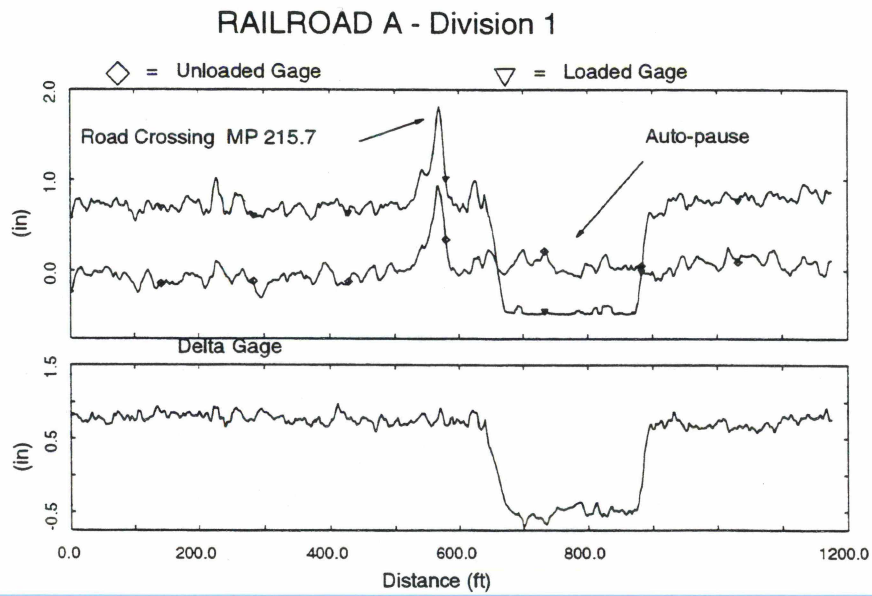

Exhibit 7. Unloaded, Loaded and Delta Gage Distance Histories over a Wide-Gage Road Crossing.

lateral loads are reduced to prevent damage by further gage widening. Delta gage changed very little through the road crossing thus implying a strong track, yet the unloaded gage was excessive, perhaps indicating a maintenance problem.

It should be mentioned that at well maintained and drained road crossings, its rigid structure greatly assists in gage control. On the other hand, at poorly drained and inadequately maintained crossings, its poor surface, cross level and alignment destroy gage control due to sloppy conditions. It is believed that drainage may explain a greater part of the differences seen in Exhibits 6 and 7.

Exhibit 8 shows distance histories of unloaded, loaded and delta gage as measured while testing through a transition from wood to concrete ties. As indicated by the spike in the delta gage history, the transition from a relatively weak track section to a strong one created a localized gage weakness in the track structure. Delta gage increased from 0.7" to 1.1" at the spike located at a distance of 570 feet in the plot. This was similar to what happens when a dramatic change in gage widening resistance is encountered, such as at a bridge or road crossing.

Distance histories of unloaded, loaded and delta gage, as measured while testing through a concrete tie section which has a bridge, are shown in Exhibit 9. The bridge was an open deck structure with wood ties. The unloaded and loaded gage increased dramatically on the bridge, with a greater increase in loaded gage. The delta gage increased from 0.5" in the concrete section to over 1.1" on the bridge. A combination of wide gage and weak gage

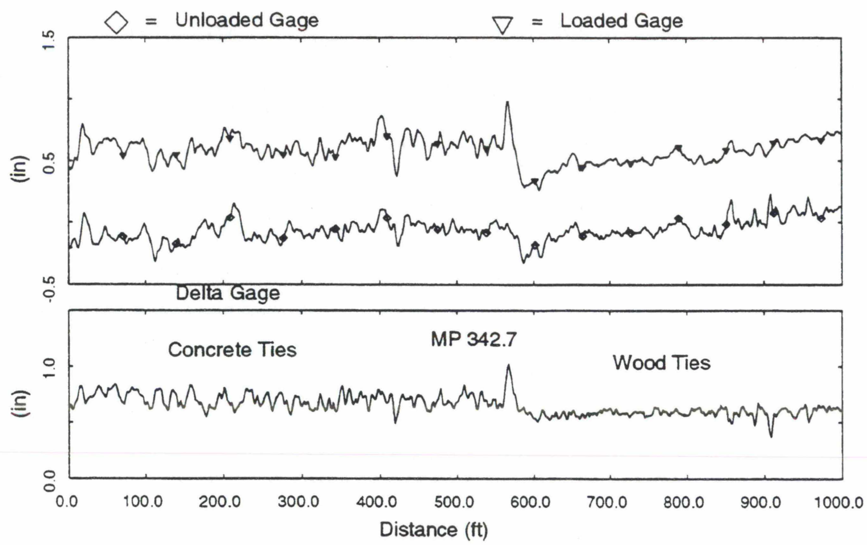

Exhibit 8. Unloaded, Loaded and Delta Gage Distance Histories over a Transition from Concrete Ties to Wood Ties.

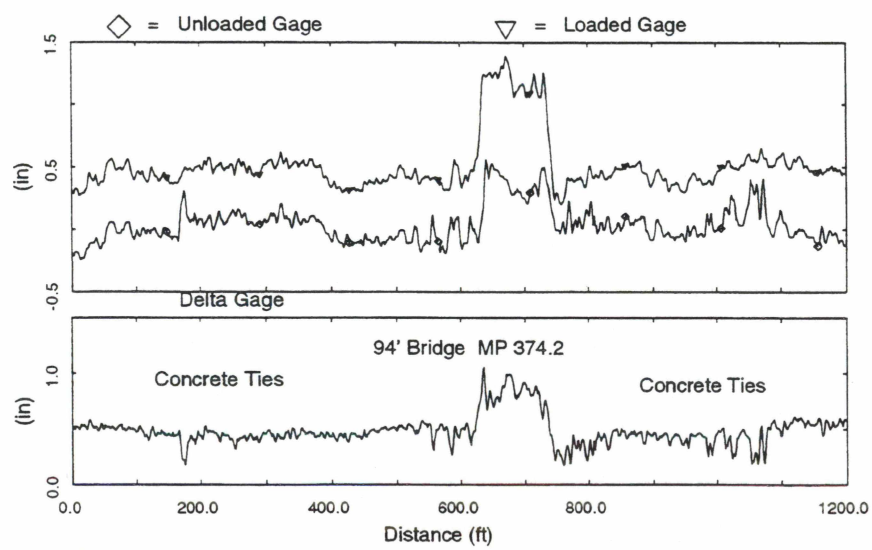

Exhibit 9. Unloaded, Loaded and Delta Gage Distance Histories over an Open Deck Bridge with Weak Gage Widening Resistance.

widening resistance on the bridge was evident in this example. This indicates weakness in the tie rail seat.

Exhibit 10 is an example of wide gage and of high gage widening resistance on a ballasted deck bridge. This exhibit shows the 1200 foot distance histories of unloaded, loaded and delta gage. At approximately 300 feet, there was a 96 foot long ballasted deck bridge, where unloaded gage increased from an average of about 56.5" to 57.4" on the bridge. Loaded gage, on the other hand, only increased from 57.2" to 57.7" on the bridge. This resulted in a reduction of delta gage of 0.7" elsewhere to a delta gage of 0.3" on the bridge. This showed that while unloaded gage was generally high, the gage widening resistance on the ballasted deck bridge was quite good.

Exhibit 11 shows another example of weak gage widening resistance on an open deck bridge (MP 762.9). As seen from the distance history, the unloaded gage on the bridge at 300 feet increased to 57.5" while loaded gage increased to 58.3". Loaded gage safety limit was exceeded. This triggered an auto pause so as to reduce forces and prevent any further gage widening. This was illustrated by the delta gage, which increased to 1.3" on the bridge. It then dropped below zero when the safety limit was exceeded.

Exhibit 12 shows distance histories of unloaded, loaded and delta gage on a section of track having four open deck bridges. As against small changes in unloaded gage, loaded gage showed substantial increases on the bridges. Weak gage widening resistance on these bridges resulted in increased delta gage.

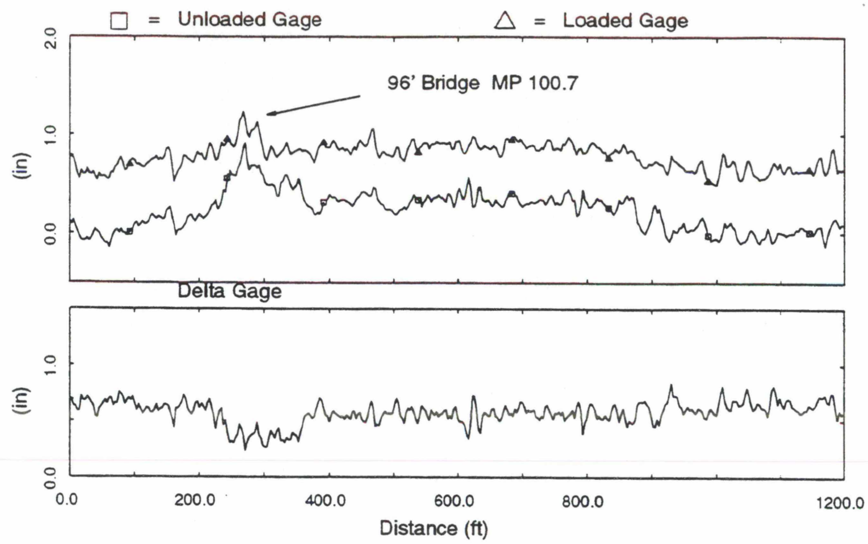

Exhibit 10. Unloaded, Loaded and Delta Gage Distance Histories over a Ballasted Deck Bridge with High Gage Widening Resistance.

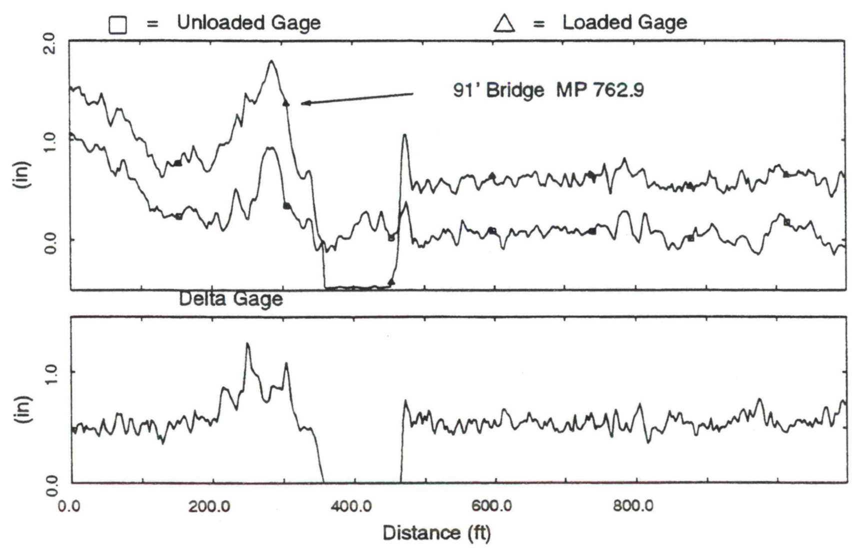

Exhibit 11. Unloaded, Loaded and Delta Gage Distance Histories over an Open Deck Bridge at MP 762.9 with Weak Gage Widening Resistance.

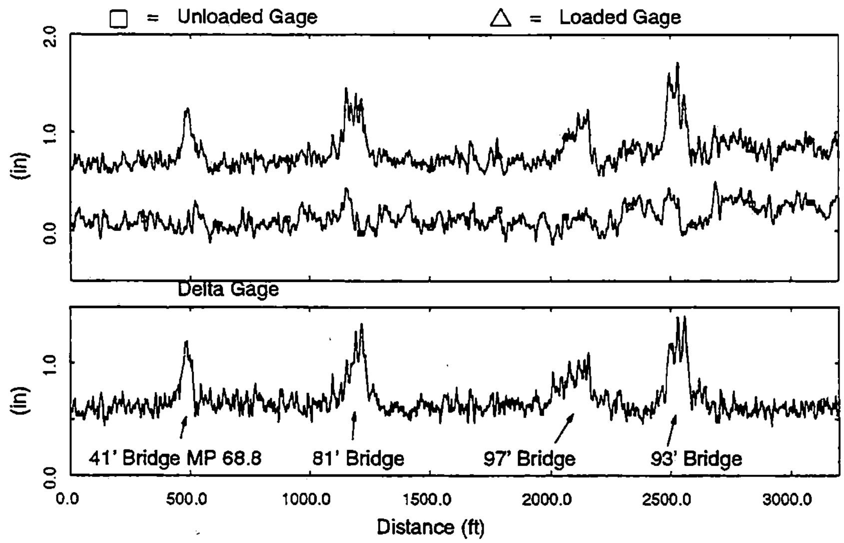

Exhibit 12. Unloaded, Loaded and Delta Gage Distance Histories over more Open Deck Bridges with Weak Gage Widening Resistances.

Delta gage averaged 0.5" elsewhere, but increased from 1.1" on the third bridge to over 1.4" on the last bridge.

As discussed in Section 2, the auto-pause mode was built into the TLV system to prevent load bogie derailment. The trigger thresholds used are a loaded gage safety limit of 58.25" and delta gage safety limit of 1.5". Examples of auto-pause were previously seen in Exhibits 7 and 11. Another set of trigger thresholds, also based on exceedence of a certain value of either the loaded gage (generally due to the presence of wide gage) or the delta gage (generally due to inadequate rail restraint), is used to indicate and list those track locations which require immediate maintenance. These track maintenance thresholds are defined as a loaded gage paint limit of 57.75" and a delta gage paint limit of 1.25".

Exhibit 13 shows listing from a typical report of gage widening exceptions occurring from exceedence of the loaded gage paint limit and the delta gage paint limit. Test speed in mph and split-axle vertical/lateral loads in kips are noted at top of the report. To the left at the top of the report, name of the railroad, mile post units and date of the test are given. Numerals assigned as error codes, as to loaded gage and delta gage paint and safety limits, are shown at the bottom of the report. The body of the report consists of eight columns listing the mile post, footage (in the direction of test) from the mile post to the start of exception, numerical listing of the exception, corresponding loaded, unloaded and delta gage at the start of exception, painted exceedence length of the exception, and error code assigned to the exception.

As an example, a loaded gage exception occurred at 4933 feet from mile post 83. Number 1 was the first exception in this test. Unloaded gage was 57.03", and the loaded gage was 57.81." As it was greater than the paint limit of 57.75", it triggered an exception, error code number 2. An 11 foot length of track, starting at 4933 feet from MP 83, was painted yellow. As noted in the report, delta gage was only 0.78". Delta gage exception is shown in Exhibit 13 at 2601 feet from mile post 81, the fourth exception in the test. At the beginning of the exception, unloaded gage of 56.21" and the loaded gage of 57.55" resulted in a delta gage of 1.34". It being greater than the delta gage paint limit of 1.25" triggered the exception, and was assigned an error code, number 4. Three feet of track was painted yellow because of this exception.

EXCEPTION REPORT

RAILROAD E
MP 85-70

PAINT LIMIT : D
LOADINGS: 33/18
SPEED : 20 MPH

SEP 13, 1991

MARKER Milepost	FOOTAGE	EXCEPTION	LOADED GAGE (Inches)	UNLOADED GAGE (Inches)	DELTA GAGE (Inches)	EXCEEDENCE LENGTH (Feet)	ERROR Code
85							
84							
83	4933	1	57.81	57.03	0.78	11	2
	5521	2	57.45	56.11	1.34	3	4
81							
	758	3	57.77	56.80	0.97	3	2
	2601	4	57.55	56.21	1.34	3	4
80							
	732	5	57.85	56.95	0.90	8	2
79							
78							
	1292	6	57.77	56.85	0.92	3	2
	4764	7	57.76	57.02	0.74	7	2
77							
76							
75							
74							
	3664	8	57.76	57.29	0.47	4	2
73							
72							
71							
	1605	9	57.82	57.32	0.50	10	2
	2577	10	57.80	57.06	0.74	7	2
	3100	11	57.79	57.16	0.63	9	2
	3188	12	57.79	57.08	0.71	12	2
	3834	13	57.81	57.32	0.49	8	2
	3894	14	57.81	57.06	0.75	20	2
	3918	15	57.81	57.23	0.52	12	2
	3938	16	57.75	57.08	0.76	12	2
	3962	17	57.84	57.05	0.80	8	2
	4001	18	57.85	57.26	0.50	8	2
	5167	19	57.76	57.18	0.58	7	2
	5222	20	57.78	57.13	0.65	17	2
	5306	21	57.77	56.99	0.78	3	2

LIMITS		Error Code if exceeded
LOADED GAGE PAINT LIMIT	57.75	2
DELTA GAGE PAINT LIMIT	1.25	4
LOADED GAGE SAFETY LIMIT	58.25	8
DELTA GAGE SAFETY LIMIT	1.50	16

Exhibit 13. A Typical Exception Report showing Exceedences of the Loaded Gage Paint Limit as well as the Delta Gage Paint Limit.

A review of all exception reports was made to determine the most common error code found on the North American Railroads tested. It was found that error code number 2 occurred in 90 percent of the exceptions. These occurrences were due to the exceedence of the loaded gage paint limit of 57.75". Wide gage was found to be the onset of exceptions, while the delta gage values did not indicate laterally weak track. The total painted length amounted to about 8 miles out of a total of 1,939 miles analyzed. This is about four-tenth of one percent of the total analyzed mileage. While any wide gage approaching the exception limit is cause for concern, and may, on examination, indicate a maintenance requirement, these results demonstrate that on the North American railroads tested, a good level of gage widening resistance is maintained. While traffic, tie replacement and track surfacing operations impact the unloaded gage, it is apparent that for much of the tested track, better gage maintenance is required rather than an increase in the lateral strength or improving tie/fastener conditions.

In these tests, unloaded, loaded and delta gage distributions were found generally to be asymmetrical about the median. Delta gage distribution, for strong track (with a significant percentage of wide gage), was less asymmetrical than was the unloaded and loaded gage distributions. Subtraction of unloaded gage from loaded gage, to determine strong-track delta gage, eliminates most of the alignment errors present in unloaded gage, and passed on to loaded gage. An example of this is shown in Exhibit 14. As seen, the unloaded and loaded gage distributions are quite asymmetrical

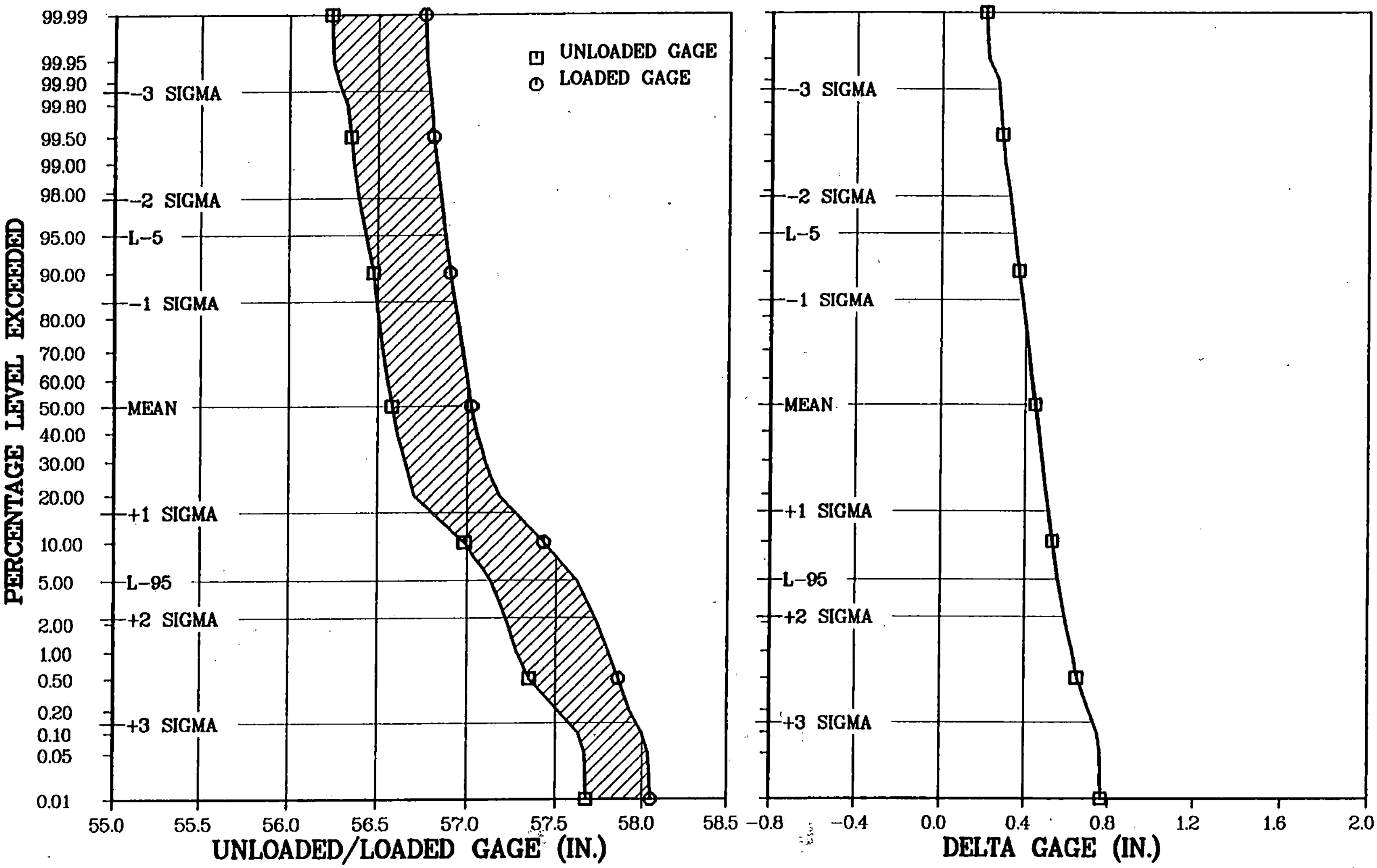

Exhibit 14. Percentage Level Exceedences of Unloaded, Loaded and Delta Gage for a Strong Track with Significant Percentage of Wide Gage.

but closely parallel. The delta gage distribution, on the other hand, is basically symmetrical.

For a laterally weak track (with a moderate percentage of wide gage), it was found that loaded gage distribution rather than delta gage distribution, was less asymmetrical than the unloaded and delta gage distributions. It is believed that, in the loaded state, this occurs due to weaker lateral stiffness compensating for the variations in track alignment. An example of this is shown in Exhibit 15. The unloaded and delta gage distributions are quite asymmetrical, while loaded gage distribution is basically symmetrical and therefore, closer to normal distribution.

As an aid in understanding the distribution curves, the following comments may be helpful. The distribution curves are plotted on normal probability paper. This is done so as to compare distribution of a gage parameter with the normal distribution, which would plot as a negatively inclined straight line on this paper. The closer the distribution of a parameter is to a straight line, the closer it is to normal distribution. The X-axis shows the gage parameter while its percentile rank, in decreasing numerical order, is shown on the Y-axis, using a normal probability scale. For example, a 'percentage level exceeded' of 5 would correspond to a magnitude of the gage parameter on the X-axis which is exceeded by only 5 percent of its values. This magnitude of parameter had a percentile rank of 95, and is so indicated in the plot by L95. The plot also shows a percentile rank of 5, indicated by L5.

It should be noted that values on the X-axis of a gage

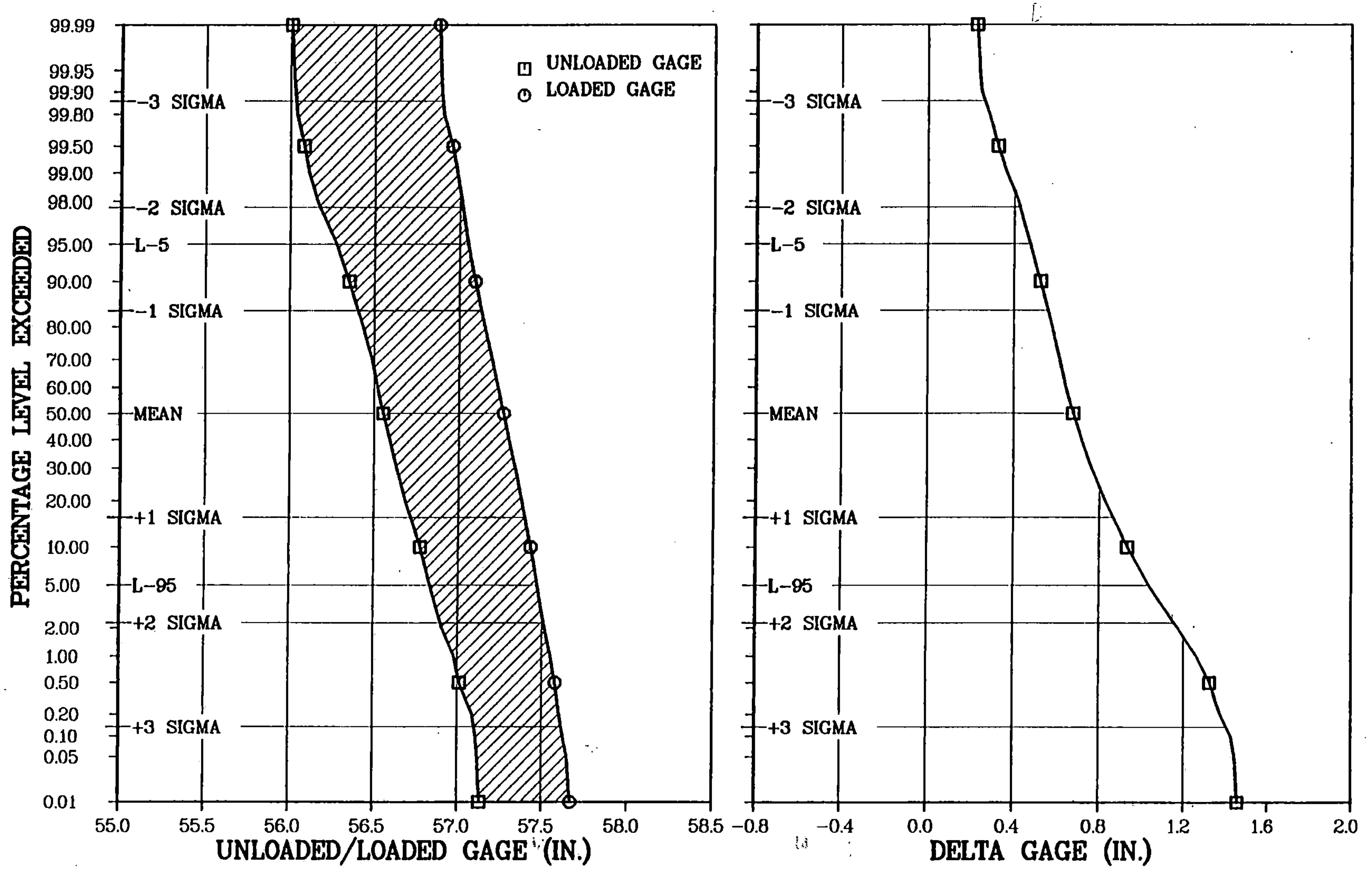

Exhibit 15. Percentage Level Exceedences of Unloaded, Loaded and Delta Gages for a Strong Track with Moderate Percentage of Wide-Gage.

parameter corresponding to 'sigma' and 'mean' on Y-axis would be correct only if the distribution of the parameter is normal; that is, a straight line for the entire distribution. For a normal distribution, 68.26% of the parameter values are contained between '1 sigma' boundaries, 90% between L5 and L95 boundaries, 95.44% between '2 sigma' boundaries, and 99.73% between '3 sigma' boundaries. It is important to note that a change in mean value shifts the whole distribution laterally, while a higher value of the standard deviation flattens the distribution.

In addition to presenting an example of asymmetrical distributions, Exhibit 14 serves as an illustration of gage parameter distributions for a mile of data in which the loaded gage paint limit of 57.75" is exceeded. As seen in the earlier general finding of the exception report, wide gage initiates the onset of the loaded gage paint limit found in this test mile. As indicated by lower portions of the curves, about 10% of the time the unloaded gage exceeds 57.0", and about 1.5% of the time, loaded gage exceeds the paint limit of 57.75". A cross reference to the exception report shows that the summation of all painted lengths in this mile is 79 feet. The total painted length amounts to about 1.5% of the mile. About 10% of the time loaded gage in this mile is greater than 57.4". This is an area of concern, requiring field inspection and/or gage correction maintenance.

Distribution of delta gage, on the other hand, is close to a steep straight line. This results from less variation in delta gage. An assumption can be made that the delta gage is normally distributed. About 95% of the time delta gage values fall between

0.3" and 0.6". The corresponding compliance values are 0.016"/kip and 0.033"/kip, with the 18 kip gage widening load used in tests. These values indicate "good" tie and rail restraint conditions. It should be emphasized that gage widening resistance is adequate in this mile, and exceptions occurring are due to wide gage.

Exhibit 15, in contrast, is an example of gage parameter distributions for a mile of data where the delta gage paint limit of 1.25" was exceeded. The distribution shows that for about 60% of the time the unloaded gage is wide and remaining 40% is tight. Alignment asymmetry is seen in the unloaded gage distribution, while loaded gage has a symmetrical distribution. Since loaded gage follows a normal distribution, much of the loaded gage data approaches the mean value of 57.25". About 95% of the time the loaded gage values fall between 57.0" and 57.5". In contrast, the unloaded gage data is distributed towards the tails of the curve. Unloaded gage has a flatter slope around the mean than does the loaded gage, indicating a greater variation in its values. It appears that the weak gage widening resistance of tight-gage track has caused the delta gage paint exceptions in this test mile.

The delta gage distribution is asymmetrical. Similar to unloaded gage, it has a denser distribution towards the tails of the curve. About 95% of the time delta gage values fall between 0.42" and 1.15". The corresponding compliance values are 0.023"/kip and 0.064"/kip due to the 18 kip gage widening load used in tests. It is apparent that about 50% of the time delta gage values are greater than 0.7", resulting in compliance values greater than 0.04"/kip. These lateral deflection rates indicate less than good tie and rail restraint conditions. Even though only about 0.5% of the time unloaded gage exceeds 57.0", and loaded gage does not exceed the paint limit of 57.75", a degrading tie/fastener condition and increasing delta gage variation are seen in the denser tails of the curves, and the flatter middle portion of delta gage distribution curve for this test mile. About 1.5% of the time delta gage values exceed the delta gage paint limit of 1.25". While this may be an area of concern, requiring an upgrade of gage widening resistance, it is not to be inferred from these test results that a greater risk of derailment exists.

Examples of gage parameter distributions for a statistical mile sample having elastic fasteners on concrete and wood ties, and with cut spikes are seen in Exhibits 16, 17 and 18, respectively. A comparison shows that these curves are more normally distributed, with less scatter for elastic fasteners than for cut spikes. Some minor wide gage is present on concrete and wood tie track having elastic fasteners. this wide gage, however, is not as pronounced as that seen on wood tie track fastened with cut spikes. As seen in Exhibit 18, wide gage exists on about 96% of the cut spike test mile, and measures as much as 57.3".

In contrast to the "good" tie and rail restraint condition seen in Exhibit 18 for cut spike track, "excellent" tie and rail restraint conditions are indicated by delta gage distributions in Exhibit 16 and 17 for wood and concrete tie tracks with elastic fasteners. As seen, 95% of delta gage distribution for both wood and concrete ties with elastic fasteners is within 0.1" and 0.35", resulting in a 95th-percentile compliance value of 0.02"/kip. It

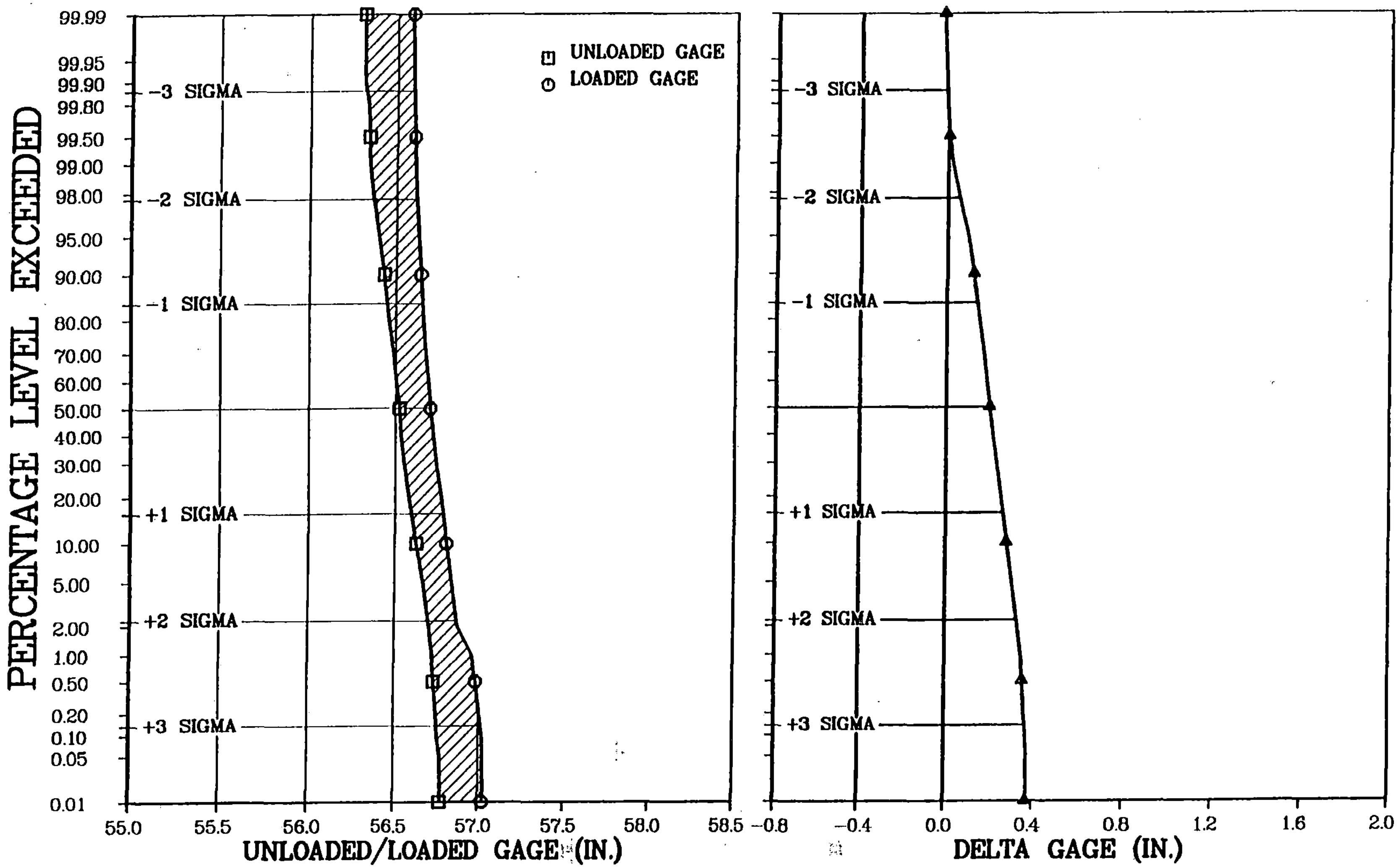

Exhibit 16. Percentage Level Exceedences of Unloaded, Loaded and Delta Gages for a Concrete Tie Track.

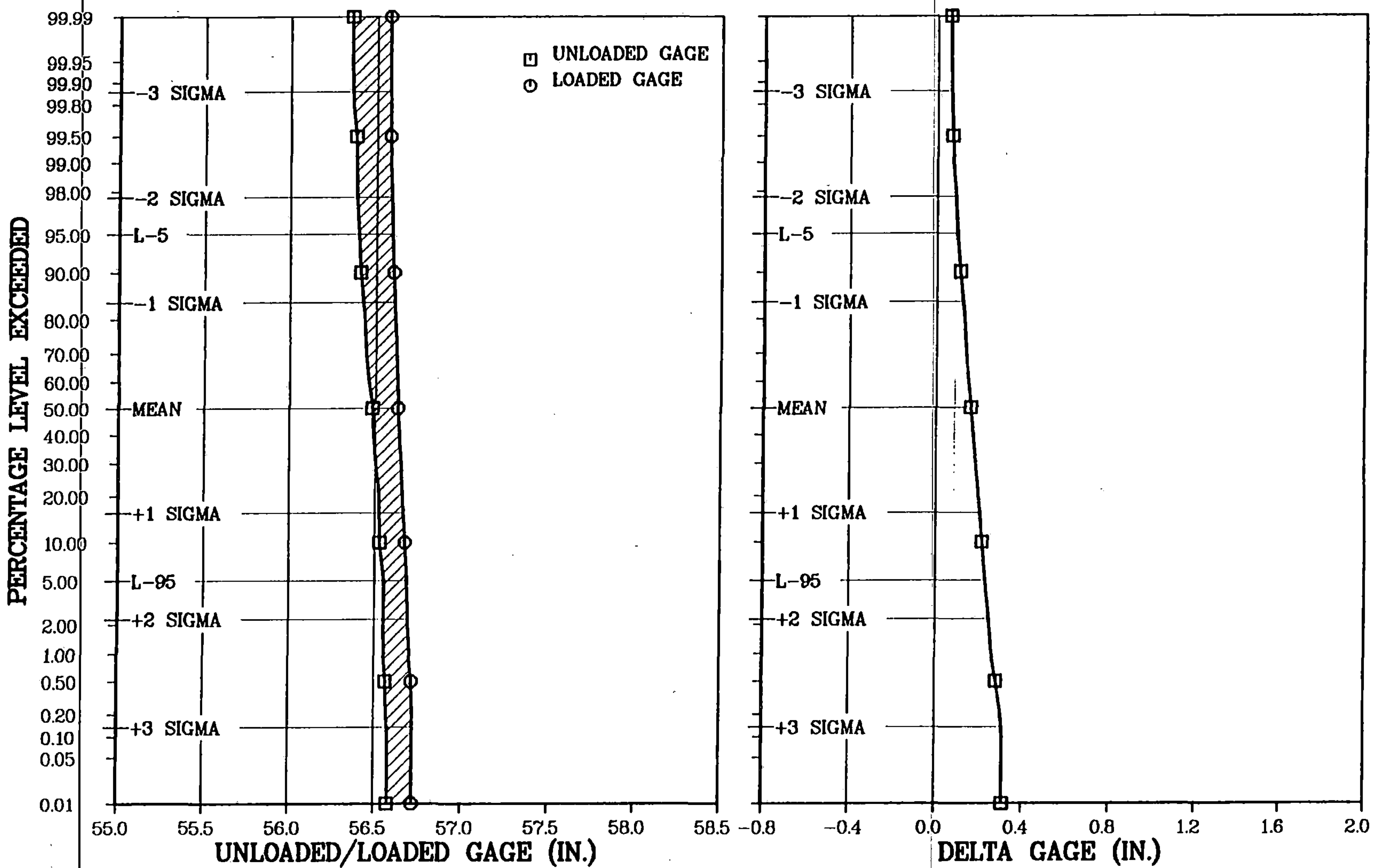

Exhibit 17. Percentage Level Exceedences of Unloaded, Loaded and Delta Gage for a Wood Tie Track with Elastic Fasteners.

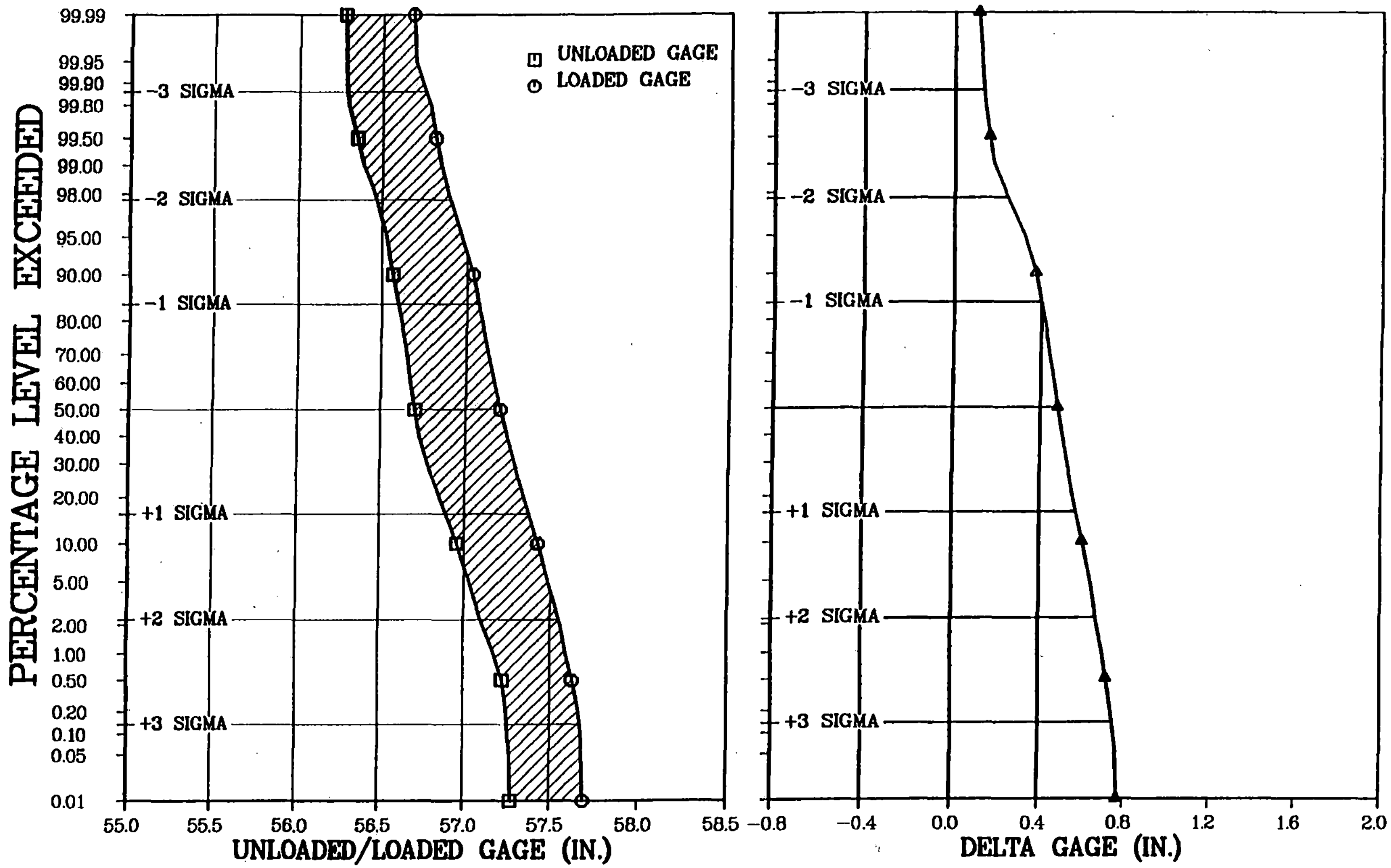

Exhibit 18. Percentage Level Exceedences of Unloaded, Loaded and Delta Gages for a Wood Tie Track with Cut Spikes.

can be inferred from these results that concrete and wood ties with elastic fasteners, in general, provide a better gage holding mechanism and also better gage widening resistance than is seen with cut spikes.

In the following sections 6.1 through 6.9, test results from individual railroads are presented in terms of medial and 95th percentile statistics. Although several hundred miles of continuous gage widening tests were conducted at designated locations on each railroad using the TLV, this sampling may be inadequate for a general inference as to the overall gage widening resistance on the various railroads since test locations selected are not necessarily representative of system conditions.

The data is presented to indicate gage widening characteristics of the sections tested to show its diversity as compared with other locations both on the parent and on other railroads. A close review of the test results will demonstrate the viability of the TLV tests as a means to quantitatively study the gage widening characteristic of a section of track. Using the test results, one may draw rational decisions as to gage maintenance requirements.

6.1 RAILROAD A

A total of 275 miles of track was tested on Railroad A. Test Section 1 comprised of 125 miles in the midwest region, while Test Section 2 comprised of 150 miles and was located in the southwest. About 35% of the track in Test Section 1, and 2.5% in Test section 2 consisted of concrete ties. The two test sections were constructed primarily with continuously welded 132 lb rail, on 7" x 9" x 8'6" oak hardwood ties. Test Section 1, which was tested in May 1991, carries 44 MGT per year of unit coal train traffic, and has FRA class 2, 3 and 4 track. Test Section 2, which was tested in October 1991, has FRA class 3 and 4 track, and carries 20 MGT per year of mixed freight traffic.

The standard spiking pattern for track on both the subgrade and bridges was the same in both test sections. Standard track spikes used were 5/8" by 6" cut spikes. Three spikes per tie plate were used on tangent track, two rail holding and one anchor spike on the gage side. On curves greater than or equal to one degree, one additional anchor spike was added per tie plate on the field side. The tie plates used on these test sections were typically 14-3/4" x 7-3/4" double shoulder.

6.1.1 Analysis Based on Mile Post

Exhibits 19, 20, 21 and 22 show the mean values of unloaded gage, loaded gage, delta gage and track compliance, respectively, for both test sections, on a mile-by-mile basis. Similarly, Exhibits 23, 24, 25 and 26 show the respective 95th-percentile values for the test sections.

Exhibit 19 reveals a marginal wide gage for both test sections. As seen, the mean unloaded gage varies from 56.27" to over 56.82" on Test Section 1, and from 56.35" to 56.78" on Test Section 2. It is apparent that unloaded gage in Test Section 2 has smaller deviation from standard gage than does Test Section 1.

In Exhibit 20, the mean loaded gage varies from just below

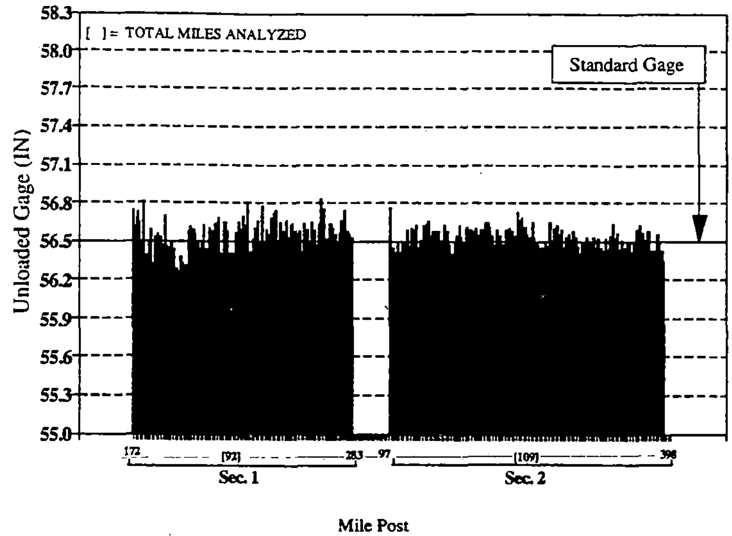

Exhibit 19. Unloaded Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 & 2 of Railroad A.

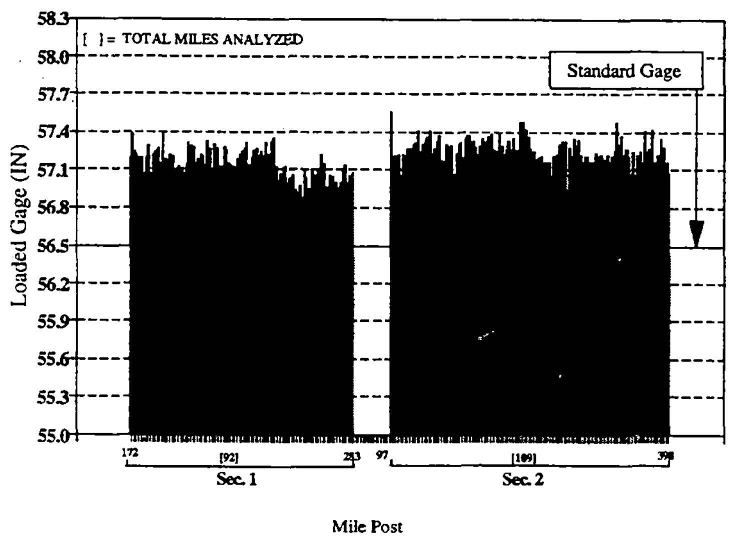

Exhibit 20. Loaded Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 & 2 of Railroad A.

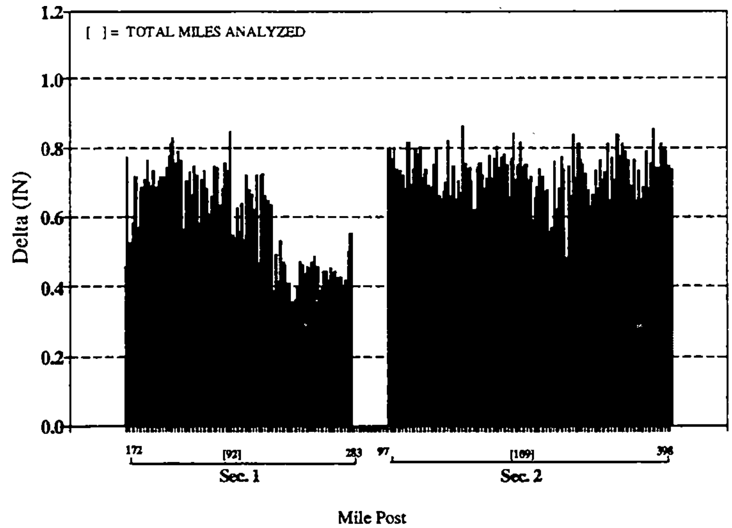

Exhibit 21. Delta Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 & 2 of Railroad A.

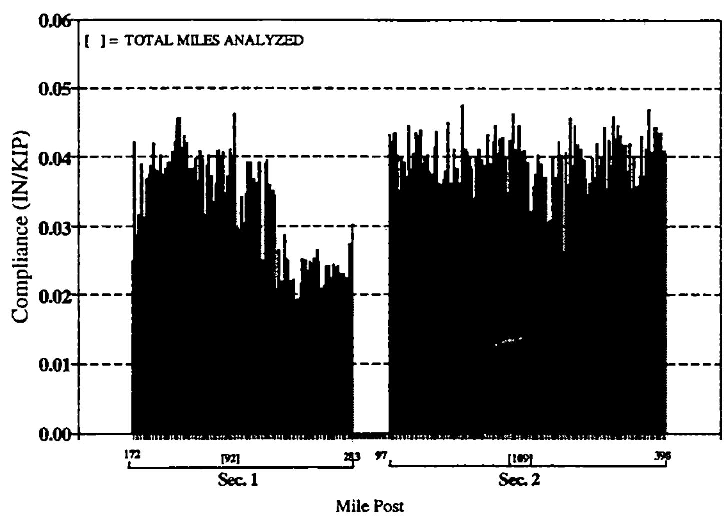

Exhibit 22. Track Compliance Mean Value for Each Statistical Mile Sample in Test Sections 1 & 2 of Railroad A.

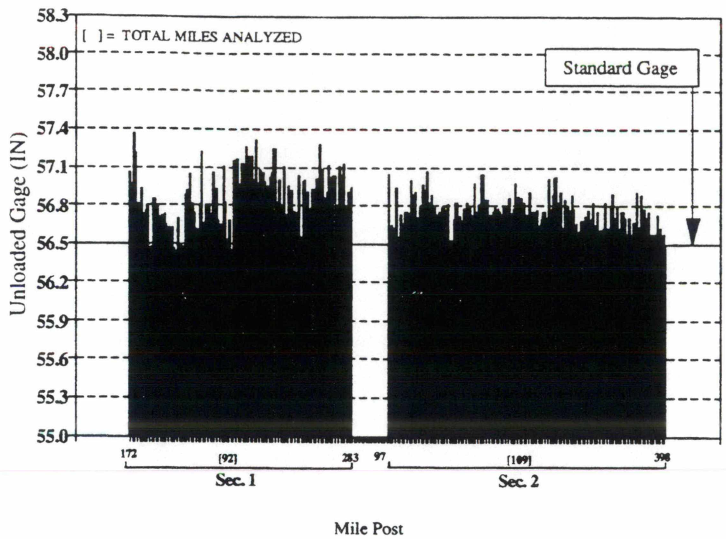

Exhibit 23. Ninety Fifth-percentile (L95) Value of Unloaded Gage for Each Statistical Mile Sample in Test Sections 1 & 2 of Railroad A.

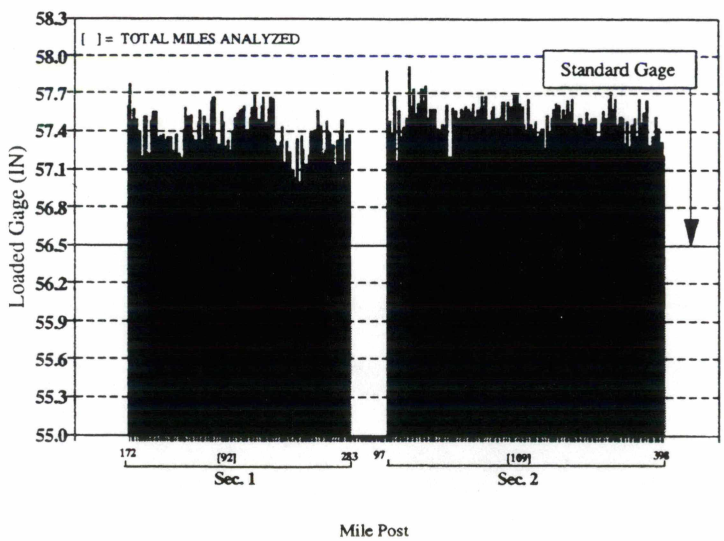

Exhibit 24. Ninety Fifth-percentile (L95) Value of Loaded Gage for Each Statistical Mile Sample in Test Sections 1 & 2 of Railroad A.

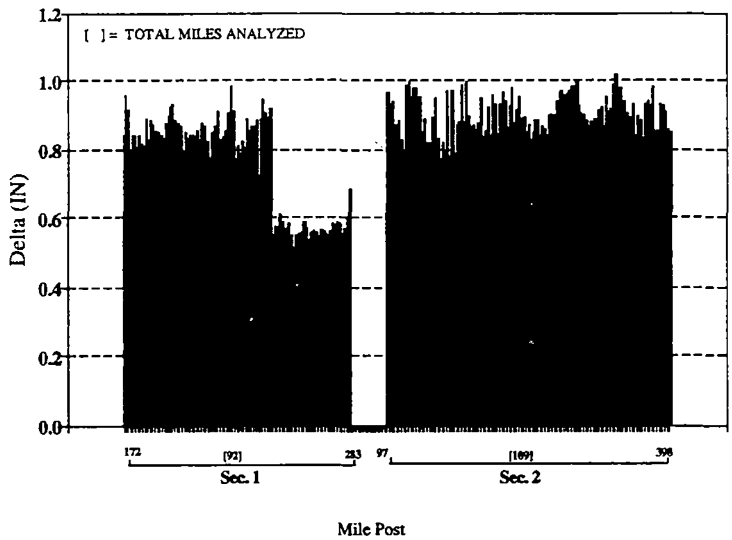

Exhibit 25. Ninety Fifth-percentile (L95) Value of Delta Gage for Each Statistical Mile Sample in Test Sections 1 & 2 of Railroad A.

