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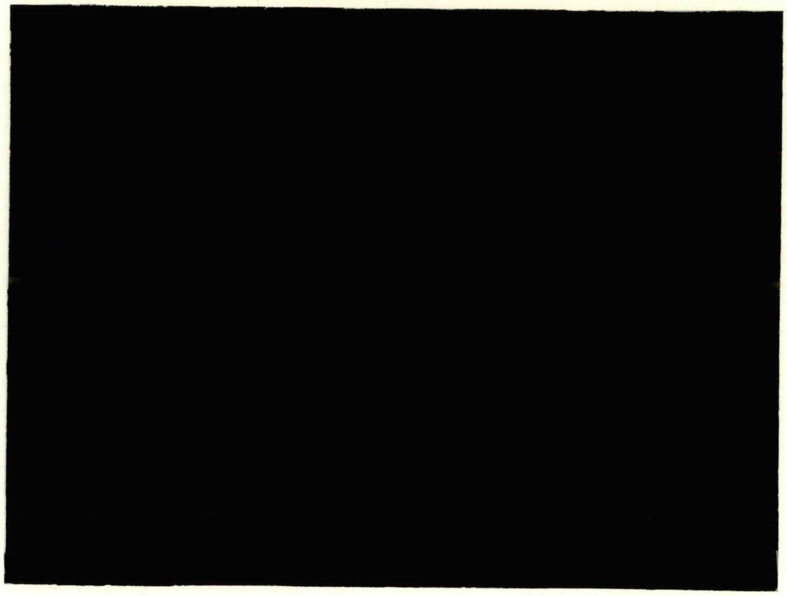

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HEAVY AXLE LOAD TRACK GAGE WIDENING TESTS BY USING THE TRACK LOADING VEHICLE

REPORT NO. R-873

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October, 1994

AAR Technical Center
Chicago, Illinois

DISCLAIMER

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13. ABSTRACT

The TLV was used to conducted a series of static and dynamic gage widening tests. The tests were conducted over the High-Tonnage Loop at the AAR's Facility for Accelerated Service Testing (FAST) in Pueblo, Colorado. The gage widening under the 39-ton axle load was compared with that under the 33-ton axle load.

For the same L/V ratio, an increase in the average dynamic gage occurred when the axle load was changed from 33 to 39 tons. However, under a constant gage widening load, the gage widening decreased under the 39 ton axle load. The Pandrol and Safelock fasteners, on domestic hard/softwood ties, provided superior gage widening strength than the cut spikes on similar ties.

A characteristic difference in the cut spike gage widening strength on ties of various wood species was not obvious except on the Azobe ties. The cut spikes on Azobe ties provided distinctly better gage widening strength. In spite of the greater hardness of wood in the Azobe ties, a significant difference between the performances of elastic fasteners on domestic hard/softwood ties and the Azobe ties was not obvious. The data on concrete ties, elastic fasteners on wood ties of all species, and cut spikes on the Azobe ties indicated that track compliance decreased with the increase in gage widening load. This implied that the gage widening strength progressively increased under higher gage widening loads.

14. **SUBJECT TERMS**	15. **AVAILABILITY STATEMENT**
Heavy Axle Loads, Track Loading Vehicle, 33-ton, 39-ton, Gage Widening, Hard/Softwood Ties, Concrete Ties, Azobe Ties, Cut spikes, Elastic Spikes, Pandrol, Safelock, Fasteners, Elastic, Lateral and vertical Loads, L/V Ratio, Revenue, Track Compliance, Gage	Document Distribution Center Association of American Railroads Technical Center 3140 South Federal Street Chicago, Illinois 60616

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EXECUTIVE SUMMARY

The Track Loading Vehicle (TLV) was used to conduct a series of heavy axle load tests over the High-Tonnage Loop (HTL) at the AAR's Facility for Accelerated Service Testing (FAST) in Pueblo, Colorado. The test program was undertaken to gather data to further the understanding of the effect of 39-ton axle loads on the gage widening strength, and compare the results with those obtained under the 33-ton axle loads. Test data were collected under both static and the moving conditions, over a broad range of track types including various types of wood ties with cut spikes and elastic fasteners, and concrete ties of various designs and fasteners. The gage widening loads used in the static tests were 2 to 24 kips under 33 kip wheel load and 2 to 26 kips under 39 kip wheel load. The in-motion tests, on the other hand, were run at 20 mph, first under a constant axle load of 33 tons, and gage widening loads ranging from 10 to 22 kips. The tests were then repeated under a 39-ton axle load at gage widening loads varying from 10 to 24 kips.

The resulting rail head deflections in the static tests were measured by using Linear Variable Displacement Transducers (LVDT). These deflections were then used to assess the gage widening strength of various fastener types on various tie types. The dynamic response of the track to the applied loads, on the other hand, was measured on-board at the gage widening axle of the TLV. This measurement was compared to the corresponding unloaded gage to determine the change in gage, termed delta gage. Track compliance

as a measure of track stiffness is defined as the ratio of dynamic gage widening to the applied gage widening load. Loaded gage, delta gage and the track compliance were used to relatively assess the gage widening strengths of various types of fasteners on various types of ties.

Test results from the 5-degree curves of Section 3, 7 and 31, and the 6-degree curve of Section 25 were used. Each section was divided into various subsections consisting of either different types of ties or fasteners. For example, Section 3 was divided into subsections consisting of wood and concrete ties. Section 7 on the other hand was divided into four primary test zones of 100 wood ties each, for tests with cut spikes, double elastic spikes, Pandrol, and Safelock. Sections 25 and 31 provided test zones with different wood species and also different fastener systems. For example, Section 31 provided gage widening data with respect to 5-cut spikes, elastic spikes and Pandrol on the Azobe ties.

The gage widening strength of concrete ties was derived from gage widening data on Sections 3 and 31. Similarly, gage widening strengths of domestic hard/softwood ties with four cut spikes, and elastic fasteners such as Pandrol, Safelock and elastic spikes were found by analyzing the gage widening data from tests on Section 7. Data from Section 31 was analyzed to deduce and compare the gage widening strengths of various fastener types on the Azobe ties with the corresponding results on domestic hard/softwood ties.

The results were supplemental to the information obtained in the FAST experiment of increasing the axle loads to 39 tons. The results of these TLV tie/fastener tests at FAST indicated that increasing the axle loads from 33 to 39 tons increased the average dynamic gage widening at the same L/V ratio. However, the gage widening at the same gage widening load decreased when the axle loads were increased to 39 tons.

The results also showed that, under heavy axle loads, elastic fasteners such as Pandrol and Safelock on domestic hard/softwood ties provided much greater gage widening strength than the cut spikes. Contrary to expectations, measurements also showed that elastic fasteners on wood ties provided greater gage widening strength than on concrete ties. However, it should be noted that the wood ties at FAST were relatively new compared with those in revenue service. The difference in performance may also be related to the insolators which are used on concrete ties but not on wood ties. Interestingly, the data on concrete ties and elastic fasteners on wood ties further indicated that the track compliance decreased as the gage widening load was increased. This implies that the gage widening strength progressively increased under higher gage widening loads.

The results of gage widening tests with cut spikes on glue laminated ties and ties of various wood species (such as the hard wood consisting of Red Oak, Hemlock Fir and Red Maple, and the soft wood of Southern Yellow Pine in Section 25) indicated no characteristic differences in the gage widening strengths among themselves. Also, these strengths were comparable to that of cut spikes on domestic hard/softwood ties. On the other hand, gage widening strength of the Azobe ties with cut spikes was distinctly better than the domestic hard/softwood ties with cut spikes. In addition, the Azobe ties with cut spikes also displayed increasing gage widening strength under increased gage widening loads similar to the elastic fasteners. It appeared that the hardness of the wood in the Azobe ties was essential in enhancing the gage widening strength of cut spikes. This factor was insignificant in effecting a substantial change in the gage widening strength of elastic fasteners on these ties. The results indicated that any significant difference between the performances of elastic fasteners on domestic hard/softwood ties and the Azobe ties was not obvious.

The results suggest that the potential gage degradation due to the increased axle loads can be minimized by either controlling the gage widening loads resulting from curve negotiation or by reducing the rail lateral deflections. The gage degradation under 39-ton axle loads can therefore be kept at or below that under the 33-ton axle loads, if the gage widening loads are maintained at the same level. This can be accomplished by the use of improved suspension systems or, alternatively, controlling gage degradation by utilizing elastic fasteners on domestic hard/softwood tie track.

Finally, the TLV tests of gage widening strength are only a small aspect of the Heavy Axle Load (HAL) research. The information obtained from these tests is expected to be useful to vehicle designers in evaluating improved suspension systems for new truck design. Since the effects of increasing axle loads are expected to be line specific, the TLV is currently being utilized to conduct dynamic gage widening tests on revenue service track. The results of the TLV heavy axle load tests at FAST, together with the statistical representation of the gage widening strength of various revenue tracks will provide useful data in an economic analysis of the use of 39-ton axle loads.

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1.0 INTRODUCTION

In the late 1950's and early 1960's, with increasing competition from other modes of transportation, the railroads increased maximum axle load from 25 to 33 tons. The railroad industry is now facing yet another major challenge: safe and economic operation of even heavier axle loads up to 39 tons. In order to provide a track structure capable of supporting the increased vertical and gage widening loads, the load carrying capacity of the track must be known. Based on the results of 160 MGT (million gross tons) of operation of 39-ton axle load at the Transportation Test Center (TTC), track maintenance costs will increase at the higher axle loads. In addition, railroads will not have as much leeway in scheduling maintenance, and spot maintenance will become more urgent. It is critical, therefore, to quantify the track strength under increased axle loads in order to maintain the track at a reasonable cost.

In 1988, the Association of American Railroads (AAR) began an extensive investigation of the operation of 39-ton axle load cars at the TTC in Pueblo, Colorado. The primary objective of the heavy axle load tests on the Facility for Accelerated Service Testing (FAST) track was to gather data to permit accurate economic evaluation of the effects of operating vehicles with axle loads greater than 33 tons. The test program was designed to compare the track deterioration associated with operation of 33-ton axle load cars with that caused by 39-ton axle load cars [1]*. Operation of

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* Numbers in brackets refer to references listed in Section 8.0.

the Heavy Axle Load (HAL) consist began in August 1988, and 180 MGT of traffic was accumulated on the FAST loop by March 1991. The tests concentrated on track degradation, including rail defect occurrence and growth, rail wear, tie/fastener performance, ballast and subgrade effects, and turnout maintenance. The test is planned to continue through 1994 when the track will have accumulated about 350 MGT of traffic under the consist of 125-ton cars.

The objective of the tie/fastener experiment at FAST is to determine the effect of increased axle load on the performance of various types of wood ties and fastening systems. These tests mainly target the deterioration of rail restraint in terms of the accumulated tonnage. In addition, static rail head and base lateral displacement measurements are made to evaluate the fastener performance at various tonnage intervals.

Accurate and continuous measurement of dynamic gage widening is an important aspect of the assessment of track performance under increased axle loads. The static measurement of gage widening provides only a limited assessment of the relative strength characteristics of ties and fastening systems at a single location on the track. Therefore, a number of static measurements need to be made along the track to obtain statistically significant data. Even then, the probability of finding weak track locations would be very small through static tests, as track responds differently under the action of moving dynamic loads.

The measurements taken from a moving vehicle not only reflect the action of a moving consist but also provide a continuous assessment of the dynamic stiffness of the track segment on which it is used. In particular, if the tests are repeated under a given vertical load at various gage widening loads, an overall assessment of the gage widening strength can be made.

The Track Loading Vehicle (TLV) has the capability to apply controlled loads to the track and measure its response while moving. Also, the Heavy Tonnage Loop (HTL) at FAST was configured to have track sections with wood and concrete ties, and various fastener systems to evaluate the characteristics of these tie/fastener systems with respect to tonnage, it provided an ideal site for the TLV/HAL tests. Tests carried out earlier to quantify the loading environment and dynamic response of typical track under heavy axle load cars (39-ton axle load) showed that the TLV is capable of reproducing similar loading in most operating and track conditions [2]. Moreover, the TLV is a second generation of the track inspection (measurement) devices. It builds on experience gained with the Decorator [3], and also the currently used Gage Restraint Measurement System (GRMS) [4].

For a detailed report on the TLV and its capabilities, the reader is referred to Reference Nos. 5, 6 and 7. In short, the TLV utilizes computer controlled vertical and gage widening loads which are applied to the track structure by hydraulic actuators through the load bogie and the split-axle wheelset. The load bogie and the split-axle wheelset are centrally located between the TLV trucks. The loaded and unloaded gages, as well as the gage widening loads, are measured. These measurements may subsequently be used to determine the gage widening strength of the track as was done in the present tests. During operation, the TLV control system deals with the small irregularities in the track vertical and lateral alignments. Active intervention by the computer is used during the transition from tangent to curves. Various fail-safe modes have been built into the TLV system to prevent load bogie derailment or in the event of hydraulic power or computer failure.

The moving vehicle/track interaction can manifest as: 1) weak lateral restraint of the rail leading to rail lateral translation and/or rail-roll over, 2) track panel shift across the ballast due to large lateral forces on the track or 3) climb of the wheel over the rail. In this report, only the weak lateral restraint aspect of the track under heavy axle loads is addressed. Accordingly, the gage widening strength of various fastener types on FAST under heavy axle loads is measured. The results of these tests are deemed useful in finding better methods of controlling the gage degradation and thereby, in the long run, providing economic operation of the heavy axle loads.

Increase in gage can result from rail lateral translation, plate cutting, tie bending, rail lateral bending, torsional rotation of the rail, rail rigid body roll and rail head wear; either individually or in some combination of these factors. The primary gage widening strength consists of 1) the resistance to twisting and bending arising from the sectional properties of the rail, 2) the torsional resistance arising from pullout resistance of the gage side fasteners which resist lift off of the gage side of the rail base, 3) the resistance to rail translation arising from the fastener-tie interface (shearing) from field side fasteners which resist the lateral tie plate displacement, and 4) the additional resistance due to the frictional forces between the base of the tie plate and the top surface of the tie. The loaded gage measurement is thus, one of the most important parameters in determining the load carrying ability of the railroad track. By comparing the loaded gage with the corresponding unloaded gage, the change in the gage termed as delta gage, and track compliance (defined as the ratio of the delta gage and the applied gage widening load) can be evaluated. The loaded gage, delta gage and the track compliance are then used to assess the gage widening strength and the relative merits of the various rail fastening devices under heavy axle loads.

The HAL simulation capabilities of the TLV were therefore used to quantify the gage widening strength of track having wood and concrete ties, and also with respect to various fastener systems available at the FAST track. The TLV was used to determine the unloaded and loaded gages. Computer controlled vertical and/or lateral wheel loads were applied to the track, and the resulting gage widening responses were measured while either the TLV was stationary or moving.

The TLV/HAL tests are a continuation of the Vehicle Track Interaction project supported by the Federal Railroad Administration (FRA). The work in this report covers the stationary and moving tests to measure the gage widening strength of various tie and fastener types. Funding for the work is partly provided by the FRA under Sub-task 6b of Task Order No.6, Contract DTFR53-86-C-00011.

Since the primary objective of these tests was to compare the relative gage widening strengths of cut spikes and a variety of elastic fasteners, both on tangent and curved track, the results of these tests would provide a precursor to the TLV Revenue Track Tests of Rail Restraint. The need here was to ascertain the trend, accuracy and consistency of the results as well as to instill confidence in the integrity of the TLV gage widening mechanism.

2.0 OBJECTIVE AND METHODOLOGY

The primary objective of the TLV/HAL tests was to determine the gage widening response to the application of simulated heavy axle loads by using the TLV split-axle wheelset. The tests were designed to measure gage widening of the HTL at FAST to a combination of vertical and gage widening loads under stationary and moving conditions.

The stationary test conditions included the application of gage widening loads under a vertically preloaded track using the TLV load bogie. This was performed to understand the gage widening strength of various types of fasteners under a variety of vertically and laterally applied loads. The dynamic tests were an extension of the static tests, and were performed to simulate the dynamically produced gage widening loads in revenue service. The moving tests as such were used to measure and quantify the dynamic gage widening characteristics of various track installations with different fastener systems. In both the stationary and the moving tests, the HAL vertical wheel loads were combined with various gage widening loads to afford increasing L/V ratios up to about 0.7. The work described in this report will encompass the determination of the gage widening strength by using the TLV to obtain relationships between gage widening load and the gage widening. The subsequent compliance functions will be determined for various types of track configurations consisting of wood and concrete ties and between the various kinds of fasteners (cut spikes and elastic) in place on the HTL at FAST.

The TLV was used for the Heavy Axle Load tests of gage widening to provide knowledge about static and the dynamic gage widening strength of track having wood and concrete ties, and cut spikes and elastic fasteners. These tests were conducted under both 33 and 39-ton axle loads, representing loading under 100 and 125-ton freight cars, respectively. Throughout these tests, the vertical loads were kept constant at either 33 or 39 kips and the gage widening loads were increased from 10 kips to reach a maximum value corresponding to an L/V ratio of about 0.7.

3.0 TEST PROGRAM

3.1 Test Consist

The TLV test consist is comprised of a locomotive, the AAR-100 Research Car and the TLV, as seen in Exhibit 1. The TLV is equipped with six servo controlled electro-hydraulic actuators, a laser unloaded gage measurement mechanism, and a split-axle wheelset loaded gage measurement mechanism [5,6,7]. The laser gage measurement system is located about 16 feet ahead of the centrally located split-axle wheelset. The TLV is operated from the AAR-100 Research Car which is equipped with an electro-hydraulic actuator control system, a digital computer, data storage and display devices, analog-to-digital convertors, keyboards, signal conditioning electronics, control-module electronics, and other hardware. The TLV computer control console is shown in Exhibit 2.

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 instrumented wheelset. The unloaded and loaded gages, as well as the gage widening forces were measured continuously. These measurements were then used to determine the gage widening of the in-place track. The measurements were converted to digital format at a sample rate of 256 per second. The spatial differences in the locations of unloaded and loaded gage measurement devices with respect to the loaded gage location at the split-axle wheelset were compensated in the calculations by using the speed of the TLV at that instant.

Exhibit 1. Track Loading Vehicle and the Test Consist.

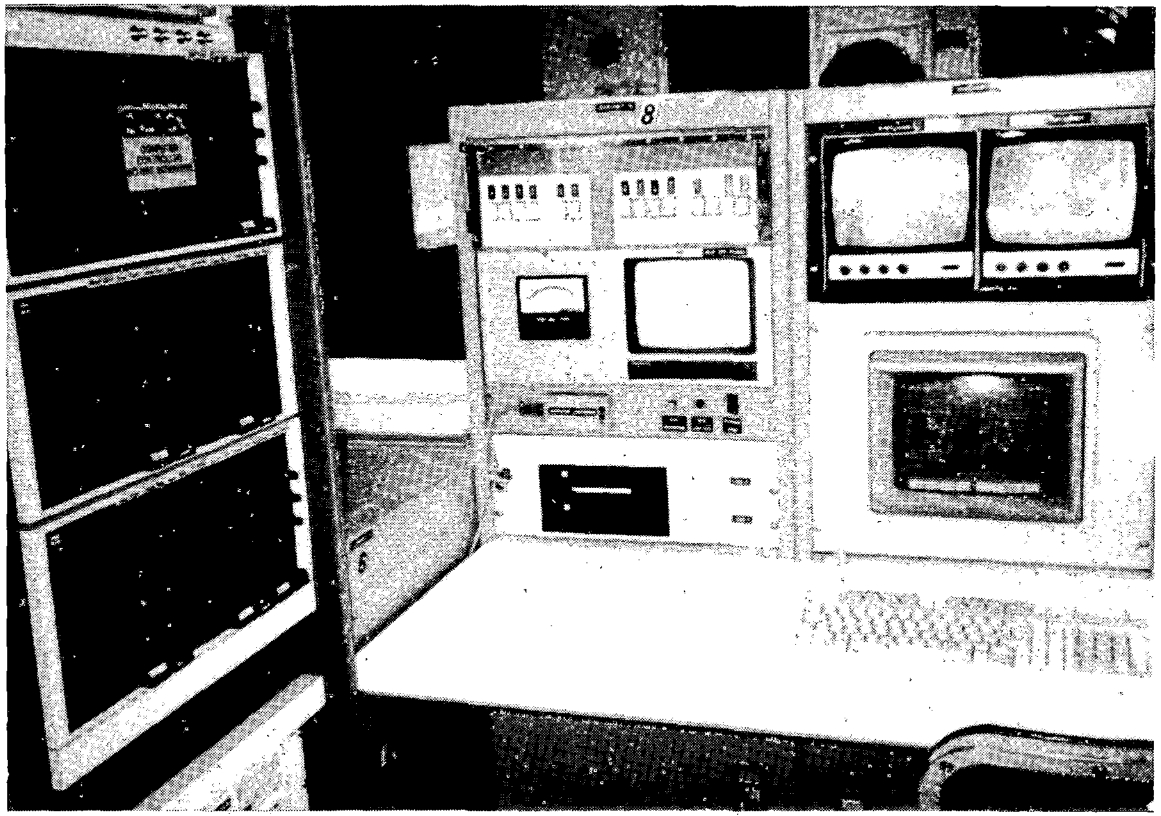


Exhibit 2. TLV Computer Control Console.

3.2 Test Track

Both the stationary and moving tests were conducted on the HTL, Exhibit 3, at FAST. The HTL, which was completed in June 1985, has a total length of 2.7 miles of various types of track including one 6-degree curve and three 5-degree curves. The HTL is divided into a number of test sections which are identified by numbers. These test sections were again rebuilt in 1988 for the HAL tests pertaining to 39-ton axle load cars. Included in specific test sections are concrete ties, jointed rail, and elastic type rail fasteners [8,9]. The locations of various test sections of the HTL are shown in Exhibit 4. The results included in this report pertain to the tests run on Sections 3, 7, 25, 29, 31 and 33. The tie and fastener types for these test sections are given in Exhibit 5 [10].

The test zones selected for these tests were the 5-degree curves in Sections 7 and 31, the 6-degree curve in Section 25, and tangent track in Section 33. In Section 7, Subsections 7A (domestic hard/softwood ties with 4 cut spikes), 7F (glue laminated ties with 4 cut spikes), 7C (domestic hard/softwood ties with Pandrol), and 7D (domestic hard/softwood ties with Safelock) were used. All ties in Section 7 are 7" x 9" x 8′-6" on 19.5" centers, and are laid on slag ballast.

In Section 31, various subsections with the Azobe (tropical hardwood) ties were used for the tests. These subsections, in the counterclockwise direction, started with a test zone of 50 Azobe ties on 19.5" centers with 5-cut spikes, followed by 50 Azobe ties

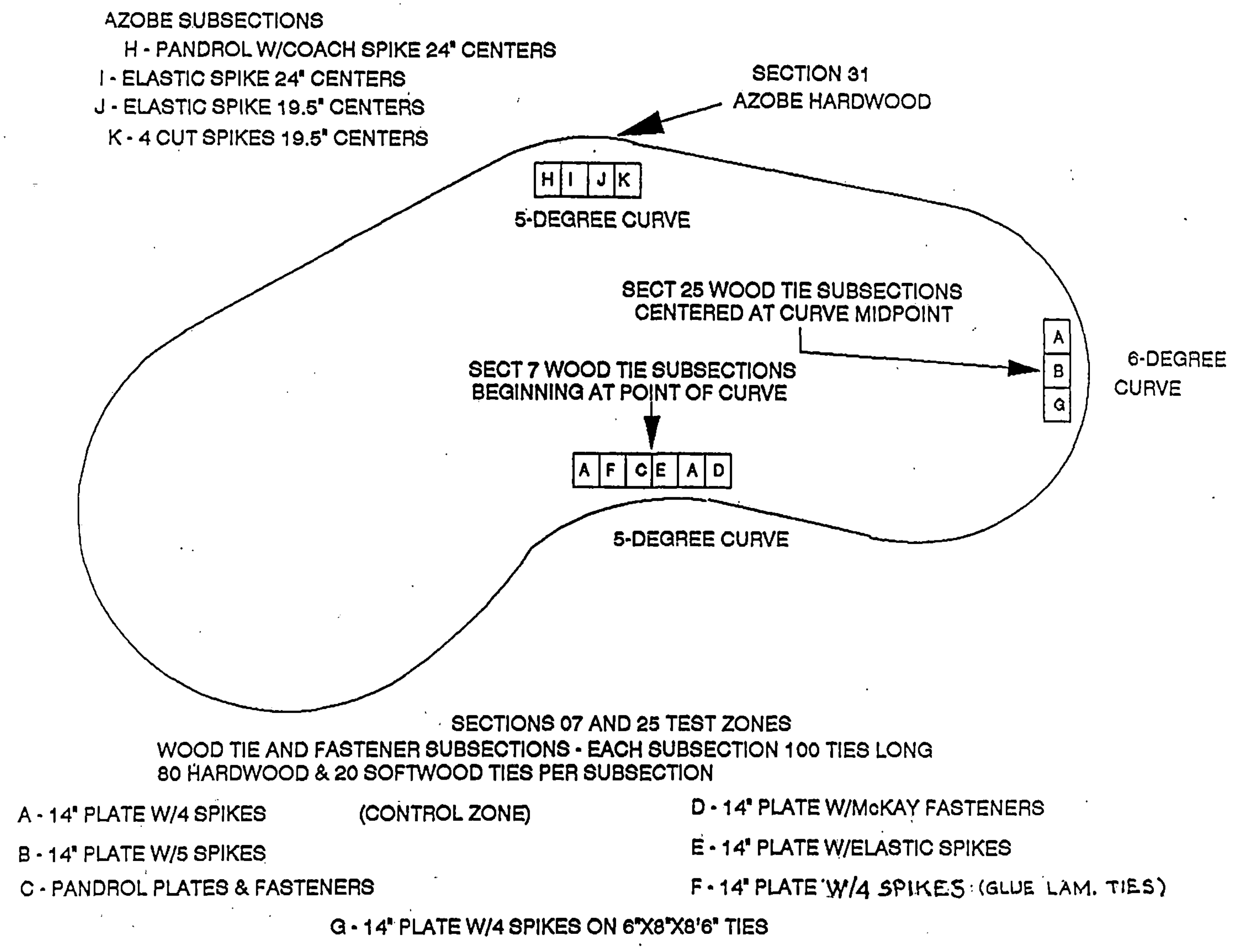


Exhibit 3. High Tonnage Loop (HTL) at FAST.

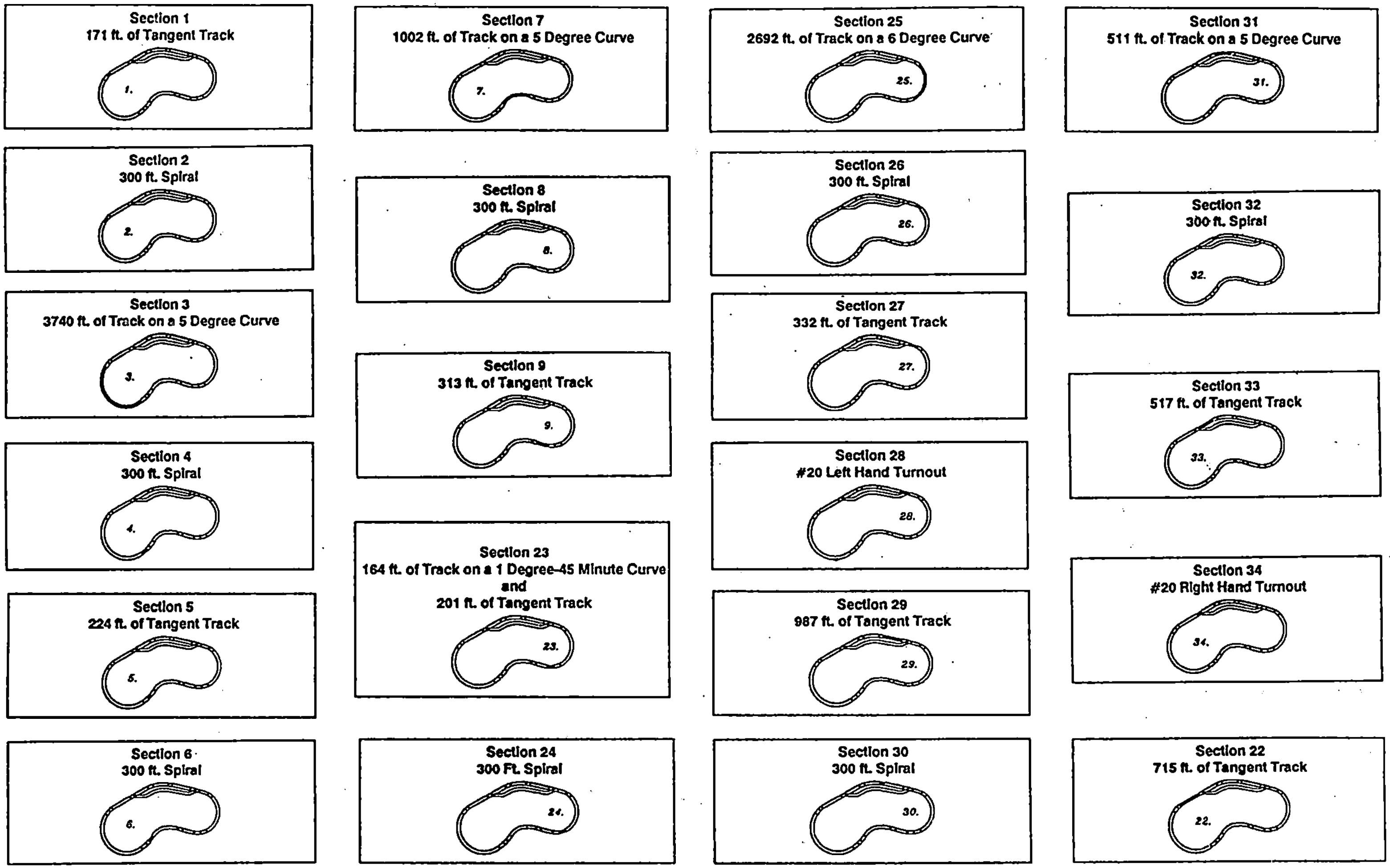


Exhibit 4. Track Sections of HTL at FAST.

SECTION	SUB-SECTION	DEGREE OF CURVE	TIE TYPE	FASTENER TYPE
3	1	5	WOOD	4-CUT SPIKES
3	2	5	CONCRETE	
3	3	5	WOOD	4-CUT SPIKES
7	A	5	WOOD	4-CUT SPIKES
7	F	5	GLUE LAMINATED	4-CUT SPIKES
7	C	5	WOOD	PANDROL
7	E	5	WOOD	ELASTIC SPIKES
7	D	5	WOOD	SAFELOCK
7	A2	5	WOOD	4-CUT SPIKES
25	A	6	WOOD	PANDROL
25	B	6	WOOD	PANDROL
25	CDE	6	WOOD	4-CUT SPIKES
25	FGH	6	WOOD	4-CUT SPIKES
25	I	6	WOOD	4-CUT SPIKES
25	J	6	WOOD	4-CUT SPIKES
25	KLMNO	6	WOOD	4-CUT SPIKES
25	PQ	6	WOOD	4-CUT SPIKES
25	R	6	WOOD	PANDROL
29		TANGENT	WOOD	PANDROL
31	1	5	AZOBE	5-CUT SPIKES
31	2	5	AZOBE	ELASTIC SPIKES
31	3	5	AZOBE	PANDROL
31	4	5	CONCRETE	
33	COMBINED	TANGENT	CONCRETE/ WOOD	PANDROL/ 4-CUT SPIKES

Exhibit 5. Tie and Fastener Types at HTL.

on 19.5" centers with Hoesch elastic fasteners and 50 Azobe ties on 24" centers with Hoesch elastic fasteners, and ended with 50 Azobe ties with Pandrol plates with E clips and four 15/16" coach screws. The ties in this section were 7" x 9" x 8'6" and were equipped with AREA 14" x 7.75" tie plates.

Section 25 tests were made to compare the performance of the track having ties of different wood species. The entire 6-degree curve was divided into various subsections of 100 or more ties each. The subsections used were Subsection 25C (Hemlock Fir with end and wear plates), 25D (Southern Yellow Pine with end and wear plates), 25E (Red Maple with end and wear plates), 25F (Red Maple, no wear plates), 25G (CN Softwood), and 25K (CN Hardwood). All ties in these subsections were 7" x 9" x 8'-6" and used 4 cut spikes as fasteners.

Section 33 was subdivided into four tangent test segments. In the counterclockwise direction, they are concrete ties, Cedrite ties with Pandrol plates and coach spikes, wood ties with 4 cut spikes, and wood ties with 5 cut spikes.

3.2.1 Stationary Tests

The main purpose of these tests was to provide an understanding and comparison of the gage widening under 33 and 39 kip wheel loads and gage widening loads up to L/V ratio of about 0.7. Track, having different kinds of rail fasteners, was subjected to the static application of the gage widening loads. By determining the relationship between the load applied to the rail head and its lateral displacement (gage widening), a comparison of different tie and fastener types was made to ascertain the advantages or disadvantages of one over the other. Tie types included were wood and concrete ties, while fastener types were cut spikes, Pandrol and double elastic fasteners. Moreover, these tests provided a link to the data collected by a different vehicle as part of the FAST test program.

During the static tests, gage widening loads were applied to the rails, using the TLV split axle wheelset, in increments of 2 kips. For one set of tests, the gage widening loads were raised, in increments, to 24 and 26 kips under 33 and 39 kip vertical loads, respectively. For the other set, the gage widening loads were applied such that the L/V ratios of 0.3, 0.5, 0.6 and 0.7 were obtained.

3.2.2 Moving Tests

The moving tests were conducted under both 33 and 39 kip wheel loads. Gage widening loads were varied from 10 to 22 kips for 33 kip wheel load case, and from 10 to 24 kips for the 39 kip wheel load case. Gage widening load increment was 2 kips. The test speed for all of the tests was about 20 mph. These tests were run in one direction only (counterclockwise) around the HTL loop for each of the vertical and gage widening load combination. For each test, the starting location for the test consist was near Section 22 which is a 715 foot of tangent track. For these tests, results from Sections 3, 7, 25, 29, 31, and 33 were analyzed. Before starting the tests, the subsections of the various sections mentioned above, were demarcated by using automatic location detectors (ALD's).

The differing track characteristics used in the tests were: wood and concrete ties in Section 3; fastener types in Section 7; ties with various wood species in Section 25; tangent track in Section 29; and wood, concrete and fastener types in Sections 31 and 33.

4.0 INSTRUMENTATION AND DATA COLLECTION

During the stationary tests, the unloaded gage measurement was taken by a hand-held track gage rod prior to the TLV being rolled onto the site. The Linear Variable Displacement Transducers (LVDT) and stands were fixed on both the gage and field sides of the rail on the test tie. The lateral displacements of the rail head and base on the field side as well as the rail base vertical lift on the gage side were measured.

The measurements taken during the stationary tests were made by using both the on board and wayside instrumentation. The on board measurements gave the total gage widening that took place under the application of a given combination of vertical and gage widening loads. Wayside instrumentation was used to determine the ways in which the total gage widening was distributed.

During moving tests, the unloaded gage was measured using the on board laser gage measuring system. Only the on-board data collection was used. Gage widening loads and displacements, vertical actuator forces and displacements, together with instrumented split-axle wheelset (raw and processed) lateral and vertical loads were collected.

Data was collected at 256 samples per second per channel. The conditioned signals were anti-alias filtered at 100 Hz. 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 shipped 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. In the following sections, the results of the tests are presented.

5.0 STATIONARY TEST RESULTS

Results from the stationary tests are divided into two broad categories, namely, the gage widening comparison among fastener types, and the comparison of the effects of heavy axle loads of 33 and 39 tons on the gage widening mechanism. The total gage widening, which is sum of the head deflections of both the rails, is used to characterize the gage widening strength. These results of track strength are presented in terms of bar graphs of the total gage widening, in steps of four L/V ratios for each fastener type.

The track strength data from Section 7 are given in Exhibit 6. Average gage widening corresponding to L/V ratios of 0.3, 0.5, 0.6 and 0.7, under the 33 kip wheel load, is shown. Similarly, Exhibit 7 shows these results under a 39 kip wheel load. The fastener types shown are: four cut spikes, Pandrol, and Safelock. Also included in the plots are four cut spikes on glue laminated ties. At low L/V ratios, the difference in the gage widening between the cut spikes and the elastic fasteners is small. This difference in the gage widening, however, increases substantially as the L/V ratio is increased. The difference in the total gage widening for four cut spikes on domestic hard/softwood ties, from an L/V ratio of 0.3 to an L/V ratio of 0.7, is approximately 0.55" for 33 kip wheel load. For a 39 kip wheel load, this difference is approximately 0.5". For both 33 and 39 kip wheel loads, the gage widening at an L/V ratio of 0.7 is more than 5 times the gage widening at an L/V ratio of 0.3. That is, a change in L/V ratio greatly affects the gage widening strength of the wood ties with

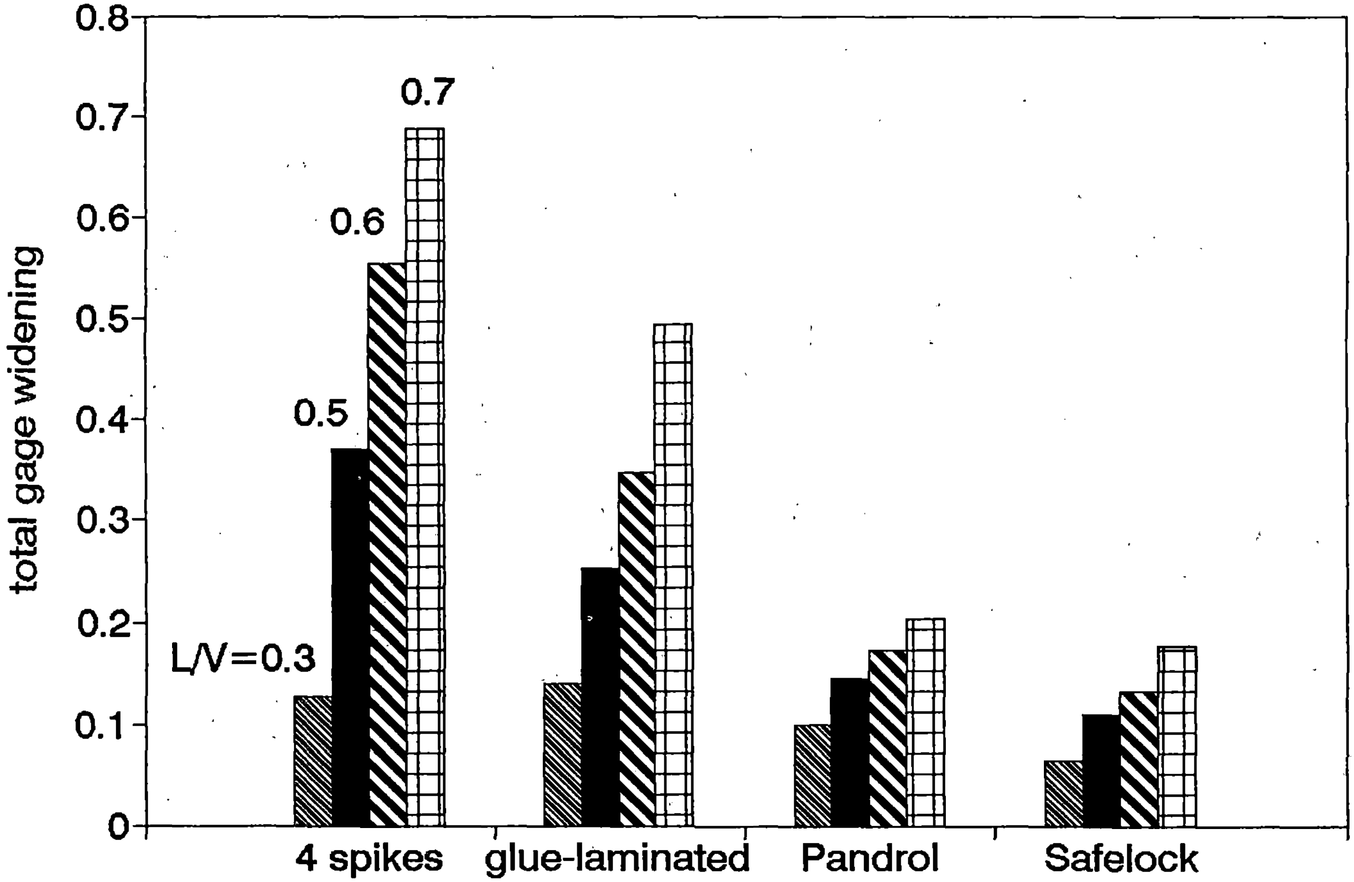


Exhibit 6. Comparison of Static Gage Widening of Different Fasteners on 5-Degree Curve (Section 7), V=33 Kips.

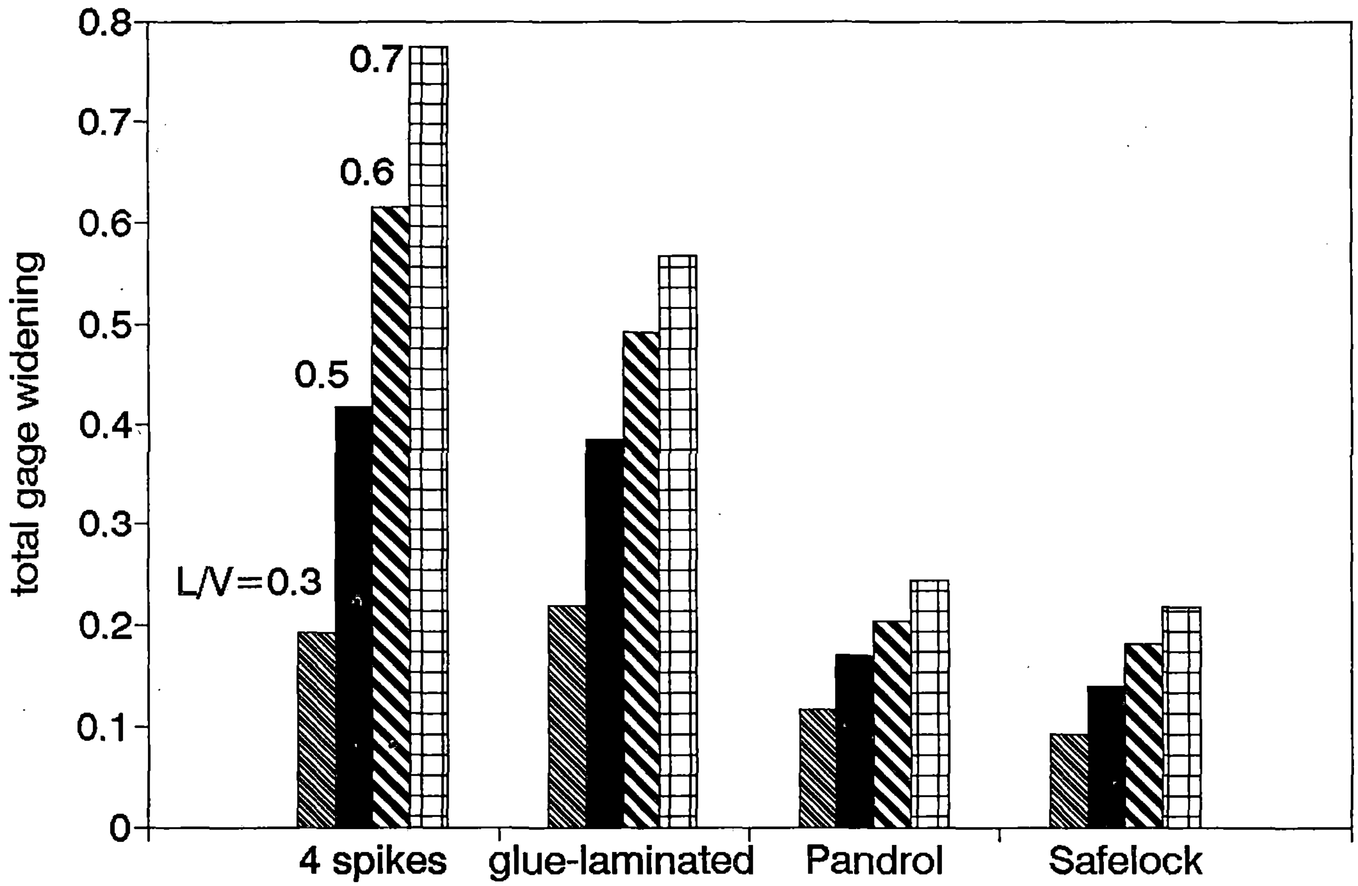


Exhibit 7. Comparison of Static Gage Widening of Different Fasteners on 5-Degree Curve (Section 7), V=39 Kips.

four cut spikes. On the other hand, such a dramatic effect with respect to the change in L/V ratio is not apparent from the responses of both Pandrol and the Safelock fasteners. Approximately a doubling of the gage widening (to about 0.2") results when the L/V ratio is increased from 0.3 to 0.7. Overall, Safelock fasteners showed the best results.

Section 25 tests were made to compare the gage widening on different wood types in the ties. Exhibit 8 shows gage widening strength of four cut spikes under 33 kip wheel loads and a gage widening load of 18 kips. Exhibit 9 results correspond to a gage widening load of 22 kips under 39 kip wheel loads. There is no significant difference in the gage widening strengths afforded by the different wood type in the ties, with the exception of the Red Maple ties with end and wear plates. For the test loads used in Section 25, the total gage widening for Red Maple wood ties with end and wear plates is approximately half of each of the other gage widening magnitudes from other wood types.

Static gage widening results of tests on Section 31, with the Azobe ties, are given in Exhibits 10 and 11 for 33 and 39 kip wheel load, respectively. These results pertain to gage widening responses from the track segments with five cut spikes, elastic spikes on ties at 19.5" centers, elastic spikes on ties at 24" centers, and Pandrol fasteners. A comparison to results of the domestic hard/softwood ties with four cut spikes in Exhibits 6 and 7 reveals that the static gage widening strength of the Azobe ties with five cut spikes improves rapidly. For L/V ratios of 0.5 and

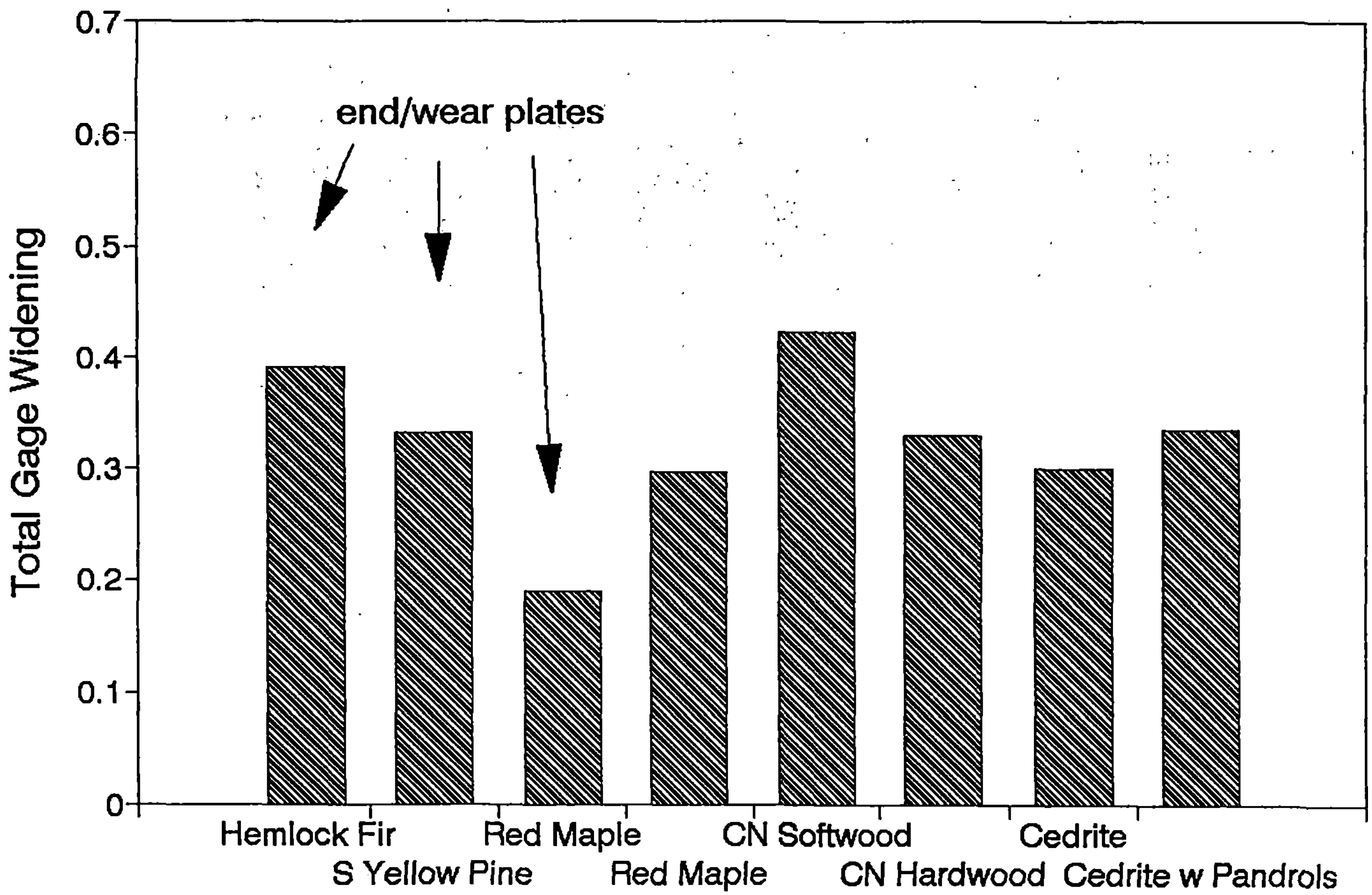


Exhibit 8. Comparison of Static Gage Widening of Different Tie Types on 6-Degree Curve (Section 25), L=18 Kips and V=33 Kips.

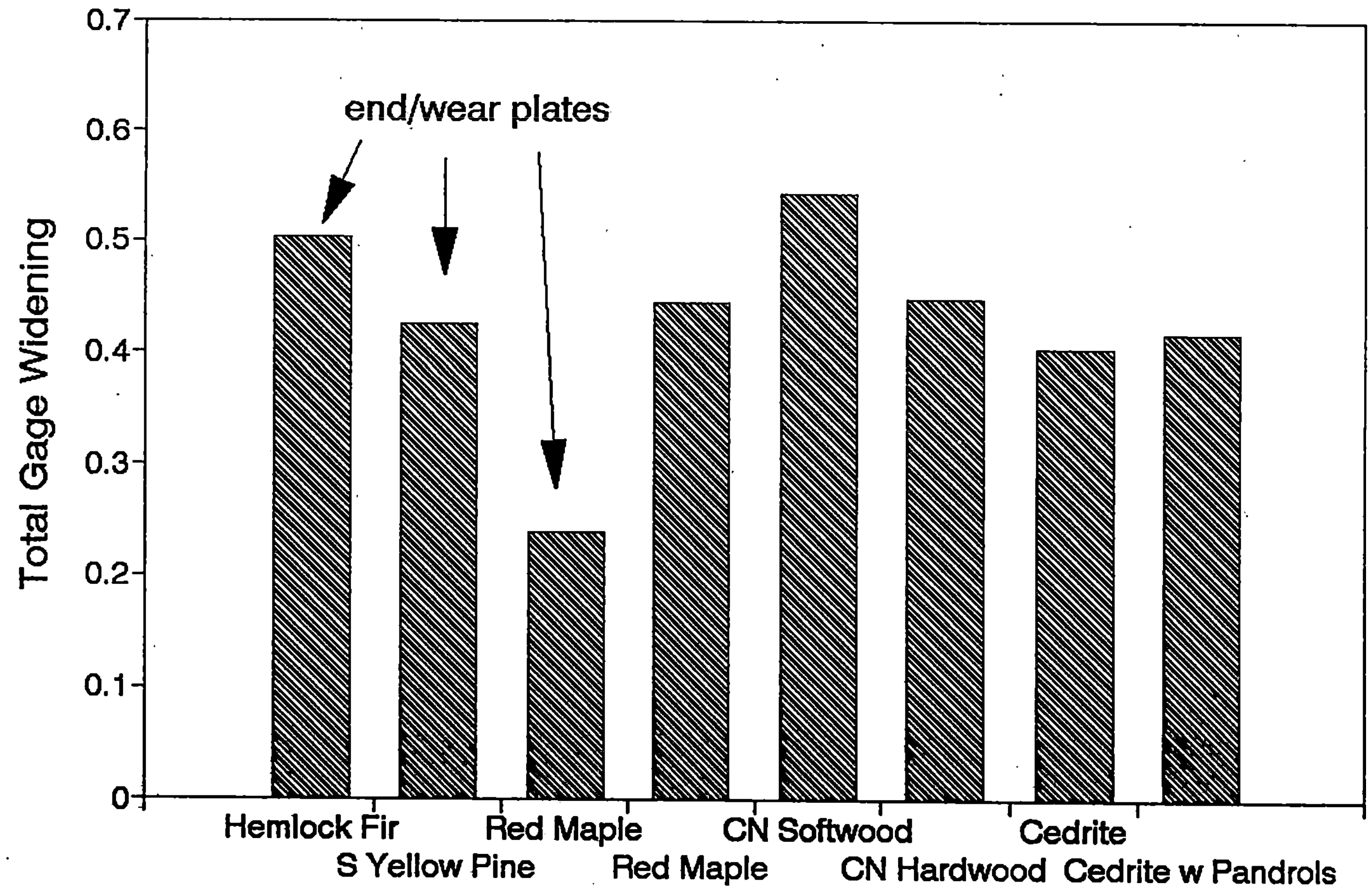


Exhibit 9. Comparison of Static Gage Widening of Different Tie Types on 6-Degree Curve (Section 25), L=22 kips and V=39 kips.

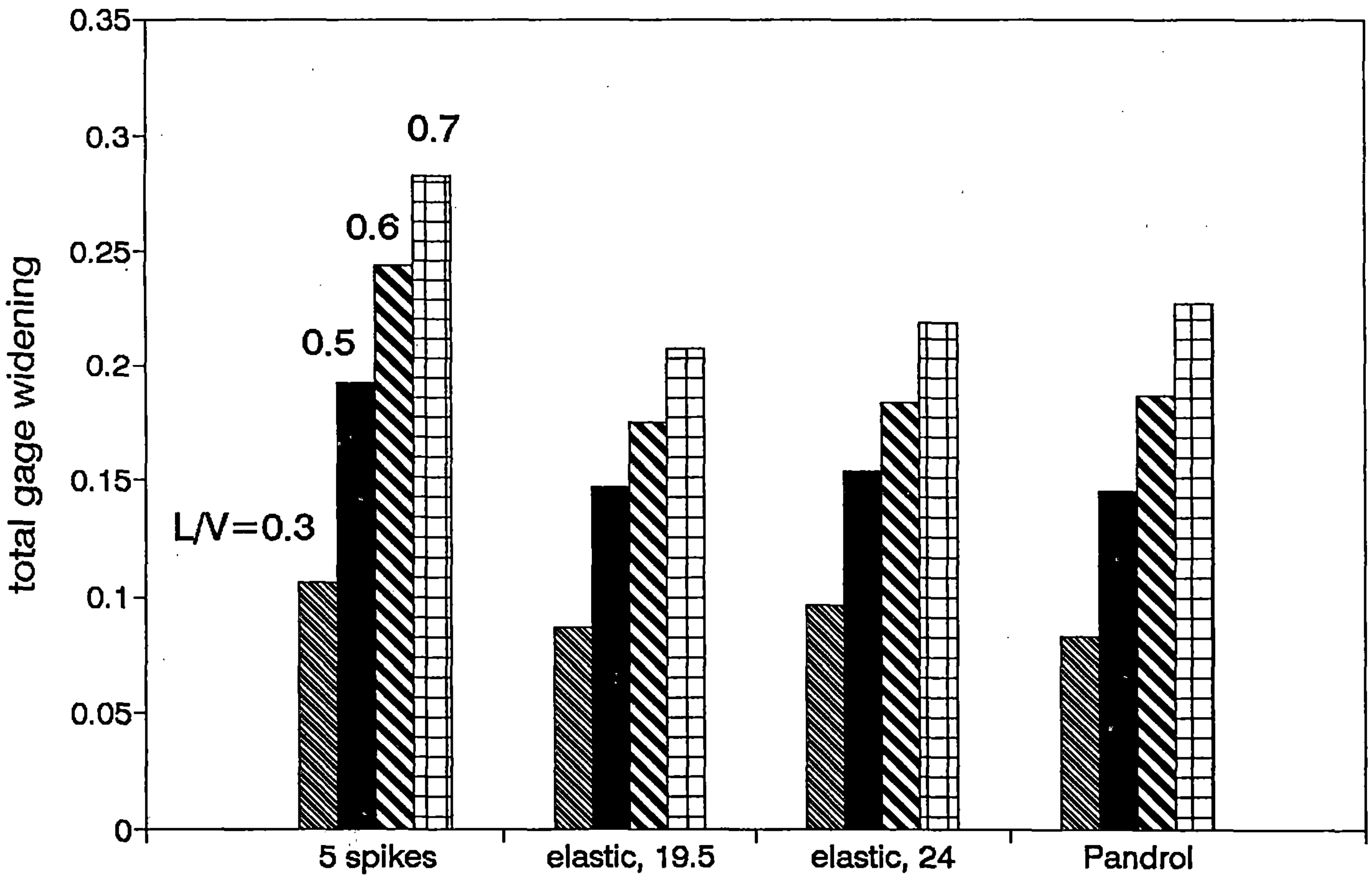


Exhibit 10. Comparison of Static Gage Widening of Different Fasteners on 5-Degree Curve (Section 31), V=33 Kips.

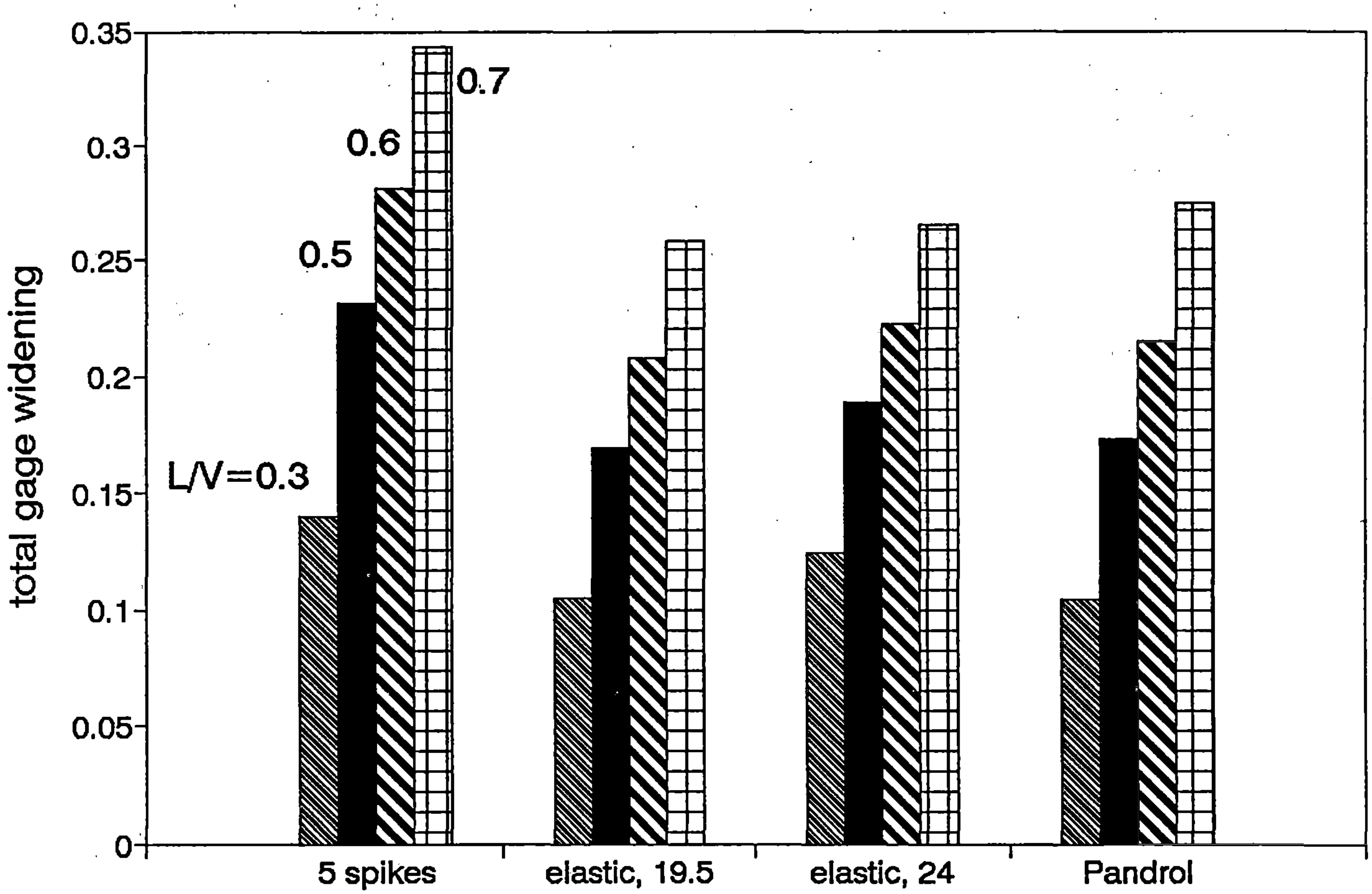


Exhibit 11. Comparison of Static Gage Widening of Different Fasteners on 5-Degree Curve (Section 31), V=39 Kips.

above, the total gage widening for the Azobe ties with five cut spikes is approximately half that of the domestic hard/softwood ties with four cut spikes. Actually, five cut spikes on the Azobe ties provide quite a comparable gage widening strength to that from Pandrol and elastic spikes on domestic hard/softwood ties. Further, the results from Pandrol on Azobe and domestic hard/softwood ties are comparable. Also, the static responses of elastic spikes for both the tie spacings are quite comparable to the response of Pandrol fasteners. Decreasing the tie spacing from 24" centers to 19.5" centers has a limited effect on the gage widening, and does not seem to create a significant improvement in the gage widening strength.

Section 33 was a tangent segment of the test track. Results from Section 33, consisting of concrete ties, domestic hard/softwood ties with four cut spikes and five cut spikes, and Cedrite ties with Pandrol are given in Exhibits 12 and 13. A study of the bar graphs in these exhibits reveals that higher gage widening resistances occur only at high L/V ratios, from the use of five cut spikes instead of four cut spikes on domestic hard/softwood ties. A comparison of responses of five spikes on the domestic hard/softwood ties in these exhibits with five cut spikes on the Azobe ties in Exhibits 10 and 11, clearly brings out the much greater gage widening strength of cut spikes on the Azobe ties over that on the domestic hard/softwood ties. The Pandrol responses on the other hand are comparable to similar responses on other sections of the HTL. It is apparent from these plots that in

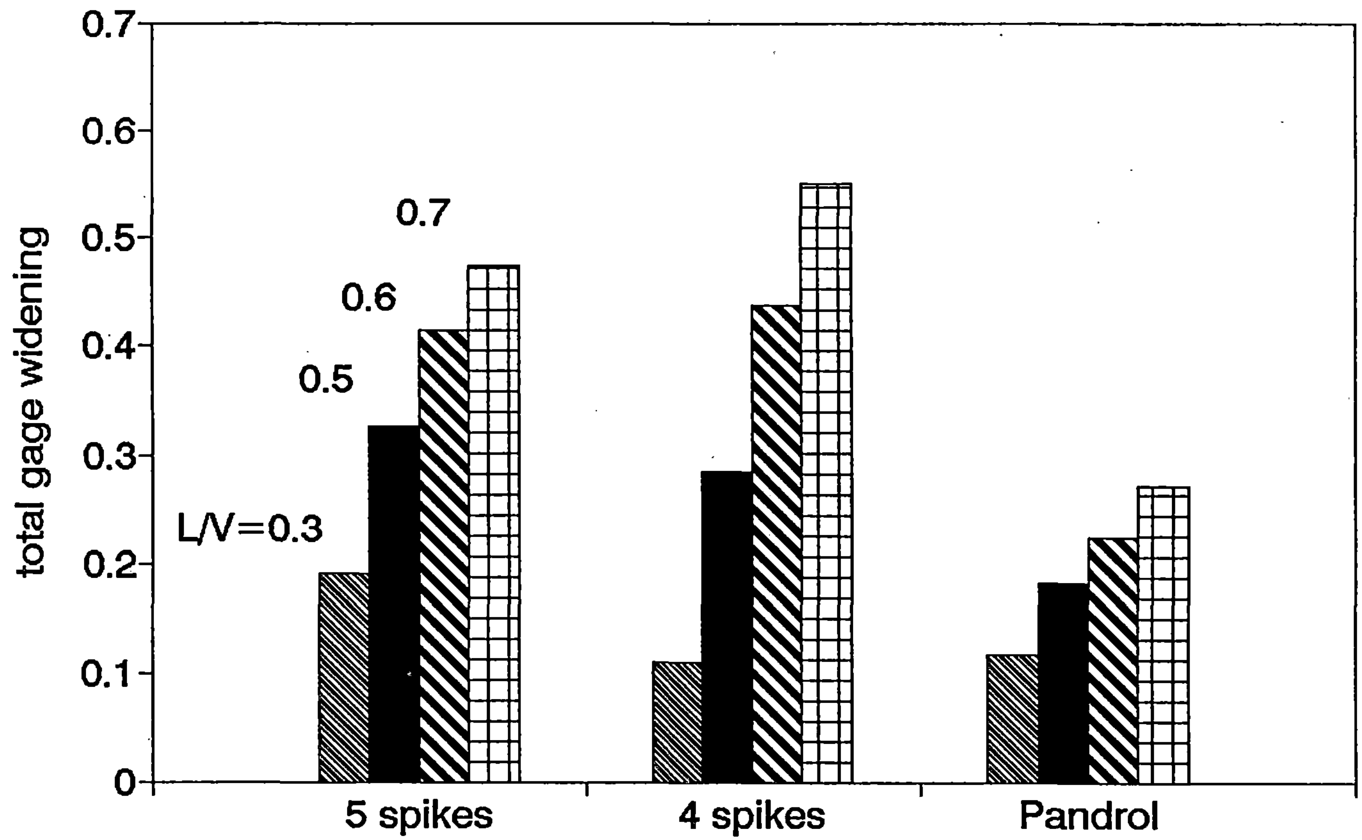


Exhibit 12. Comparison of Static Gage Widening of Different Fasteners on Tangent Track (Section 33), V=33 Kips.

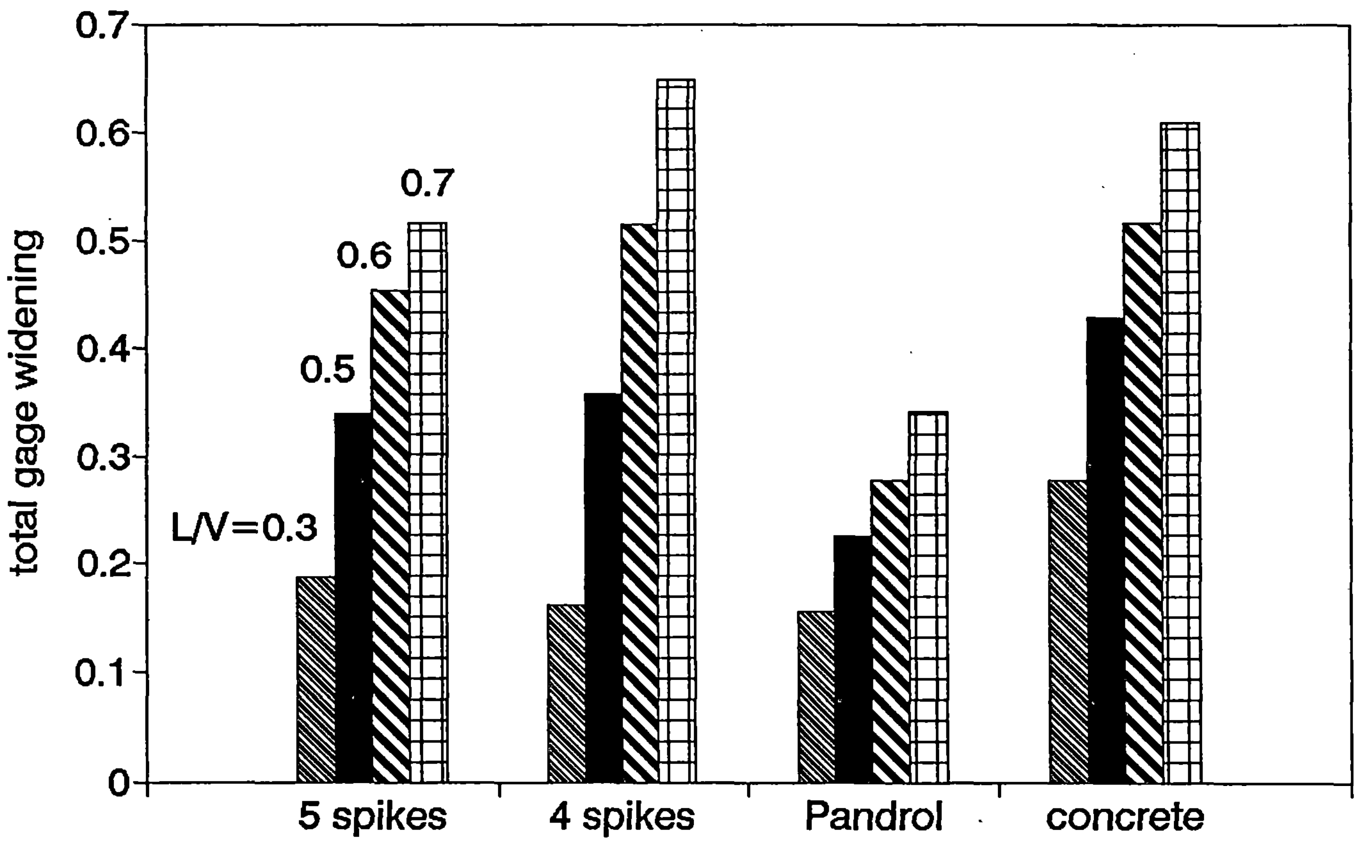


Exhibit 13. Comparison of Static Gage Widening of Different Fasteners on Tangent Track (Section 33), V=39 kips.

the static case, concrete tie response is similar to that of five cut spikes.

An overall comparison of the responses of all the fasteners tested in Sections 7, 31 and 33 is shown in Exhibit 14 for the 33 kip wheel load. A similar comparison for a 39 kip wheel load is given in Exhibit 15. As can clearly be seen in these exhibits, an increasing L/V ratio results in a much greater increase in the gage widening for domestic hard/softwood ties with four cut spikes, while for the elastic fasteners such as Pandrol and Safelock, the L/V ratio effects are not similarly pronounced. Five cut spikes on the Azobe ties improve the gage widening strength significantly, compared to the strength from four cut spikes on domestic hard/softwood ties. Overall, Safelock provides the best gage widening strength found from the analyses of the stationary tests.

A comparison of corresponding gage widening between 33 and 39 kip wheel loads shows that, for each L/V ratio, the gage widening that occurs is greater under 39 kip wheel load, and increases with the L/V ratio. The corresponding test results, in terms of total gage widening, at L/V ratios of 0.3, 0.5, 0.6 and 0.7, are given in Exhibits 16 and 17 for Section 7, Exhibits 18 and 19 for Section 31, and Exhibits 20 and 21 for Section 33, respectively. As can be seen from these plots, the gage widening that occurs with a given L/V ratio is always greater under the 39 kip wheel load. The gage widening loads, corresponding to the L/V ratio of 0.7, are about 23 kips for 33 kip wheel load, and about 27 kips for 39 kip wheel load. Though the stabilizing holddown moment from 39 kip wheel

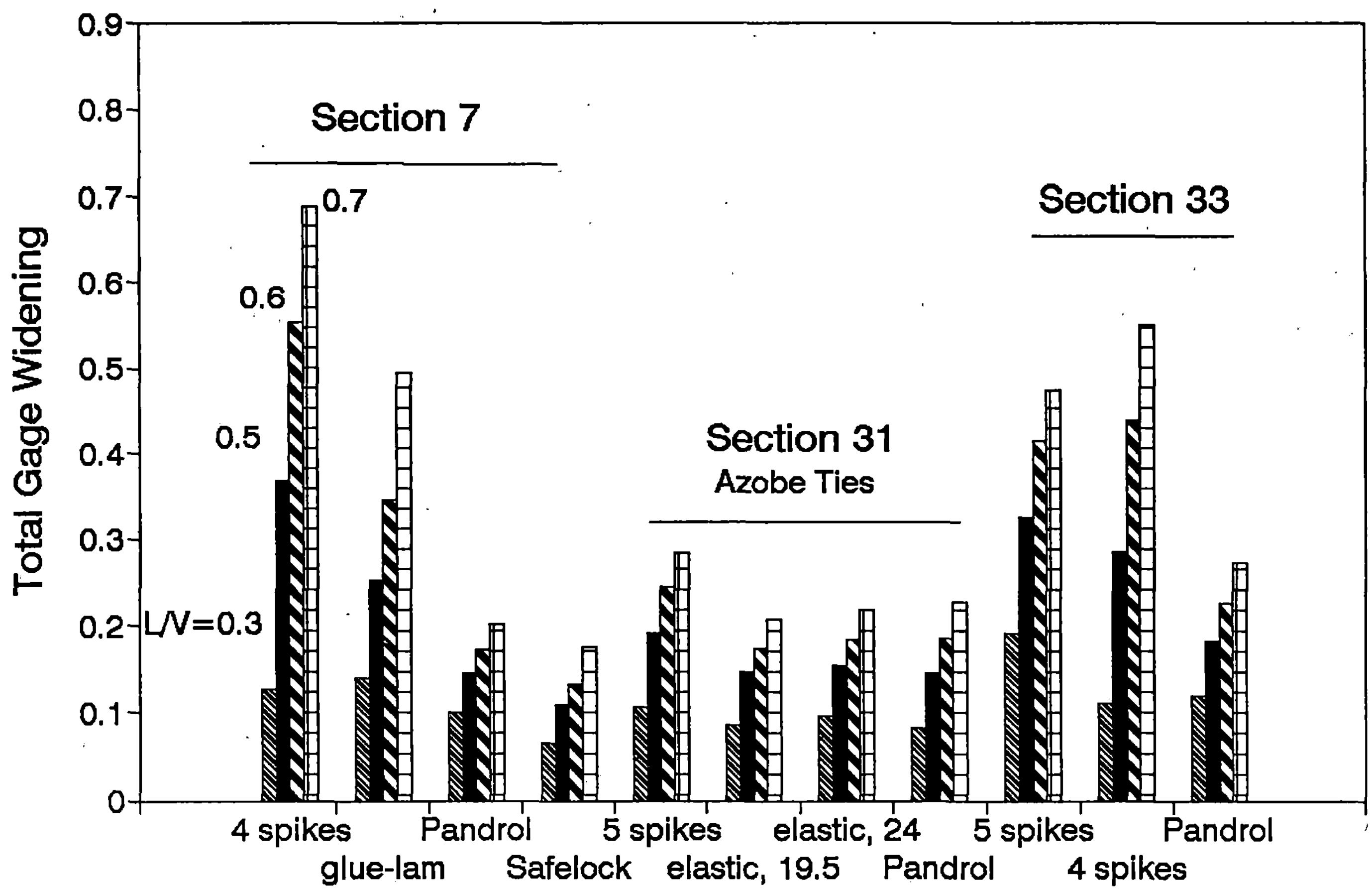


Exhibit 14. Comparison of Average Static Gage Widening of Different Fasteners on Sections 7, 31 and 33, V=33 Kips.

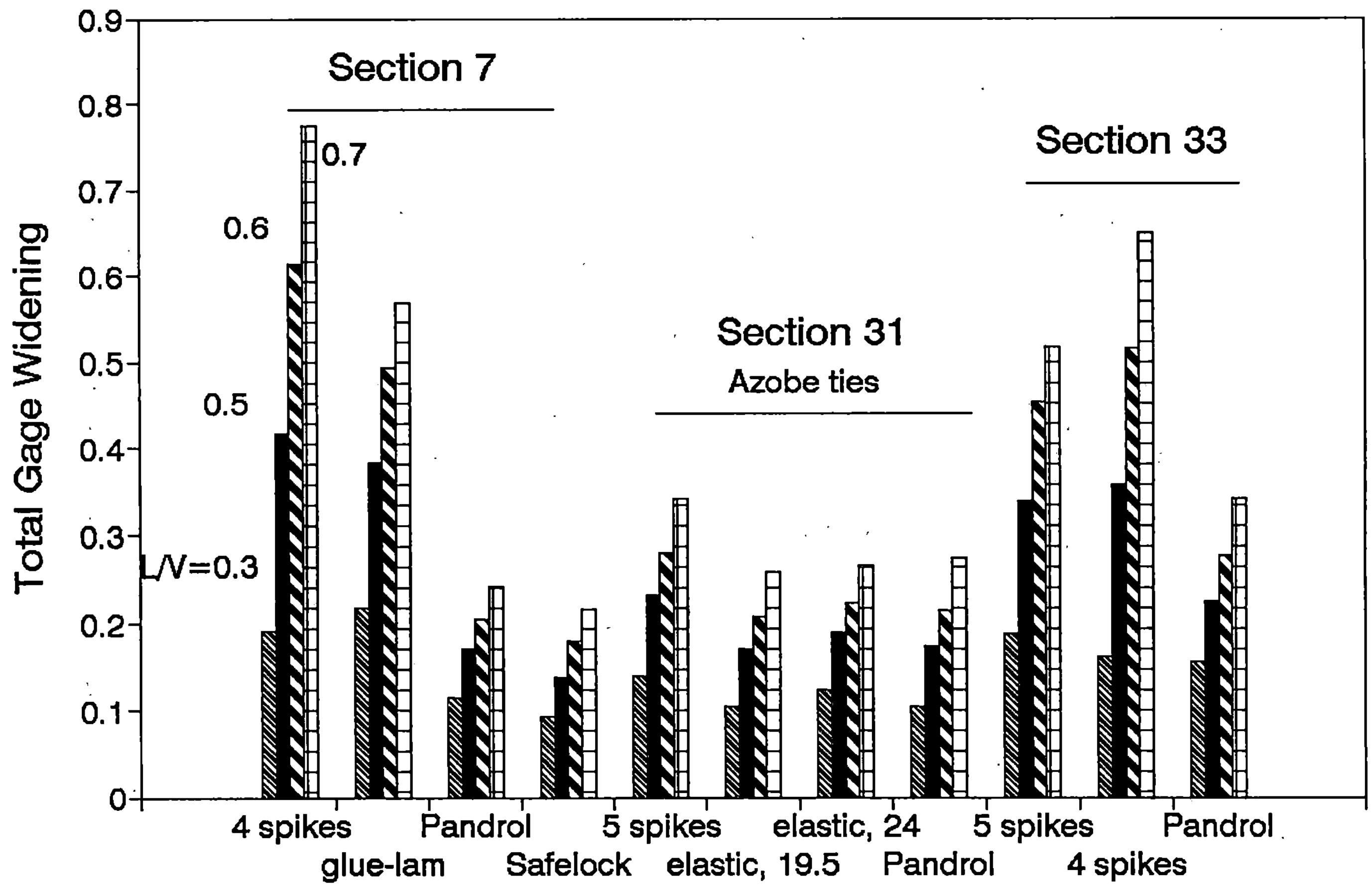
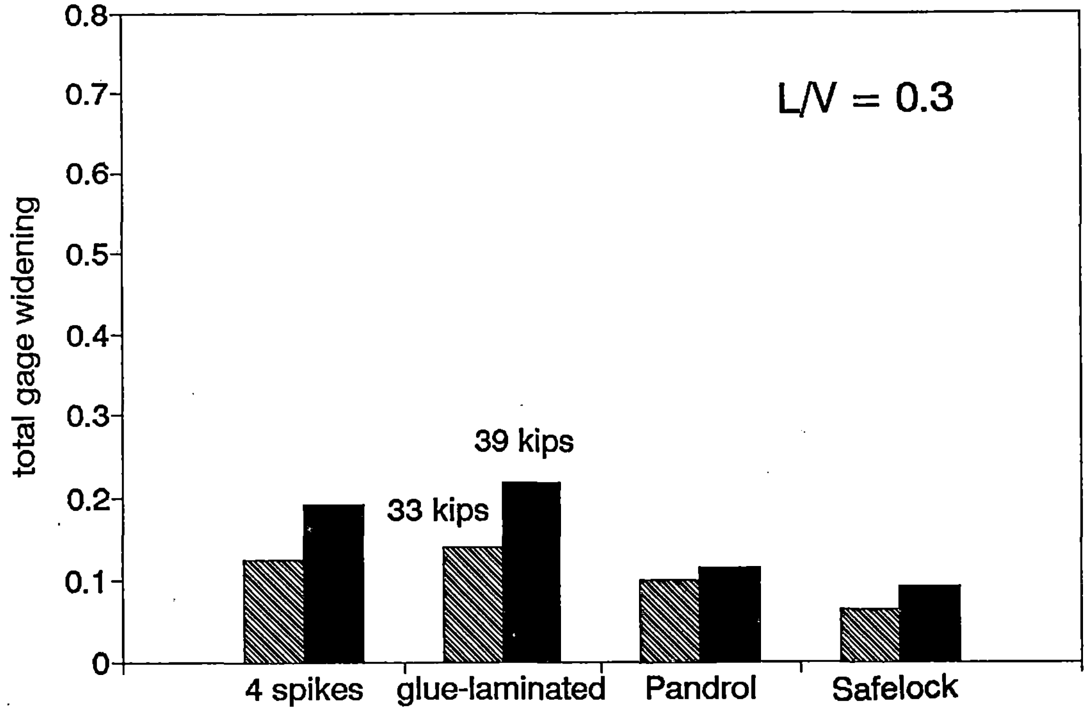


Exhibit 15. Comparison of Average Static Gage Widening of Different Fasteners on Sections 7, 31 and 33, V=39 Kips.



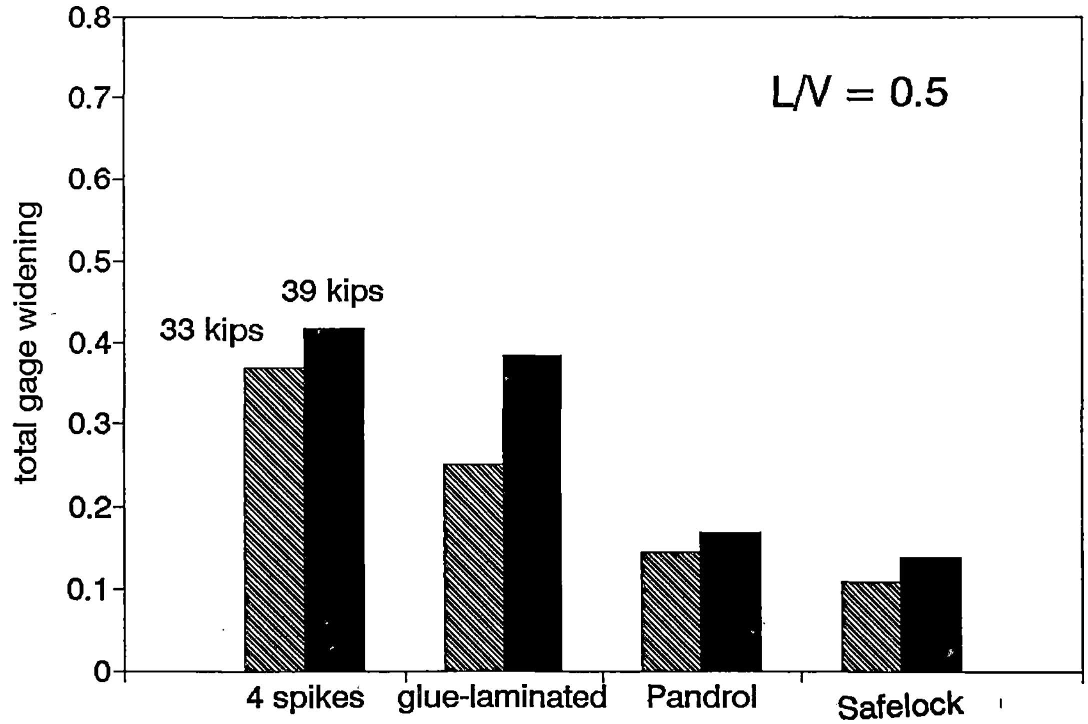
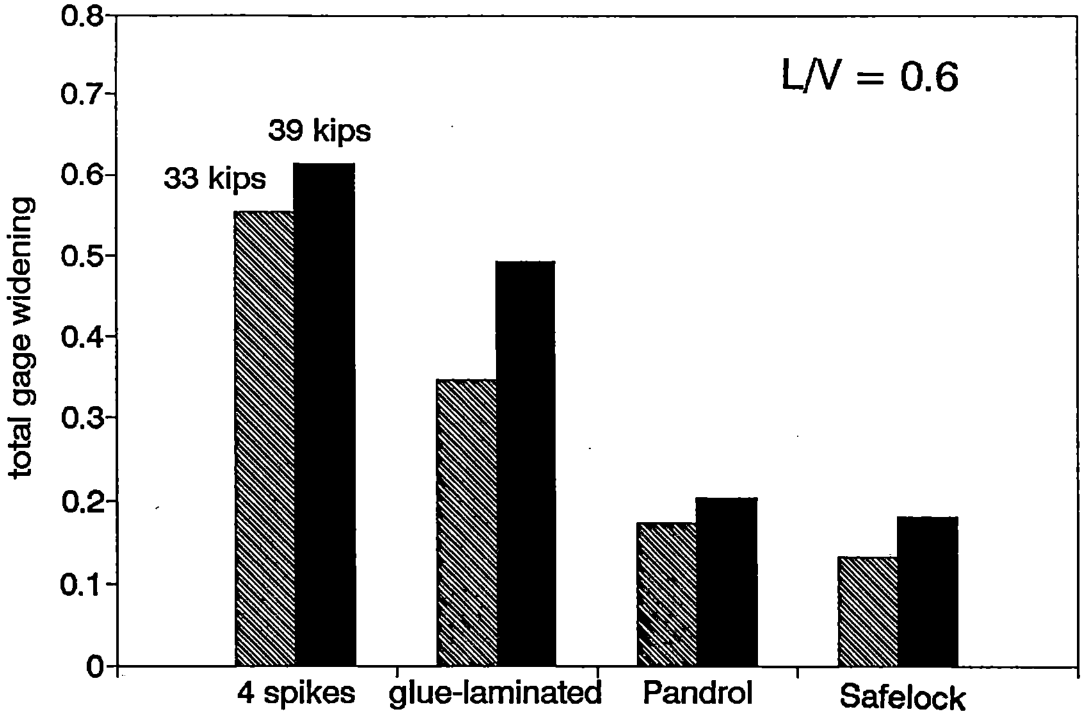


Exhibit 16. Comparison of Static Gage Widening of Different Fasteners at L/V=0.3 and 0.5, on 5-Degree Curve (Section 7), for V=33 and 39 Kips.



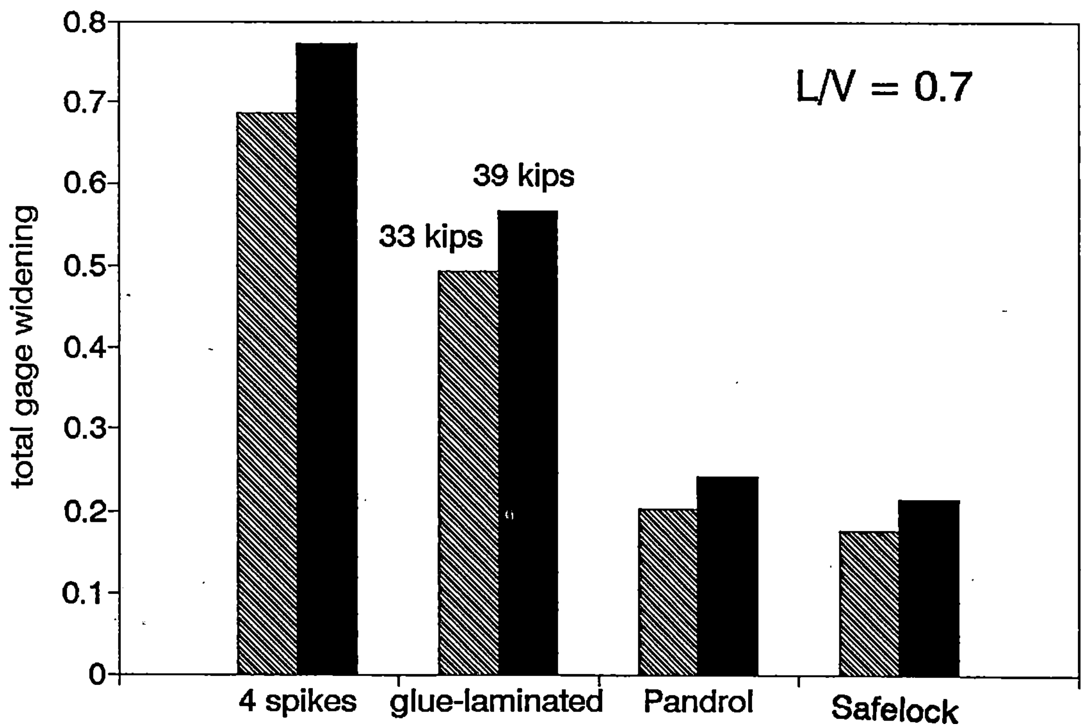


Exhibit 17. Comparison of Static Gage Widening of Different Fasteners at L/V=0.6 and 0.7, on 5-Degree Curve (Section 7), for V=33 and 39 Kips.

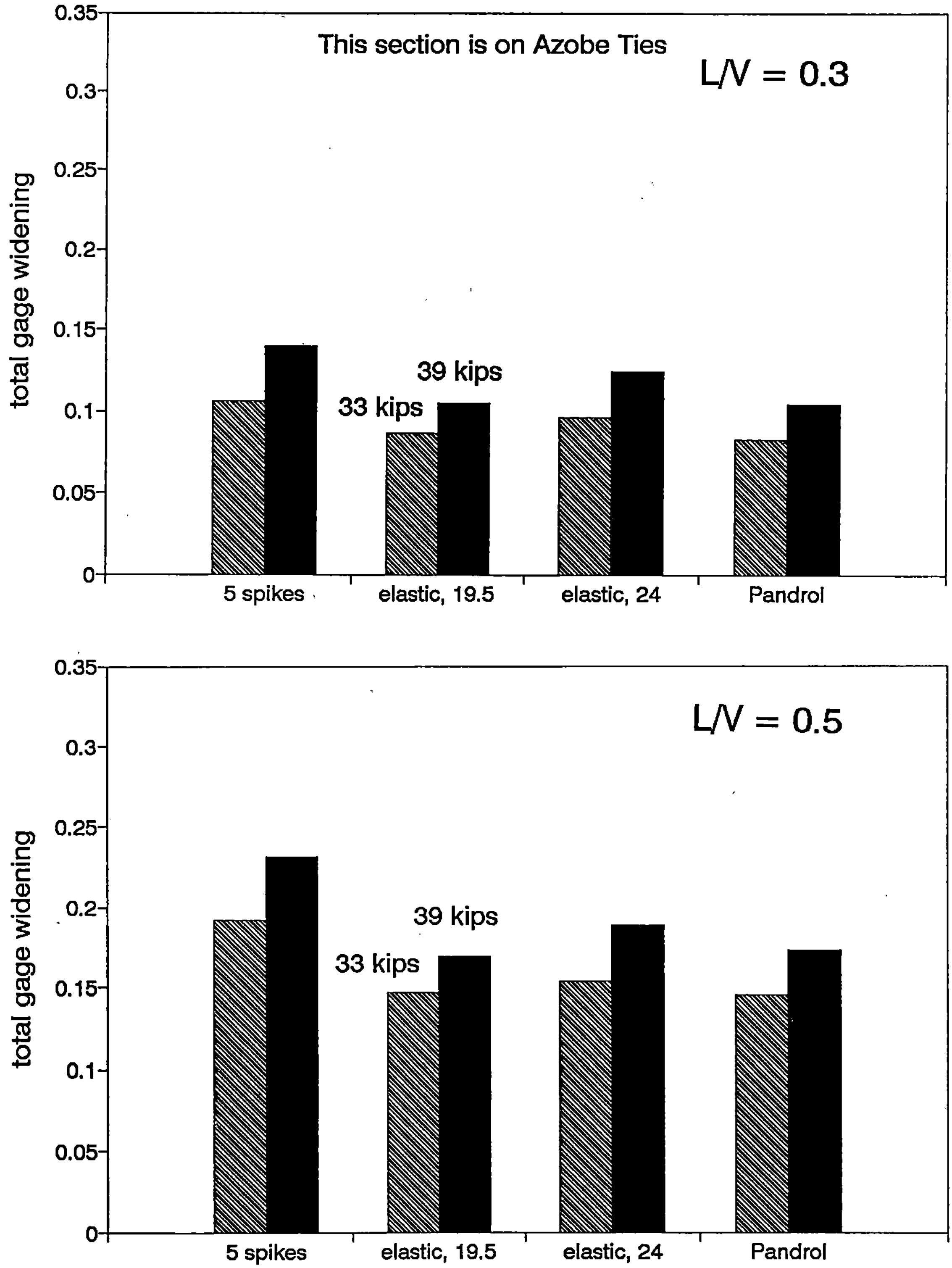


Exhibit 18. Comparison of Static Gage Widening of Different Fasteners at L/V=0.3 and 0.5, on 5-Degree Curve (Section 31), for V=33 and 39 Kips.

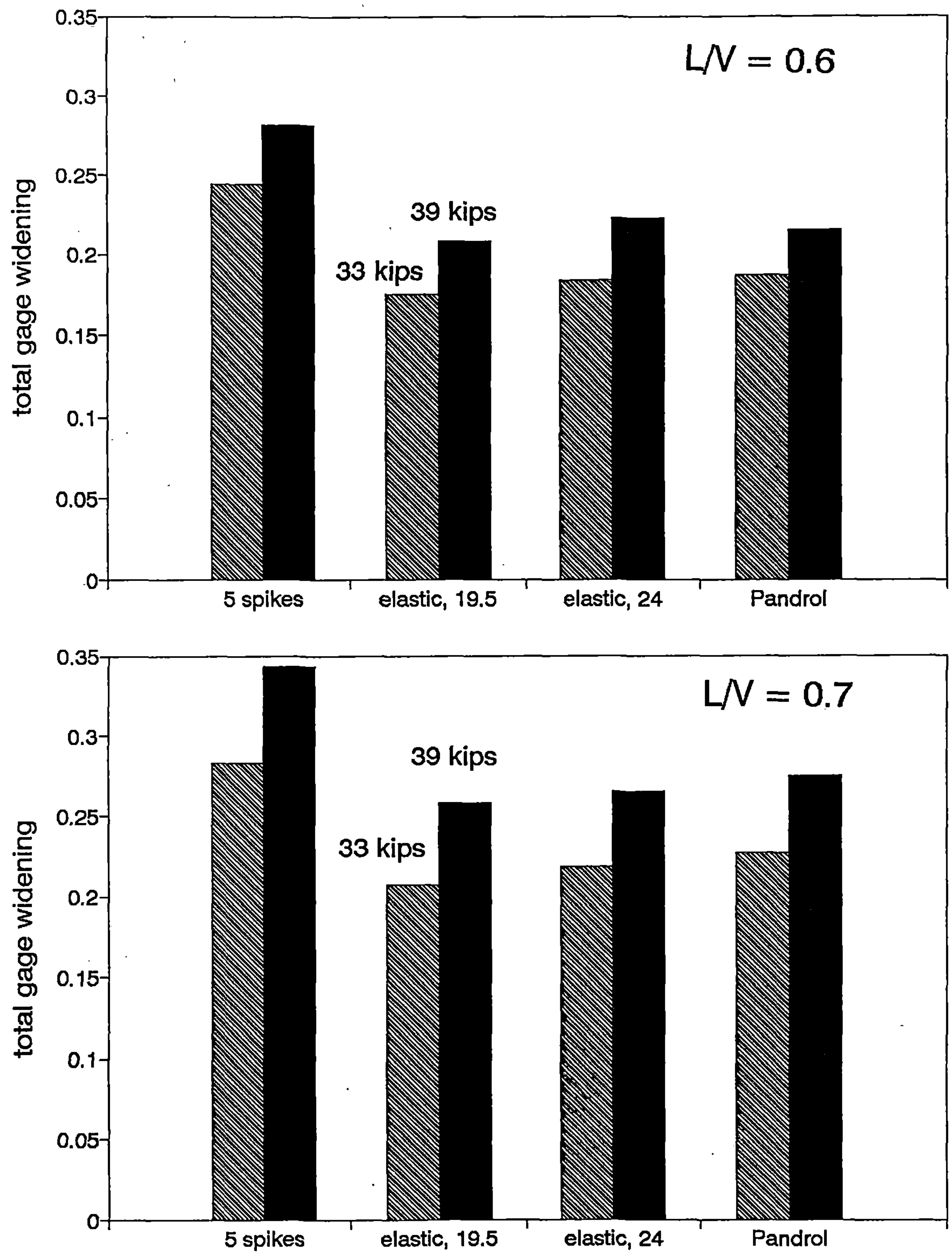
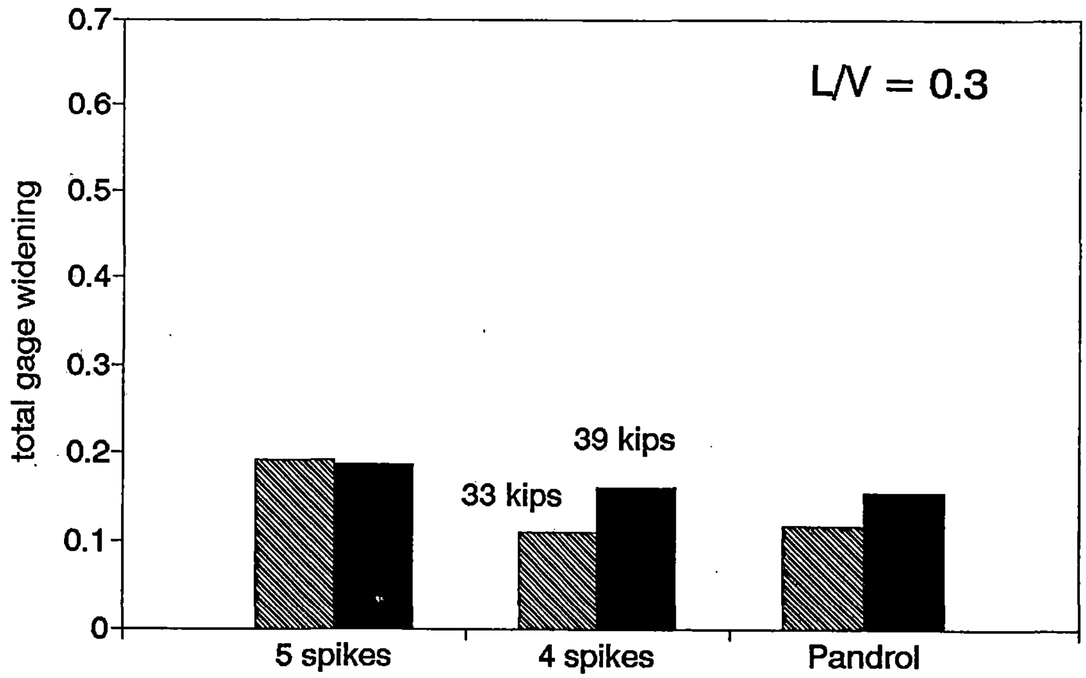


Exhibit 19. Comparison of Static Gage Widening of Different Fasteners at L/V=0.6 and 0.7, on 5-Degree Curve (Section 31), for V=33 and 39 Kips.