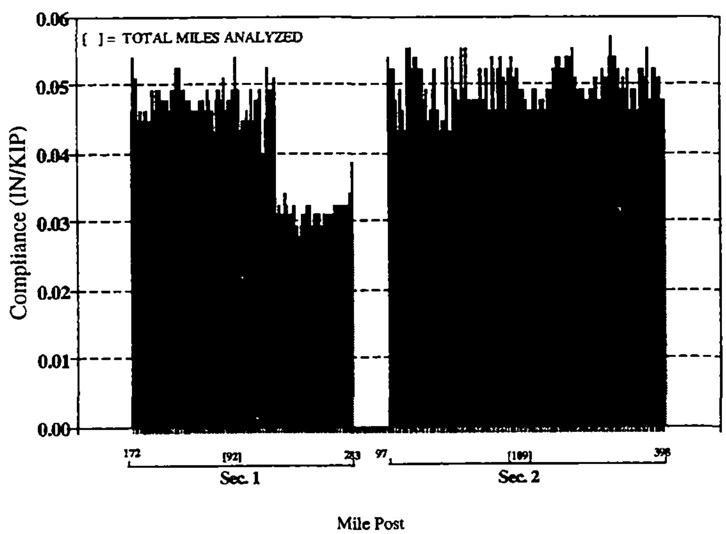

Exhibit 26. Ninety Fifth-percentile (L95) Value of Track Compliance for Each Statistical Mile Sample in Test Sections 1 & 2 of Railroad A.

56.9" to 57.39" in Test Section 1, and from just over 56.9" to over 57.55" in Test Section 2. The lower loaded gage on concrete ties seen in the last third of Test Section 1 is obvious. In Test Section 2, concrete ties are used in some curves, and their contribution is averaged with wood ties in each mile tested and is therefore, hard to recognize. Even though it appears that track in Test Section 1 has greater gage holding ability than seen in Test Section 2, a general concern emerges regarding a need for regaging and respiking of the track in both of the test sections. As will be seen from a study of delta gage values, a large loaded gage may not imply weak track if wide gage exists before loading. A study of the exception reports shows that almost all of the exceptions in these two test sections are due to exceedence of the loaded gage paint limit of 57.75".

Exhibit 21 indicates which miles of the track are relatively strong and which are weak. The mean delta gage varies from just below 0.37" on concrete ties, to 0.85" on cut spikes in Test Section 1. In Test Section 2, the variation is from just under 0.5" to 0.86". It can be deduced from the mean delta gage results that the addition of concrete ties in the last third of Test Section 1 gives it an overall greater gage widening resistance than seen in Test Section 2. It is apparent that in the miles of the track where tight gage exists, higher values are seen for delta gage.

Exhibit 22 gives a quantitative measure of the tie and rail restraint provided by the track in Test Sections 1 and 2. The higher the compliance value, the weaker the track lateral condition. Variation of mean compliance from just under 0.02"/kip to 0.03"/kip on the concrete tie portion of Test Section 1, indicates high gage widening resistance for this track. Mean compliance between 0.03"/kip to 0.045"/kip on the cut spike track in both test sections indicates good rail restraint conditions.

A measure of dispersal in the data is required to better differentiate between weak and strong tie/fastener conditions. Though a mean value is affected by every data value, whether extremely large or extremely small, it does not accurately reflect a statistical distribution of the data. On the other hand, L95, a discrete data value approximately 1.64 standard deviations away from the mean value, accounts for a large amount of scatter in the data because 95% of the data is below this value. This 95th-percentile value, therefore, is a good representation of the overall tie/fastener condition in the track. L95 values of unloaded, loaded and delta gage are discussed below.

A widespread presence of wide gage is apparent from the L95 values of unloaded gage in Exhibit 23. As apparent, wider unloaded gage occurrences are more obvious in Test Section 1 than Test Section 2. This is also evident in the concrete tie track in Test Section 1. Symptoms of gage widening in wide-gage track, with good lateral resistance, are revealed in loaded gage Exhibit 24. As seen, most of the L95 loaded gage values are between 57.4" and 57.7". The last one third concrete tie segment in Test Section 1 has somewhat lower values. A L95 value closer to 57.7" is an indication of the incipience of the loaded gage paint limit exception. At the beginning of Test Section 2, there are few miles of track where L95 is actually above the loaded gage paint limit of 57.75".

The extent of gage widening resistance provided by tie and rail restraint on each mile are clearly revealed in Exhibits 25 and 26. L95 delta gage values of 0.55" on concrete tie track in Test Section 1 result in L95 compliance values of 0.031"/kip. Since 95% of the data is below these values, a high gage widening resistance is indicated for the concrete tie track. Comparatively, a good tie and rail restraint condition is also evident for the cut spike track as seen from the delta gage and compliance values in these exhibits.

6.1.2 Analysis Based on Track Type

Exhibit 27 shows in Column 1 the FRA track classes in Test Section 1 and 2 of Railroad A. Column 2 lists track geometry, defined as curvature in degrees, while column 3 defines the tie and fastener types. Columns 4 and 5, respectively, show individual track miles analyzed in Test Section 1 and 2. The last column gives the sum of all the miles analyzed on both sections for each type of track. The last row, on the other hand, gives the total track miles analyzed on each test section with a grand total in the last column. As seen, the majority of track tested in Test Section 1 was Class 3 wood and concrete tie track having curvatures up to 2 degrees. In Test Section 2, the majority of track tested was Class 3 and 4 cut spike track with curvatures also up to 2 degrees. Out of a total of about 201 miles analyzed, 57 miles of Class 3, and 43 miles of Class 4 consisted of cut spike track having

Class	Geometry (Degrees)	Tie/Fastener	Track Analyzed (Miles)		
			Test Section		Total
			1	2	
2	0-2	Wood/Spike	0.78	0.00	0.78
2	0-2	Concrete	0.68	0.00	0.68
2	6-10	Concrete	1.12	0.00	1.12
3	0-2	Wood/Spike	25.93	31.07	57.00
3	2-4	Wood/Spike	5.61	8.30	13.91
3	4-6	Wood/Spike	7.36	9.84	17.20
3	6-10	Wood/Spike	4.59	1.88	6.47
3	0-2	Concrete	20.63	0.16	20.79
3	2-4	Concrete	5.47	0.17	5.64
3	4-6	Concrete	5.30	2.47	7.77
3	6-10	Wood/Spike	7.33	1.11	8.44
4	0-2	Wood/Spike	6.94	36.09	43.03
4	2-4	Wood/Spike	0.33	13.78	14.11
4	4-6	Wood/Spike	0.00	4.37	4.37
Total Miles			92.07	109.24	201.31

Exhibit 27. Total Miles Analyzed in Test Sections 1 & 2 of Railroad A for Wide Gage and Gage Resistance with respect to Track Class, its Geometry and Tie and Fastener Types.

curvatures up to 2 degrees.

Exhibit 28 shows the mean, standard deviation and L95 of unloaded gage in Test Section 1, as a function of the track curvature, class and tie/fastener type. This exhibit shows that as the degree of curvature increases, the mean and L95, in general, increase along with the standard deviation for both the wood and concrete tie sections. Standard deviations on 6-10 degree curves, however, do not follow this trend. As seen in 0-2 and 4-6 degree plots for cut spike track, unloaded gage decreases as a function of track class. Such a class dependence is not quite obvious for concrete tie track. From these observations, one may conclude that lower operating speed, requiring only limited maintenance on lower class track, and the higher gage widening loads seen on higher degree curves, are probably the reasons for wider unloaded gage on lower class and higher degree track. There is not much of a difference in unloaded gage between wood and concrete tie track in this test section. This may be due to the cut spike track being newer or carrying lesser traffic than the concrete tie track. In general, a concern to control gage seems to exist for higher degree and higher class track on both the wood and concrete tie track in this test section.

Exhibit 29 shows the mean, standard deviation and L95 of loaded gage in Test Section 1. Trends similar to those seen in unloaded gage in the previous exhibit are present in this exhibit for loaded gage. That is, greater loaded gage is apparent in higher curvature track and lower class cut spike track in this exhibit. As apparent from L95 values, 95% of the time loaded gage

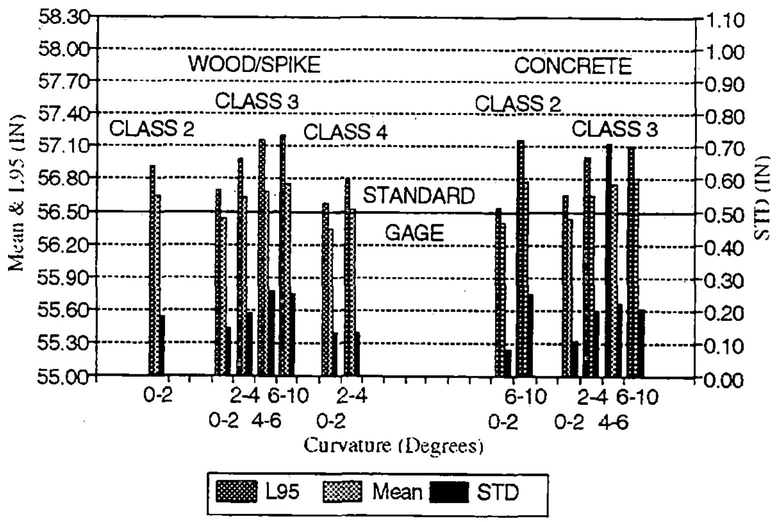

Exhibit 28. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad A, Segmented by Track Class, Tie and Fastener Types.

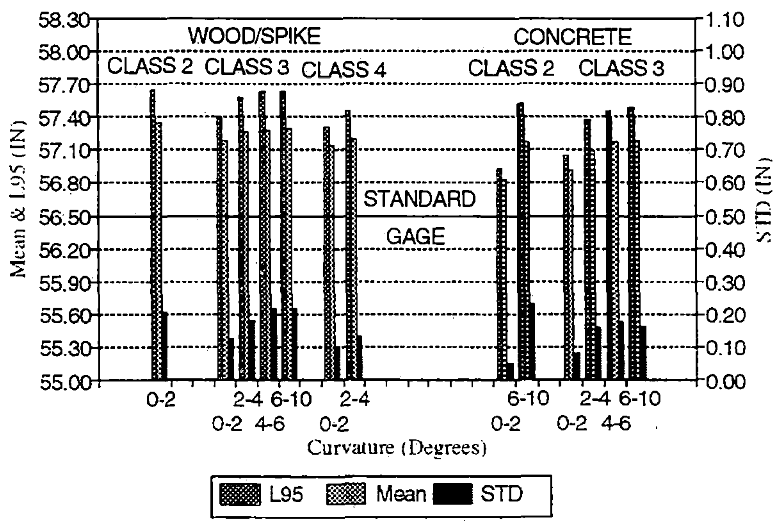

Exhibit 29. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad A, Segmented by Track Class, Tie and Fastener Types.

is below 57.65" for cut spike track and 57.5" for concrete tie track.

The mean, standard deviation and L95 of delta gage in Test Section 1 are given in Exhibit 30. Significantly smaller delta gage and, therefore, greater gage widening resistance is seen with concrete tie track, as compared to cut spike track. The largest L95 value for delta gage of 0.6" on concrete tie track, and resulting in 95th-percentile track compliance value of about 0.03"/kip, indicates good tie and rail restraint conditions. The largest L95 value of delta gage on cut spike track is 0.9". The corresponding L95 value of track compliance is 0.05"/kip. This indicates adequate tie and rail restraint conditions.

There are three quite discernible trends seen in the delta gage values in Test Section 1. First, the mean and L95 value of delta gage decrease as a function of curvature. Second, the standard deviation increases as a function of curvature. Third, the standard deviation decreases, contrary to what may be expected, while the corresponding mean and L95 of delta gage on 0-2 degree cut spike track increase with track class.

Track areas having high curvature are generally problem areas, and hence, more maintenance attention is required. Similarly, higher operating speeds on higher class track require added maintenance. On lower degrees of curvature one might add an extra spike, while a higher degree of curvature generally warrants some type of elastic fastener. Such practices will improve the gage widening resistance of track. A decrease in the delta gage mean and in L95 value with respect to curvature is generally related to

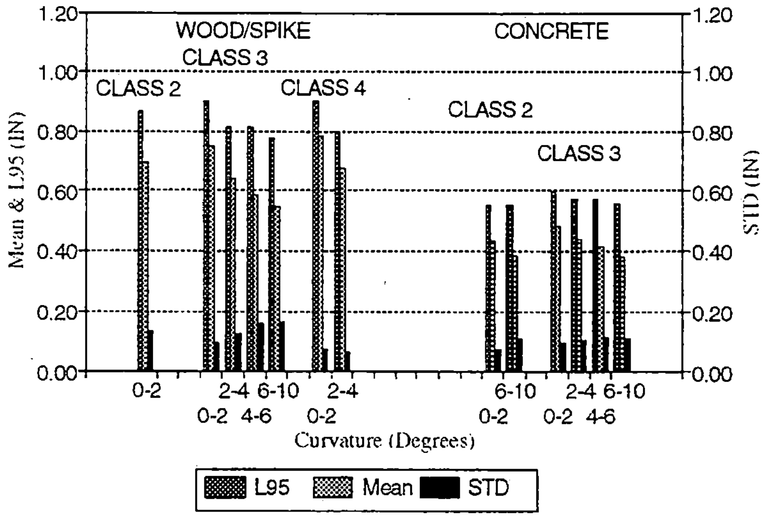

Exhibit 30. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad A, Segmented by Track Class, Tie and Fastener Types.

better track maintenance. On the other hand, a slight increase in the standard deviation with curvature may have resulted due to higher volume of traffic and greater lateral forces at higher degrees of curvature.

While better maintained, as indicated by the decreasing standard deviation with increasing 0-2 degree cut spike track class, the moderate increases seen in mean and L95 values with track class may be the result of higher speed traffic at higher track class, thus exerting higher lateral forces on the track. The moderate differences seen, in general, in delta gage among various track types, for both the wood and concrete tie track, suggest that these differences are not largely due to different maintenance practices, but are, in a significant way, related to the past load history on the track.

The unloaded, loaded and delta gage in Test Section 2, with respect to track type, are shown in Exhibits 31, 32 and 33, respectively. A comparison shows that Test Section 1 and Test Section 2 have similar gage widening characteristics. On both test sections, concrete tie track shows a significantly lower delta gage than does cut spike track. Concrete tie track, with a maximum delta gage mean value of 0.55" and a resulting mean track compliance of about 0.03"/kip, indicates good tie and rail restraint conditions. On cut spike track, the largest mean track compliance value of 0.043"/kip, with respect to 0.77" delta gage mean value, implies suitable rail restraint.

In contrast to Test Section 1, gage widening variations with respect to track curvature or class in Test Section 2, are only slightly discernible in the unloaded and loaded gage plots, and not at all in the delta gage plots on cut spike track. However, on concrete tie track, a relationship seems to exist between gage widening and track curvature, except for the 6-10 degree track. Mean and L95 values of unloaded and loaded gage increase with track curvature. On the other hand, only the mean value of delta gage seems to decrease with curvature, and such a trend is not present in the L95 values. It may be noted that sample averaging smooths the mean value, while L95 is a discrete value in the sample. It appears that the L95 delta gage value of 0.83" occurs due only to localized weak tie/fastener condition on the 2-4 degree concrete tie track in Test Section 2. This localized weak tie/fastener condition, however, does not significantly affect the mean value.

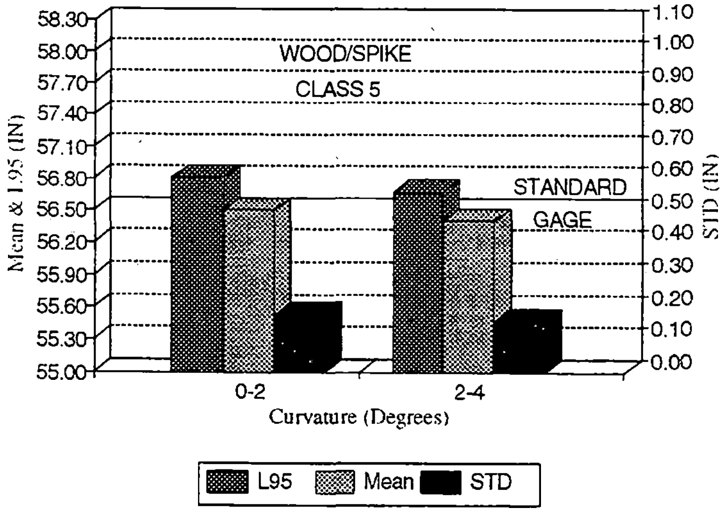

Exhibit 31. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad A, Segmented by Track Class, Tie and Fastener Types.

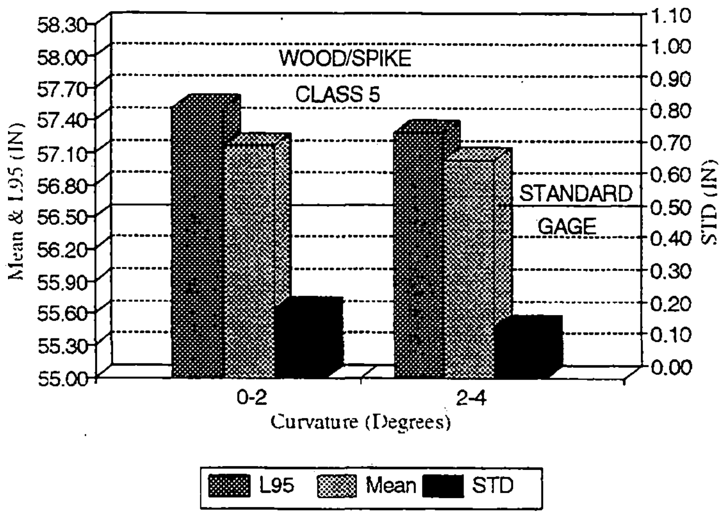

Exhibit 32. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad A, Segmented by Track Class, Tie and Fastener Types.

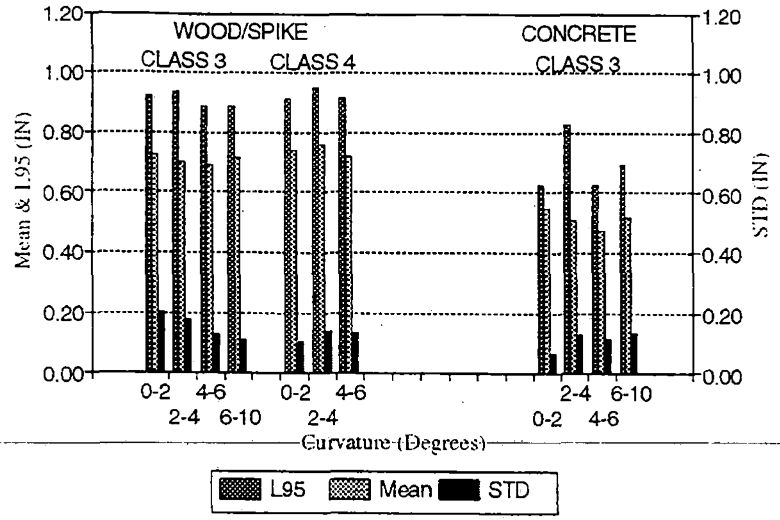

Exhibit 33. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad A, Segmented by Track Class, Tie and Fastener Types.

6.2 <u>RAILROAD B</u>

A total of 195 miles of track was tested on Railroad B in three test sections. Test mileage consisted of 150 miles in Test Section 1 located in the southeast, 20 miles in Test Section 2 located in the mid-Atlantic region, and 25 miles in Test Section 3 located in the midwest. About 25% of the track in Test Section 2 has concrete ties. All three test sections were constructed primarily with continuously welded 132 lb rail, on 7" x 9" x 8'6" oak and mixed hardwood ties except for the concrete tie track. Ties in Test Section 1 were air dried, and in Test Section 2 and 3 were vapor dried. Test Section 1, which was tested in June 1991, experiences 40 MGT per year of mixed freight traffic, and consisted of FRA class 2, 3 and 4 track. Test Section 2, also tested in June

1991, consisted of FRA class 3 track, and experiences 40 MGT per year of unit coal train traffic and is in mountain terrain. Test Section 3, which was tested in October 1992, experiences 15 MGT per year of mixed freight traffic on FRA class 4 track.

The standard spiking pattern for track on both subgrade and bridges is the same in all three test sections. Standard track spikes used are 5/8" by 6" cut spikes. Two rail holding spikes per tie plate are used on tangent track. For curves of less than two degrees, spiking is the same as for tangent track, except in special situations. For curves equal to or greater than two degrees, but less than six degrees, two additional anchor spikes are added per tie plate. On curves equal to or greater than six degrees, but less than eight degrees, an additional rail holding spike is added on the high rail gage side. For curves equal to or greater than eight degrees, an additional rail holding spike is added on the low rail gage side. Tie plates used on these test sections were typically 14-3/4" x 7-3/4" double shoulder plates. For curves, greater than 2 degrees and with tonnage exceeding 15 MGT annually, or on curves greater than 4 degrees and tonnage exceeding 8 MGT annually, 18" x 8" tie plates are used.

6.2.1 Analysis Based on Mile Post

Exhibits 34, 35, 36 and 37 show the mean values of unloaded gage, loaded gage, delta gage and track compliance, respectively, on all test sections, on a mile-by-mile basis. Similarly, Exhibits 38, 39, 40 and 41 show the respective 95th-percentile values for the test sections.

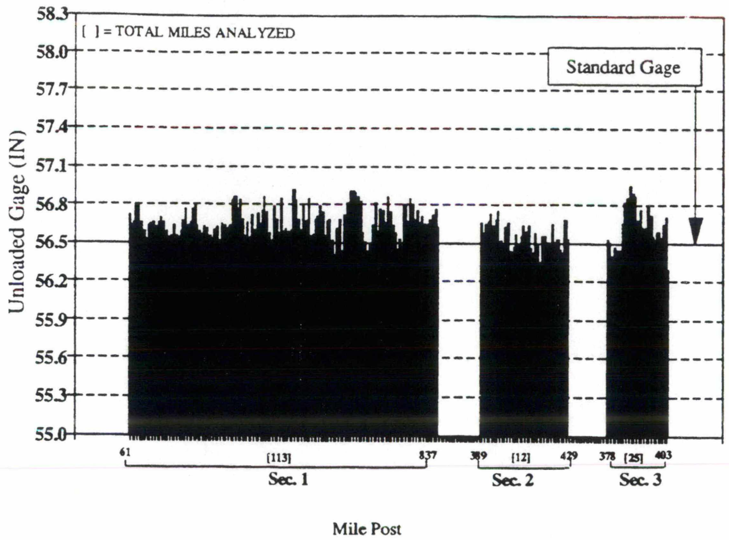

Exhibit 34. Unloaded Gage Mean Value for Each Statistical Mile Sample in Test Sections 1, 2 & 3 of Railroad B.

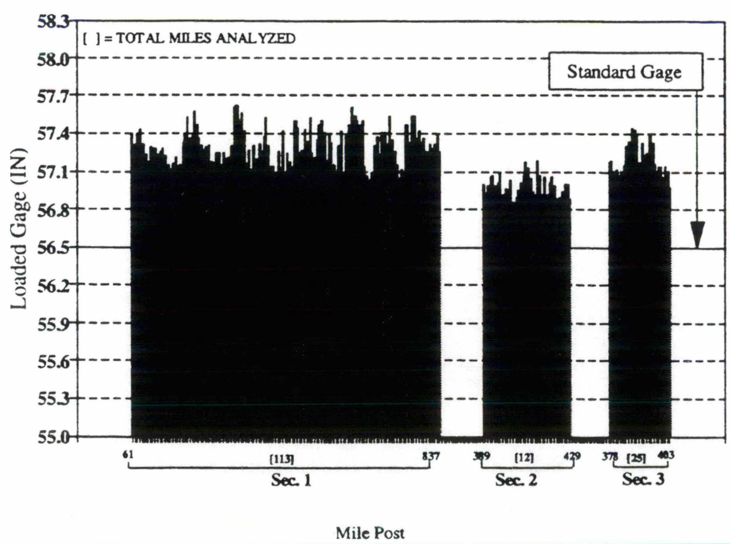

Exhibit 35. Loaded Gage Mean Value for Each Statistical Mile Sample in Test Sections 1, 2 & 3 of Railroad B.

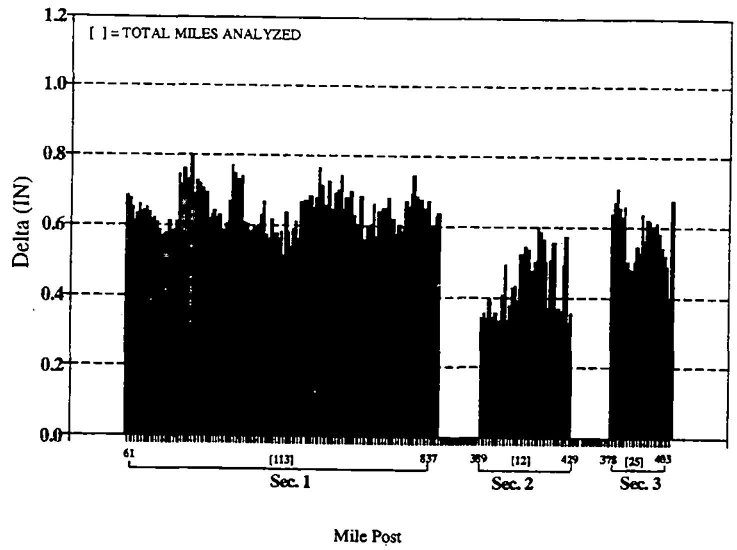

Exhibit 36. Delta Gage Mean Value for Each Statistical Mile Sample in Test Sections 1, 2 & 3 of Railroad B.

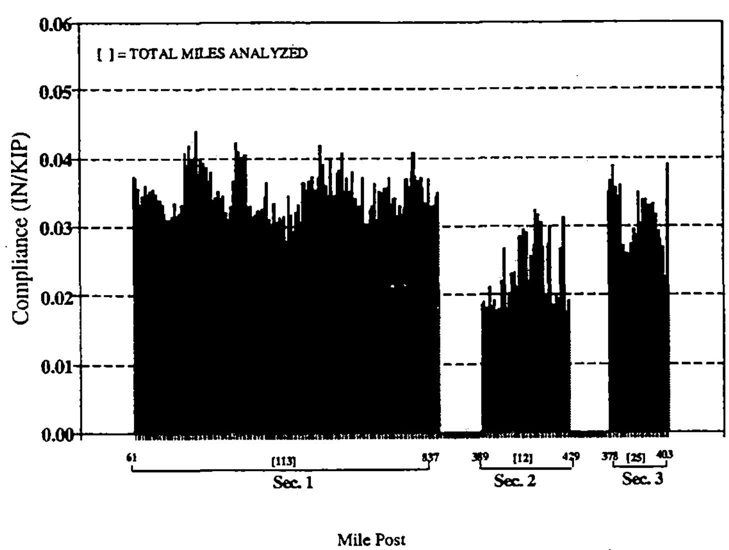

Exhibit 37. Track Compliance Mean Value for Each Statistical Mile Sample in Test Sections 1, 2 & 3 of Railroad B.

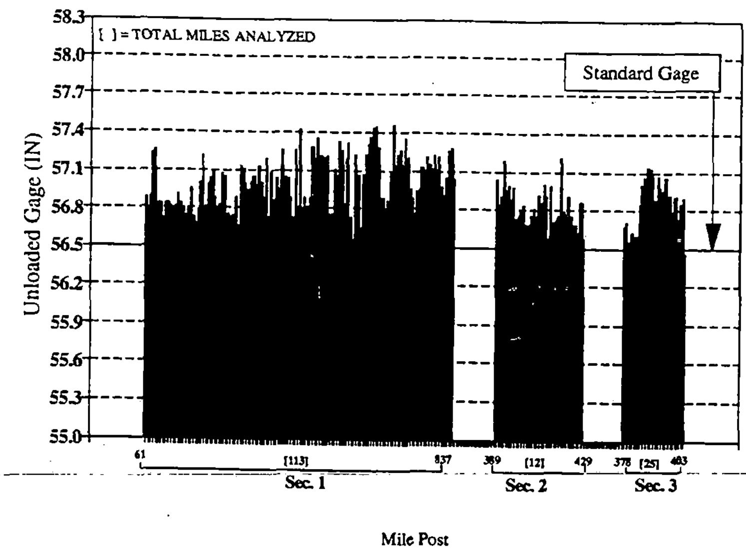

Exhibit 38. Ninety Fifth-percentile (L95) Value of Unloaded Gage for Each Statistical Mile Sample in Test Sections 1, 2 & 3 of Railroad B.

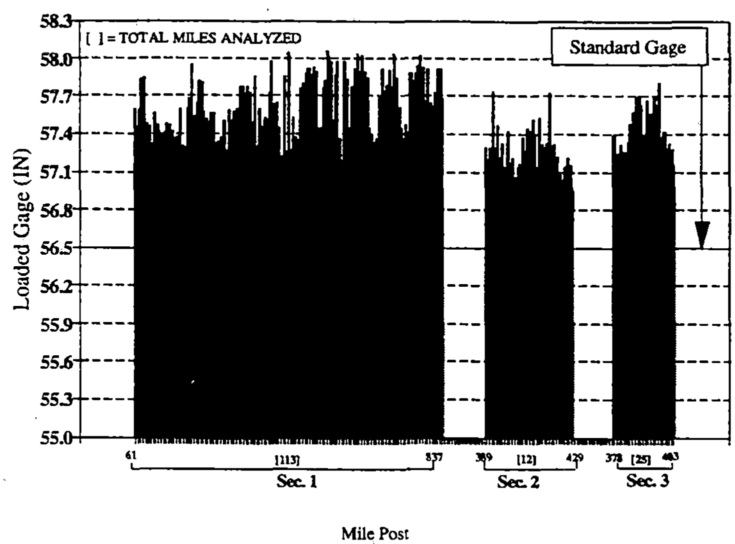

Exhibit 39. Ninety Fifth-percentile (L95) Value of Loaded Gage for Each Statistical Mile Sample in Test Sections 1, 2 & 3 of Railroad B.

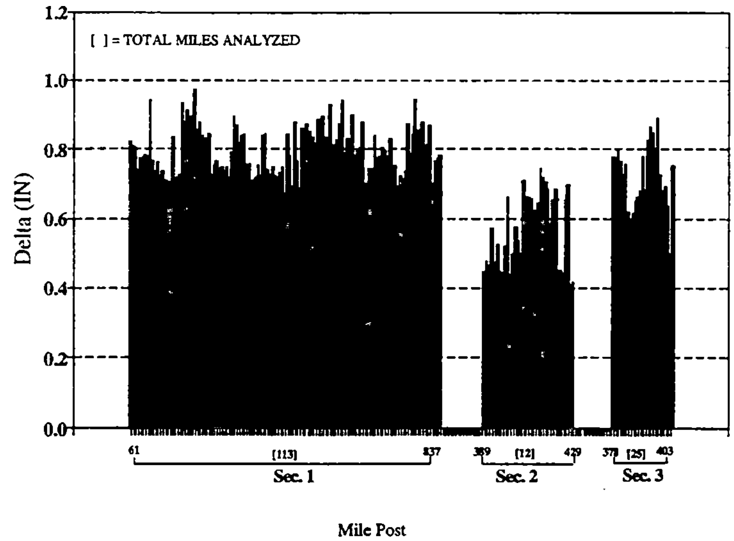

Exhibit 40. Ninety Fifth-percentile (L95) Value of Delta Gage for Each Statistical Mile Sample in Test Sections 1, 2 & 3 of Railroad B.

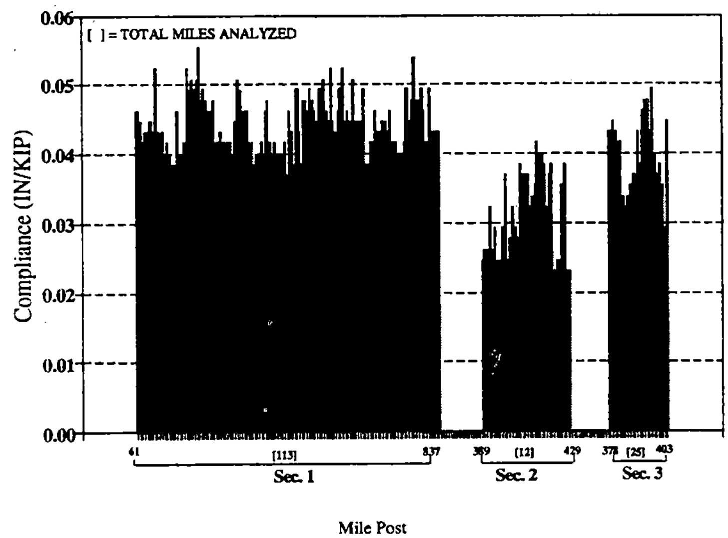

Exhibit 41. Ninety Fifth-percentile (L95) Value of Track Compliance for Each Statistical Mile Sample in Test Sections 1, 2 & 3 of Railroad B.

As seen in Exhibit 34, wide gage is present in all test sections. Gage degradation is least in Test Section 2 and most in Test Section 3. The overall better gage seen in Test Section 2 may result from the use of concrete ties as well as good maintenance practices on higher degree curves. As seen, the mean unloaded gage varies from 56.4" to over 56.9" in Test Section 1, and from 56.36" to 56.68" in Test Section 2. In Test Section 3, the unloaded gage varies from 56.3" to 56.95".

In Exhibit 35, the mean loaded gage varies from 57.05" to over 57.55" in Test Section 1, and from under 56.9" to 57.2" in Test Section 2. In Test Section 3, the loaded gage varies from 57.0" to 57.45". The lower loaded gage in Test Section 2, which carries unit coal train traffic, is obvious in this exhibit. In contrast, track in Test Section 1 and 3, carrying mixed freight traffic, seems to show average loaded gage characteristics. The average gage widening resistance seen in Test Section 1 and 3 results from the fact that, most of the sections has 0-2 degree curves, and two rail holding spikes per tie plate. In contrast, Test Section 2 has concrete ties, as well as wood ties with more than two spikes per plate. This results in higher gage widening resistance in Test Section 2. Even though it appears that the track in all test sections has an ample ability to hold gage, a general concern exists as to a need for regaging and respiking of track in all test sections. A study of delta gage values seen in the following paragraph, indicates that a large loaded gage may not imply weak track if wide gage existed before the loading. A study of the exception reports shows that most of the exceptions in these three test sections on Railroad B were due to exceedence of the loaded gage paint limit of 57.75".

Exhibit 36 gives an indication as to which miles of the track are relatively strong and which are weak. The mean delta gage varies from 0.5" to 0.8" in Test Section 1. In Test Section 2, the variation is from less than 0.32" on concrete ties, to 0.6" with cut spikes. In Test Section 3, the mean delta gage varies from 0.4" to over 0.7". It is apparent that the track in Test Section 2, consisting mostly of concrete ties and wood ties having additional spikes on higher degree curves, has an overall greater gage widening resistance than track in Test Section 1 and 3.

Exhibit 37 reflects a quantitative measure of the tie and rail restraint provided by the track in Test Section 1, 2 and 3. The higher the compliance value, the weaker is the gage widening resistance. Variation of mean compliance from 0.018"/kip on concrete ties, to 0.032"/kip with cut spikes in Test Section 2, indicates the high gage widening resistance of this track. Mean compliance, in general, between 0.03"/kip to 0.04"/kip with cut spike track of both Test Section 1 and 3 also indicates good rail lateral restraint conditions. Those miles of track in Test Sections 1 and 3, where compliance is below 0.03"/kip, may include data from higher degree curves having extra spikes for added strength.

The 95th-percentile values of unloaded gage, loaded gage, delta gage and compliance, for each track mile analyzed on Railroad B, are given in the following to demonstrate dispersal in data, and to differentiate between weak and strong tie/fastener conditions.

Exhibit 38 shows the L95 values of unloaded gage for all three test sections. A wider unloaded gage is obvious in Test Section 1. The corresponding L95 values of loaded gage are given in Exhibit 39. Most of the L95 loaded gage values are between 57.4" and 58.0" in Test Section 1, between 57.1" and 57.4" in Test Section 2, and between 57.3" and 57.7" in Test Section 3. A L95 value closer to 57.7" is an indication of the onset of the loaded gage paint limit exception. In fact, there are many miles of track in Test Section 1 and few miles in Test Section 3, where L95 is actually above the loaded gage paint limit of 57.75". There seems to follow a resemblance between a wide gage of over 57.1" in Exhibit 38, to a loaded gage exceedence of 57.75" in Exhibit 39 for Test Section 1.

The extent of gage widening resistance provided by tie and rail restraint in each mile are clearly revealed in Exhibits 40 and 41. A check of L95 delta gage values, corresponding to those miles of track where L95 loaded gage exceeded 57.75", shows that these values may not necessarily lead to loaded gage exceedences. It is not the deficiency in gage widening resistance but the initial presence of wide gage which leads to the loaded gage paint limit exceedences. On the other hand, L95 unloaded gage of 56.9" is present in the track mile where L95 loaded gage exceeds 57.75" in Test Section 3, yet it appears that weak gage widening resistance, producing as much as 0.9" L95 delta gage, is the responsible for this exceedence.

L95 delta gage values of 0.45" in concrete tie track in Test Section 2 result in L95 compliance values of 0.025"/kip. Since 95% of the data is below these values, a high gage widening resistance is indicated for the concrete tie track in Exhibits 40 and 41. A good tie and rail restraint condition is evident for the cut spike track from the delta gage and compliance values in these exhibits.

6.2.2 Analysis Based on Track Type

Exhibit 42 shows in Column 1 the FRA track classes in Test Sections 1, 2 and 3 of Railroad B. The majority of track tested in Test Section 1 is Class 4 cut spike track having curvatures of up to 2 degrees. In Test Section 2 and 3, the majority of tests were conducted on track having curvatures up to 2 degrees. Test Section 2 has Class 3 track, and Test Section 3 has Class 4 track. Also, there are concrete ties only in Test Section 2. Of a total of 149 miles analyzed, 16 miles of Class 3 track and 82 miles of Class 4 track was cut spike track having curvatures of up to 2 degrees.

Exhibit 43 shows the mean, standard deviation, and L95 of unloaded gage in Test Section 1 as a function of track curvature, class and tie/fastener type. As the degree of track curvature increases, the mean and L95 and standard deviation generally increase. Standard deviations in Class 2 track and also in 6-10 degree curves, however, do not follow this trend. Unloaded gage, except for the 0-2 degree curves, also seems to increase as a function of track class. Such a class dependence is not, however, obvious for standard deviation. From these observations, one may conclude that the higher gage widening loads required for steering in higher degree curves, and higher operating speed result in high lateral forces in the higher class track, and are probably the reasons for wider unloaded gage on higher degree or higher class

Class	Geometry (Degrees)	Tie/Fastener	Track Analyzed (Miles)			
			Test Section			Total
			1	2	3	
2	0-2	Wood/Spike	0.11	0.00	0.00	0.11
2	2-4	Wood/Spike	0.96	0.00	0.00	0.96
2	4-6	Wood/Spike	1.29	0.00	0.00	1.29
2	6-10	Wood/Spike	5.77	0.00	0.00	5.77
3	0-2	Wood/Spike	12.25	3.86	0.00	16.11
3	2-4	Wood/Spike	3.04	0.45	0.00	3.49
3	4-6	Wood/Spike	6.91	1.36	0.00	8.27
3	6-10	Wood/Spike	8.82	2.93	0.00	11.75
3	0-2	Concrete	0.00	1.21	0.00	1.21
3	2-4	Concrete	0.00	0.40	0.00	0.40
3	4-6	Concrete	0.00	0.79	0.00	0.79
3	6-10	Concrete	0.00	0.56	0.00	0.56
4	0-2	Wood/Spike	59.54	0.00	22.28	81.82
4	2-4	Wood/Spike	11.64	0.00	2.75	14.39
4	4-6	Wood/Spike	1.98	0.00	0.00	1.98
4	6-10	Wood/Spike	0.46	0.00	0.00	0.46
Total Miles			115.77	11.56	25.03	149.36

Exhibit 42. Total Miles Analyzed in Test Sections 1, 2 & 3 of Railroad B for Wide Gage and Gage Resistance with respect to Track Class, its Geometry and Tie and Fastener Types.

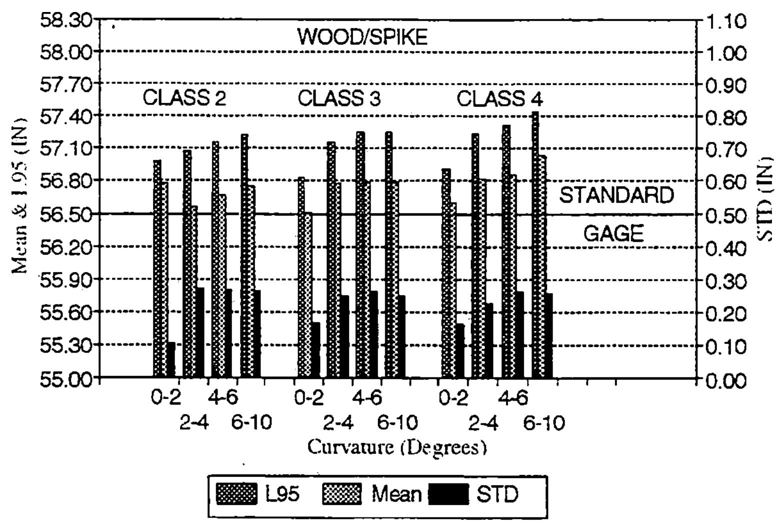

Exhibit 43. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad B, Segmented by Track Class, Tie and Fastener Types.

track. A concern to control gage exists for the higher degree and higher track class in this test section.

Exhibit 44 shows the mean, standard deviation and L95 of loaded gage in Test Section 1. Trends similar to the unloaded gage in the previous exhibit are present. Greater loaded gage is seen with higher curvature and class track. As seen from L95 values, 95% of the time loaded gage is below 57.97". Except for the 0-2 degree, and 2-4 degree Class 3 track, L95 values exceed the loaded gage paint limit of 57.75". The exceptions in this test section are due to wide gage. The need to control gage by adding spikes, or installing elastic fasteners, is indicated by the loaded gage results.

The mean, standard deviation, and L95 of delta gage in Test

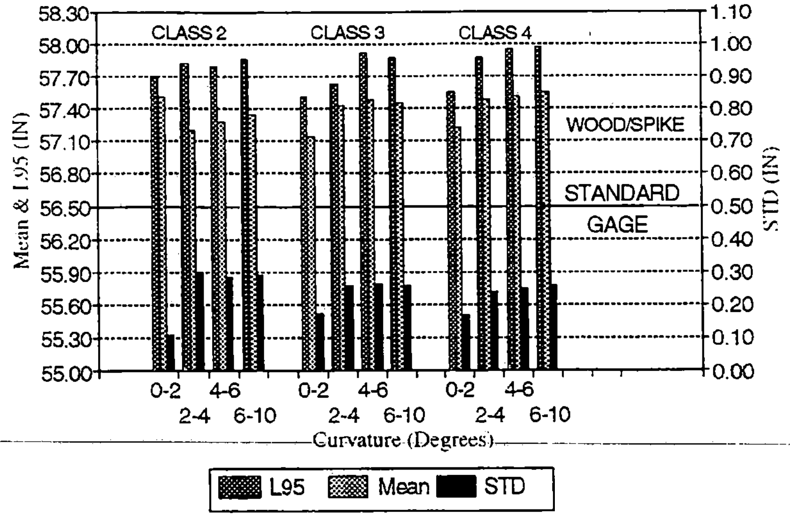

Exhibit 44. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad B, Segmented by Class, Tie and Fastener Types.

Section 1, are given in Exhibit 45. The largest L95 value of delta gage is 0.88". The corresponding L95 value of track compliance, for a gage widening load of 18 kips, is 0.049"/kip, and indicates adequate tie and rail restraint conditions. A delta gage exception requiring exceedence of 1.25" is not imminent.

There is no strong indication that a general trend is discernible from delta gage values with respect to either track curvature or class in Test Section 1. Taken separately, the mean and L95 values of delta gage decrease slightly as a function of curvature for Class 2 track. For Class 3 track, there is an indication of a slight increase in the mean and L95 values with curvature, while on Class 4 track no such trend exists. Also, for track with curvature greater than 2 degrees, slight increases in

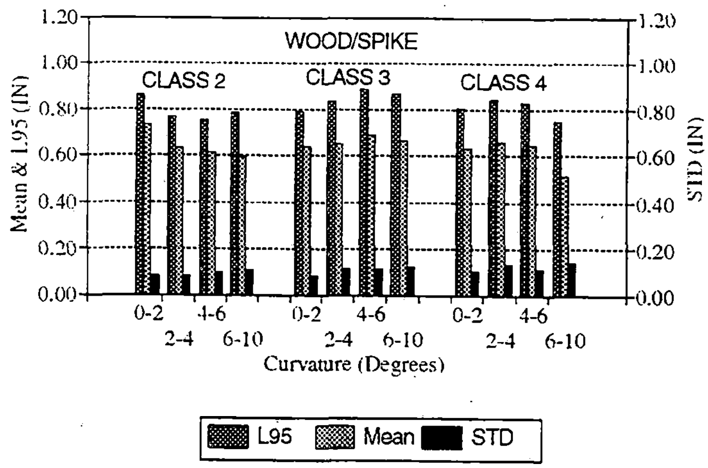

Exhibit 45. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad B, Segmented by Class, Tie and Fastener Types.

mean, L95 and standard deviation values, seem to occur with an increase in track class.

Track areas of high curvature may generally be problem areas, hence more maintenance attention is required. Higher operating speed on higher class track requires added track maintenance. An extra spike may be added on a lower degree of curvature. A higher degree of curvature generally warrants some type of elastic fastener. Such practices will improve the gage widening resistance of track. The decrease in delta gage mean and L95 value with respect to curvature is related to good track maintenance. A slight increase in the standard deviation with curvature may result from higher traffic volume, and greater lateral forces at higher degrees of curvature.

The moderate increases seen in mean, and L95 values with track class, is a result of higher speed traffic exerting higher lateral forces on the track. The moderate differences seen, in delta gage among various track types, seem to also suggest that these differences are, in a significant way, related to the past load history.

The unloaded, loaded and delta gage by track type in Test Section 2, are shown in Exhibits 46, 47 and 48, respectively. Slight increases in unloaded and loaded gage on curved track are apparent for both the wood and concrete tie track. Similar to Class 2 track in Test Section 1, delta gage appears to decrease with curvature for both the wood and concrete tie track. Concrete tie track shows a significantly lower delta gage than is seen in cut spike track. Concrete tie track with a maximum delta gage mean value of 0.37", producing a mean track compliance of 0.02"/kip, indicates very good tie and rail restraint conditions. The largest mean track compliance of 0.029"/kip, corresponding to a delta gage mean value of 0.52", implies good rail restraint for the cut spike track.

Test Section 3 has Class 4 cut spike track and curvatures up to 4 degrees. The corresponding unloaded, loaded, and delta gage with respect to track type, are shown in Exhibits 49, 50 and 51, respectively. A comparison shows that Test section 3 and the Class 3 cut spike track in Test Section 2, have similar gage widening characteristics. There is no significant difference in the gage widening behavior between 0-2 degree and 2-4 degree curvature track in Test Section 3. It is important to mention that 22.28 miles of

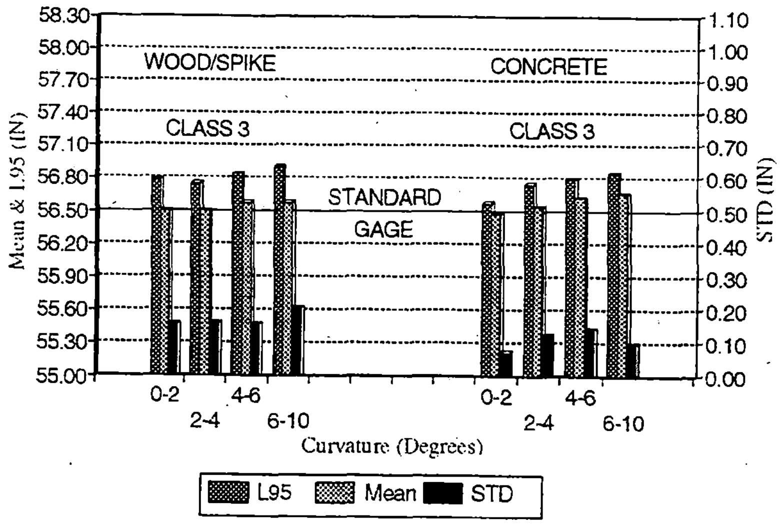

Exhibit 46. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad B, Segmented by Class, Tie and Fastener Types.

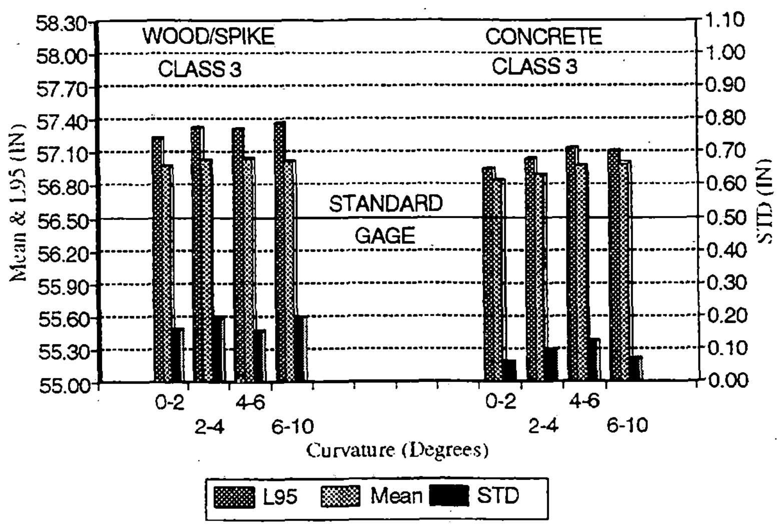

Exhibit 47. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad B, Segmented by Class, Tie and Fastener Types.

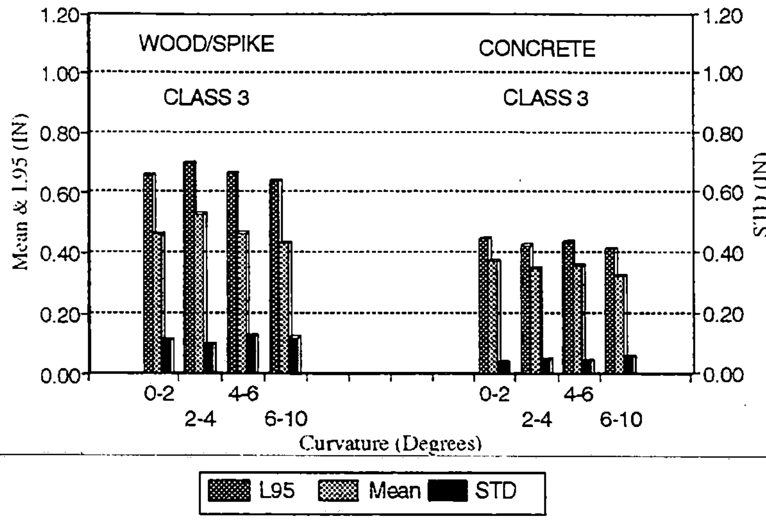

Exhibit 48. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad B, Segmented by Class, Tie and Fastener Types.

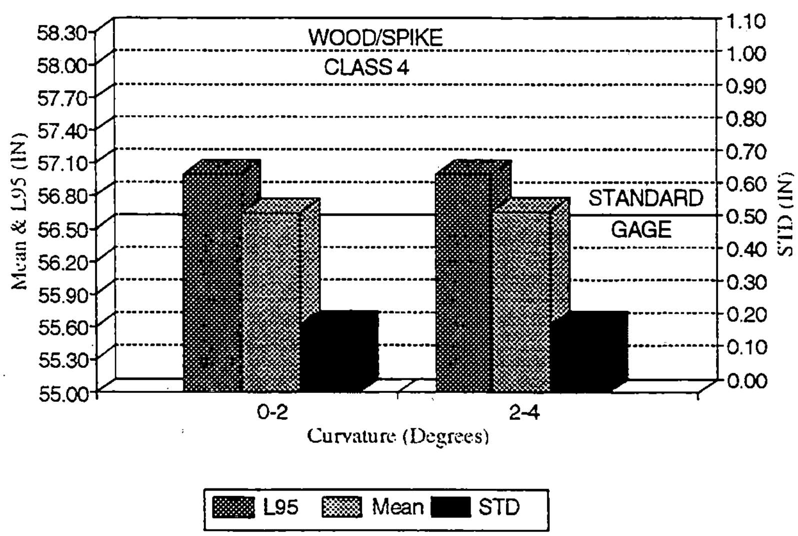

Exhibit 49. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad B, Segmented by Class, Tie and Fastener Types.

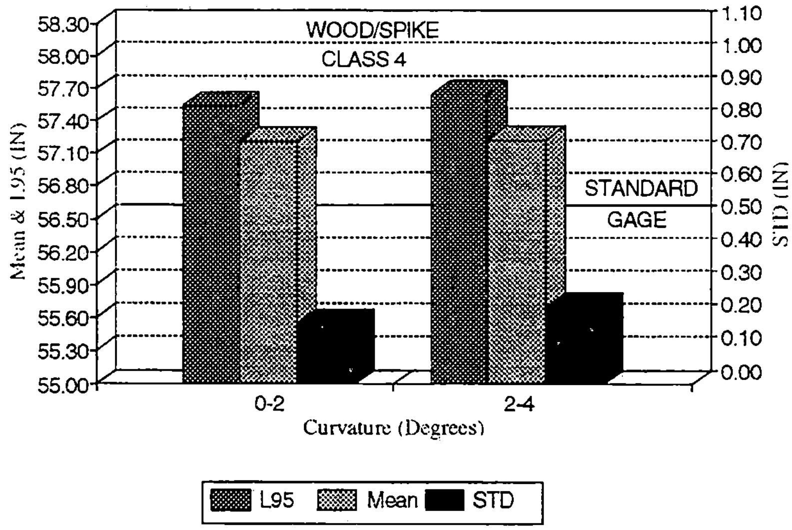

Exhibit 50. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad B, Segmented by Class, Tie and Fastener Types.

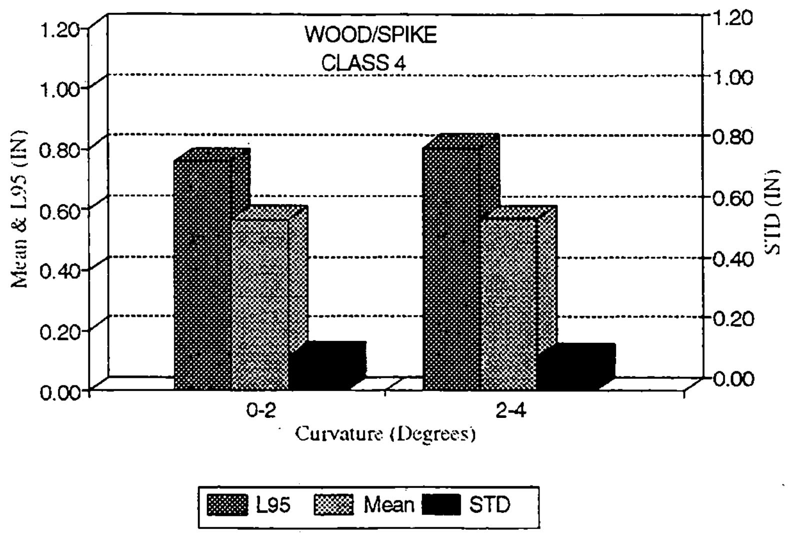

Exhibit 51. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad B, Segmented by Class, Tie and Fastener Types.

data was analyzed for 0-2 degree track as compared to only 2.75 miles for 2-4 degree track. Adequacy of the smaller sample size for comparison is debatable. Despite this, the L95 loaded gage values do not indicate an incipience of loaded gage paint limit exceedence. A maximum delta gage mean value of 0.57", resulting in a mean track compliance of 0.031"/kip, indicates good tie and rail restraint conditions in Test Section 3.