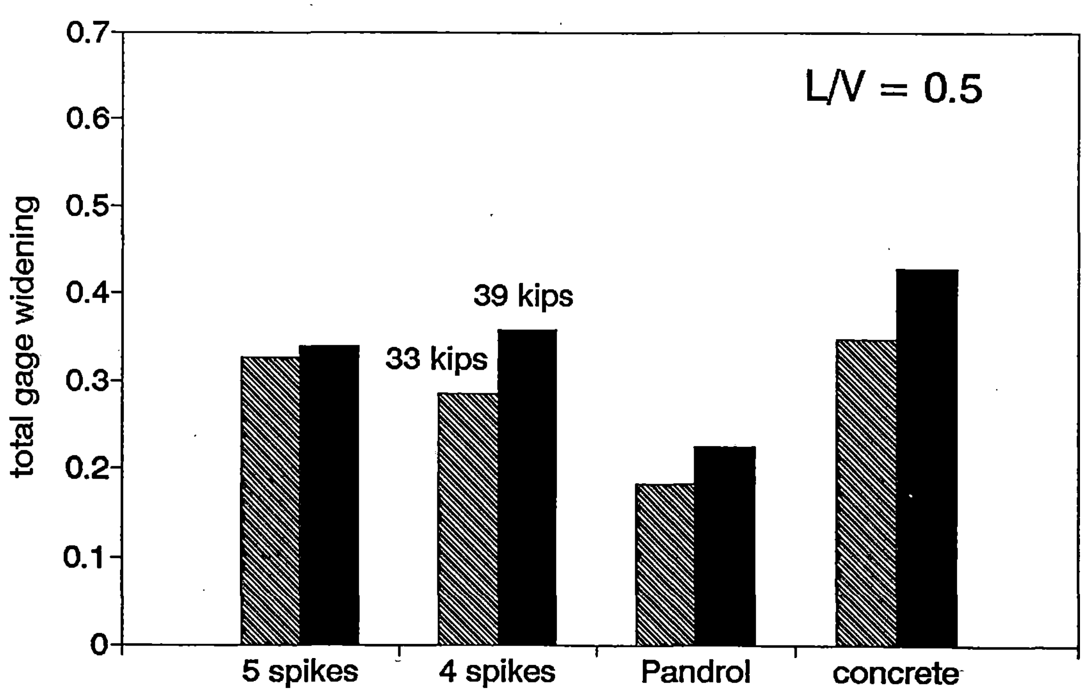
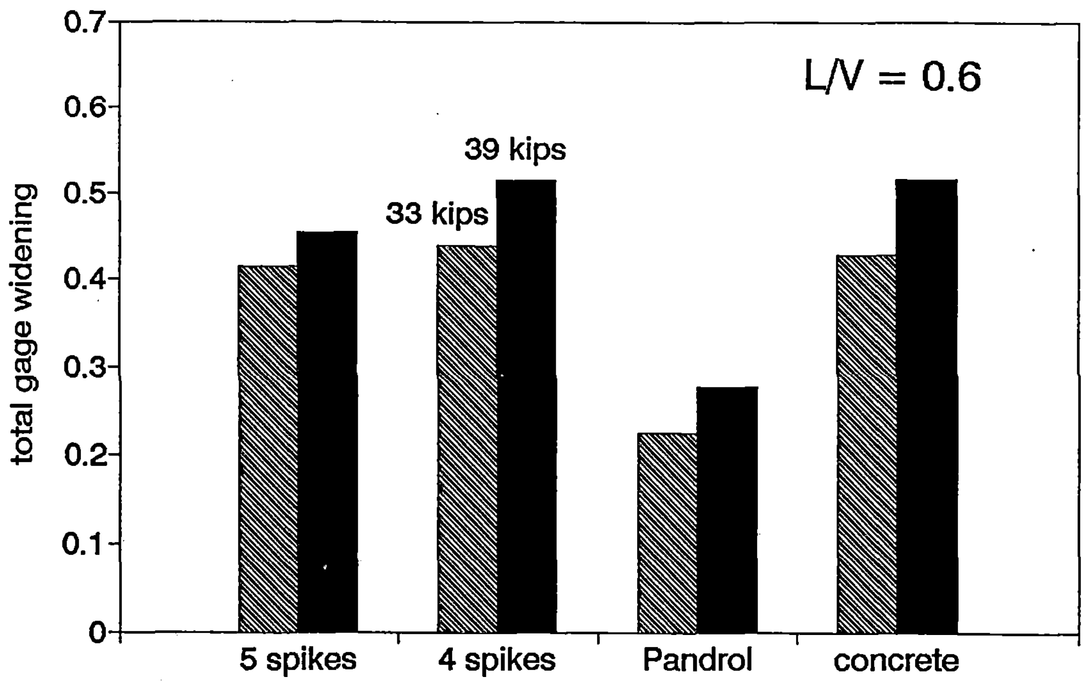


Exhibit 20. Comparison of Static Gage Widening of Different Fasteners at L/V=0.3 and 0.5, on Tangent Track (Section 33), for V=33 and 39 Kips.



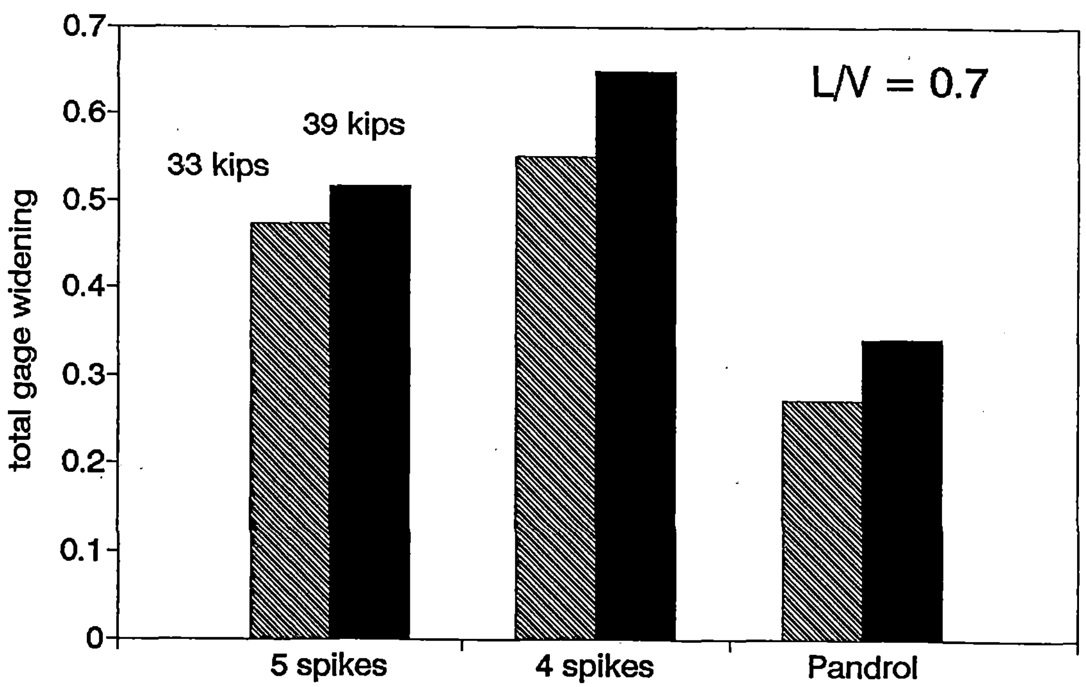


Exhibit 21. Comparison of Static Gage Widening of Different Fasteners at L/V=0.6 and 0.7, on Tangent Track (Section 33), for V=33 and 39 Kips.

load is greater than 33 kip wheel load, the overall rollover moment from a combination of lateral and vertical loads, resulting in the same L/V ratio, is more for 39 kip wheel load case than 33 kip wheel load case. This happens due to two reasons: 1) the destabilizing moment arm for the lateral load increases with the increase in gage widening, and 2) the fact that an equal and simultaneous change in the magnitudes of the vertical and lateral load results in a larger resultant rollover moment about the field side edge of the rail. And as such, the load combination of L=27 kips and V=39 kips (L/V=0.7) could produce more gage widening as is evident in these exhibits.

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6.0 MOVING TEST RESULTS

Four basic factors contributing to gage widening strength, discussed in Section 1.0 are: the lateral rail head bending and twisting resistances from rail section, pull out resistance of gage side fasteners, translational resistance from field side fasteners, and the frictional resistances between rail/tie plate and tie plate/tie. Of these factors, the lateral rail head bending occurs as soon as any lateral load is applied. This is because a measure of appropriate reactive forces is always present to facilitate lateral bending.

It is believed that the sequence of the other remaining resistances occurs first in the overcoming of the frictional resistances between rail and tie plate and also between tie plate and tie. The friction is overcome when the lateral load applied at the rail head just exceeds the interface frictional forces noted above. When this occurs, the rail slides on the tie plate until the field side edge of the rail base contacts with the tie plate shoulder. Concurrently, any existing lateral clearance between the spikes and the respective holes are also taken up once the friction level between the tie plate and the tie has been exceeded. Beyond this magnitude of applied lateral load, the translational resistance, against lateral tie plate movement, is provided by the field side fasteners in terms of shearing resistance of the fastener-tie interface. Additional rail roll (lateral deflection of rail head with respect to rail base over and above that due to lateral bending), also occurs beyond this magnitude of lateral load. This rotation of the rail section now is resisted by the torsional resistance of the rail section and the pullout resistance of the gage side fasteners.

Loaded gage, delta gage and track compliance are used to describe gage widening strength of track in the moving tests. Delta gage is the direct difference between the loaded gage and the corresponding unloaded gage in the test. Track compliance is the value of quotient of the delta gage and the gage widening load. It is given as the increment in gage in inches per kip of gage widening load.

It is important to explain the significance of loaded gage and delta gage measurements. This significance is related to the possible presence of tight or wide unloaded 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 to begin with. The results presented in this report deal only with the aspect of relative rail restraint provided by the different types of ties and fasteners, and does not deal with whether a certain magnitude of delta gage or loaded gage will result in derailment.

Moving test results, under both the 100 and 125-ton car wheel load, are presented in **four formats**: distance history plots of loaded gage and delta gage; unloaded and loaded gages, delta gage and track compliance versus gage widening load and L/V ratio plots;

frequency-of-exceedance plots with respect to the gage widening loads; and frequency-of-exceedance plots with respect to tie and fastener type at each magnitude of the gage widening load.

6.1 Distance History Plots

Loaded gage and delta gage with respect to distance, from subsection 7A which has wood ties with 4 cut spikes, are shown in Exhibits 22 to 25, respectively, for 33 and 39-kip wheel loads. The labels and legends included in these exhibits are self explanatory. Only the first 165 feet of data is included in these plots to show the general trend and the basic integrity of the collected data. For illustration, the loaded gage history plots, only under 39-kip wheel load, from other sections of the HTL are given in Appendix A as Exhibits A1 to A23.

Distance history plots, in general, show that the higher the gage widening load, the larger the magnitude of the loaded gage and delta gage. A comparison at any two gage widening loads suggests that the change in loaded gage and delta gage from one gage widening load to another is not uniform along the distance. Moreover, the difference in loaded gage and delta gage between two consecutive gage widening loads seems to decrease at higher gage widening loads. The difference in loaded gage and delta gage at different gage widening loads, in general, is least when the loaded gages and delta gages are smallest and most when they are largest. An important observation to be made is that, even after about 180 MGT operation of HAL test, the tight gage locations exist; and that

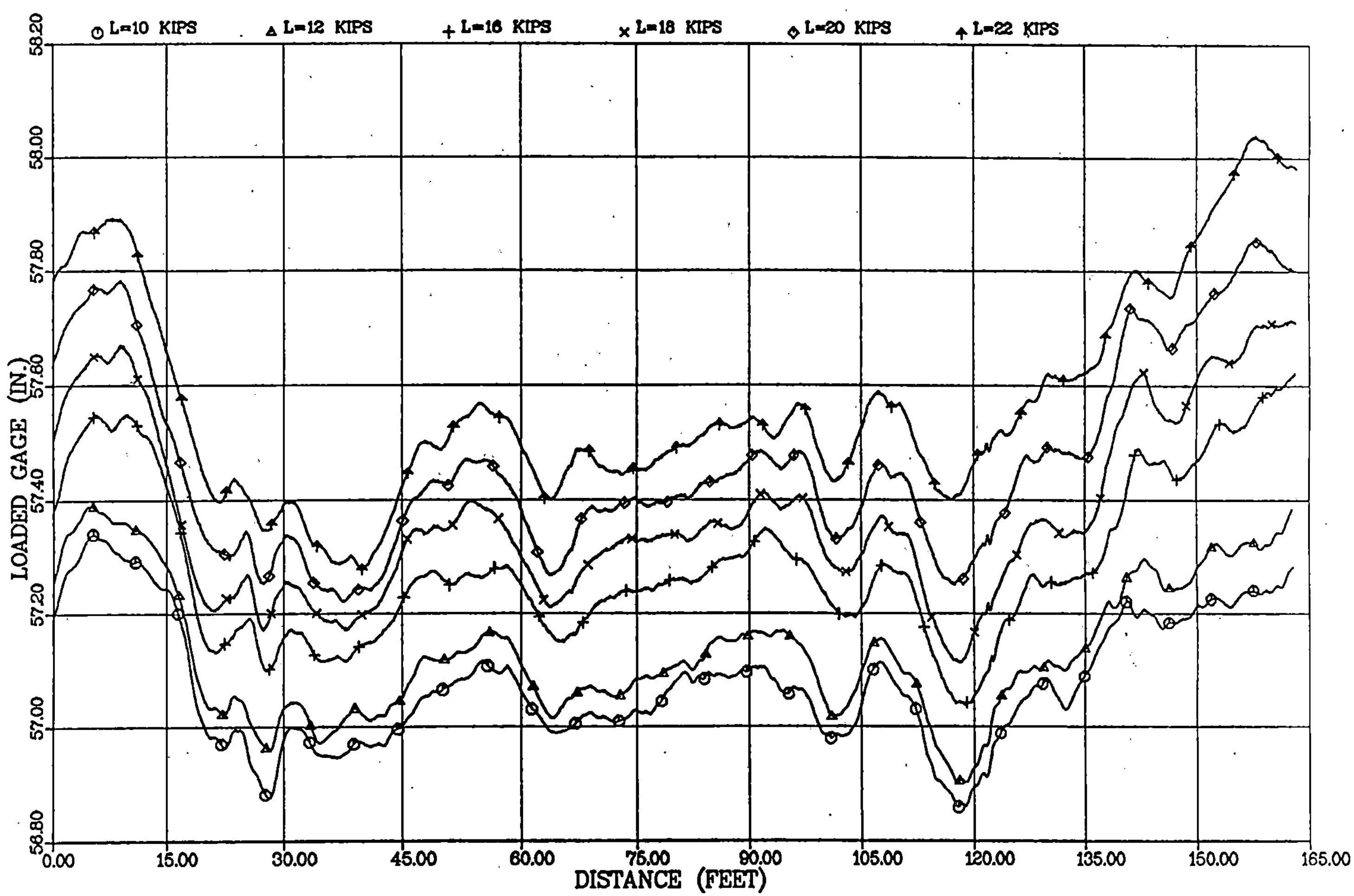

Exhibit 22. Loaded Gage Distance History, 5-Degree Curve (Section 7A), V=33 Kips.

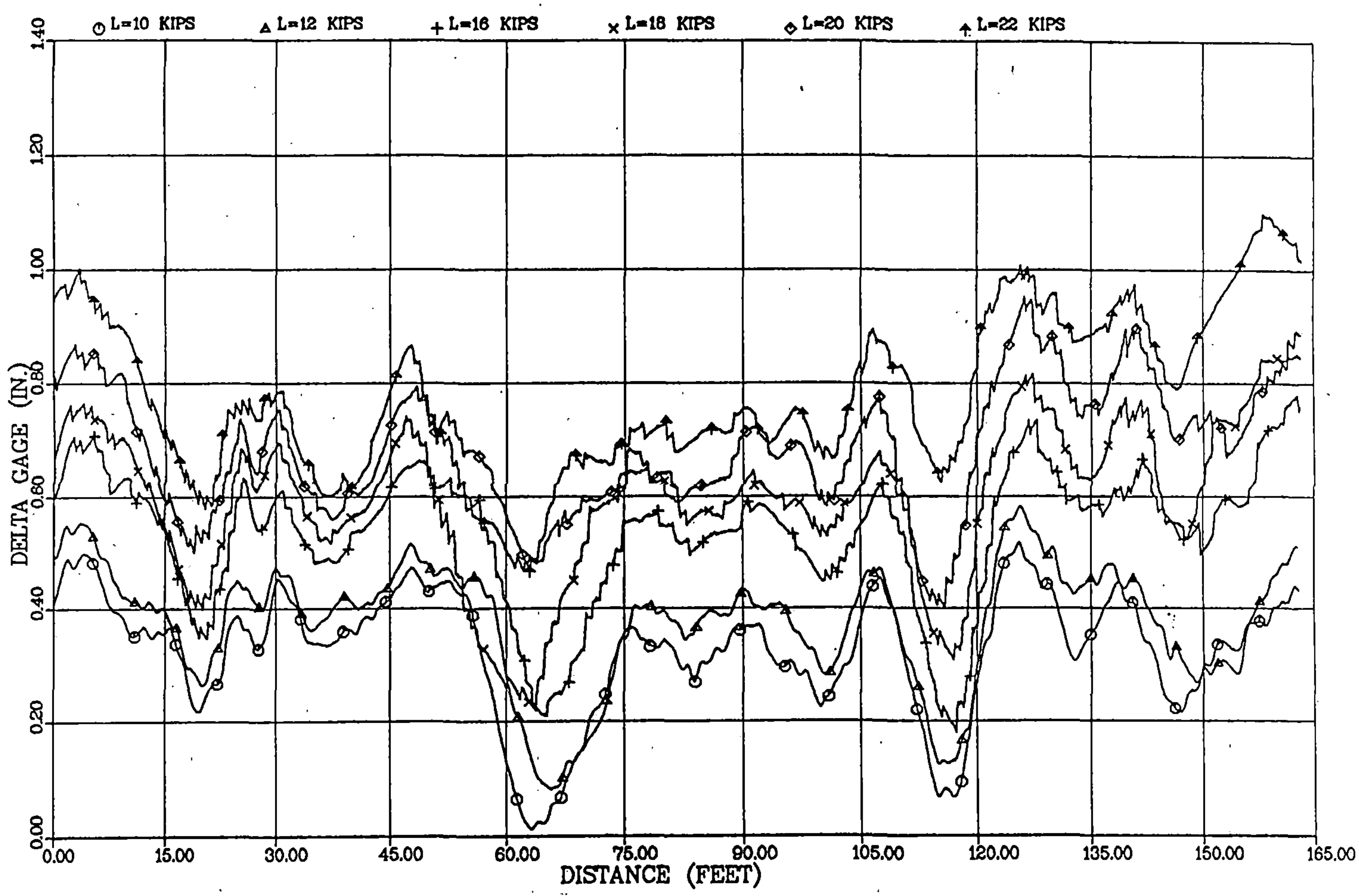

Exhibit 23. Delta Gage Distance History, 5-Degree Curve (Section 7A), V=33 Kips.

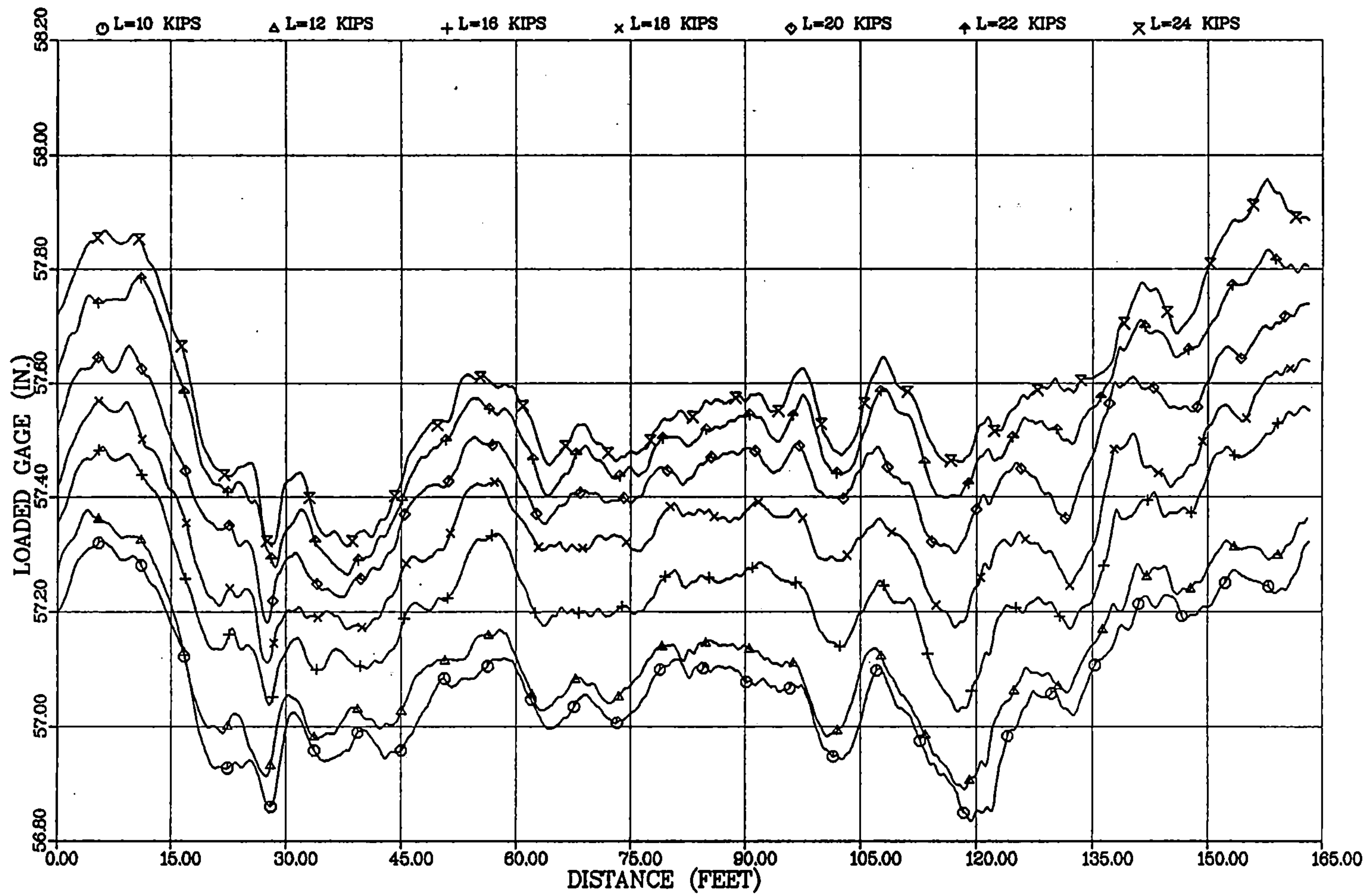

Exhibit 24. Loaded Gage Distance History, 5-Degree Curve (Section 7A), V=39 Kips.

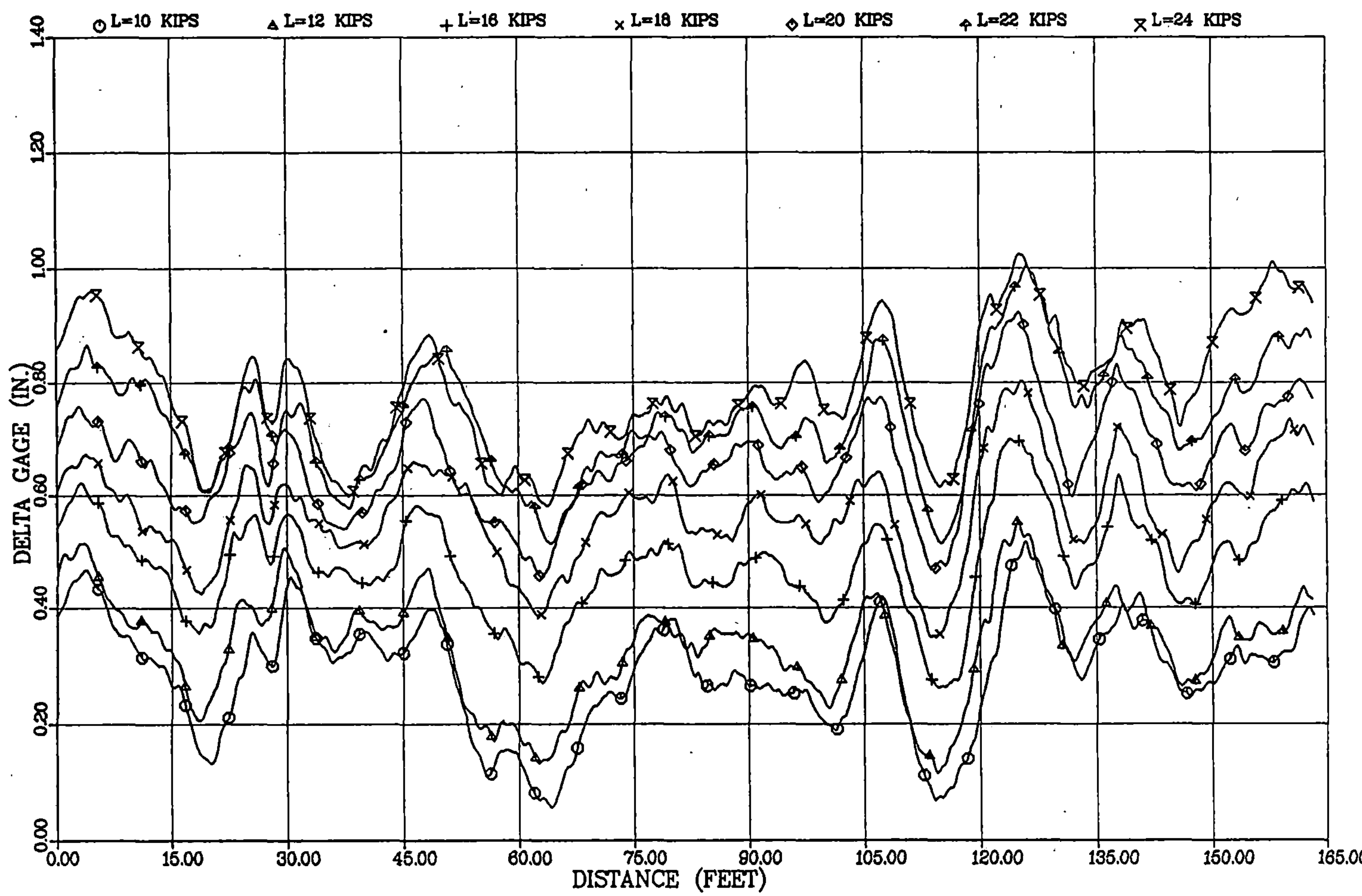

Exhibit 25. Delta Gage Distance History, 5-Degree Curve (Section 7A), V=39 Kips.

these could only occur due to the large gage widening strength of the track in these tight gage locations.

6.2 Average Magnitude Plots

In the following section, the average values of the unloaded gage, loaded gage, delta gage, and track compliance with respect to gage widening load are given. The average values are analyzed for slope, and initial and final magnitude. A Comparison of fasteners and tie types is made to assess the effectiveness of one combination over the other in providing gage widening strength.

Results for concrete ties of Section 3; and domestic hard/softwood ties with 4 cut spikes, Pandrol, Safelock and elastic spikes, and glue laminated ties with 4 cut spikes of Section 7 are included for discussion. Graphs for each fastener type, under both 33 and 39 kip wheel loads, are shown in Exhibits 26 through 31. On the other hand, a comparison of loaded gage and delta gage among various fasteners, for each wheel load, is given in Exhibits 32 through 35. Graphs for other segments of the HTL are given in Appendix B as Exhibits B1 to B17.

The slopes of the unloaded gage curves stay almost horizontal through all the gage widening loads. Therefore, the subtraction of the unloaded gage magnitude from the loaded gage magnitude, to give delta gage, makes the slope of the delta gage curve parallel to the slope of the corresponding loaded gage curve. A study of slope of loaded gage and delta gage reveals that for wood ties with elastic fasteners, such as Pandrol and Safelock, and also concrete ties, the

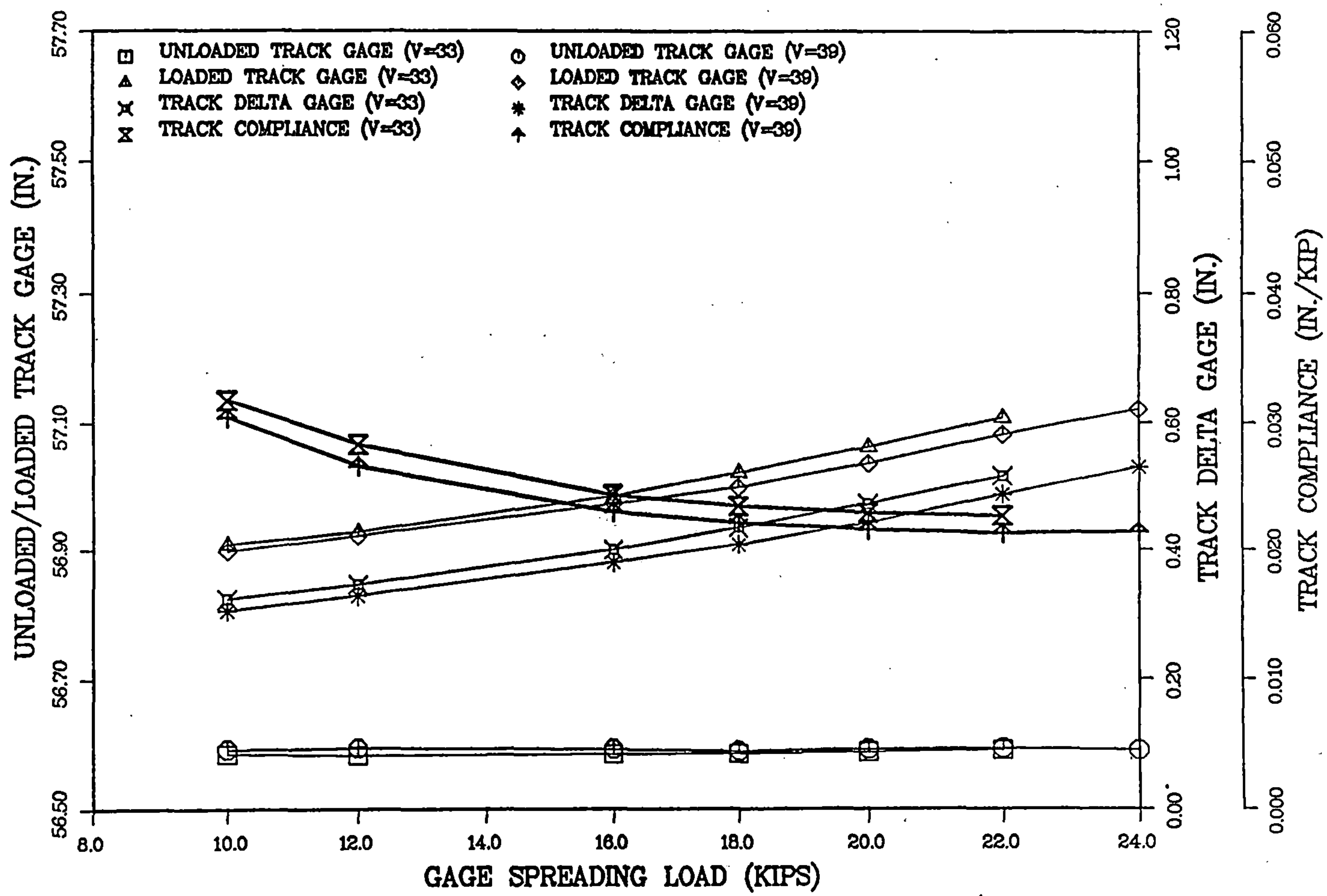

Exhibit 26. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Widening Load, 5-Degree Curve (Section 3), Concrete Ties, V=33 and 39 Kips.

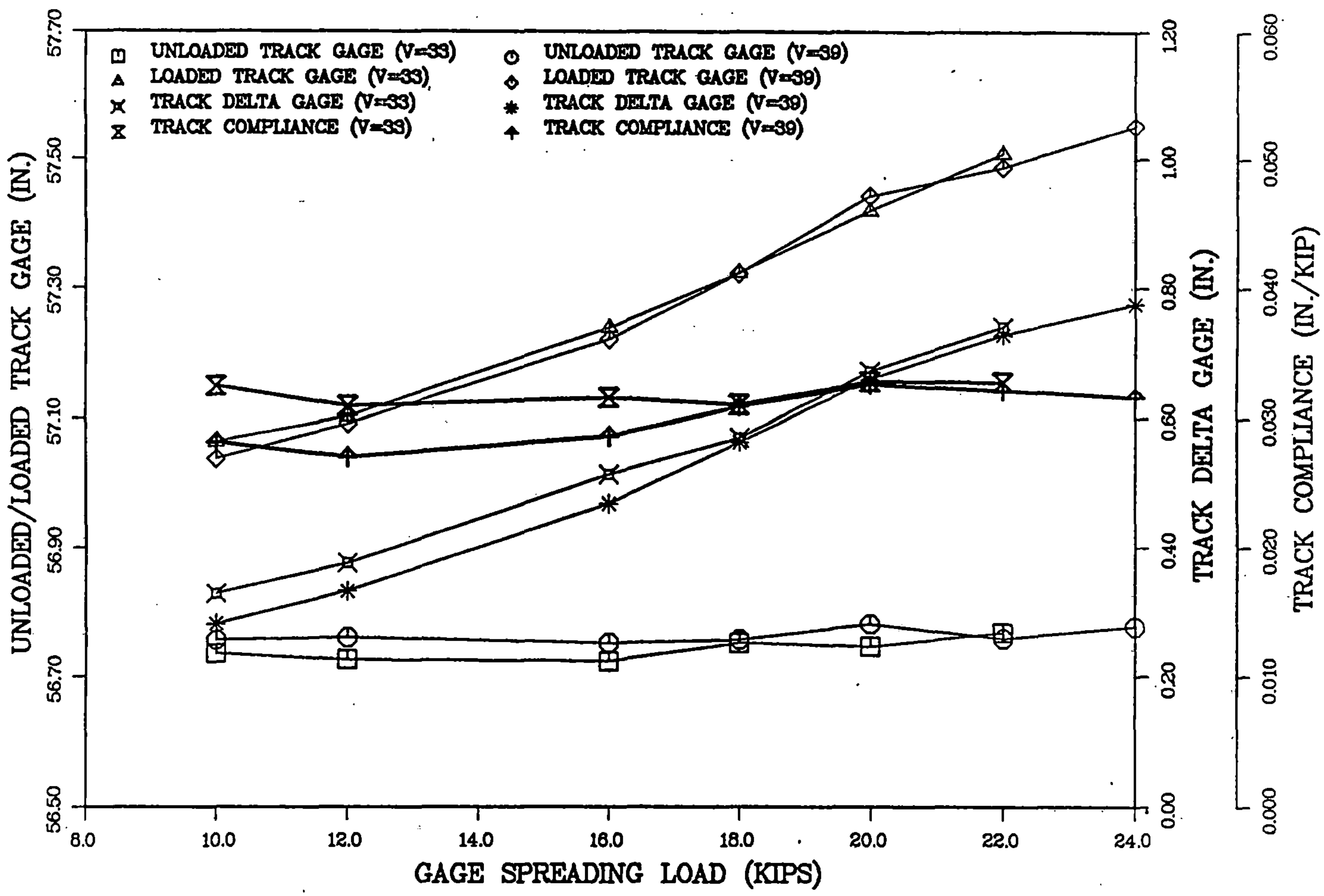

Exhibit 27. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Widening Load, 5-Degree Curve (Section 7A), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

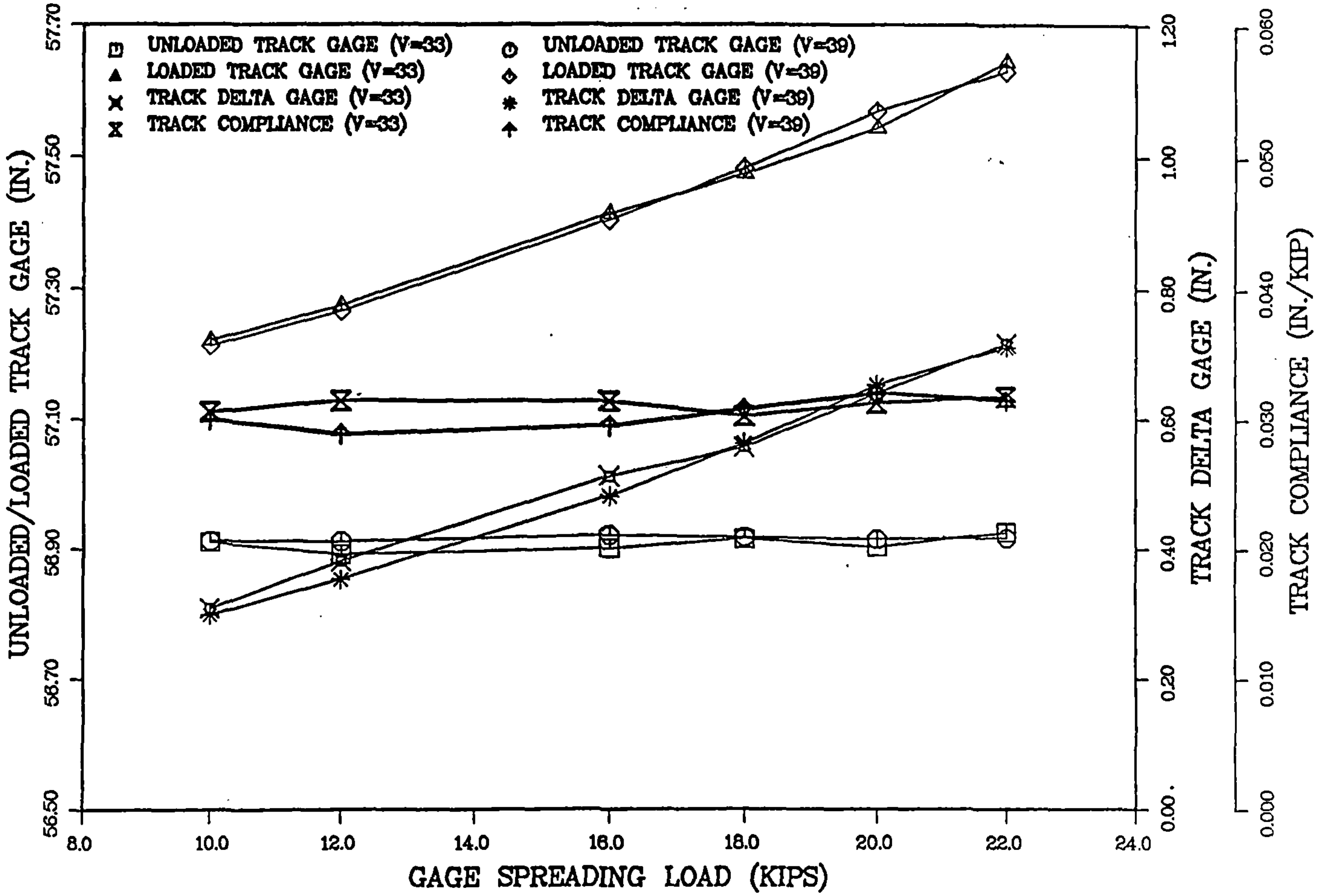

Exhibit 28. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Widening Load, 5-Degree Curve (Section 7F), Glue Laminated Ties/4-Cut Spikes, V=33 and 39 Kips.

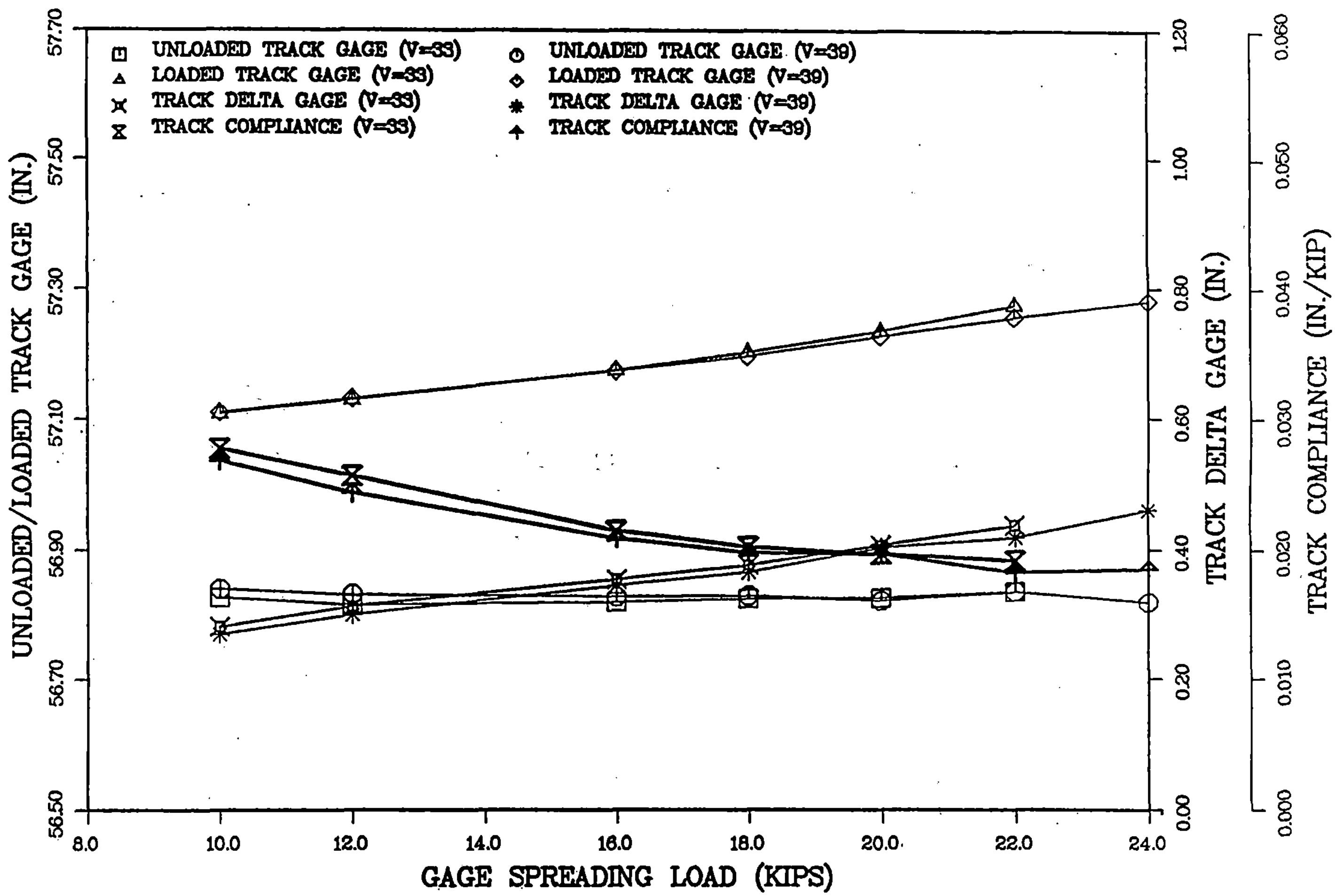

Exhibit 29. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Widening Load, 5-Degree Curve (Section 7C), Wood Ties/Pandrol Fasteners, V=33 and 39 Kips.

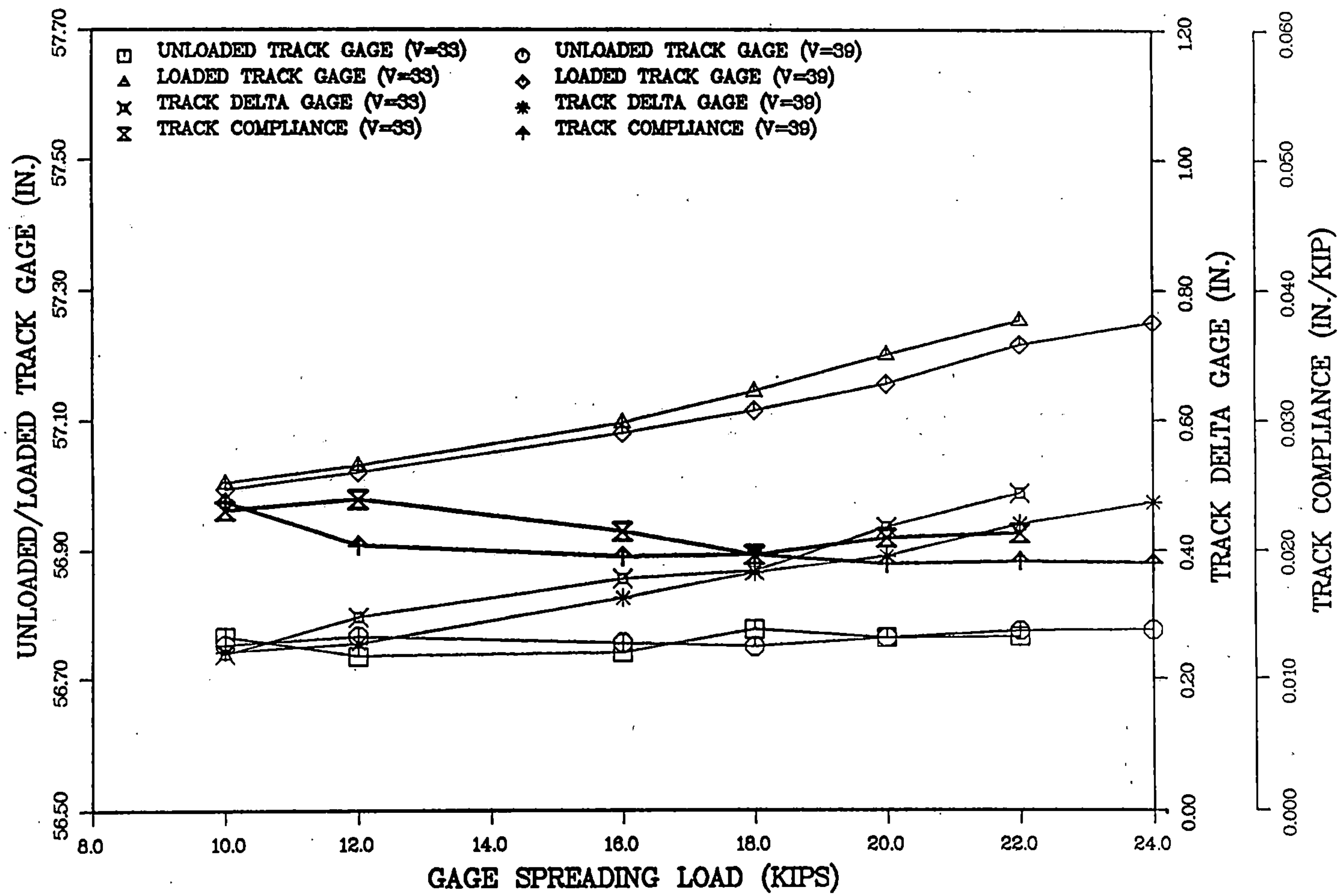

Exhibit 30. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Widening Load, 5-Degree Curve (Section 7E), Wood Ties/Elastic Spikes, V=33 and 39 Kips.

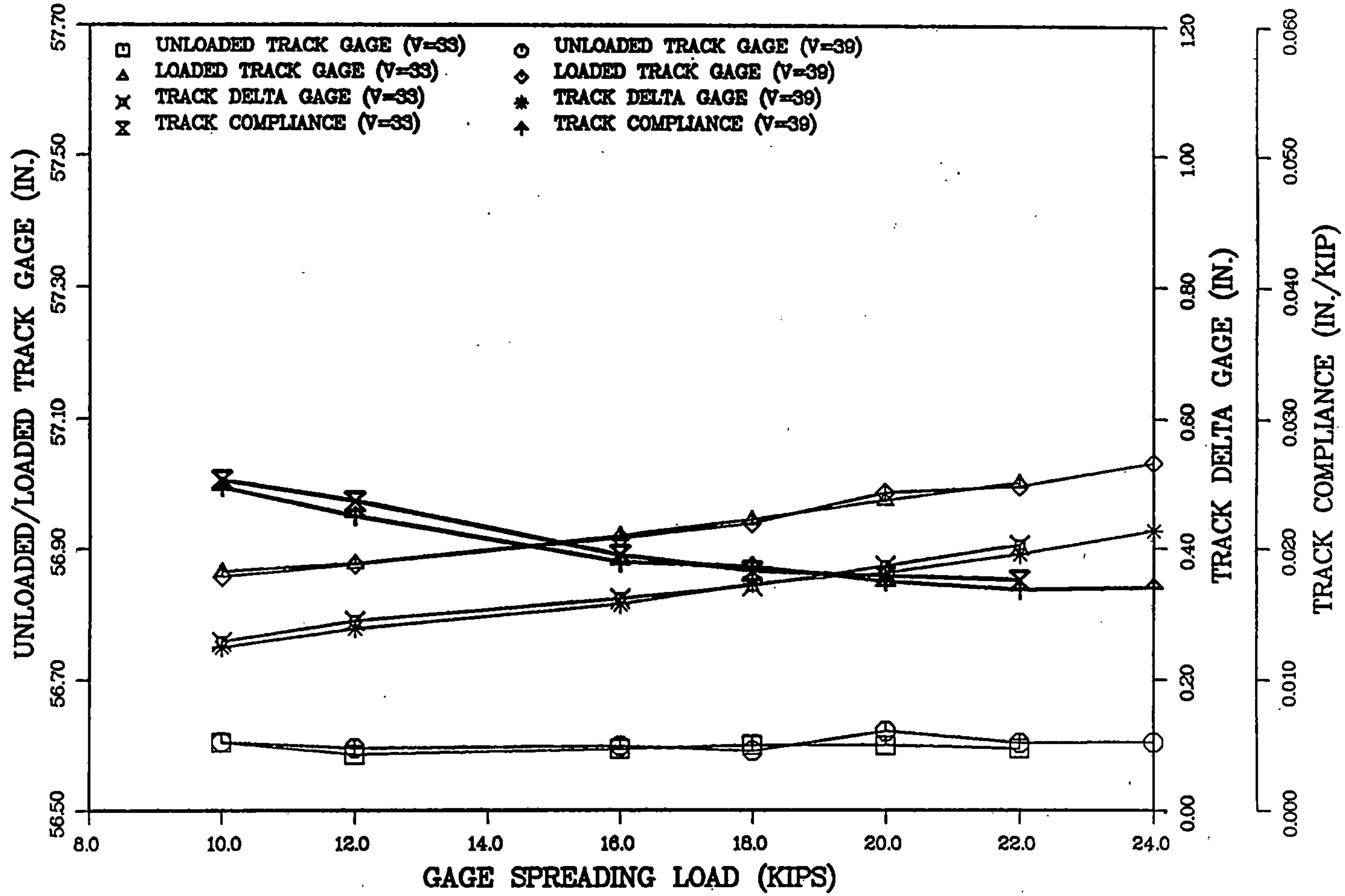

Exhibit 31. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Widening Load, 5-Degree Curve (Section 7D), Wood Ties/Safelock Fasteners, V=33 and 39 Kips.

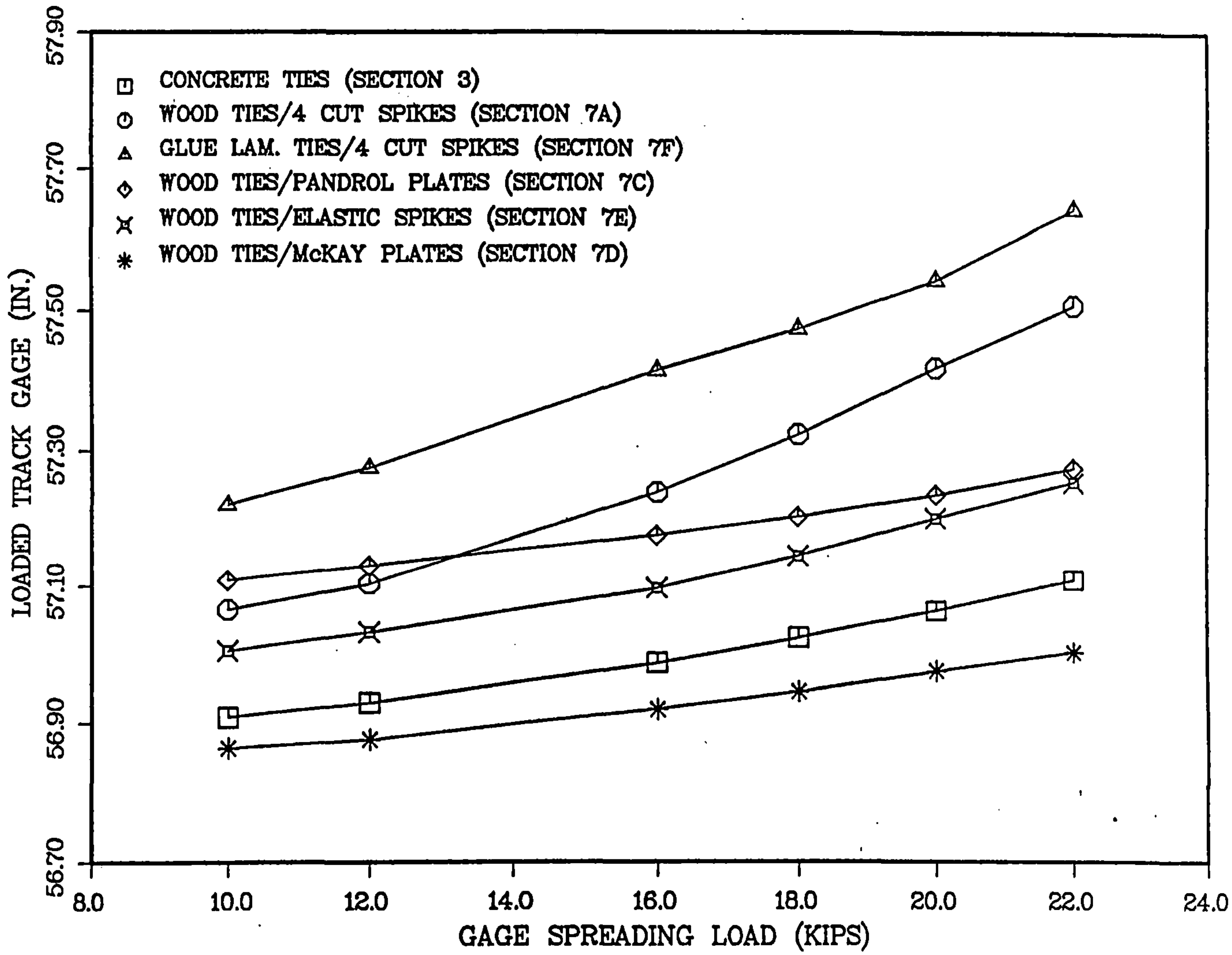

Exhibit 32. Loaded Gage versus Gage Widening Load, Comparison among Fasteners, V=33 Kips.

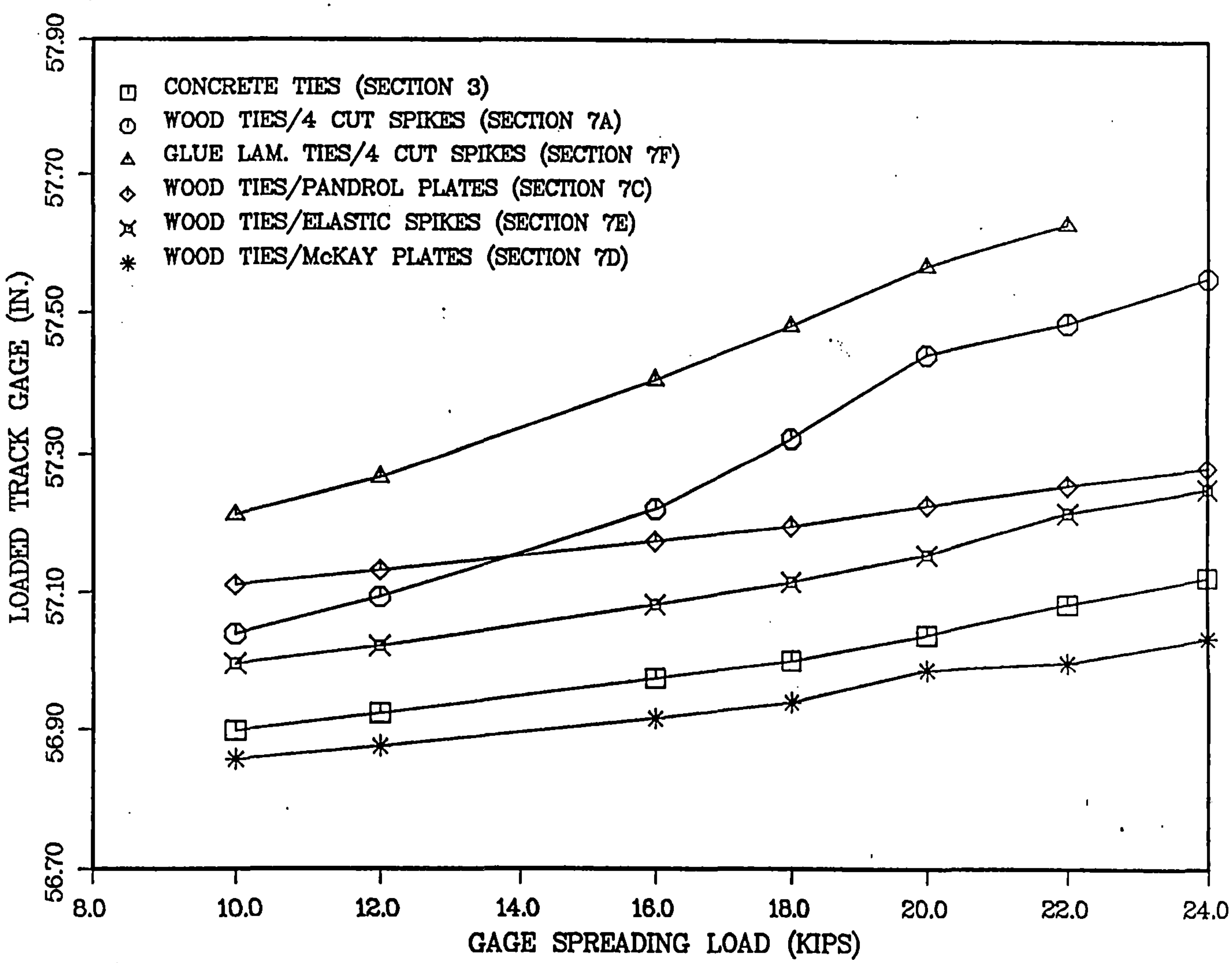

Exhibit 33. Loaded Gage versus Gage Widening Load, Comparison among Fasteners, V=39 Kips.

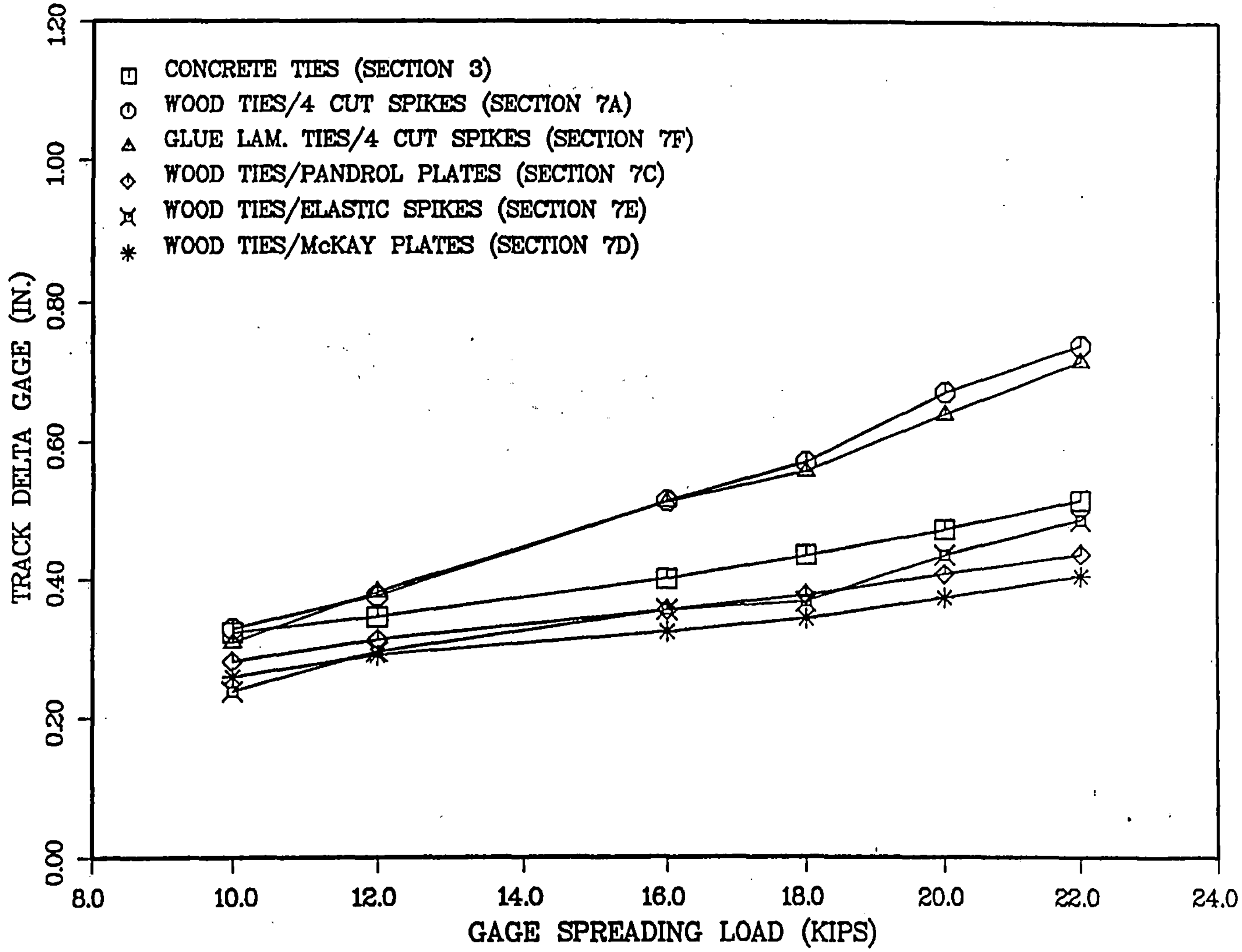

Exhibit 34. Delta Gage versus Gage Widening Load, Comparison among Fasteners, V=33 Kips.

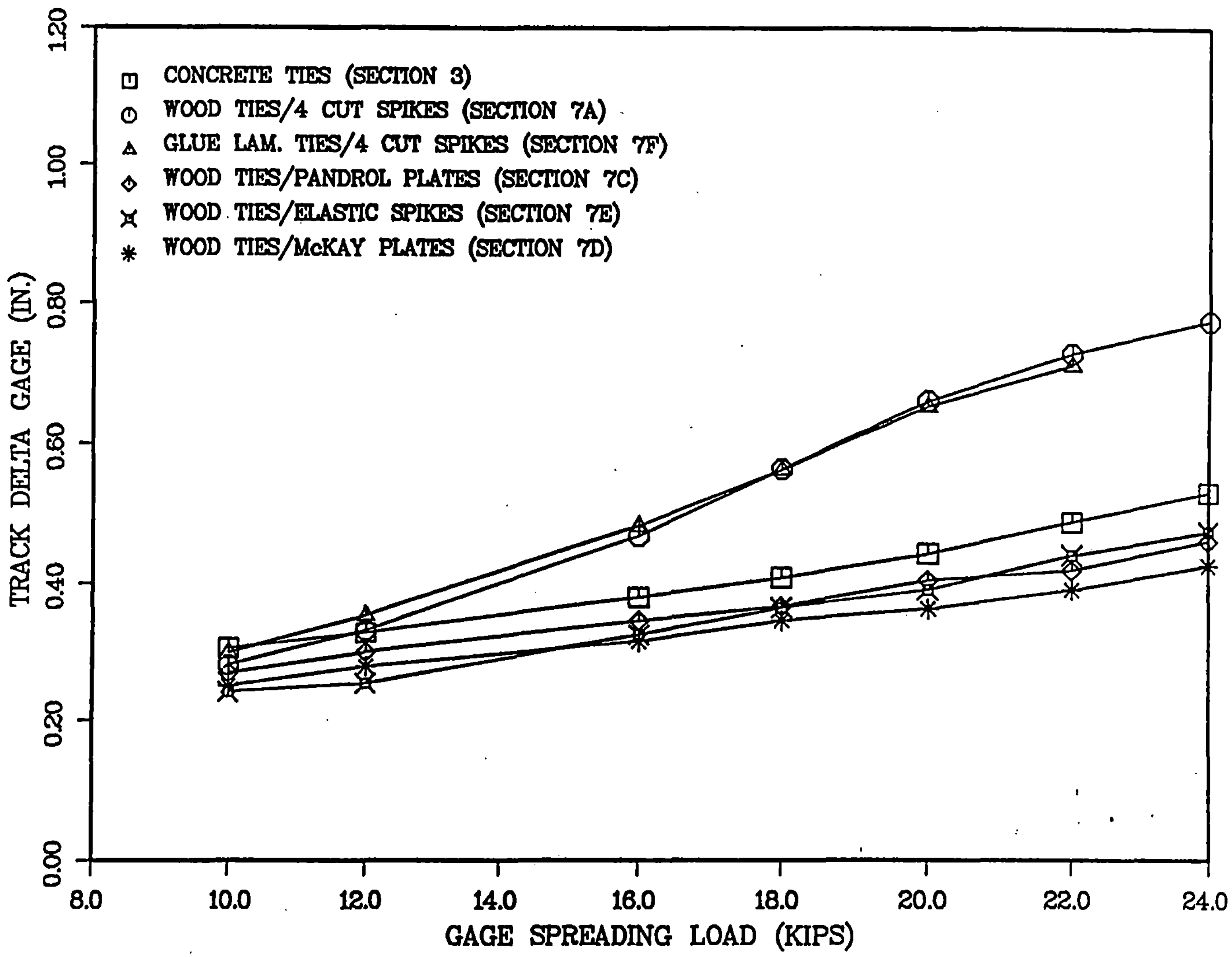

Exhibit 35. Delta Gage versus Gage Widening Load, Comparison among Fasteners, V=39 Kips.

corresponding slope is much shallower than that from domestic hard/softwood or glue laminated wood ties with cut spikes or elastic spikes.

For a 33 kip wheel load, the maximum loaded gage at L=22 kips, for concrete ties is about 57.1"; while for wood ties with Pandrol it is about 57.25"; and 57.0" for wood ties with Safelock. In comparison, the loaded gage for domestic hard/softwood ties with 4 cut spikes is about 57.5"; and 57.65" for glue laminated ties with 4 cut spikes. The elastic spikes on domestic hard/softwood ties, on the other hand, give a loaded gage in between that of domestic hard/softwood ties with 4 cut spikes and concrete ties or domestic hard/softwood ties with Pandrol or Safelock. The corresponding loaded gage for 39 kip wheel load is also of about the same magnitude as for 33 kip wheel load.

Results also show that magnitude of delta gage, for 33 kip wheel load and 22 kip gage widening load, is approximately 0.75" for domestic hard/softwood ties with 4 cut spikes, 0.7" for glue laminated ties with 4 cut spikes, 0.52" for concrete ties, and 0.49", 0.42" and 0.4", respectively for elastic spikes, Pandrol and Safelock on domestic hard/softwood ties. Comparable magnitude of delta gage exists for a 39 kip wheel.

From a study of delta gage, it is clear that the highest gage widening occurs with 4 cut spikes and the least with Safelock, both on domestic hard/softwood ties. Also, at a given gage widening load, both the loaded gage and delta gage are generally somewhat higher for the 33 kip wheel load tests than for the 39 kip tests.

Also, this difference is largest for domestic hard/softwood ties with 4 cut spikes, and is almost negligible on the track segments where either concrete ties or domestic hard/softwood ties with elastic fasteners such as Pandrol and Safelock are used. In the case of domestic hard/softwood ties with elastic spikes, this difference is somewhere between that occurring for cut spikes and the elastic fasteners mentioned above. The slope (rate of change of gage widening with respect to the gage widening load) is highest for cut spikes on domestic hard/softwood ties and glue laminated ties and least for the domestic hard/softwood ties with Pandrol or Safelock. Overall, more gage widening occurs for wood ties with cut spikes than either concrete ties or domestic hard/softwood ties with Pandrol and Safelock. Safelock also seems to have given the lowest gage widening results in these tests.

The L/V plots of delta gage, with respect to concrete ties and various fastener types on wood ties, for the 33 and 39 kip wheel loads, are given in Exhibits 36 and 37, respectively. Exhibits 38 through 43 show comparisons of selected track parameters under 33 and 39 kip wheel loads for concrete ties and each fastener type on wood ties individually. The remaining L/V plots for other track segments are included in Appendix B in Exhibits B18 through B34.

For the same L/V ratio, the applied gage widening load is higher for 39 kip wheel load than for 33 kip load. Also, the loaded gage and delta gage readings are larger for 39 kip wheel load than 33 kip load. Characteristics similar to those noted earlier, when discussing plots of track parameters with respect to

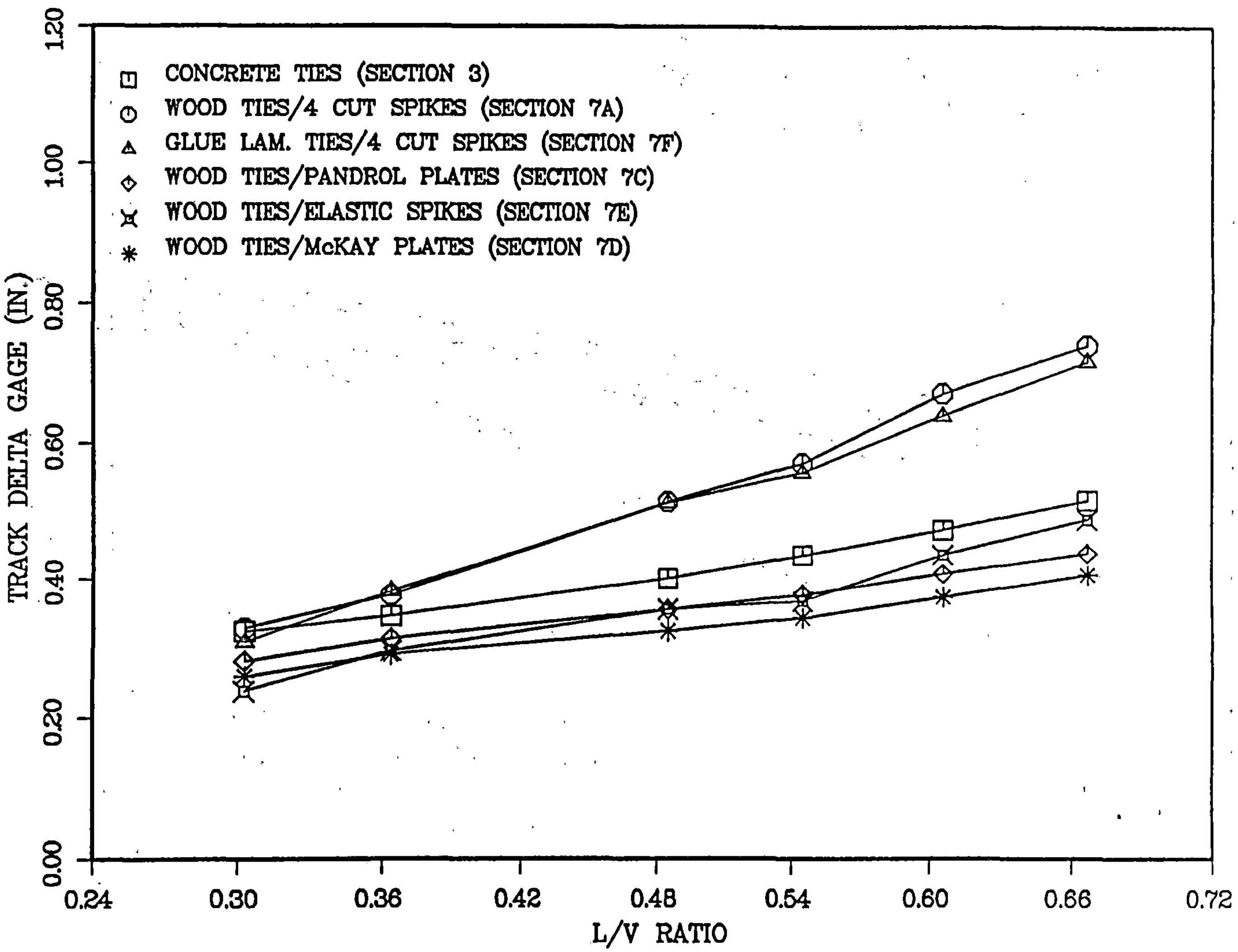

Exhibit 36. Delta Gage versus L/V Ratio, Comparison among Fasteners, V=33 Kips.

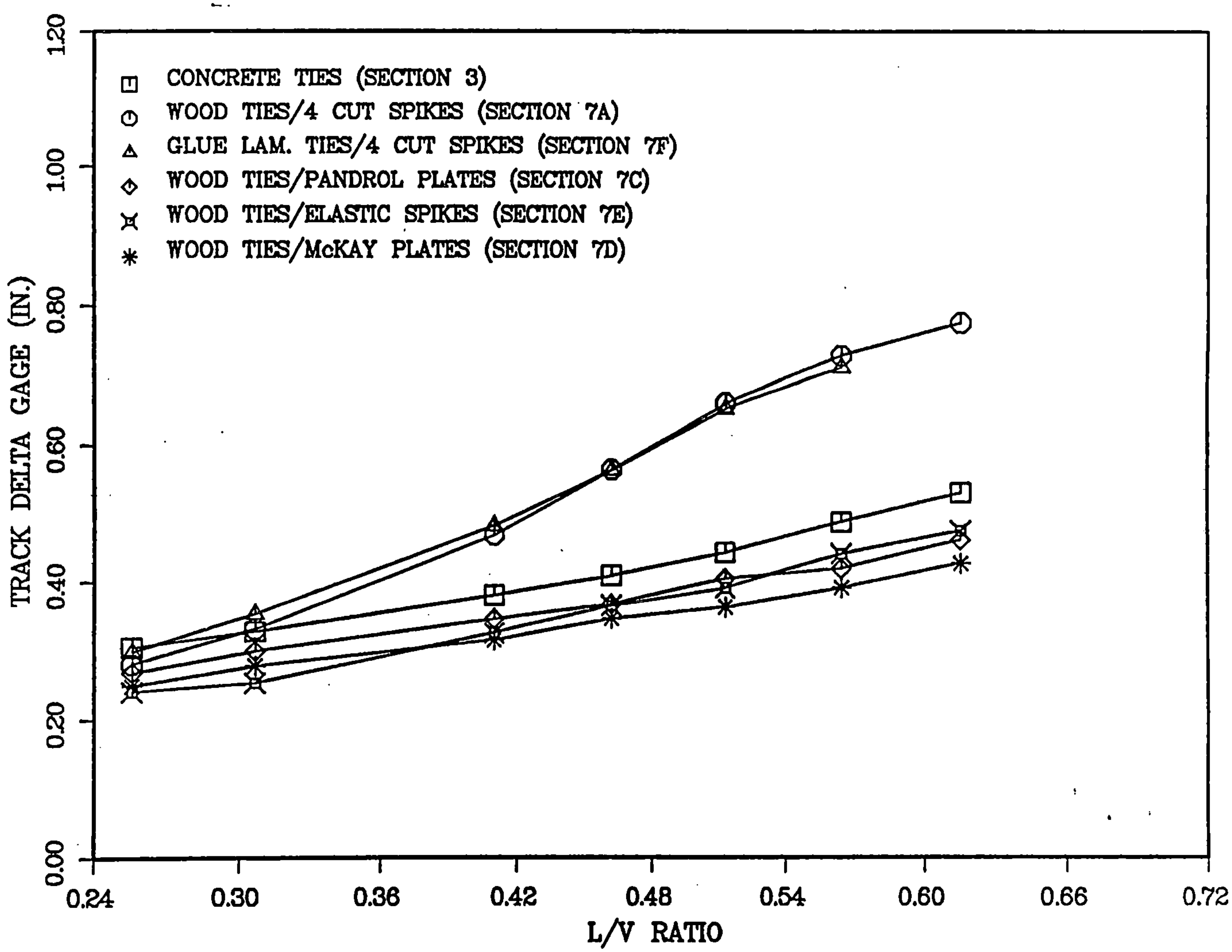

Exhibit 37. Delta Gage versus L/V Ratio, Comparison among Fasteners, V=39 Kips.

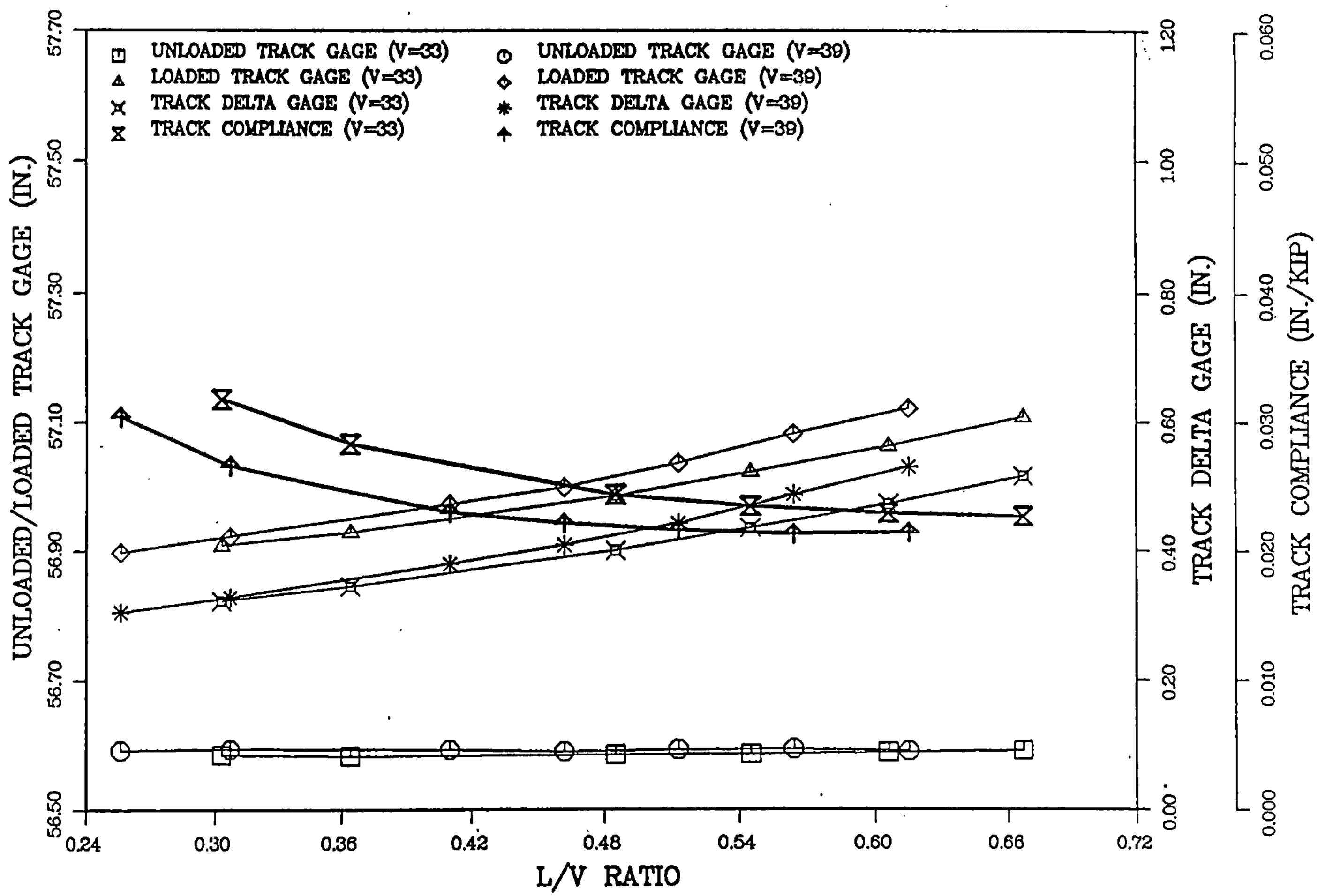

Exhibit 38. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 5-Degree Curve (Section 3), Concrete Ties, V=33 and 39 Kips.

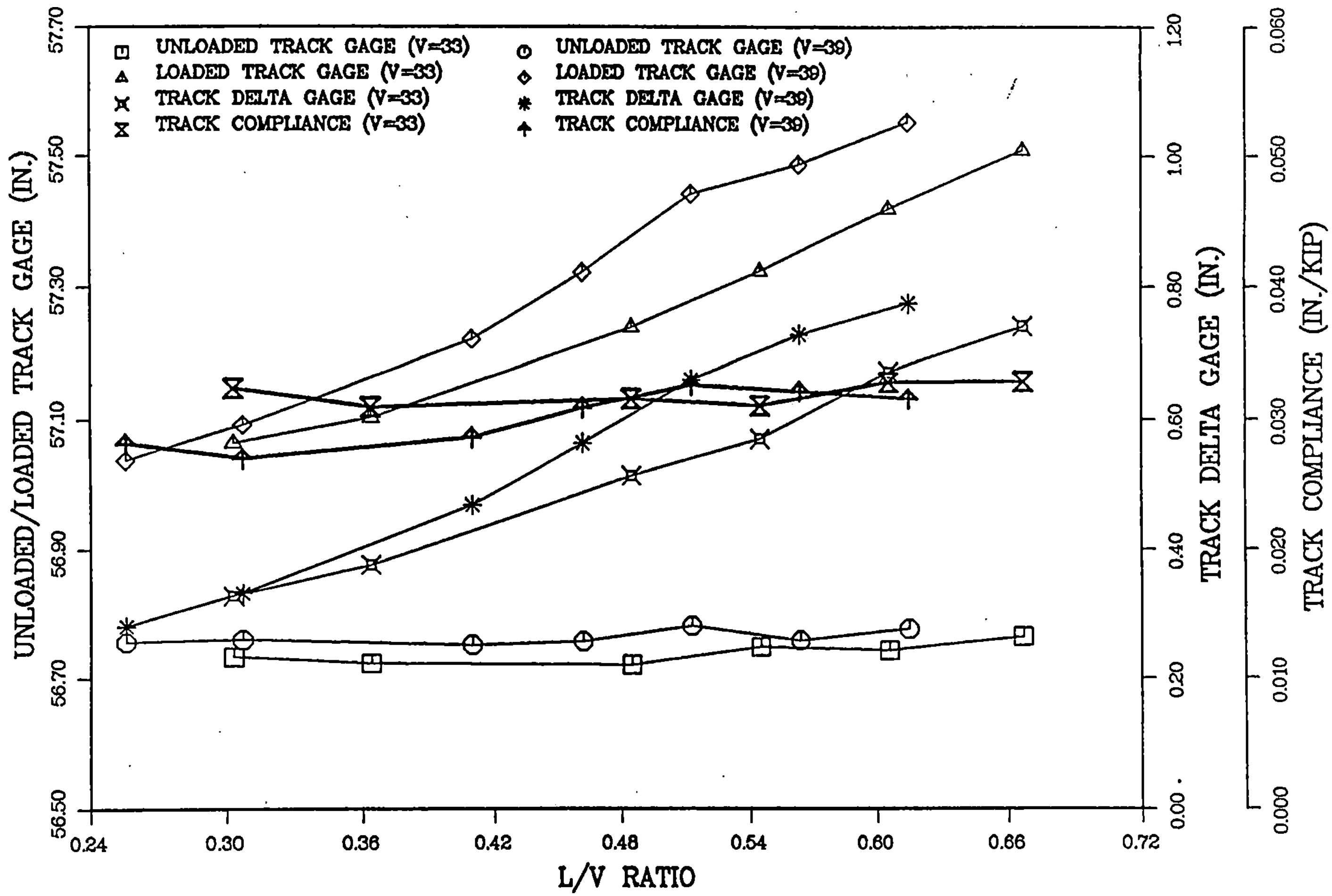

Exhibit 39. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 5-Degree Curve (Section 7A), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

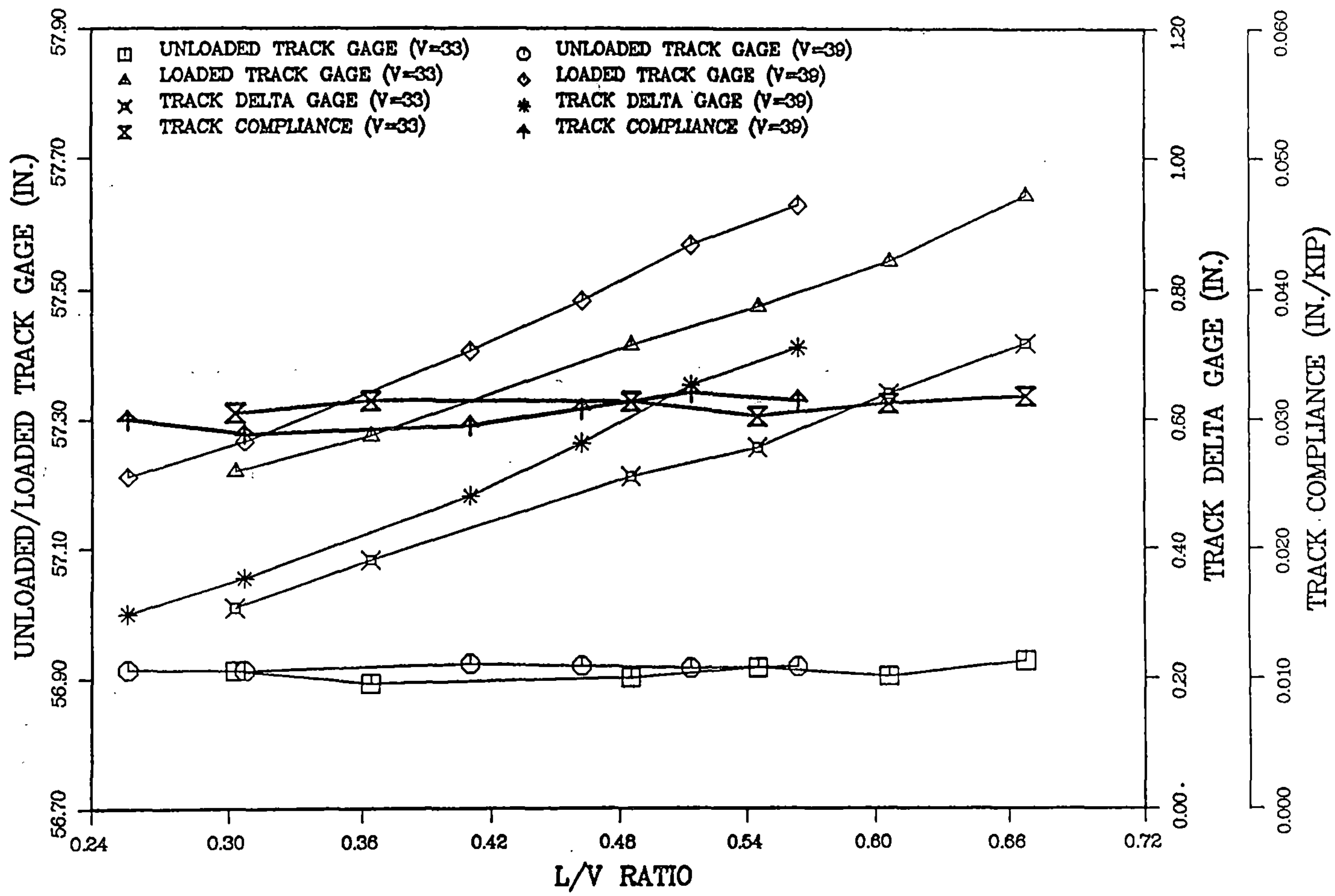

Exhibit 40. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 5-Degree Curve (Section 7F), Glue Laminated Ties/4-Cut Spikes, V=33 and 39 Kips.

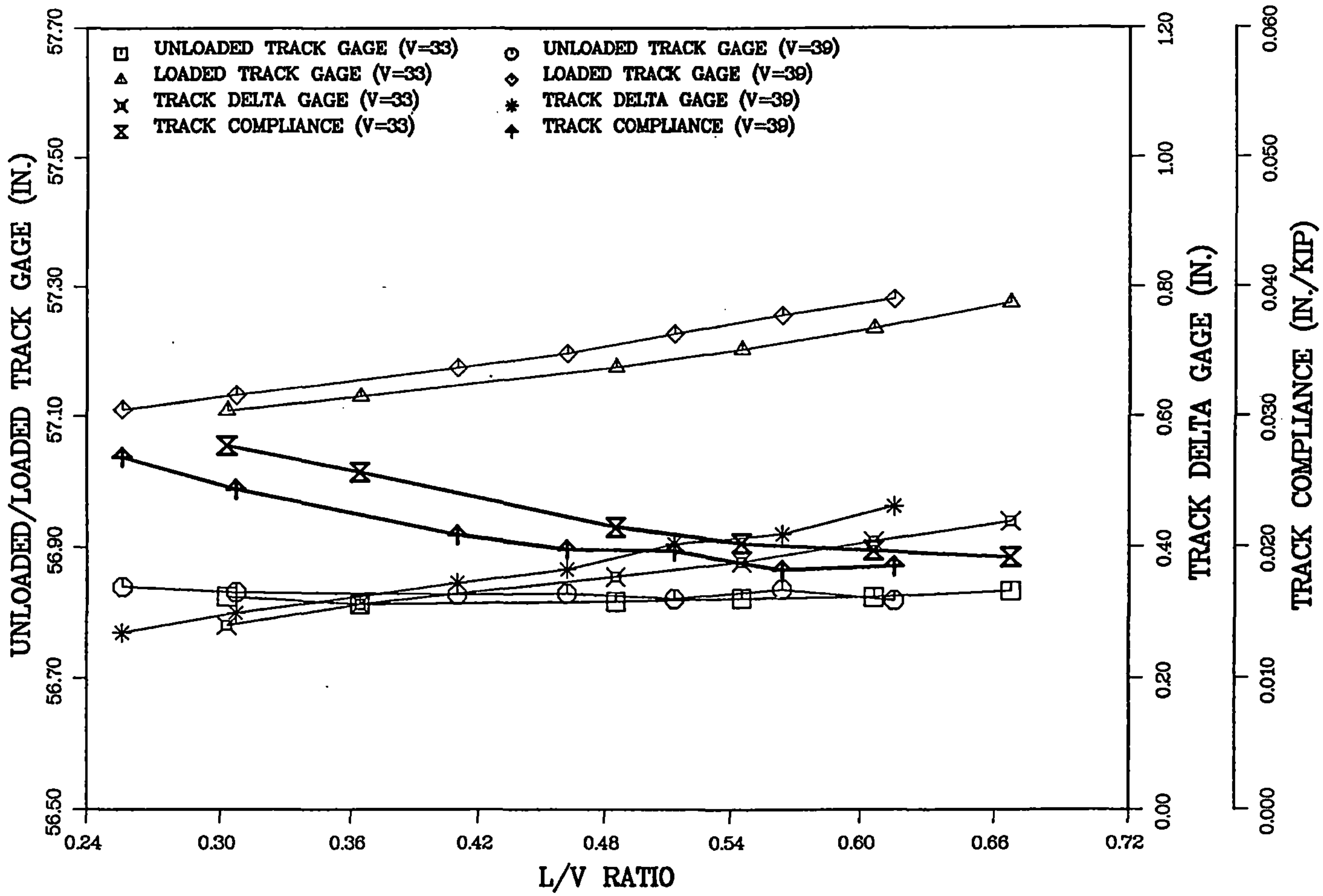

Exhibit 41. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 5-Degree Curve (Section 7C), Wood Ties/Pandrol Fasteners, V=33 and 39 Kips.

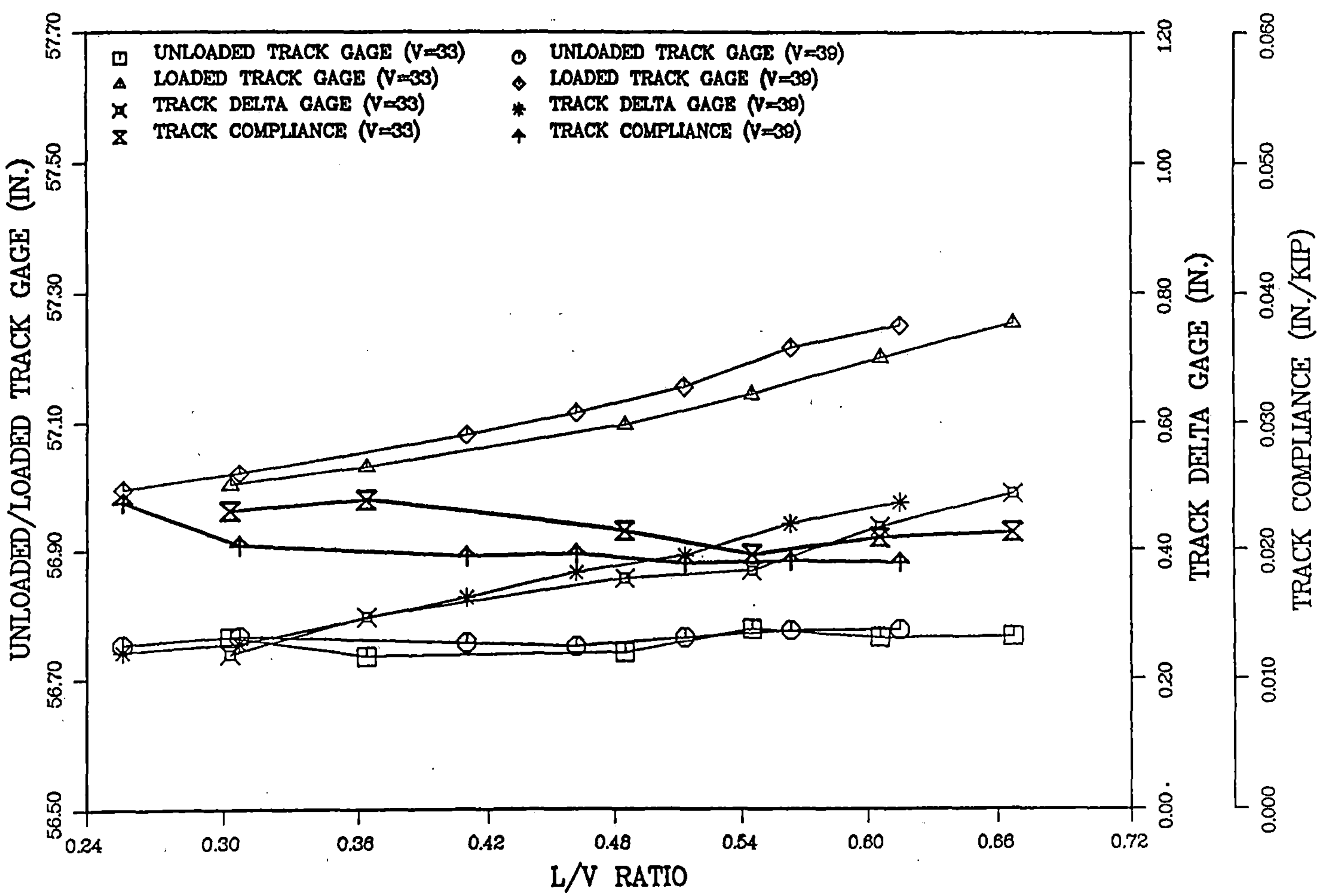

Exhibit 42. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 5-Degree Curve (Section 7E), Wood Ties/Elastic Spikes, V=33 and 39 Kips.

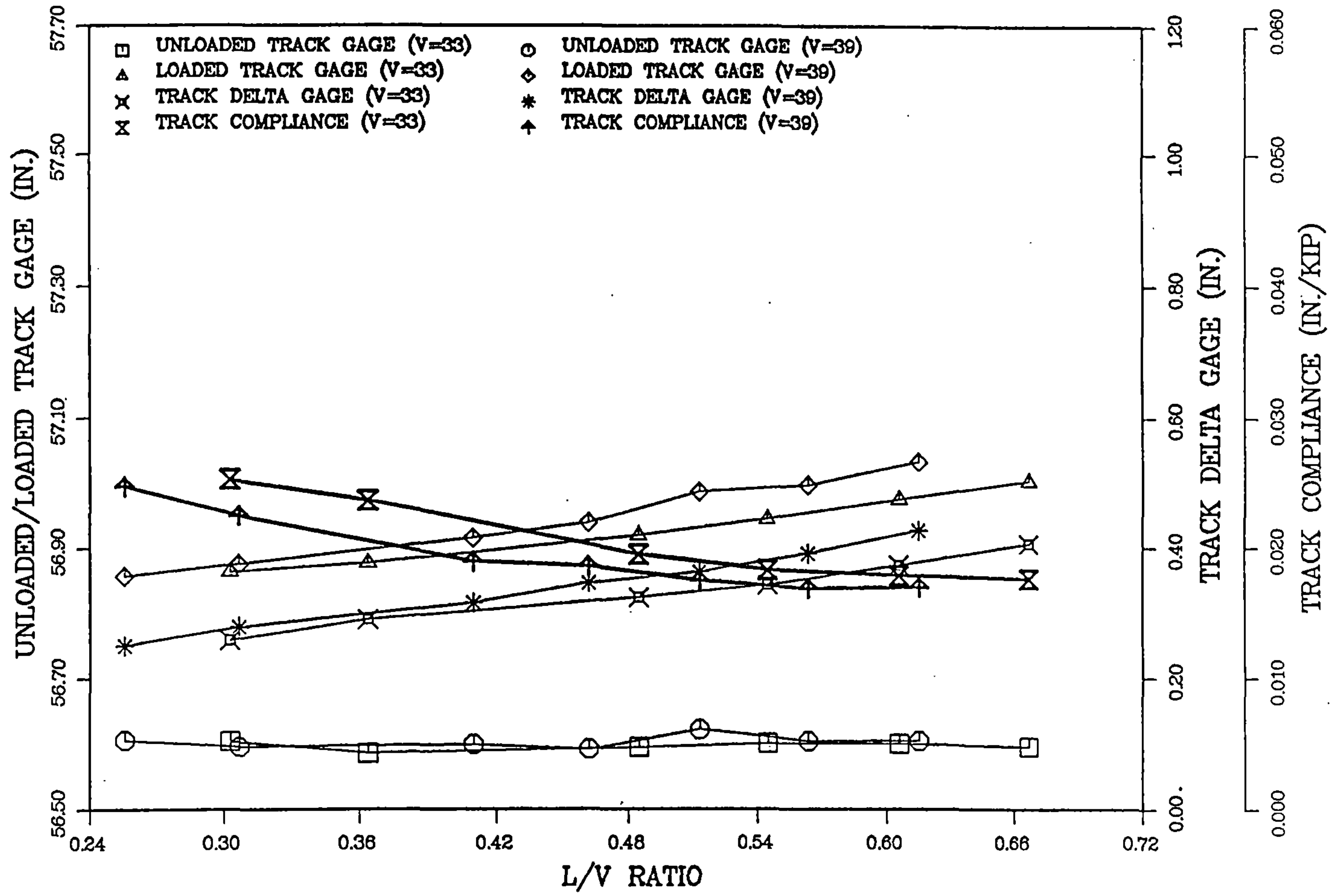

Exhibit 43. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 5-Degree Curve (Section 7D), Wood Ties/Safelock Fasteners, V=33 and 39 Kips.

gage widening loads, are obvious from these L/V plots. That is, the highest gage widening occurs for wood ties with cut spikes and the least for wood ties with Safelock fasteners. The slopes of the track response curves for cut spikes on domestic hard/softwood ties and glue laminated ties are significantly higher than those for concrete ties and wood ties with Pandrol and Safelock fasteners. In fact, the L/V curves for concrete ties and wood ties with elastic fasteners are all parallel to each other.