6.3 RAILROAD C

A total of 200 miles of track was tested on Railroad C in three test sections. These tests were conducted in July and August of 1991. Test mileage consisted of 40 miles in Test Section 1, 65 miles in Test Section 2, and 95 miles in Test Section 3. All test sections are located in the midwestern region of the United States. Only limited mileage of curved track was available for testing. No concrete tie track was tested on this railroad. The three test sections have continuously welded 132 lb rail. Standard track spikes used are 5/8" by 6" cut spikes. Generally, 4 spikes per plate, 3 field side/1 gage side spikes on older ties, and 2 field side/2 gage side on new ties, are used. Test Section 1 carries 22 MGT traffic per year on FRA class 2, 3 and 4 track. Test Section 2 carries 60 MGT traffic per year on FRA class 5 track, and Test Section 3 carries 45 MGT traffic per year on FRA class 3, 4 and 5 track.

6.3.1 Analysis Based on Mile Post

Exhibits 52, 53, 54 and 55 show the mean values of unloaded gage, loaded gage, delta gage and track compliance, respectively, for all test sections on a mile-by-mile basis. Similarly, Exhibits 56, 57, 58 and 59 show the respective 95th-percentile values for the test sections.

While there is an indication of wide gage, the mean unloaded gage is quite close to the standard gage in all three test sections. The mean unloaded gage varies from 56.35" to 56.78" in Test Section 1, and from just under 56.3" to 56.7" in Test Section 2. In Test Section 3, the unloaded gage varies from 56.37" to over 56.8".

As seen in Exhibit 53, the mean loaded gage varies from under 56.6" to 57.36" in Test Section 1, and from just above 56.8" to 57.5" in Test Section 2. In Test Section 3, the loaded gage varies from 56.83" to above 57.4". Most of the sampling in these test sections is on 0-4 degree curves carrying traffic at speeds between 40 and 80 mph. A uniform practice in controlling gage can be assumed to exist in all the test sections. This is evident from the similarity of mean loaded gage variations mentioned above. Test Section 1, overall, has lower mean loaded gage, except for some miles near its beginning (MP 147). A reference to test notes indicated that a track maintenance gang was working in Test Section 1, and had, by the time of the test, nearly completed maintenance on this test section, except for those miles where loaded gage rose beyond 57.0". The notes do not clearly state the corrective measures taken by the maintenance gang, however the unaffected unloaded gage and decreased loaded gage suggest that only respiking was done, and substantial regaging was not

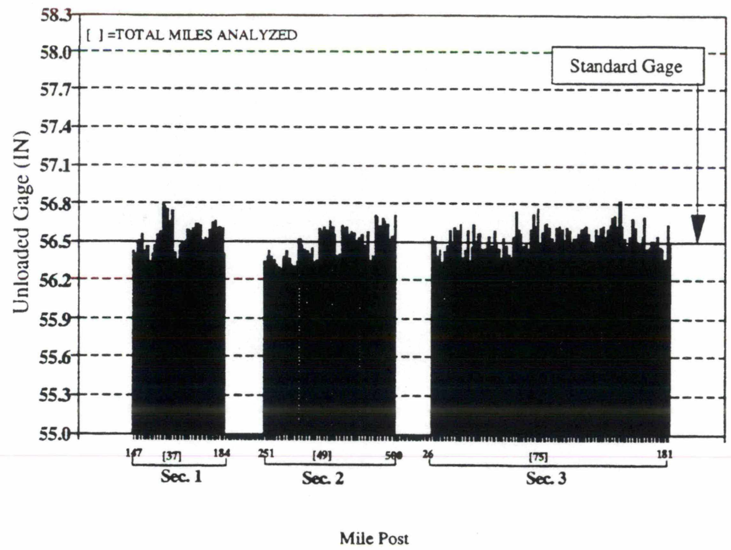

Exhibit 52. Unloaded Gage Mean Value for Each Statistical Mile Sample in Test Sections 1, 2 & 3 of Railroad C.

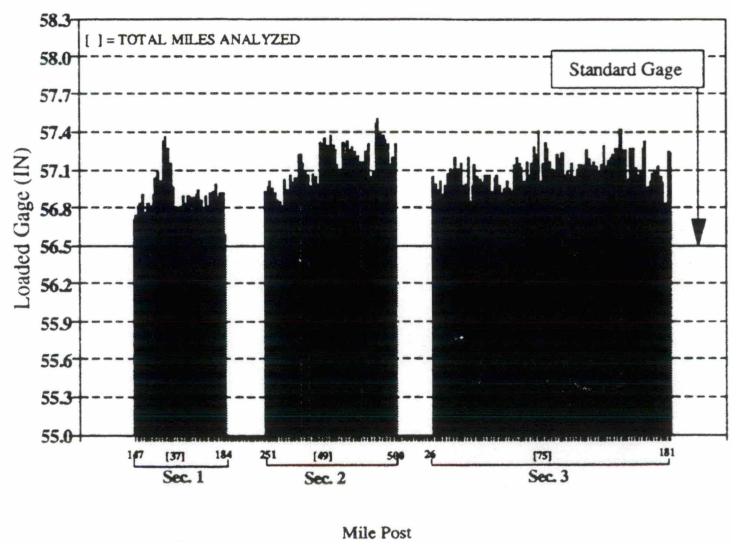

Exhibit 53. Loaded Gage Mean Value for Each Statistical Mile Sample in Test Sections 1, 2 & 3 of Railroad C.

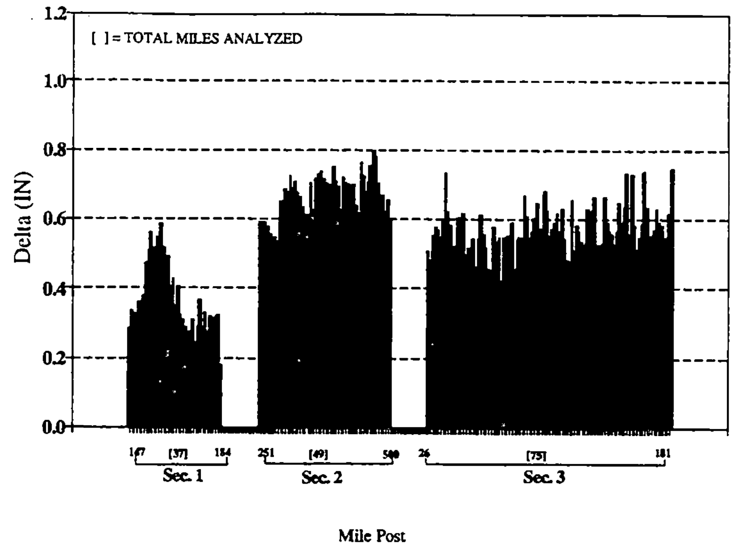

Exhibit 54. Delta Gage Mean Value for Each Statistical Mile Sample in Test Sections 1, 2 & 3 of Railroad C.

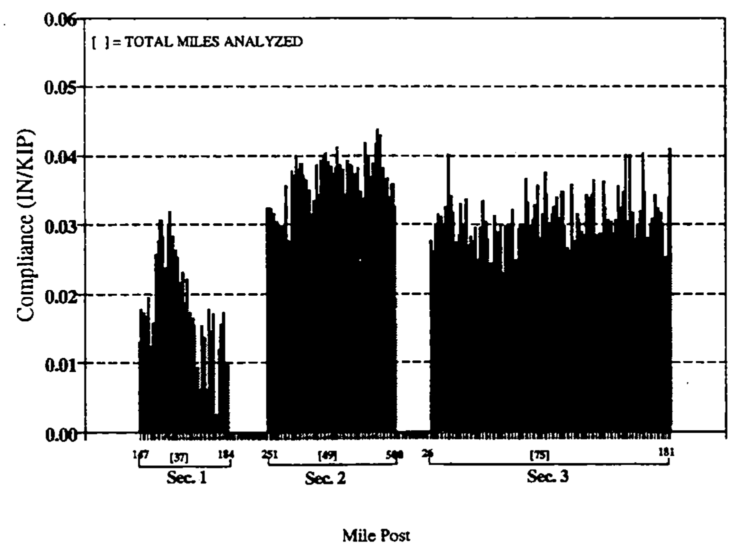

Exhibit 55. Track Compliance Mean Value for Each Statistical Mile Sample in Test Sections 1, 2 & 3 of Railroad C.

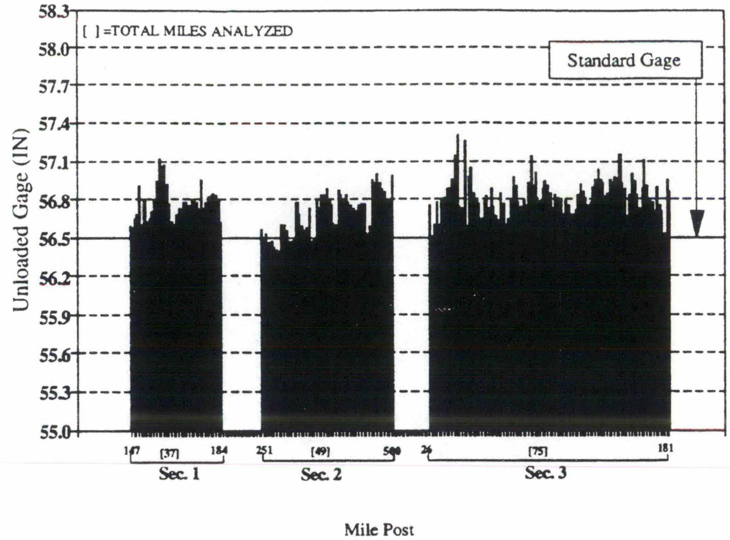

Exhibit 56. Ninety Fifth-percentile (L95) Value of Unloaded Gage for Each Statistical Mile Sample in Test Sections 1, 2 & 3 of Railroad C.

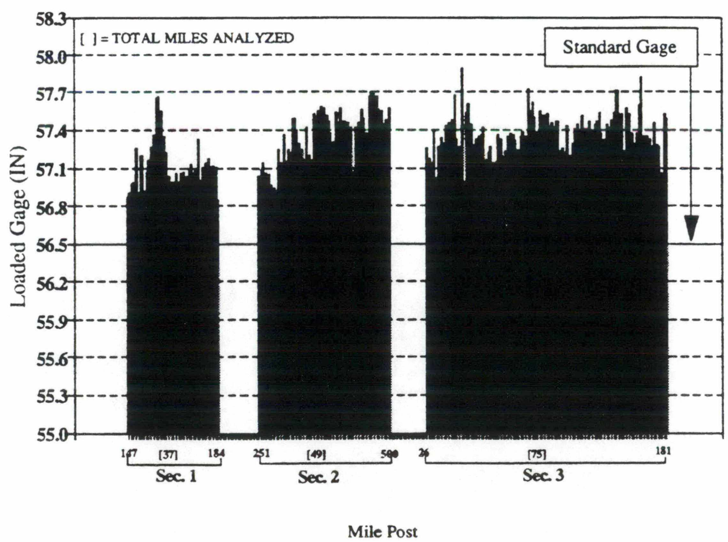

Exhibit 57. Ninety Fifth-percentile (L95) Value of Loaded Gage for Each Statistical Mile Sample in Test Sections 1, 2 & 3 of Railroad C.

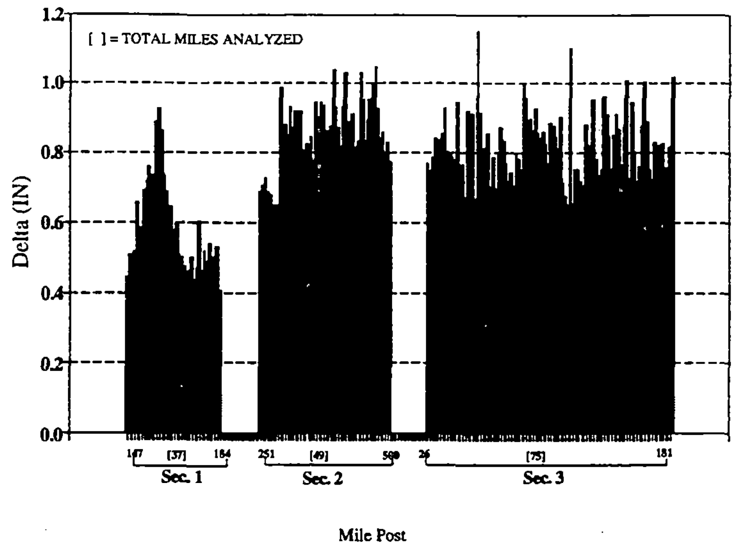

Exhibit 58. Ninety Fifth-percentile (L95) Value of Delta Gage for Each Statistical Mile Sample in Test Sections 1, 2 & 3 of Railroad C.

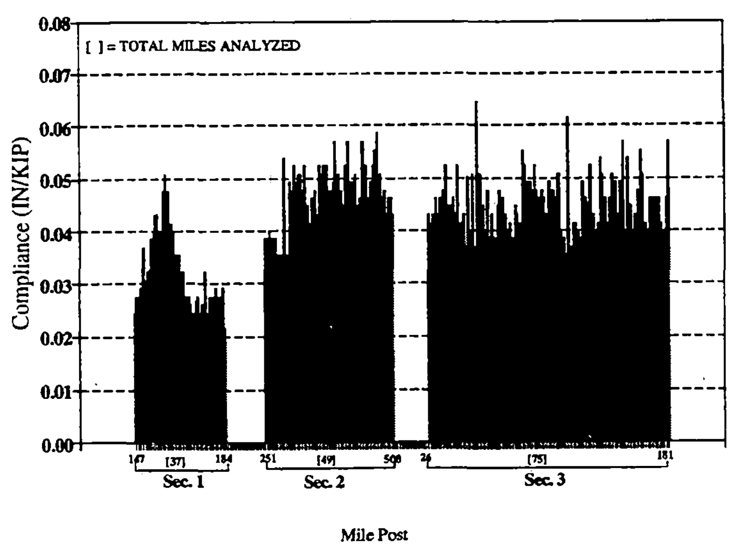

Exhibit 59. Ninety Fifth-percentile (L95) Value of Track Compliance for Each Statistical Mile Sample in Test Sections 1, 2 & 3 of Railroad C.

undertaken. This demonstrates the average decrease in loaded gage which can occur due to respiking. Even though it appears that track in all test sections has ample ability to holding gage, a general concern emerges regarding a need for both regaging and respiking of track in all test sections. It is true that an unloaded gage of about 56.5", is of little value if excessive gage widening is experienced under load. Controlling gage on these test sections is important, and its need is indicated by a study of the exception reports. The reports show that most of the exceptions in these three test sections on Railroad C were due to exceedence of the loaded gage paint limit of 57.75", and not to exceedence of the delta gage paint limit of 1.25".

Exhibit 54 gives an indication of the miles of track which are relatively strong and those which are weak. It is apparent from the delta gage values that excessive gage widening is not seen on Railroad C. However, a need for continuing control of the gage is indicated. The increase in gage widening resistance on the portion of track in Test Section 1 where the maintenance gang had respiked the track is readily seen. While slightly more gage widening is seen in Test Section 2, except in the respiked portion, a similarity in gage widening behavior, is apparent among all test sections in Exhibit 54.

The mean delta gage varies from below 0.2" to 0.59" in Test Section 1. In Test Section 2, the gage variation is from 0.5" to 0.8". In Test Section 3, the mean delta gage varies from 0.43" to 0.75". The decrease from 0.59" to 0.3" in delta gage due to respiking is obvious in Test Section 1. Exhibit 55 indicates a quantitative measure to the tie and rail restraint provided by track in Test Sections 1, 2 and 3. The higher the compliance value, the weaker is the gage widening resistance. Mean compliance around 0.03"/kip indicates good gage widening resistance of Test Section 3. On the other hand, while mean compliance between 0.03"/kip to 0.04"/kip, points to adequate rail lateral restraint in Test Section 2, a need for respiking is probably indicated as future work. Mean compliance values in Test Section 1 are in a transitory state of gage widening resistance, and clearly indicate a strong tie and rail restraint condition following respiking, producing not only smaller delta gage values but smaller loaded gage values as well.

The 95th-percentile values of unloaded gage, loaded gage, delta gage and compliance, for each track mile analyzed on Railroad C, are discussed in the following to demonstrate dispersal in data and to differentiate between weak and strong tie/fastener conditions.

Exhibit 56 shows the L95 values of unloaded gage for all three test sections. Similar to the mean unloaded gage, respiking does not seem to affect the L95 values of unloaded gage in Test Section 1. Except for few miles in Test Section 2, existence of wide gage, some above 57.3", is seen in Exhibit 56. The corresponding L95 values of loaded gage are given in Exhibit 57. The benefits of respiking are evident, as seen in lower L95 loaded gage values in Test Section 1. Similarity of gage widening behavior between the test sections is evident from the L95 values in this exhibit. Most of the L95 loaded gage values seen are between 57.1" and 57.7". A

L95 value closer to 57.7" is an indication of the onset of the loaded gage paint limit exception. There are few miles of track in Test Section 3 where L95 is actually above the loaded gage paint limit of 57.75". There seems to follow a resemblance between an L95 unloaded gage of over 57.1" in Exhibit 56, to a loaded gage exceedence of 57.75" in Exhibit 57.

The extent of gage widening resistance provided by tie and rail restraint for each mile are clearly revealed in Exhibits 58 and 59. Even though there are many miles where L95 delta gage is above 0.8", the corresponding L95 loaded gage, in general, remains between 57.4" and 57.7". An L95 unloaded gage of 56.95" and above, combined with L95 delta gage of 0.8", would lead to exceedence of the loaded gage paint limit of 57.75". It is quite apparent that regaging of all test sections on Railroad C is indicated. The point that should be stressed is the fact that respiking adds substantially to gage widening resistance. This is seen by a comparison of L95 delta gage and compliance values of the portion of track in Test Section 1 which was respiked, and that not respiked. About a 0.4" lowering of L95 delta gage, because of respiking, is evident in Test Section 1. A tendency toward exceptions is seen in the large compliance values found in Exhibit 59, Test Sections 2 and 3. Respiking, as was done in Test Section 1, is indicated for these sections to improve weak locations, and restore gage widening resistance to values seen in the respiked portion of Test Section 1.

6.3.2 Analysis Based on Track Type

Exhibit 60 shows in column 1 the FRA track classes in Test Section 1, 2 and 3 of Railroad C. The majority of track tested in Test Section 1 is Class 4 track having curvatures of up to 2 degrees. In Test Section 2, most of the tests were conducted on Class 5 track having curvatures of between 2-4 degrees. Most of the mileage in Test Section 3 was about evenly divided between Class 4 and 5 track having curvatures of up to 2 degrees. No concrete ties were tested on Railroad C. Of about 161 analyzed miles, 56 miles consisted of 0-2 degree Class 4 track, and 48 miles consisted of 2-4 degree Class 5 track, accounting for the bulk of the data.

Exhibit 61 shows the mean, standard deviation, and L95 of unloaded gage in Test Section 1, as a function of track curvature, class and tie/fastener type. The sample sizes of 0-2 degree Class 2 and 3 track and of 2-4 degree Class 3 and 4 track, in Test Section 1, are quite small. The results for these tracks, as seen in Exhibit 61, may not be generally applicable. Given this limited scope, the results show that as the degree of track curvature increases, the mean and L95 increase along with the standard deviation. A clear class dependence is not easily discernible from these results, except in the case of 0-2 degree Class 2 and 3 track. The mean and L95 decrease, as does the standard deviation, when the class increases from 2 to 3 for 0-2 degree track. For the reasons mentioned, not too much emphasis should be given to these trends.

Exhibit 62 shows the mean, standard deviation and L95 of

Class	Geometry (Degrees)	Tie/Fastener	Track Analyzed (Miles)			
			Test Section			Total
			1	2	3	
2	0-2	Wood/Spike	0.61	0.00	0.00	0.61
3	0-2	Wood/Spike	0.37	0.00	4.46	4.83
3	2-4	Wood/Spike	0.94	0.00	1.77	2.71
3	4-6	Wood/Spike	0.00	0.00	5.05	5.05
3	6-10	Wood/Spike	0.00	0.00	0.66	0.66
4	0-2	Wood/Spike	34.67	0.00	20.97	55.64
4	2-4	Wood/Spike	0.44	0.00	14.35	14.79
4	4-6	Wood/Spike	0.00	0.00	0.12	0.12
5	0-2	Wood/Spike	0.00	1.42	27.69	29.11
5	2-4	Wood/Spike	0.00	47.87	0.00	47.87
Total Miles			37.03	49.29	75.07	161.39

Exhibit 60. Total Miles Analyzed in Test Sections 1, 2 & 3 of Railroad C for Wide Gage and Gage Resistance with respect to Track Class, its Geometry and Tie and Fastener Types.

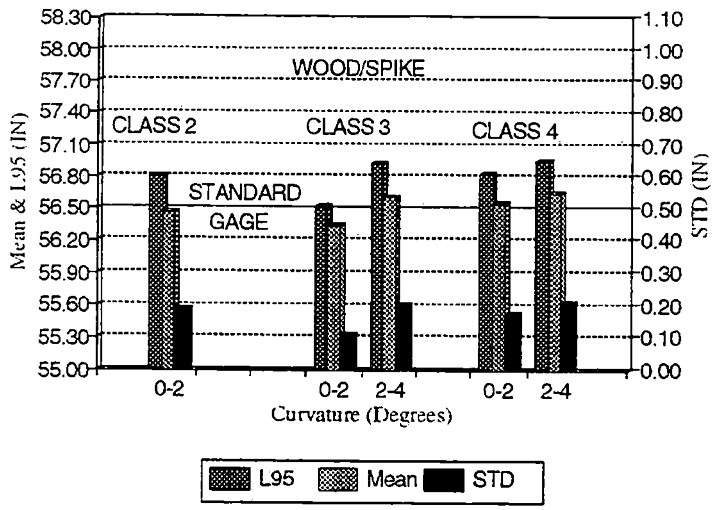

Exhibit 61. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad C, Segmented by Class, Tie and Fastener Types.

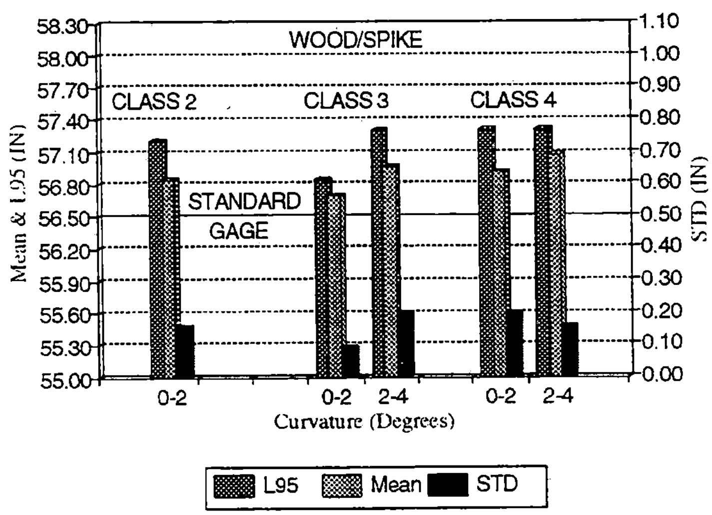

Exhibit 62. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad C, Segmented by Class, Tie and Fastener Types.

loaded gage in Test Section 1. Trends similar to those seen with unloaded gage in the previous exhibit are present in this exhibit of loaded gage. Greater loaded gage is seen at higher curvature track. As seen from L95 values, 95% of the time loaded gage is below 57.3" for all classes of track. A comparison with unloaded gage shows that only a modest increase occurs in loaded gage. Respiking improved the gage widening resistance in Test Section 1. This is seen in the low delta gage mean values in Exhibit 63. As will subsequently be discussed, these lower delta gage mean values are about one-half of the corresponding values in Test Section 2 and 3. The need to improve gage widening resistance on Railroad C is clearly indicated by these results.

The largest L95 value of delta gage on 0-2 degree Class 4 track, comprising most of Test Section 1, is 0.65". The corresponding L95 value of track compliance, for a gage widening load of 18 kips, is 0.036"/kip. This represents good tie and rail restraint conditions. These results indicate that respiking can significantly improve the lateral stiffness of track.

No strong indication of a general trend is discernible from a review of delta gage values in Test Section 1, for either curvature or class. For Class 3 and 4 track, there is an indication of a slight increase in the mean and L95 values with curvature. Also, a slight increases in mean, L95 and standard deviation values seems to occur with an increase in track class from 3 to 4.

The unloaded, loaded and delta gage, with respect to track type, are shown in Exhibits 64, 65 and 66 respectively for Test Section 2, and in Exhibits 67, 68 and 69 respectively for Test

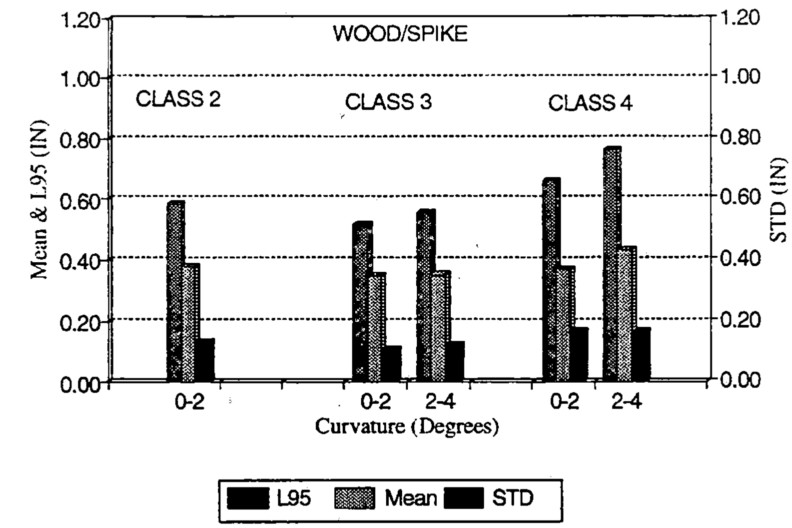

Exhibit 63. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad C, Segmented by Class, Tie and Fastener Types.

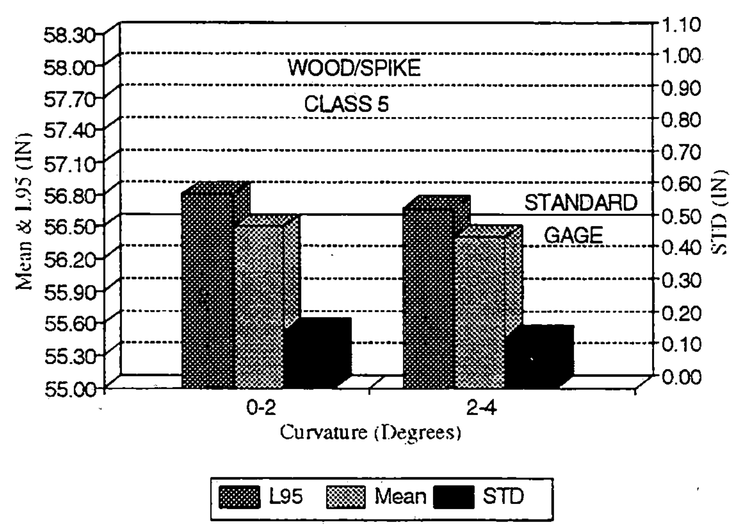

Exhibit 64. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad C, Segmented by Class, Tie and Fastener Types.

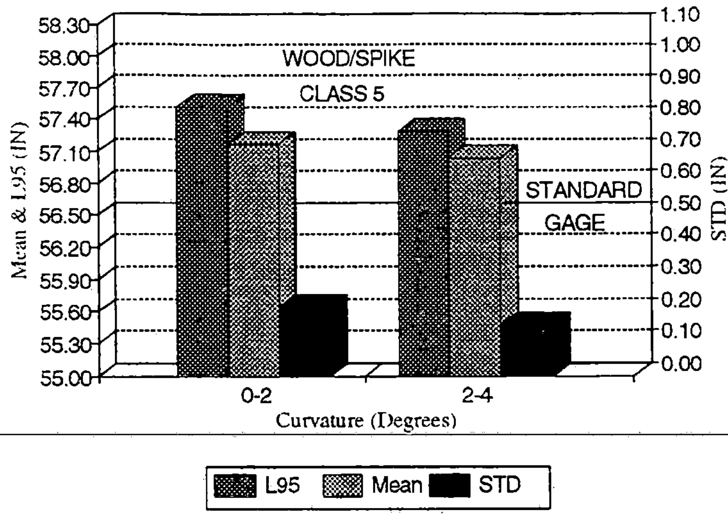

Exhibit 65. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad C, Segmented by Class, Tie and Fastener Types.

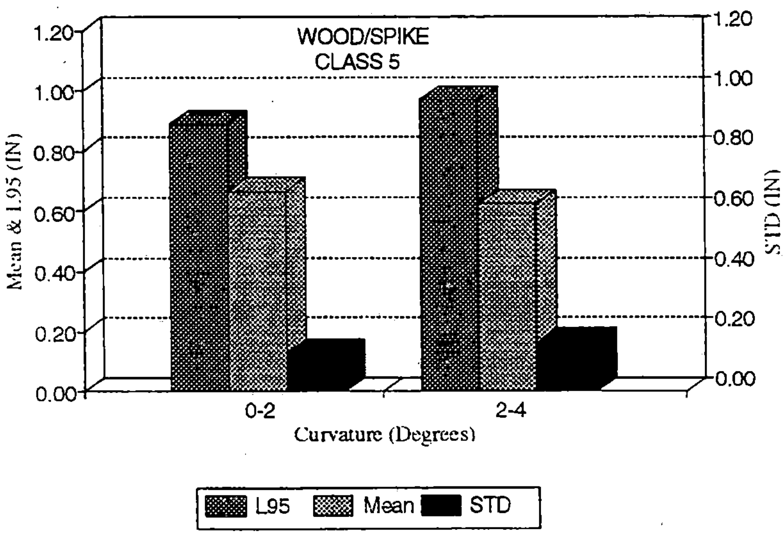

Exhibit 66. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad C, Segmented by Class, Tie and Fastener Types.

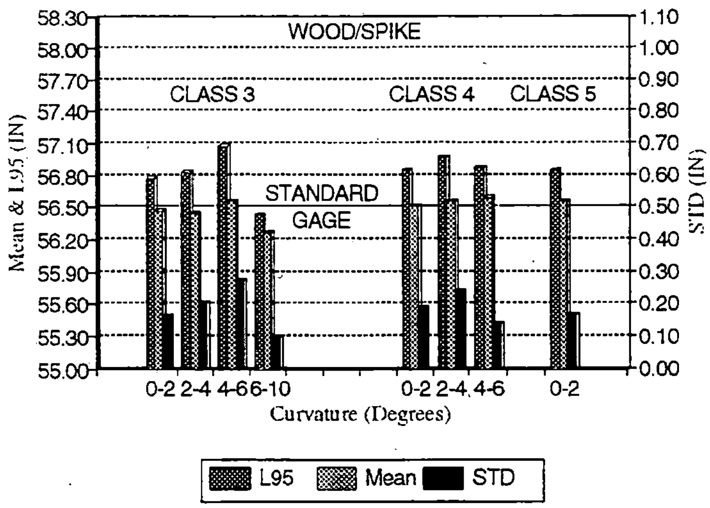

Exhibit 67. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad C, Segmented by Class, Tie and Fastener Types.

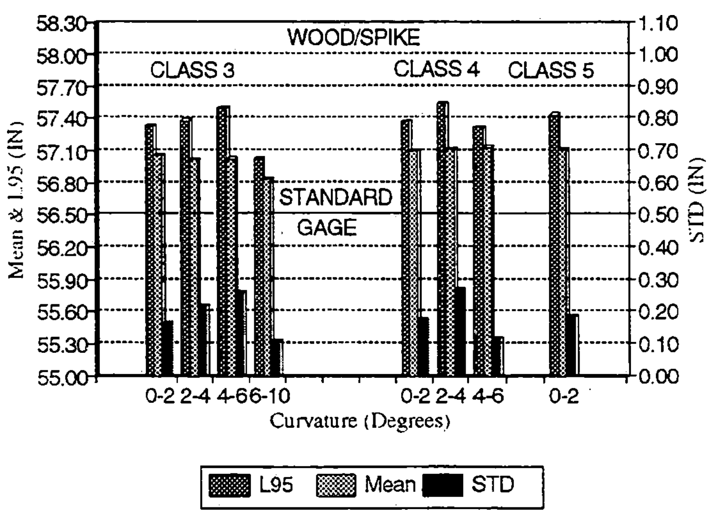

Exhibit 68. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad C, Segmented by Class, Tie and Fastener Types.

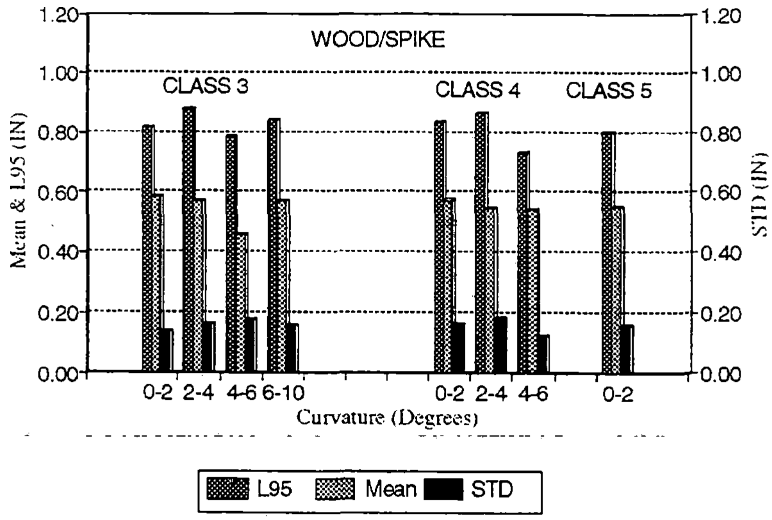

Exhibit 69. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad C, Segmented by Class, Tie and Fastener Types.

Section 3. An overall delta gage comparison, in the three test sections, clearly indicates the increased gage widening resistance of Test Section 1 track due to maintenance immediately preceding the test. It is clearly seen that for the Class 2 track in Test Section 1 gage widening resistance following maintenance surpasses that of Class 5 track in Test Section 2 and 3.

Test Section 2 is primarily 2-4 degree Class 5 track. Freight trains operating at speeds up to 80 mph, increase the demand for a regular maintenance of this track. The unloaded gage L95 value of 56.67" on 2-4 degree track is an indication of good gage control. Slight decreases in unloaded, loaded, and mean delta gage, with respect to curvature, show that increased maintenance should be allocated to areas of high curvature. The level of such increased maintenance is dependent upon the railroad's maintenance practices and tolerances, and on the class and curvature of the track. The mean track compliance found around 0.033"/kip indicates good tie and rail restraint conditions in Test Section 2.

Slight increases in mean and L95 values of unloaded and loaded gage, and standard deviation, with respect to both the curvature and class, are seen in Test Section 3. An exception to the trend is seen in the 6-10 degree Class 3 track. Greater lateral forces developed in 6-10 degree track require greater gage control. This is seen in the lower unloaded and loaded gage values. Higher gage widening resistance, at a higher degree of curvature, is seen in the lower delta gage values found with curvature. An exception to this is seen in the 6-10 degree Class 3 track. The higher delta gage on 6-10 degree curve seen in the test, points to a higher lateral load history on this segment. In general, mean track compliance of below 0.033"/kip indicates good gage widening resistance in Test Section 3.

6.4 RAILROAD D

Gage widening tests using the TLV were performed on four test sections on Railroad D. A total of 220 miles of track were tested in August and September 1991. Test mileage consisted of 30 miles in Test Section 1, 45 miles in Test Section 2, 20 miles in Test Section 3, and 125 miles in Test Section 4. One mile of track in Test Section 3 consisted of elastic fasteners on wood ties. No concrete tie track was tested on this railroad. The test sections are located in southern Canada. Continuously welded 132 or 136 lb rail having 14" tie plates on 7" x 9" x 8'6" hardwood ties was used in curves of greater than four degrees. Tangent sections of 100 and 115 lb rail had 11" tie plates on softwood ties. Test Section 4 utilized softwood ties throughout, with Improved Fair rail anchors. Test Section 1 carries 7 MGT traffic per year on FRA class 3 track. Test Section 2 carries 13 MGT traffic per year on FRA class 2 track. Test Section 3 carries 9 MGT traffic per year on FRA class 2 track, and Test Section 4 carries 18 MGT traffic per year on FRA class 3 and 4 track.

6.4.1 Analysis Based on Mile Post

Exhibits 70, 71, 72 and 73 show the mean values of unloaded gage, loaded gage, delta gage and track compliance, respectively, on all test sections, on a mile-by-mile basis. Similarly, Exhibits 74, 75, 76 and 77 show the respective 95th-percentile values for the test sections.

Wide gage is present in all test sections as seen in Exhibit 70. It is also apparent that unloaded gage in Test Section 4 has smaller deviation from standard gage. The unloaded gage on the first one-third of Test Section 4 is notably low. Test notes refer to a track maintenance gang working on this section of the track. This is reflected in the overall decrease in gage as a result of the work of the track maintenance gang. The elastic fastener section contributed less than 5% of the data from tests in Test Section 3. Due to the small sample size, any benefit to gage control and lateral stiffness by the use of elastic fasteners, is not obvious in the Test Section 3 results. The mean unloaded gage

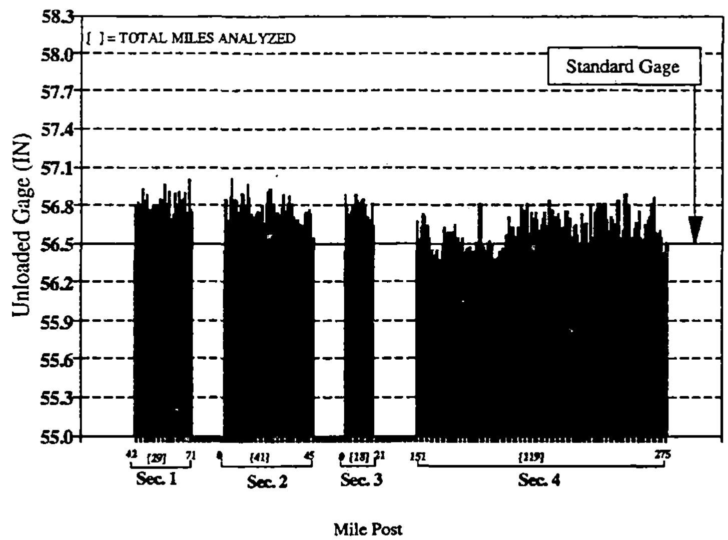

Exhibit 70. Unloaded Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 to 4 of Railroad D.

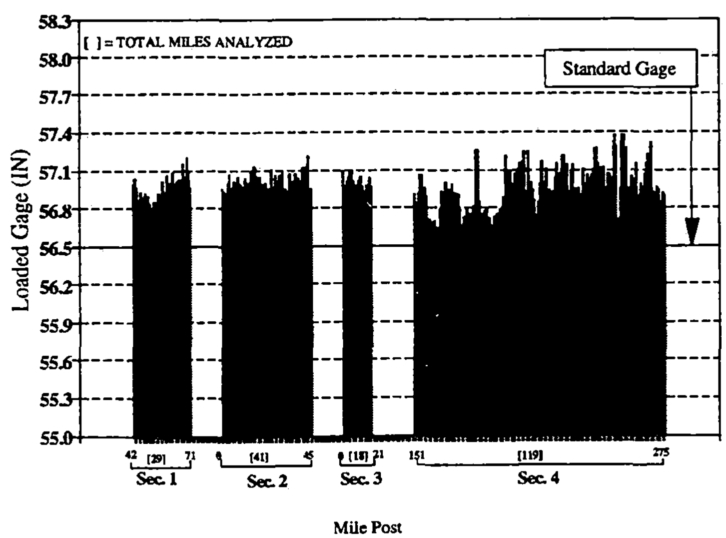

Exhibit 71. Loaded Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 to 4 of Railroad D.

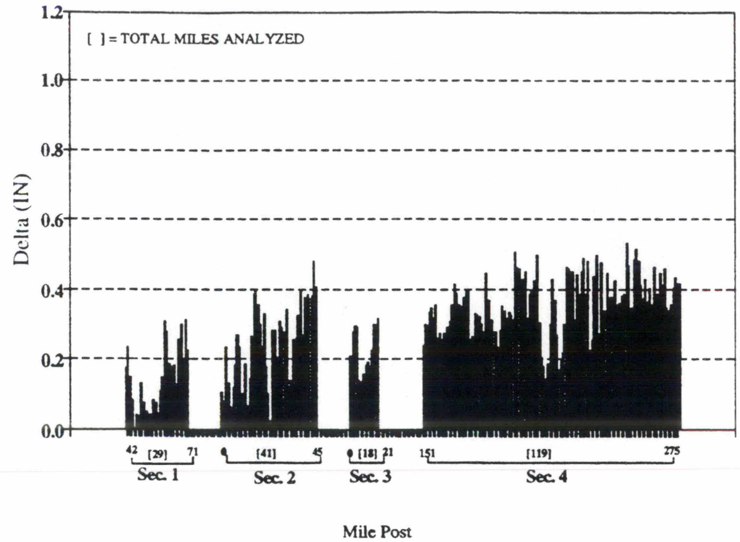

Exhibit 72. Delta Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 to 4 of Railroad D.

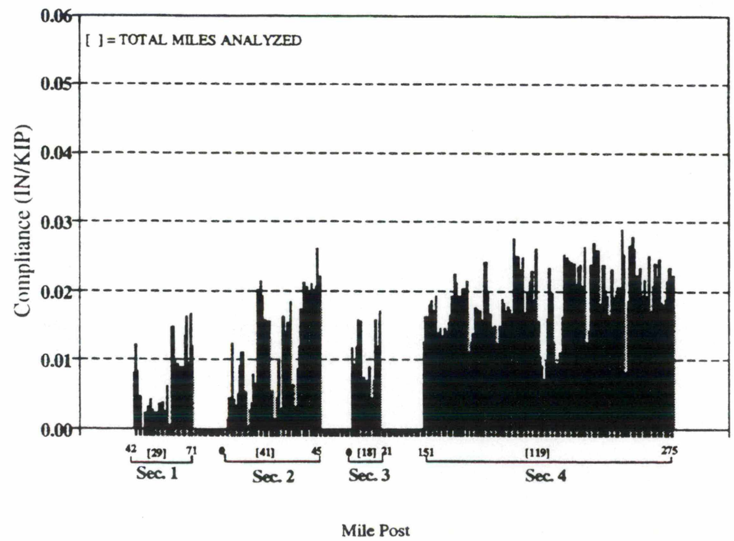

Exhibit 73. Track Compliance Mean Value for Each Statistical Mile Sample in Test Sections 1 to 4 of Railroad D.

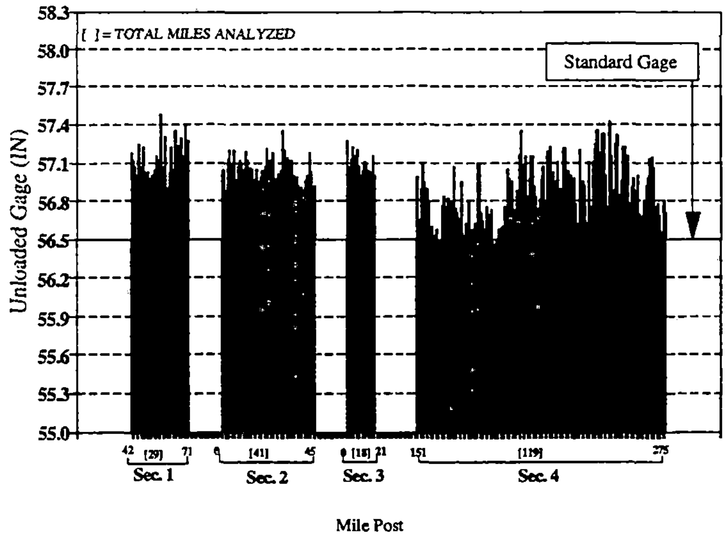

Exhibit 74. Ninety Fifth-percentile (L95) Value of Unloaded Gage for Each Statistical Mile Sample in Test Sections 1 to 4 of Railroad D.

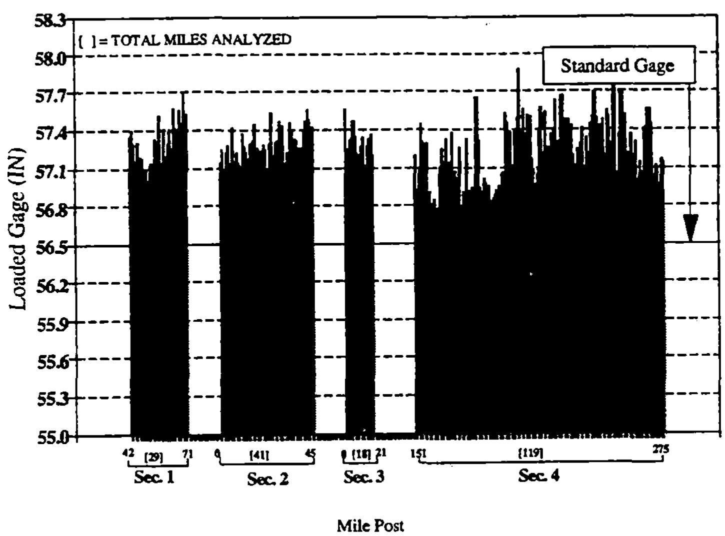

Exhibit 75. Ninety Fifth-percentile (L95) Value of Loaded Gage for Each Statistical Mile Sample in Test Sections 1 to 4 of Railroad D.

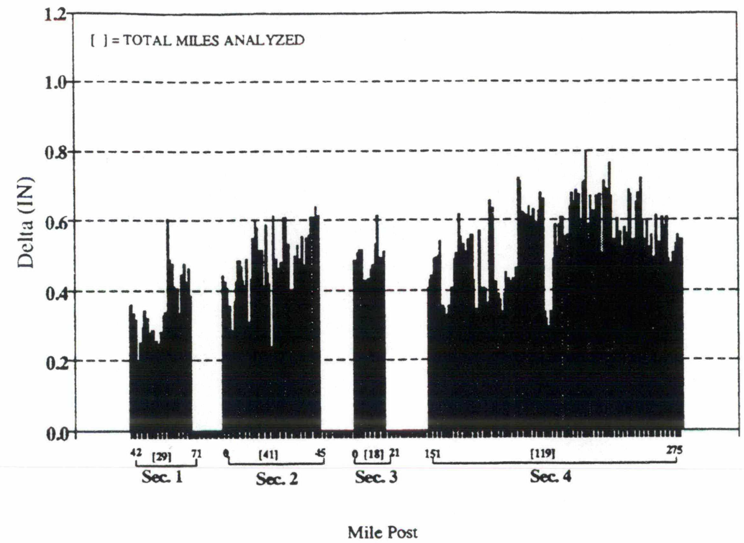

Exhibit 76. Ninety Fifth-percentile (L95) Value of Delta Gage for Each Statistical Mile Sample in Test Sections 1 to 4 of Railroad D.

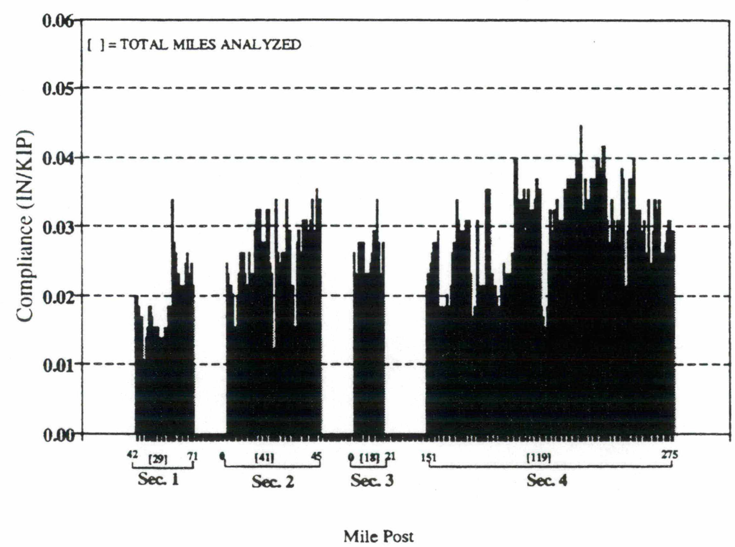

Exhibit 77. Ninety Fifth-percentile (L95) Value of Track Compliance for Each Statistical Mile Sample in Test Sections 1 to 4 of Railroad D.

varies from 56.68" to 57.0" in Test Section 1, and from 56.54" to over 57.0" in Test Section 2. In Test Section 3, the unloaded gage varies from 56.65" to 57.0", while it varies from 56.38" to 56.9" in Test Section 4.

As seen in Exhibit 71, the mean loaded gage varies from 56.8" to 57.2" in Test Section 1, and from under 56.9" to over 57.2" in Test Section 2. In Test Section 3, the loaded gage varies from 56.94" to 57.1", while it varies from 56.63" to under 57.4" in Test Section 4. The decrease in loaded gage in the first one-third of post-maintenance segment of Test Section 4 is seen in this exhibit. Though it appears that the track in all test sections has ample ability to hold gage, a general concern emerges regarding a need for track maintenance in all test sections. As will be seen from a study of delta gage values in the following, a large loaded gage may not imply weak track if wide gage exists before loading. A study of the exception reports shows that most of the exceptions in the four test sections on Railroad D are due to the exceedence of the loaded gage paint limit of 57.75".

Exhibit 72 gives an indication of which miles of the track are relatively strong and which are weak. The mean delta gage rises to over 0.3" in Test Section 1 and 3, and to 0.48" in Test Section 2. In Test Section 4, the variation in delta gage is from under 0.2" to over 0.5". The lower mean delta gage values, combined with exceedences of the loaded gage paint limit, clearly indicate a need for gage control maintenance on the sections tested on Railroad D. The benefits of such maintenance are apparent from the lower delta gage values seen in the first one-third of Test Section 4. Exhibit

73 gives a quantitative measure of the tie and rail restraint provided by the track in Test Sections 1, 2, 3 and 4. The higher the compliance value, the weaker is the gage widening resistance. Good to strong rail lateral restraint conditions on the Railroad D test sections are indicated by the lesser than 0.03"/kip mean compliance values seen in this exhibit.

The 95th-percentile values of unloaded gage, loaded gage, delta gage and compliance, for each track mile analyzed on Railroad D, are discussed in the following to demonstrate dispersal in data, and to differentiate between weak and strong tie/fastener conditions.

Exhibit 74 shows the L95 values of unloaded gage for all four test sections. Gage degradation is seen in all test sections. More than 5% of the time unloaded gage is above 56.9" in Test Section 1, 56.8" in Test Section 2, 57.0" in Test Section 3, 56.5" in the post-maintenance segment in Test Section 4 and 56.8" in the remainder of Test Section 4. The corresponding L95 values of loaded gage are given in Exhibit 75. Most of the L95 loaded gage values are between 57.1" and 57.7", except the in post-maintenance segment of Test Section 4. On this segment, the values are between 56.8" and 57.4". A L95 value closer to 57.7" indicates the onset of the loaded gage paint limit exception. There are few miles of track in Test Section 4 where L95 loaded gage is actually above the loaded gage paint limit of 57.75".

The extent of gage widening resistance provided by tie and rail restraint on each mile is seen in Exhibits 76 and 77. A check of L95 delta gage values corresponding to those miles of track where L95 loaded gage exceeded 57.75" shows that these values may not necessarily be the critical values. It is not necessarily the deficiency in gage widening resistance, but rather the initial presence of substantial wide gage, which leads to the loaded gage paint limit exceedences. For example, the highest L95 loaded gage of 57.9" in Test Section 4 has a corresponding L95 delta gage of only 0.62". L95 delta gage of 0.62" does not indicate a weak tie and fastener condition. A study of the corresponding L95 unloaded gage reveals a value of 57.35". That such wide gage does in fact lead to the loaded gage paint limit exception is indicated in these exhibits. The sound tie and fastener condition indicates regaging as a remedy.

Most of the L95 delta gage values are between 0.4" and 0.6", except for some miles in Test Section 4. The corresponding L95 compliance values are mostly below 0.03"/kip. Since 95% of the data is below these values, good gage widening resistance is indicated for Test Section 1, 2 and 3, and the post-maintenance segment of Test Section 4. An adequate tie and rail restraint is evident for the rest of Test Section 4, as seen from delta gage and compliance values in these exhibits.

6.4.2 Analysis Based on Track Type

Exhibit 78 shows, in Column 1, the FRA track classes in Test Sections 1, 2, 3 and 4 of Railroad D. The majority of tests were conducted on cut spike track with curvatures of up to 2 degrees. Test Section 1 has Class 3 track, Test Section 2 and 3 have Class 2 track, while Test Section 4 has both Class 3 and Class 4 track.

Class	Geometry (Degrees)	Tie/Fastener	Track Analyzed (Miles)				
			Test Section				Total
			1	2	3	4	
2	0-2	Wood/Spike	0.00	26.54	9.84	0.00	36.38
2	2-4	Wood/Spike	0.00	5.75	2.32	0.00	8.07
2	4-6	Wood/Spike	0.00	5.73	2.18	0.00	7.91
2	6-10	Wood/Spike	0.00	3.36	3.22	0.00	6.58
2	6-10	Wood/Pandrol	0.00	0.00	0.86	0.00	0.86
3	0-2	Wood/Spike	16.31	0.00	0.00	11.63	27.94
3	2-4	Wood/Spike	3.76	0.00	0.00	5.28	9.04
3	4-6	Wood/Spike	5.41	0.00	0.00	3.96	9.37
3	6-10	Wood/Spike	3.74	0.00	0.00	2.82	6.56
4	0-2	Wood/Spike	0.00	0.00	0.00	58.20	58.20
4	2-4	Wood/Spike	0.00	0.00	0.00	18.00	18.00
4	4-6	Wood/Spike	0.00	0.00	0.00	12.42	12.42
4	6-10	Wood/Spike	0.00	0.00	0.00	6.44	6.44
Total Miles			29.22	41.38	18.42	118.75	207.77

Exhibit 78. Total Miles Analyzed in Test Sections 1 to 4 of Railroad D for Wide Gage and Gage Resistance with respect to Track Class, its Geometry and Tie and Fastener Types.

There are elastic fasteners on wood ties in only a small portion of Test Section 3. Of 208 miles analyzed, 36 miles are of Class 2 track, 28 miles are of Class 3 track and 58 miles are of Class 4 track, generally, with cut spikes and curvatures of up to 2 degrees.

Exhibit 79 shows the mean, standard deviation and L95 of unloaded gage in Test Section 1, as a function of track curvature, class and tie/fastener type. There is no characteristic dependence of mean and L95 values on curvature, yet higher magnitudes are seen in higher degree curves. The standard deviation, on the other hand, increases with curvature, except for 6-10 degree curved track. This indicates that as the degree of track curvature increases, the variability in unloaded gage increases. Smaller unloaded gage on 6-10 degree curves indicates better control of gage due to an inspection and maintenance response to high lateral loads seen on high curvature track. L95 unloaded gage as large as 57.36" occurs on 2-4 degree curves. A concern to control gage is indicated for this test section.

Exhibit 80 shows the mean, standard deviation and L95 of loaded gage in Test Section 1. Trends similar to unloaded gage in the previous exhibit are also present in this exhibit of loaded gage. Greater loaded gage at higher curvature is seen in this exhibit. The highest L95 value of 57.55" is seen on 4-6 degree curves. An increased variability in loaded gage with respect to curvature is indicated by higher standard deviation values up to 4-6 degree curves. Even though the unloaded gage values in the previous exhibit do point a need to control gage, the loaded gage

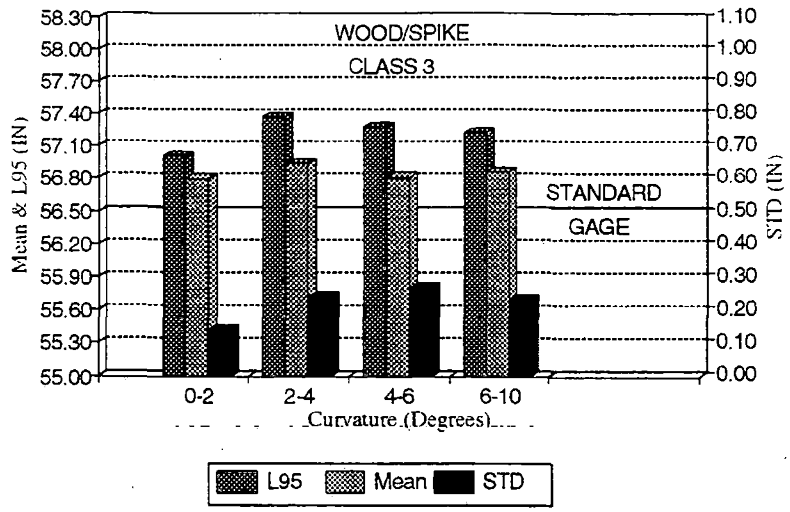

Exhibit 79. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad D, Segmented by Class, Tie and Fastener Types.

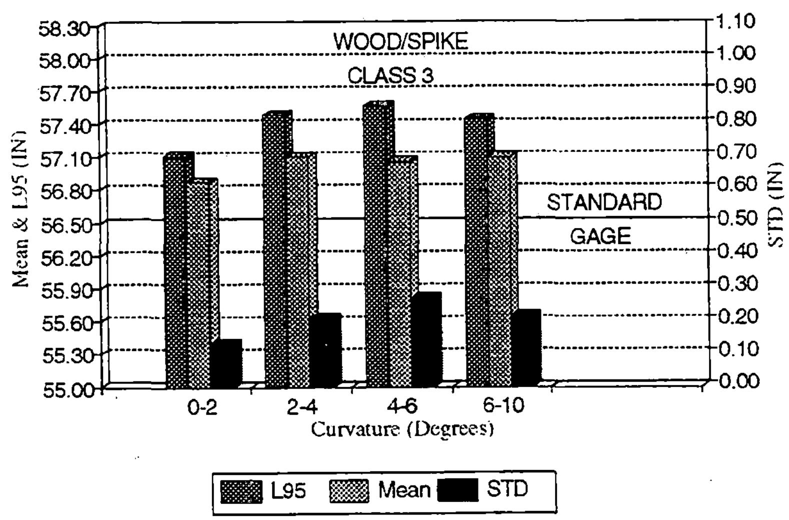

Exhibit 80. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad D, Segmented by Class, Tie and Fastener Types.

values do not seem to indicate an immediate improvement.

The mean, standard deviation and L95 of delta gage in Test Section 1 are seen in Exhibit 81. The largest L95 value of delta gage is 0.45". The corresponding L95 value of track compliance, for a gage widening load of 18 kips, is 0.025"/kip. This indicates strong tie and rail restraint conditions in Test Section 1. It is interesting to compare the relative dispersion of delta gage in terms of a coefficient of variation. This coefficient is defined as the ratio of the standard deviation to the mean. The coefficient of variation is 1.86 for 0-2 degree curves, 1.0 for 2-4 degree curves, 0.52 for 4-6 degree curves, and 0.54 for 6-10 degree curves. The variability in delta gage values is highest on 0-2 degree curves, and least on 4-6 degree curves. The confidence that a measured delta gage value is near to the mean value is very low in the case of 0-2 degree track, while there is a much greater confidence that the value is closer to the mean in the case of 4-6 degree track.

Test notes indicate the presence of metal flow at the gage corner of the low rail, and gage wear on the high rail of curves. Since the laser gage system on the TLV measures unloaded gage 5/8" below the tops of rails, the metal flow lip remains unaccounted for in the measurement of unloaded gage in the tests. With loaded gage, the metal flow lip is accounted for by applying a gage spreading load to the lip and measuring the corresponding gage spreading. On the high rail, it is estimated that discrepancies in the measurements of unloaded and loaded gage, due to gage face wear, are of a much smaller order, so that no substantial error is

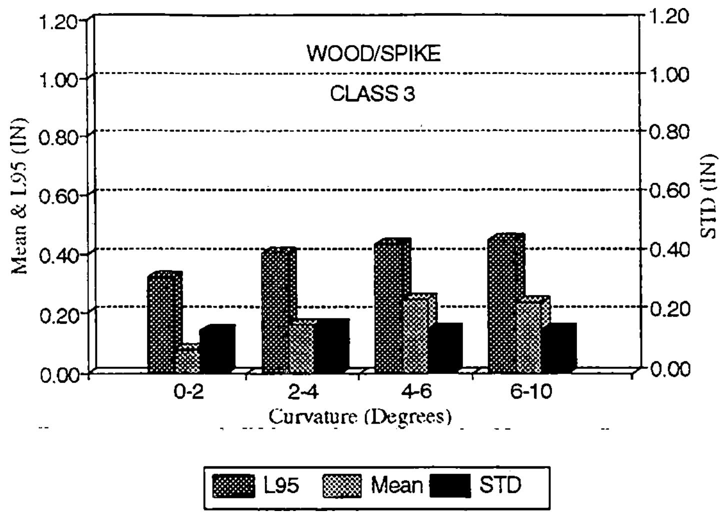

Exhibit 81. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad D, Segmented by Class, Tie and Fastener Types.

anticipated. The metal flow errors are systematic errors. Since the extent of flow errors can be estimated, a correction can be made to the data to compensate for this. Otherwise, these errors will combine with uncertainties from statistical fluctuations. A reasonable estimate of 0.2" is made and this amount is subtracted from the unloaded gage and added to the delta gage values found in the tests. The loaded gage is assumed not to be affected by the metal flow error. The unloaded and delta gage corrected for metal flow are seen in Exhibits 82 and 83.

The unloaded, loaded and delta gage in Test Section 2, with respect to track type, are shown in Exhibits 84, 85 and 86, respectively. Slight decrease in unloaded gage mean value is seen with respect to curvature. The maximum L95 unloaded gage value of

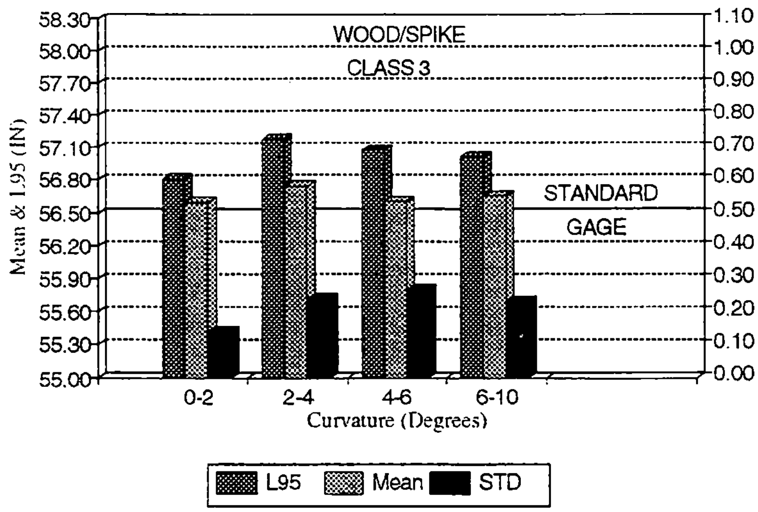

Exhibit 82. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad D, Segmented by Class, Tie and Fastener Types (Corrected for Metal Flow).

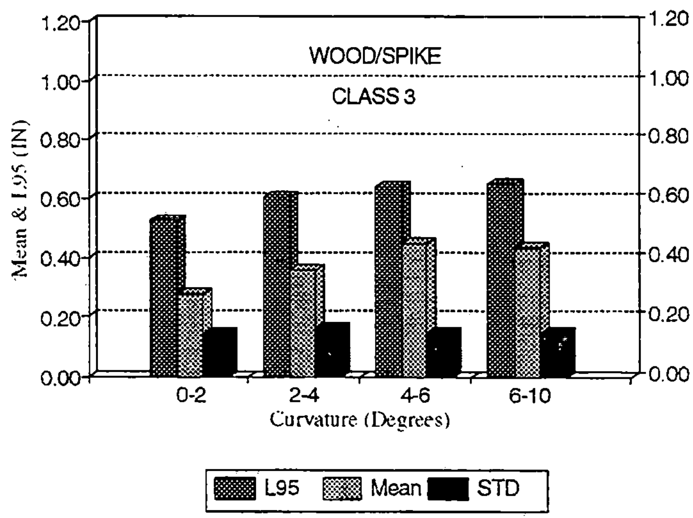

Exhibit 83. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad D, Segmented by Class, Tie and Fastener Types (Corrected for Metal Flow).

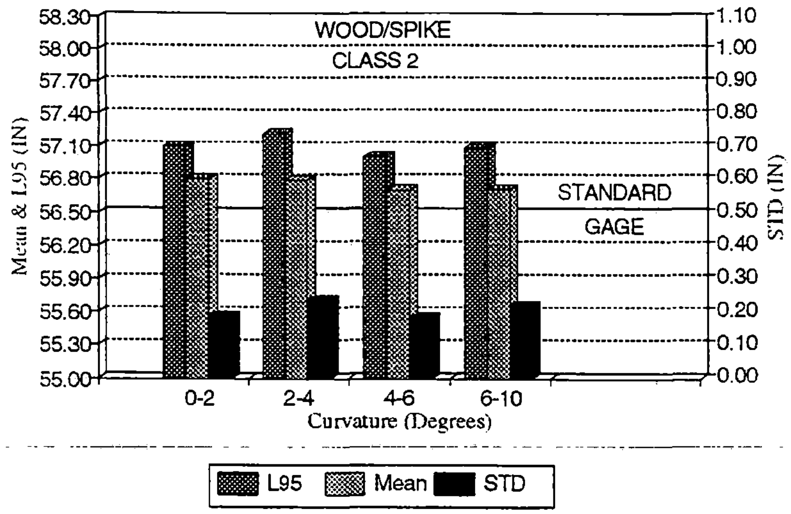

Exhibit 84. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad D, Segmented by Class, Tie and Fastener Types.

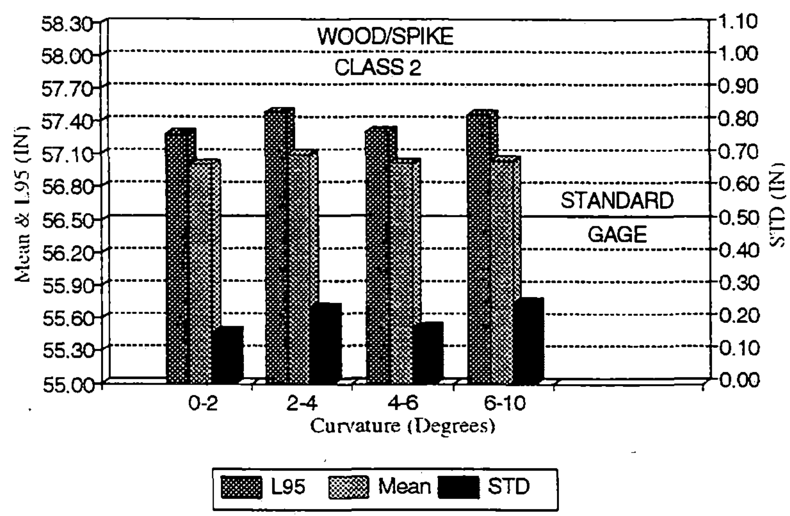

Exhibit 85. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad D, Segmented by Class, Tie and Fastener Types.

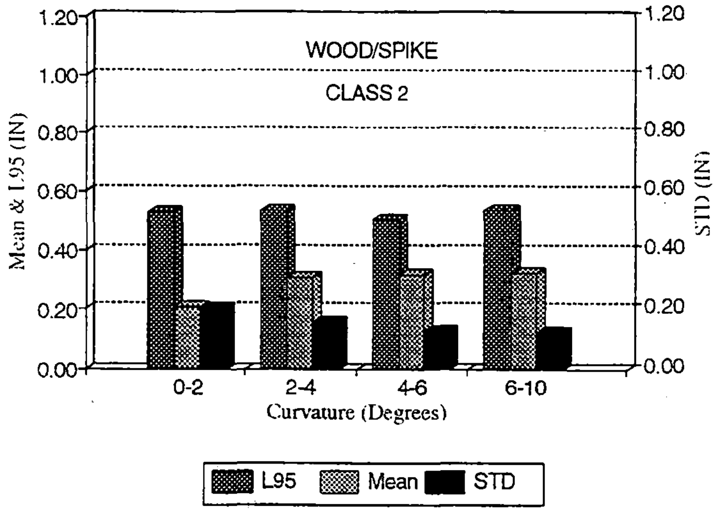

Exhibit 86. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad D, Segmented by Class, Tie and Fastener Types.

over 57.2" is seen on 2-4 degree curves. No trend in unloaded gage variability is apparent due to the up-and-down change in standard deviation with respect to curvature, nor is a characteristic change in loaded gage values, with respect to curvature, discernible in Exhibit 85. The highest L95 loaded gage value of 57.5" occurs on 2-4 degree curves. Delta gage mean values appear to increase, while standard deviations decrease with curvature in Exhibit 86. A maximum delta gage mean value of 0.32", giving a mean track compliance of 0.018"/kip, indicates very good tie and rail restraint conditions in Test Section 2.

Test Section 3 is comprised of only Class 2 track with curvatures up to 10 degrees. Most of this test section consisted of cut spike track, except a small mileage of 6-10 degree curvature track having elastic fasteners on wood ties. The corresponding unloaded, loaded and delta gage, with respect to track type are shown in Exhibits 87, 88 and 89, respectively. The characteristic change in unloaded and loaded gage mean and L95 values, with respect to curvature, is not obvious in this test section. Standard deviation, on the other hand, seems to increase with curvature for both the unloaded and the loaded gage. Even though the elastic fastener segment has only one-fourth the mileage of the corresponding cut spike segment, a comparison shows that both the L95 and mean values of unloaded and loaded gage are smaller on elastic fastener segment. However, standard deviation is comparable for unloaded gage while it is smaller for loaded gage on elastic fastener segment. This indicates that elastic fasteners hold gage better than do cut spikes. All delta gage values in Exhibit 89 are below 0.6" indicating a substantial reserve of gage widening resistance in Test Section 3. A maximum delta gage mean value of 0.28", resulting in a mean track compliance of 0.016"/kip, indicates very good tie and rail restraint conditions on this test section.

Test Section 4, unlike other test sections on Railroad D, contains both Class 3 and Class 4 cut spike track with curvatures up to 10 degrees. Even though none of the test segments is small, most test mileage was on 0-2 degree Class 4 track. The corresponding unloaded, loaded and delta gage, by track type, are shown in Exhibits 90, 91 and 92, respectively. Exhibits 90 and 91 show that as the degree of track curvature increases, the mean and L95 increase along with the standard deviation. Obvious from these

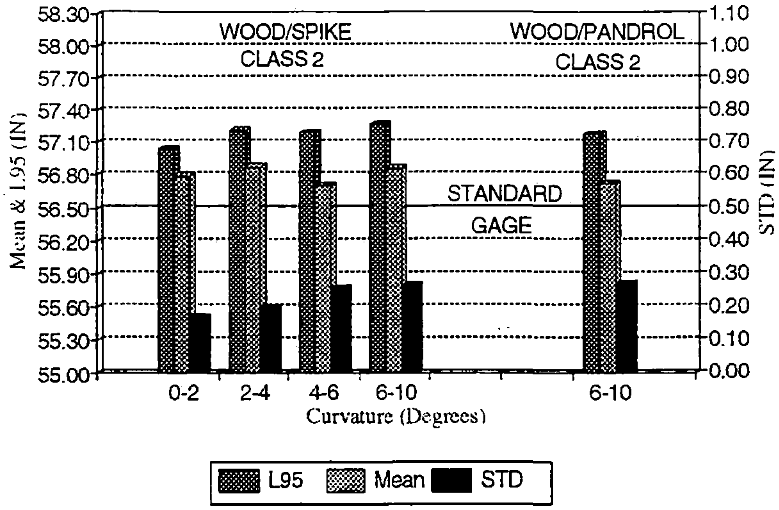

Exhibit 87. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad D, Segmented by Class, Tie and Fastener Types.

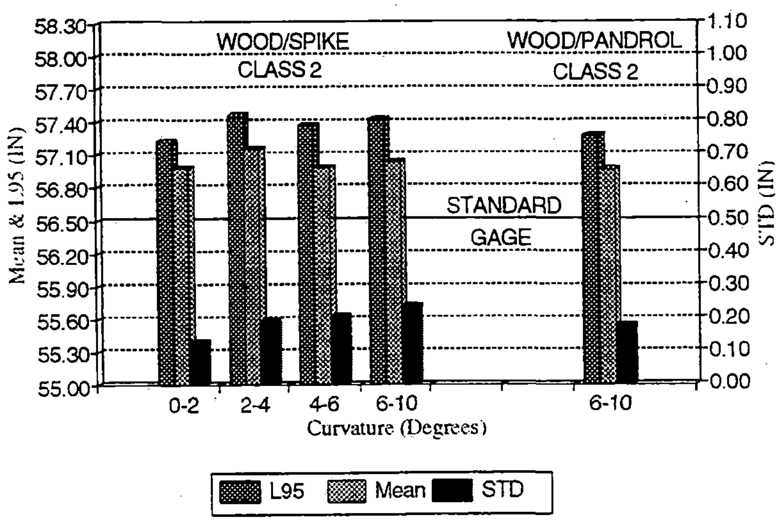

Exhibit 88. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad D, Segmented by Class, Tie and Fastener Types.

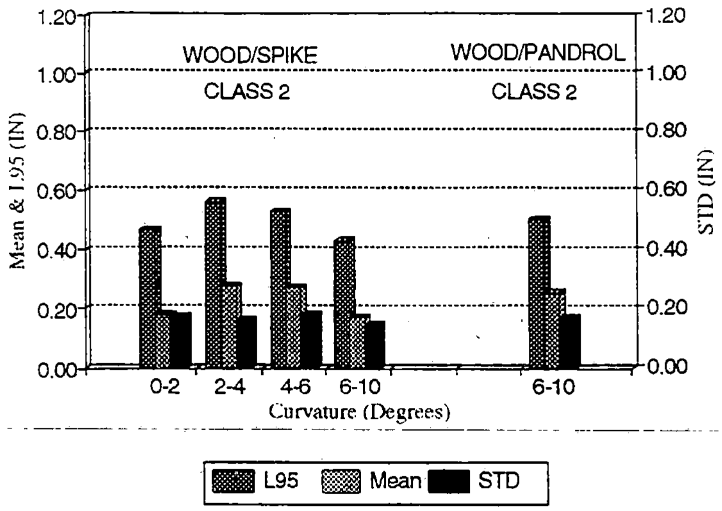

Exhibit 89. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad D, Segmented by Class, Tie and Fastener Types.

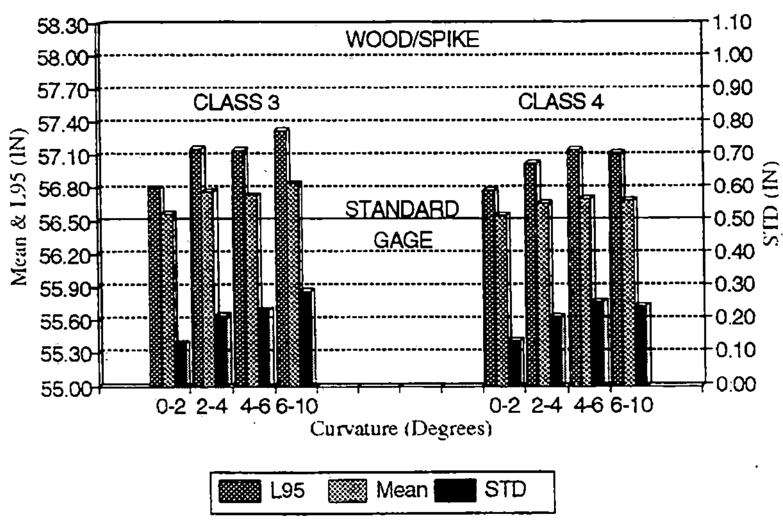

Exhibit 90. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 4 of Railroad D, Segmented by Class, Tie and Fastener Types.

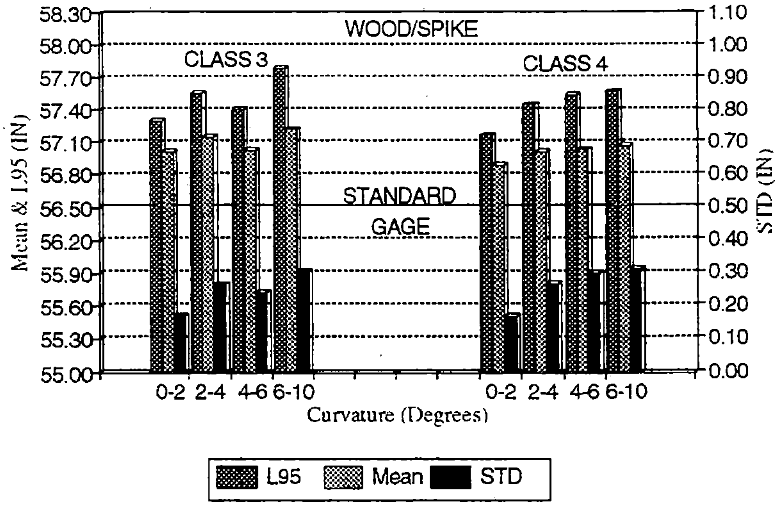

Exhibit 91. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 4 of Railroad D, Segmented by Class, Tie and Fastener Types.

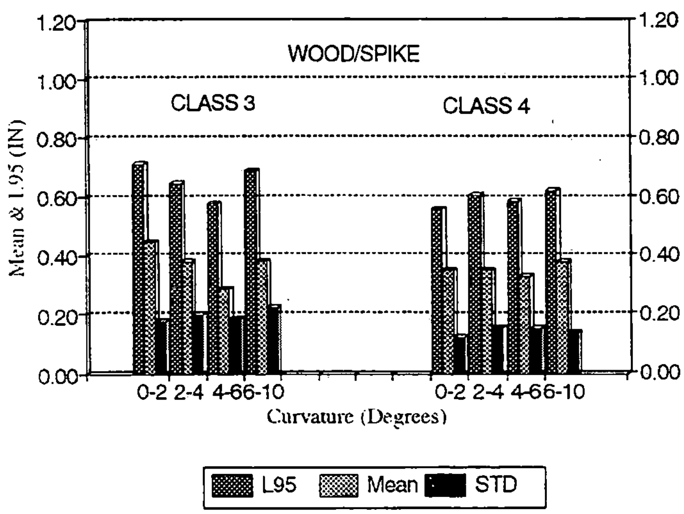

Exhibit 92. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 4 of Railroad D, Segmented by Class, Tie and Fastener Types.

exhibits is a general lowering of these values at higher class track. The higher gage widening loads required for steering on higher degree curves are responsible for wider unloaded gage on higher degree track. Lower unloaded gage values indicate better gage control in the Class 4 track, which experiences higher operating speeds and higher lateral forces. The highest L95 unloaded gage of 57.3" occurs on 6-10 degree Class 3 track, and corresponds to L95 loaded gage of 57.78" seen in Exhibit 91. The L95 loaded gage exceeds the loaded gage paint limit of 57.75". Since most of the exceptions in this test section are due to wide gage, a need is indicated to control gage by adding spikes or using elastic fasteners.

The delta gage values in Exhibit 92, indicate that the mean and L95 values decrease with respect to curvature up to the 6 degree Class 3 track. Such a decrease is only slightly evident for Class 4 track. A slight decrease in these values, together with standard deviation, is seen from Class 3 to Class 4 track. Delta gage values in Exhibit 92 are below 0.7", indicating a good reserve of gage widening resistance in Test Section 4. A maximum delta gage mean value of 0.45", resulting in a mean track compliance of 0.025"/kip, indicates good tie and rail restraint conditions on this test section.

6.5 RAILROAD E

Gage widening tests using the TLV were performed in four test sections on Railroad E. A total of 145 miles of track was tested in August and September 1991. Thirty miles were tested in Test

Section 1, 25 miles in Test Section 2, 25 miles in Test Section 3, and 65 miles in Test Section 4. Ten miles of track in Test Section 2 has concrete ties. All test sections are located in southern Canada. 132 lb rail was used on tangent track, and track with light curvature. With curves equal to and greater than 3 degrees of curvature, 136 lb rail was used. Test Section 1 carries 30 MGT traffic per year on FRA class 3 track. Test Section 2 carries 48 MGT traffic per year on FRA class 2 and 3 track. Test Section 3 carries 48 MGT traffic per year on FRA class 3 and 4 track. Test Section 4 carries 19 MGT traffic per year on FRA class 4 and 5 track.

6.5.1 Analysis Based on Mile Post

Exhibits 93, 94, 95 and 96 show the mean values of unloaded gage, loaded gage, delta gage and track compliance, respectively, in all test sections, on a mile-by-mile basis. Similarly, Exhibits 97, 98, 99 and 100 show the respective 95th-percentile values for the test sections.

Wide gage is present in Test Section 4, while in Test Sections 1 and 3 there are large portions of track where tight gage is seen as shown in Exhibit 93. Except for the last one-third of Test Section 4, good control on gage is seen as the unloaded gage mean values are close to the standard gage. The mean unloaded gage varies from 56.3" to above 56.6" in Test Section 1, and from under 56.4" to above 56.7" in Test Section 2. In Test Section 3, the unloaded gage varies from just above 56.2" to 56.6", while it varies from above 56.4" to under 57.0" in Test Section 4.

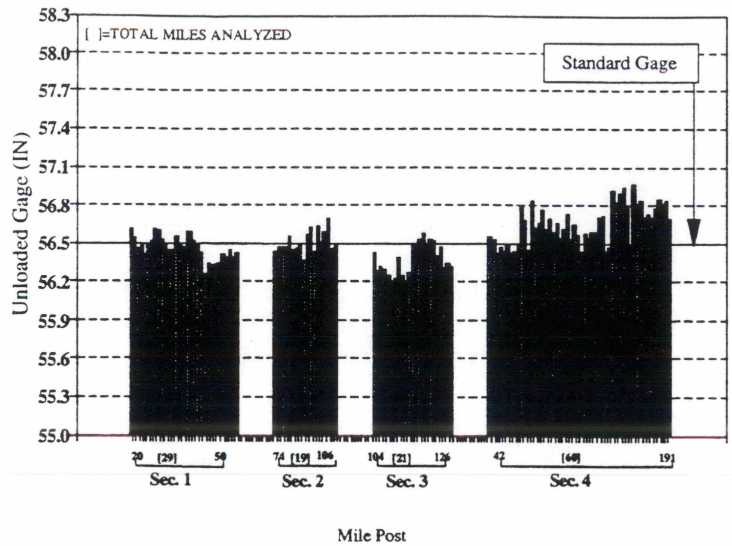

Exhibit 93. Unloaded Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 to 4 of Railroad E.

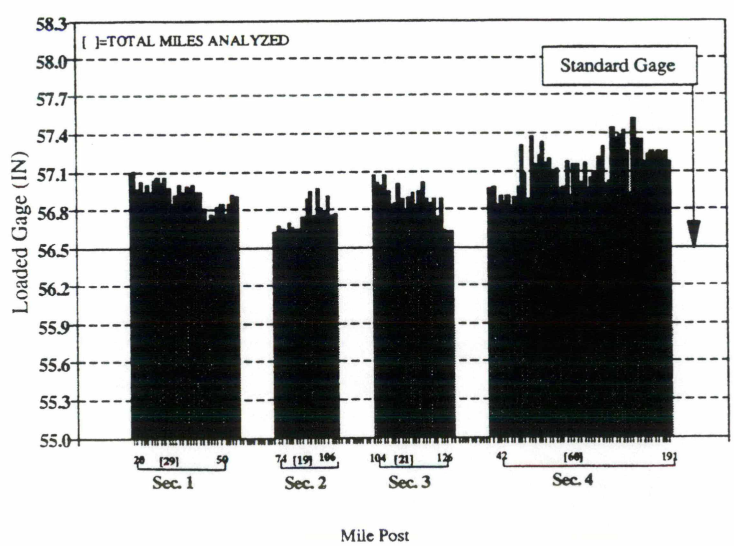

Exhibit 94. Loaded Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 to 4 of Railroad E.

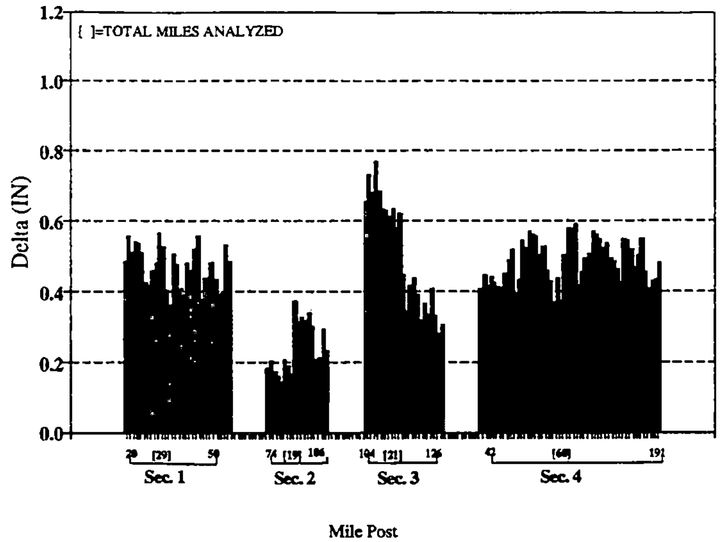

Exhibit 95. Delta Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 to 4 of Railroad E.

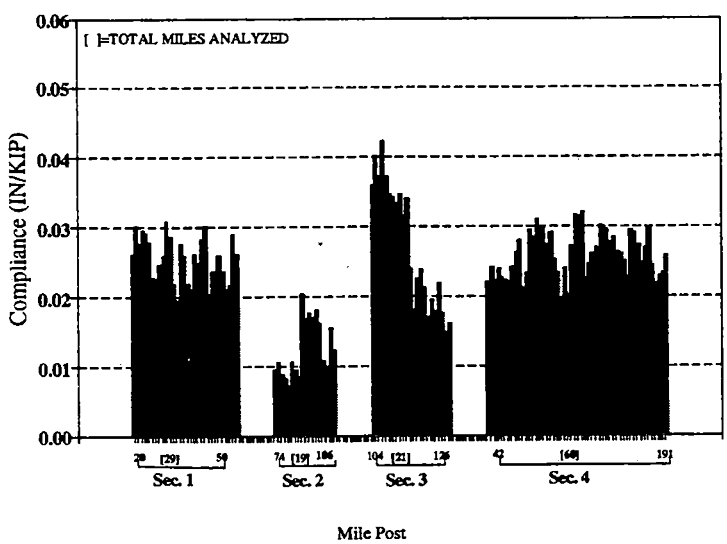

Exhibit 96. Track Compliance Mean Value for Each Statistical Mile Sample in Test Sections 1 to 4 of Railroad E.

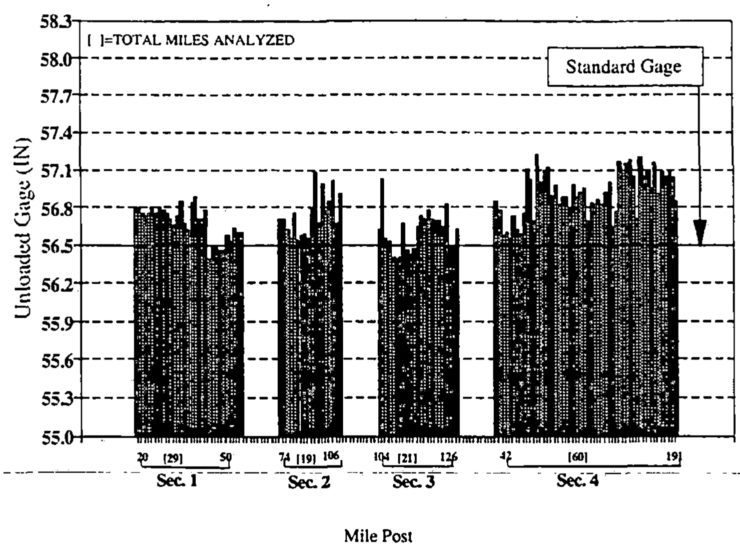

Exhibit 97. Ninety Fifth-percentile (L95) Value of Unloaded Gage for Each Statistical Mile Sample in Test Sections 1 to 4 of Railroad E.

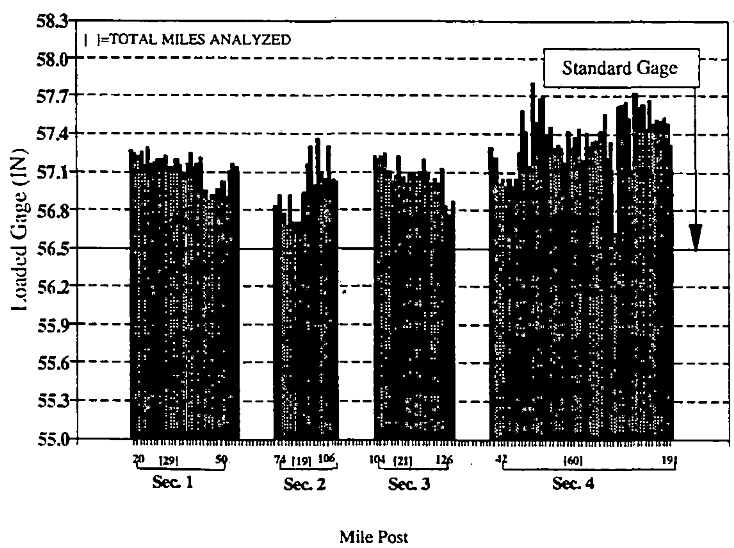

Exhibit 98. Ninety Fifth-percentile (L95) Value of Loaded Gage for Each Statistical Mile Sample in Test Sections 1 to 4 of Railroad E.

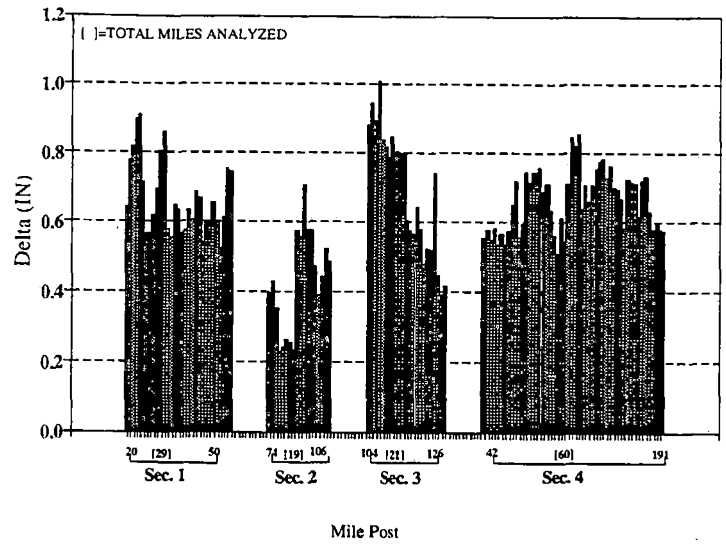

Exhibit 99. Ninety Fifth-percentile (L95) Value of Delta Gage for Each Statistical Mile Sample in Test Sections 1 to 4 of Railroad E.

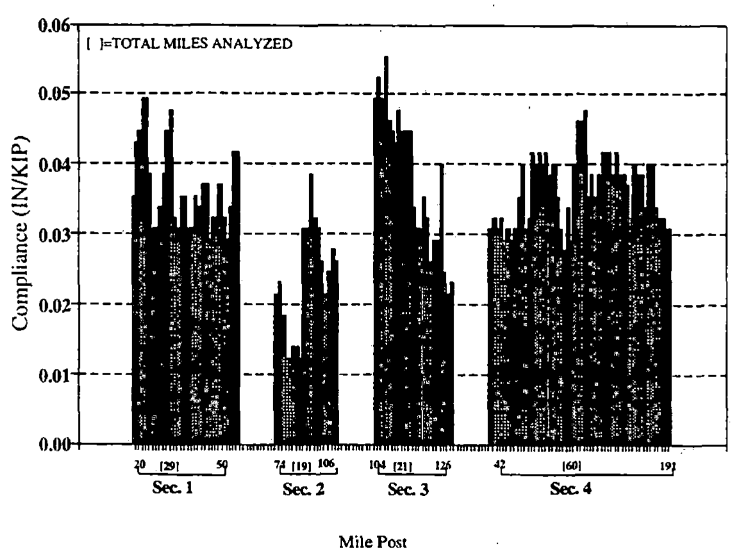

Exhibit 100. Ninety Fifth-percentile (L95) Value of Track Compliance for Each Statistical Mile Sample in Test Sections 1 to 4 of Railroad E.

The mean loaded gage seen in Exhibit 94 varies from 56.7" to 57.1" in Test Section 1, and from 56.63" to 56.97" in Test Section 2. In Test Section 3, the loaded gage varies from 56.64" to under 57.1", while it varies from above 56.8" to 57.52" in Test Section 4. The lower loaded gage with concrete ties in the first half of Test Section 2 is obvious in this exhibit. While any loaded gage value beyond a specified threshold is unacceptable for track safety reasons, itself it does not always indicate the level of gage widening resistance present. Even then, the moderately high loaded gage mean values in Test Section 1, 2 and 3 indicate adequate gage widening resistance. Loaded gage mean values higher than 57.1" in Test Section 4 do, on the other hand, indicate a concern as to the presence of adequate gage widening resistance.

Exhibit 95 gives an indication of the miles of the track which are relatively strong and which are weak. As seen, the mean delta gage rises to 0.57" in Test Section 1, and to 0.2" in the concrete tie track, and 0.37" in cut spike track of Test Section 2. In Test Section 3, the variation is from 0.3" to 0.77", while in Test Section 4, it is from 0.36" to under 0.6".

Exhibit 96 gives a quantitative measure of the tie and rail restraint provided by the track in Test Sections 1, 2, 3 and 4. The higher the compliance value, the weaker is the gage widening resistance. Good to strong rail lateral restraint conditions are seen in Test Sections 1, 2 and 4, as indicated by 0.03"/kip and below compliance mean values in the exhibit. The higher delta gage and compliance mean values in the first half of Test Section 3 indicate weak gage widening resistance.

A study of the exception reports indicates that there are no exceptions in Test Section 2. In Test Section 1 and 3 the exceptions seen are due to exceedence of the delta gage paint limit of 1.25". In Test Section 4 exceedence of the loaded gage paint limit of 57.75" caused the exceptions. The implication of loaded gage or delta gage is related to the prior presence of either tight or wide gage. It is true that excessive loaded gage can result in a derailment. However, a large loaded gage may not imply weak track if wide gage existed prior to loading. Similarly, a weak track as indicated by a large delta gage may not cause derailment if the unloaded gage was tight. In these cases, field inspection is indicated to determine tie and fastener conditions and to determine maintenance requirements.

While it appears that track in all of the test sections has ample ability at holding gage, the large delta gage seen in Test Section 3 and the higher loaded gage in Test Section 4, create a concern as to weak tie/fastener condition in Test Section 3 and as to wide gage in Test Section 4.

The 95th-percentile values of unloaded gage, loaded gage, delta gage and track compliance, for each track mile analyzed on Railroad E, are discussed in the following to demonstrate dispersal in data and to differentiate between weak and strong tie/fastener conditions.

Exhibit 97 shows the L95 values of unloaded gage for the four test sections. Wide unloaded gage is seen in Test Section 4. The highest L95 value of unloaded gage is 56.9" in Test Section 1, 57.09" in Test Section 2, 57.02" in Test Section 3, and 57.23" in

Test Section 4. The corresponding L95 values of loaded gage are seen in Exhibit 98. All of the L95 loaded gage values in Test Sections 1, 2 and 3 are below 57.4". In Test Section 4, most of the values are between 57.1" and 57.7". A L95 value closer to 57.7" is an indication of the onset of the loaded gage paint limit exception. There are few miles of track in Test Section 4 where L95 loaded gage is actually above the loaded gage paint limit of 57.75".

The extent of gage widening resistance provided by tie and rail restraint in each mile is seen in Exhibits 99 and 100. A review of L95 delta gage values for those miles of track in Test Section 4 where L95 loaded gage exceeded 57.75", shows that these values may not necessarily be the higher values. It is not necessarily the deficiency in gage widening resistance, but rather the initial presence of substantial wide gage, which leads to the loaded gage paint limit exceedence. For example, the highest L95 loaded gage of 57.8" in Test Section 4, has a corresponding L95 unloaded gage of 57.23" and delta gage of only 0.74". A L95 delta gage of 0.74" does not actually indicate a weak tie and fastener condition. That a 57.23" value of unloaded gage leads to the loaded gage paint limit exception, is indicated in this example.

The largest L95 delta gage value of 1.01" is seen in Test Section 3. The corresponding L95 unloaded and loaded gage values, respectively, are 56.52" and 57.25". It is obvious that the discrete values of unloaded and loaded gage, as noted above, do not yield the discrete delta gage of 1.01". It is, however, apparent that a less than 57.25" loaded gage gave rise to a delta gage of

1.01" on this locally weak and tight-gage track segment.

A tendency toward delta gage exceptions is indicated by large L95 compliance and delta gage values in Test Sections 1 and 3. Barring these localized weak track conditions, most of the L95 delta gage values in Test Sections 1, 3, and 4 are between 0.6" and 0.8". The corresponding L95 compliance values are generally below 0.04"/kip. Since 95% of the data is below these values, an adequate gage widening resistance is indicated for Test Sections 1, 3 and 4. L95 compliance values below 0.015"/kip indicate high gage widening resistance for the concrete tie track in Test Section 2. A good tie and rail restraint condition is evident for the rest of Test Section 2, as seen in delta gage and compliance values.

6.5.2 Analysis Based on Track Type

Exhibit 101 shows, in column 1, the FRA track classes in Test Sections 1, 2, 3 and 4 of Railroad E. The majority of tests were conducted on cut spike track with curvatures of up to 2 degrees. Test Sections 1 and 2 have Class 2 and 3 track, Test Section 3 has Class 3 and 4 track, while Test Section 4 has Class 4 and 5 track. Test Section 2 has 9.79 miles of concrete tie track. Of 129 miles analyzed, there are 4 miles of Class 2, 24 miles of Class 3, 13 miles of Class 4 and 55 miles of Class 5 track which consisted of cut spikes and curvatures of up to 2 degrees.

Exhibit 102 shows the mean, standard deviation and L95 of unloaded gage in Test Section 1, as a function of track curvature, class and tie/fastener type. There is no characteristic dependence of mean and L95 values seen as related to curvature, and the

Class	Geometry (Degrees)	Tie/Fastener	Track Analyzed (Miles)				
			Test Section				Total
			1	2	3	4	
2	0-2	Wood/Spike	0.00	3.76	0.00	0.00	3.76
2	2-4	Wood/Spike	0.00	0.46	0.00	0.00	0.46
2	4-6	Wood/Spike	0.00	1.00	0.00	0.00	1.00
2	6-10	Wood/Spike	0.13	4.17	0.00	0.00	4.30
3	0-2	Wood/Spike	18.21	0.00	5.63	0.00	23.84
3	2-4	Wood/Spike	5.18	0.00	1.01	0.00	6.19
3	4-6	Wood/Spike	4.65	0.00	0.00	0.00	4.65
3	6-10	Wood/Spike	0.86	0.00	0.00	0.00	0.86
3	0-2	Concrete	0.00	7.39	0.00	0.00	7.39
3	2-4	Concrete	0.00	1.70	0.00	0.00	1.70
3	4-6	Concrete	0.00	0.41	0.00	0.00	0.41
3	6-10	Concrete	0.00	0.29	0.00	0.00	0.29
4	0-2	Wood/Spike	0.00	0.00	12.45	0.61	13.06
4	2-4	Wood/Spike	0.00	0.00	1.23	1.14	2.37
4	4-6	Wood/Spike	0.00	0.00	0.22	0.23	0.45
4	6-10	Wood/Spike	0.00	0.00	0.23	0.00	0.23
5	0-2	Wood/Spike	0.00	0.00	0.00	54.94	54.94
5	2-4	Wood/Spike	0.00	0.00	0.00	3.18	3.18
Total Miles			29.03	19.18	20.77	60.10	129.08

Exhibit 101. Total Miles Analyzed in Test Sections 1 to 4 of Railroad E for Wide Gage and Gage Resistance with respect to Track Class, its Geometry and Tie and Fastener Types.

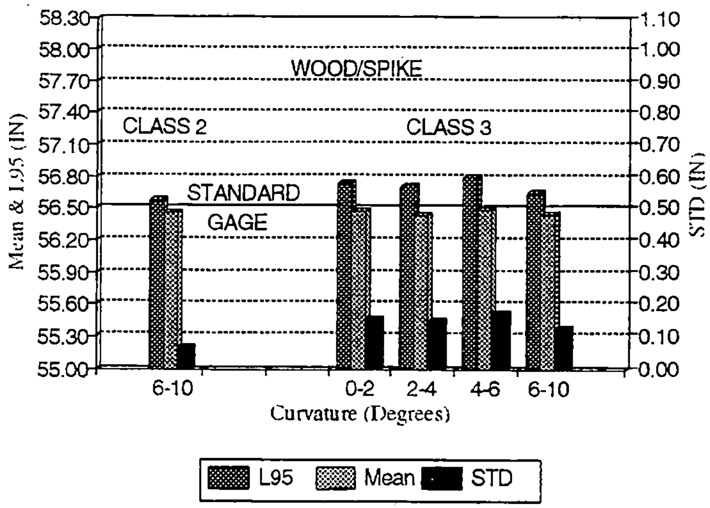

Exhibit 102. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad E, Segmented by Class, Tie and Fastener Types.

standard deviation does not appear also to be curvature dependent. With Class 2 track and Class 3 track on 6-10 degree curves, no discernible change in the mean and L95 values is seen; however, the standard deviation on Class 3 track is higher. This indicates that there is a slight increase in variability in unloaded gage on track having higher operating speed. Mean unloaded gage values below standard gage and L95 values close to it indicate good gage control in Test Section 1.

Exhibit 103 shows the mean, standard deviation and L95 of loaded gage in Test Section 1. No clear trends are seen of loaded gage; however a slight indication of decrease in loaded gage mean value at higher curvature is seen in this exhibit. An increased variability in loaded gage with respect to curvature is discernible

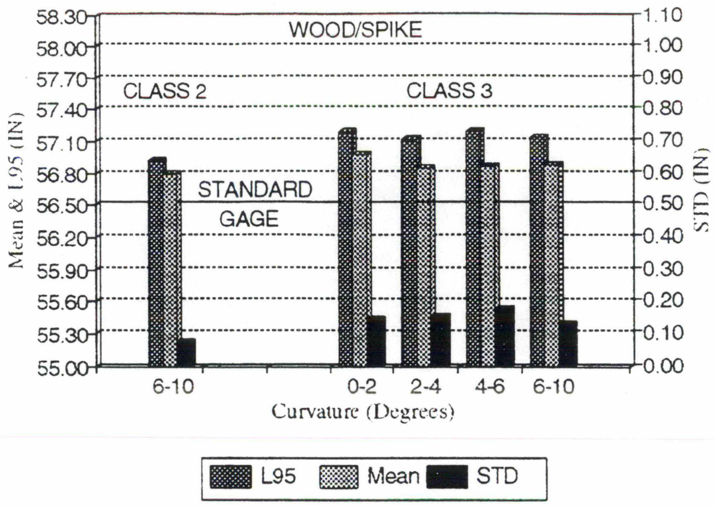

Exhibit 103. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad E, Segmented by Class, Tie and Fastener Types.

from higher standard deviation values in curves of up to 4-6 degree. Higher operating speed on higher class track increases both the loaded gage and its variability. The highest L95 value of 57.2" is seen in 0-2 degree curves, however, no loaded gage exception occurs.

The mean, standard deviation and L95 of delta gage in Test Section 1 are seen in Exhibit 104. Delta gage mean values on Class 3 track are essentially the same for 2-4 to 6-10 degree curves. L95 values, on the other hand, decrease with curvature for 0-2 to 4-6 degree curves. Standard deviation values for the curves are basically the same, and no discernible change is seen in variability in delta gage on Class 3 track. What is obvious, however, is the increase in delta gage values on Class 3 track, as

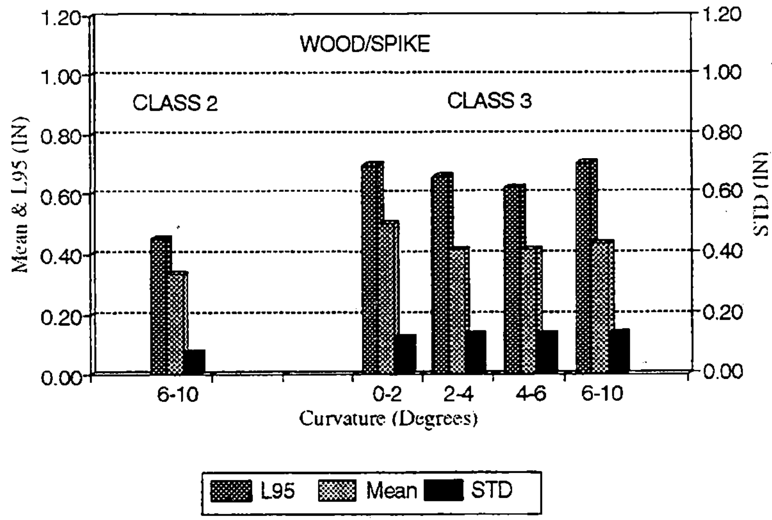

Exhibit 104. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad E, Segmented by Class, Tie and Fastener Types.

compared to these values for Class 2 track. Mean and L95 values, and standard deviation, are notably higher on Class 3 track. This indicates that higher lateral forces due to higher operating speed on Class 3 track adversely affect the gage widening strength over time. The highest L95 value of delta gage is 0.7". In test Section 1, the corresponding L95 value of track compliance, for a gage widening load of 18 kips, is 0.039"/kip, and indicates good tie and rail restraint conditions.

The unloaded, loaded and delta gage in Test Section 2 with respect to track type are shown in Exhibits 105, 106 and 107, respectively. A slight increase in unloaded gage mean value with respect to curvature is seen on both wood and concrete tie track. Except for the L95 value on 4-6 degree curves in class 2 Track,

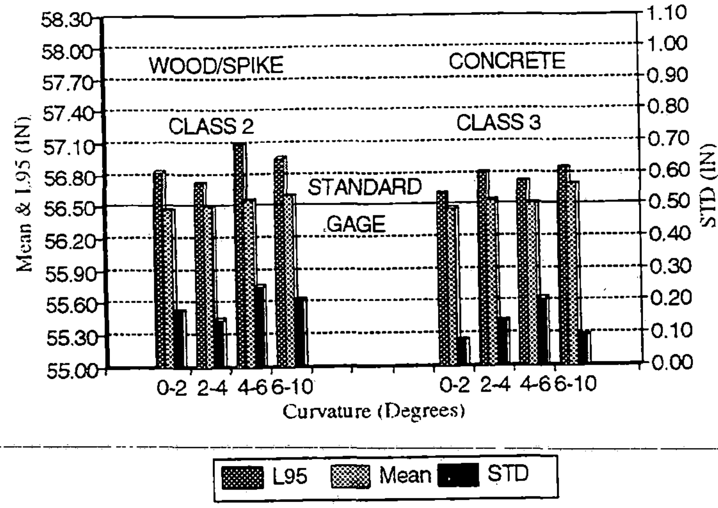

Exhibit 105. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad E, Segmented by Class, Tie and Fastener Types.

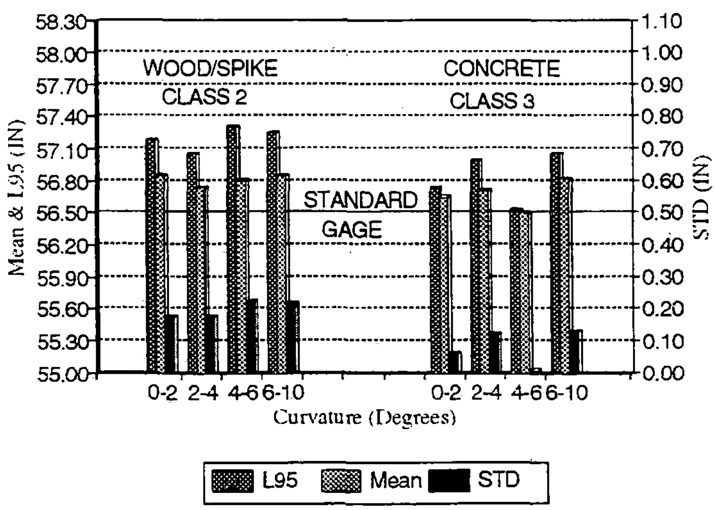

Exhibit 106. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad E, Segmented by Class, Tie and Fastener Types.

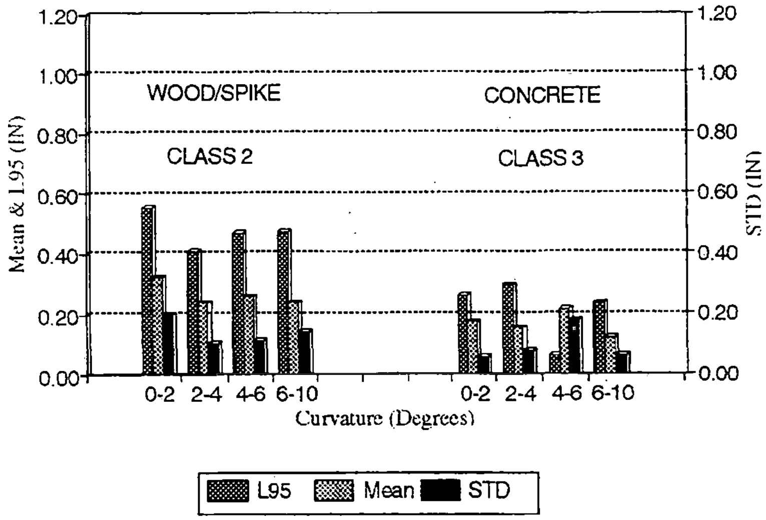

Exhibit 107. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad E, Segmented by Class, Tie and Fastener Types.

unloaded gage characteristics are similar for both wood and concrete tie track. Higher operating speeds on Class 3 concrete tie track are responsible for these comparative values. Mean values are close to standard gage, and the maximum L95 unloaded gage value of 57.1" is seen in cut spike track. Standard deviation increases with curvature on concrete tie track of up to 4-6 degree curvature. No such trend in unloaded gage variability is seen in cut spike track due to the random changes in standard deviation with respect to curvature.