The track compliance results are quite dramatic. For discussion, Exhibits 26 to 31 with respect to gage widening loads, and Exhibits 38 to 43 with respect to L/V ratios are again referenced. A comparison of track compliance plots for 33 and 39 kip wheel loads clearly shows the stabilizing effect of the higher vertical load on the rail. Another very important characteristic to note from these curves is that for cut spikes on domestic hard/softwood ties and glue laminated ties, the track compliance stays approximately constant with increasing magnitude of the gage widening load or the corresponding L/V ratio. On the other hand, for concrete ties and wood ties with Pandrol and Safelock fasteners, the track compliance decreases with increasing load or L/V ratio.

Since track compliance is the quotient between delta gage and the corresponding gage widening load, constant compliance implies linearly increasing magnitude of delta gage with respect to gage widening load. In other words, the behavior of wood ties with cut spikes is like that of a linear spring. In contrast, for concrete ties and wood ties with Pandrol and Safelock fasteners, gage hardening characteristics are apparent. That is, concrete ties and wood ties with Pandrol and Safelock fasteners provide increasing gage widening strength at higher gage widening loads.

The discussion would be incomplete without mentioning the gage widening strength of the Azobe ties with five cut spikes in the first subsection of Section 31 of the HTL. The caution of not including these results with other results in the previous sections of the report, comes from the non-availability of other similar track sections on the HTL in judging the consistency of the results. In spite of this fact, in-motion gage widening test results on the Azobe ties with five cut spikes show a superior gage widening strength. The question as to whether such a behavior will also be found in revenue service, and also the question of the degree of such a gage widening strength when compared to the strengths from elastic fasteners, are left to the reader for assessment. This question may be the object of additional tests.

Exhibits 44 and 45 show gage widening results of the Azobe ties with 5 cut spikes. Upto about 16 kips of gage widening load, delta gage on the Azobe ties is comparable to that on domestic hard/softwood ties with four cut spikes. However, at higher gage widening loads, the difference continuously increases such that the delta gages are higher for the domestic hard/softwood and glue laminated ties. Furthermore, the slope of the delta gage curves for the Azobe ties are flatter in comparison to these slopes for domestic hard/softwood or glue laminated ties, throughout the gage

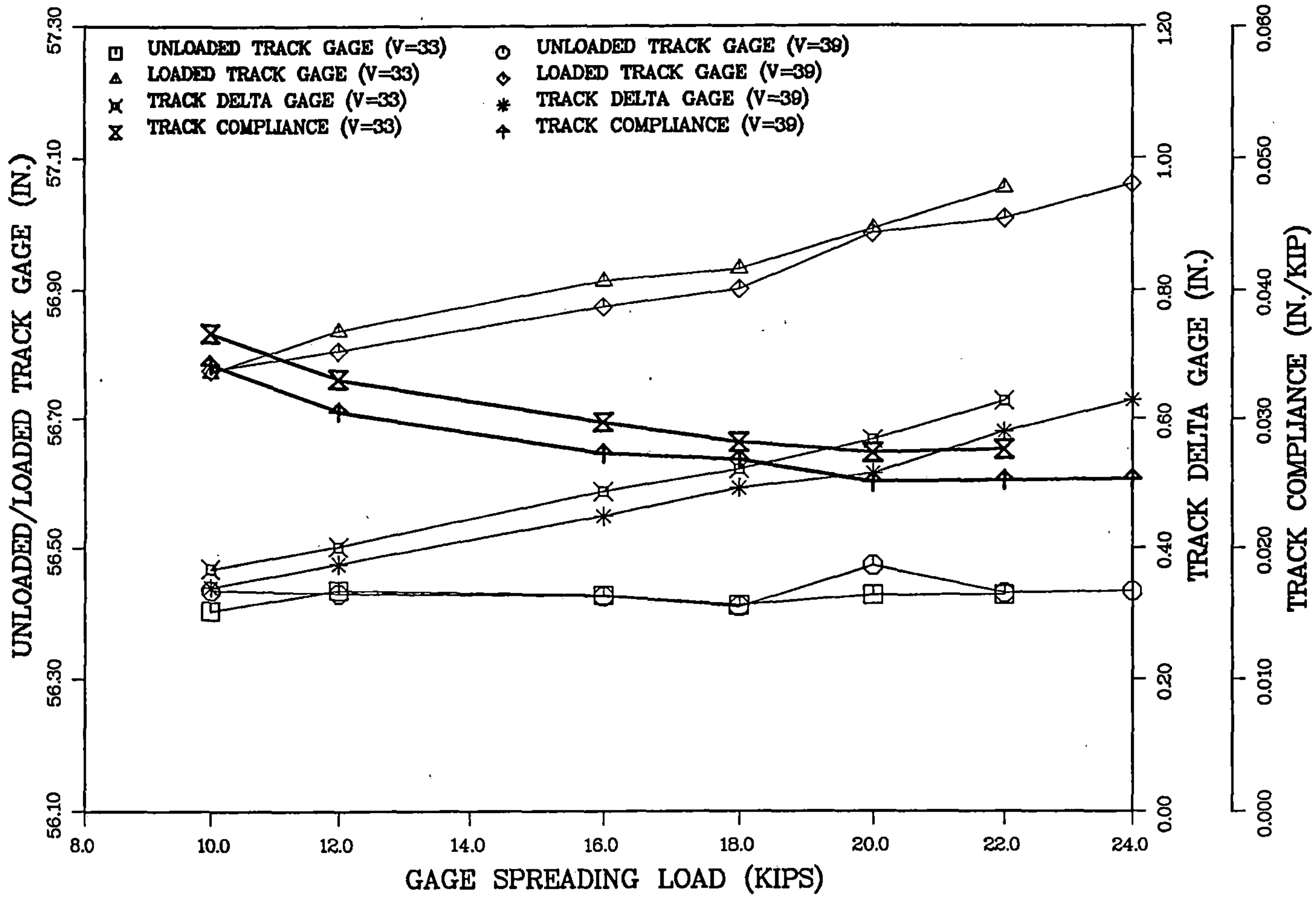

Exhibit 44. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Widening Load, 5-Degree Curve (Section 31), Azobe Ties/5-Cut Spikes, V=33 and 39 Kips.

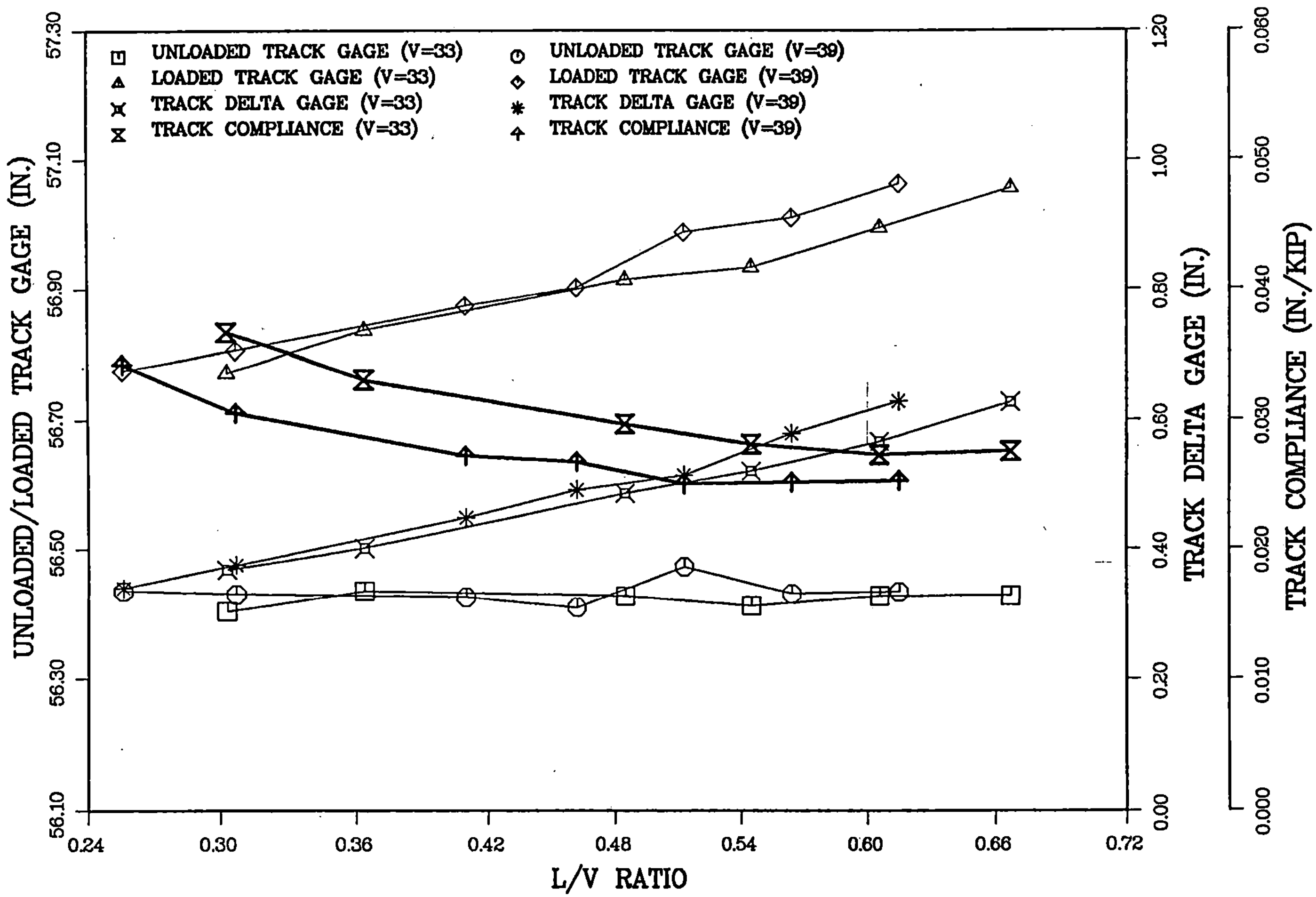

Exhibit 45. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 5-Degree Curve (Section 31), Azobe Ties/5-Cut Spikes, V=33 and 39 Kips.

widening load range. As a result of these differences, track compliance curves for the Azobe ties show gage hardening characteristics similar to, but not as pronounced as those of concrete ties and wood ties with Pandrol and Safelock fasteners. The superior gage widening strength of cut spikes on Azobe ties is also apparent in Exhibit 45, in which the curves are plotted against L/V ratios.

6.3 Statistical Distributions

The probability distribution used for descriptive statistics is termed as the percentage level exceedance of the sample value being studied. It gives the probability of all data values which are greater than the sample value. The probability exceedance levels are plotted on Gaussian probability paper. If the data is completely random, exceedance levels will plot as a straight line. The comparison between the model (Gaussian) and data is thus reduced to a comparison between the curve of the data and a straight line probably through the 50 percentile level or some other closely fitting straight line. In interpreting the results, it should, however, be noted that a change in the mean value of the data will shift the straight line laterally, while an increase in the standard deviation will flatten it. Thus, both the location and scale parameters of the distribution can be estimated by the probability paper plots. Also included in the plots are Standard Deviation (Sigma) levels as they pertain to the Gaussian distribution. It is clearly pointed out that the Sigma levels do not pertain to the data that is plotted on these papers unless the data itself is random. Also, it should be noted that purely sinusoidal data will plot on the Gaussian paper like an elongated 'S' when the ends are not curved.

As in earlier discussions, the distribution of gage parameters for the track segments having concrete ties of Section 3 and the track segments of Section 7 having wood ties with cut spikes and various other elastic fasteners will be discussed. Also, since distribution trends between the 33 and 39-ton axle loads are very similar, only the 39-ton axle load distribution plots are included. The distribution plots from other track sections, for 39-ton axle load, are included in Appendix C.

The percentage level exceedance plots are divided into two groups. Curves in the first group are used to show the comparative distributions of a track parameter, on the same track segment, from different gage widening loads. Curves in the second group, on the other hand, compare the performance of track in various track segments, for each combination of gage widening load and vertical load in the test. Unloaded gage distribution is included to emphasize the initial condition of the test track segment.

Exceedance curves, for Section 3, are given in Exhibits 46 to 49 for unloaded, loaded and delta gages, and track compliance, respectively. These distribution curves are discussed with respect to the middle portion of the distribution, where most of the data generally resides, and the tails (end portions) which deal with the limits of data. The initial condition of this test track segment,

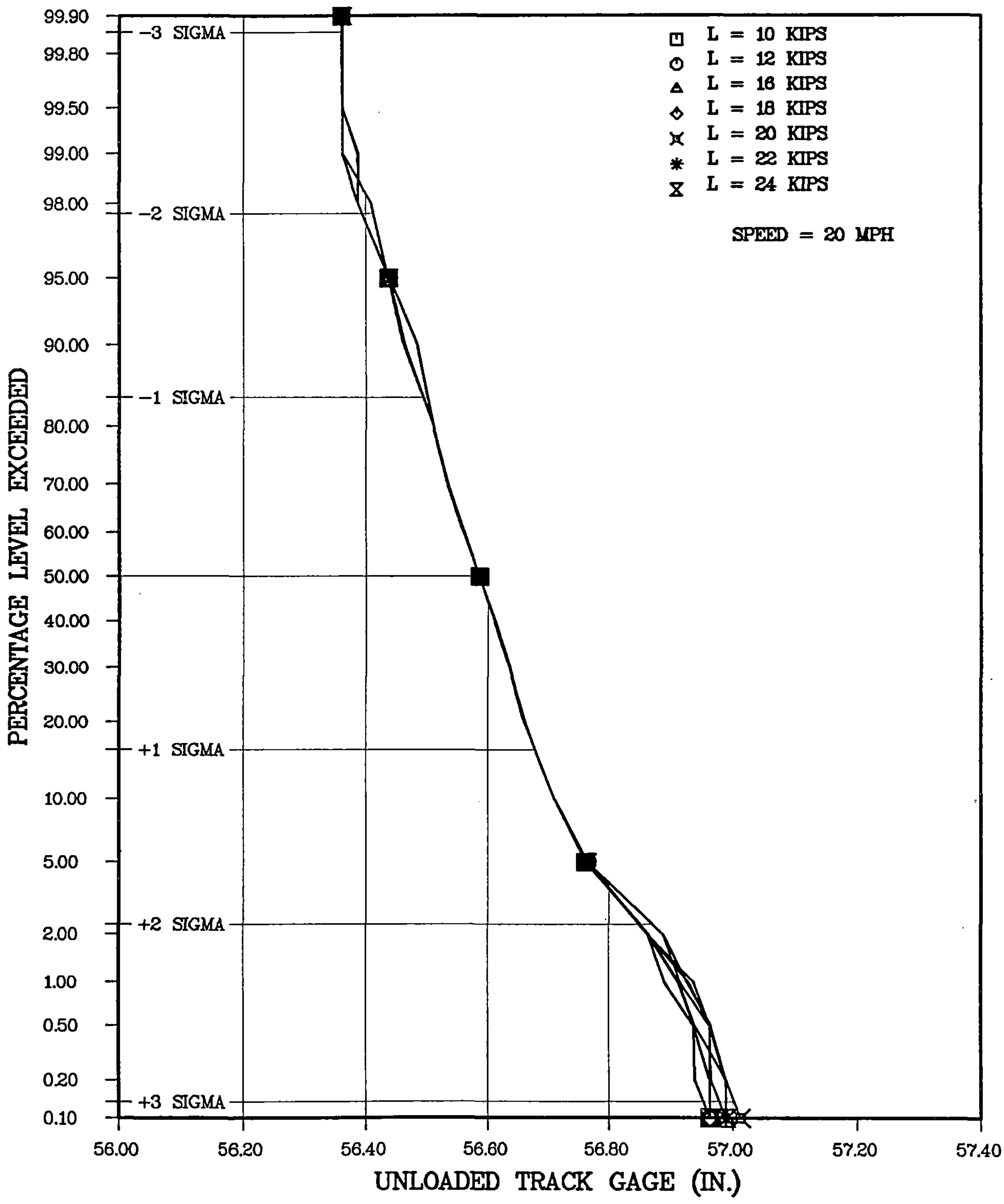

Exhibit 46. Percentage Level Exceedances of Unloaded Gage, 5-Degree Curve (Section 3), Concrete Ties, V=39 Kips.

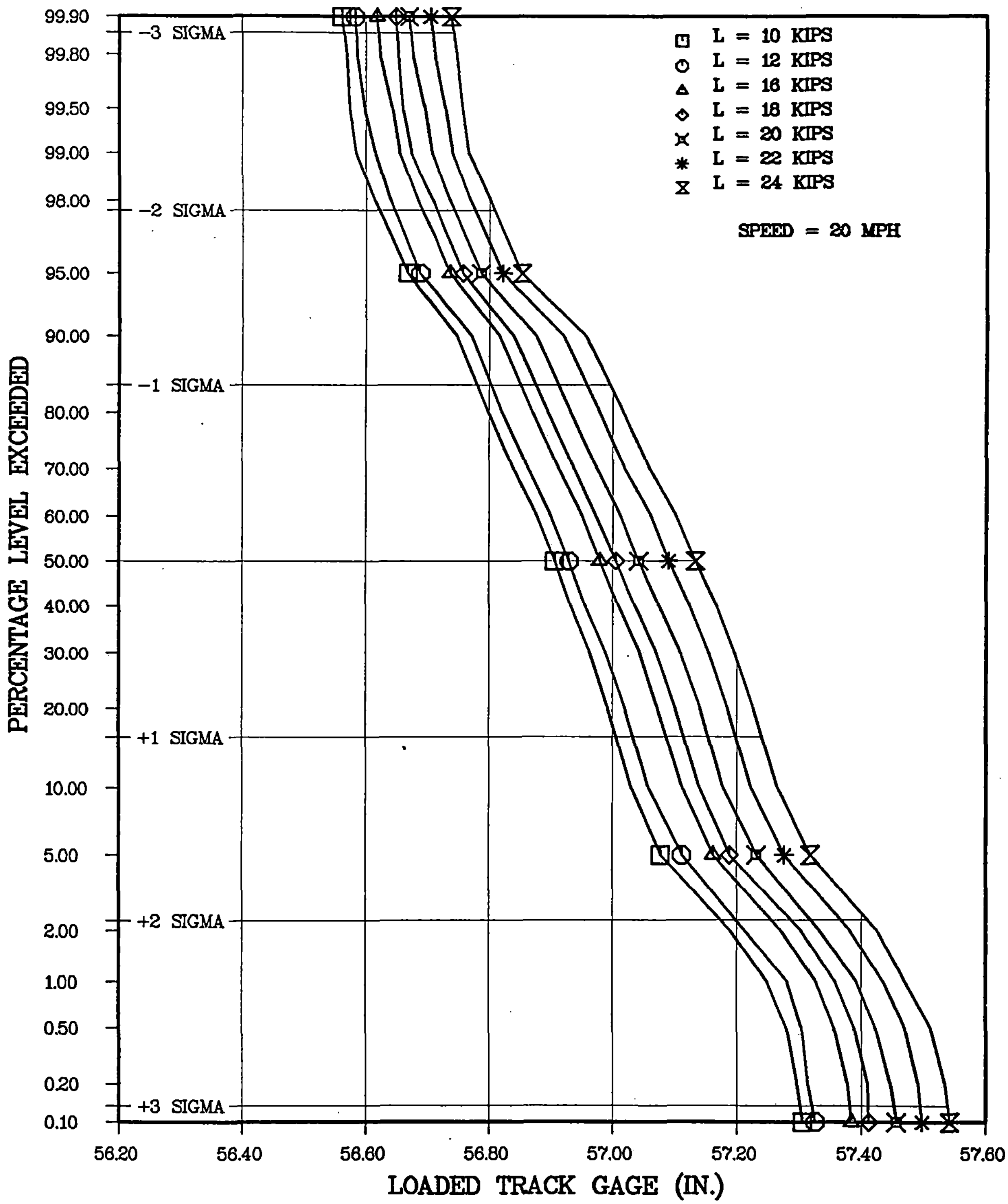

Exhibit 47. Percentage Level Exceedances of Loaded Gage, 5-Degree Curve (Section 3), Concrete Ties, V=39 Kips.

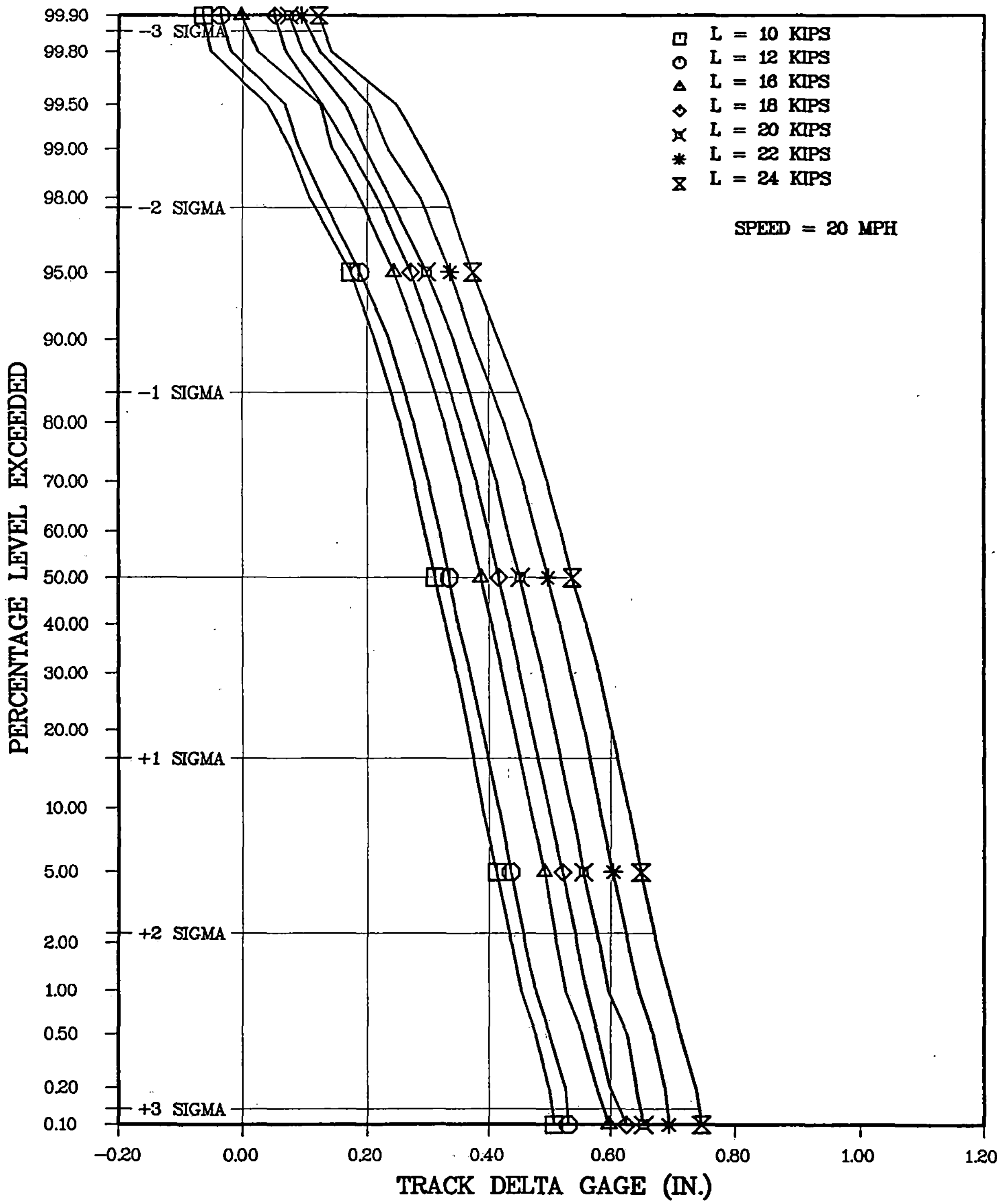

Exhibit 48. Percentage Level Exceedances of Delta Gage, 5-Degree Curve (Section 3), Concrete Ties, V=39 Kips.

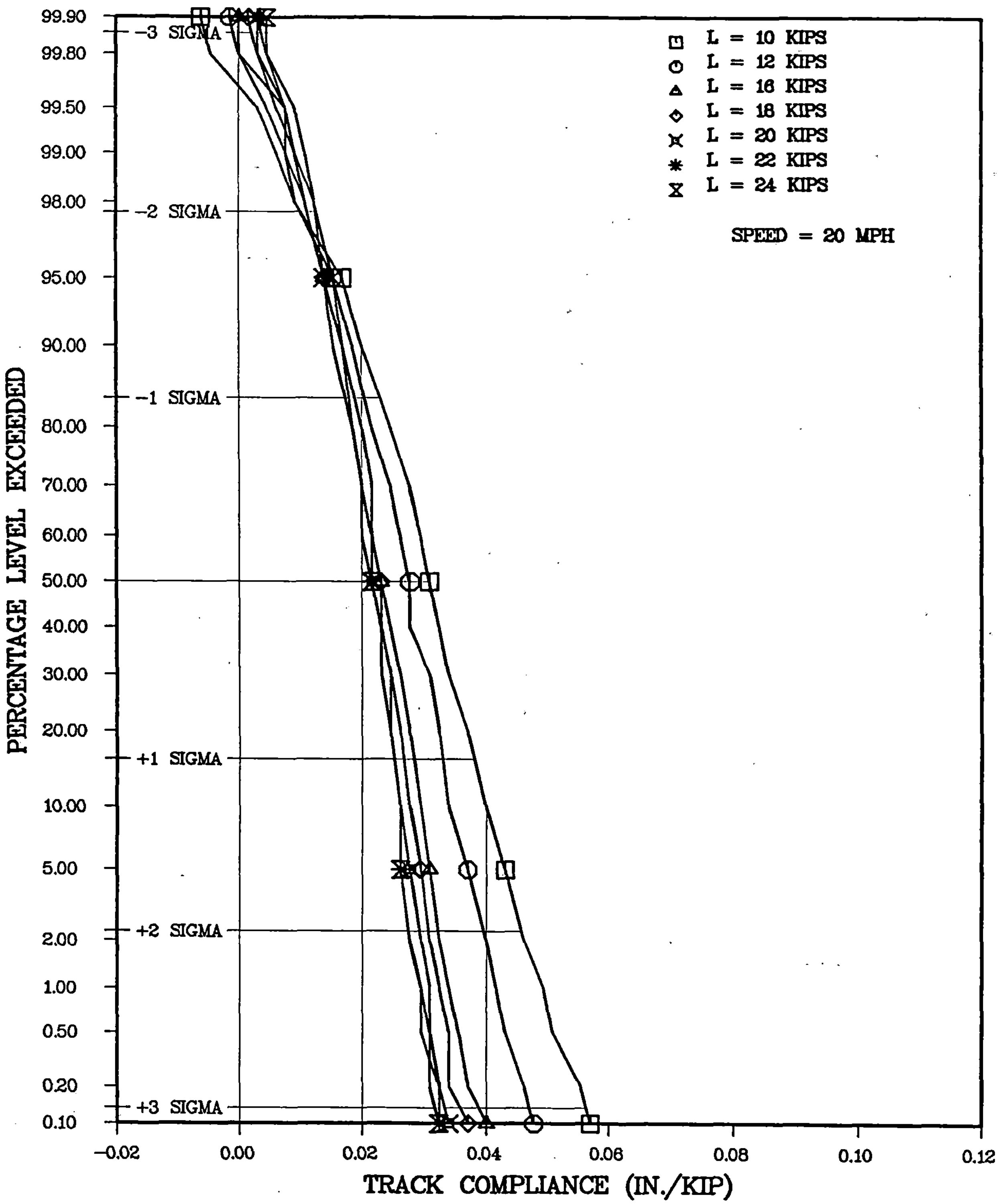

Exhibit 49. Percentage Level Exceedances of Track Compliance, 5-Degree Curve (Section 3), Concrete Ties, V=39 Kips.

in terms of the degree of closeness of curves to a straight line Gaussian model, are apparent in Exhibit 46. Very little scatter appears at the ends of the distributions and is confined within two percent exceedance levels on either end. The unloaded gage geometry is very close to random data between about 5 and 98 percentile levels of exceedance. The Standard Deviation of the unloaded gage increases towards the low tail, while there is no evidence of such an increase towards the upper tail where lower values of the unloaded gage occur.

The loaded gage distribution curves, Exhibit 47, follow rather closely the trend of the distribution of the unloaded gage. Between about 5 and 95 percentile levels, the loaded gage distributions are very close to random data distribution. The slopes of the distribution curves are parallel to each other. The steeper slopes at tail ends suggest that the low and high occurrences of loaded gage have lower variability than the average variability. The loaded gage distribution curves shift laterally to the right indicating increased gage widening, at both the middle portion and the tail ends, with increasing gage widening load. An approximately proportional increase in the loaded gage can be inferred to occur with increasing gage widening load at all exceedance levels. The delta gage distribution curves, Exhibit 48, show the distribution of the values of the difference between the dynamic response of the track to the applied gage widening load and the corresponding unloaded gage. A uniform shift of curves laterally to the right (indicating increased delta gage) for all distribution levels, occurs with increasing gage widening load. The delta gage seems to decrease more or less uniformly from the highest gage widening load to the lowest gage widening load in the tests. A steeper slope (lower Standard Deviation) is present at the lower tail where higher values of delta gage occur. Conversely, the flatter slope (higher Standard Deviation) at the upper tail indicates the presence of lower values of delta gage. It can thus be inferred from this study that the probability density is skewed to the right where the delta gage values are higher. This means that the density of distribution of higher values of the delta gage is more compact than its lower values; that is, higher delta values are more likely to occur.

Track compliance curves, in Exhibit 49, reveal an inflection point (cross over point) at about 98 percent level. Above the 98 percent level, hardening of track compliance occurs while a compliance softening occurs at lower levels. Also, below the 98 percent level, the various compliance curves approximate straight lines, and are therefore closer to random models. A study of compliance values at 50 percent level suggests the gage hardening characteristic for concrete ties. What is more dramatic is the fact that if the gage widening loads are increased, the gage hardening characteristic is increasingly enhanced. That is, the gage widening stiffness increases towards the lower tail starting from the inflection point. A greater compliance at lower gage widening load and a lesser compliance at higher gage widening load imply that as the gage widening load increases, gage widening increases at a decreasing rate. This is the very characteristic of a hardening spring. The occurrence of increasing gage widening stiffness is one of the most important results from these tests.

Distributions curves for domestic hard/softwood ties with 4 cut spikes in Section 7A are given in Exhibits 50 to 53. Elongated 'S' shapes of the unloaded gage curves indicate some sinusoidal effect, yet the middle portions (between about 5 and 95 percentile levels) of the distributions are quite close to the random model. A measure of sinusoidal characteristics is also present in the loaded gage as seen in Exhibit 51. The delta gage distributions, Exhibit 52, also show some sinusoidal effect which seems to decrease with increase in the gage widening load. In general, the slope is flatter in the middle compared to slopes at the tails, meaning that the density of the distribution of the delta gages is more towards the tails.

The compliance results from Section 7A (Exhibit 53) and Section 3(1) (Exhibit 54) are used to draw an inference on the gage widening stiffness provided by 4 cut spikes on domestic hard/softwood ties. This supplement is done because Section 7A is only 165 feet long, while Section 3(1) is 1710 feet long. In contrast to the concrete ties (Exhibit 49), the inflection point for track compliance curves in Exhibit 53 (Section 7A) is not quite apparent. The track compliance curves (Section 7A) are, however, all bunched together at about the 50 percentile level. Any characteristic difference in the compliances, with respect to gage widening load, is not apparent.

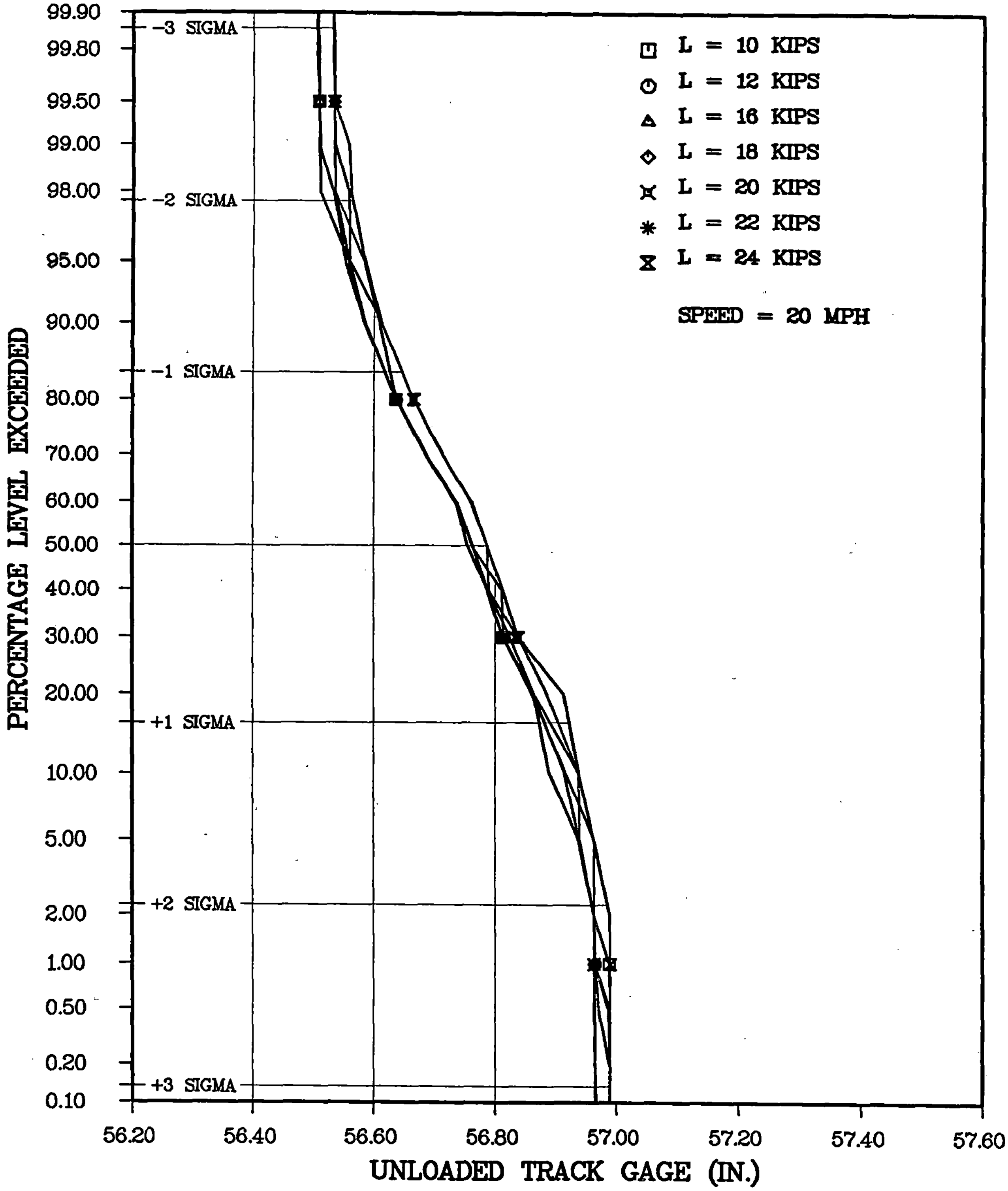

Exhibit 50. Percentage Level Exceedances of Unloaded Gage, 5-Degree Curve (Section 7A), Wood Ties/4-Cut Spikes, V=39 Kips.

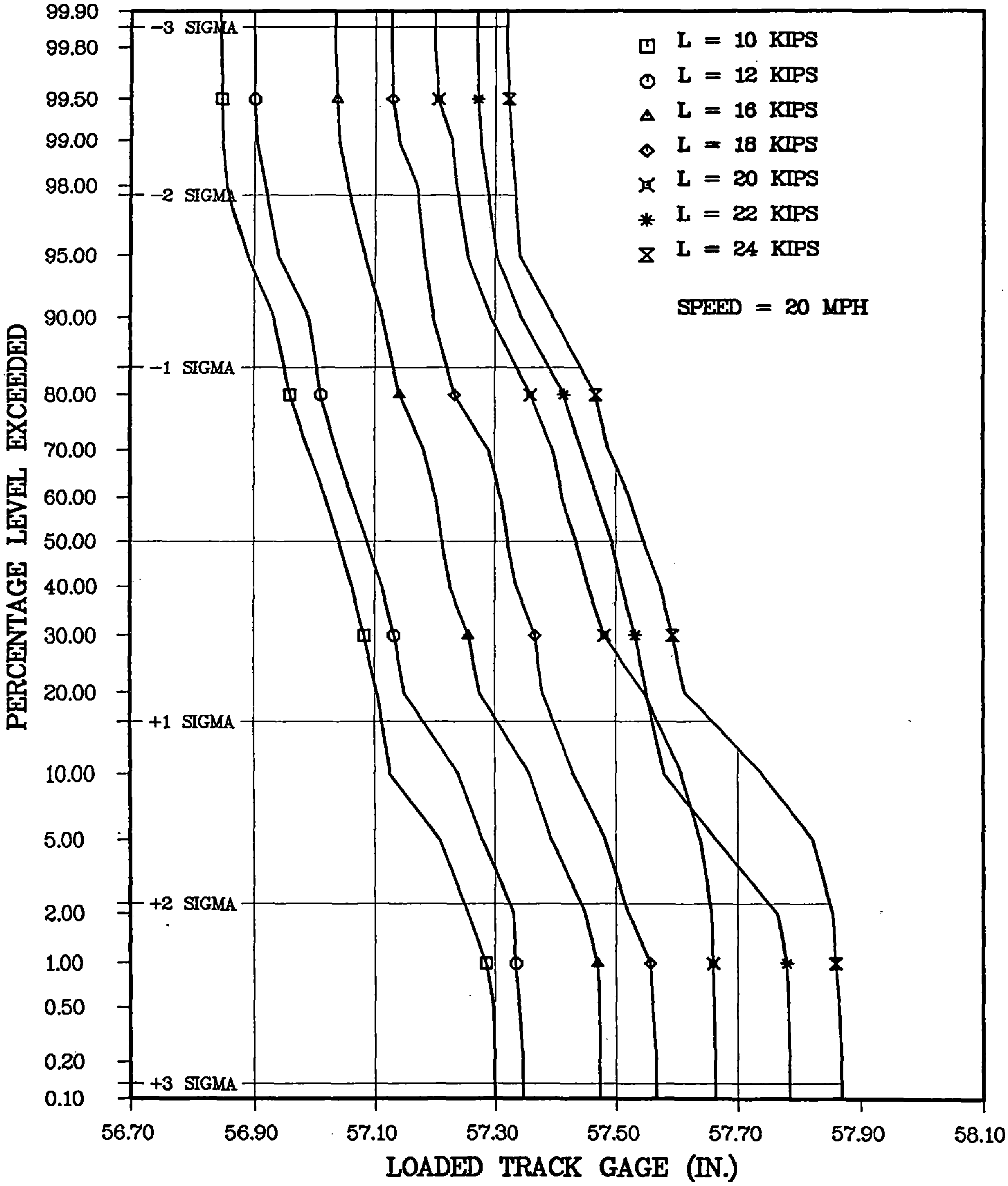

Exhibit 51. Percentage Level Exceedances of Loaded Gage, 5-Degree Curve (Section 7A), Wood Ties/4-Cut Spikes, V=39 Kips.

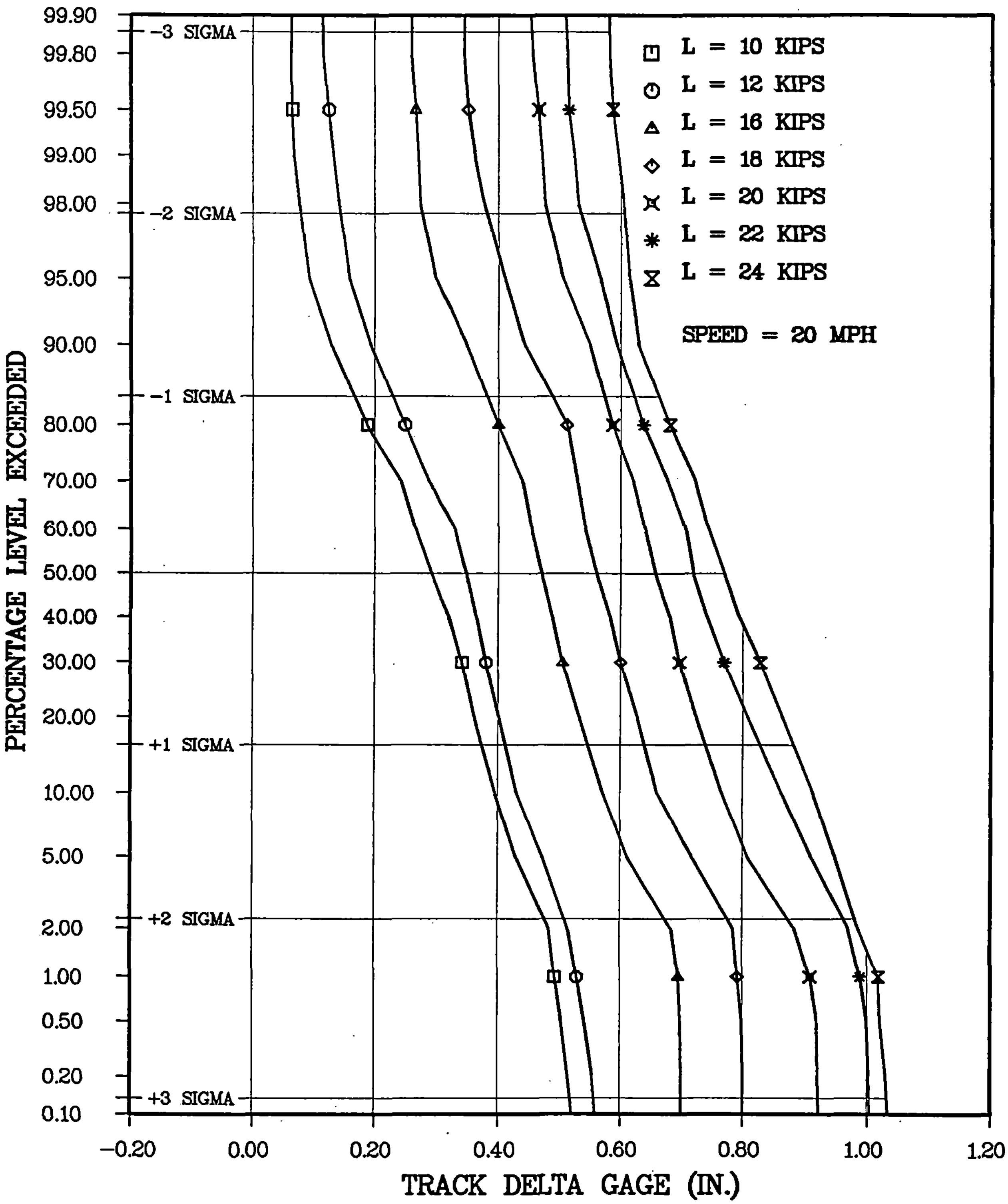

Exhibit 52. Percentage Level Exceedances of Delta Gage, 5-Degree Curve (Section 7A), Wood Ties/4-Cut Spikes, V=39 Kips.

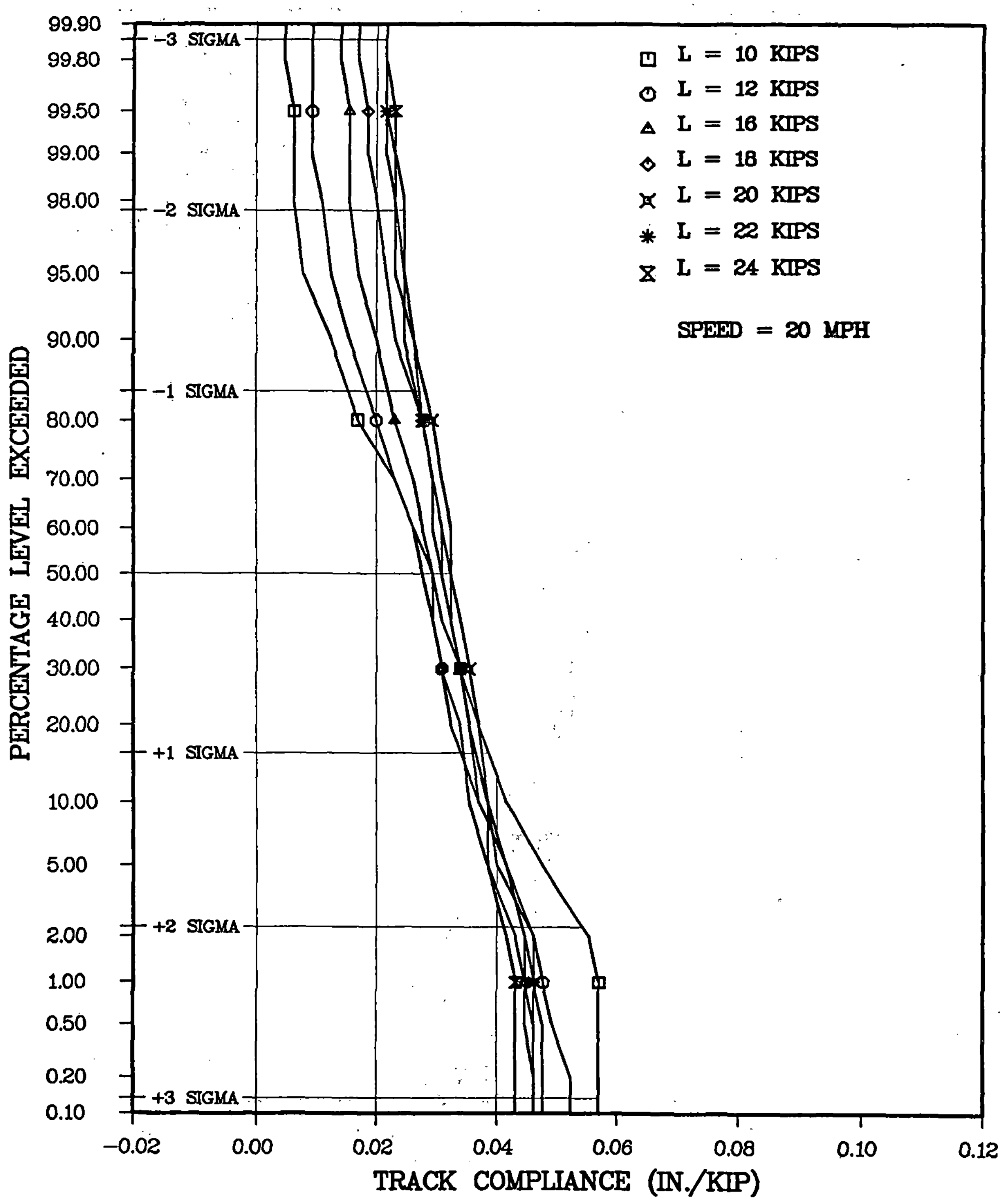

Exhibit 53. Percentage Level Exceedances of Track Compliance, 5-Degree Curve (Section 7A), Wood Ties/4-Cut Spikes, V=39 Kips.