No characteristic change in loaded gage value, with respect to curvature, is seen in Exhibit 106. Loaded gage in concrete tie track is lower than in cut spike track. In cut spike track, the highest L95 loaded gage value of 57.3" is seen on 2-4 degree curves, while on concrete tie track, the value is 57.05" in 6-10 degree curves. In Exhibit 107, the delta gage mean value and standard deviation appear to decrease with curvature for cut spike track. While a trend with respect to curvature is not seen for delta gage values in concrete tie track, these values are dramatically lower than for cut spike track, indicating a much higher gage widening resistance for concrete tie track. A maximum delta gage mean value of 0.32", and a mean track compliance of 0.018"/kip, indicate very good tie and rail restraint conditions on the cut spike track. A maximum delta gage mean value of 0.22" and the corresponding compliance of 0.012"/kip indicate high gage widening resistance for concrete tie track in Test Section 2.

The unloaded, loaded and delta gage, in Test Section 3, with respect to track type are shown in Exhibits 108, 109 and 110, respectively. Decrease in unloaded gage mean value with respect to curvature, except for the 6-10 degree curves, is seen in this test section. A characteristic trend, however, is not obvious for either the L95 values or the standard deviations. While the mean unloaded gage is lower than the standard gage, it is clear from L95 values that for more than 5% of the time, a wider unloaded gage exists in Test Section 3. The highest L95 value of 56.9" occurs on 6-10 degree Class 4 track.

Exhibit 109 shows a slight increase in loaded gage with curvature on Class 4 track, and a decrease on Class 3 track. The standard deviation increases with curvature on Class 3 track, while there is no such characteristic trend in Class 4 track. More variability is seen in Class 4 loaded gage on 0-4 degree curves and

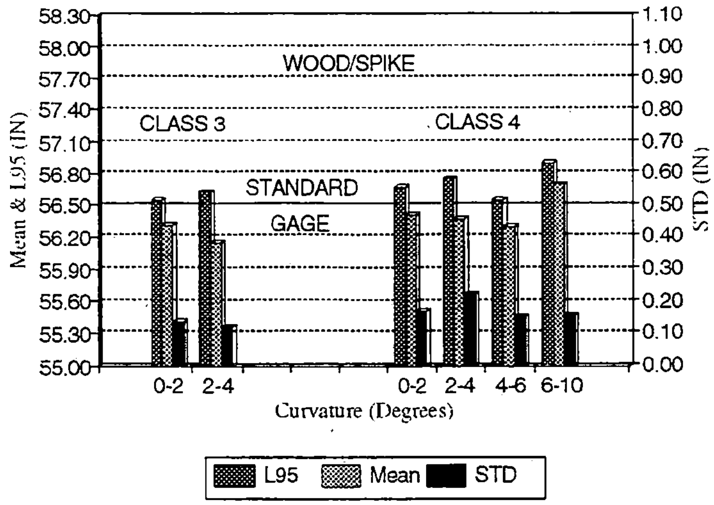

Exhibit 108. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad E, Segmented by Class, Tie and Fastener Types.

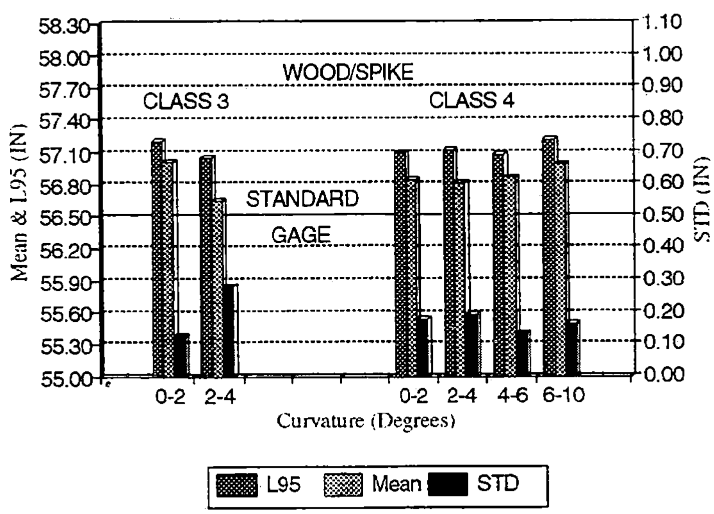

Exhibit 109. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad E, Segmented by Class, Tie and Fastener Types.

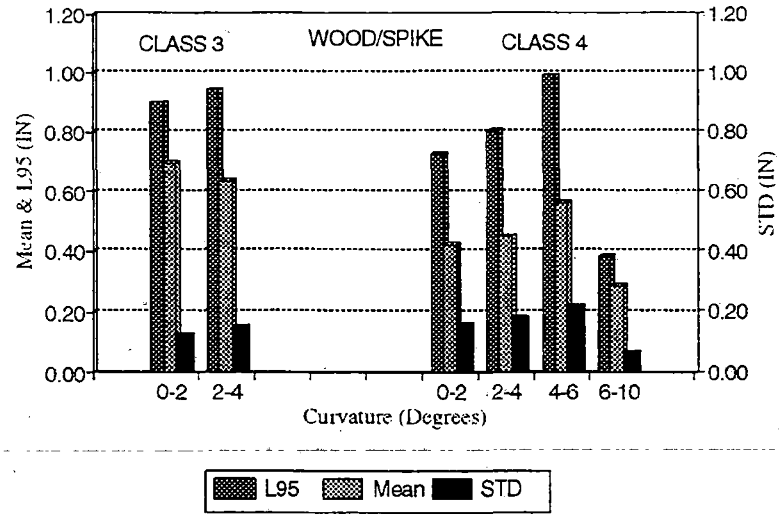

Exhibit 110. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad E, Segmented by Class, Tie and Fastener Types.

less in 4-10 degree curves. Between the classes of track, mean and L95 values decrease with class on 0-2 degree curves, and increase with class on 2-4 degree curves. The highest L95 value of over 57.2" is seen on 0-2 degree curves in Class 3 track, as well as on 6-10 degree curves in Class 4 track. Mean delta gage values in Exhibit 110 are below 0.62". While mean values indicate a good reserve of gage widening resistance in Test Section 3, it is seen from L95 values that 5% of the time the delta gage values exceed 1.0" on 4-6 degree curves in Class 4 track, and 0.94" on 2-4 degree curves in Class 3 track. This indicates that Test Section 3 has a number of localized weak tie/fastener conditions.

Test Section 4 consists of Class 4 and Class 5 cut spike track, having curvatures of up to 6 degrees. Most of the test mileage is on 0-2 degree curves in Class 5 track. The unloaded, loaded and delta gage, with respect to track type, are shown in Exhibits 111, 112 and 113, respectively. Good gage control is apparent in Exhibit 111 for both Class 4 and Class 5 track. The highest L95 unloaded gage value of 57.0" occurs on 0-2 degree curves in Class 5 track. Exhibit 112 gives an indication of a decrease in loaded gage with increase in curvature, and an increase in loaded gage with increase in track class. The highest L95 loaded gage value of 57.55" occurs also on 0-2 degree curves in Class 5 track.

Exhibit 113 indicates a decrease in delta gage with an increase in curvature in Class 5 track. Such a decrease is only mildly evident for Class 4 track with up to 4 degree curvature. Furthermore, a slight increases in delta gage and standard deviation values are seen to occur from Class 4 to Class 5 track. All delta gage values in Exhibit 113 are below 0.7", indicating a good reserve of gage widening resistance in Test Section 4. A maximum delta gage mean value of 0.45", resulting in a mean track compliance of 0.025"/kip, indicates good tie and rail restraint conditions in this test section.

6.6 <u>RAILROAD F</u>

The TLV gage widening tests on this railroad were conducted in September and October of 1991. A total of 250 miles of track in six test sections was tested on Railroad F. The test mileage consisted of 60 miles in Test Section 1, 20 miles in Test Section 2, 35 miles in Test Section 3, 80 miles in Test Section 4, 30 miles

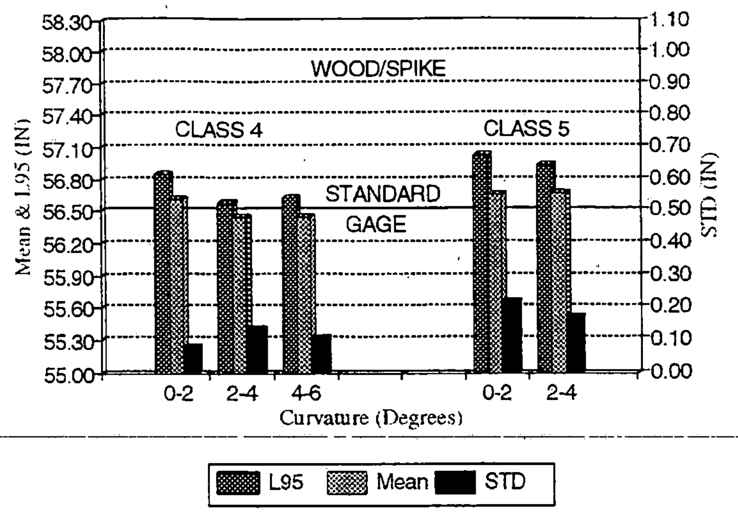

Exhibit 111. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 4 of Railroad E, Segmented by Class, Tie and Fastener Types.

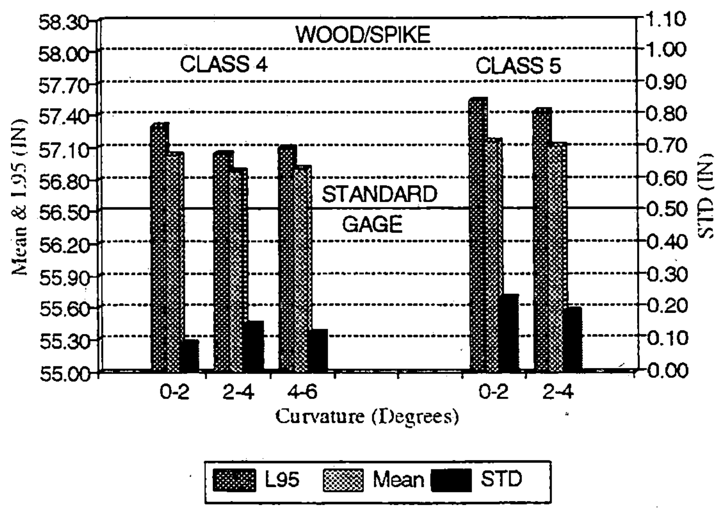

Exhibit 112. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 4 of Railroad E, Segmented by Class, Tie and Fastener Types.

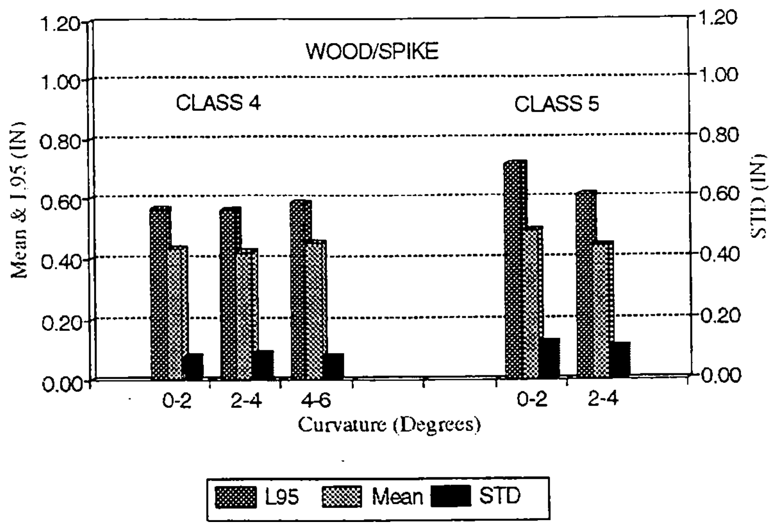

Exhibit 113. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 4 of Railroad E, Segmented by Class, Tie and Fastener Types.

in Test Section 5 and 25 miles in Test Section 6. About 3 miles of track in Test Section 4 had elastic fasteners on wood ties, and about 1.5 miles of track in Test Section 2 had concrete ties. All test sections are located in the northeast region. Continuously welded 130 and 132 lb rail is used. On curves, four spikes per tie plate are used, while three spikes per plate are used on tangent track. Each tie is anchored on curves, while every other tie is anchored on tangent track. Except Test Section 6, all the test sections have FRA class 3 and 4 track. Test Section 6 has FRA class 4 track. The freight tonnage is 8 MGT per year in Test Section 1, 23 MGT in Test Section 2, 18 MGT in Test Section 3, 34 MGT in Test Section 4, and 58 MGT each in Test Section 5 and 6.

6.6.1 Analysis Based on Mile Post

Exhibits 114, 115, 116 and 117 show the mean values of unloaded gage, loaded gage, delta gage and track compliance, respectively, in all test sections on a mile-by-mile basis. Similarly, Exhibits 118, 119, 120 and 121 show the respective 95th-percentile values for the test sections.

Wide gage is present in all test sections, as seen in Exhibit 114. It is apparent that the unloaded gage in Test Sections 3, 5 and 6 has a smaller overall deviation from standard gage than seen in the remaining test sections. A review of the test mileage shows that the elastic fastener section contributed less than 3.5% of the data in Test Section 4, and the concrete section contributed less than 9.3% of the data in Test Section 2. With the smaller sample sizes, no enhancement of gage control and lateral stiffness is seen through the use of elastic fasteners in Test Section 2 and 4 results. The mean unloaded gage varies from a low of 56.4" in Test Section 1 to a high of 57.0" in Test Section 4.

Exhibit 115 indicates that most of the mean loaded gage variation is between 56.9" and 57.3". Several miles in Test Sections 2, 4 and 6 have loaded gage mean values above 57.4". It appears that in all test sections the track has ample ability to hold gage. There is, however a concern indicated as to the extent and value of wide gage in the test sections. A strong tie/fastener condition has little value if excessively wide gage is present. A large loaded gage may not imply weak track if wide gage exists before the loading. A study of the exception reports shows that all of the exceptions in the six test sections on Railroad F are

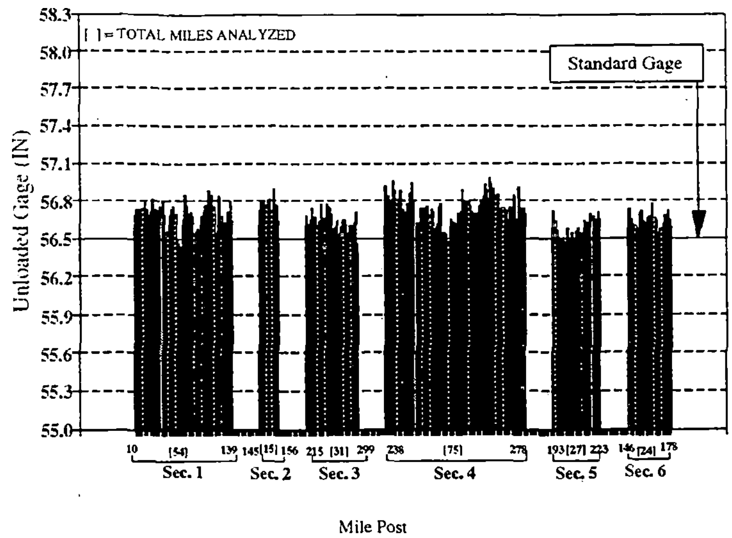

Exhibit 114. Unloaded Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 to 6 of Railroad F.

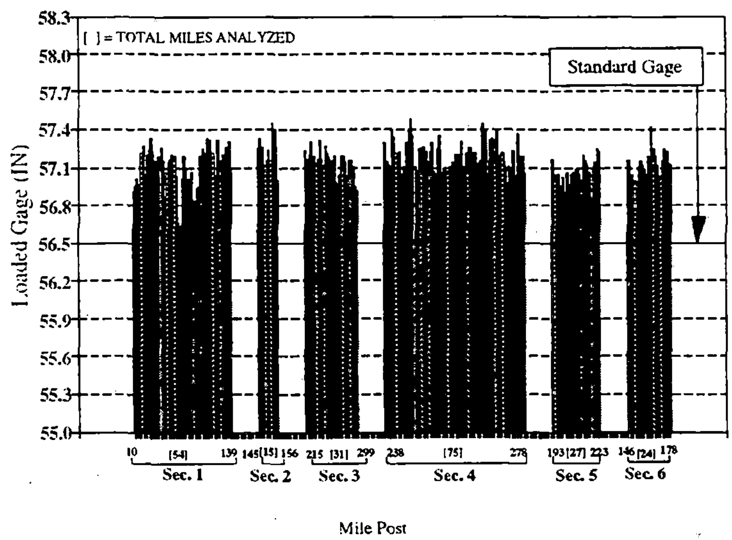

Exhibit 115. Loaded Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 to 6 of Railroad F.

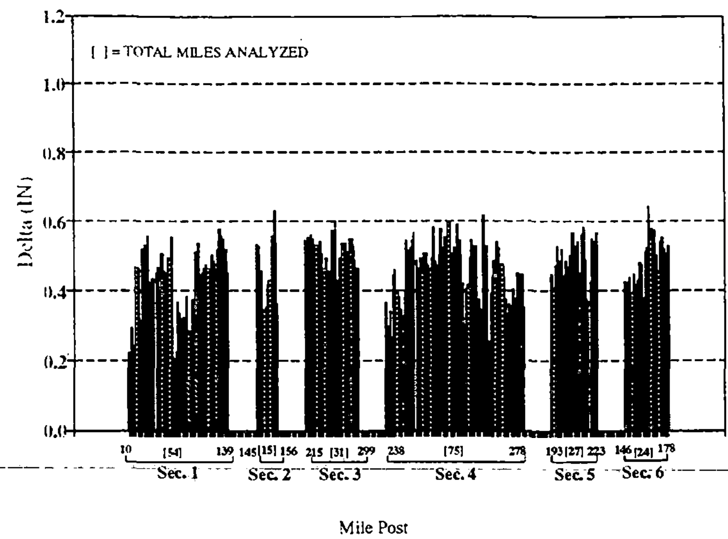

Exhibit 116. Delta Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 to 6 of Railroad F.

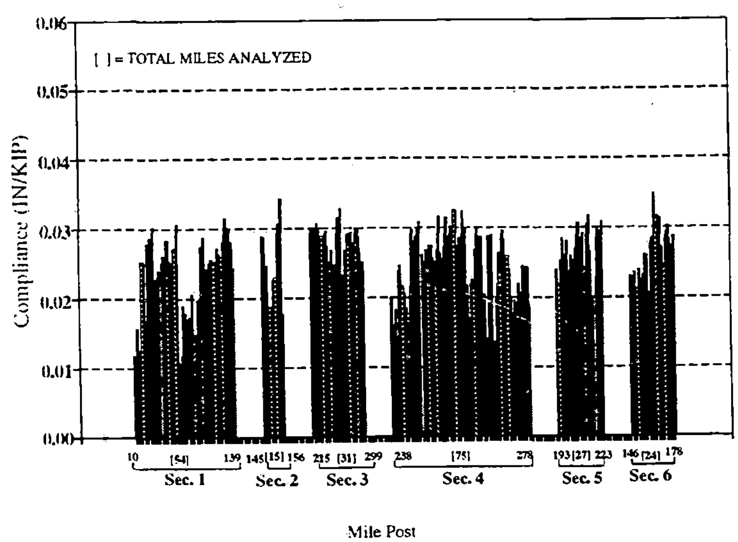

Exhibit 117. Track Compliance Mean Value for Each Statistical Mile Sample in Test Sections 1 to 6 of Railroad F.

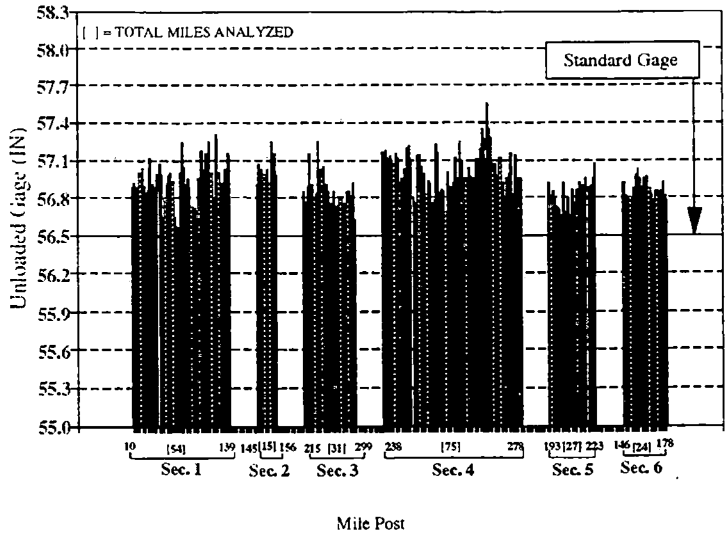

Exhibit 118. Ninety Fifth-percentile (L95) Value of Unloaded Gage for Each Statistical Mile Sample in Test Sections 1 to 6 of Railroad F.

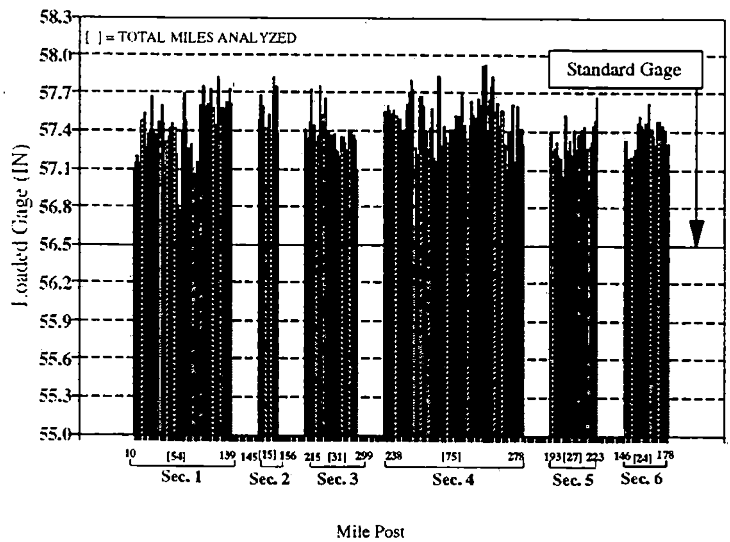

Exhibit 119. Ninety Fifth-percentile (L95) Value of Loaded Gage for Each Statistical Mile Sample in Test Sections 1 to 6 of Railroad F.

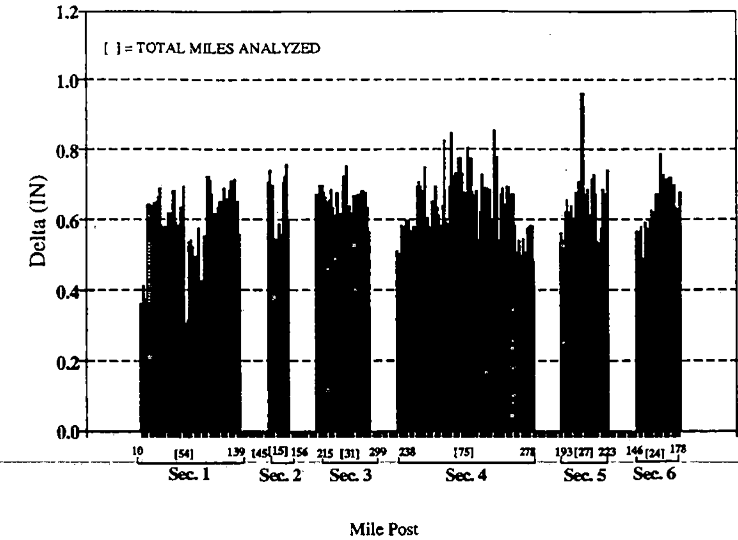

Exhibit 120. Ninety Fifth-percentile (L95) Value of Delta Gage for Each Statistical Mile Sample in Test Sections 1 to 6 of Railroad F.

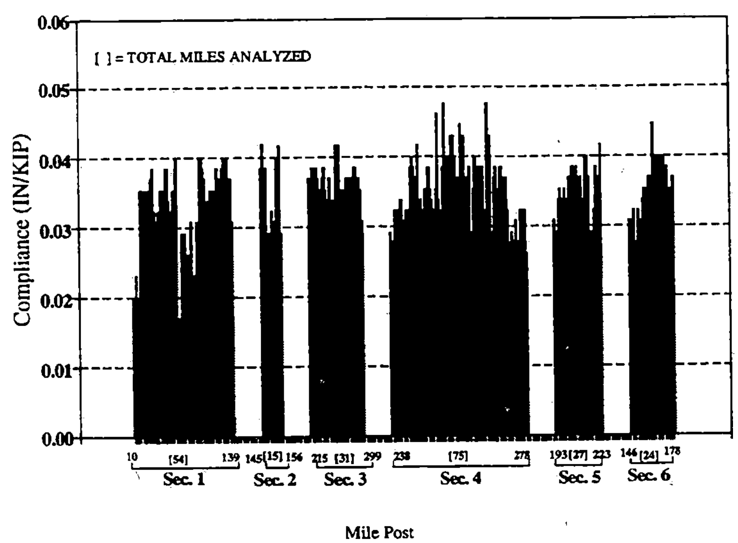

Exhibit 121. Ninety Fifth-percentile (L95) Value of Track Compliance for Each Statistical Mile Sample in Test Sections 1 to 6 of Railroad F.

due to the exceedence of the loaded gage paint limit of 57.75".

Exhibit 116 gives an indication of those miles of the track which are relatively strong and those which are weak. The mean delta gage is to over 0.6" in Test Sections 2, 4 and 6 and as low as 0.2", in Test Section 1. Most of the variation is, however, between 0.4" and 0.6". The overall lower mean delta gage values, combined with exceedences of the loaded gage paint limit, clearly indicate a need for gage control maintenance on Railroad F.

Exhibit 117 gives a quantitative value of the tie and rail restraint provided by the track in all sections of Railroad F. The higher the compliance value, the weaker is the gage widening resistance. Good to strong rail lateral restraint conditions in Railroad F's test sections are indicated by the less than 0.035"/kip compliance mean values seen in this exhibit.

The 95th-percentile values of unloaded gage, loaded gage, and delta gage and track compliance for each track mile analyzed on Railroad F, are discussed in the following to demonstrate dispersal in data and to differentiate between weak and strong tie/fastener conditions.

Exhibit 118 shows the L95 values of unloaded gage for the six test sections. Wide gage is seen in all test sections. For more than 5% of the time, unloaded gage is above 56.6" in Test Section 1, 56.9" in Test Section 2 and 56.65" in Test Section 3 to 6. The highest L95 value for unloaded gage is 57.3" in Test Section 1, 57.25" in Test Section 2 and 3, 57.55" in Test Section 4, 57.08" in Test Section 5 and 57.0" in Test Section 6. The corresponding L95 values of loaded gage are seen in Exhibit 119. Many of the L95 loaded gage values are between 57.4" and 57.7". A L95 value closer to 57.7" is an indication of the onset of the loaded gage paint limit exception. There are a number of miles in Test Sections 1 to 4 where L95 loaded gage is actually above the loaded gage paint limit of 57.75".

The extent of gage widening resistance provided by tie and rail restraint for each mile are seen in Exhibits 120 and 121. A check of L95 delta gage values corresponding to those miles of track where L95 loaded gage exceeded 57.75" shows that these values may not necessarily be the higher delta gage values. It is not always the deficiency in gage widening resistance, but rather the initial presence of substantial wide gage which leads to the loaded gage paint limit exceedences. For example, the highest L95 loaded gage of 57.85" in Test Section 1 has a corresponding L95 delta gage of only 0.65". L95 delta gage of 0.65" does not indicate a weak tie and fastener condition. A study of the corresponding L95 unloaded gage reveals a value of 57.3". It is seen in these exhibits that a wide gage does lead to the loaded gage paint limit exception.

The L95 delta gage values are below 0.8", except for a few miles in Test Sections 4 and 5. The corresponding L95 compliance values are generally below 0.04"/kip. Since 95% of the data are below these values, good gage widening resistance is indicated for the test sections on Railroad F. Delta gage values which are above 0.8" only indicate a localized weak tie/fastener condition in the corresponding track mile. Such a weak tie/fastener condition may not always lead to a loaded gage paint exceedence, however, field examination is indicated to determine any maintenance requirement.

6.6.2 Analysis Based on Track Type

Exhibit 122 shows, in column 1, the FRA track classes analyzed in Test Sections 1 to 6 of Railroad F. The majority of tests were on cut spike track with curvatures of up to 2 degrees. Test Sections 1 to 5 have both Class 3 and Class 4 track, while Test Section 6 has Class 4 track. There are elastic fasteners on wood ties in a portion of Test Section 4, and concrete ties in a portion of Test Section 2. Of 226 analyzed miles, there are 45 miles of Class 3 track and 99 miles of Class 4 track with cut spikes and curvatures of up to 2 degrees.

Exhibit 123 shows the mean, standard deviation and L95 of unloaded gage in Test Section 1, as a function of track curvature, class and tie/fastener type. It is seen that as the degree of curvature increases, the mean, L95, and standard deviation increase. However, the mean and L95 values on 6-10 degree curves do not follow this trend. The lower unloaded gage values seen on 6-10 degree curves indicate better gage control due to maintenance performed in reaction to high lateral forces on high curvature track. The higher standard deviation seen indicates that as the degree of track curvature increases, the variability in unloaded gage also increases. An increase in unloaded gage is seen with the increase in track class. The higher gage widening loads experienced are responsible for the wider unloaded gage seen on higher degree of curvature or higher class track. L95 unloaded gage as large as 57.25" is seen on 4-6 degree Class 3 track. These

Class	Geometry (Degrees)	Tie/Fastener	Track Analyzed (Miles)						
			Test Section						Total
			1	2	3	4	5	6	
3	0-2	Wood/Spike	15.72	1.45	7.27	16.04	4.53	0.00	45.01
3	2-4	Wood/Spike	5.89	1.02	1.34	9.27	1.94	0.00	19.46
3	4-6	Wood/Spike	7.61	0.71	1.69	8.24	2.42	0.00	20.67
3	6-10	Wood/Spike	0.85	1.33	0.00	8.71	0.30	0.00	11.19
3	2-4	Wood/Pandrol	0.00	0.00	0.00	0.14	0.00	0.00	0.14
3	4-6	Wood/Pandrol	0.00	0.00	0.00	1.19	0.00	0.00	1.49
3	6-10	Wood/Pandrol	0.00	0.00	0.00	1.24	0.00	0.00	1.24
3	0-2	Concrete	0.00	0.84	0.00	0.00	0.00	0.00	0.84
3	2-4	Concrete	0.00	0.20	0.00	0.00	0.00	0.00	0.20
3	4-6	Concrete	0.00	0.33	0.00	0.00	0.00	0.00	0.33
4	0-2	Wood/Spike	21.57	5.67	16.04	25.94	11.82	17.59	98.63
4	2-4	Wood/Spike	2.37	3.27	4.67	3.78	6.06	5.51	25.66
4	4-6	Wood/Spike	0.00	0.00	0.00	0.61	0.20	0.63	1.44
4	6-10	Wood/Spike	0.00	0.00	0.25	0.00	0.00	0.24	0.49
Total Miles			54.01	14.82	31.26	75.16	26.97	23.97	226.19

Exhibit 122. Total Miles Analyzed in Test Sections 1 to 6 of Railroad F for Wide Gage and Gage Resistance with respect to Track Class, its Geometry and Tie and Fastener Types.

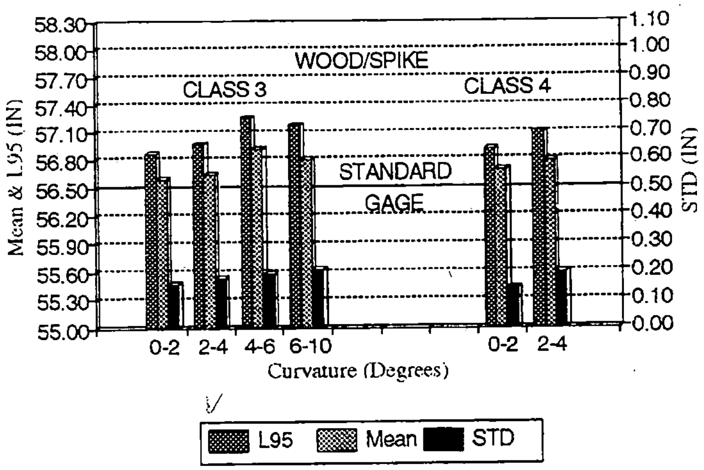

Exhibit 123. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad F, Segmented by Class, Tie and Fastener Types.

results, indicate a need to control gage in this test section.

Exhibit 124 shows the mean, standard deviation and L95 of loaded gage in Test Section 1. Trends similar to those seen with unloaded gage in Exhibit 123 are present in this exhibit. Greater loaded gage at higher curvature or higher track class is seen in this exhibit. The highest L95 value of 57.70" occurs on the 4-6 degree and the 6-10 degree curves in Class 3 track. Since 5% of loaded gage is above 57.70", exceedences of the loaded gage paint limit of 57.75" are seen in these curves. The wide gage in the previous exhibit indicates a need to control gage, while the loaded gage values require an immediate improvement. No trend to variability in loaded gage with respect to curvature is seen in Class 3 track. This is indicated by the random standard deviation

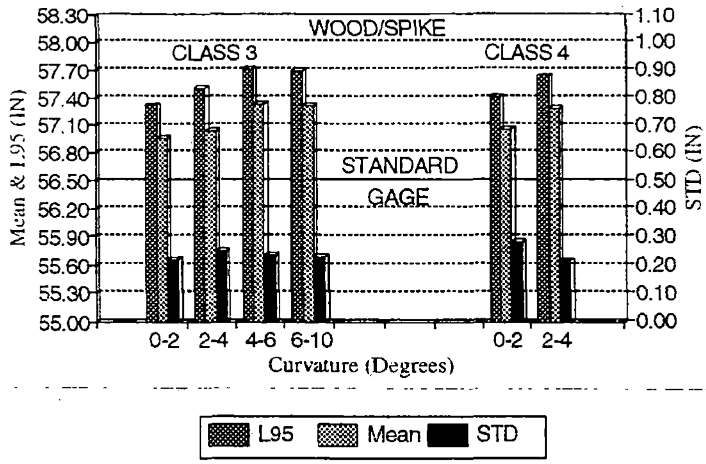

Exhibit 124. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad F, Segmented by Class, Tie and Fastener Types.

values. On the other hand, it appears that better maintenance in 2-4 degree Class 4 curves resulted in a lower standard deviation values.

The mean, standard deviation and L95 of delta gage in Test Section 1 are seen in Exhibit 125. Higher delta gage with respect to curvature is seen for both Class 3 and Class 4 track. Also, there is an increase in delta gage in the higher class track. The variability in delta gage is seen to decrease with an increase in curvature of the track. This variability is most on 0-2 degree curves and least on 2-4 degree curves in Class 4 track. The highest L95 value of delta gage is 0.68", and is seen on 6-10 degree curves in Class 3 track. The corresponding L95 value of track compliance, for a gage widening load of 18 kips, is

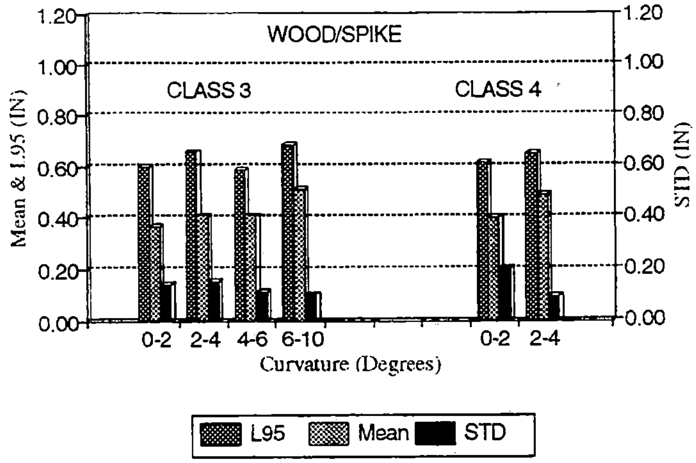

Exhibit 125. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad F, Segmented by Class, Tie and Fastener Types.

0.038"/kip. This indicates good tie and rail restraint conditions in Test Section 1.

The unloaded, loaded and delta gage with respect to track type, in Test Section 2, are shown in Exhibits 126, 127 and 128, respectively. No trend in the unloaded gage mean values with respect to curvature, is seen for the Class 3 concrete tie and wood tie track. Slight increases in both the mean and L95 value with respect to curvature are, however, seen for Class 4 track. Overall, lower values of unloaded gage are seen for concrete tie track of up to 4 degree curves. The maximum L95 unloaded gage value of over 57.2" is seen on 6-10 degree Class 3 cut spike track. No trend in unloaded gage variability is seen on Class 3 cut spike track due to the random changes in standard deviation with respect

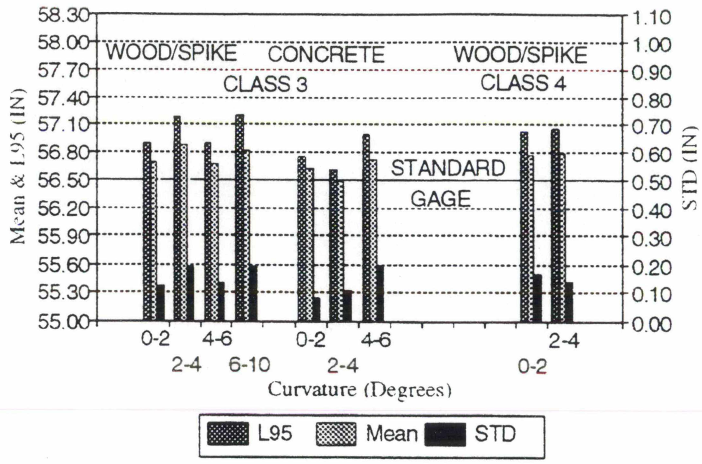

Exhibit 126. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad F, Segmented by Class, Tie and Fastener Types.

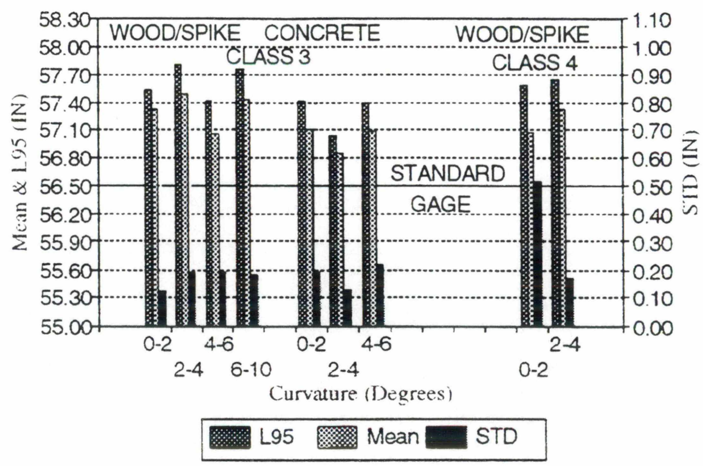

Exhibit 127. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad F, Segmented by Class, Tie and Fastener Types.

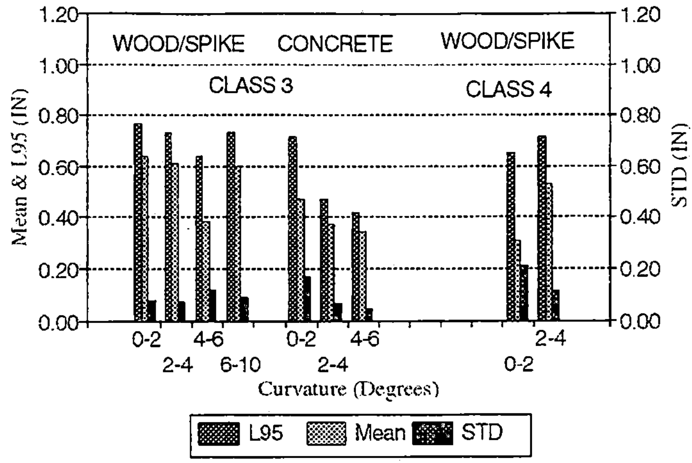

Exhibit 128. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad F, Segmented by Class, Tie and Fastener Types.

to curvature. On the other hand, variability in unloaded gage increases on concrete tie track and decreases on Class 4 cut spike track.

Variations similar to that of the unloaded gage seen in the previous exhibit, are also seen in the loaded gage values in Exhibit 127. The highest L95 loaded gage value of 57.8" is seen on 2-4 degree Class 3 cut spike track. More than 5% of the loaded gage values on the 2-4 degree curves, exceed the loaded gage paint limit of 57.75". About 5% of loaded gage values on 6-10 degree Class 3 cut spike track are also found to exceed the loaded gage paint limit. In Exhibit 128, delta gage is seen to decrease with curvature of up to 6 degree curves. Lower delta gage values and greater gage widening resistance is seen on concrete tie track as compared to cut spike track in this exhibit. A maximum delta gage mean value of 0.62", giving a mean track compliance of 0.034"/kip, indicates good tie and rail restraint conditions in Test Section 2.

Test Section 3 has Class 3 and Class 4 cut spike track. The unloaded, loaded and delta gage with respect to track type are shown in Exhibits 129, 130 and 131, respectively. A characteristic increase in mean, L95 value and standard deviation of unloaded and loaded gage, with respect to curvature, is evident in this test section, except for the loaded gage on 2-4 degree Class 4 track. Unloaded and loaded gage dependence on track class, however, is not seen. The L95 values of loaded gage on 4-6 degree Class 3 track and on 6-10 degree Class 4 track exceed the loaded gage paint limit of 57.75". The corresponding L95 unloaded gage mean values are above 57.2". Since all L95 delta gage mean values in Exhibit 131 are below 0.7", presence of wide gage, is the reason for the loaded gage paint limit exceedences. A maximum delta gage mean value of 0.54", resulting in a mean track compliance of 0.03"/kip, indicates an ample reserve of gage widening resistance on this test section.

Test Section 4 has Class 3 and Class 4 track. This test section consisted of cut spike track except for a total of 2.59 miles of 2-10 degree curved track small segments having wood ties and elastic fasteners. The corresponding unloaded, loaded and delta gage with respect to track type are shown in Exhibits 132, 133 and 134, respectively. In exhibits 132 and 133 it is seen that as the degree of track curvature increases, the mean and L95 increase with the standard deviation. The unloaded and loaded gage is similar in the cut spike and the elastic fastener track and no

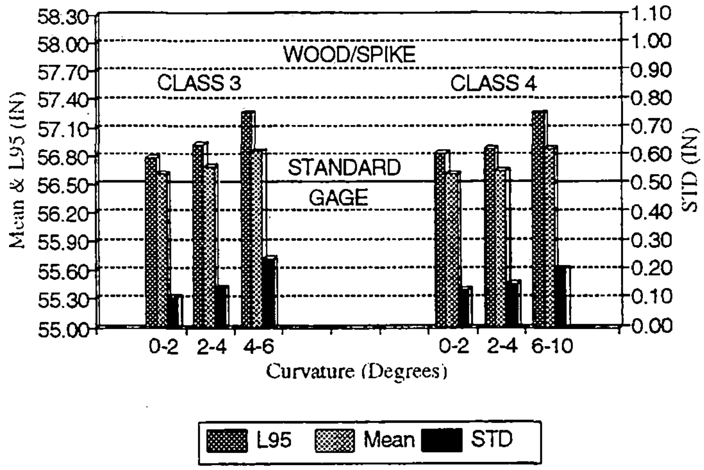

Exhibit 129. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad F, Segmented by Class, Tie and Fastener Types.

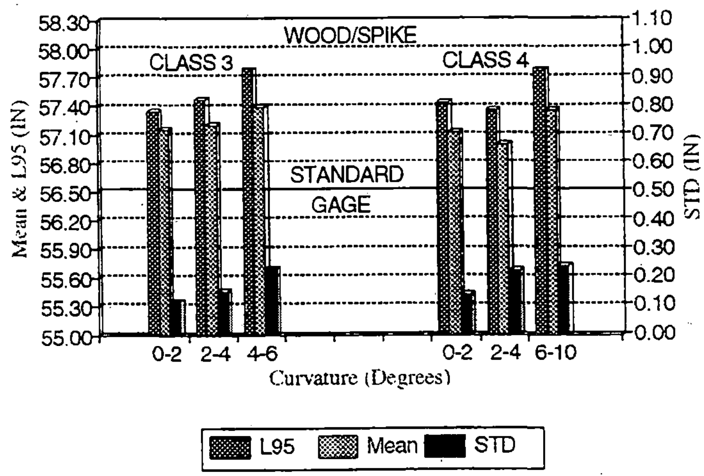

Exhibit 130. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad F, Segmented by Class, Tie and Fastener Types.

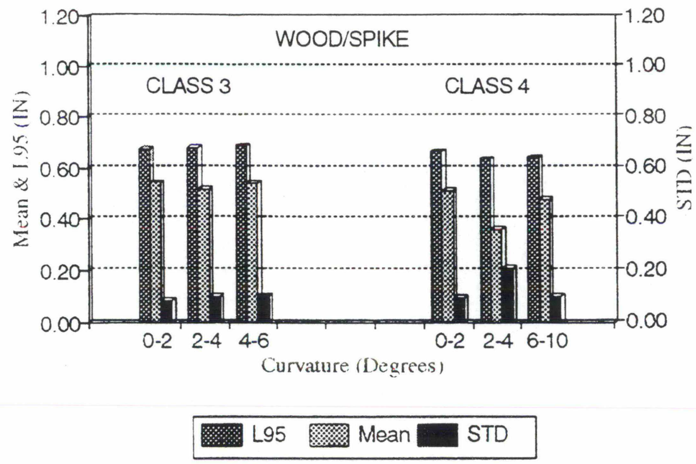

Exhibit 131. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad F, Segmented by Class, Tie and Fastener Types.

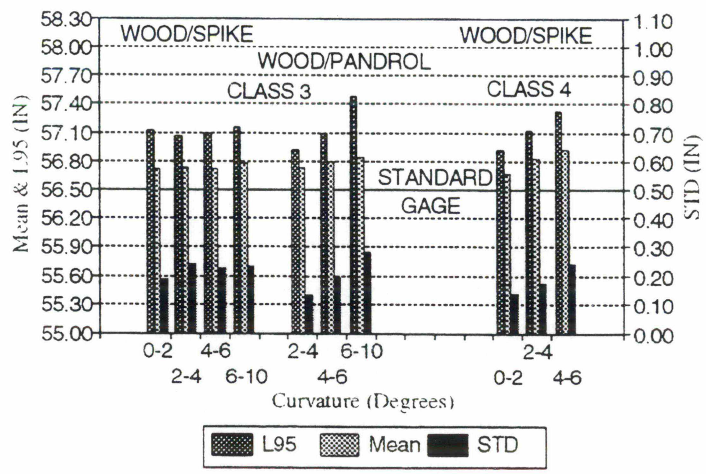

Exhibit 132. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 4 of Railroad F, Segmented by Class, Tie and Fastener Types.

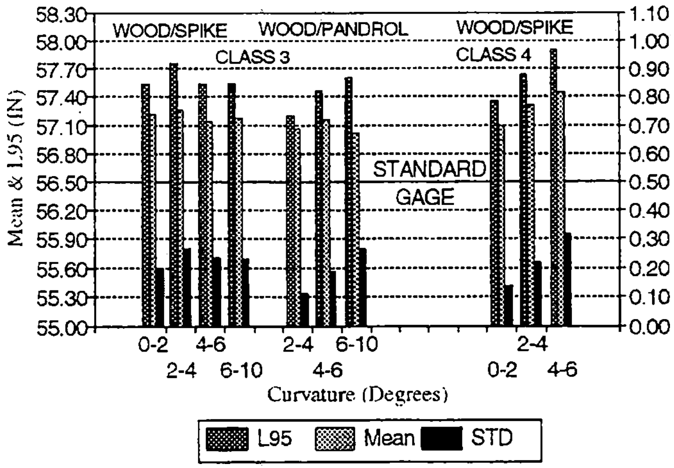

Exhibit 133. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 4 of Railroad F, Segmented by Class, Tie and Fastener Types.

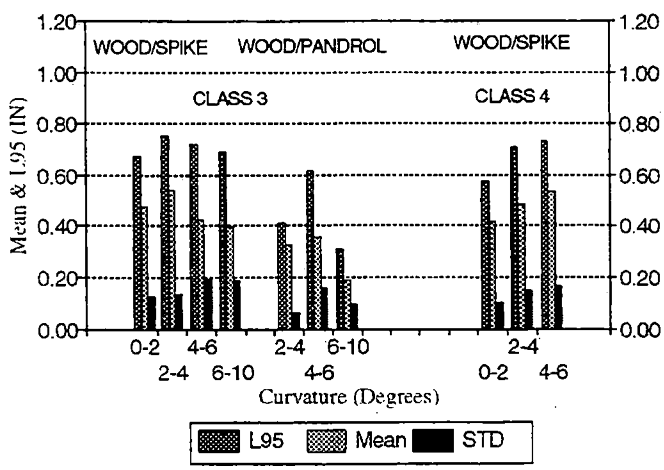

Exhibit 134. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 4 of Railroad F, Segmented by Class, Tie and Fastener Types.

clear class dependence is seen. The higher gage widening loads required for steering with increased curvature is the cause of wider unloaded gage seen on high curvature track.

The greater variance seen in these exhibits in the L95 and the mean values for 6-10 degree elastic fastener track indicates a wide scatter of data. This is also seen by a high value for the standard deviation. While the highest L95 unloaded gage value of 57.5" occurs on 6-10 degree elastic fastener track, the corresponding L95 loaded gage is only 57.6" as seen in Exhibit 133. The L95 loaded gage values exceeding the loaded gage paint limit of 57.75" are seen on 2-4 degree Class 3 track, and 4-6 degree Class 4 cut spike track. Since most of the exceptions in this test section are due to wide gage, a need exists to control gage. Results seen in Exhibits 132 and 133 demonstrate that elastic fasteners provide superior gage restraint.

Delta gage values in Exhibit 134 also demonstrate that elastic fasteners provide distinctly better gage widening resistance. Results in this test section indicate that delta gage decreases as a function of curvature on Class 3 track, while on Class 4 track, delta gage increases with curvature. A slight increase in standard deviation with curvature is seen for both Class 3 and Class 4 track. Delta gage values in Exhibit 134 are below 0.75", indicating a good reserve of gage widening resistance in Test Section 4. A maximum delta gage mean value of 0.55", resulting in a mean track compliance of 0.03"/kip, indicates good tie and rail restraint conditions on this test section.

Test Section 5, has cut spike Class 3 and 4 track. The unloaded, loaded and delta gage, with respect to track type, are shown in Exhibits 135, 136 and 137, respectively. Increases in mean, L95 value and standard deviation of unloaded gage, with respect to curvature, are seen in this test section. In Exhibit 136 a decrease is seen in loaded gage on curved Class 3 track, while an increase in loaded gage is seen on curved Class 4 track. Unloaded and loaded gage is not dependent on track class. The L95 value of loaded gage on 4-6 degree Class 4 track, exceeds the loaded gage paint limit of 57.75". The corresponding L95 unloaded gage value is 57.25". Since all L95 delta gage values in Exhibit 137 are below 0.7", presence of wide gage is the cause for loaded gage paint limit exceedences. A maximum delta gage mean value of 0.54", resulting in a mean track compliance of 0.03"/kip, indicates an ample reserve of gage widening resistance in this test section.

Test Section 6 has cut spike Class 4 track. The unloaded, loaded and delta gage, with respect to track type are shown in Exhibits 138, 139 and 140, respectively. Increases in mean and L95 values of unloaded, loaded and delta gage are seen in curves of up to 6 degrees. The good track maintenance on 6-10 degrees curves is evidently the reason for lower values of unloaded, loaded and delta gage in these curves. The highest L95 value of 57.6" occurs on 4-6 degree curves, and is below the loaded gage paint limit of 57.75". Delta gage values in Exhibit 140 are below 0.7". A maximum delta gage mean value of 0.52", resulting in a mean track compliance of under 0.03"/kip, indicates an ample reserve of gage widening resistance on this test section.

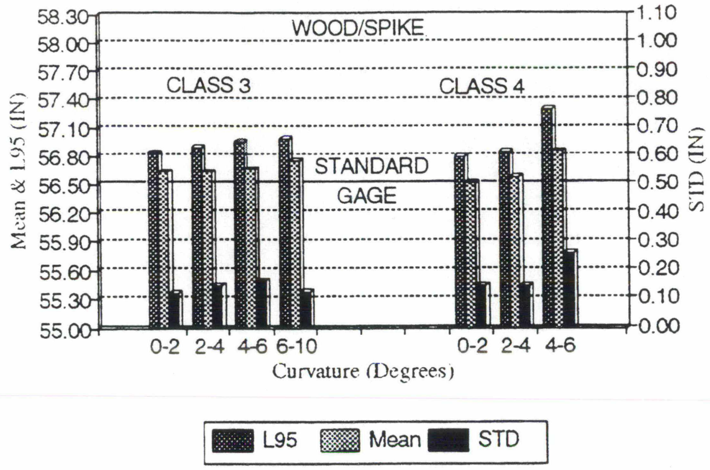

Exhibit 135. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 5 of Railroad F, Segmented by Class, Tie and Fastener Types.

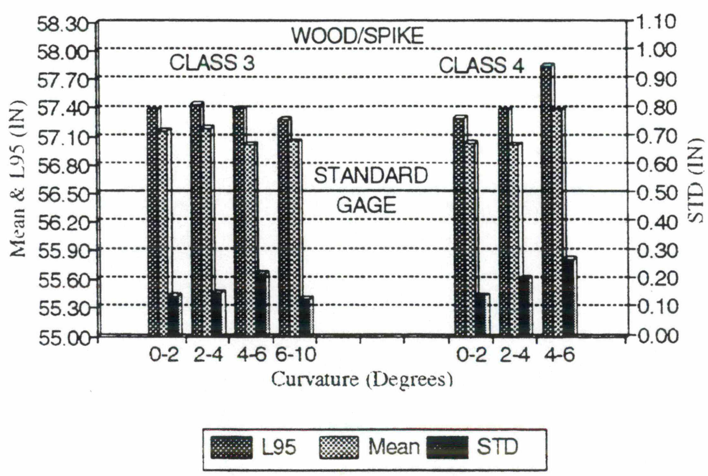

Exhibit 136. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 5 of Railroad F, Segmented by Class, Tie and Fastener Types.

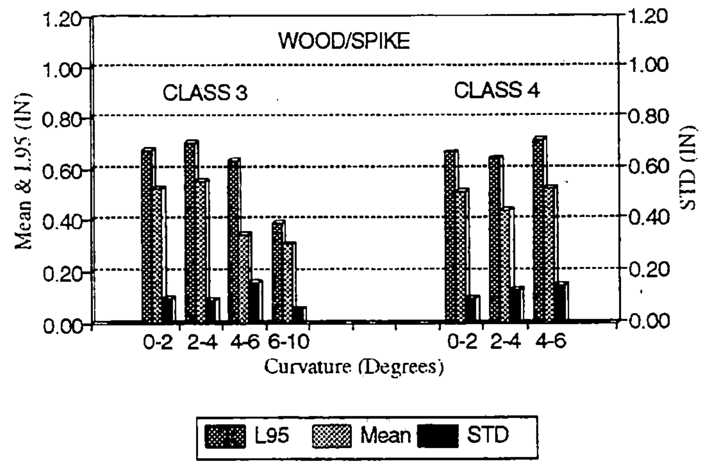

Exhibit 137. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 5 of Railroad F, Segmented by Class, Tie and Fastener Types.

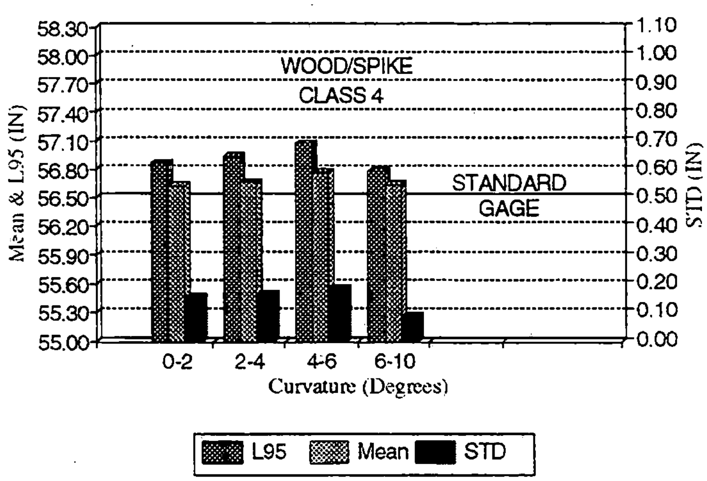

Exhibit 138. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 6 of Railroad F, Segmented by Class, Tie and Fastener Types.

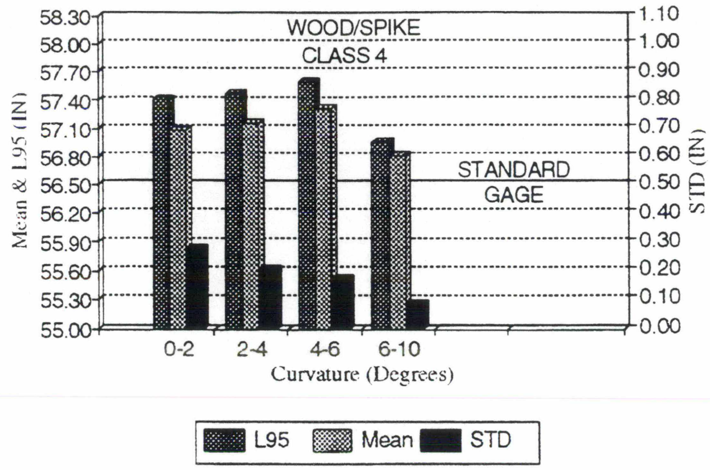

Exhibit 139. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 6 of Railroad F, Segmented by Class, Tie and Fastener Types.

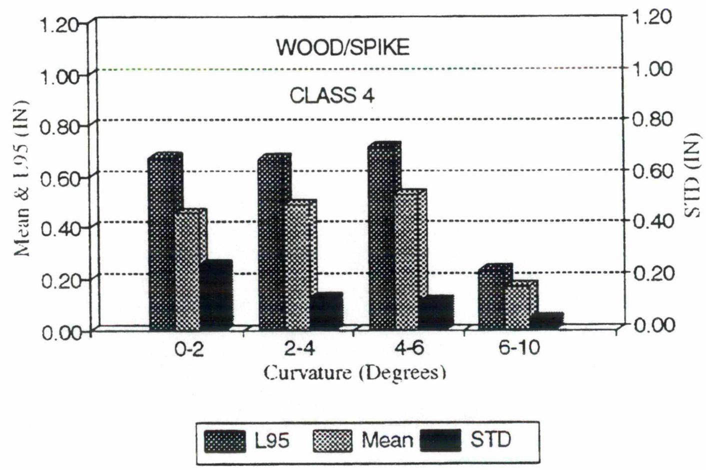

Exhibit 140. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 6 of Railroad F, Segmented by Class, Tie and Fastener Types.

6.7 RAILROAD G

The TLV gage widening tests on Railroad G were conducted in October 1991. A total of 370 miles of track in five test sections was tested on this railroad. The test mileage consisted of 50 miles in Test Section 1, 50 miles in Test Section 2, 35 miles in Test Section 3, 70 miles in Test Section 4, and 165 miles in Test Section 5. About 1.5 miles of track in Test Section 3 has elastic fasteners on wood ties. The test sections are located in the northeast region. Continuously welded 132 lb rail is used. Four spikes per tie are used on tangent track. On curves of greater than 2 degree of curvature but less than 6 degrees, 6 spikes per tie, and for 6 degree curves or greater 10 spikes are used. Hairpins are used only intermittently. Every other tie is anchored. Test Sections 1 and 2 carry 41 MGT traffic per year on FRA class 3 and 4 track. Test Section 3 carries 24 MGT traffic per year on FRA class 2 and 3 track. Test Section 4 carries 11 MGT traffic per year on FRA class 2, 3 and 4 track. Test Section 5 carries 28 MGT traffic per year on FRA class 3 and 4 track.

6.7.1 Analysis Based on Mile Post

Exhibits 141, 142, 143 and 144 show the mean values of unloaded gage, loaded gage, delta gage and track compliance, respectively, on all test sections on a mile-by-mile basis. Similarly, Exhibits 145, 146, 147 and 148 show the respective 95th-percentile values for the test sections.

Wide gage is present in all test sections as seen in Exhibit 141. A check of test mileage indicates that elastic fastener

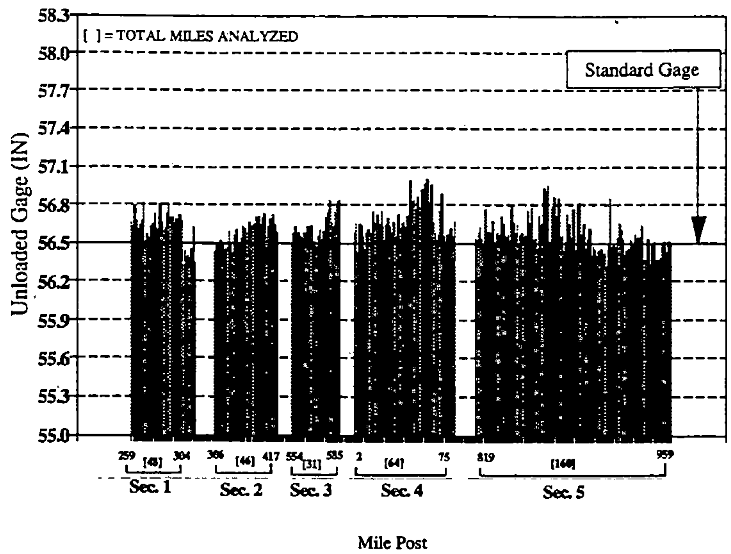

Exhibit 141. Unloaded Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad G.

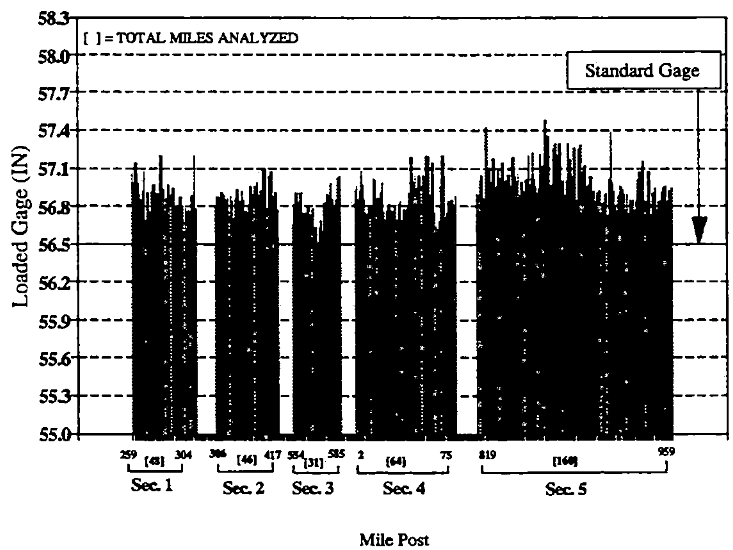

Exhibit 142. Loaded Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad G.

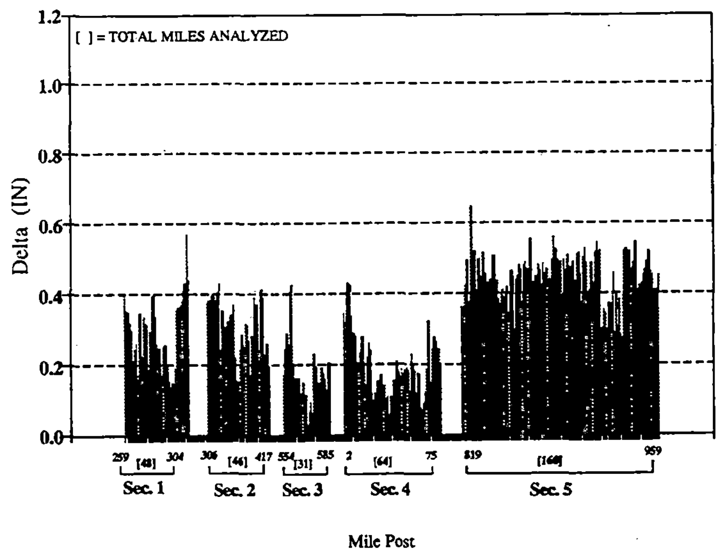

Exhibit 143. Delta Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad G.

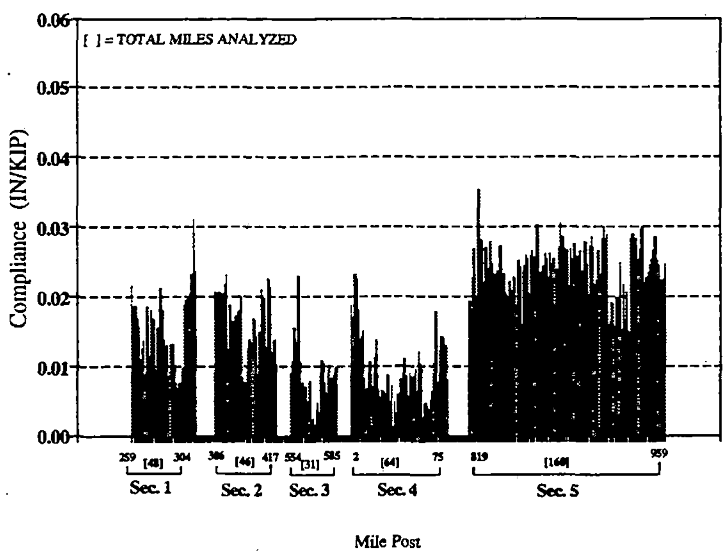

Exhibit 144. Track Compliance Mean Value for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad G.

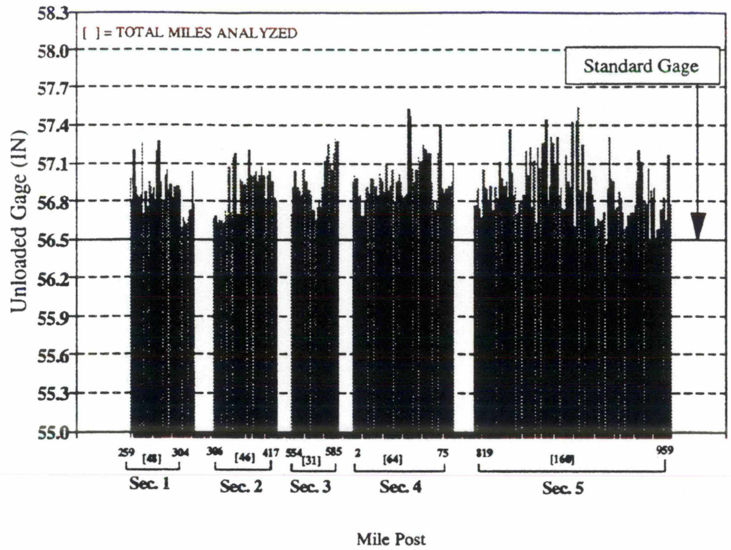

Exhibit 145. Ninety Fifth-percentile (L95) Value of Unloaded Gage for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad G.

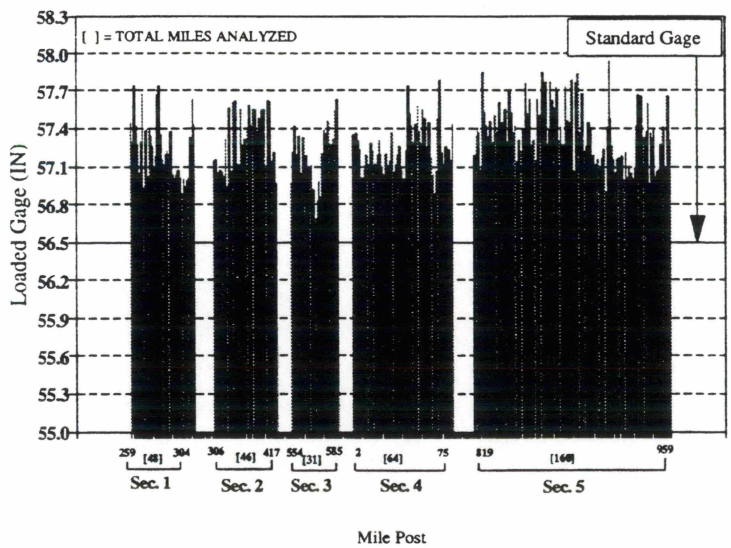

Exhibit 146. Ninety Fifth-percentile (L95) Value of Loaded Gage for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad G.

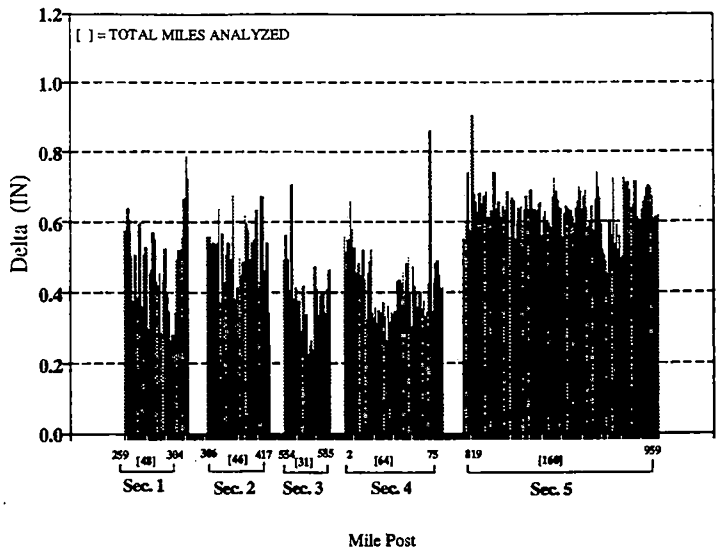

Exhibit 147. Ninety Fifth-percentile (L95) Value of Delta Gage for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad G.

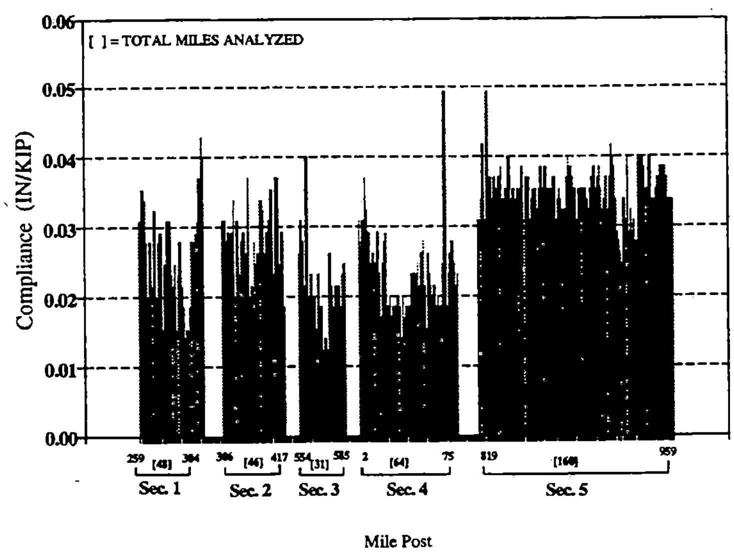

Exhibit 148. Ninety Fifth-percentile (L95) Value of Track Compliance for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad G.

section contributed less than 4.5% of the data analyzed in Test Section 3. With the small sample size, no enhancement of gage control and its lateral stiffness through the use of elastic fasteners is seen in the Test Section 3 results. The mean unloaded gage varies from a low of 56.3" in Test Section 5, to a high of 57.0" in Test Section 4.

Exhibit 142 indicates that most of the mean loaded gage variation is between 56.7" and 57.0" in Test Sections 1, 2 and 4. In Test Section 3, it is between 56.5" and 56.8", while in Test Section 5, it is between 56.8" and 57.2". Several miles in Test Section 5 have loaded gage mean values above 57.4". It appears that in all test sections the track has ample ability to hold gage. There is, however, general concern indicated as to the extent and value of wide gage in the test sections. A strong tie/fastener condition has little value if excessively wide gage is present. A large loaded gage may not imply weak track if wide gage exists before loading. A study of the exception reports shows that all of the exceptions in the five test sections on Railroad G are due to the exceedence of the loaded gage paint limit of 57.75".

Exhibit 143 gives an indication of those miles of track which are relatively strong and those which are weak. The mean delta gage rises over 0.6" in Test Section 5. Lower than 0.1" values of mean delta gage are present in Test Sections 3 and 4. Most of the variation seen is between 0.1" and 0.4" in Test Sections 1 to 4, while in Test Section 5, it is between 0.4" and 0.5". The lower mean delta gage values, combined with exceedences of the loaded gage paint limit, clearly indicate a need for gage control maintenance on Railroad G.

Exhibit 144 depicts a quantitative value of the tie and rail restraint provided by track in all sections of Railroad F. The higher the compliance value, the weaker is the gage widening resistance. Good to strong rail lateral restraint conditions on Railroad G's test sections are indicated by the less than 0.03"/kip compliance mean values seen in this exhibit.

The 95th-percentile values of unloaded gage, loaded gage, delta gage and track compliance, for each track mile analyzed on Railroad G, are discussed in the following to demonstrate dispersal in data and to differentiate between weak and strong tie/fastener conditions.

Exhibit 145 shows the L95 values of unloaded gage for the five test sections. Wide gage is seen in all test sections. Most of the L95 unloaded gage values are above 56.8". The highest L95 value of unloaded gage is 57.3" in Test Section 1 and 3, 57.2" in Test Section 2, 57.55" in Test Section 4 and 5. The corresponding L95 values of loaded gage are seen in Exhibit 146. Many L95 loaded gage values are between 57.4" and 57.7". A L95 value closer to 57.7" is an indication of the onset of the loaded gage paint limit exception. There are a number of miles in Test Sections 1, 4 and 5 where L95 loaded gage is actually above the loaded gage paint limit of 57.75".

The extent of gage widening resistance provided by tie and rail restraint in each mile are seen in Exhibits 147 and 148. A check of L95 delta gage values for those miles of track where L95 loaded gage exceeded 57.75" indicates that these values may not necessarily be the higher values. It is not always the deficiency in gage widening resistance but rather the initial presence of substantial wide gage, which leads to the loaded gage paint limit exceedences. For example, the highest L95 loaded gage of 57.75" in Test Section 1 has a corresponding L95 delta gage of only 0.64". The L95 delta gage of 0.64" does not actually indicate a weak tie and fastener condition. A study of the corresponding L95 unloaded gage reveals a value of 57.2". It is seen in these exhibits that a wide gage does lead to the loaded gage paint limit exception. The L95 delta gage values are below 0.8" except for a few miles in Test Sections 4 and 5. The corresponding L95 compliance values are generally below 0.04"/kip. Since 95% of the data are below these values, good gage widening resistance is indicated for the test sections on Railroad G. The delta gage values which are above 0.8" only indicate a localized weak tie/fastener conditions in the corresponding track miles. Such weak tie/fastener conditions may not always lead to a loaded gage paint limit exceedences, however, it appears that this is not the case here. In both instances where delta gage is above 0.8", the loaded gage paint limit is exceeded. The corresponding unloaded gage is 57.4" in Test Section 4 and 57.05" in Test Section 5. Both the wide gage and the weak tie/fastener condition lead to the exceedences seen in Test Section 4 and 5.

6.7.2 Analysis Based on Track Type

Exhibit 149 shows in Column 1 the FRA track classes analyzed in Test Sections 1 to 5 of Railroad G. The majority of the tests

Class	Geometry (Degrees)	Tie/Fastener	Track Analyzed (Miles)					
			Test Section					Total
			1	2	3	4	5	
2	0-2	Wood/Spike	0.00	1.70	0.87	1.52	0.00	4.09
2	2-4	Wood/Spike	0.00	0.89	0.17	0.28	0.00	1.34
2	4-6	Wood/Spike	0.00	0.00	0.21	0.76	0.00	0.97
3	0-2	Wood/Spike	5.67	1.66	14.90	1.53	9.16	32.92
3	2-4	Wood/Spike	3.19	0.15	7.13	1.33	5.69	17.49
3	4-6	Wood/Spike	0.76	0.46	3.78	0.00	5.45	10.45
3	6-10	Wood/Spike	0.00	0.00	2.84	0.00	10.29	13.13
3	6-10	Wood/Pandrol	0.00	0.00	1.36	0.00	0.00	1.36
4	0-2	Wood/Spike	33.48	31.24	0.00	44.54	72.15	181.41
4	2-4	Wood/Spike	3.82	6.33	0.00	14.53	48.18	72.86
4	4-6	Wood/Spike	0.69	3.60	0.00	0.30	6.60	11.19
4	6-10	Wood/Spike	0.00	0.00	0.00	0.00	2.54	2.54
Total Miles			47.61	46.03	31.26	64.49	160.06	349.45

Exhibit 149. Total Miles Analyzed in Test Sections 1 to 5 of Railroad G for Wide Gage and Gage Resistance with respect to Track Class, its Geometry and Tie and Fastener Types.

were on cut spike track with curvatures of up to 2 degrees. Test Sections 1 and 5 have Class 3 and 4 track, Test Section 3 has Class 2 and 3 track, and Test Section 2 and 4 have Class 2, 3 and 4 track. There are elastic fasteners in a small portion of Test Section 3. Of a total of about 349 analyzed miles, 4 miles of Class 2 track, 33 miles of Class 3 track and 181 miles of Class 4 track have cut spikes, and curvatures of up to 2 degrees.

Exhibit 150 shows the mean, standard deviation and L95 of unloaded gage in Test Section 1, as a function of track curvature, class and tie/fastener type. Increase in unloaded gage mean value with respect to curvature is seen, except on 2-4 degree Class 2 track. The greater differences between mean and L95 values and higher standard deviations on 2-4 degree curves, for both Class 2 and Class 3 track, indicate an increased variability of unloaded gage data for these curves. Whether or not the above conditions on 2-4 degree curves indicate a need for maintenance is dependent upon the railroad's maintenance policy for Class 3 track. Gage maintenance seen on Class 3 curves is better than that for Class 2 curves. In Class 2 curves, higher standard deviation indicates that as the degree of track curvature increases, the variability in unloaded gage also increases. It appears that higher gage widening loads seen on higher degree curves are the cause for wider unloaded gage on the higher degree of curvature track. L95 unloaded gage values of over 57.2" are seen on 2-4 degree curves for both Class 2 and Class 3 track. A concern to control gage exists for this test section.

Exhibit 151 shows the mean, standard deviation and L95 of

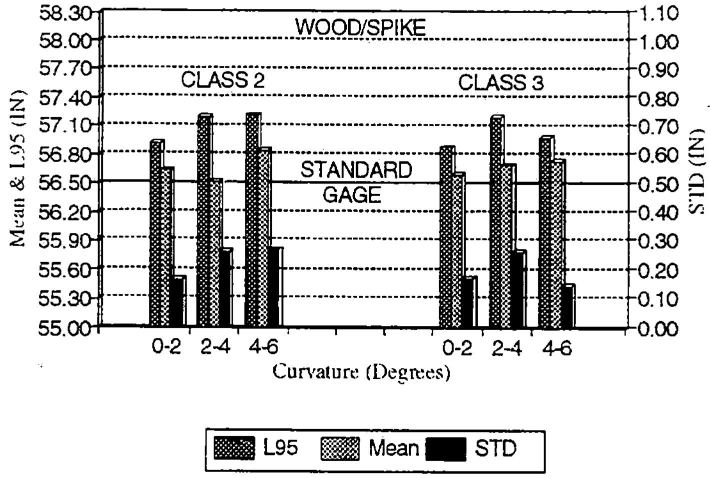

Exhibit 150. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad G, Segmented by Class, Tie and Fastener Types.

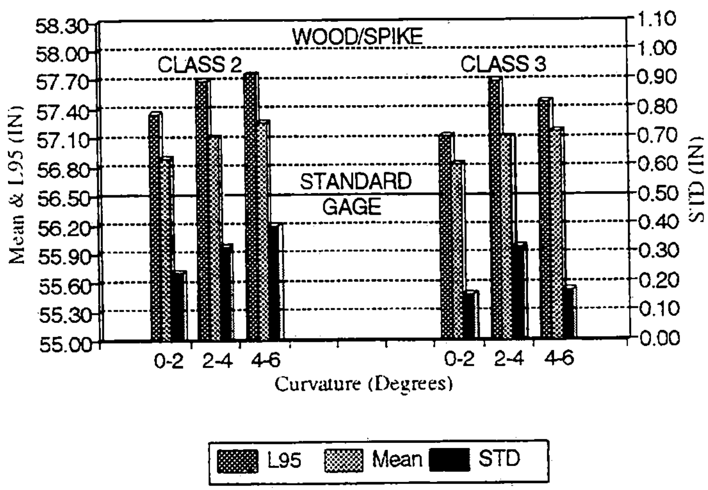

Exhibit 151. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad G, Segmented by Class, Tie and Fastener Types.

loaded gage in Test Section 1. This exhibit indicates that as the degree of curvature increases, the mean, L95, and the standard deviation increase in Class 2 track. In Class 3 track, only the mean value increases with the increase in curvature. There is a greater difference seen between mean and L95 values on 2-4 degree curves for Class 3 track. No trend toward variability in loaded gage with respect to curvature is seen in Class 3 track, as reflected by the random standard deviation values. It appears that improved maintenance on 0-2 and 4-6 degree curves of Class 3 track results in lower standard deviations. As apparent, L95 values near 57.70" are seen in 2-4 and 4-6 degree curves of Class 2 track and in 2-4 degree curves of Class 3 track. Since about 5% of loaded gage is above 57.70", exceedences of the loaded gage paint limit of 57.75" are to be expected in these curves. The wide gage seen in the previous exhibit indicates a need to control gage, while loaded gage values suggest immediate inspection and/or maintenance.

The mean, standard deviation and L95 of delta gage in Test Section 1 are seen in Exhibit 152. This exhibit indicates a satisfactory tie/fastener condition in this test section, however, a higher delta gage with respect to curvature is seen for both the Class 2 and Class 3 track. No delta gage dependence by track class is seen. The variability in delta gage does not follow a characteristic dependence on either the curvature or class of the track. The highest L95 value of delta gage is 0.7". The corresponding L95 value of track compliance, for a gage widening load of 18 kips, is 0.038"/kip, and indicates good tie and rail restraint conditions in Test Section 1.

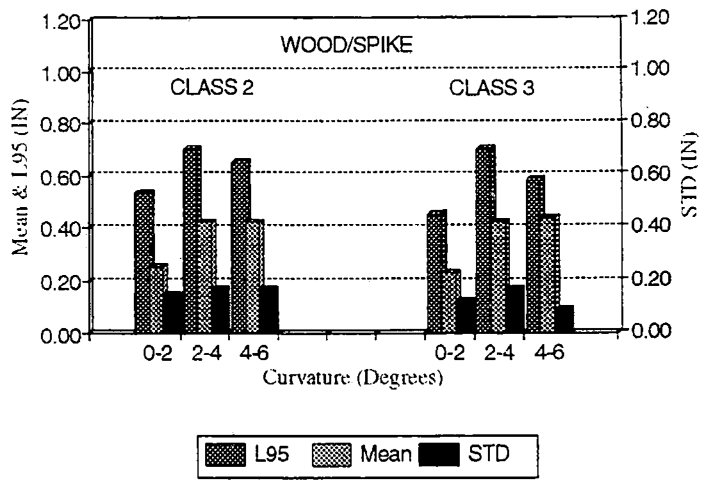

Exhibit 152. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad G, Segmented by Class, Tie and Fastener Types.

The unloaded, loaded and delta gage in Test Section 2 by track type are shown in Exhibits 153, 154 and 155, respectively. Exhibit 153 shows that as the degree of curvature increases, the mean, L95, and the standard deviation increase on Class 2 and 3 track. On Class 4 track, the mean value decreases while L95 and standard deviation increase. No definitive trend with respect to class is seen. The maximum L95 unloaded gage value of 57.3" is seen on 4-6 degree Class 3 track.

The loaded gage values are seen in Exhibit 154. In contrast to the trend for unloaded gage in the previous exhibit, the loaded gage mean value with respect to curvature increases in Class 4 track. The L95 loaded gage value of over 57.75" is seen on 4-6 degree Class 3 track. This indicates that more than 5% of the

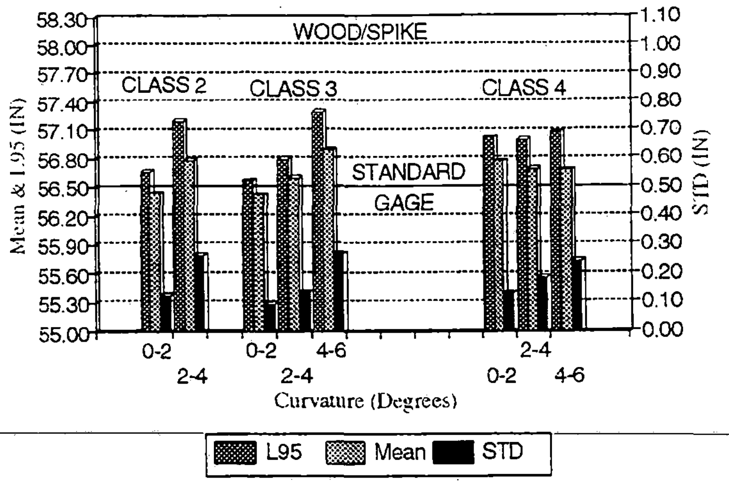

Exhibit 153. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad G, Segmented by Class, Tie and Fastener Types.

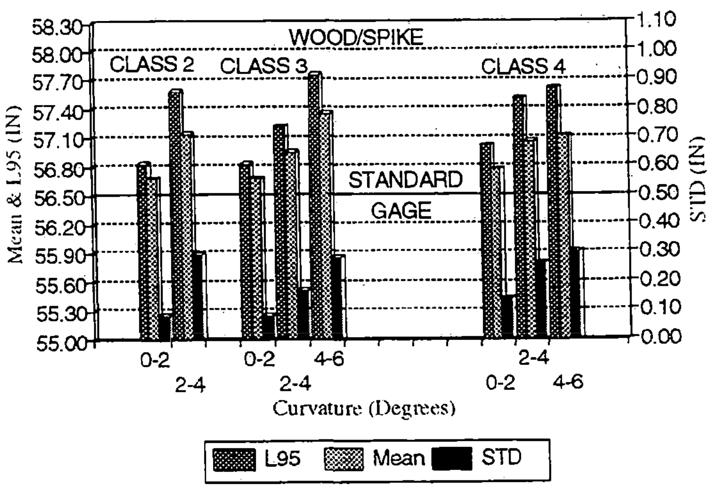

Exhibit 154. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad G, Segmented by Class, Tie and Fastener Types.

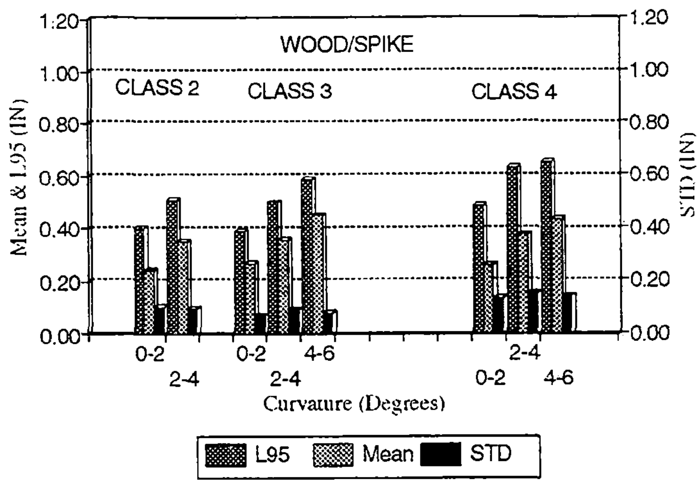

Exhibit 155. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad G, Segmented by Class, Tie and Fastener Types.

loaded gage values, in the 4-6 degree curves, exceed the loaded gage paint limit of 57.75". In Exhibit 155, the delta gage value is seen to increases with curvature. A maximum delta gage mean value of 0.45", giving a mean track compliance of 0.025"/kip, indicates very good tie and rail restraint conditions in Test Section 2.

Test Section 3 has cut spike and elastic fastener track. The unloaded, loaded and delta gage by track type are seen in Exhibits 156, 157 and 158, respectively. Characteristics similar to those in Test Section 2 are seen in Test Section 3. Increases in mean, L95 value and standard deviation of unloaded and loaded gage, with respect to curvature, are seen in this test section, except in 2-4 degree Class 2 track. No dependence of unloaded and loaded gage

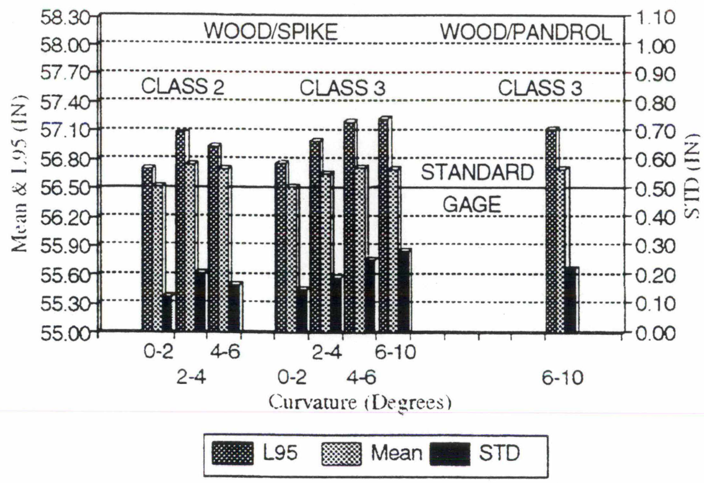

Exhibit 156. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad G, Segmented by Class, Tie and Fastener Types.

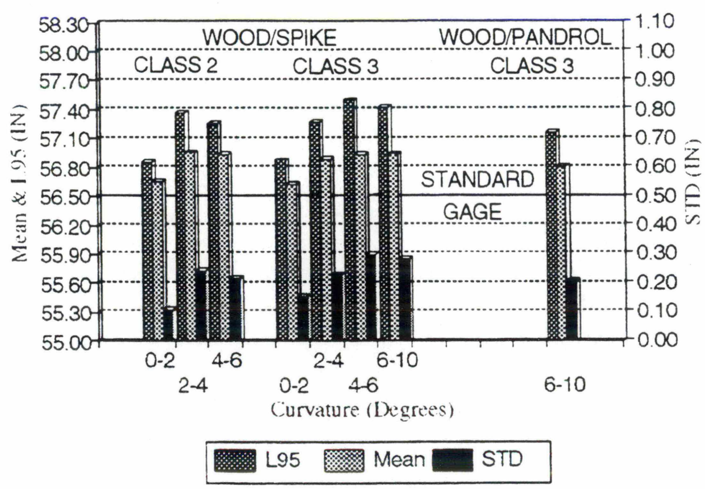

Exhibit 157. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad G, Segmented by Class, Tie and Fastener Types.

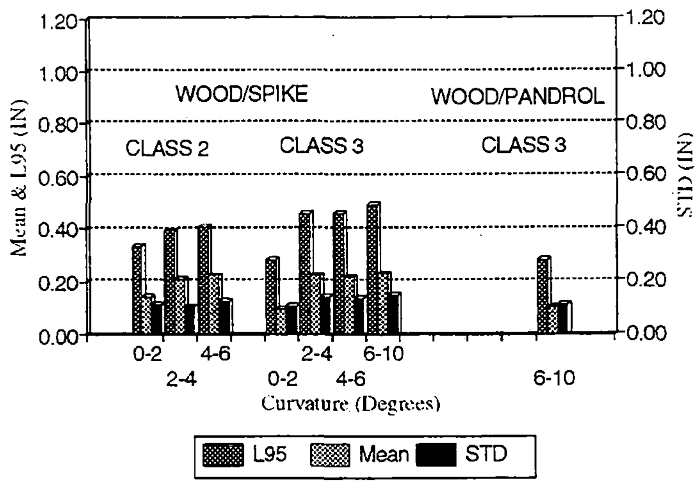

Exhibit 158. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad G, Segmented by Class, Tie and Fastener Types.

upon track class is seen. There is little difference in unloaded and loaded gage seen between the cut spike and elastic fastener track for 6-10 degree curves in this test section. No L95 values exceeds the loaded gage paint limit of 57.75". The highest L95 loaded gage value of 57.5" is seen on 4-6 degree Class 3 cut spike track. Since all L95 delta gage values in Exhibit 158 are below 0.5", very strong tie/fastener conditions are seen in these results. A maximum delta gage mean value of only 0.23", resulting in a mean track compliance of 0.013"/kip, indicates a substantial reserve of gage widening resistance on this test section.

Test Section 4 has spike track. The corresponding unloaded, loaded and delta gage with respect to track type are seen in Exhibits 159, 160 and 161, respectively. The wide gage

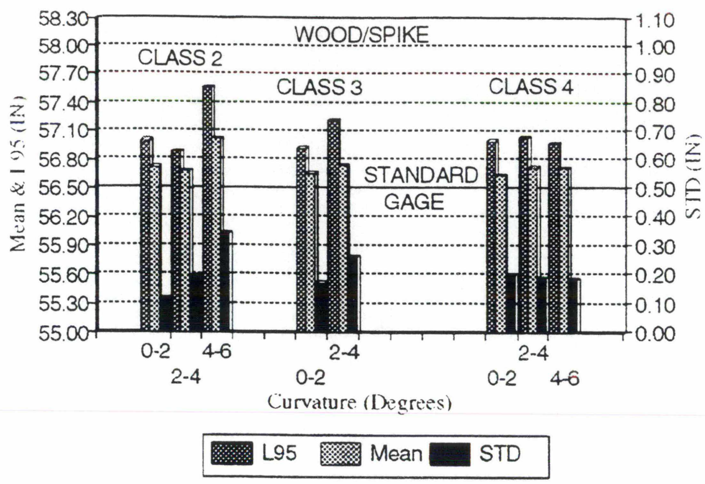

Exhibit 159. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 4 of Railroad G, Segmented by Class, Tie and Fastener Types.

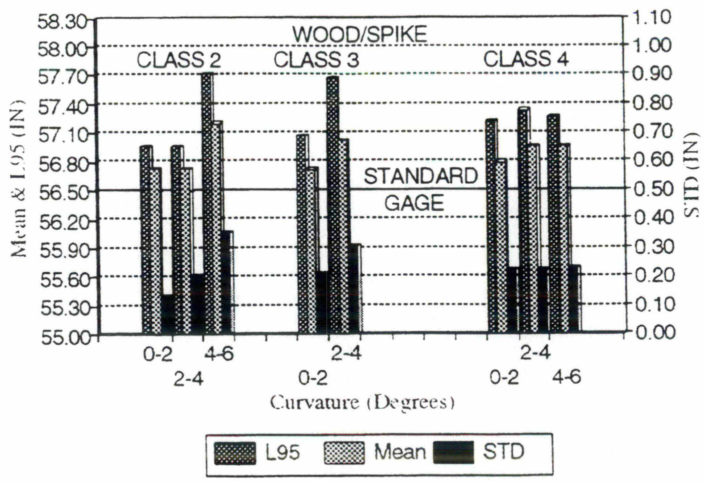

Exhibit 160. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 4 of Railroad G, Segmented by Class, Tie and Fastener Types.

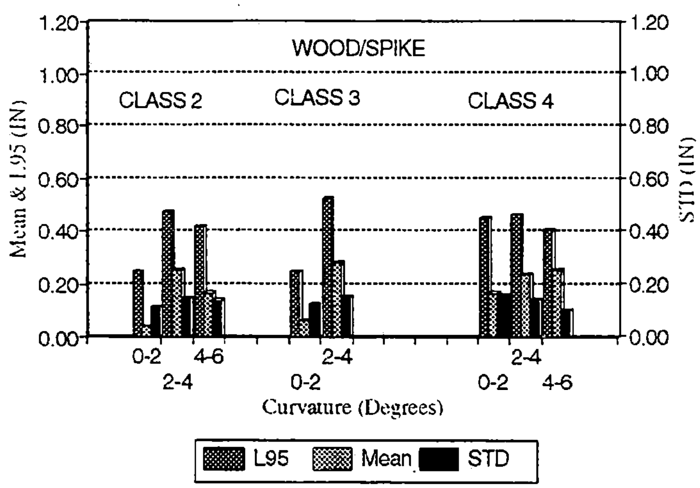

Exhibit 161. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 4 of Railroad G, Segmented by Class, Tie and Fastener Types.

characteristics shown in Exhibits 159 and 160 are similar to those seen in the previous test sections. As the degree of track curvature increases, the mean and L95 and the standard deviation also increase. No clear class dependence is seen in these exhibits. The highest L95 unloaded gage of 57.57" is seen on 4-6 degree Class 2 track. Exhibit 160 shows that the L95 loaded gage values do not exceed the loaded gage paint limit of 57.75". The highest L95 unloaded gage value, and the corresponding highest L95 loaded gage value, of over 57.7", is seen in the 4-6 degree Class 2 track.The higher gage widening loads required for steering on higher degree curves are the causes for the wider unloaded gage on higher degree of curvature track. Since most of the exceptions in this test section are due to wide gage, a need exists to control gage.

The L95 delta gage values in Exhibit 161 are below 0.52". These results reflect very strong tie/fastener conditions. A maximum delta gage mean value of only 0.27" is seen in Test Section 4. The corresponding track compliance of 0.015"/kip indicates a substantial reserve of gage widening resistance on this test section.

Test Section 5 results provide definitive trends for the identification of wide gage and gage widening resistance. This test section has cut spikes in Class 3 and 4 track. The corresponding unloaded, loaded and delta gage by track type are shown in Exhibits 162, 163 and 164, respectively. Increases in mean, L95 value and standard deviation of unloaded and loaded gage, with respect to curvature, are clearly seen in the exhibits. The wider unloaded gage at higher degrees of curvature results from the higher traffic volume and increased lateral forces at higher degrees of curvature. The effect of speed on both the unloaded and loaded gage is not discernible in a comparison of the Class 3 and the Class 4 results. The L95 values of loaded gage on 6-10 degree Class 3 and 4 track, exceed the loaded gage paint limit of 57.75", while the corresponding L95 unloaded gage values are about 57.4". Since all L95 delta gage values in Exhibit 164 are below 0.7", presence of higher wide gage is the cause of the loaded gage paint limit exceedences. A maximum delta gage mean value of 0.5", resulting in a mean track compliance under 0.03"/kip, indicates an ample reserve of gage widening resistance on this test section.

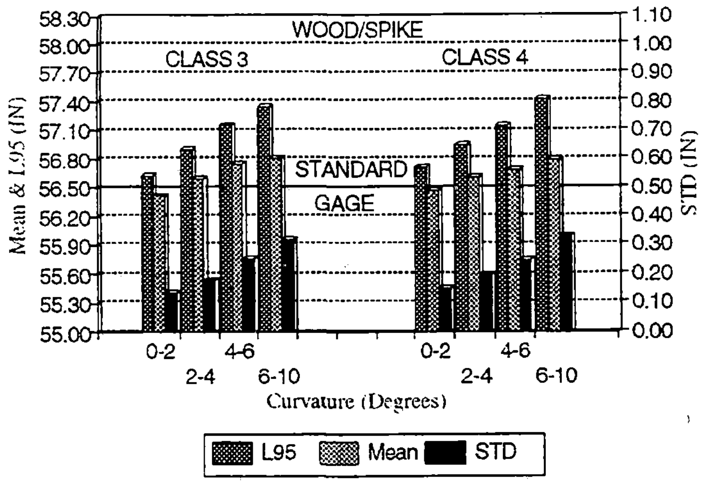

Exhibit 162. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 5 of Railroad G, Segmented by Class, Tie and Fastener Types.

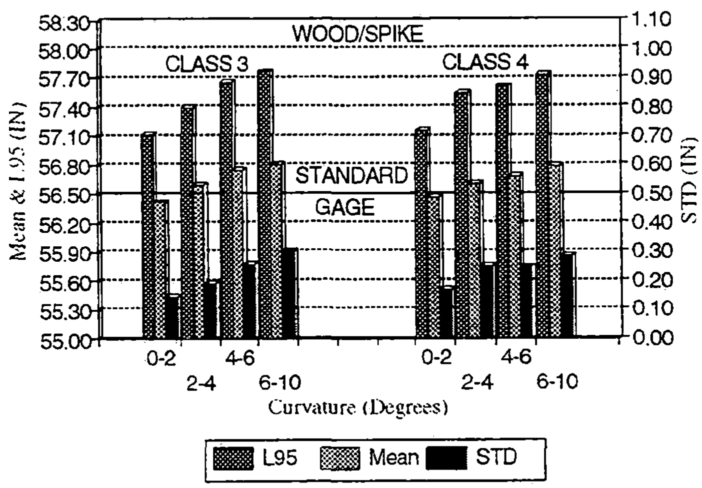

Exhibit 163. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 5 of Railroad G, Segmented by Class, Tie and Fastener Types.

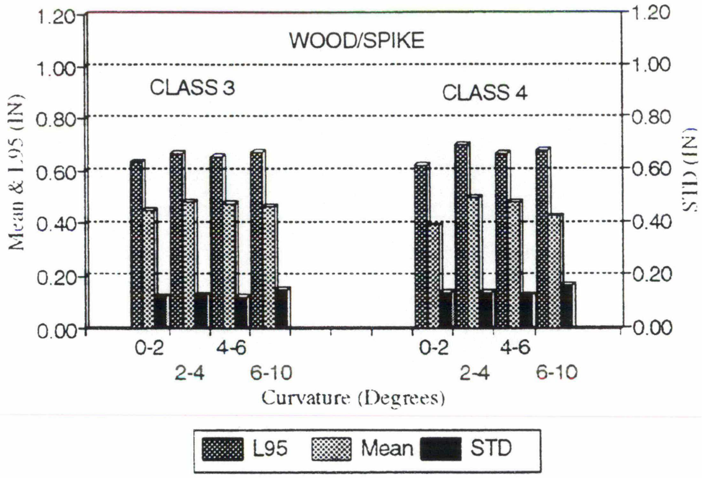

Exhibit 164. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 5 of Railroad G, Segmented by Class, Tie and Fastener Types.

6.8 RAILROAD H

The TLV gage widening tests on Railroad H were conducted in December 1991. A total of 280 miles of track, in five test sections, was tested on this railroad located in the south. The breakdown of test mileage consisted of 90 miles in Test Section 1, 40 miles in Test Section 2, 50 miles in Test Section 3, 50 miles in Test Section 4, and 50 miles in Test Section 5. Approximately 14.5 miles of track in Test Section 2 has cut spikes. All five test sections have primarily continuously welded 115 and 136 lb rail and concrete ties. Except for 1 mile of Class 1 track in Section 2, all test sections consisted of FRA class 3 and 4 track.

6.8.1 Analysis Based on Mile Post

Exhibits 165, 166, 167 and 168 show the mean values of unloaded gage, loaded gage, delta gage and track compliance, respectively, in all test sections on a mile-by-mile basis. Similarly, Exhibits 169, 170, 171 and 172 show the respective 95th-percentile values for the test sections.

Exhibit 165 shows large portions of track in Test Section 2 and 5 with tight gage. Good gage control is seen, except for a few miles. The unloaded gage means values are close to standard gage. It is seen in the exhibit that concrete ties do enhance gage control. The mean unloaded gage varies from 56.35" to over 57.0" in Test Section 1 and to 56.96" in Test Section 2. In Test Section 3, the unloaded gage varies from 56.46" to under 56.8", while it varies from under 56.4" to 56.8" in Test Section 4. Most of the tight gage seen in Test Section 5 varies between a low of 56.25" and a high of 56.55".

In Exhibit 166, most of the mean loaded gage variation is between 56.55" and 57.0". In Test Section 1, a few miles of loaded gage mean values are above 57.1" and even 57.2". Ample ability to hold gage is seen in all test sections. A study of the exception reports shows that most of the exceptions on Railroad H were due to the exceedence of the loaded gage paint limit of 57.75". There are no exceptions in Test Sections 3 and 5, and less than 10 exceptions in Test Sections 2 and 4. Concrete cross ties and good maintenance practices provide excellent gage control on this railroad.

Exhibit 167 gives an indication of those miles of track which are relatively strong and those which are weak. The mean delta

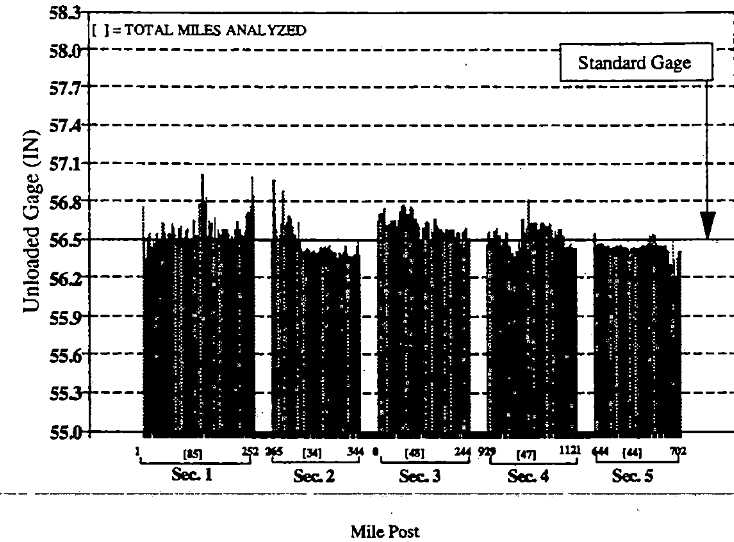

Exhibit 165. Unloaded Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad H.

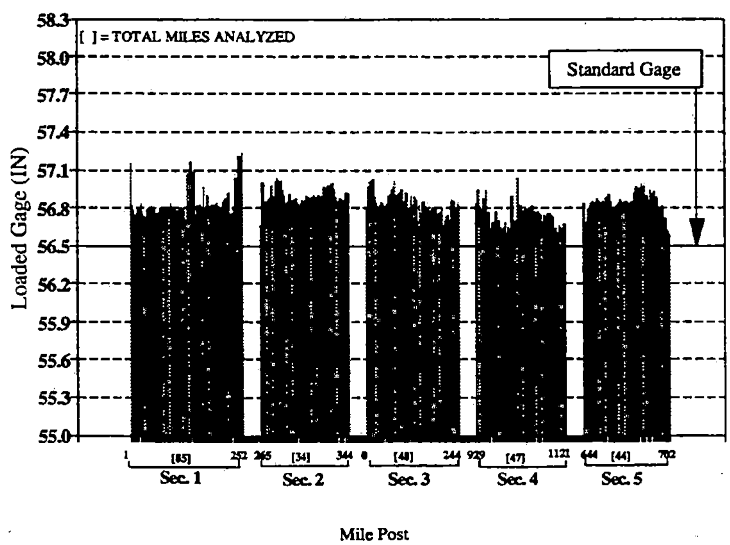

Exhibit 166. Loaded Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad H.

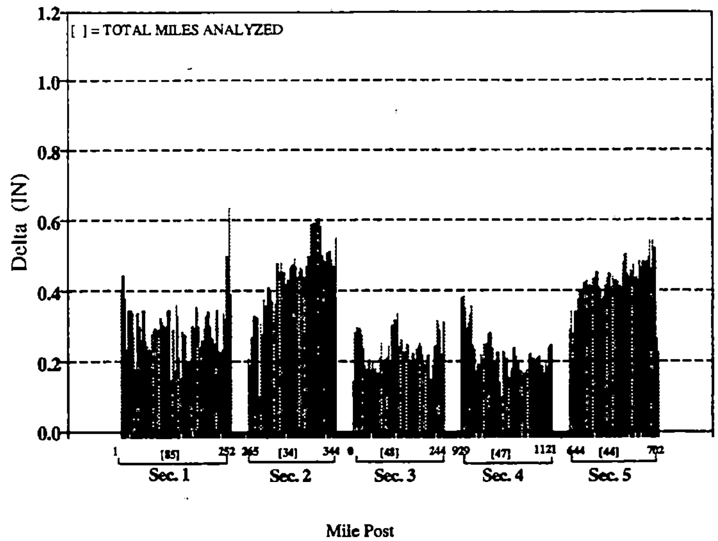

Exhibit 167. Delta Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad H.

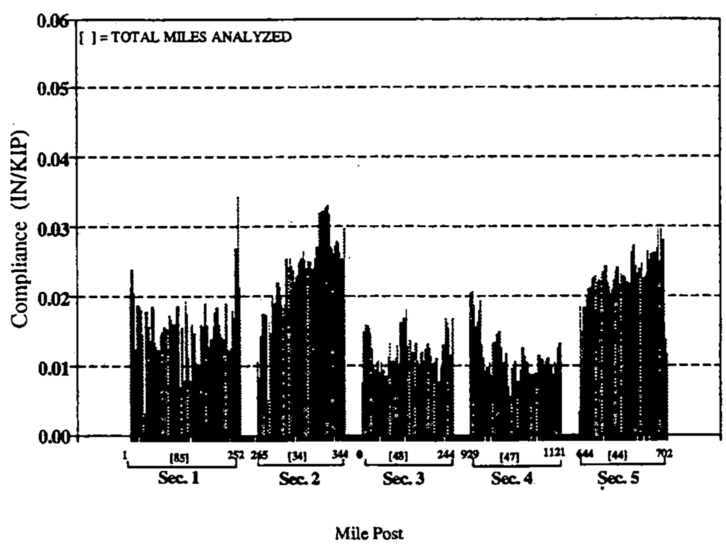

Exhibit 168. Track Compliance Mean Value for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad H.

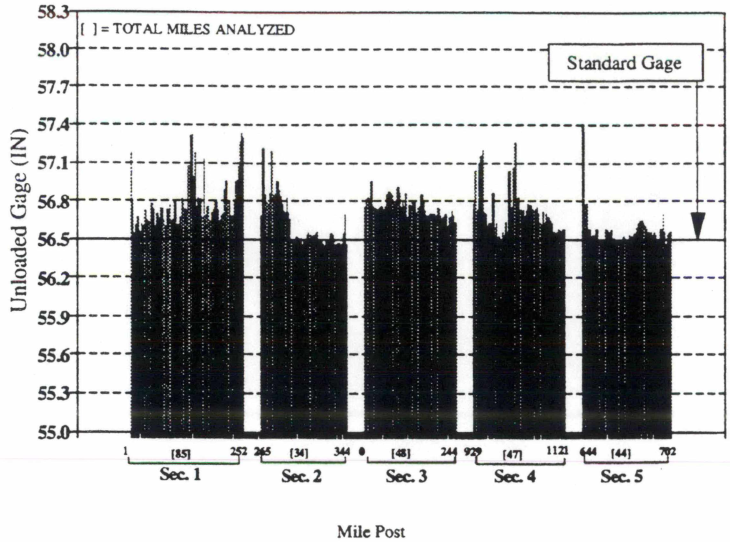

Exhibit 169. Ninety Fifth-percentile (L95) Value of Unloaded Gage for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad H.