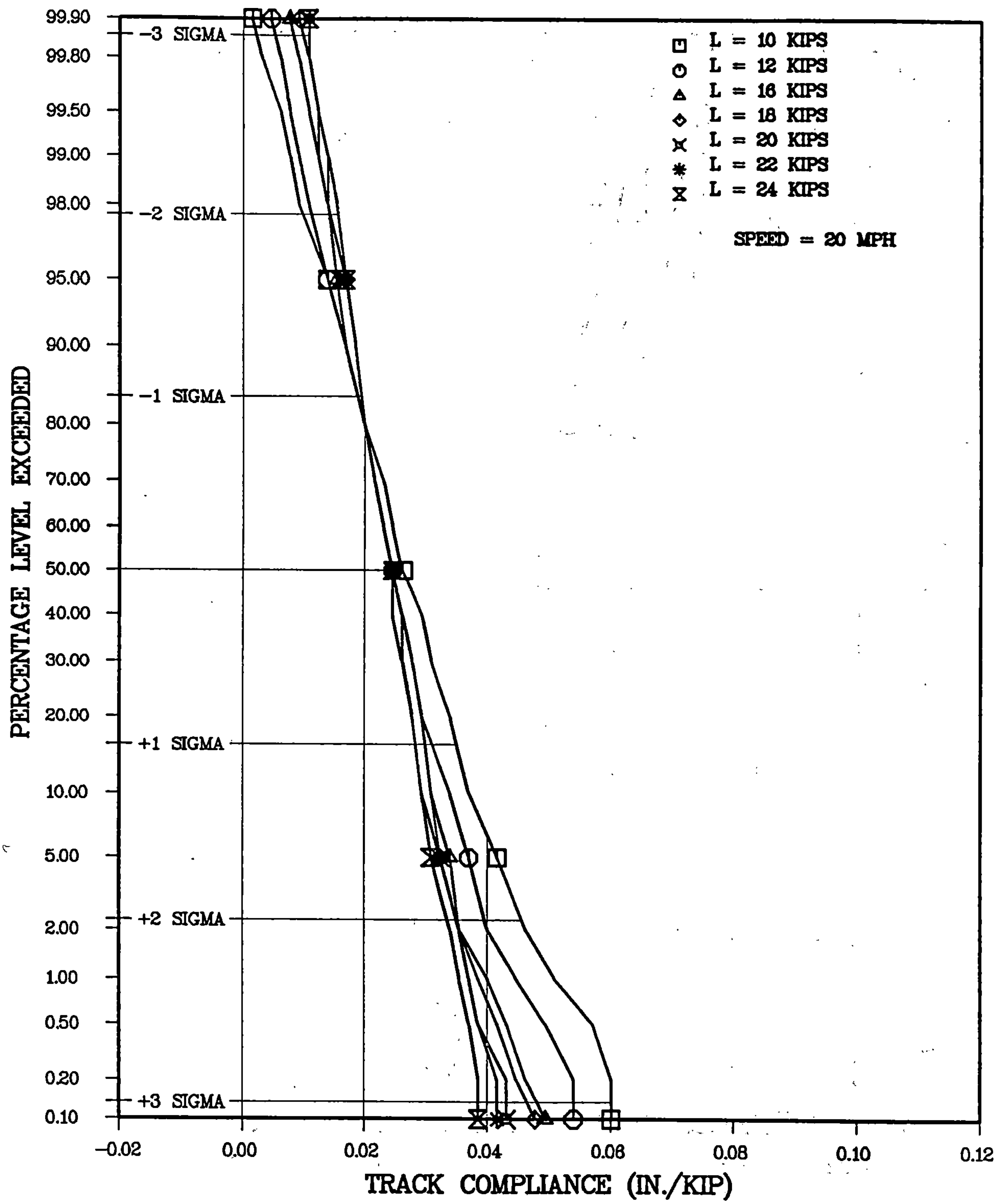

Exhibit 54. Percentage Level Exceedances of Track Compliance, 5-Degree Curve (Section 3), Wood Ties/4-Cut Spikes, V=39 Kips.

On the other hand, the track compliance curves in Exhibit 54 (Section 3(1)) have a distinct inflection point at about 80 percentile level. Yet, the 50 percentile magnitudes do not lead to any discernible characteristic differences in compliance values with respect to the gage widening loads. If 50 percentile magnitudes of the track compliance curves can be taken to be the corresponding average responses, it can be concluded that track compliance for domestic hard/softwood ties with 4 cut spikes remains, in general, constant with respect to the gage widening load. The wood ties with cut spikes can thus be taken to behave, more or less, like linear springs when dealing with average values of the delta gage.

Additional examination of Exhibits 49, 53 and 54, shows that for gage widening loads above 18 kips, the compliance curves follow each other rather closely. It can thus be inferred that at higher gage widening loads, the gage widening strength approaches that of a linear spring for both the wood ties with cut spikes and the concrete ties. In addition, at higher gage widening loads, the track compliance curves are almost linear or Gaussian. As such, more values of the track compliance at higher loads are distributed closer to the mean value which concides with the median value at the 50 percentile level.

In the following, distributions of unloaded, loaded and delta gages, and compliance for the domestic hard/softwood ties with Pandrol, Safelock and elastic spikes, and the Glue Laminated ties with 4 cut spikes are given. At the outset, it should be mentioned that behavior of wood ties with Pandrol and Safelock is quite similar to that of concrete ties discussed previously. The behavior of the Glue Laminated ties with cut spikes is similar to domestic hard/softwood ties with cut spikes, also discussed previously. On the other hand, wood ties with elastic spikes may be seen to perform somewhere between concrete ties and wood ties with cut spikes.

The above mentioned distribution curves for the domestic hard/softwood ties with Pandrol are given in Exhibits 55 to 58; and with Safelock in Exhibits 59 to 62. A comparison between Pandrol and Safelock shows that delta gage curves for Safelock are closer together among themselves at all the exceedance levels, while for Pandrol such a closeness occurs only in the middle portion. The results with Pandrol have a better Gaussian distribution between about 5 to 95 percentile levels. This means that for Pandrol, the delta gage is distributed more about the mean value which approximately concides with the median value at the 50 percentile level, while the similar distribution is more towards the tails for Safelock. Note that a flatter slope in the middle and steeper at ends of the distribution, for both Pandrol and Safelock, exist. This means that dispersion of delta gage about the mean has greater Standard Deviation than for values at the tails.

Track compliance curves, Exhibits 58 and 62, clearly reveal gage hardening characteristics, at 50 percentile level, for Pandrol and Safelock. The inflection point occurs at about 95 percentile level for Pandrol, and at about 85 percentile level for Safelock.

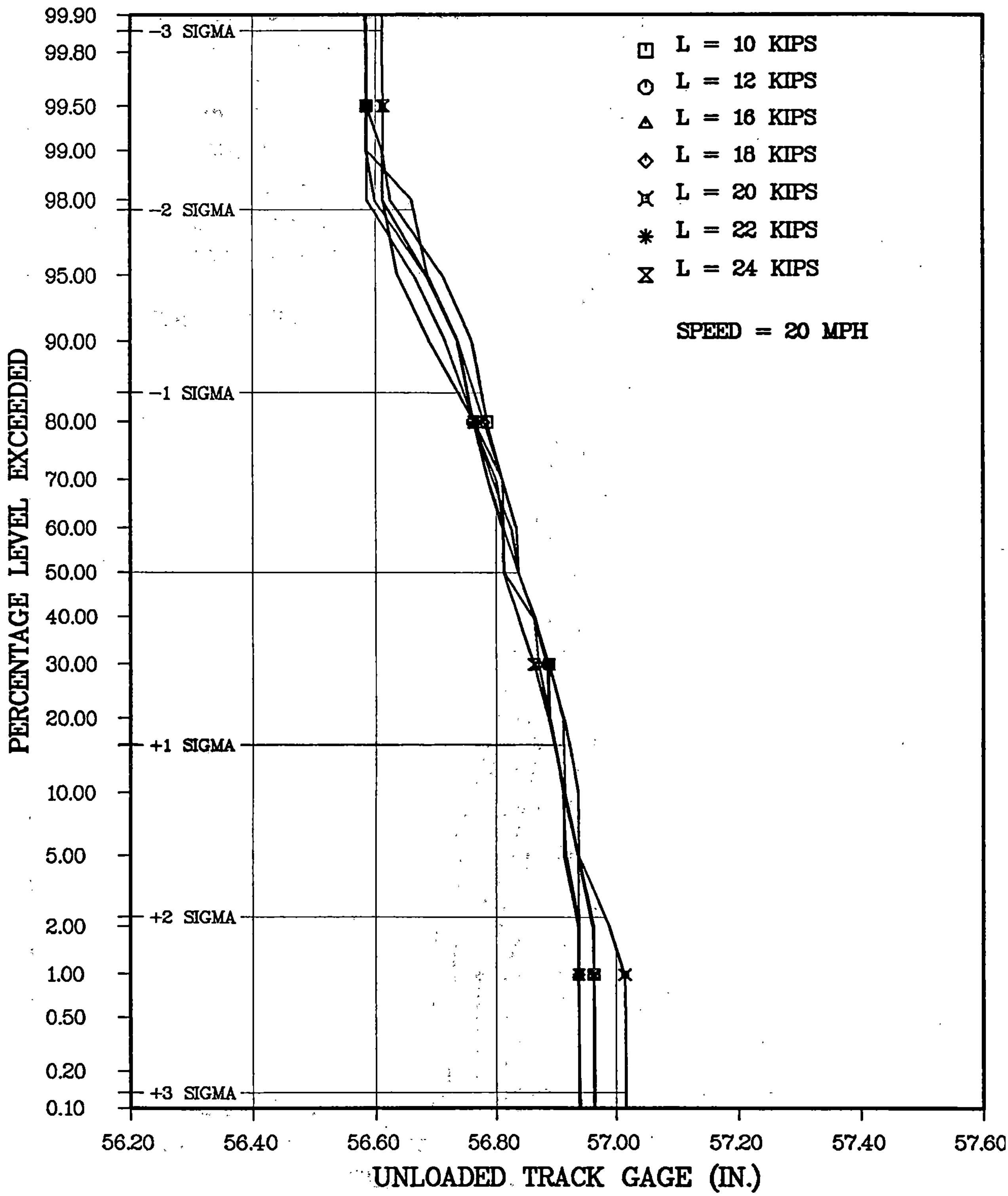

Exhibit 55. Percentage Level Exceedances of Unloaded Gage, 5-Degree Curve (Section 7C), Wood Ties/Pandrol Fasteners, V=39 Kips.

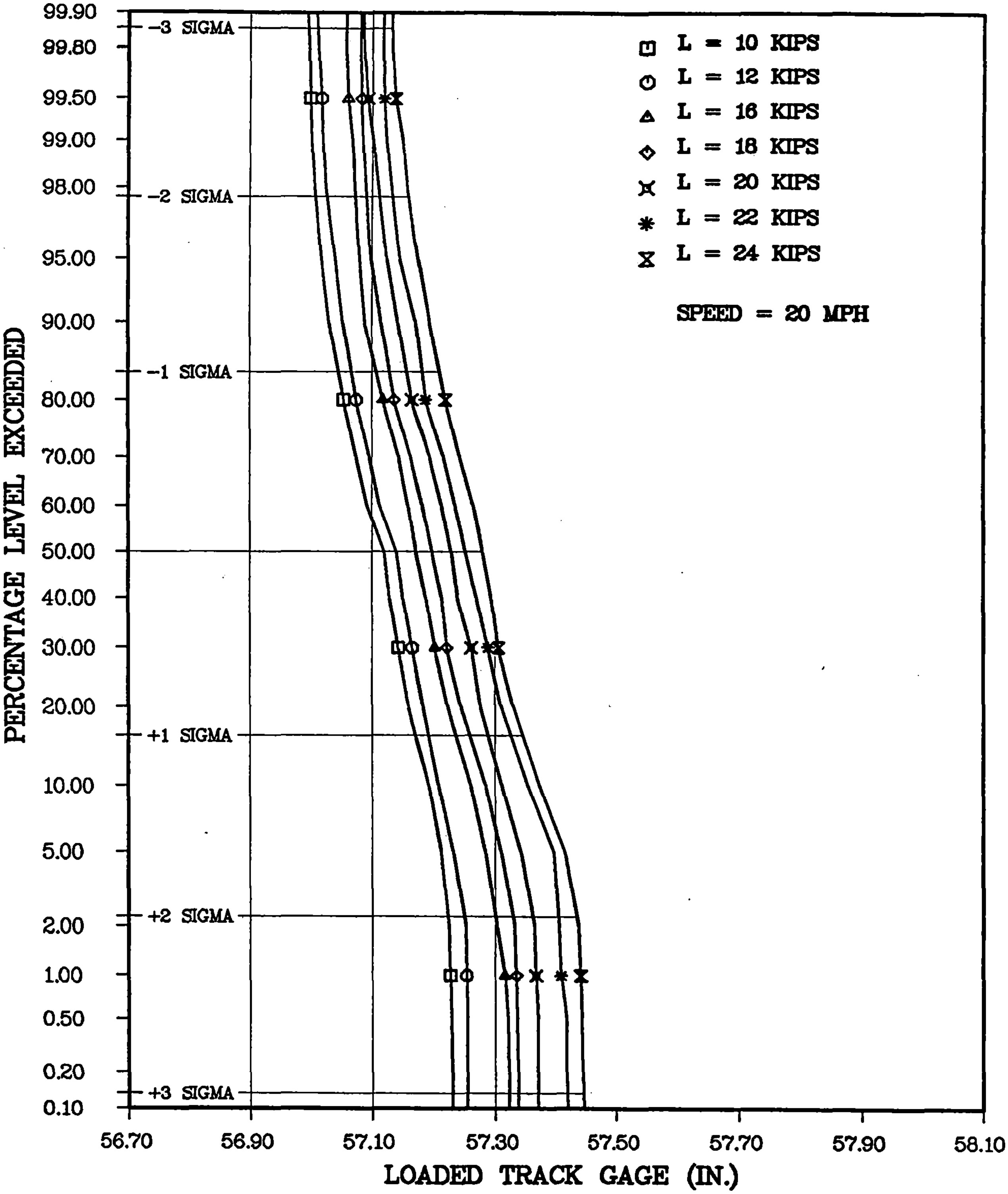

Exhibit 56. Percentage Level Exceedances of Loaded Gage, 5-Degree Curve (Section 7C), Wood Ties/Pandrol Fasteners, V=39 Kips.

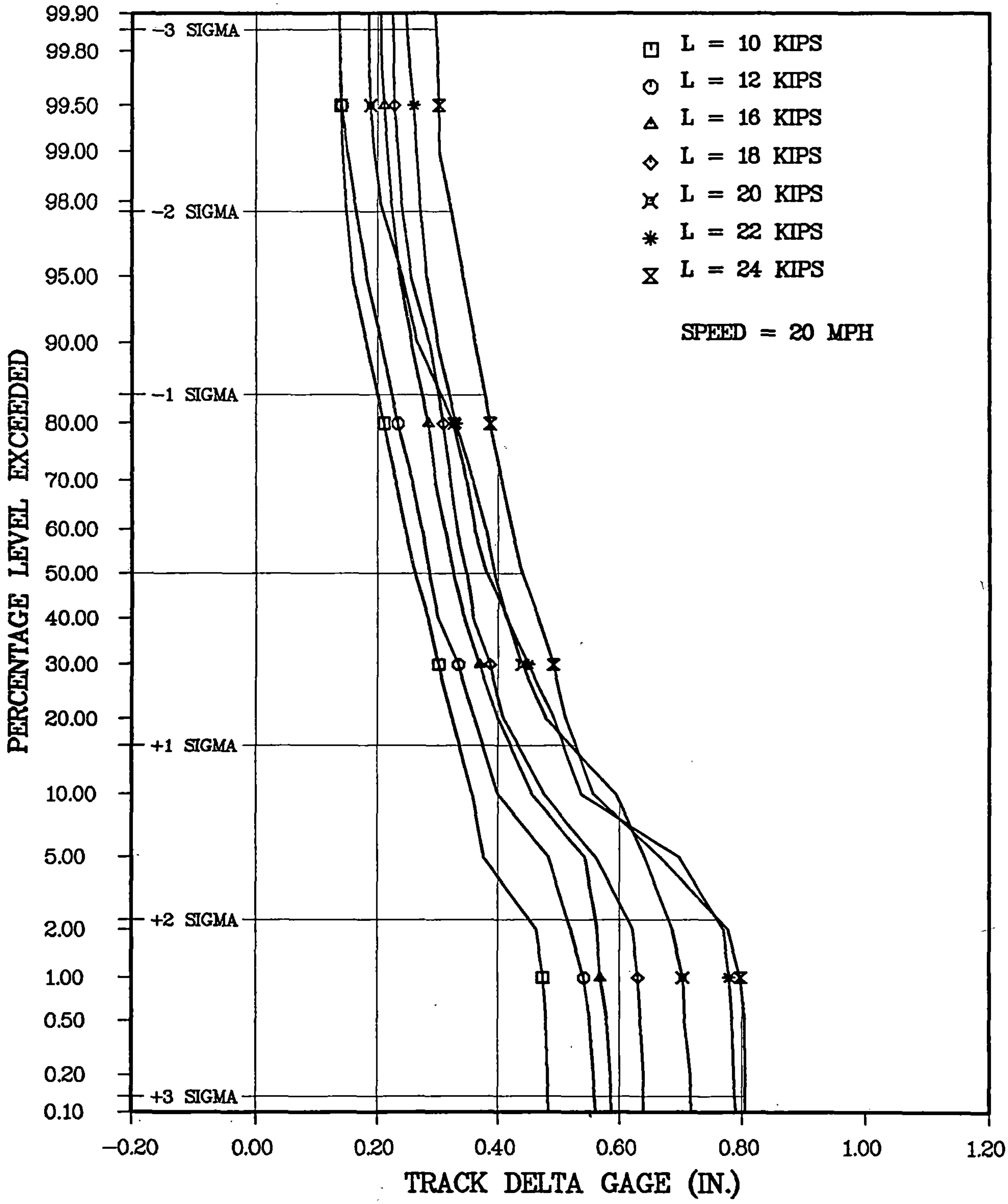

Exhibit 57. Percentage Level Exceedances of Delta Gage, 5-Degree Curve (Section 7C), Wood Ties/Pandrol Fasteners, V=39 Kips.

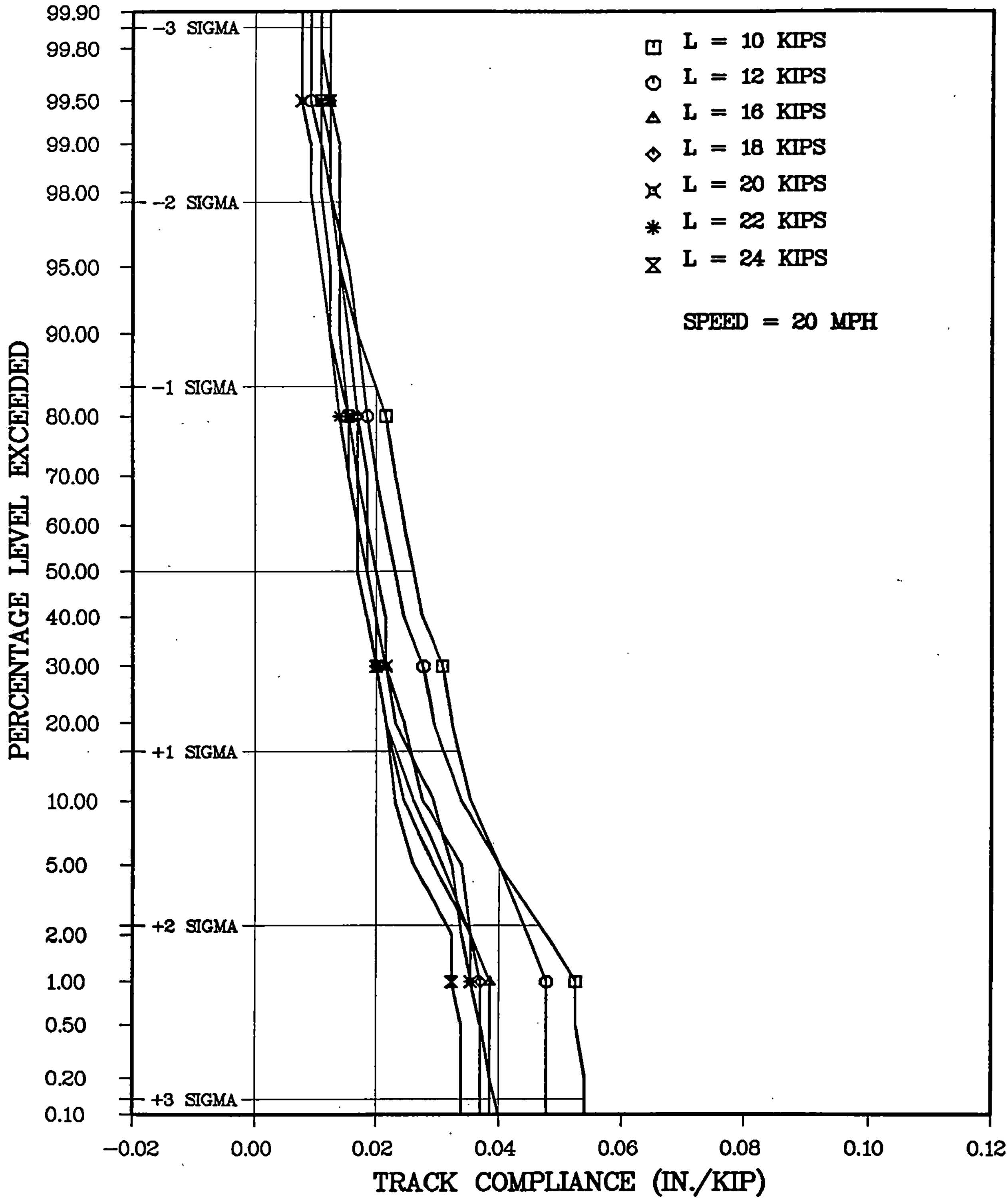

Exhibit 58. Percentage Level Exceedances of Track Compliance, 5-Degree Curve (Section 7C), Wood Ties/Pandrol Fasteners, V=39 Kips.

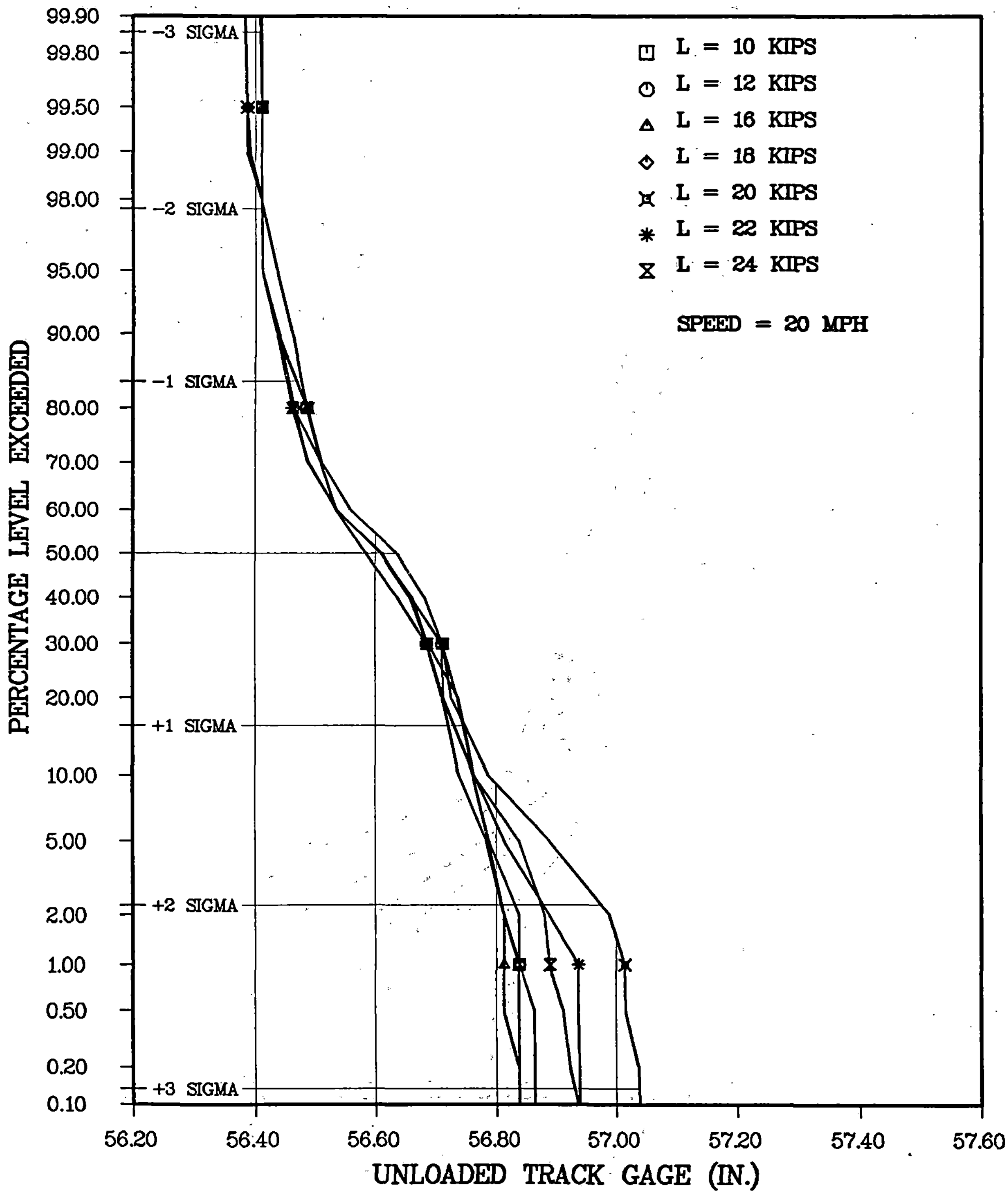

Exhibit 59. Percentage Level Exceedances of Unloaded Gage, 5-Degree Curve (Section 7D), Wood Ties/Safelock Fasteners, V=39 Kips.

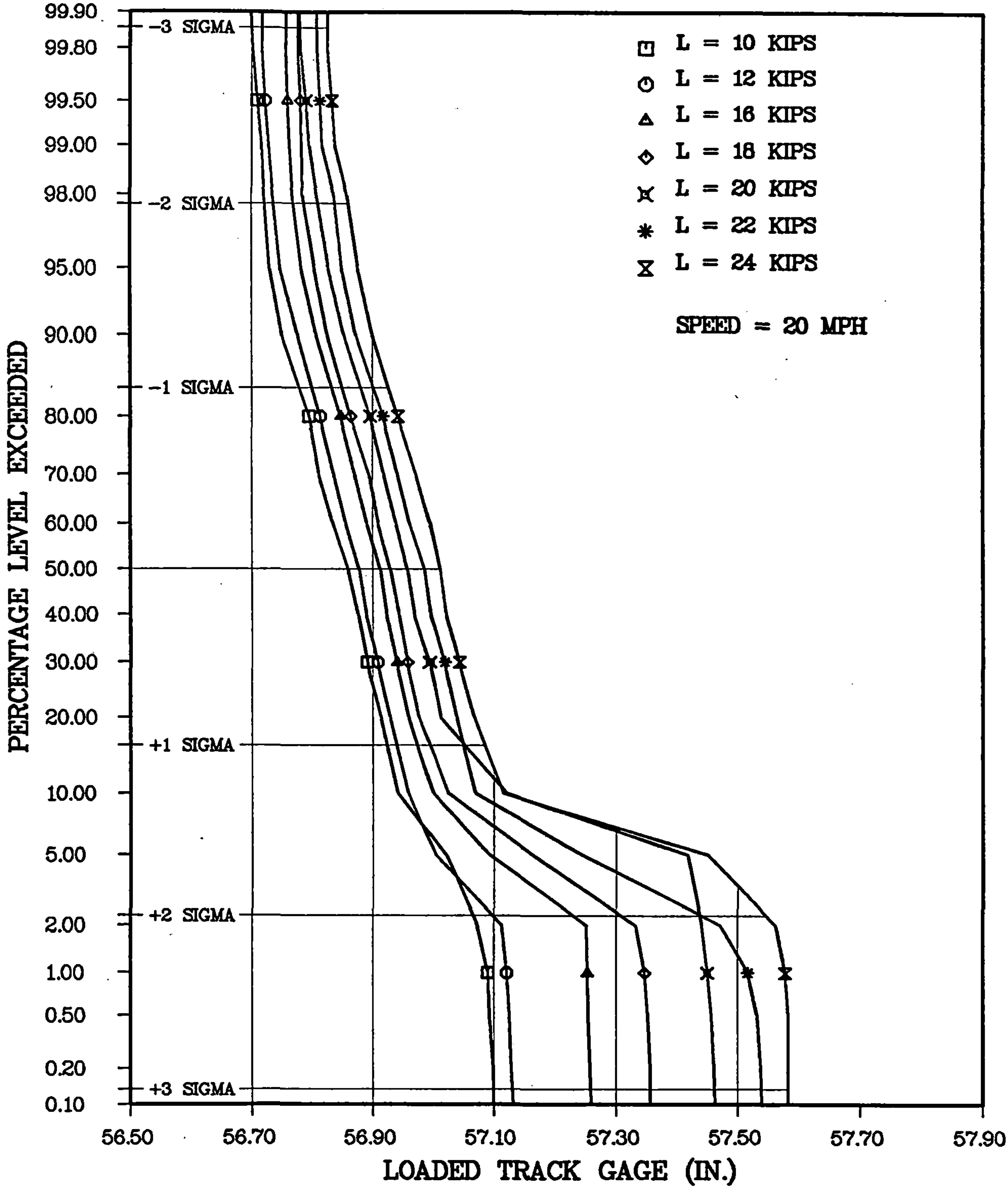

Exhibit 60. Percentage Level Exceedances of Loaded Gage, 5-Degree Curve (Section 7D), Wood Ties/Safelock Fasteners, V=39 Kips.

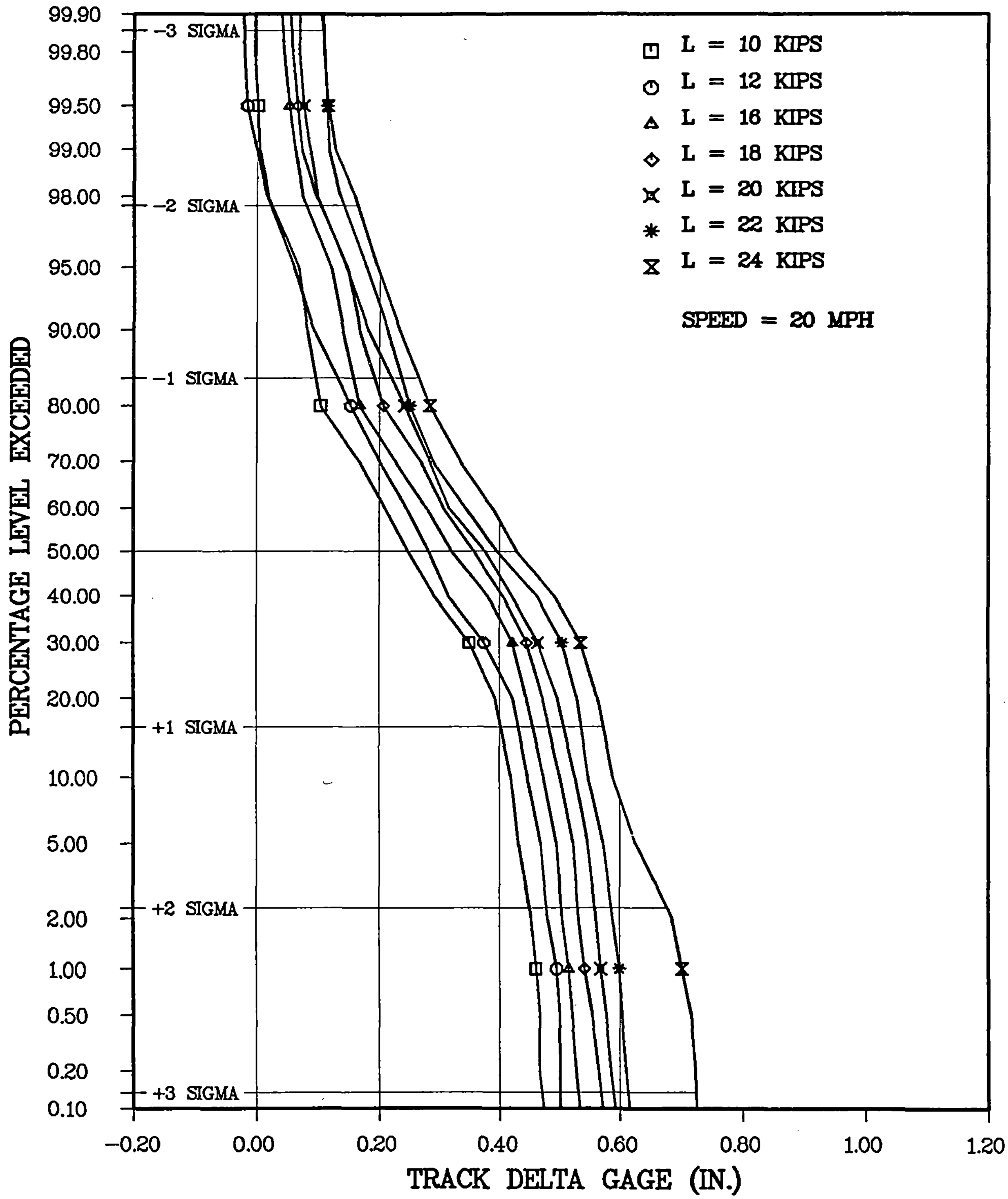

Exhibit 61. Percentage Level Exceedances of Delta Gage, 5-Degree Curve (Section 7D), Wood Ties/Safelock Fasteners, V=39 Kips.

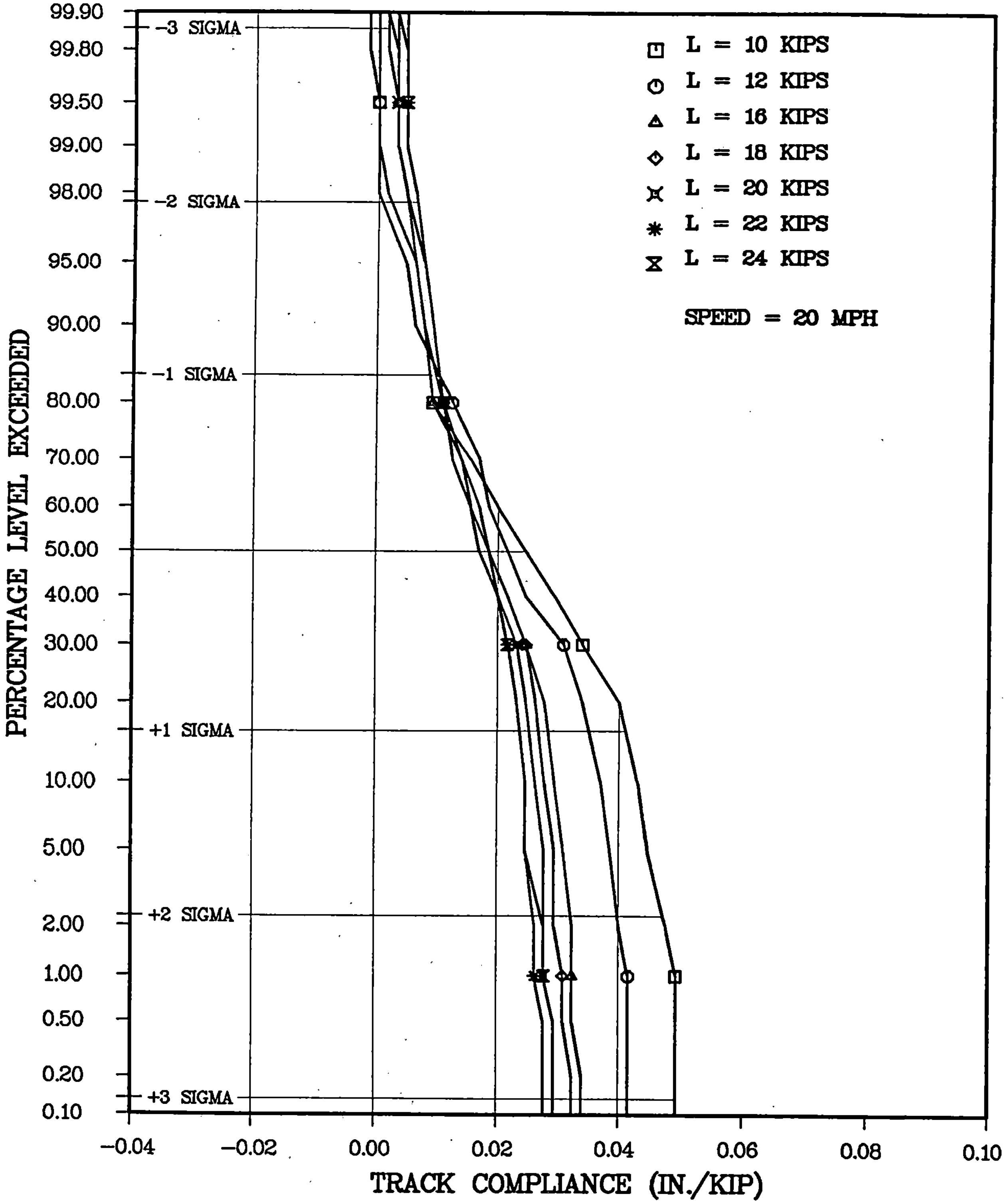

Exhibit 62. Percentage Level Exceedances of Track Compliance, 5-Degree Curve (Section 7D), Wood Ties/Safelock Fasteners, V=39 Kips.

All other observations made previously about concrete ties also apply to results on wood ties with these elastic fasteners.

Distributions of unloaded, loaded and delta gages, and track compliance for domestic hard/softwood ties with elastic spikes are given in Exhibits 63 to 66. As noted in the first paragraph of this section, a likeness to elongated 'S' shape indicates some presence of sinusoidall effect in unloaded gage geometry. It is also apparent from unloaded gage curves that about 30 percent of the track has wide gage, greater than approximately 56.9". Loaded gage curves in Exhibit 64 show that the wide gage effect is amplified with an increase in the gage widening load. Compliance curves appear to cross over at approximately 70 percentile exceedance level. In spite of this, characteristic differences in the 50 percentile track compliance magnitudes are not quite evident. However, evidence of some increase in the gage widening stiffness can still be detected in the average track compliance responses. Also, at higher gage widening loads, compliance curves tend to become linear, and thus approximate a Gaussian model.

Exhibits 67 to 70 show the distributions of unloaded, loaded and delta gages, and track compliance for glue laminated ties with 4 cut spikes. Wide gage, of about 56.95" at 50 percentile level, is apparent in Exhibit 67. Gage restraining characteristics similar to that of domestic hard/softwood ties with 4 cut spikes are evident from these curves. Track compliances at 50 percentile level, in Exhibit 70, show a linear spring characteristics for glue laminated ties with 4 cut spikes.

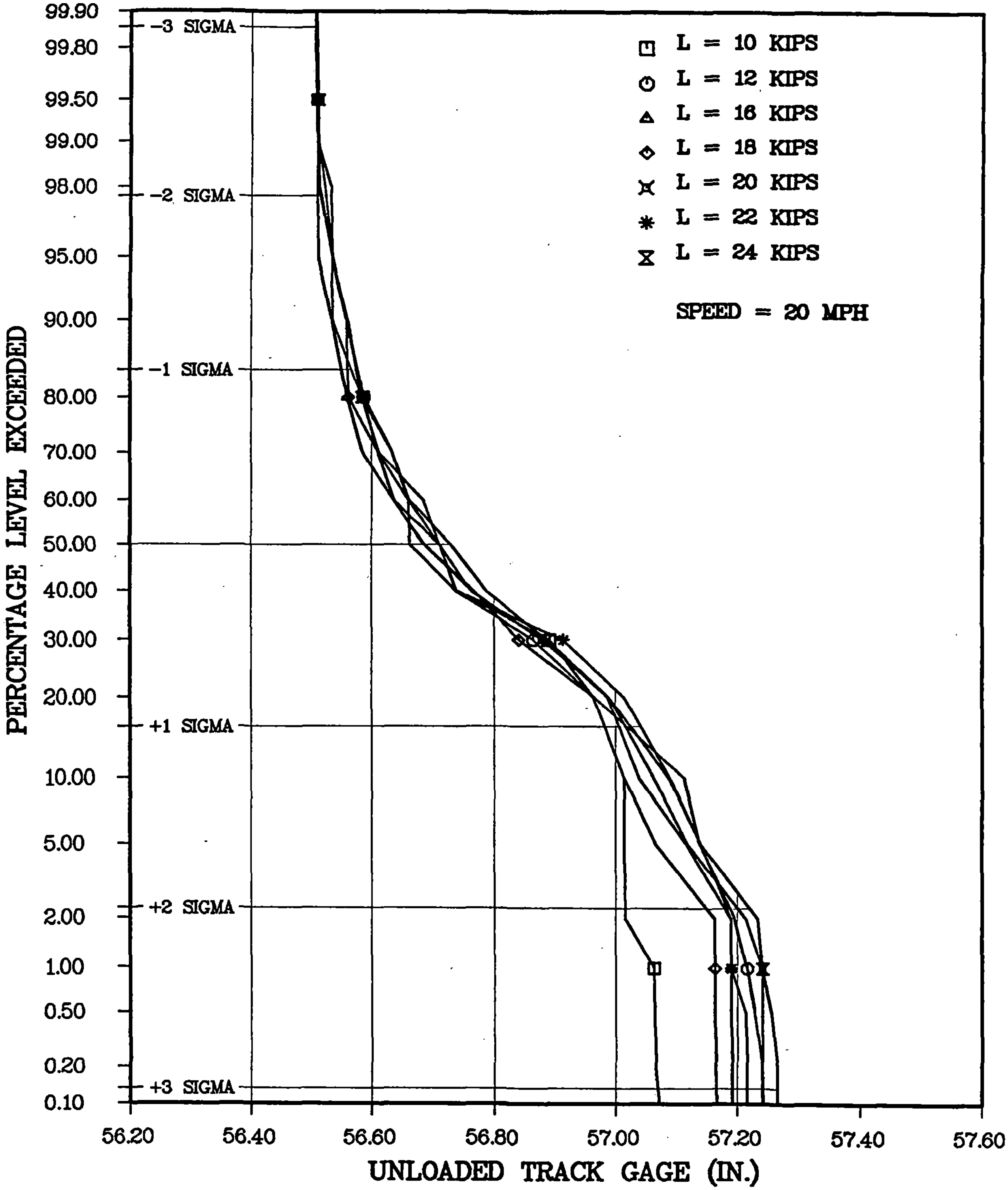

Exhibit 63. Percentage Level Exceedances of Unloaded Gage, 5-Degree Curve (Section 7E), Wood Ties/Elastic Spikes, V=39 Kips.

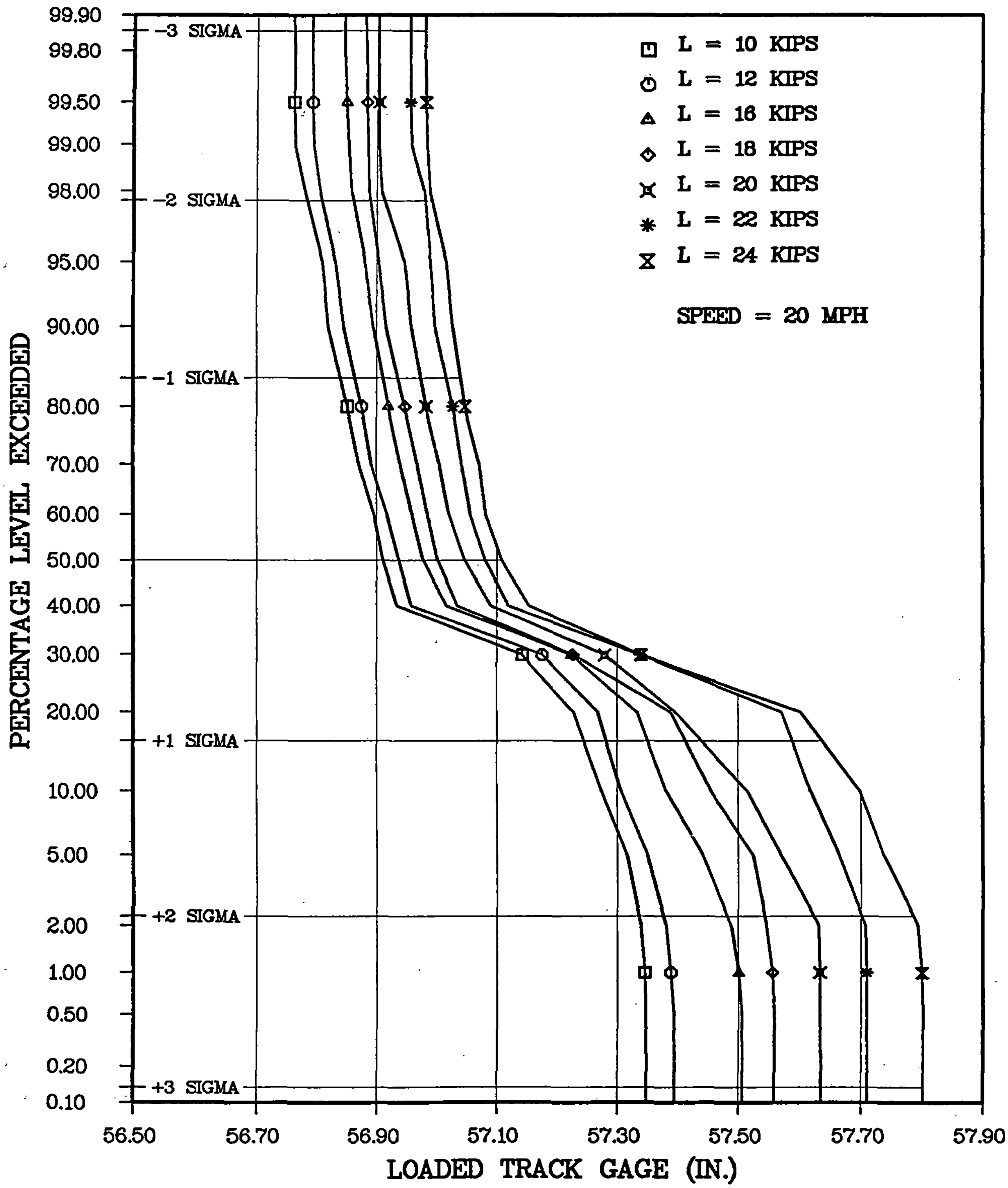

Exhibit 64. Percentage Level Exceedances of Loaded Gage, 5-Degree Curve (Section 7E), Wood Ties/Elastic Spikes, V=39 Kips.

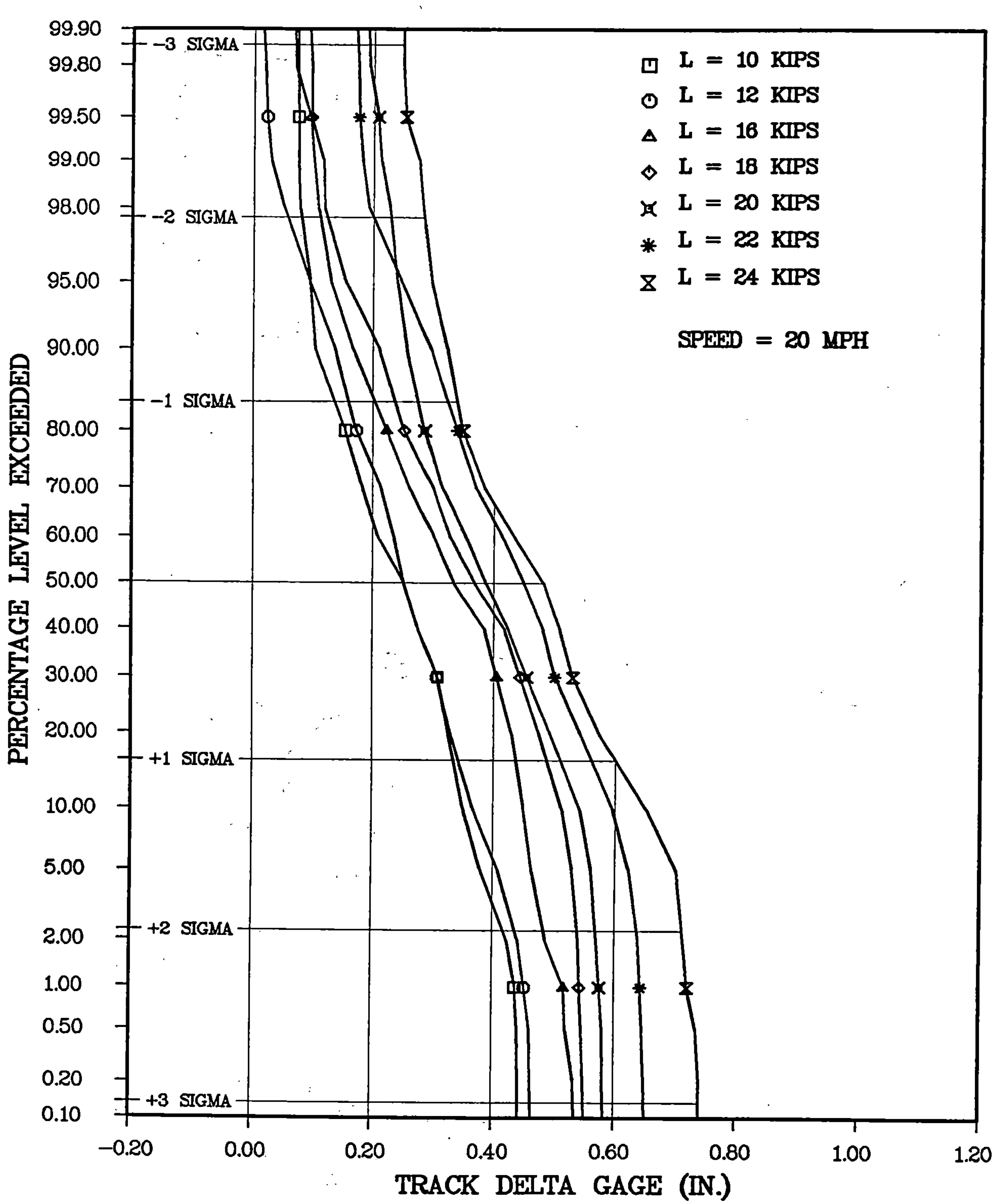

Exhibit 65. Percentage Level Exceedances of Delta Gage, 5-Degree Curve (Section 7E), Wood Ties/Elastic Spikes, V=39 Kips.