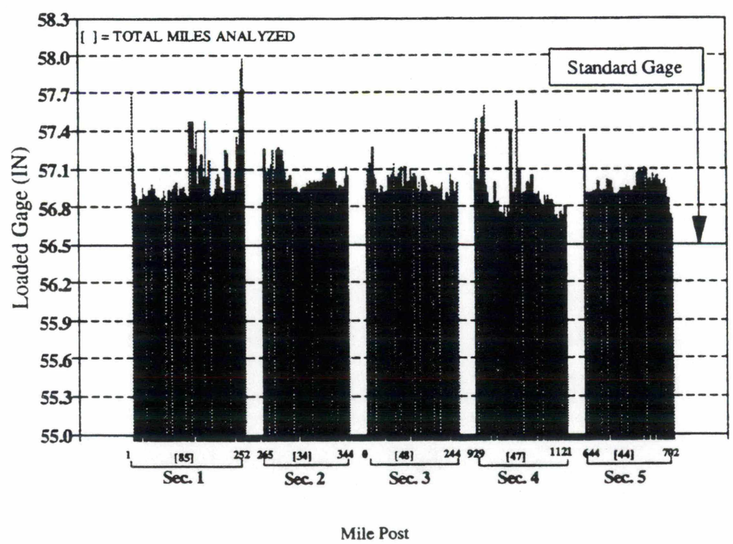

Exhibit 170. Ninety Fifth-percentile (L95) Value of Loaded Gage for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad H.

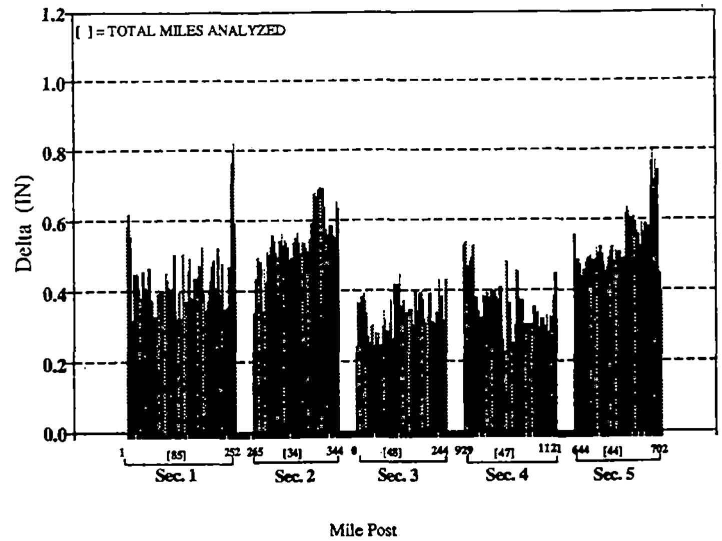

Exhibit 171. Ninety Fifth-percentile (L95) Value of Delta Gage for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad H.

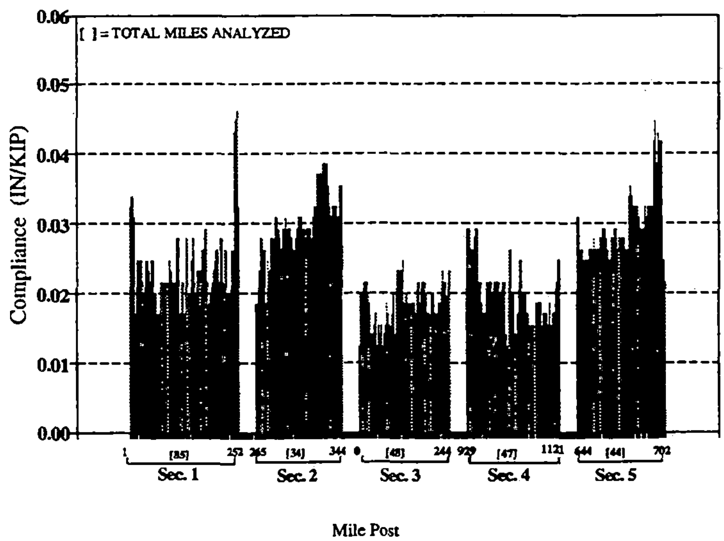

Exhibit 172. Ninety Fifth-percentile (L95) Value of Track Compliance for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad H.

gage is over 0.6" in Test Sections 1 and 2. Lower than 0.1" mean delta gage values are also seen in Test Section 4. Most of the variation seen is below 0.3" in Test Sections 1, 3 and 4. In Test Sections 2 and 5 the variation is between 0.4" and 0.5".

Exhibit 168 depicts a quantitative measure of the tie and rail restraint provided by track in all sections. The higher the compliance value, the weaker is the gage widening resistance. Good to strong rail lateral restraint conditions on Railroad H are indicated by the less than 0.03"/kip compliance mean values seen in this exhibit.

The 95th-percentile values of unloaded gage, loaded gage, delta gage and track compliance, for each track mile analyzed on Railroad H, are discussed in the following to demonstrate dispersal in data and to differentiate between weak and strong tie/fastener conditions.

Exhibit 169 shows the L95 values of unloaded gage for the five test sections. Good control of the unloaded gage is seen in all test sections. Most of the L95 unloaded gage values are below 56.8". The highest L95 value of unloaded gage is 57.4" in Test Section 5, 57.3" in Test Section 1, 57.25" in Test Sections 2 and 4, and 56.95" in Test Section 3. The corresponding L95 values of loaded gage are seen in Exhibit 170. Most of the L95 loaded gage values are between 56.8" and 57.1". Some miles in Test Sections 1, 4 and 5 have L95 values which do indicate excessive gage widening. A L95 value close to 57.7" is an indication of the onset of the loaded gage paint limit exception. There are a number of miles towards the end of Test Section 1 where L95 loaded gage is above the loaded gage paint limit of 57.75".

The extent of gage widening resistance provided by tie and rail restraint in each mile are seen in Exhibits 171 and 172. A check of L95 delta gage values for those miles of track where excessive L95 loaded gage occurred indicates that these values may not necessarily be the higher values. It is not always the deficiency in gage widening resistance, but rather the initial presence of substantial wide gage which leads to large loaded gage values. For example, a check of unloaded and delta gage corresponding to the highest loaded gage in Test Section 5, indicates that initial unloaded gage of over 57.4" results in the loaded gage spike seen in Exhibit 170. On the other hand, the highest L95 loaded gage of 58.0" in Test Section 1 has a corresponding L95 delta gage of 0.8" and unloaded gage of 57.3". As the L95 delta gage of 0.8" is not excessive, it appears that the combination of wide gage and weak tie/fastener condition causes this loaded gage paint limit exceedence.

Most of the L95 delta gage values on Railroad H are below 0.6", except for a few miles in Test Sections 1, 2 and 5. The corresponding L95 compliance values are generally below 0.03"/kip. Since 95% of the data are below these values, a high gage widening resistance is indicated for all test sections on Railroad H.

6.8.2 Analysis Based on Track Type

Exhibit 173 shows the FRA track classes analyzed in Test Sections 1 to 5 of Railroad H. The majority of tests were on concrete tie track with curvatures of up to 2 degrees. Except for

Class	Geometry (Degrees)	Tie/Fastener	Track Analyzed (Miles)					
			Test Section					Total
			1	2	3	4	5	
1	0-2	Wood/Spike	0.00	1.01	0.00	0.00	0.00	1.01
3	0-2	Concrete	10.86	0.00	16.47	12.01	7.59	46.93
3	2-4	Concrete	0.81	0.00	0.00	0.80	0.51	2.12
3	4-6	Concrete	1.02	0.00	0.00	0.21	0.00	1.23
3	6-10	Concrete	0.00	0.00	0.00	0.26	0.00	0.26
3	0-2	Wood & Conc. Mix	1.86	0.00	0.00	0.00	0.00	1.86
3	0-2	Wood/Spike	0.00	5.55	0.00	0.00	0.00	5.55
4	0-2	Wood/Spike	0.00	7.15	0.00	0.00	0.00	7.15
4	0-2	Concrete	69.74	20.22	31.23	32.45	35.74	189.38
4	2-4	Concrete	0.00	0.81	0.00	1.27	0.36	2.44
Total Miles			85.30	33.73	47.70	47.00	44.20	257.93

Exhibit 173. Total Miles Analyzed in Test Sections 1 to 5 of Railroad H for Wide Gage and Gage Resistance with respect to Track Class, its Geometry and Tie and Fastener Types.

1 mile of Class 1 track in Test Section 2, the test sections have Class 3 and Class 4 track. Section 2 has about 15 miles of cut spike track. Of a total of about 258 analyzed miles, 48 miles of Class 3 track and 189 miles of Class 4 track, have concrete ties and curvatures of up to 2 degrees. The remaining 7 miles have concrete ties and curvatures of 2-10 degrees in short sections.

Exhibit 174 shows the mean, standard deviation and L95 of unloaded gage in Test Section 1, as a function of track curvature, class and tie/fastener type. As the degree of curvature increases from 0 to 4 degrees, the mean, L95, and the standard deviation increase on Class 3 concrete tie track. On curves higher than 4 degrees, there is a slight decrease in both the mean and L95 values, and the standard deviation. No such difference in unloaded gage characteristics is seen on 0-2 degree Class 3 and Class 4 concrete tie track. A comparison between the unloaded gage characteristics on 0-2 degree Class 3 track having concrete ties and the cut spikes/wood ties mixed with concrete ties, indicates that the corresponding mean values are basically the same. However, the averaging of the superior gage holding contribution of the concrete ties, with that of cut spikes on wood ties, creates a greater variability in unloaded gage on track consisting of the mixture of wood and concrete ties. This is seen by a value of twice the standard deviation on mixed tie track as compared to that on concrete tie track. L95 unloaded gage values of over 57.2" are seen in 2-4 and 4-6 degree curves of Class 3 concrete tie track. A concern to control gage is seen in this test section, and field inspection is indicated.

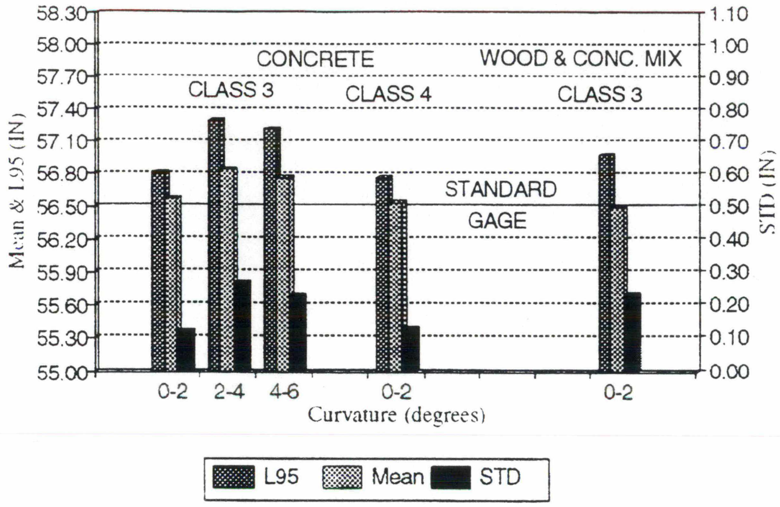

Exhibit 174. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad E, Segmented by Class, Tie and Fastener Types.

Exhibit 175 shows the mean, standard deviation and L95 of loaded gage in Test Section 1. This exhibit shows that as the degree of curvature increases, the mean, L95, and the standard deviation value increase in Class 3 concrete tie track. The mixture of wood and concrete ties causes increased variability in the loaded gage, however, there is no appreciable difference in the loaded gage mean characteristics of the various class or tie type of track. L95 values of near 57.70" are seen in 2-4 and 4-6 degree curves of the Class 3 concrete tie track. Since about 5% of loaded gage is above 57.70", exceedences of the loaded gage paint limit of 57.75" are indicated for these curves. This confirms the need for immediate field inspection and/or maintenance, as also mentioned earlier.

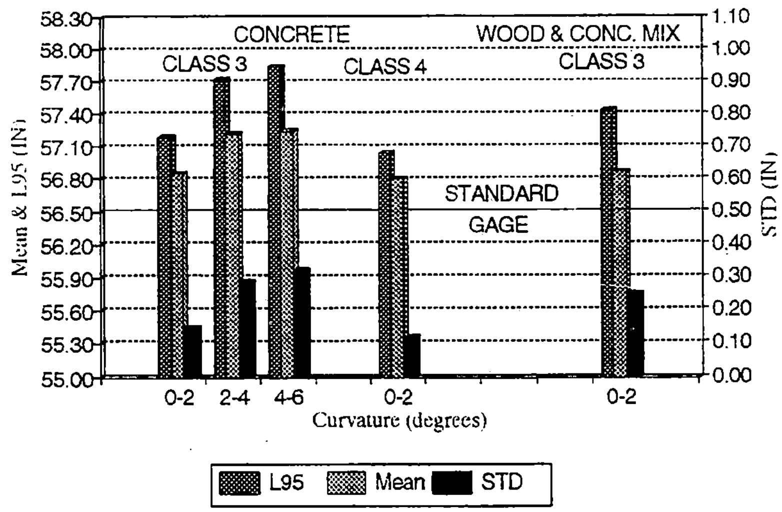

Exhibit 175. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad H, Segmented by Class, Tie and Fastener Types.

The mean, standard deviation and L95 of delta gage in Test Section 1 are seen in Exhibit 176. The L95 delta gage value of close to 0.8" suggest a weak tie/fastener condition in 4-6 degree Class 3 concrete tie track in this test section. Higher delta gage with respect to curvature is seen on the Class 3 concrete tie track. A delta gage dependence by track class is seen. Gage widening resistance is reduced by the mixing of cut spikes/wood ties with concrete ties. This is seen in higher mean and L95 delta gage values for Class 3 track with this tie mix. Other than the 0.8" L95 value in 4-6 degree curves, the second highest L95 delta gage value is 0.57" on 2-4 degree curve track. The corresponding L95 value of track compliance, for a gage widening load of 18 kips, is 0.032"/kip. Since 4-6 degree curves make up only 1.2% of Test

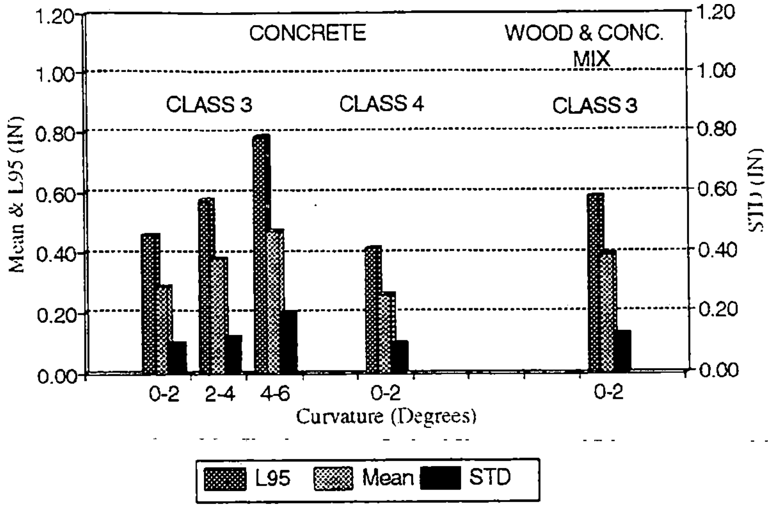

Exhibit 176. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad H, Segmented by Class, Tie and Fastener Types.

Section 1 track, 95% compliances below 0.032"/kip indicate very good tie and rail restraint conditions in Test Section 1.

The unloaded, loaded and delta gage in Test Section 2 by track type are shown in Exhibits 177, 178 and 179, respectively. Exhibit 177 shows that unloaded gage mean values are close to the standard gage in Test Section 2. On concrete tie track, the mean values are less than the standard gage. Slight increases in mean, L95, and standard deviation with respect to curvature are seen for concrete tie track, however, no definitive trend with respect to track class is seen. The maximum L95 unloaded gage value of 57.0" is seen in 0-2 degree Class 3 cut spike track. This track also has the highest standard deviation.

The loaded gage values are seen in Exhibit 178. In contrast

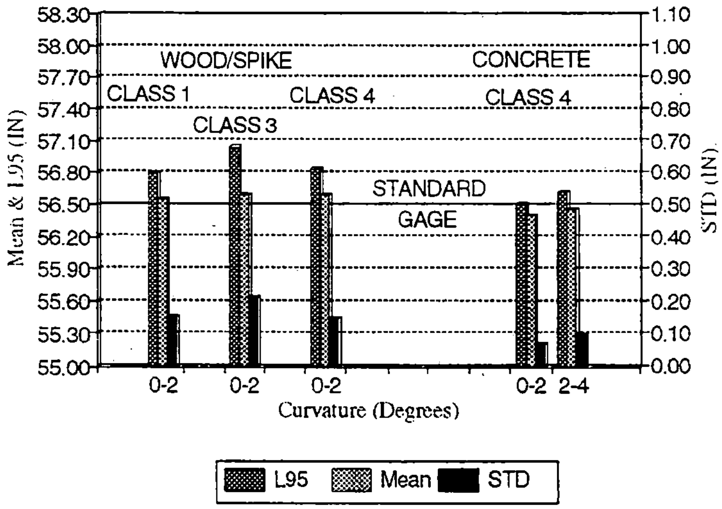

Exhibit 177. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad H, Segmented by Class, Tie and Fastener Types.

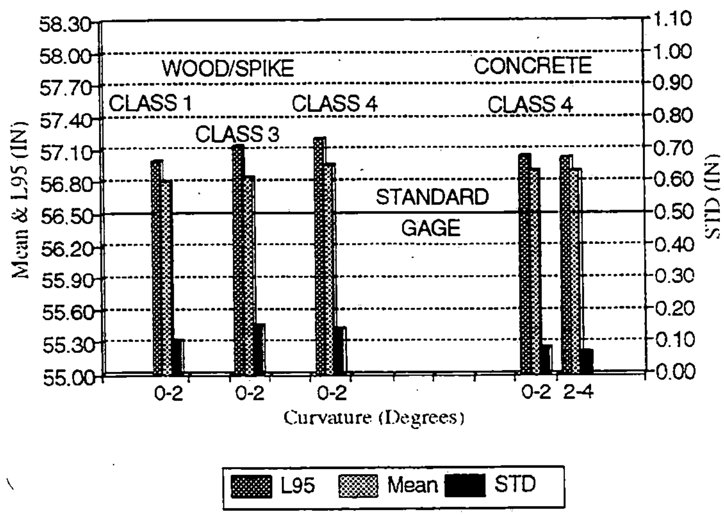

Exhibit 178. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad H, Segmented by Class, Tie and Fastener Types.

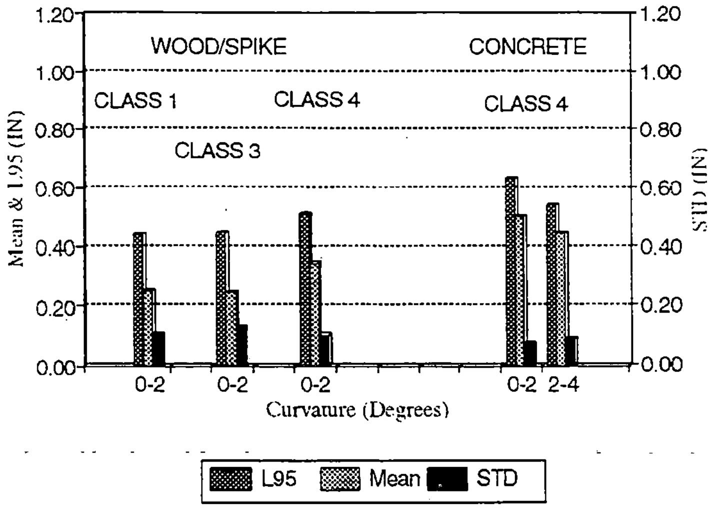

Exhibit 179. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad H, Segmented by Class, Tie and Fastener Types.

to the trend for unloaded gage in the previous exhibit, the trends for loaded gage in concrete tie track are similar. The highest L95 loaded gage value of 57.2" occurs in 0-2 degree Class 4 cut spike track. While it shows that 5% of the loaded gage values in these 0-2 degree curves, are greater than 57.2", no clear indication of excessive loaded gage is seen in this exhibit. Exhibit 179 shows that delta gage values are greater for concrete tie track than on cut spike track. The highest L95 value of 0.64" and maximum delta gage mean value of 0.5" are seen in 0-2 degree Class 4 concrete tie track. The mean value of 0.5" indicates a mean track compliance of 0.028"/kip for a gage widening load of 18 kips, and very good tie and rail restraint conditions in Test Section 2.

Test Section 3 has 0-2 degree Class 3 and Class 4 track. The unloaded, loaded, and delta gage by track type are shown in Exhibits 180, 181 and 182, respectively. Slight increases in mean, L95 and standard deviation of unloaded gage values are seen with respect to track class. The unloaded gage values approximate standard gage. Exhibit 181 shows that although loaded gage L95 value and standard deviation increase on Class 4 track, the corresponding mean value decreases. The higher loaded gage variability results from pockets of isolated higher unloaded gage values in Class 4 track. No exceptions were reported in Test Section 3, as none of the L95 loaded gage values exceed the loaded gage paint limit of 57.75". The highest L95 loaded gage value of 57.0" is seen in 0-2 degree Class 4 track. Since all L95 delta gage values in Exhibit 182 are below 0.4", very strong tie/fastener conditions are seen in these results. A maximum delta gage mean value of only 0.22", resulting in a mean track compliance of 0.012"/kip, indicates a large reserve of gage widening resistance on this test section.

Test Section 4 provides a good mix in track curvature, and has Class 3 and 4 concrete tie track. The corresponding unloaded, loaded and delta gage by track type are seen in Exhibits 183, 184 and 185, respectively. The wide gage characteristics, as shown in Exhibits 183 and 184, are similar to those seen in 0-10 degree curves of other railroads in this report. As the degree of track curvature increases, the mean, L95, and the standard deviation increase on curves of up to 6 degree due to the higher lateral loads experienced, and decrease on higher degree curves because of improved track maintenance practices. However, no clear class

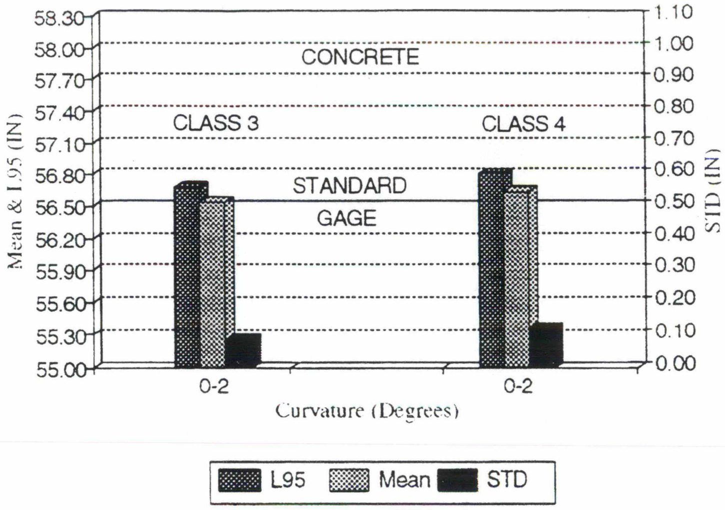

Exhibit 180. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad H, Segmented by Class, Tie and Fastener Types.

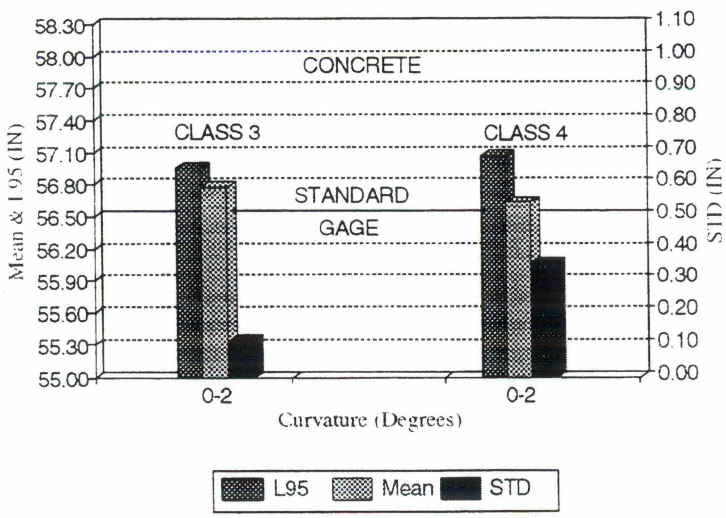

Exhibit 181. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad H, Segmented by Class, Tie and Fastener Types.

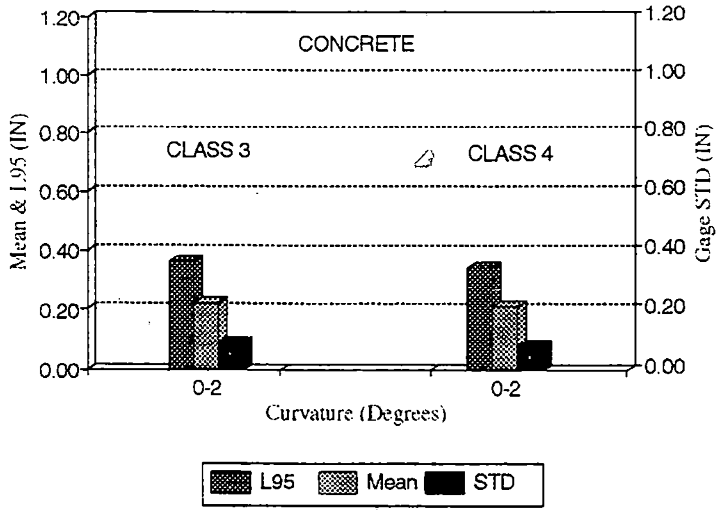

Exhibit 182. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad H, Segmented by Class, Tie and Fastener Types.

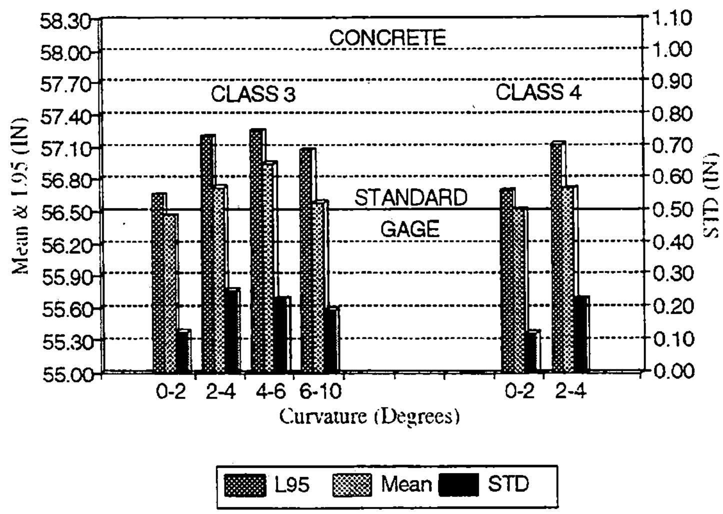

Exhibit 183. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 4 of Railroad H, Segmented by Class, Tie and Fastener Types.

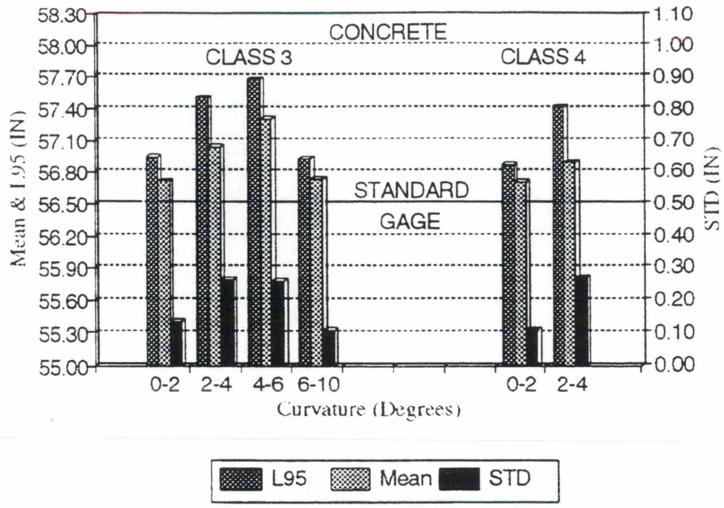

Exhibit 184. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 4 of Railroad H, Segmented by Class, Tie and Fastener Types.

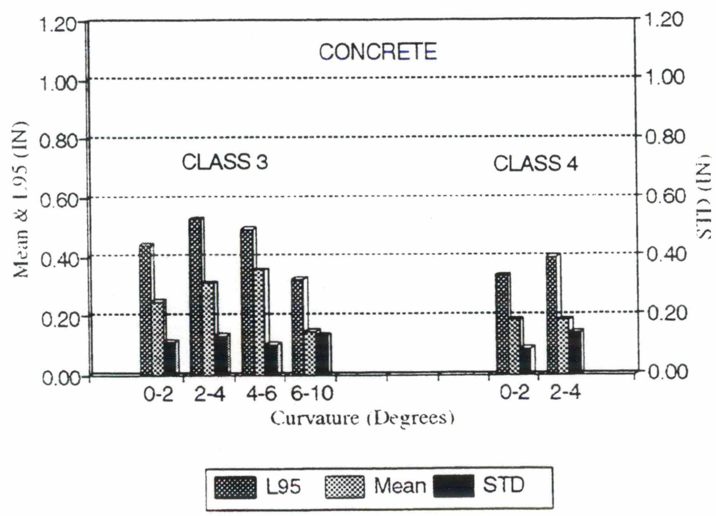

Exhibit 185. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 4 of Railroad H, Segmented by Class, Tie and Fastener Types.

dependence is seen in these exhibits. The highest L95 unloaded gage of 57.26" occurs in 4-6 degree Class 3 track. Exhibit 184 indicates that the L95 loaded gage values do not exceed the loaded gage paint limit of 57.75". The highest L95 loaded gage of 57.7", corresponding to the highest L95 unloaded gage, is also seen in 4-6 degree Class 3 track. Since most of the exceptions in this test section are due to wide gage, a need exists to control gage.
The L95 delta gage values in Exhibit 185 are below 0.52". Very strong tie/fastener conditions are seen in these values. A maximum delta gage mean value of 0.36" occurs in Test Section 4, and the corresponding track compliance of 0.02"/kip indicates a substantial reserve of gage widening resistance in this test section.

Test Section 5 has tangent concrete tie track with, generally, light curves. The unloaded, loaded, and delta gage by track type are seen in Exhibits 186, 187 and 188, respectively. A comparison of the results from Test Sections 4 and 5 indicates that both of these sections have similar characteristics as to wide gage and gage widening resistance. The unloaded gage mean values on 2-4 degree Class 3 curves in Test Sections 4 and 5 are comparable, however, there appears to be a greater scatter in these values in Test Section 5. For Class 4 track better gage maintenance is seen in Test Section 5 as a result of lower standard deviation values and closeness of mean and L95 values to the standard gage. Little effect of speed is seen on both the unloaded and loaded gage in a comparison of Class 3 and Class 4 results. As seen in Exhibit 187, the highest L95 loaded gage value of 57.4" is seen on 2-4 degree Class 3 track. Even though 5% of the loaded gage values on 2-4

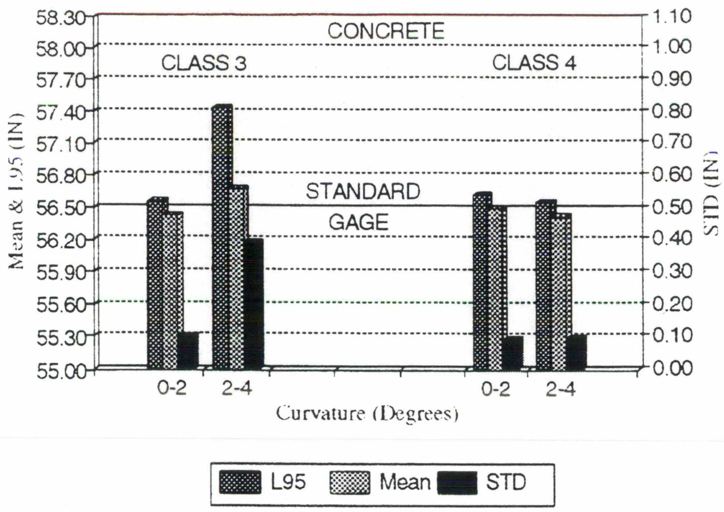

Exhibit 186. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 5 of Railroad H, Segmented by Class, Tie and Fastener Types.

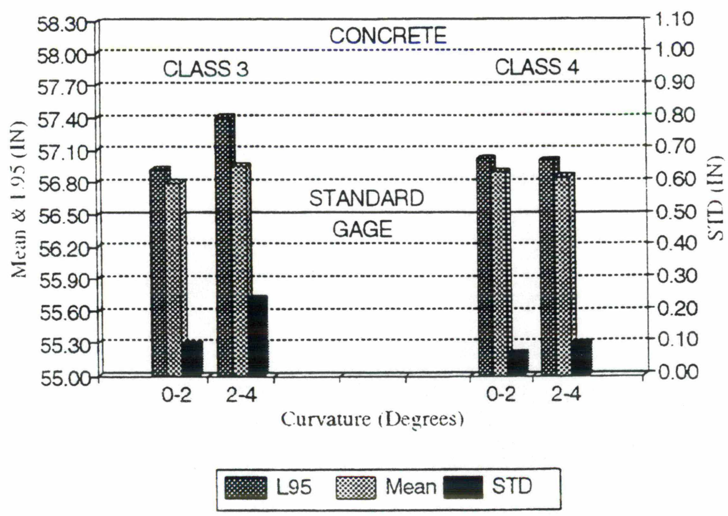

Exhibit 187. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 5 of Railroad H, Segmented by Class, Tie and Fastener Types.

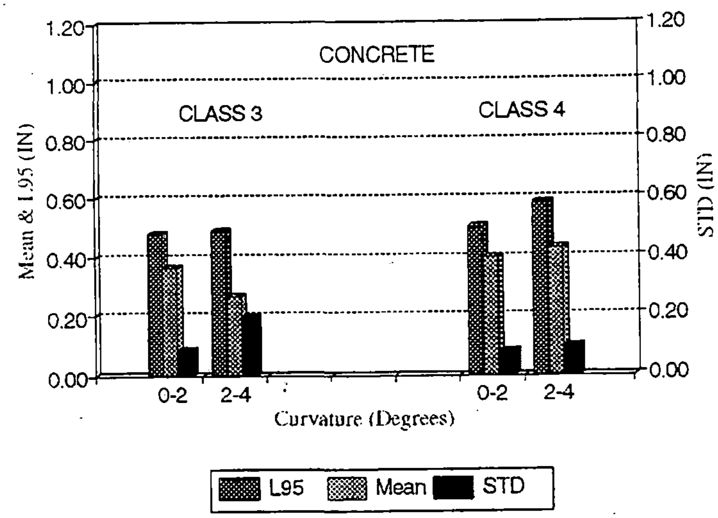

Exhibit 188. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 5 of Railroad H, Segmented by Class, Tie and Fastener Types.

degree curves do exceed 57.4", none of these values exceed the loaded gage paint limit of 57.75". All L95 delta gage values in Exhibit 188 are below 0.6". A maximum delta gage mean value of 0.42", resulting in a mean track compliance of 0.023"/kip, indicates a large reserve of gage widening resistance on this test section.

6.9 RAILROAD I

Two hundred seventy miles of track were tested on Railroad I in five test sections, located in the southwest region. Test mileage consisted of 130 miles in Test Section 1, 55 miles in Test Section 2, 40 miles in Test Section 3, 25 miles in Test Section 4 and 20 miles in Test Section 5. About 10 miles of track in Test

Section 1, and about 2 miles each in Test Sections 2 and 3 consisted of elastic fasteners on wood ties. Continuously welded 136 lb rail is used. Hairpins are used intermittently. Elastic fasteners are used in all curves of 4 degrees and above, and also on curves of 2 degree and above on selected heavy freight tonnage lines. Test Sections 1 and 2 have FRA class 3, 4 and 5 track, while Test Sections 3, 4 and 5 have FRA class 3 and 4 track. Also, there is 3.5 miles of Class 2 track in Test Section 4.

6.9.1 Analysis Based on Mile Post

Exhibits 189, 190, 191 and 192 indicate the mean values of unloaded gage, loaded gage, delta gage and track compliance, respectively, in all test sections on a mile-by-mile basis. Similarly, Exhibits 193, 194, 195 and 196 show the respective 95th-percentile values for the test sections.

Exhibit 189 shows large portions of track in all test sections with tight gage. Good gage control is seen as unloaded gage mean values are within 0.2" of the standard gage. Elastic fastener sections contain less than 10% of the test data in Test Section 1 and less than 1% and 4%, respectively, of the test data in Test Section 2 and 3. No enhancement of gage control and its lateral stiffness by the limited use of elastic fasteners is seen in these test sections. The mean unloaded gage varies from over 56.2" to under 56.8" in Test Section 1, and from under 56.2" to 57.0" in Test Section 2. In Test Section 3, the unloaded gage varies from 56.15" to over 56.5", and from 56.3" to over 56.6" in Test Section 4. In Test Section 5, the gage is between a low of 56.37" and a

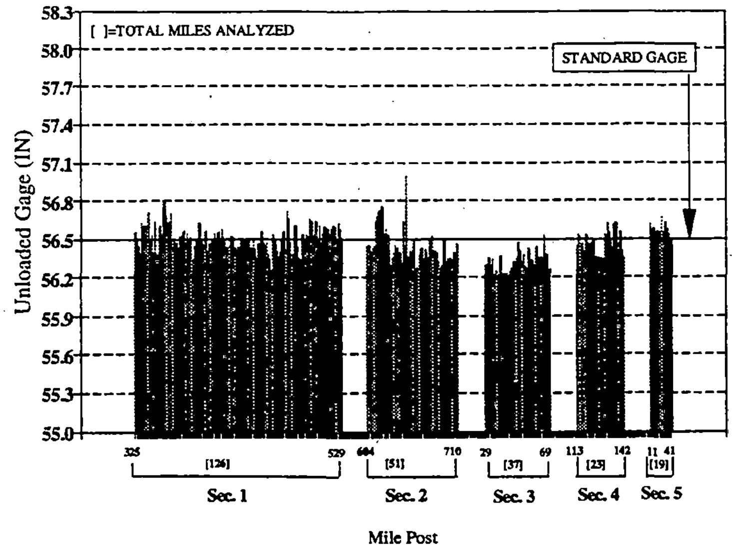

Exhibit 189. Unloaded Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad I.

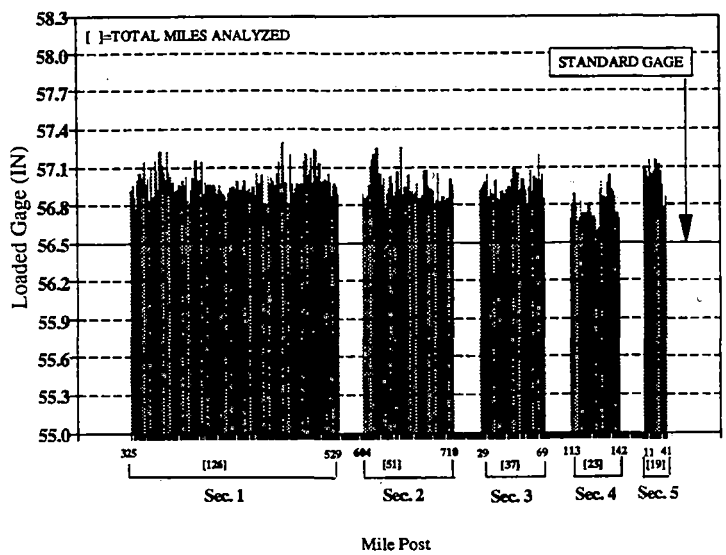

Exhibit 190. Loaded Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad I.

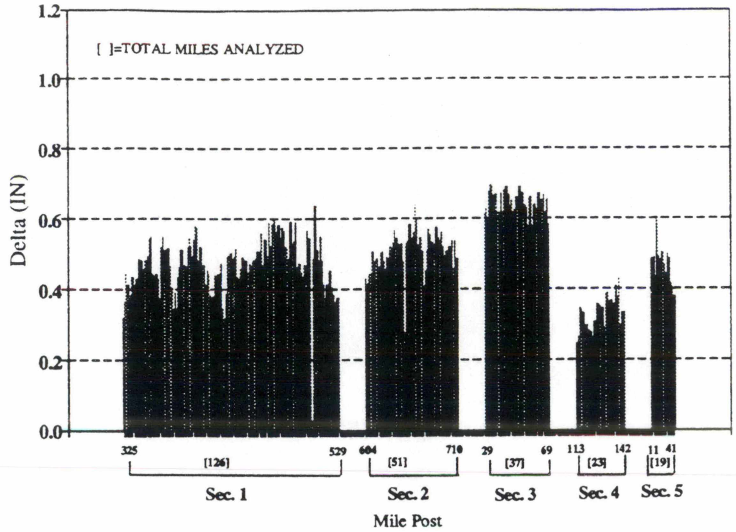

Exhibit 191. Delta Gage Mean Value for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad I.

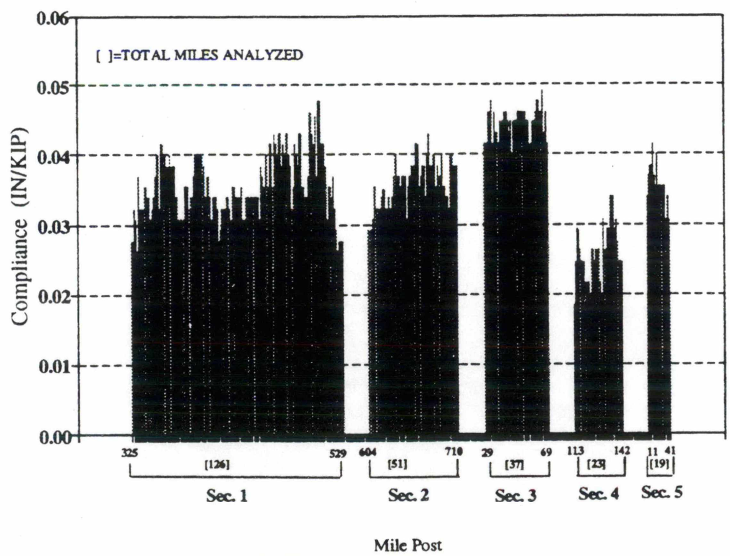

Exhibit 192. Track Compliance Mean Value for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad I.

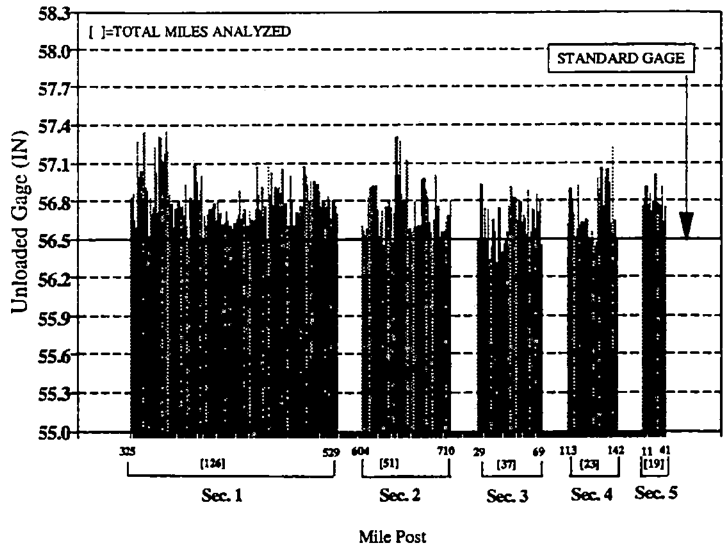

Exhibit 193. Ninety Fifth-percentile (L95) Value of Unloaded Gage for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad I.

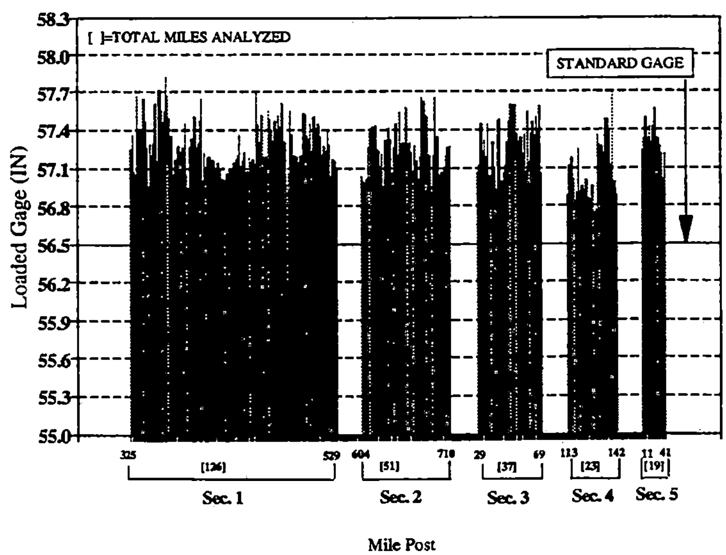

Exhibit 194. Ninety Fifth-percentile (L95) Value of Loaded Gage for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad I.

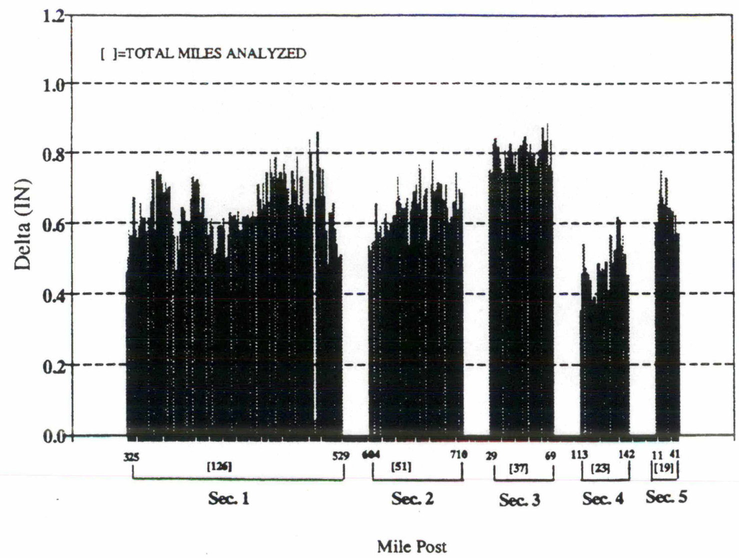

Exhibit 195. Ninety Fifth-percentile (L95) Value of Delta Gage for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad I.

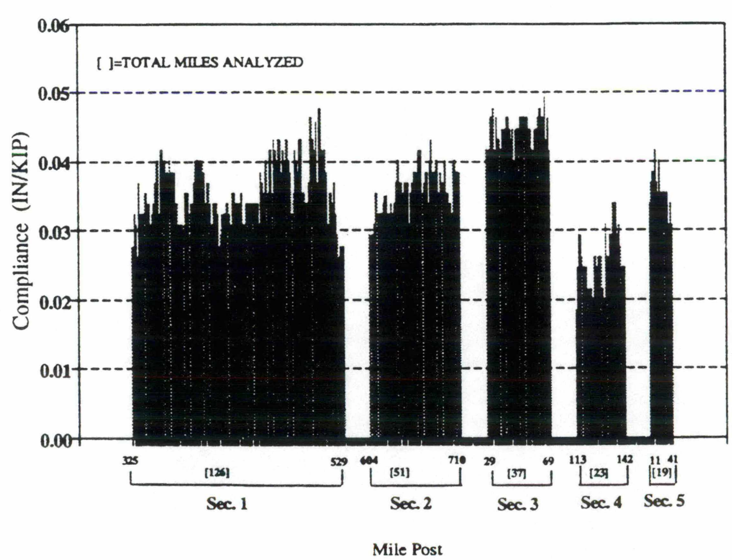

Exhibit 196. Ninety Fifth-percentile (L95) Value of Track Compliance for Each Statistical Mile Sample in Test Sections 1 to 5 of Railroad I.

high of 56.68".

In Exhibit 190, most of the mean loaded gage variation is between 56.6" and 57.0". There are, however, a few miles where loaded gage mean values are above 57.1" and some approaching 57.3". Test Section 4 has the lowest loaded gage mean values, however, ample ability to hold gage is seen in all test sections. A study of the exception reports reveals that most of the exceptions occurring on Railroad I are due to the exceedence of the loaded gage paint limit of 57.75". The exceptions are isolated and are limited to a few miles in the tests, however, however, a concern remains regarding wide gage in some test sections. The tests reflect good maintenance practices on Railroad I.

Exhibit 191, indicates which miles of track are relatively strong and which are weak. The least gage widening is seen in Test Section 4, followed in order in Test Sections 5, 1 and 2. The gage widening seen in Test Section 3 does not indicate a weakened tie/fastener condition. The mean delta gage rises above 0.6" in Test Sections 1, 2, 3 and 5. Also, lower than 0.1" values of mean delta gage are seen in Test Section 1. The variation is generally between 0.4" and 0.5" in Test Sections 1, 2 and 5, between 0.25" and 0.35" in Test Section 4, and between 0.6" and 0.67" in Test Section 3.

Exhibit 192 gives a quantitative measure of the tie and rail restraint provided by the track in all sections. The higher the compliance value, the weaker is the gage widening resistance. Good to strong rail lateral restraint conditions on Railroad I test sections are seen in the less than 0.038"/kip compliance mean values in this exhibit.

The 95th-percentile values of unloaded gage, loaded gage, delta gage and compliance, for each track mile analyzed on Railroad I, are discussed in the following to demonstrate dispersal in data and to differentiate between weak and strong tie/fastener conditions.

Exhibit 193 shows the L95 values of unloaded gage for the five test sections. A significant degree of wide gage is seen in all test sections. Many of the L95 unloaded gage values are above 56.8". The highest L95 value of unloaded gage is 57.36" in Test Section 1, 57.3" in Test Section 2, over 56.9" in Test Section 3, and over 57.2" and 57.0", respectively, in Test Sections 4 and 5. The corresponding L95 values of loaded gage are seen in Exhibit 194. There are many L95 loaded gage values between 57.4" and 57.7". A L95 value near 57.7" is an indication of onset of the loaded gage paint limit exception. There are a number of miles in Test Section 1 where L95 loaded gage is actually above the loaded gage paint limit of 57.75".

The extent of gage widening resistance provided by tie and rail restraint in each mile are seen in Exhibits 195 and 196. A check of L95 delta gage values, for those miles of track where L95 loaded gage values were closer to the loaded gage paint limit of 57.75", indicates that these values may not necessarily be the higher values. It is not always the deficiency in gage widening resistance but rather the initial presence of substantial wide gage which leads to the loaded gage paint limit exceedences. The highest L95 loaded gage of over 57.8" in Test Section 1 has a corresponding L95 delta gage of 0.7". The L95 delta gage of 0.7" does not indicate a weak tie and fastener condition. A study of the corresponding L95 unloaded gage reveals a value of 57.35". A wide gage of 57.35 may, in fact, lead to the loaded gage paint limit exception, as is seen in these exhibits.

The L95 delta gage values are below 0.85", except a few miles in Test Sections 1 and 3. The corresponding L95 compliance values are generally below 0.045"/kip. Since 95% of the data is below these values, good gage widening resistance is indicated for the test sections on Railroad I. Even though comparatively higher L95 delta gage values are seen in Test Section 3, it appears that the lower L95 unloaded gage values cause lower than 57.6" L95 loaded gage values in this section.

6.9.2 Analysis Based on Track Type

Exhibit 197 shows the FRA track classes analyzed in Test Sections 1 to 5 of Railroad I. The majority of tests were on cut spike track with curvatures of up to 2 degrees. In addition to Class 2 track in Test Section 4 and Class 5 in Test Sections 1 and 2, the test sections have Class 3 and 4 track. Elastic fasteners are installed in small portions of Test Sections 1, 2 and 3. Of the 256 miles analyzed, there are 2 miles of Class 2 track, 21 miles of Class 3 track , 127 miles of Class 4 track and 56 miles of Class 5 track which consists of cut spikes and having curvatures of up to 2 degrees. The remaining 50 miles consists of curved track of above 2 degrees and up to 10 degrees, in small mileages over Sections 1 to 5.

Class	Geometry (Degrees)	Tie/Fastener	Track Analyzed (Miles)					
			Test Section					Total
			1	2	3	4	5	
2	0-2	Wood/Spike	0.00	0.00	0.00	1.95	0.00	1.95
2	2-4	Wood/Spike	0.00	0.00	0.00	1.19	0.00	1.19
2	4-6	Wood/Spike	0.00	0.00	0.00	0.36	0.00	0.36
2	6-10	Wood/Spike	0.00	0.00	0.00	0.38	0.00	0.38
3	0-2	Wood/Spike	5.63	0.00	7.67	6.59	0.72	20.61
3	2-4	Wood/Spike	1.21	0.00	1.74	0.47	0.49	3.91
3	4-6	Wood/Spike	0.00	0.00	0.88	0.00	0.00	0.88
3	6-10	Wood/Spike	0.00	0.00	1.11	0.24	0.00	1.35
3	2-4	Wood/Pandrol	1.02	0.00	0.00	0.00	0.00	1.02
3	4-6	Wood/Pandrol	3.94	0.00	0.31	0.00	0.00	4.25
3	6-10	Wood/Pandrol	1.95	0.37	0.00	0.00	0.00	2.32
4	0-2	Wood/Spike	45.78	37.19	18.08	10.54	15.77	127.36
4	2-4	Wood/Spike	12.44	4.64	4.89	0.59	1.48	24.04
4	4-6	Wood/Spike	2.65	1.62	0.00	0.00	0.62	4.80
4	6-10	Wood/Spike	0.00	0.46	1.11	0.32	0.00	1.89
4	2-4	Wood/Pandrol	0.24	0.00	0.00	0.00	0.00	0.24
4	4-6	Wood/Pandrol	0.67	0.00	1.18	0.00	0.00	1.85
5	0-2	Wood/Spike	49.84	6.27	0.00	0.00	0.00	56.11
5	2-4	Wood/Spike	0.8	0.87	0.00	0.00	0.00	1.67
5	4-6	Wood/Spike	0.24	0.00	0.00	0.00	0.00	0.24
Total Miles			126.41	51.42	36.97	22.63	19.08	256.51

Exhibit 197. Total Miles Analyzed in Test Sections 1 to 5 of Railroad I for Wide Gage and Gage Resistance with respect in Track Class, its Geometry and Tie and Fastener Types.

Exhibit 198 shows the mean, standard deviation, and L95 of unloaded gage in Test Section 1, as a function of track curvature, class and tie/fastener type. As the degree of curvature increases, the mean, L95, and standard deviation increase in Class 3 and 4 cut spike track, and in the Class 3 elastic fastener track. In Class 4 elastic fastener track, the mean and L95 decrease, while standard deviation slightly increases as the curvature increases. In Class 5 cut spike track, no discernible trend is seen. Greater variability in unloaded gage data is seen in the higher standard deviation values in 2-4 degree Class 3 track, in 4-6 degree Class 4 cut spike track, and also in Class 3 elastic fastener track. These conditions are of concern, depending upon the railroad's maintenance practices and tolerances in Class 3 track and Class 4 track.

The mean, L95 values and standard deviation decrease with track class in 2-4 degree cut spike track. No clear class dependence is seen for other track in Exhibit 198. Class 5 cut spike track has the best gage control seen in this exhibit. It can be concluded that the higher gage widening loads experienced on higher degree curves cause the wider unloaded gage seen on the higher degree of curvature track. L95 unloaded gage values over 57.2" occur in Class 3 curves for both cut spike and elastic fastener track. A concern to control gage exists in Class 3 track in this test section.

Exhibit 199 shows the mean, standard deviation and L95 of loaded gage in Test Section 1. A decrease in loaded gage and its variability is seen as track class increases in cut spike track. A

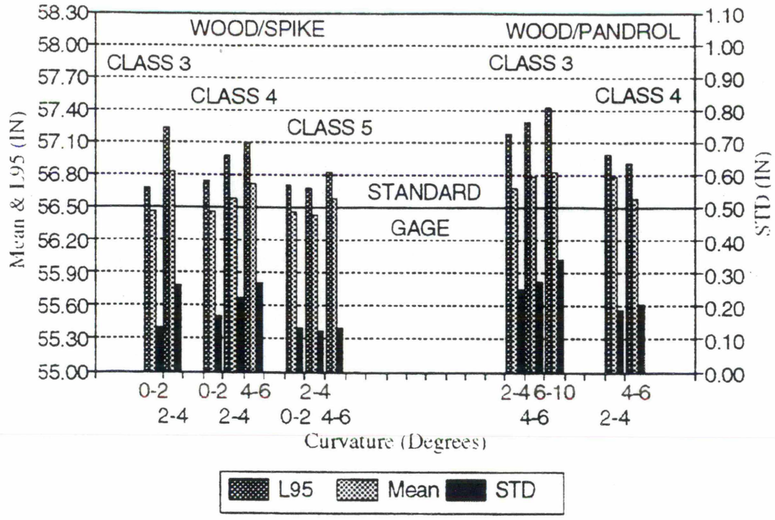

Exhibit 198. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad I, Segmented by Class, Tie and Fastener Types.

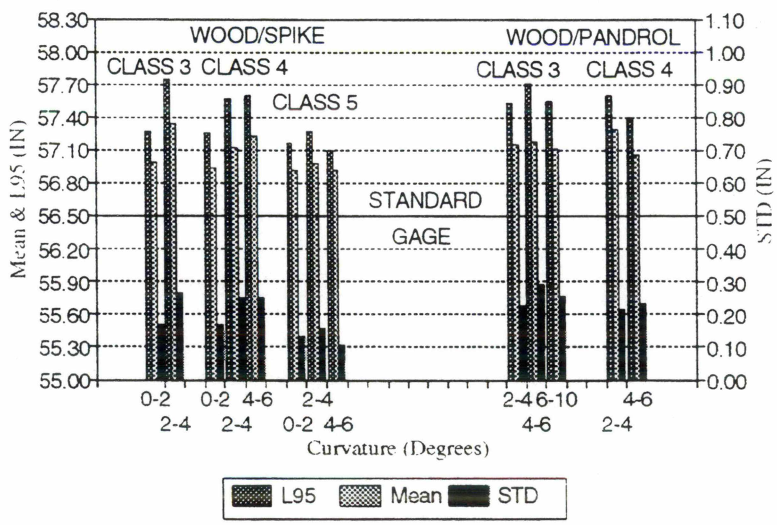

Exhibit 199. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad I, Segmented by Class, Tie and Fastener Types.

decrease in loaded gage in elastic fastener track is discernible in 4-6 degree curves. An increase in loaded gage with respect to curvature is seen in Class 3 and 4 cut spike track. In Class 5 track, a decrease in loaded gage is seen with respect to curvature. Class 4 elastic fastener track also shows a decrease in loaded gage at higher curvature, while the corresponding Class 3 curves do not seem to follow a definite trend with respect to track curvature. L95 values near 57.70" are seen in 2-4 degree cut spike curves and 4-6 degree elastic fastener curves, in Class 3 track. As about 5% of loaded gage is above 57.70", exceedences of the loaded gage paint limit of 57.75" are seen in these curves. The wide gage and loaded gage values in Exhibits 198 and 199 indicate a need for an immediate inspection and/or maintenance improvement.

The mean, standard deviation and L95 values of delta gage in Test Section 1 are seen in Exhibit 200. No weak tie/fastener conditions are seen in this exhibit indicating delta gage exceedences of 1.25". The highest L95 value of delta gage is 0.79". The corresponding L95 value of track compliance, for a gage widening load of 18 kips, is 0.044"/kip, and indicates good tie and rail restraint conditions.

No strong correlation is seen in cut spike track between delta gage values, track curvature and class in Test Section 1. In elastic fastener sections, the mean and L95 delta gage values decrease with curvature for both Class 3 and Class 4 track. Tracks with high curvature are problem areas, and increased maintenance is required. Higher operating speed in higher class track requires increased track maintenance. The decrease in delta gage mean and

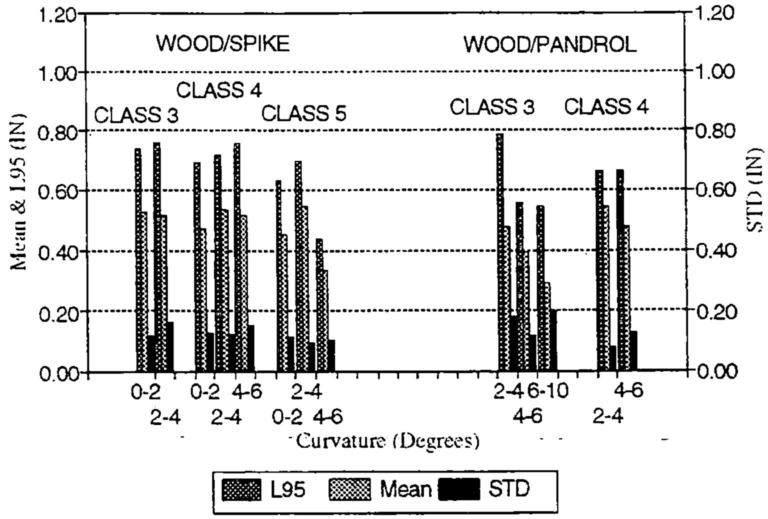

Exhibit 200. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 1 of Railroad I, Segmented by Class, Tie and Fastener Types.

L95 value with respect to curvature seen is related to better track maintenance. A slight increase in the standard deviation with curvature results from higher traffic volume and greater lateral forces at the higher degrees of curvature.

The unloaded, loaded and delta gage in Test Section 2, by track type, are seen in Exhibits 201, 202 and 203, respectively. Exhibit 201 indicates that as the degree of curvature increases, the mean, L95 values and standard deviation increase for both Class 4 and Class 5 track. A slight decrease in unloaded gage is seen with respect to track class. The Class 5 track in Test Section 2 indicates better control of unloaded gage. The maximum L95 unloaded gage value of over 57.3" is seen on 6-10 degree Class 4 track.

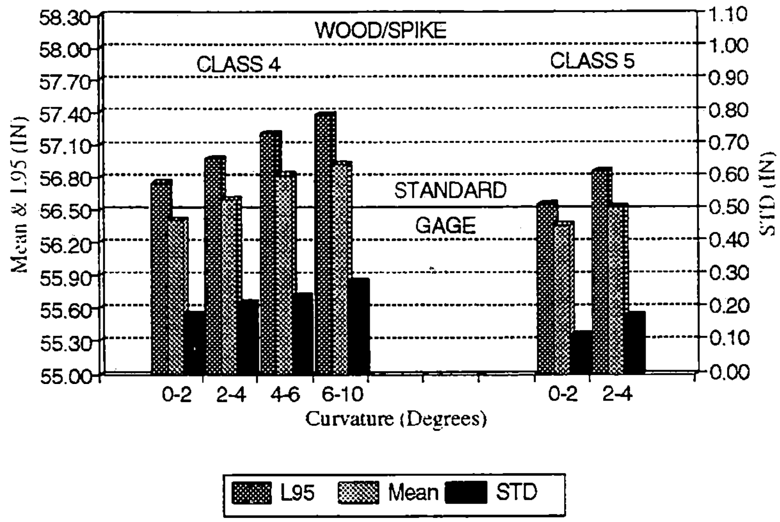

Exhibit 201. Unloaded Gage Mean, 195 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad I, Segmented by Class, tie and Fastener Type.

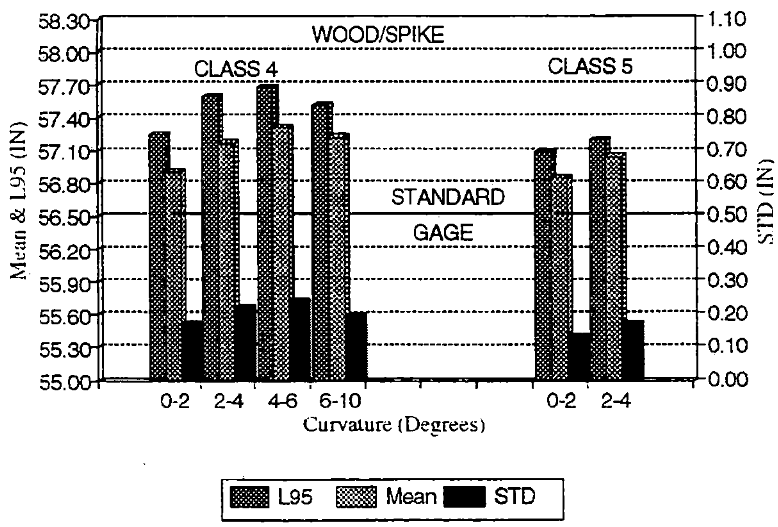

Exhibit 202. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad I, Segmented by Class, Tie and Fastener Types.

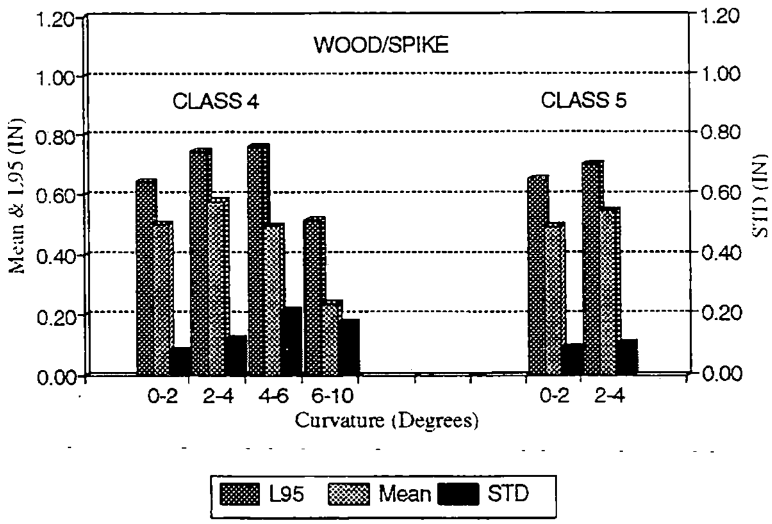

Exhibit 203. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 2 of Railroad I, Segmented by Class, Tie and Fastener Types.

Similar trends as in unloaded gage values, are seen in values for loaded gage in Exhibit 202. In contrast, however, to the increasing unloaded gage trend in the previous exhibit, loaded gage decreases on 6-10 degree curves in Class 4 track. The smaller loaded gage values, in 6-10 degree curves, reflect additional gage widening resistance, provided by adequate maintenance practices on high curvature track. The Class 5 track shows lower loaded gage values in this section. The highest L95 loaded gage value of 57.68" in 4-6 degree Class 4 curve, shows that there is no excessive loaded gage in this exhibit. Exhibit 203 indicates that delta gage values are higher in Class 4 track than in Class 5 track. Both the highest L95 value and maximum mean value of delta gage are seen in Class 4 track, and are respectively, 0.76" and

0.57". With a gage widening load of 18 kips, the mean value of 0.57" translates into a mean track compliance of 0.032"/kip, and indicates good tie and rail restraint conditions in Test Section 2.

Test Section 3, has cut spike and elastic fastener track. The corresponding unloaded, loaded and delta gage by track type are seen in Exhibits 204, 205 and 206, respectively. With two exceptions, seen in Exhibit 204, where the values are slightly higher, the unloaded gage mean values are below standard gage. The unloaded gage increases with curvature in cut spike track. While no such trend is seen in the elastic fastener track due to the limited curvature. In spite of this, the unloaded gage decreases in 6-10 degree curves in elastic fastener track. Also, a decrease is seen in unloaded gage at higher track class. Similar trends, as in unloaded gage, are seen in loaded gage in Exhibit 205. None of the L95 values is seen to exceed the loaded gage paint limit of 57.75". The highest L95 loaded gage value of 57.6" is seen in 2-4 degree cut spike track. Since all L95 delta gage values in Exhibit 206 are below 0.9", no excessive gage widening is seen in these results. The elastic fasteners appear to improve gage widening resistance. A maximum delta gage mean value of 0.7", resulting in a mean track compliance of 0.038"/kip for a gage widening load of 18 kips, indicates adequate tie and rail restraint conditions on this test section.

Test Section 4 has cut spike track. The corresponding unloaded, loaded and delta gage, by track type, are shown in Exhibits 207, 208 and 209, respectively. A comparison of test results shows that Test Section 4 has similar gage control and gage

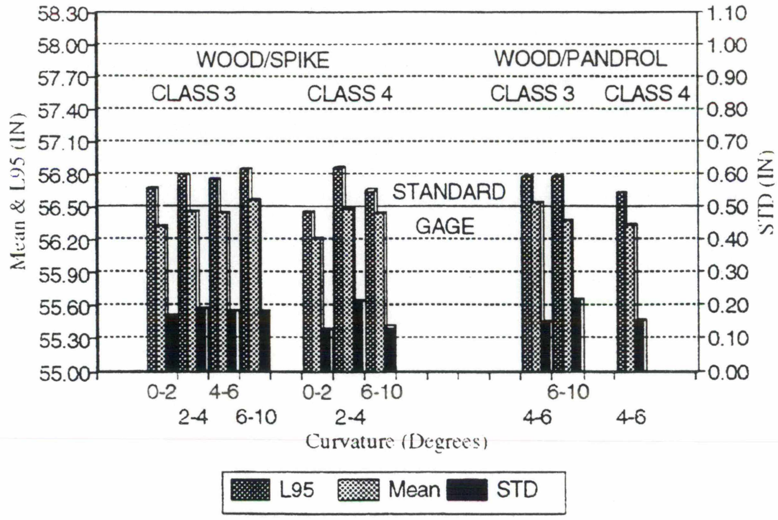

Exhibit 204. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad I, Segmented by Class, Tie and Fastener Types.

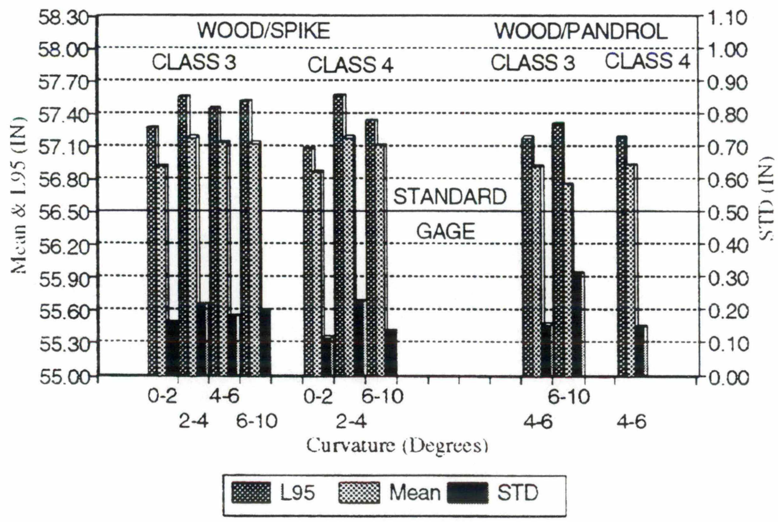

Exhibit 205. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad I, Segmented by Class, Tie and Fastener Types.

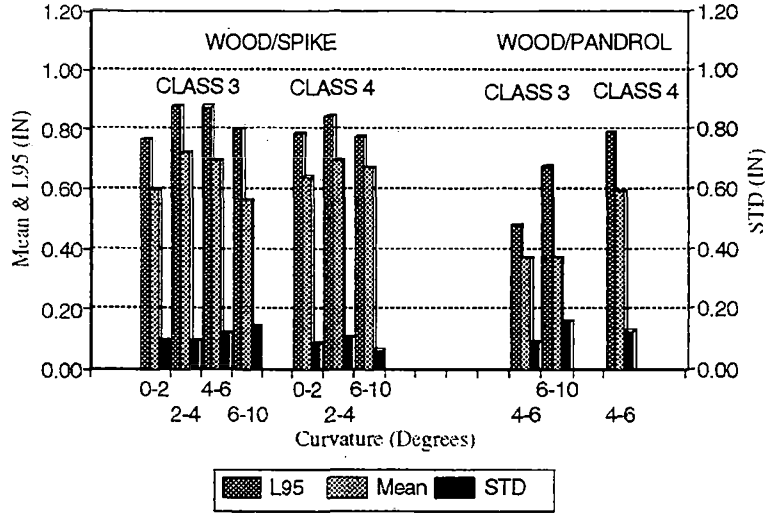

Exhibit 206. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 3 of Railroad I, Segmented by Class, Tie and Fastener Types.

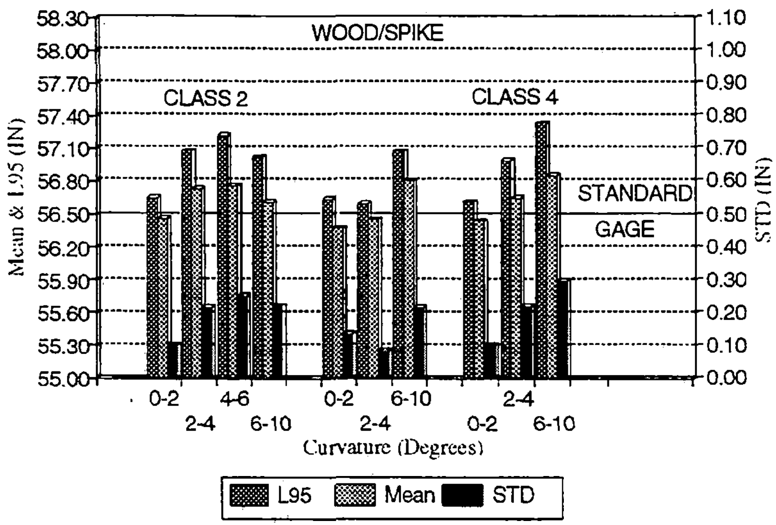

Exhibit 207. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 4 of Railroad I, Segmented by Class, Tie and Fastener Types.

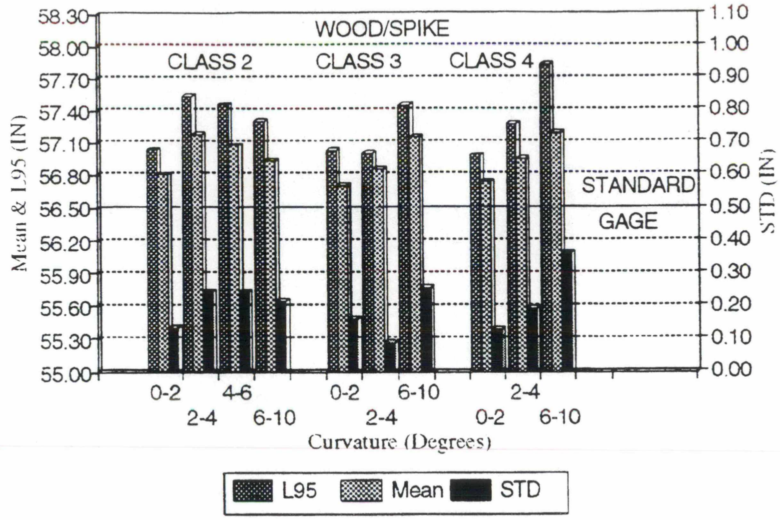

Exhibit 208. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 4 of Railroad I, Segmented by Class, Tie and Fastener Types.

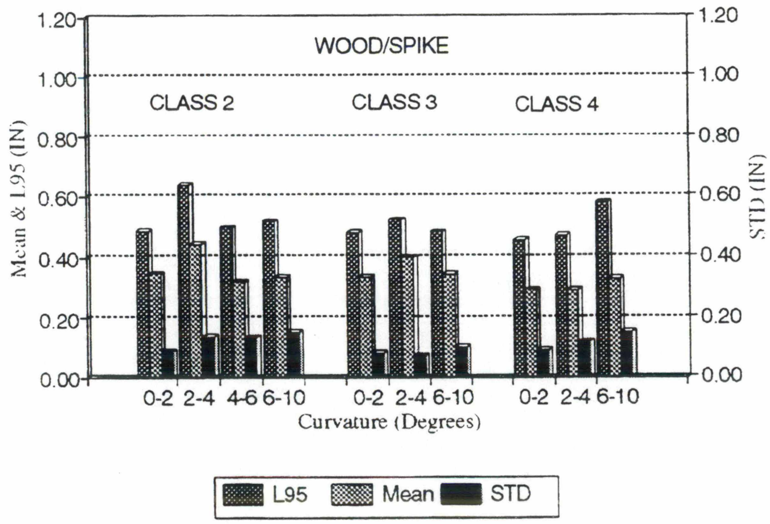

Exhibit 209. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 4 of Railroad I, Segmented by Class, Tie and Fastener Types.

widening characteristics as do other cut spikes sections seen on this railroad. As the degree of track curvature increases, the mean, L95 values, and in general, the standard deviation of the unloaded and loaded gage increase. No clear track class dependence is seen in these exhibits. The highest L95 unloaded gage value of over 57.3", and the highest L95 loaded gage of over 57.8" are seen on 4-6 degree Class 4 track. Except for the 4-6 degree Class 4 track, the L95 loaded gage values do not exceed the loaded gage paint limit of 57.75".

All L95 delta gage values seen in Exhibit 209 are below 0.63". Strong tie/fastener conditions are seen in these results. A maximum delta gage mean value of 0.44" is seen in Test Section 4. The corresponding track compliance of 0.024"/kip, for a gage widening load of 18 kips, again indicates a substantial reserve of gage widening resistance on this test section.

Test Section 5, like Test Section 4, has cut spike track. The unloaded, loaded and delta gage, by track type, are seen in Exhibits 210, 211 and 212, respectively. Test Section 5 appears to have less gage control and gage widening resistance than does Test Section 4. The unloaded gage mean values seen in Exhibit 201 are equal to or greater than standard gage. The highest L95 value of unloaded gage is over 57.0", and is seen on 2-4 degree Class 4 track. Exhibit 211 indicates that highest loaded gage value of 57.55" is seen on 2-4 degree Class 4 track. All L95 delta gage values in Exhibit 212 are below 0.75". A maximum delta gage mean value of 0.56", resulting in a mean track compliance under 0.031"/kip, indicates an ample reserve of gage widening resistance

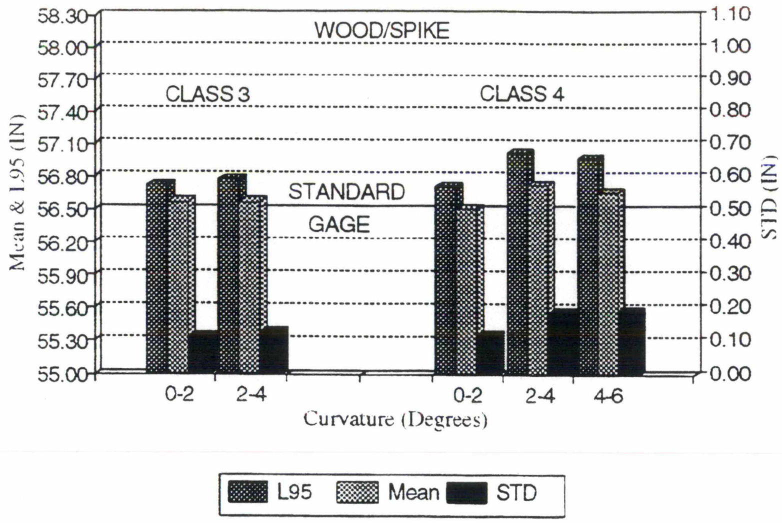

Exhibit 210. Unloaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 5 of Railroad I, Segmented by Class, Tie and Fastener Types.

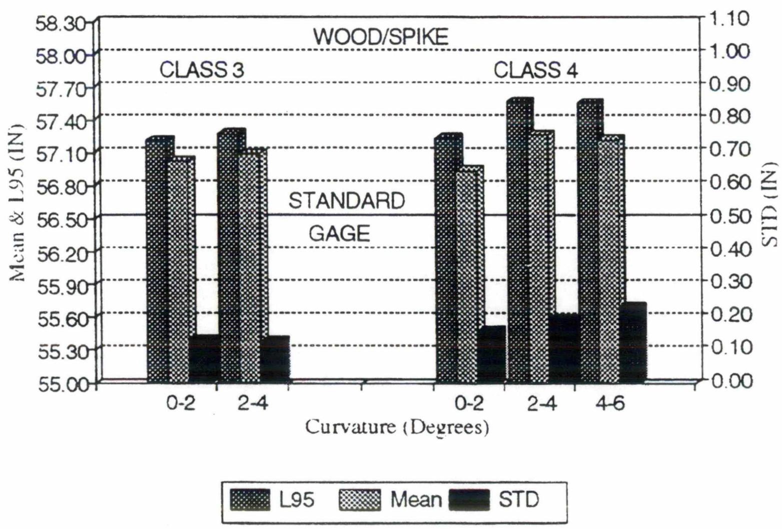

Exhibit 211. Loaded Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 5 of Railroad I, Segmented by Class, Tie and Fastener Types.

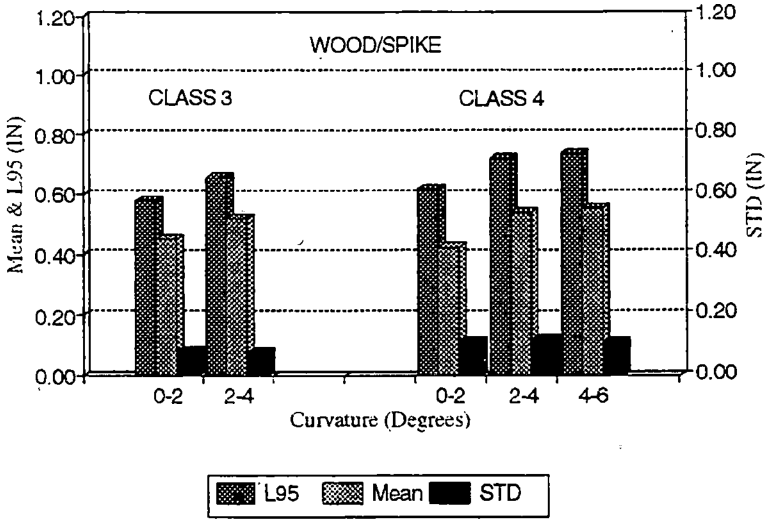

Exhibit 212. Delta Gage Mean, L95 and Standard Deviation Versus Track Curvature in Test Section 5 of Railroad I, Segmented by Class, Tie and Fastener Types.

on this test section.

6.10 ALL RAILROADS: AGGREGATE RESULTS

The analysis in this report is intended to illustrate the general condition of the railroad track tested on nine (9) Railroads in North America. The information developed in this TLV gage widening survey is also intended to demonstrate the TLV's value as a tool to guide decisions as to track lateral strength maintenance requirements. It is not the purpose of this study to define the track sections and/or railroads tested which have the best track, but to compile a representative data base of gage widening resistance and to identify any general disparity which may exist.

The test results not only demonstrate the consistency in maintenance quality and gage widening resistance seen in Revenue Service track, but the results also demonstrate the unique ability of the TLV to consistently capture and record lateral strength characteristics of the track and present the data in a format useful in making maintenance decisions.

The data from the test sections of a single railroad are combined, without regard to track type, to determine the railroad's overall gage widening resistance characteristics. This data combination resulted in a good sample size for each railroad. The smallest sample consisted of approximately 6 million data points on Railroad E, while the largest sample consisted of over 16 million data points on Railroad G. It is believed that there are no systematic errors in the data, and that the variations seen are from statistical fluctuations. It is believed that in the large sample of gage widening data, such as the above, the statistical fluctuations will tend to be normal in nature.

The trends, seen in the individual railroad analyses by mile post and track type, are smoothed by both combining the data and averaging it for the mean value. Variability in the combined data from each railroad is seen in the standard deviation, and the data scatter or dispersal is seen in the L95 values. On the assumption that each combination of data approaches normal distribution, it is expected that a L95 value will be approximately equal to 1.64 times the standard deviation plus the corresponding mean value.

Exhibit 213 shows the mean, standard deviation and L95 value of unloaded gage, developed from the combined data, on each of the

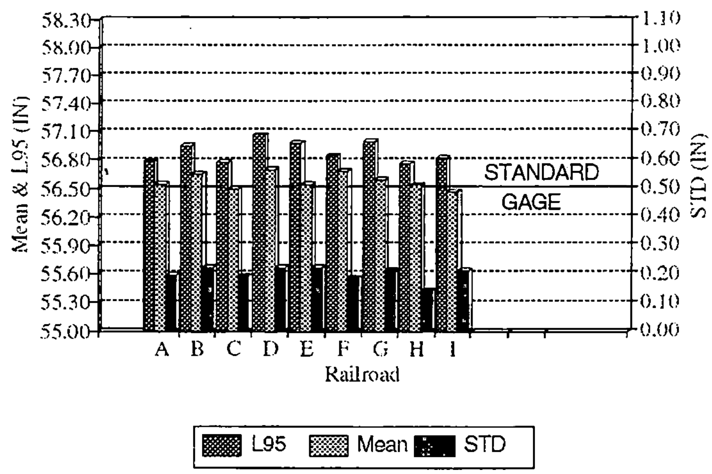

Exhibit 213. Unloaded Gage, L95 and Standard Deviation Over All Tested Miles for each Railroad A through I.

nine Class I North American railroads tested. On six of the railroads, the unloaded gage mean values are very close to the standard gage, and on the remaining three railroads they are within 0.2" of the standard gage. The average of all mean values is 56.58". The extent of wide gage is apparent from the L95 values in the exhibit. On five railroads, the L95 values are close to 56.8". On the remaining four railroads, the L95 values vary from over 56.9" to under 57.1". Unloaded gage variability, on the other hand, is seen in the respective value of standard deviation on each railroad. The respective standard deviation value, except for Railroad H, is about 0.2". For railroad H, it is 0.14". The average of the respective standard deviations is 0.2". Since each North American railroad tested has essentially the same unloaded gage mean value and standard deviation, it may be expressed as a normal distribution with constants mean = 56.58" and standard deviation = 0.2", and written as N(unloaded gage, 56.58", 0.2"), where N denotes normal distribution.

As an example of unloaded gage dispersal, the highest unloaded gage L95 value occurs on Railroad D, and has a magnitude of 57.06". Five percent of the time, unloaded gage data on this railroad exceed 57.06". Expressed quantitatively, approximately 10.3 miles, out of a total of about 208 analyzed miles, have unloaded gage in excess of 57.06". From the results seen in Exhibit 213, it is evident that at least 5% of the track miles on each North American Class I railroad tested have unloaded gage in access of 56.8". These tests do not determine whether the wide gage occurrences are due to failure to detect by visual inspection, variation in maintenance practice, or past load history of the track. The manner in which a railroad reacts to wide gage, and rectifies it, is determined by its maintenance practice, policy and tolerances, and on the class and curvature of the track.

Suffice it to say that the unloaded gage mean values in Exhibit 213 point to an adequate gage maintenance. The extent of wide gage is indicated by the L95 values in the exhibit. It is seen that a need exists to control gage on the North American railroads tested.

Exhibit 214 indicates that the mean loaded gage varies from 56.8" on Railroad H, to 57.26" on Railroad B. The average of the mean loaded gages of all nine railroads is 57.02". The extent of gage holding ability is depicted by the L95 values seen in the exhibit. The L95 values vary from 57.05" on Railroad H, to 57.62"

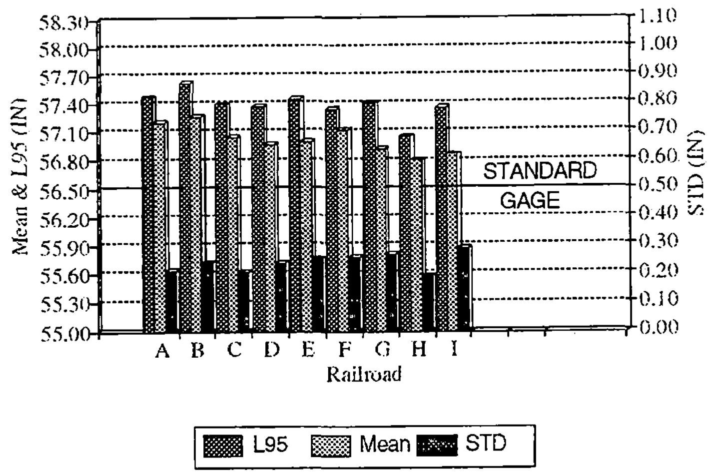

Exhibit 214. Loaded Gage, L95 and Standard Deviation Over All Tested Miles for each Railroad A through I.

on Railroad B. The L95 values are less than 0.1" from 57.4", except on Railroads B and H. Although in close approximation, the standard deviation varies from 0.19" on Railroad H, to 0.28" on Railroad I. Most of the respective standard deviations are in the neighborhood of 0.23". The average of all the respective standard deviations is 0.24". The normal distribution of loaded gage for the North American railroads tested will have constants mean = 57.02" and standard deviation = 0.24", and written as N(loaded gage, 57.02", 0.24").

The highest L95 loaded gage value in the exhibit is 57.62" on Railroad B, and does not exceed the 57.75" paint limit. Five percent (5%) of the time, the loaded gage on Railroad B exceeds 57.62". At least 5% of the time the loaded gage exceeds 57.05" on each of the North American railroads tested. Quantitatively, this

5% exceedence may be directly convertible to 5% of the track mile on each railroad. Loaded gage exceeding the 57.75" paint limit is thus seen in 5% of a railroad's track mile, where the loaded gage has exceeded 57.05".

The conclusion that the loaded gage paint limit exceptions are not widespread on the North American Class I railroads tested is basically correct. A summation of exceedence lengths noted in the exception reports, and reported to the railroads, totals only 8.03 miles. A total of 1,939 miles were analyzed. The exceedence lengths are thus 0.41% of the total analyzed miles. This small percentage indicates that exceptions are not widespread, and that good maintenance practices exist on these railroads. It should, however, be pointed out that in the track tested most of the loaded gage exceptions were initiated by the presence of excessive wide gage.

Gage widening resistance provided by tie and rail restraint on each railroad is measured by the delta gage value in Exhibit 215 and the compliance value in Exhibit 216. Exhibit 215 indicates that excessive gage widening is not seen on the North American railroads tested. The highest L95 delta gage value is 0.86", and is less than the delta gage paint limit of 1.25" used in these tests. Although delta gage values higher than 0.86" are seen, a review of the exception reports indicates only a few exceedences of the delta gage paint limit. It is apparent that some railroads have mean delta gage values less than half of the mean values seen on other railroads, and indicates that gage widening resistance on the North American railroads tested varies substantially among the

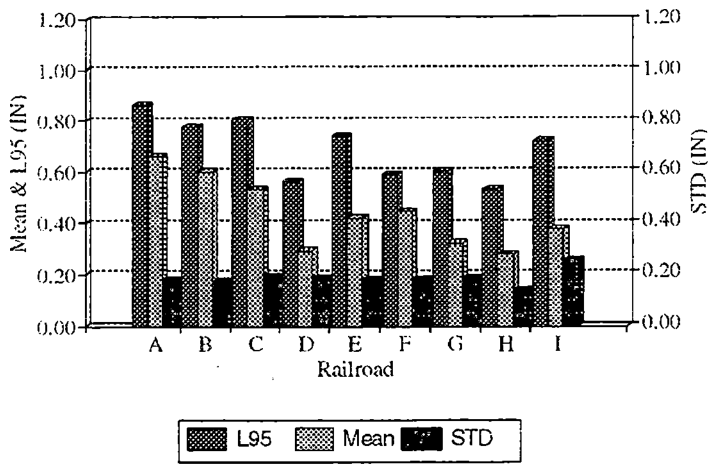

Exhibit 215. Delta Gage, L95 and Standard Deviation Over All Tested Miles for each Railroad A through I.

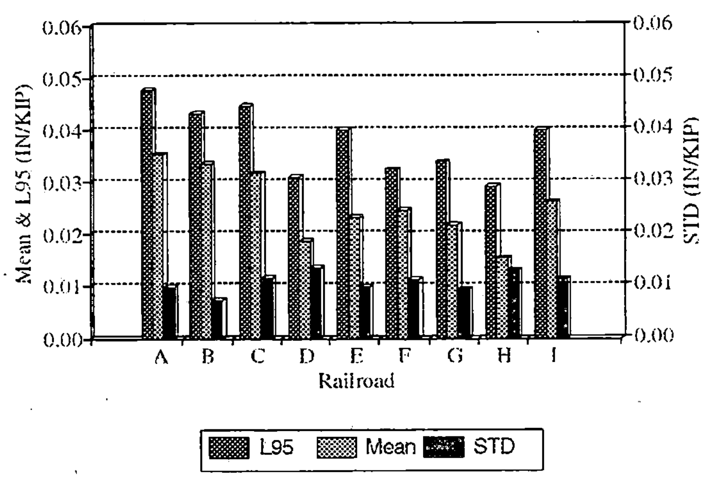

Exhibit 216. Track Compliance, L95 and Standard Deviation Over All Tested Miles for each Railroad A through I.

railroads. The lowest delta gage mean value of 0.28" occurs on Railroad H and the highest of 0.66" on Railroad A. The average of all the respective delta gage mean values is 0.44". The respective standard deviations are close to 0.18", except on Railroads H and I. On Railroad H, it is 0.14" and on Railroad I 0.27". The average of all the respective standard deviations is 0.185". An approximation to the normal distribution of delta gage on the North American railroads tested will have constants mean = 0.44" and standard deviation = 0.185", and written as N(delta gage, 0.44", 0.185").

It is instructive to compare the dispersion of the respective delta gage values in terms of a coefficient of variation. This coefficient is defined as the ratio of the standard deviation to the mean. It provides an index of the deviation of overall data from the mean value. The lowest value of the coefficient of variation of 0.27 occurs on Railroad A, and the highest value of 0.68 on Railroad I. Two railroads have coefficients of variation which are closer to the lowest value. Three railroads are closer to the highest value, while the remaining railroads have values which are in between the low and the high values. These values indicate that the confidence in a delta gage value to be near the mean value is low for five of the railroads which have higher values of the coefficients. In comparison, there is a much better confidence that a delta gage data is closer to the mean value on the remaining four railroads.

While no excessive gage widening is seen in Exhibit 215, delta gage uniformity is seen to be lacking on the North American railroads tested. High values of coefficients of variation and large differences among railroads indicate a greater scatter of delta gage data about the respective mean value. Whether this scatter reflects different maintenance practices, segmental upgrading of track lateral strength, or traffic considerations as to accumulation of load cycles, is not ascertained in these tests.

The lack of uniformity in gage widening resistance among the railroads tested is quantified in Exhibit 216. The higher the compliance value, the weaker is the gage widening resistance. Track compliance mean value as low as 0.015"/kip occurs on Railroad H, while the highest mean value of 0.035"/kip occurs on Railroad A. These results indicate that the gage widening resistance varies from strong to good on the North American railroads tested. The average of all the respective compliance mean values is 0.025"/kip. The highest L95 value in Exhibit 216 is 0.048"/kip. This indicates that at least 95% of all the track compliance data in these tests is below 0.048"/kip, and a good reserve of gage widening resistance is thus apparent on the North American railroads tested. An approximation to the normal distribution of track compliance on the North American railroads tested will have constants mean = 0.025"/kip and standard deviation = 0.0107"/kip, and written as N(track compliance, 0.025"/kip, 0.0107"/kip).

To present a systems view, each railroad's aggregate data was consolidated to generate a combined data base for the North American Class I railroads tested. This combination of 1,939 miles of analyzed track data corresponds to over 89 million data points, which were then analyzed for unloaded gage and gage widening resistance. Exhibits 217 to 219 show the combined statistical results, which are as follows: 1) unloaded gage mean = 56.58", standard deviation = 0.215" and L95 = 56.97", 2) loaded gage mean = 57.0", standard deviation = 0.28" and L95 = 57.48", 3) delta gage mean = 0.417", standard deviation = 0.227" and L95 = 0.78", and 4) track compliance mean = 0.0247"/kip, standard deviation = 0.0126"/kip and L95 = 0.043"/kip.

The gage parameter distributions, from the combined data, are seen in Exhibit 220. The distributions are plotted on normal probability paper. Since a normal distribution plots as a straight line on this paper, the adherence of each curve to a straight line indicates that the corresponding gage parameter has approximately a normal distribution. Using the mean values and standard deviations from the combined data, the gage parameters of the North American railroads tested can be described as follows: N(unloaded gage, 56.58", 0.215"), N(loaded gage, 57.0", 0.28"), N(delta gage, 0.417", 0.227"), and N(track compliance, 0.0247"/kip, 0.0126"/kip). It is interesting to note the close correlation of these combined data constants with the corresponding constants seen earlier in this section, derived by averaging the respective railroad constants.

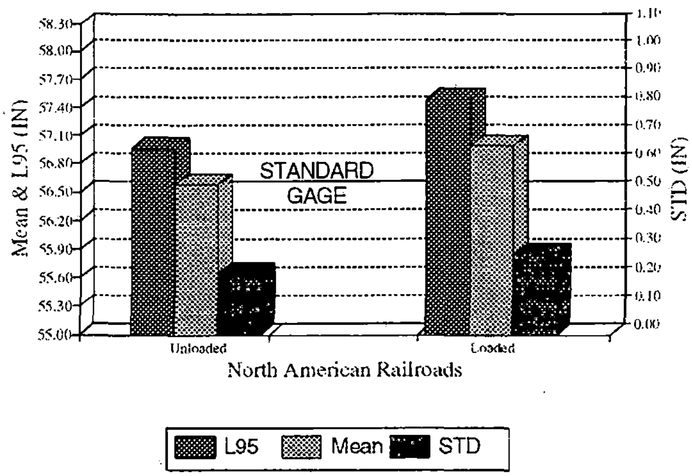

Exhibit 217. Unloaded and Loaded Gage Mean, L95 and Standard Deviation Over All Tested Miles of All Railroads A through I.

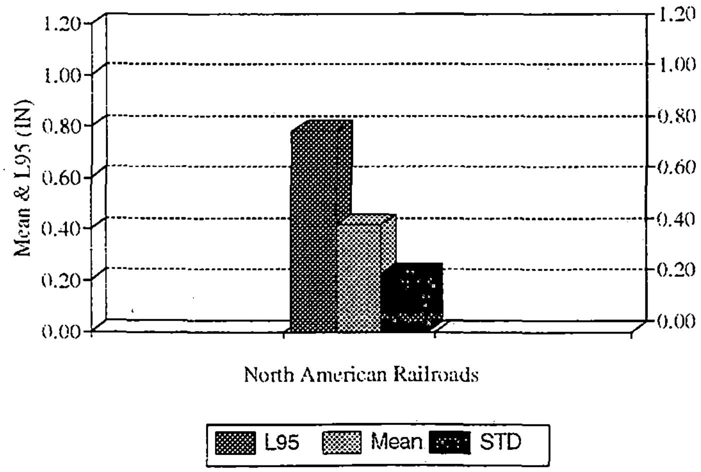

Exhibit 218. Delta Gage Mean, L95 and Standard Deviation Over All Tested Miles of All Railroads A through I.

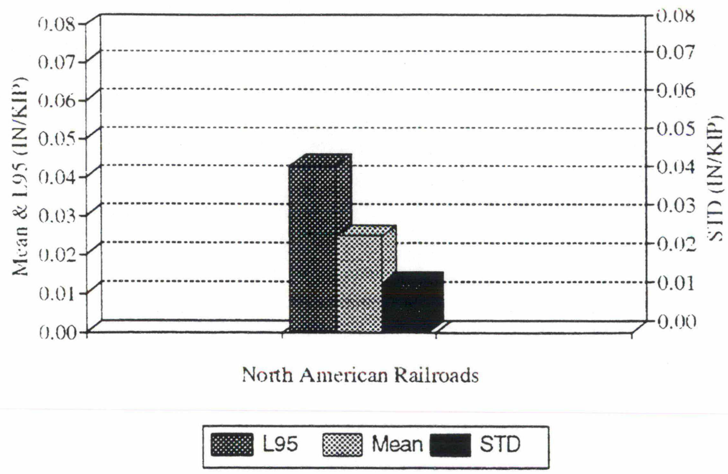

Exhibit 219. Track Compliance Mean, L95 and Standard Deviation Over All Tested Miles of All Railroads A through I.

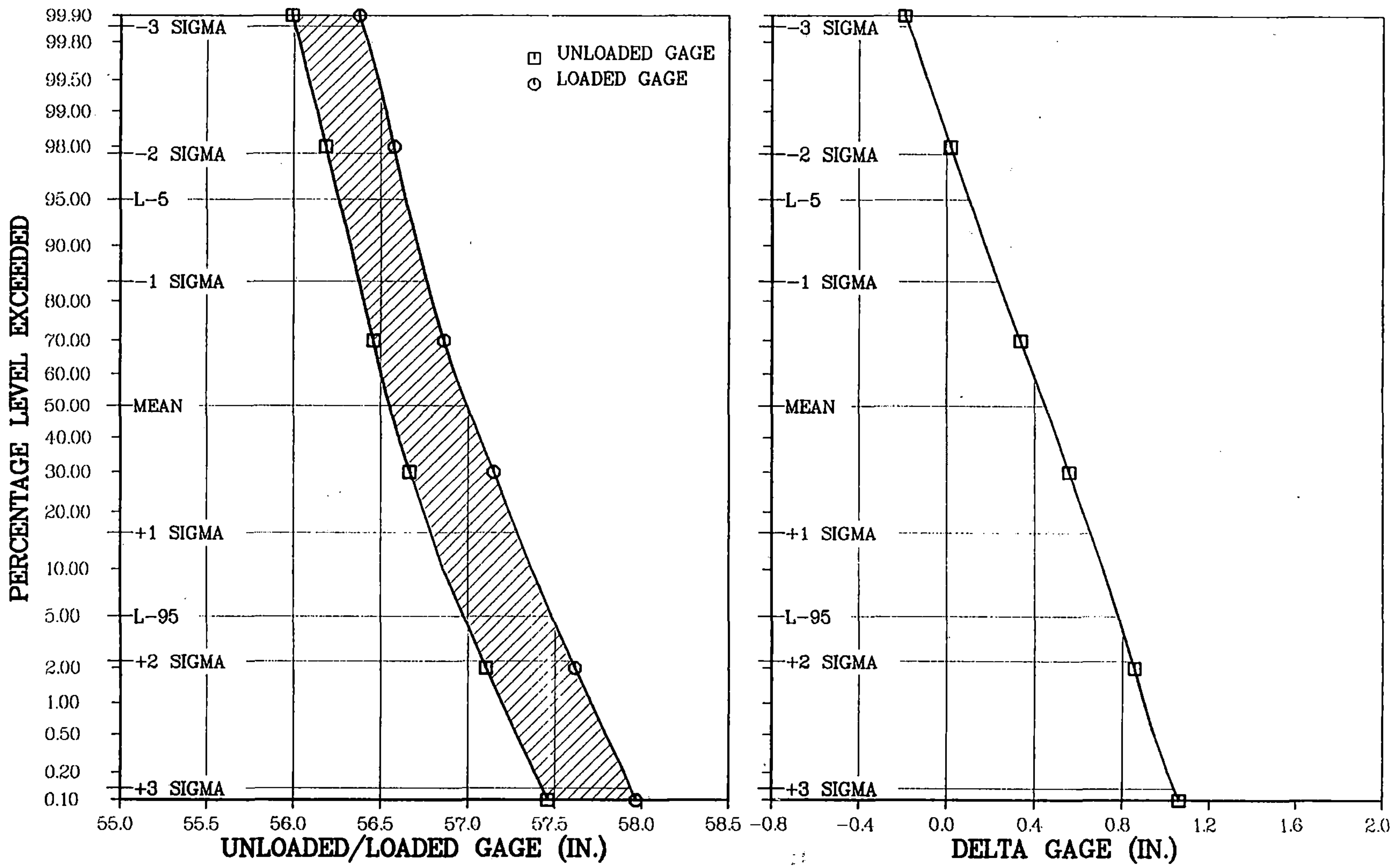

Exhibit 220. Percentage Level Exceedences of Unloaded, Loaded and Delta Gage Using Data Over All Tested Miles of All Railroads A through I.

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7.0 SUMMARY AND CONCLUSIONS

A series of TLV revenue track gage widening tests were conducted on selected sections of North American railroads in 1991 and 1992. The primary objective of these tests was to assemble a data base of North American track gage and its lateral strength. A secondary objective was to demonstrate the TLV's utility for automated and in-motion inspection of the tie/fastener performance. This was achieved by the TLV's ability to locate and spray paint those track sites where excessive loaded gage and/or delta gage was found.

A total of 1,939 miles of main line track, in 37 separate and distinctive test sections containing both good and problem track, and representing nine Class I railroads were analyzed in the United States, Canada, and Mexico. The track types included curvatures from 0 to 10 degrees, FRA classes from 2 to 6, concrete and wood ties, and cut spikes and elastic fasteners. The variety of track types, curvatures, component types, and traffic provide a valuable data base from which to study track lateral strength. The tests were conducted at an average speed of 20 mph. A 33-ton split-axle load and an 18-kip gage widening load were applied to the track.

The loaded gage, under controlled vertical and gage widening loads applied by the TLV's split-axle, were measured. These measurements were compared to the measured unloaded gage to determine the change in gage, termed delta gage. The delta gage was normalized by the applied gage widening load to compute the compliance of the track, which is a direct measure of its gage widening resistance. The measured unloaded gage and loaded gage, along with the computed delta gage and track compliance are used to identify wide gage, and to determine the gage widening resistance of the North American railroad track tested.

Each railroad was examined individually, by performing statistical analyses on the four primary parameters described above. Each parameter was analyzed for mean value, standard deviation, and the 95th-percentile value by segmenting the data from each railroad in two ways, (1) by each mile tested and (2) by each track type tested. Each railroad was also analyzed without segmenting its aggregate data on a track mile basis or a track type basis. Finally, the data from all of the railroads were combined to provide an overall assessment of gage parameters of the North American railroad track tested.

Based on the results presented in this report, the following observations and conclusions are reached:

1. Gage exceptions are not widespread on the North American Class I railroads tested. The total painted length due to all exceptions was about four-tenth of one percent of the total analyzed miles. Overall, the North American railroad track tested was in a very good gage state.

2. More than 90% of the time, exceptions occurred due to the exceedence of the loaded gage paint limit of 57.75". Wide gage was determined to be the onset of these exceptions, as the computed delta gage values did not, in most cases, imply laterally weak track.

3. The causes for the wide gage presence were not ascertained in these tests. The test results, however,

indicate that the solution may reside in correcting gage by regaging, rather than improving the lateral strength of the track by component replacement.

4. The presence of wide gage and/or existence of weak tie/fastener condition at painted track locations was verified by the respective railroad personnel. These tests demonstrated the TLV's utility, as an objective and automated inspection tool, for the in-motion inspection of tie/fastener performance.

5. Often dramatic changes in gage widening resistance are seen when entering a bridge or road crossing, or testing through a transition from cut spike to elastic fastener track, and vice versa. The localized gage weakness at the transition is easily detected by a spike in the delta gage data.

6. Whether exhibiting tight or wide gage, high gage widening resistance is always encountered over road crossings. It is believed that at well maintained and drained road crossings, its rigid structure greatly assists in gage control.

7. Low gage widening resistance generally is seen on open-deck bridges, while ballasted-deck bridges exhibit high gage widening resistance. Because of the limited number of bridges in these tests, the low gage widening resistance can not be judged as a typical of open-deck bridges, however, further examination may be required, and field inspection is recommended when low gage widening resistance is seen.

8. Evidence and magnitude of wide gage are more pronounced in cut spike track than is the case in elastic fastener track.

The delta gage values in elastic fastener track are generally about half these values in cut spike track. It can be inferred that elastic fasteners, whether on wood or concrete ties, provide a better gage holding mechanism and a higher gage widening resistance than seen in cut spikes.

9. The unloaded gage and loaded gage, and their respective standard deviations, generally increased with higher curvature track. Delta gage, on the other hand, generally decreased with an increase in track curvature. Although higher traffic volume can increase delta gage, it is believed that the delta gage decreases seen on higher degrees of curved track are due to better maintenance practices and greater gage widening resistance. A characteristic change with respect to track class was not as clear. It appears that higher traffic volume on initially stronger track would increase its delta gage such that it could be comparable to that of lower class track with lower traffic volume.

10. The averages of the respective low and high values from the mile-by-mile analyzed test sections were calculated. It was found that:

a) the mean unloaded gage varied from 56.4" to 56.82", and the 95th-percentile variation from 56.6" to 57.23" showed that, at least 5% of the time, the unloaded gage data had magnitudes of more than 56.6";

b) the mean loaded gage varied from 56.8" to 57.25", and the 95th-percentile values varied from 57.0" to 57.7" showing that the loaded gage data thus had magnitudes of more than 57.0" for at least 5% of the time;

c) the mean delta gage varied from 0.3" to 0.6", and the 95th-percentile values varied from 0.47" to 0.76", showing that at least 5% of the time the delta gage data had values greater than 0.47";

d) the mean compliance varied from 0.0166"/kip to 0.033"/kip, while the 95th-percentile values varied from 0.026"/kip to 0.042"/kip showing that compliance data had magnitudes of more than 0.026"/kip for at least 5% of the time.

11. The averages, on the other hand, from all of the respective railroad-by-railroad values showed that:

a) the mean unloaded gage was 56.58", standard deviation 0.2", and at least 5% of the track miles on each railroad had wide gage in excess of 56.8";

b) the mean loaded gage was 57.02", standard deviation 0.24", and at least 5% of the time, the loaded gage exceeded 57.05" on each railroad;

c) the mean delta gage was 0.44", standard deviation 0.185", and at least 95% of the track miles on each railroad had delta gage less than 0.86"; and

d) the mean compliance was 0.025"/kip, standard deviation 0.0107"/kip, and at least 95% of the time, the compliance was below 0.048"/kip.

12. A systems view was achieved in this study by combining data from all railroads into a common data base. This combination comprised of 1,939 miles of analyzed track which

corresponded to over 89 million points in the data base. The combined data results are:

a) the unloaded gage mean = 56.58", standard deviation = 0.215", and L95 = 56.97";

b) the loaded gage mean = 57.0", standard deviation = 0.28", and L95 = 57.48";

c) the delta gage mean = 0.417", standard deviation = 0.227", and L95 = 0.782"; and

d) the compliance mean = 0.0247"/kip, standard deviation = 0.0126"/kip, and L95 = 0.043"/kip.

13. The combined results also indicated a closeness to normal distribution. Due to this significant behavior, normal distributions can be used to describe the unloaded, loaded and delta gage and the compliance of the North American railroad tracks tested. Using the mean values and standard deviations from the combined data, these distributions in condensed normal distribution (N) forms are as follows:

N(unloaded gage, 56.58", 0.215"),

N(loaded gage, 57.0", 0.28"),

N(delta gage, 0.417", 0.227"), and

N(track compliance, 0.0247"/kip, 0.0126"/kip).

14. Delta gage results show that excessive gage widening is not present, and that there exists a good reserve of gage widening resistance on the North American railroads tested.

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