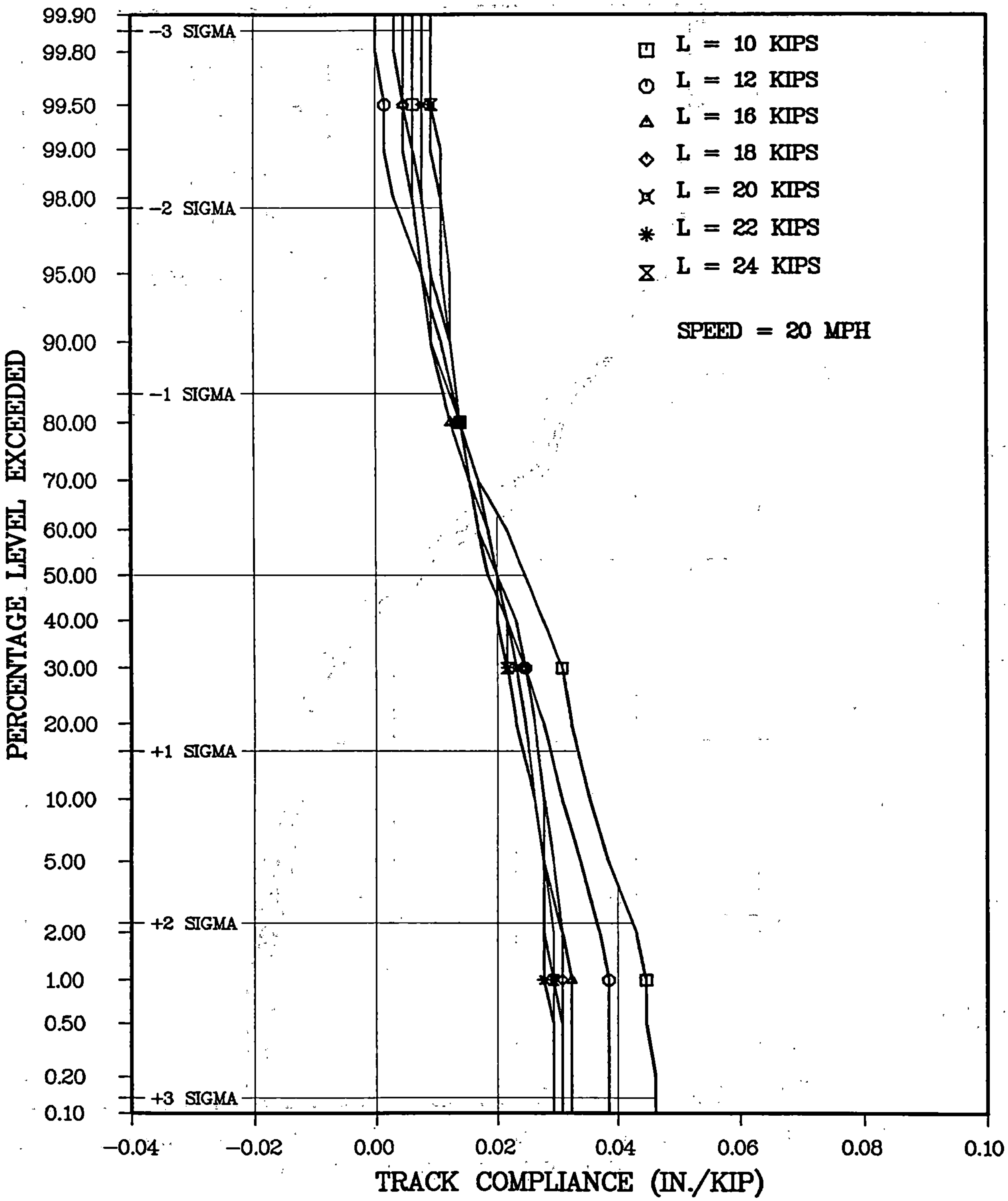

Exhibit 66. Percentage Level Exceedances of Track Compliance, 5-Degree Curve (Section 7E), Wood Ties/Elastic Spikes, V=39 Kips.

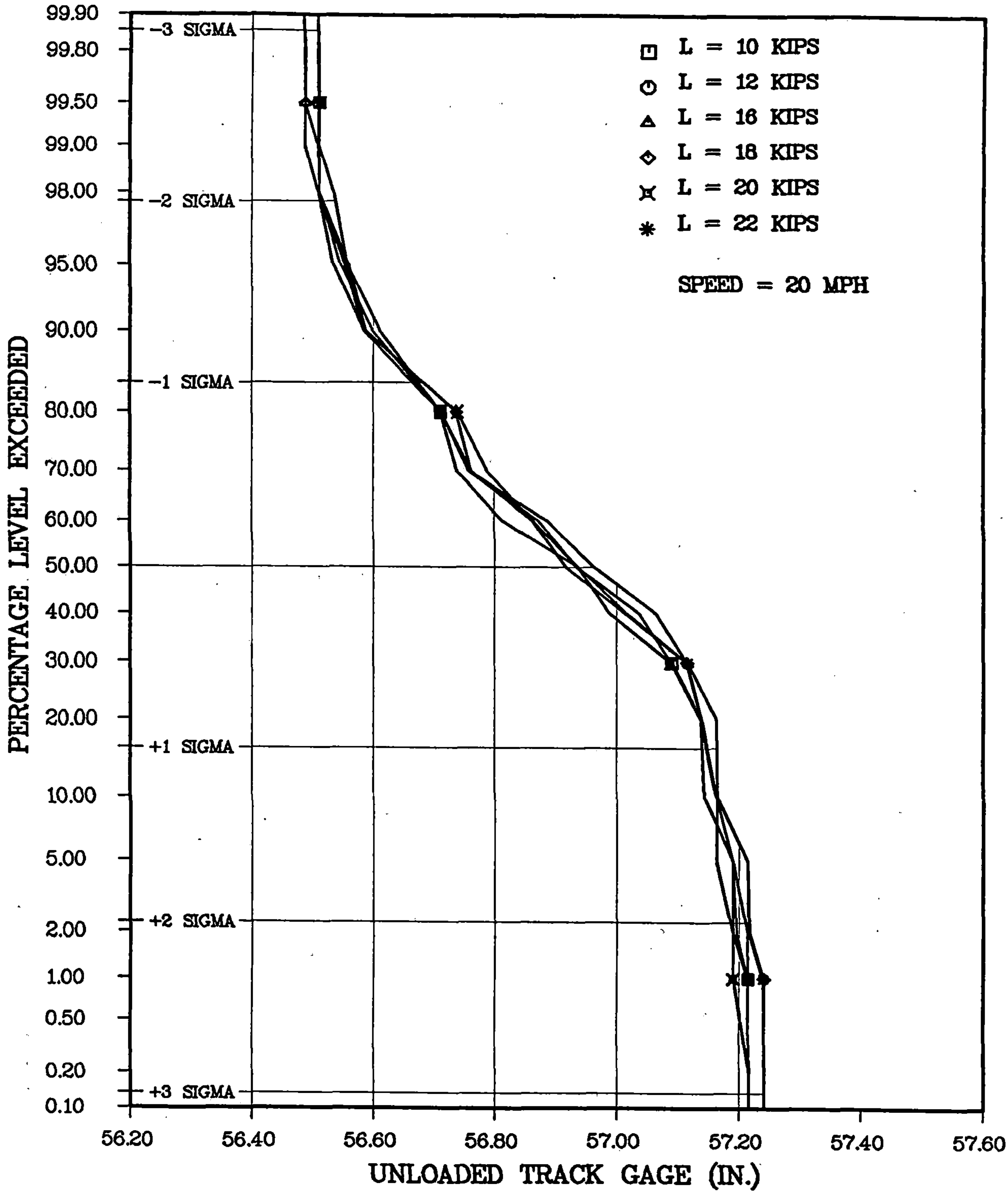

Exhibit 67. Percentage Level Exceedances of Unloaded Gage, 5-Degree Curve (Section 7F), Glue Laminated Ties/4-Cut Spikes, V=39 Kips.

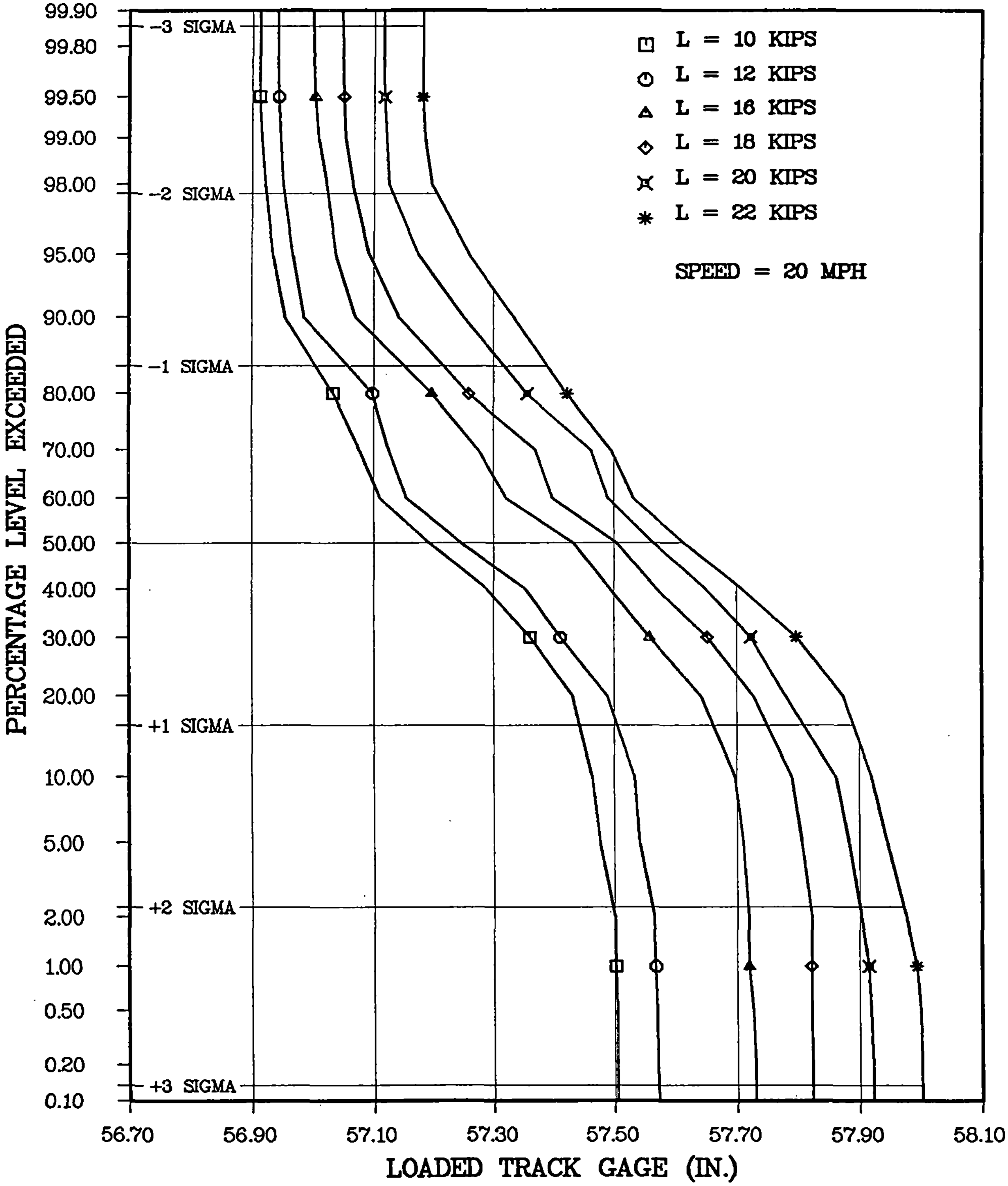

Exhibit 68. Percentage Level Exceedances of Loaded Gage, 5-Degree Curve (Section 7F), Glue Laminated Ties/4-Cut Spikes, V=39 Kips.

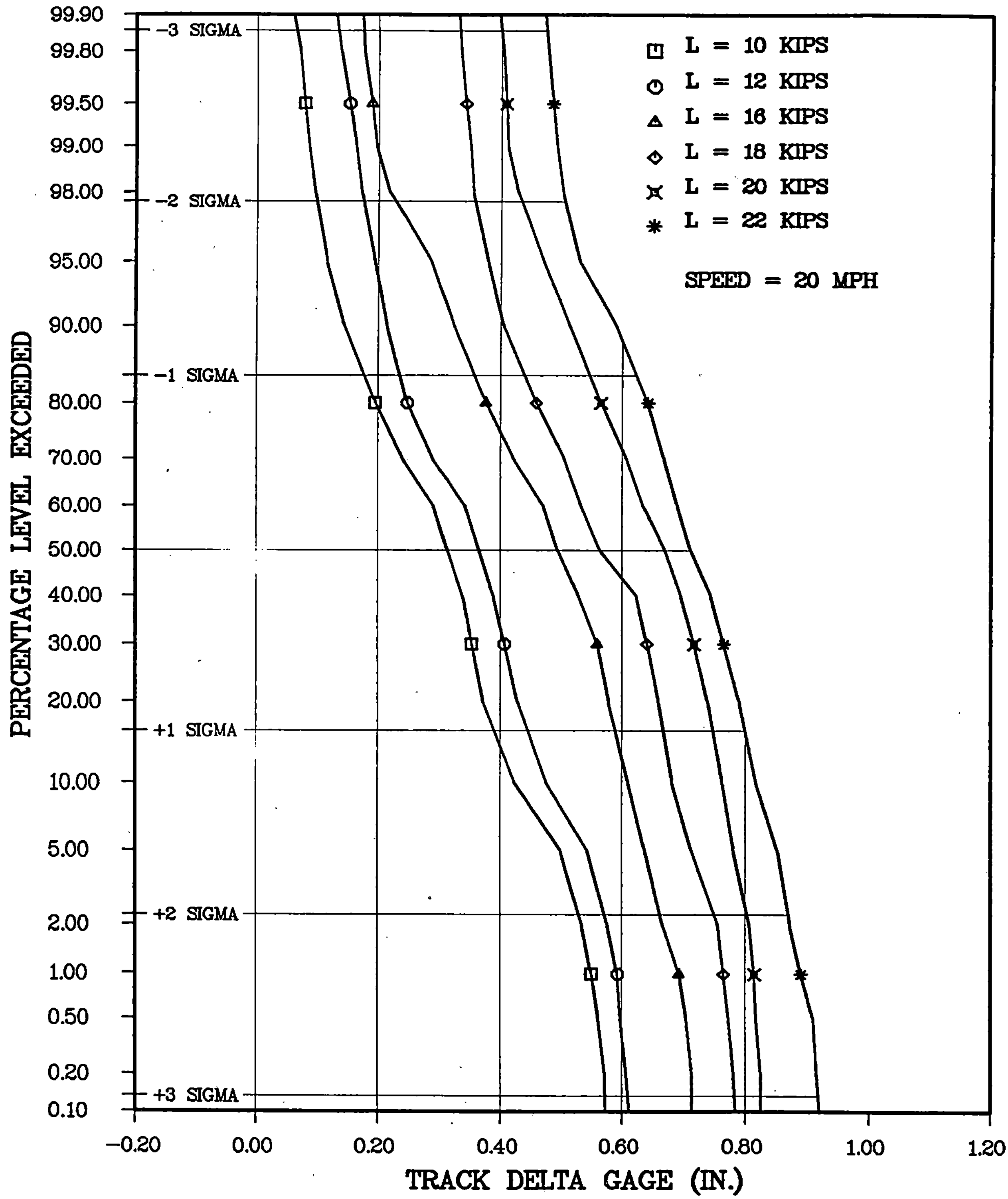

Exhibit 69. Percentage Level Exceedances of Delta Gage, 5-Degree Curve (Section 7F), Glue Laminated Ties/4-Cut Spikes, V=39 Kips.

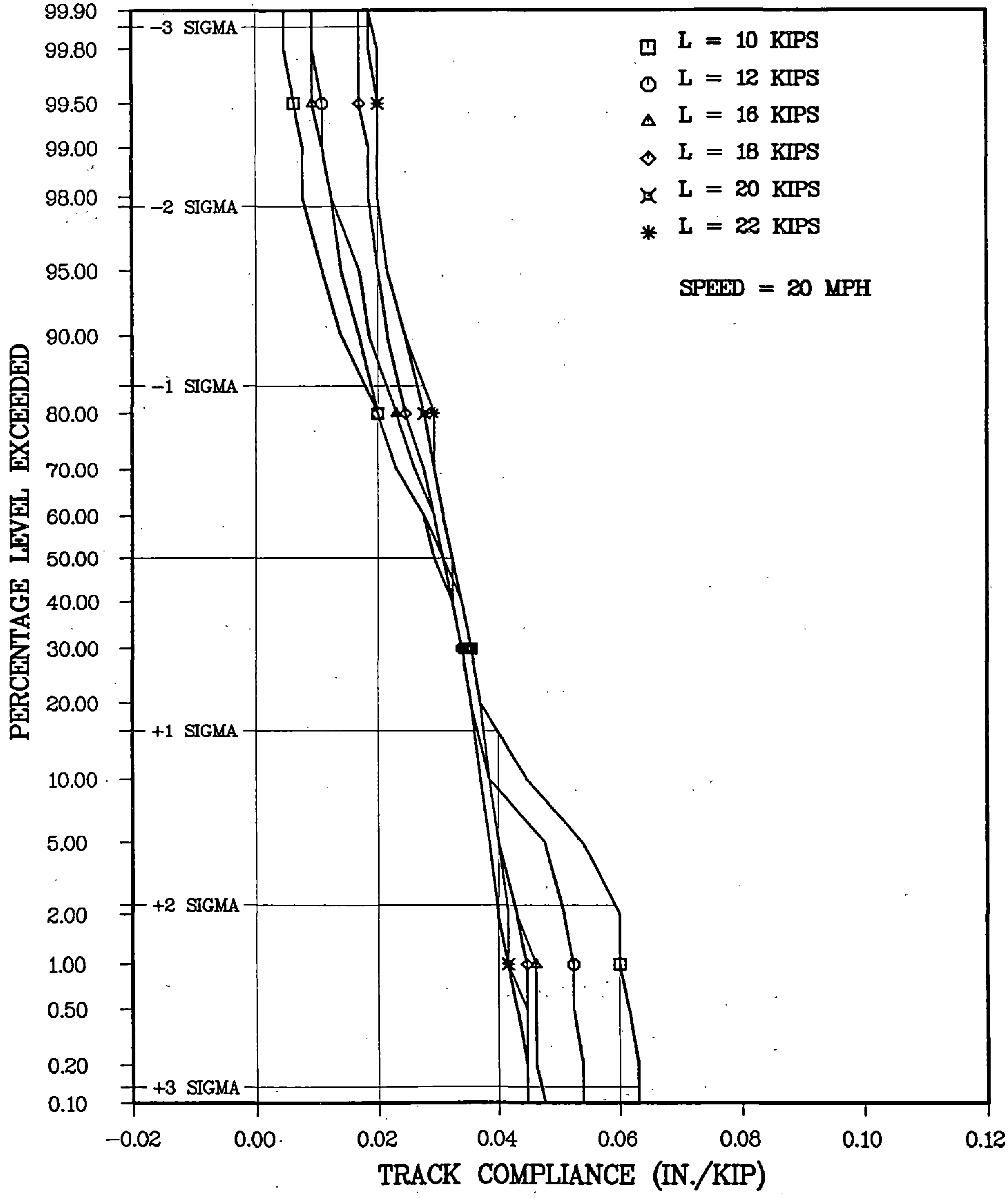

Exhibit 70. Percentage Level Exceedances of Track Compliance, 5-Degree Curve (Section 7F), Glue Laminated Ties/4-Cut Spikes, V=39 Kips.

Distribution curves of gage widening results on the Azobe ties with five cut spikes are given in Exhibits 71 to 74. A comparison of these curves with the corresponding curves in Exhibits 63 to 66 for domestic hard/softwood ties with elastic spikes shows that gage widening strength characteristics of these two rail fastening systems are quite comparable. However, characteristic differences in 50 percentile magnitudes, with respect to gage widening load (Exhibit 74), do exist for the Azobe ties with five cut spikes. The resulting gage hardening characteristics of the Azobe ties with five cut spikes are thus similar to those of domestic hard/softwood ties with elastic fasteners, as well as the concrete ties.

A study of the gage widening responses under 33-ton axle load showed similar results.

In the following section, comparison of delta gage and track compliance between various types of fasteners is made for each track segment of the HTL. The comparison is presented, in terms of percentage level exceedance plots under two combinations of vertical and gage widening loads. The plots at a gage widening load of 18 kips under 33-ton axle load, and 22 kips under 39-ton axle load are given. These gage widening and vertical load combinations are chosen because the resulting L/V ratios are approximately equal, and the fact that these combinations are close to loads found in revenue service.

In order to cover the full range of various types of gage restraining devices tested at the HTL, the exceedance distribution results from Sections 3, 7 and 31 are included in the main text.

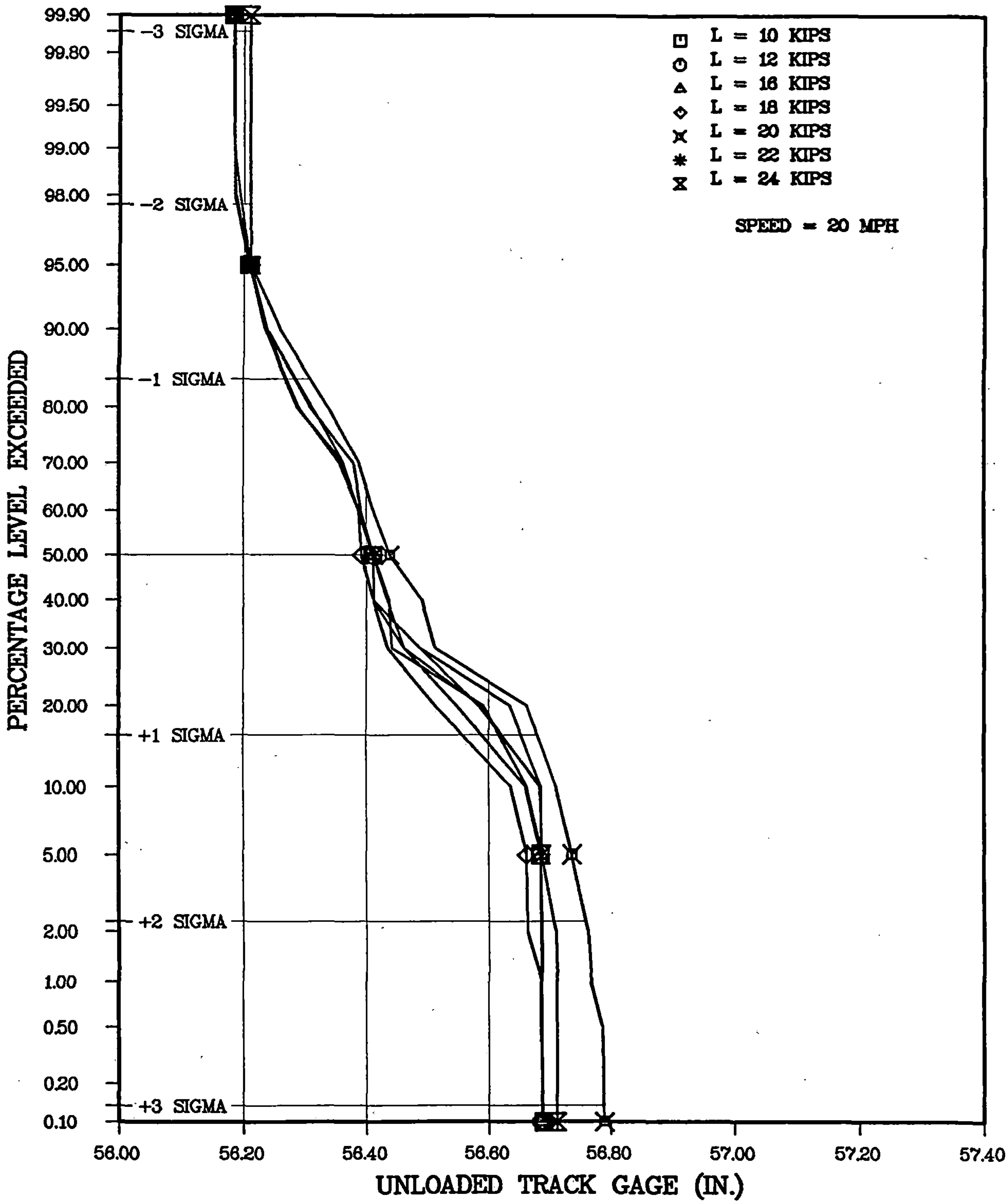

Exhibit 71. Percentage Level Exceedances of Unloaded Gage, 5-Degree Curve (Section 31), Azobe Ties/5-Cut Spikes, V=39 Kips.

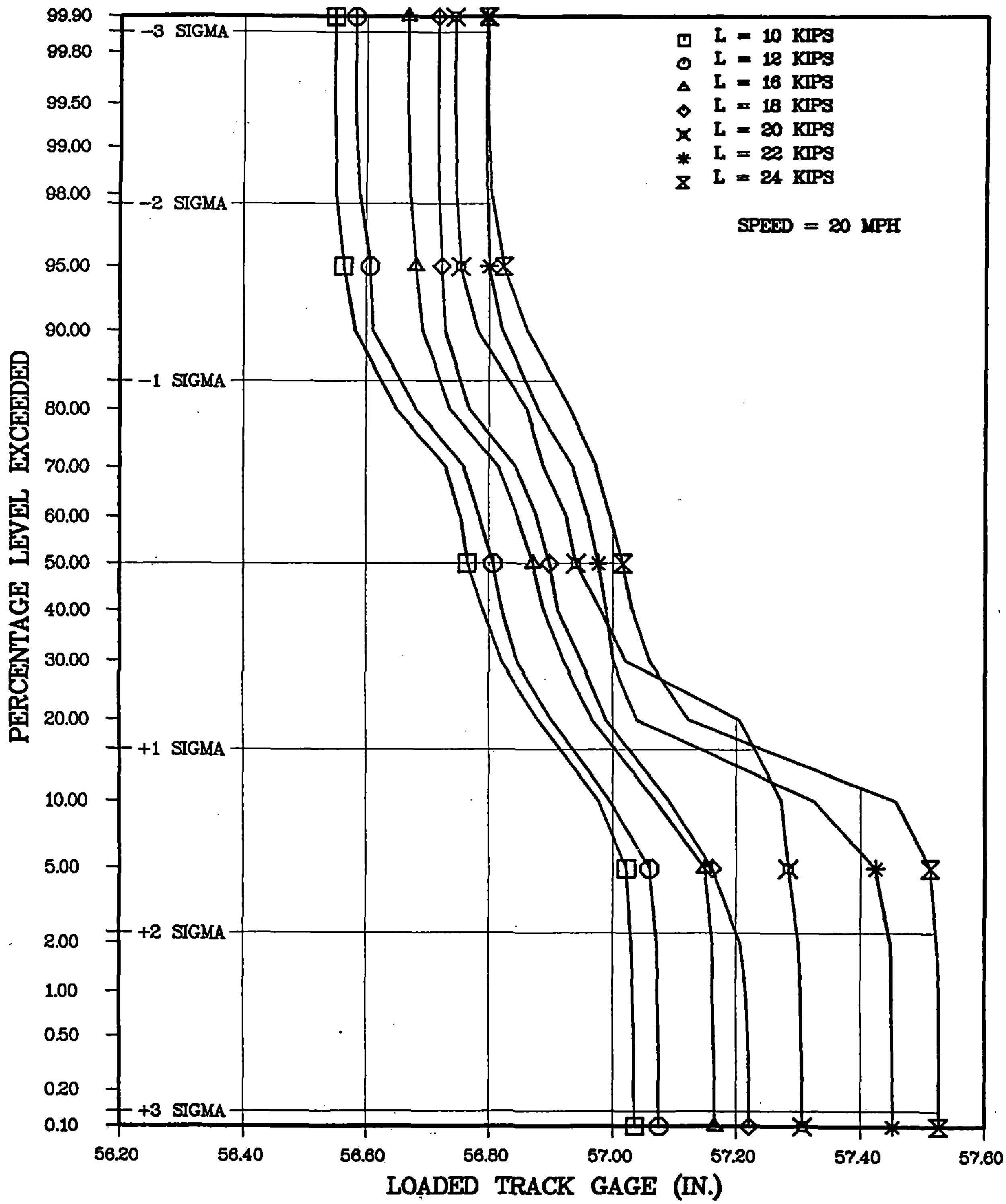

Exhibit 72. Percentage Level Exceedances of Loaded Gage, 5-Degree Curve (Section 31), Azobe Ties/5-Cut Spikes, V=39 Kips.

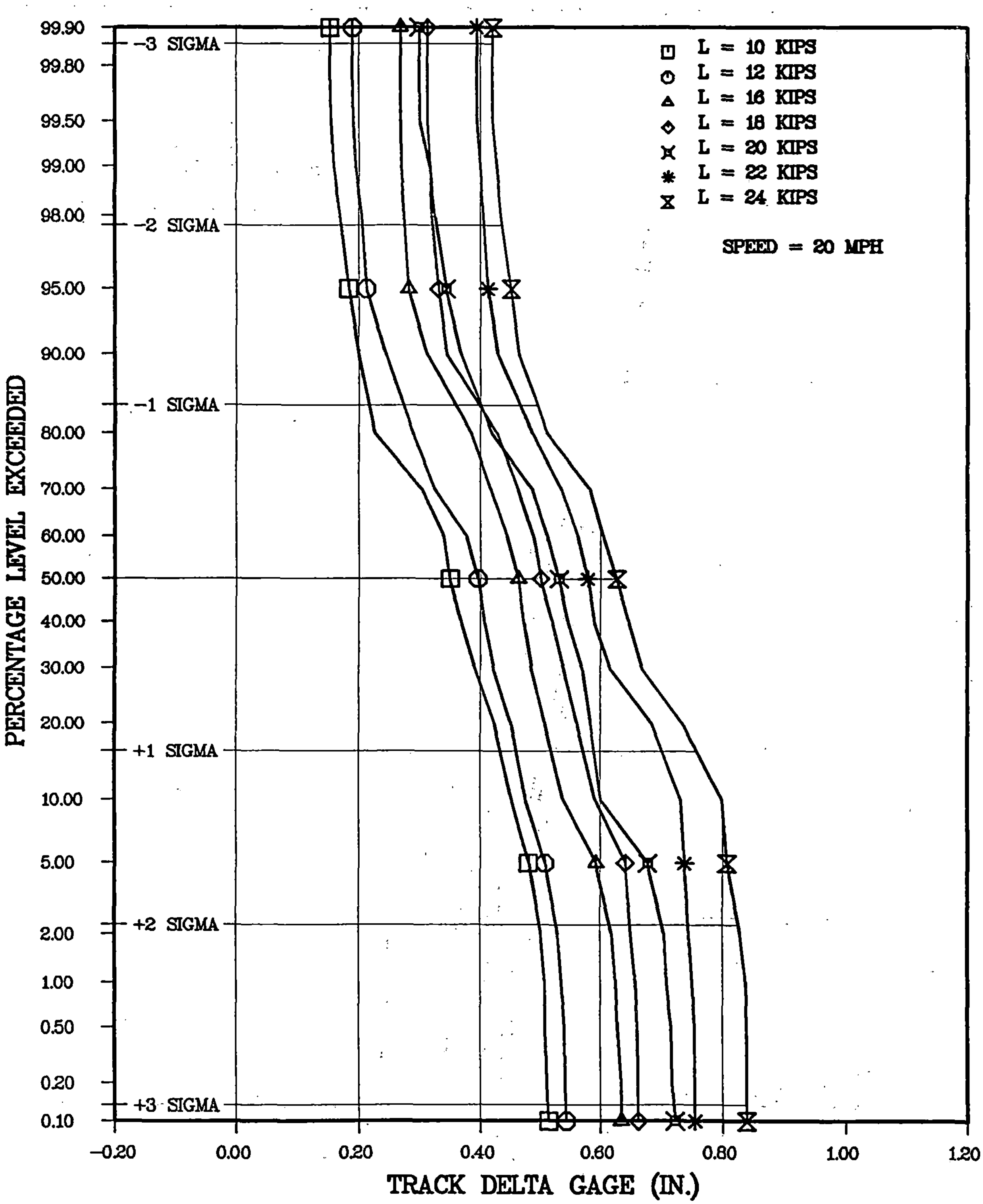

Exhibit 73. Percentage Level Exceedances of Delta Gage, 5-Degree Curve (Section 31), Azobe Ties/5-Cut Spikes, V=39 Kips.

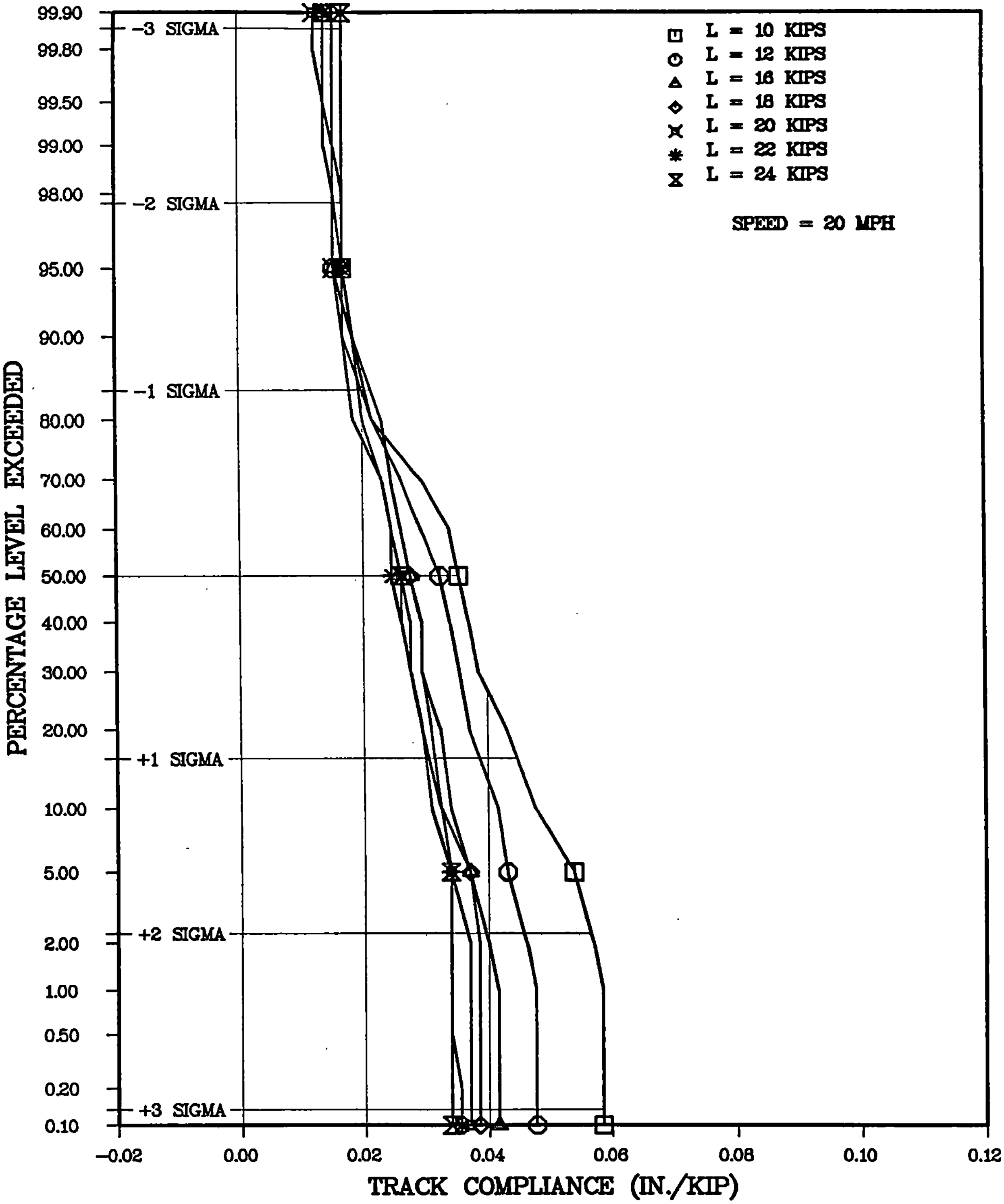

Exhibit 74. Percentage Level Exceedances of Track Compliance, 5-Degree Curve (Section 31), Azobe Ties/5-Cut Spikes, V=39 Kips.

Results from Section 3 will afford a comparison between wood ties with cut spikes and concrete ties. Section 7 results will provide a comparison of wood ties with cut spikes, elastic spikes, Pandrol and Safelock. Results from Section 31 will give a comparison of the Azobe ties with cut spikes, elastic spikes and Pandrol, and concrete ties. Results from other segments of the HTL, under 39 ton axle load, are included in Appendix D.

For Section 3, distribution curves of delta gage and compliance under 33-ton axle load are given in Exhibits 75 and 76. Similar curves under 39-ton axle load are given in Exhibits 77 and 78. A comparison between domestic hard/softwood ties with 4 cut spikes and concrete ties shows that concrete ties provide better gage widening strength. Also seen in these curves is the marked difference between the performances of two wood tie subsections. Each of the subsections 3(1) and 3(3), as designated in the above exhibits, has domestic hard/softwood ties with 4 cut spikes. One of the physical differences between subsection 3(1) and 3(3) is the length of the subsection. Subsection 3(1) is 1710 feet long, while subsection 3(3) is only 310 feet long. The other difference, and probably the major one, is that subsection 3(1) was re-timbered prior to these TLV heavy axle load tests. The qualities of data for the two subsections are different, and will result in some difference in the statistical reliabilities of results. This difference is probably insignificant. The marked difference in the results of subsection 3(1) and 3(3), is most probably due to the fact of the ages (FAST MGT) of ties in the two subsections.

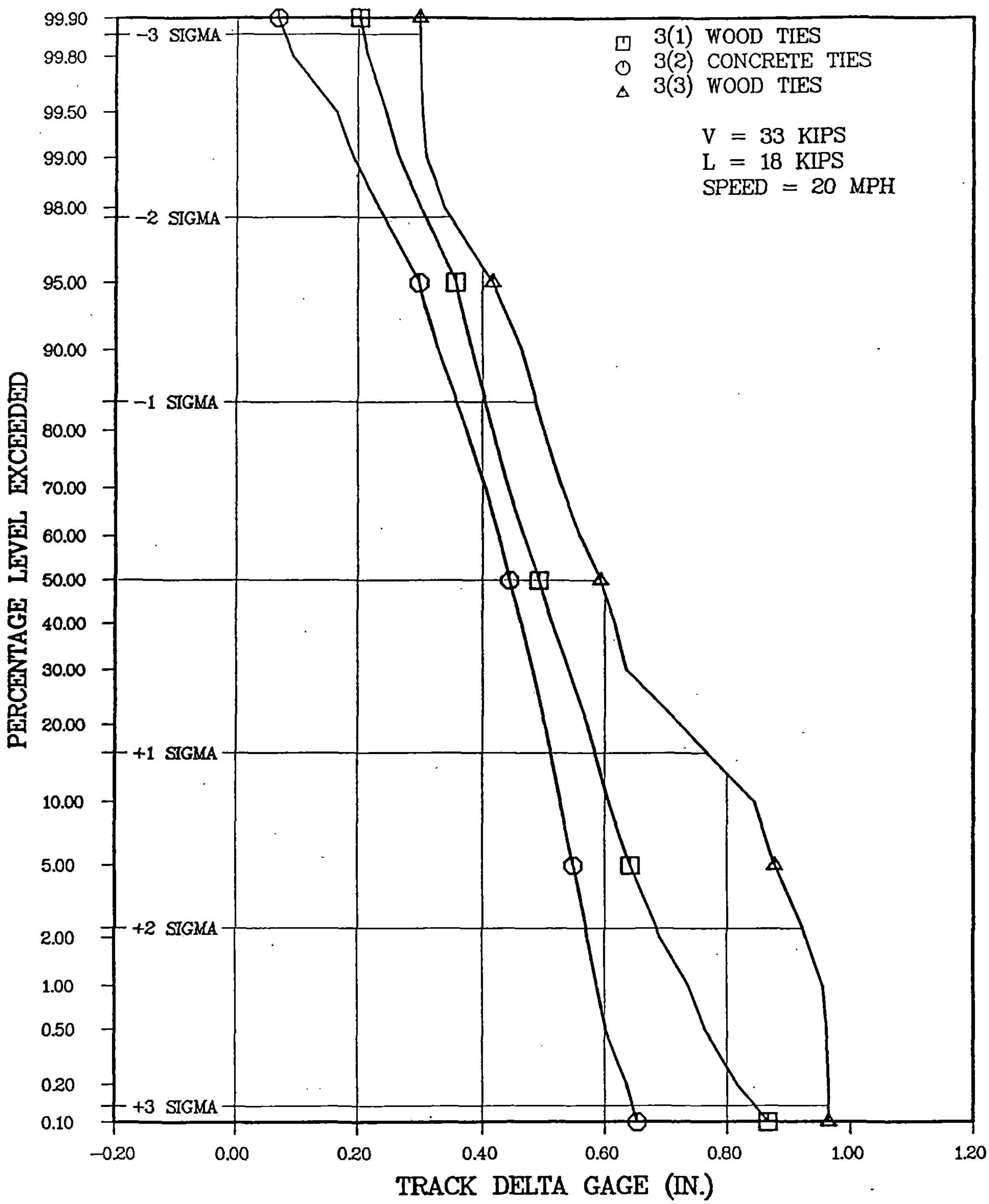

Exhibit 75. Percentage Level Exceedances of Delta Gage, 5-Degree Curve (Section 3), All Segments, L=18 Kips and V=33 Kips.

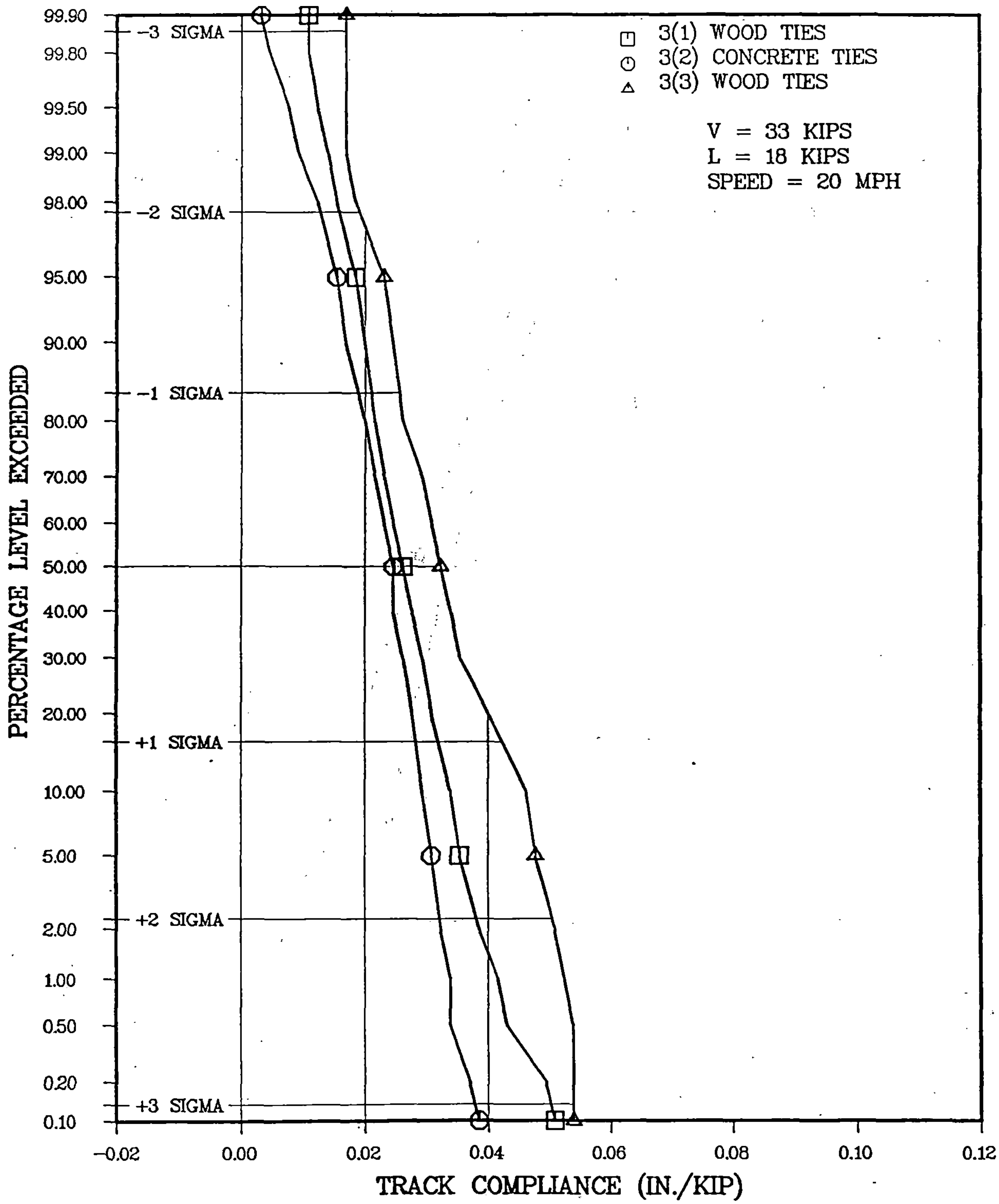

Exhibit 76. Percentage Level Exceedances of Track Compliance, 5-Degree Curve (Section 3), All Segments, L=18 Kips and V=33 Kips.

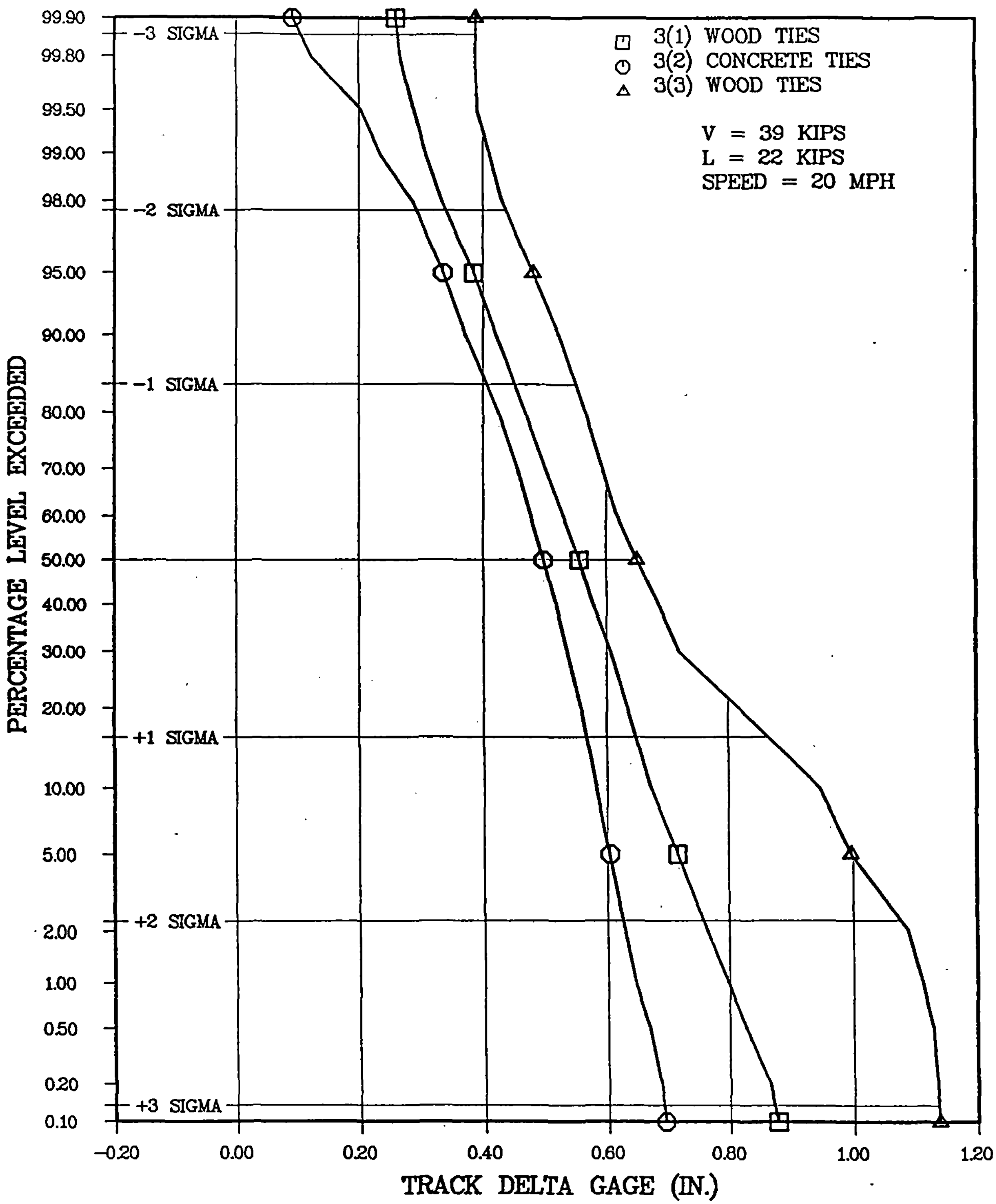

Exhibit 77. Percentage Level Exceedances of Delta Gage, 5-Degree Curve (Section 3), All Segments, L=22 Kips and V=39 Kips.

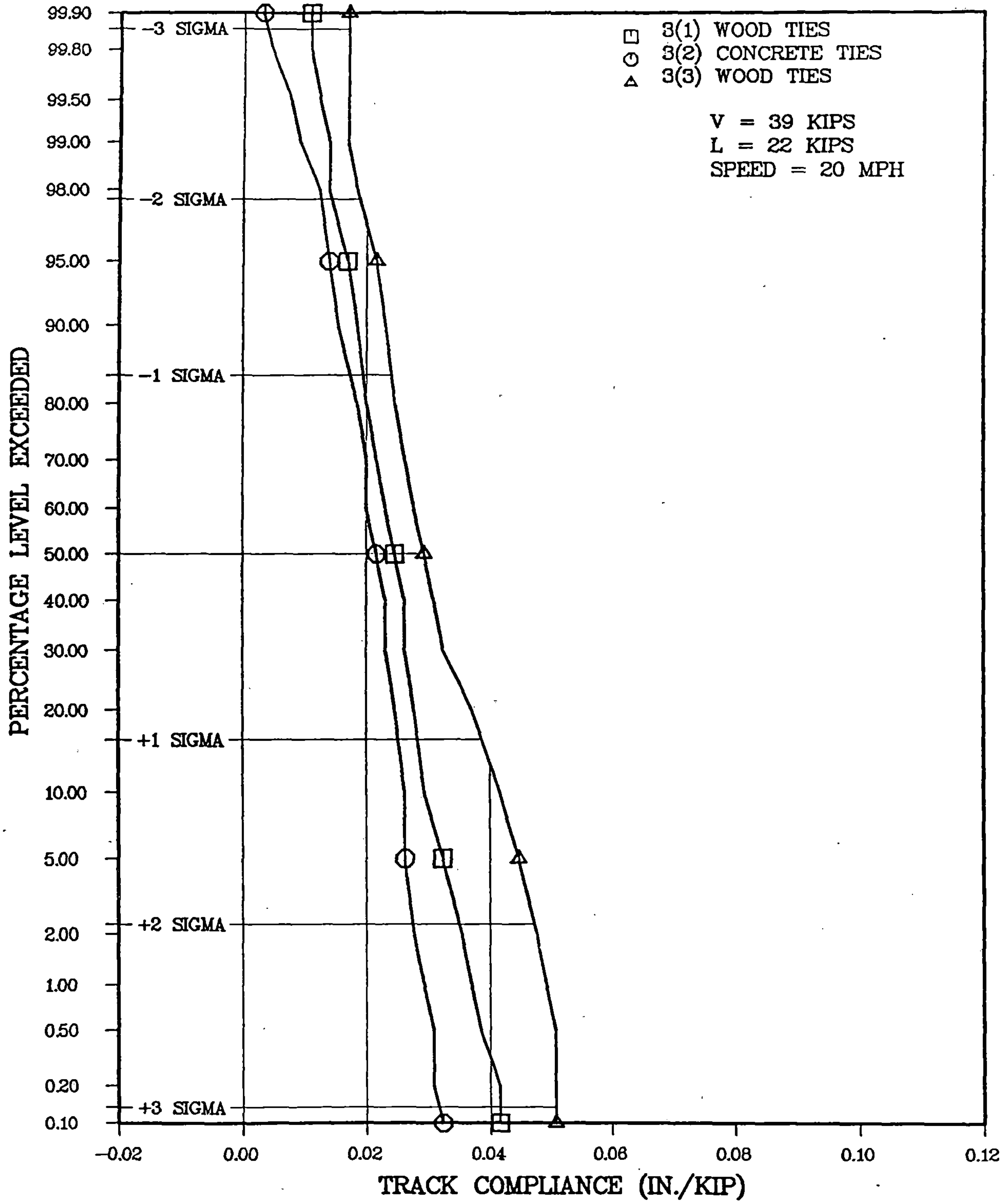

Exhibit 78. Percentage Level Exceedances of Track Compliance, 5-Degree Curve (Section 3), All Segments, L=22 Kips and V=39 Kips.

If gage widening strength of track in subsection 3(3) could be assumed to be the performance of re-timbered track in subsection 3(1) after about 180 MGT of FAST heavy axle load traffic, then a comparison of performance between domestic hard/softwood ties with 4 cut spikes of subsection 3(3) and concrete ties of subsection 3(2) reveals a much better gage widening strength of concrete ties. Also apparent in these exhibits is the fact that trends of the distribution between 33 and 39 kip wheel load are similar except that on average, more delta gage results under a 39 kip wheel load. This increase in delta gage under 39 kips wheel load (L/V almost constant) thus gives lower magnitudes of the track compliance. This is in corroboration with the mean value results given earlier wherein track compliance had a lower magnitude under 39 kip wheel load than 33 kip wheel load with similar L/V ratios.

The comparisons of delta gage and track compliance among various fasteners in Section 7 (Exhibits 79 to 82) show that the average characteristics can be separated in two groups. One group consists of the domestic hard/softwood ties and the glue laminated ties both with 4 cut spikes, and the other group is comprised of domestic hard/softwood ties with Pandrol and Safelock and elastic spikes. Some scatter at both tails of the distribution occurs. Substantially better gage restraining characteristics of the second group are evident from these curves. Since the scale for all of these plots are kept the same, a comparison of curves between Section 3 and Section 7 shows that concrete ties depict distribution trends quite comparable to those of domestic

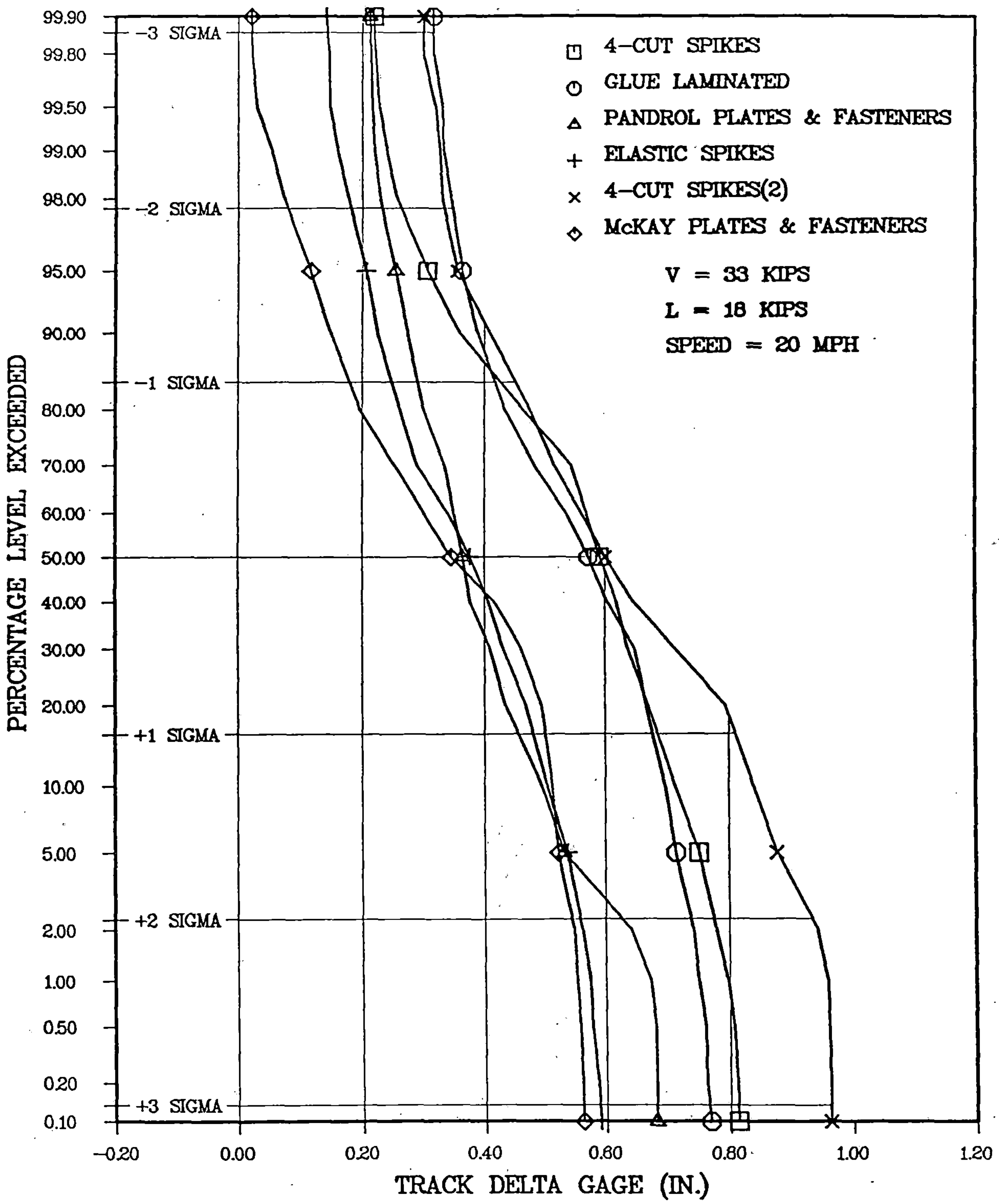

Exhibit 79. Percentage Level Exceedances of Delta Gage, 5-Degree Curve (Section 7), All Segments, L=18 Kips and V=33 Kips.

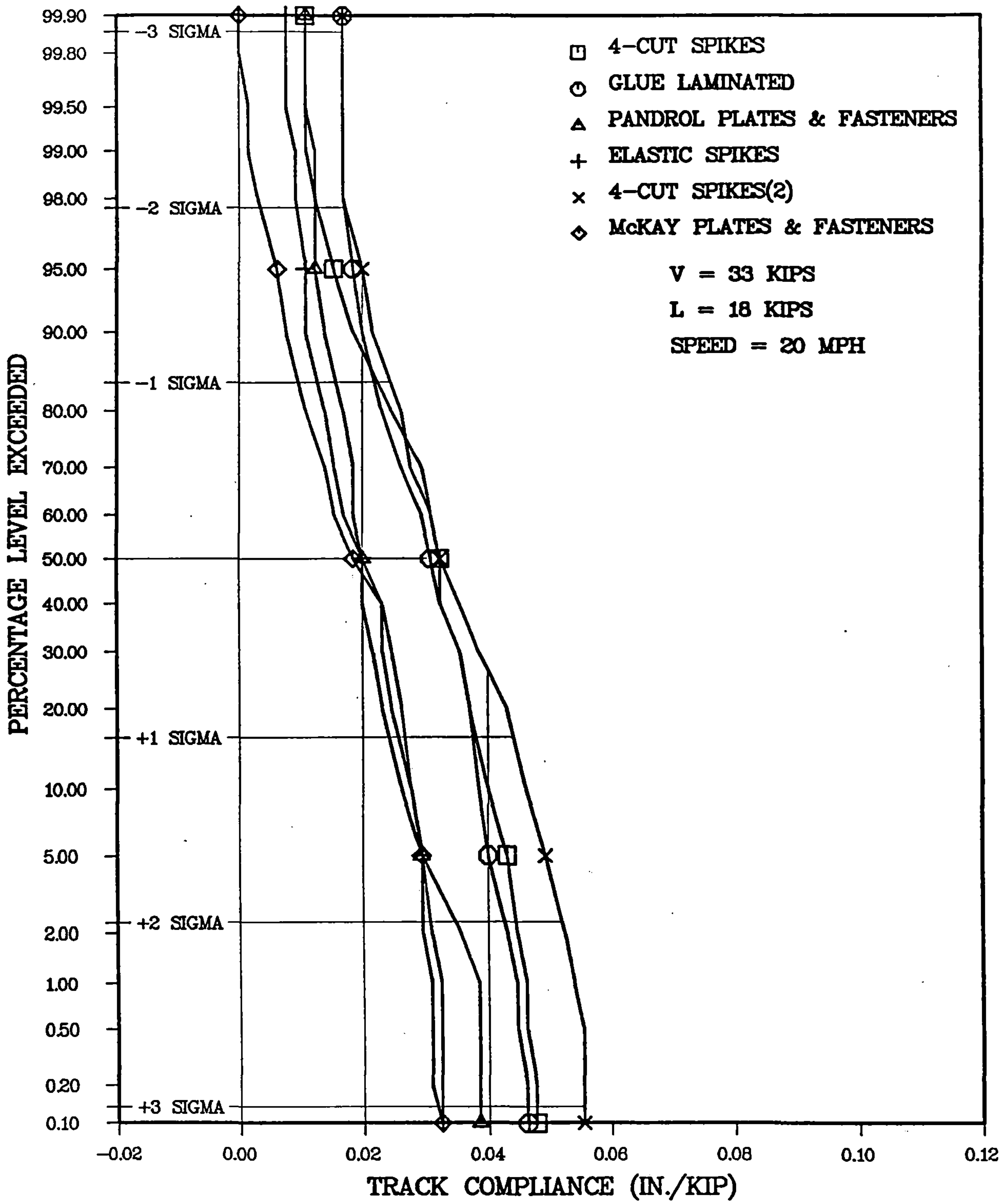

Exhibit 80. Percentage Level Exceedances of Track Compliance, 5-Degree Curve (Section 7), All Segments, L=18 Kips and V=33 Kips.

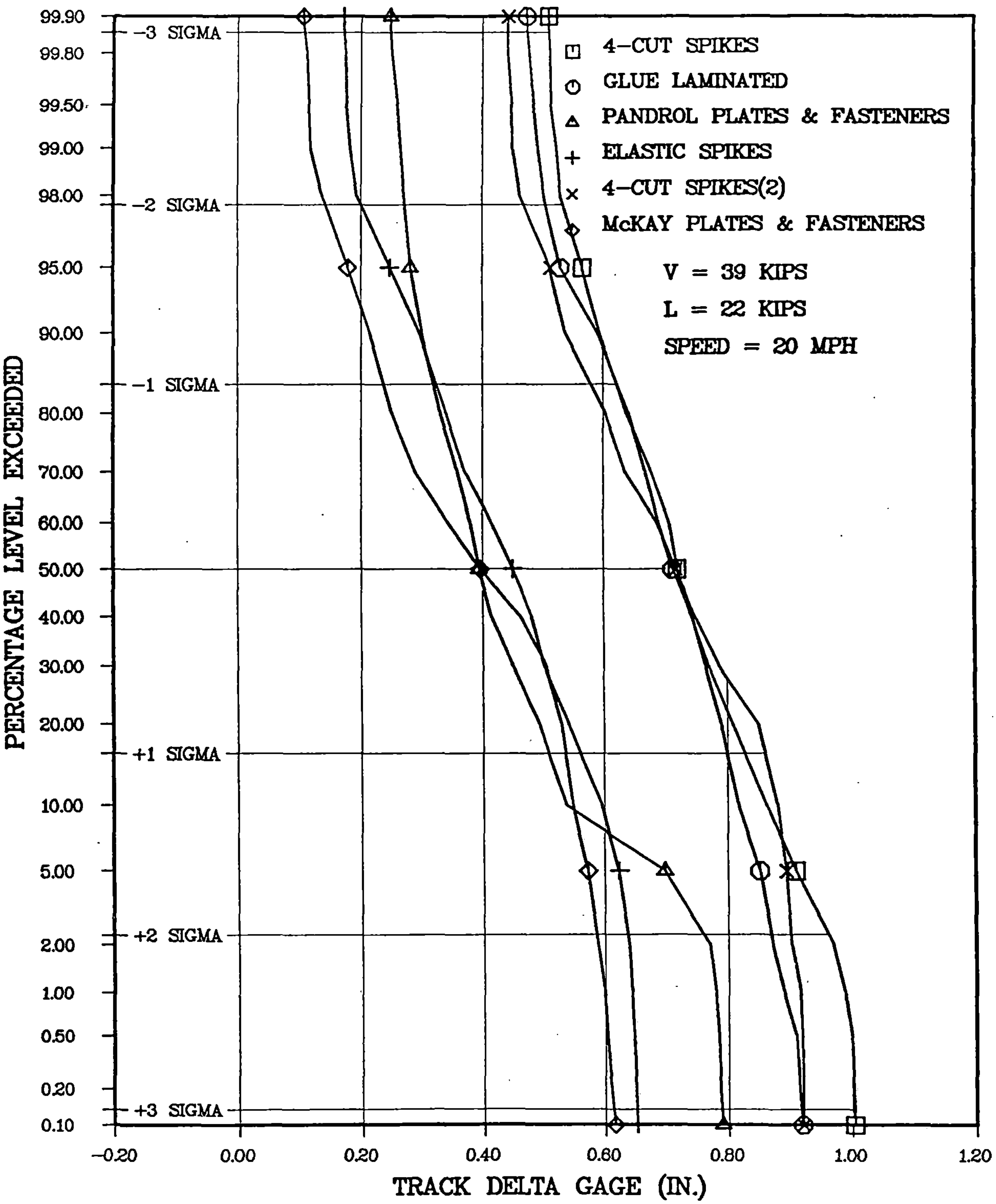

Exhibit 81. Percentage Level Exceedances of Delta Gage, 5-Degree Curve (Section 7), All Segments, L=22 Kips and V=39 Kips.

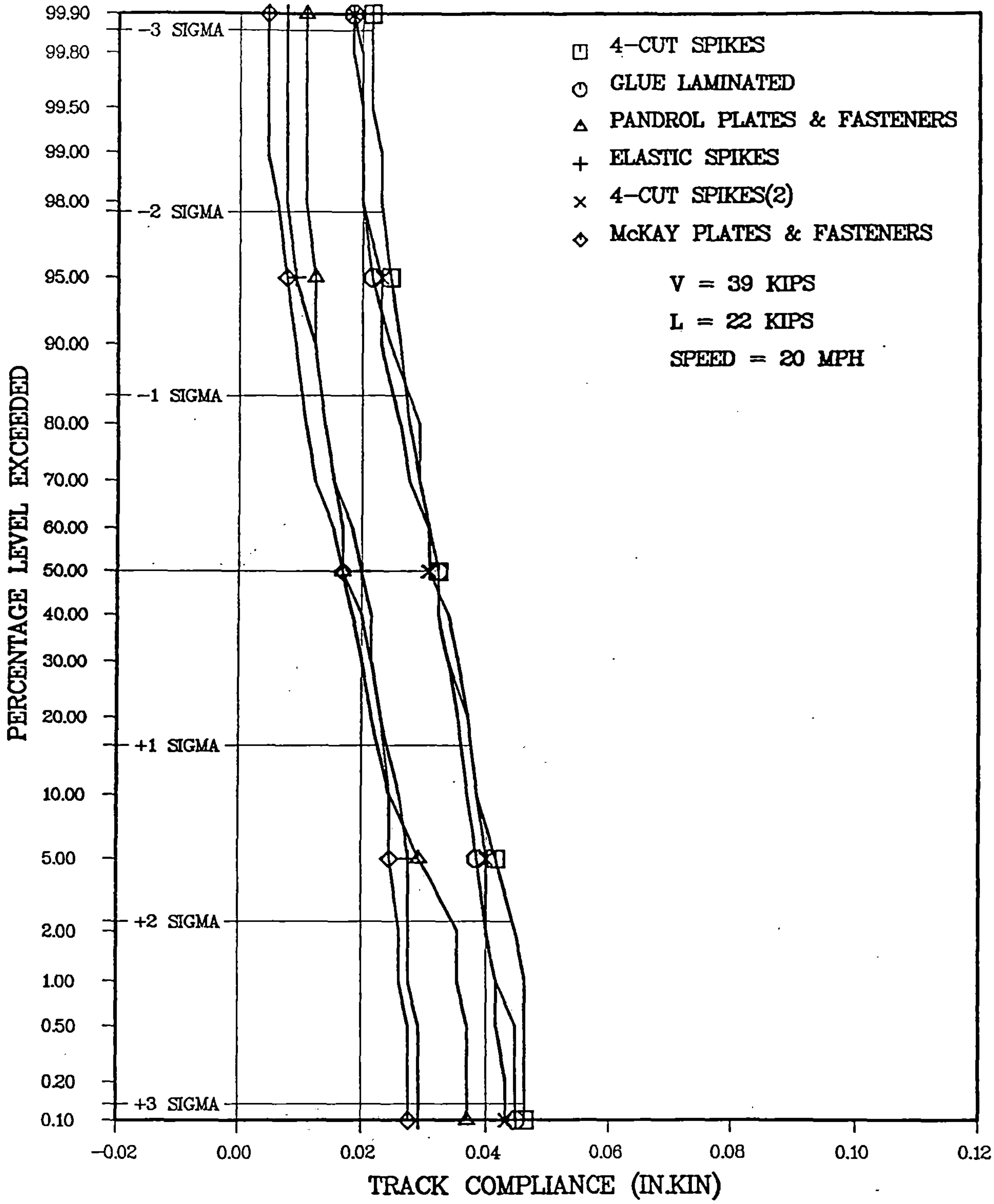

Exhibit 82. Percentage Level Exceedances of Track Compliance, 5-Degree Curve (Section 7), All Segments, L=22 Kips and V=39 Kips.

hard/softwood ties with Pandrol and Safelock fasteners.

The distributions of delta gage and track compliance for Section 31 (Azobe ties) are given in Exhibits 83 to 86. This section, for gage widening tests, was divided into four subsections: five cut spikes, elastic spikes on ties at 19.5" and 24" centers, Pandrols, and concrete ties, respectively. The correspondence between legend in exhibits and the subsections is as follows: ties 0-48 refer to the 5 cut spike subsection, ties 49-138 to the elastic spike subsection, ties 139-179 to the pandrol subsection, and ties 180-276 to the concrete subsection.

As can be seen, the average (approximately the 50 percentile) values of both delta gage and track compliance, under both 33 and 39 kip wheel load, fall into two groups. The elastic spikes, the Pandrols and the concrete ties appear to have similar distributions, and as such provide better gage widening strength than the 5 cut spikes on Azobe ties in Section 31. Again, somewhat lower values of track compliance under 39 kip wheel load, as previously mentioned, are evident in these exhibits. The comparisons of distributions of delta gage and track compliance in Sections 7 and 31 show that the gage widening strength of 5 cut spikes on Azobe ties is midway between those of the elastic fasteners and the 4 cut spikes on domestic hard/softwood ties. On the other hand, any significant difference between the performances of elastic fasteners on domestic hard/softwood ties and the Azobe ties is not obvious in these distribution curves.

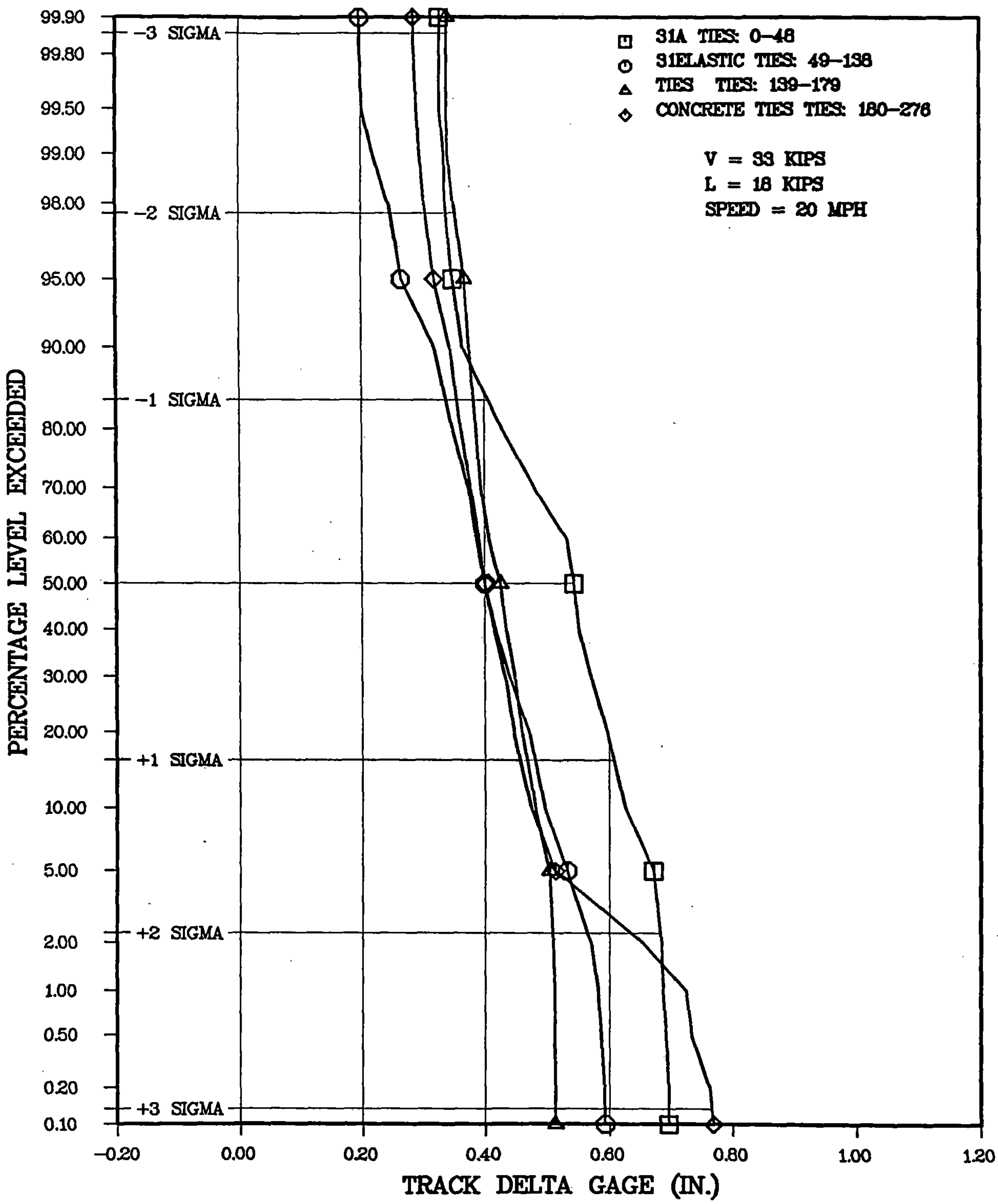

Exhibit 83. Percentage Level Exceedances of Delta Gage, 5-Degree Curve (Section 31), All Segments, L=18 Kips and V=33 Kips.

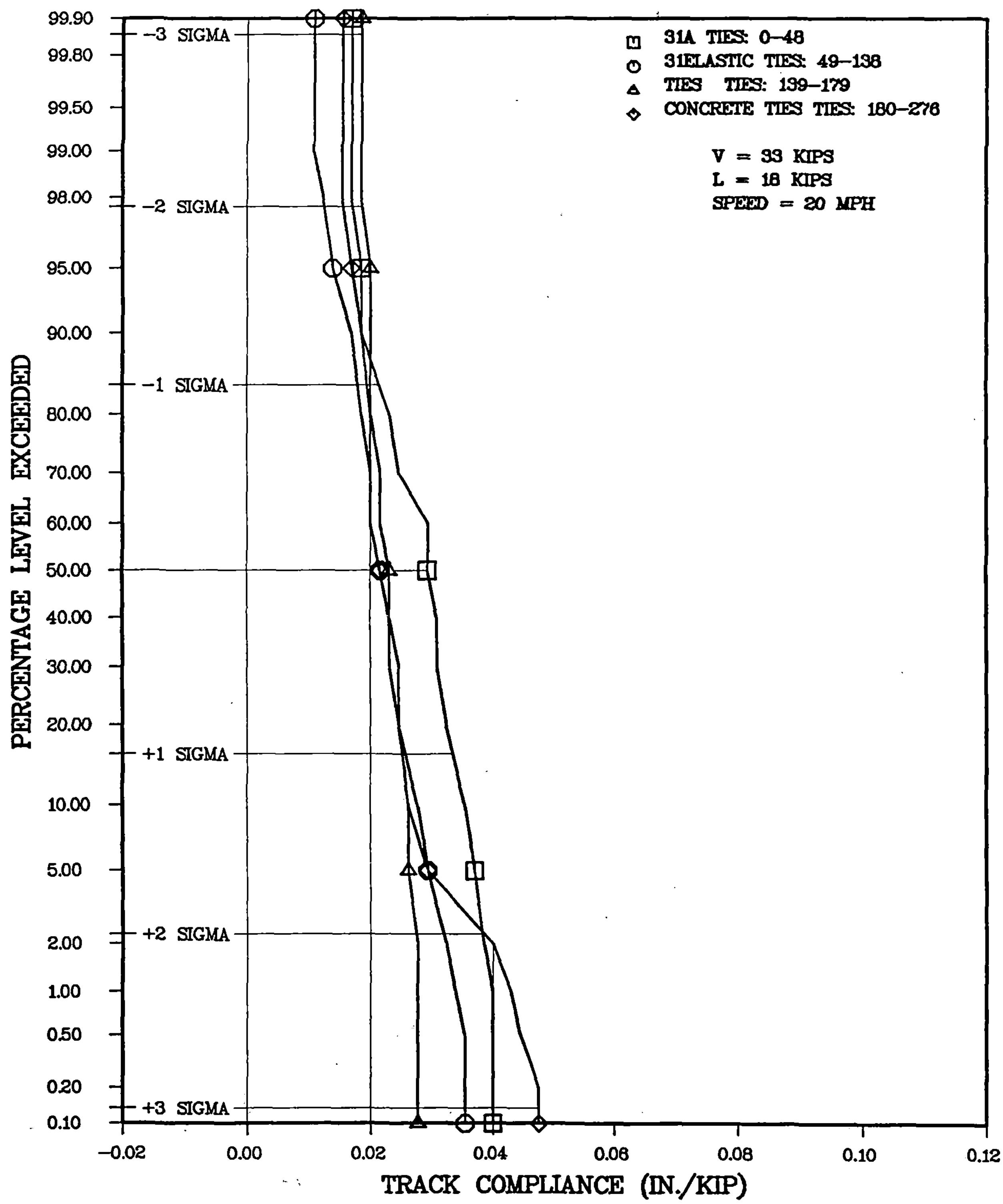

Exhibit 84. Percentage Level Exceedances of Track Compliance, 5-Degree Curve (Section 31), All Segments, L=18 Kips and V=33 Kips.

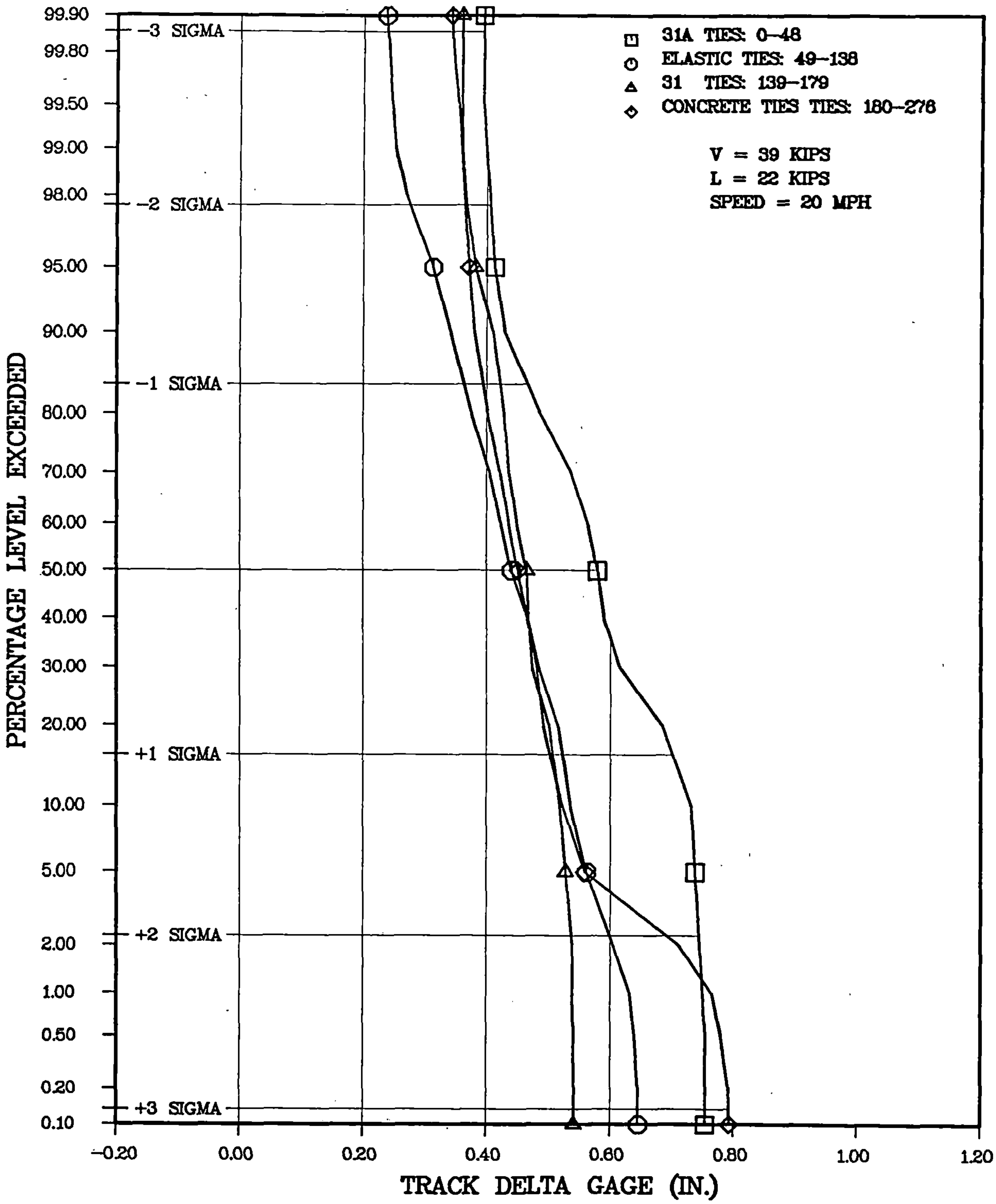

Exhibit 85. Percentage Level Exceedances of Delta Gage, 5-Degree Curve (Section 31), All Segments, L=22 Kips and V=39 Kips.

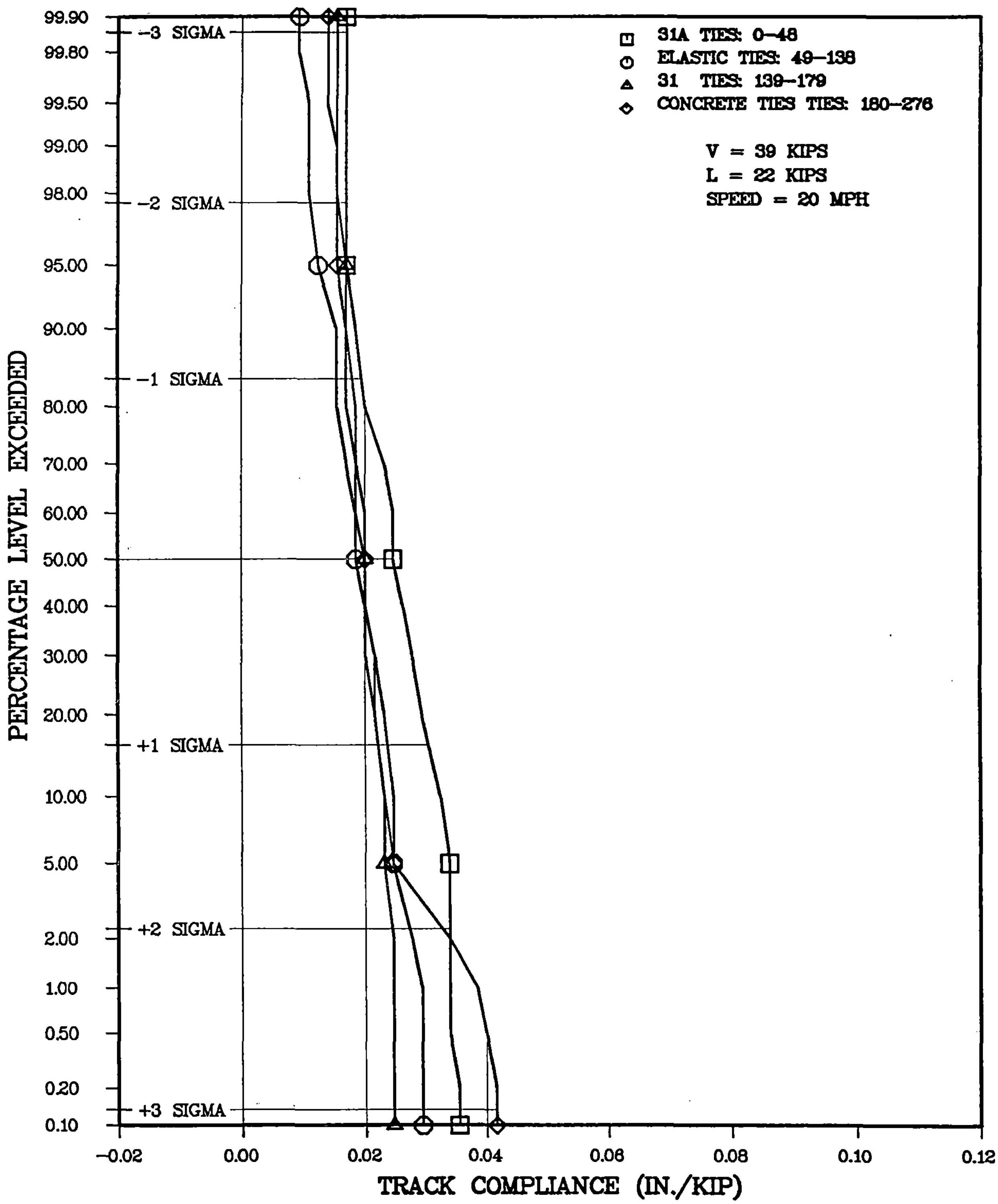

Exhibit 86. Percentage Level Exceedances of Track Compliance, 5-Degree Curve (Section 31), All Segments, L=22 Kips and V=39 Kips.

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7.0 SUMMARY AND CONCLUSIONS

In March 1990, a series of tests over the High-Tonnage Loop at the AAR's Facility for Accelerated Service Testing in Pueblo, Colorado, was conducted using the TLV. The primary objectives of these tests were to determine the effect of 39-ton axle loads on gage widening strength, and compare the results with those obtained under 33-ton axle loads. Data were collected over a broad range of track types including various types of wood ties with cut spikes and elastic fasteners, and concrete ties of various designs and fasteners.

This report presents the results of the gage widening tests conducted under simulated 33 and 39-ton axle loads. The results provide a basis for the comparison of gage widening resulting from various gage widening loads found in revenue service. The gage widening loads used in the static tests were 2 to 24 kips under 33 kip wheel load and 2 to 26 kips under 39 kip wheel load. The sum of rail head deflections, termed the total gage widening, was used to assess the gage widening strength of various fastener types on various tie types.

The in-motion tests, on the other hand, were run at 20 mph over the entire High-Tonnage Loop, first under a constant axle load of 33 tons, and gage widening loads ranging from 10,000 to 22,000 lbs. The tests were then repeated under a 39-ton axle load at gage widening loads from 10,000 to 24,000 lbs, providing a typical spectra of gage widening loads generated at FAST. The data were collected over a variety of tracks, consisting of domestic hard/softwood ties with cut spikes and elastic fasteners, as well as concrete ties of various designs and equipped with various fasteners. The dynamic loaded gage was measured at the gage widening axle of the TLV. This measurement was compared to the corresponding unloaded gage to determine the change in gage, termed delta gage. Track compliance, as a measure of gage widening stiffness, is defined as the ratio of dynamic gage widening to the applied gage widening load. Loaded gage, delta gage and track compliance were used to determine the gage widening strength of various types of fasteners on various types of ties.

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

1. Increasing the axle load from 33 to 39 tons decreased the average dynamic gage widening at a given gage widening load.
2. Increasing the axle load from 33 to 39 tons increased the average dynamic gage widening at a given L/V ratio.
3. The increase in average delta gage, with respect to gage widening load, was largest in the case of domestic hard/softwood ties with 4 cut spikes and least for domestic hard/softwood ties with Safelock fasteners under both the 33 and 39 kip wheel loads.
4. The increase in average loaded gage, with respect to gage widening load, was largest in the case of glue laminated ties with 4 cut spikes and least for domestic hard/softwood ties with Safelock fasteners under both the 33 and 39 kip wheel loads.

5. The dynamic gage widening of track having concrete ties was found to be more than that of track having pandrols, Safelocks and elastic spikes on domestic hard/softwood ties under both the 33 and 39 kip wheel loads. It should ne noted that the wood ties at FAST are relatively new compared with those in revenue service.

6. The gage widening strength provided by glue laminated ties with 4 cut spikes was comparable to that of domestic hard/softwood ties with 4 cut spikes under both the 33 and 39 kip wheel loads.

7. The dynamic gage widening strength (under both the 33 and 39 kip wheel loads) of track having domestic hard/softwood ties with elastic spikes could be compared to the strength of track having Azobe ties with 5 cut spikes. Elastic spikes on domestic hard/softwood ties and 5 cut spikes on Azobe ties resulted in dynamic gage widening between those with 4 cut spikes and elastic fasteners, such as Safelock and Pandrol, on domestic hard/softwood ties. Also, the gage widening strength of elastic spikes on Azobe ties appeared to be much better than elastic spikes on domestic hard/softwood ties.

8. There appeared to be no gain in the dynamic gage widening strength provided by elastic fasteners when domestic hard/softwood ties were replaced with the Azobe ties.

9. It is reasonable to expect the gage widening loads under 39-ton axle load cars to be proportionally higher than those under 33-ton axle load cars. Consequently, the resulting gage

widening is likely to be higher under 39-ton axle load cars. This was apparent in the average delta gage plots.

10. Based on the results in the report, on average, elastic fasteners on domestic hard/softwood ties provided a much greater gage widening strength compared with 4 cut spikes on domestic hard/softwood or glue laminated wood ties.

11. Variability or scatter of data was least for domestic hard/softwood ties with Pandrol fasteners, and was most for the glue laminated ties with 4 cut spikes.

12. Average values of the dynamic strength data indicated that for domestic hard/softwood ties with cut spikes and glue laminated ties with cut spikes, track compliance values more or less remained constant as the gage widening load (or L/V) was increased. This indicates that track having cut spikes on either domestic hard/softwood ties or glue laminated ties, responded to the applied gage widening loads in a somewhat linear fashion.

13. On the other hand, test results on concrete ties and elastic fasteners on domestic hard/softwood ties indicated that track compliance values decreased (however, lesser so in the case of elastic spikes) as the gage widening load was increased. This implied that elastic fasteners provided increased gage widening strength under higher gage widening loads.

14. Results of data on the Azobe ties with 5 cut spikes also indicated increased gage widening strength under higher gage

widening loads.

15. The stiffening gage characteristics (decreasing gage widening at higher gage widening loads) were found to be most prevalent for domestic hard/softwood ties with Safelock fasteners.

16. The average track compliance value of about 0.030 in/kip (gage widening stiffness of about 33 kips/in) at most gage widening loads used in these tests indicated "good" tie and rail restraint condition for cut spikes on both the domestic hard/softwood and glue laminated ties.

17. For elastic fasteners on domestic hard/softwood ties, the average track compliance values decreased from about 0.030 in/kip at 10 kip gage widening load to about 0.020 in/kip (gage widening stiffness of 50 kips/in) at 22 kip gage widening load. This indicated an enhancement to the gage widening strength at increased gage widening loads.

19. The best gage widening strength was provided by Safelock fasteners on domestic hard/softwood ties. A track compliance value, at 24 kip gage widening load under 39 kip wheel load, of about 0.017 in/kip (gage widening stiffness of about 59 kips/in) was obtained.

20. The elastic spikes on domestic hard/softwood ties and the Azobe ties with 5 cut spikes also provided "good" tie and rail restraint which was quite a bit better than that of 4 cut spikes on domestic ties.

21. The percentage level exceedance curves of delta gage

indicated that, in general, the distributions were close to the Gaussian model between about 5 and 95 percentile levels. Between these levels, concrete ties and the elastic fasteners on wood ties gave parallel and closely spaced delta gage curves at different gage widening loads compared to these curves for wood ties with cut spikes. This means that the change in the average delta gage value from one gage widening load to another was smaller for elastic fasteners and concrete ties than cut spikes. Also, between these levels, the Standard Deviation of delta gage values at a given percentile level was approximately same at different gage widening loads.

22. The cross over (inflection point) in the track compliance curves, with respect to gage widening loads, occurred at distinct percentile levels for concrete ties and elastic fasteners on wood ties. These inflection points generally occurred between approximately 90 and 98 percentile levels. Distinct gage hardening characteristics, therefore, were discernible up to these levels for concrete ties and elastic fasteners on wood ties.

23. Inflection points in the distribution curves of track compliance of wood ties with cut spikes were not distinctly apparent. Any characteristic differences at 50 percentile level (approximating average magnitudes) thus could not be derived. At lower percentile levels, gage hardening characteristics for cut spikes on wood ties also were apparent.

23. Regardless of the tie/fastener type, the distribution curves of track compliance showed that at higher gage widening loads, the distribution curves tended to bunch together to result in almost the same distribution. This seemed to occur at gage widening loads above 16 kips. Gage hardening characteristics, therefore, could not be very apparent if tests were run only at gage widening loads in excess of 16 kips.

24. Comparison of delta gage and compliance exceedance curves with respect to tie/fastener types showed that these distributions were clearly separated into two groups. One group consisted of concrete ties and the elastic fasteners on wood ties. The other group consisted of cut spikes on wood ties. Much better gage widening strength of the first group compared to the second was clearly evident from the test results.

25. Any significant difference between the performances of elastic fasteners on domestic hard/softwood ties and Azobe ties was not obvious in the tests.

26. The results from the TLV stationary static tests corroborate the above conclusions derived from the moving tests. The performance of elastic fasteners on domestic hard/softwood ties was found to be much better than that of cut spikes on the same type of ties. Again, in these stationary tests, superiority of the gage widening strength of the Azobe ties with 5 cut spikes compared to that of domestic

hard/softwood ties with 4 cut spikes was evident.

In conclusion, it can be mentioned that under heavy axle loads, elastic fasteners on wood ties provide much greater gage widening strength than do cut spikes. In fact, all elastic fasteners performed well. The test results imply that the potential track damage due to the increased axle loads can be minimized by either controlling the gage widening loads resulting from curve negotiation or by reducing the rail lateral deflections. The gage degradation under 39-ton axle loads can therefore be kept at or below that under the 33-ton axle loads, if the gage widening loads are maintained at the same level. This can be achieved by the use of improved suspension systems, or alternatively controlling gage degradation by utilizing elastic fasteners on domestic hard/softwood tie track.

It is expected that the data obtained from the TLV heavy axle load tests will prove vital to vehicle designers in evaluating improved suspension systems. This information will be equally important in the final economic analysis of heavier axle loads in terms of overall assessment of cost reductions, primarily those attributable to reduced gage degradation provided by premium trucks and tie fastener systems. The TLV has subsequently been utilized to conduct dynamic gage widening tests on revenue service track. The data collected during these tests will provide a statistical representation of the gage widening strength of various track types. In addition, the TLV will provide data in the selection of track sites which require immediate attention.

Recent AAR research has demonstrated the need to control rail roll on both the high and low rails of curves. This is especially true in areas subject to low rail rollover. An investigation of the possible benefits of alternative suspensions is currently underway as part of the Heavy Axle Load Research Program. The information obtained during the TLV tests is expected to be of vital importance to vehicle designers in evaluating improved suspension systems for new truck designs. Concurrently, the Association of American Railroads is developing a freight car truck performance specification. Trucks meeting that specification should produce maximum benefits to the railroad industry.

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8.0 REFERENCES

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9.0 APPENDICES

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9.1 Appendix-A Distance History Plots

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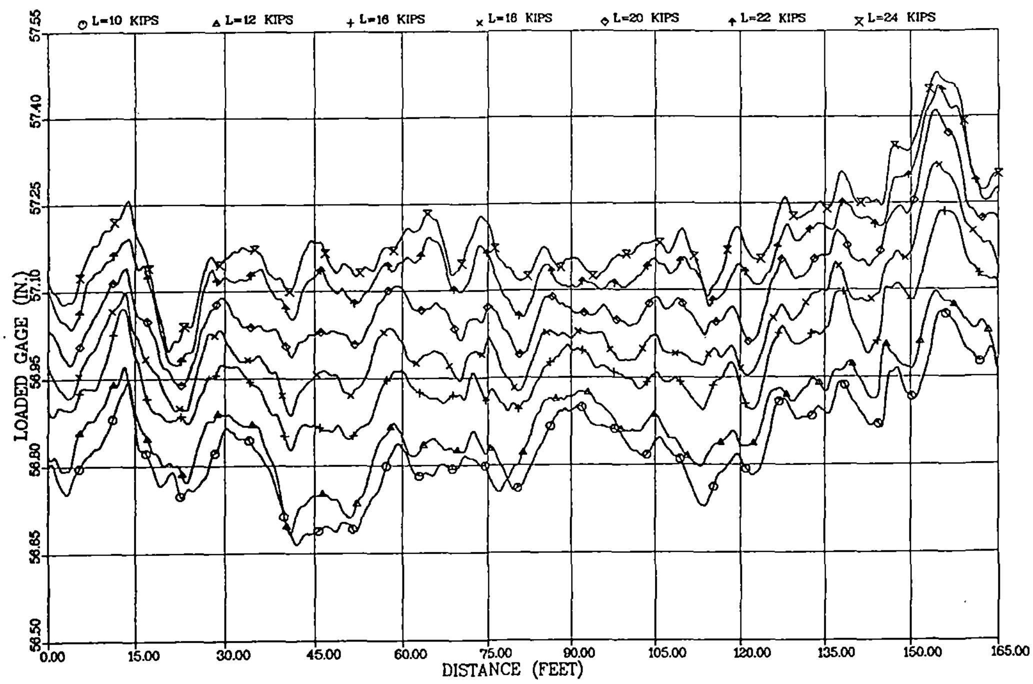

Exhibit A1. Loaded Gage Distance History, 5-Degree Curve (Section 3(1)), Wood Ties/4-Cut Spikes, V=39 Kips.

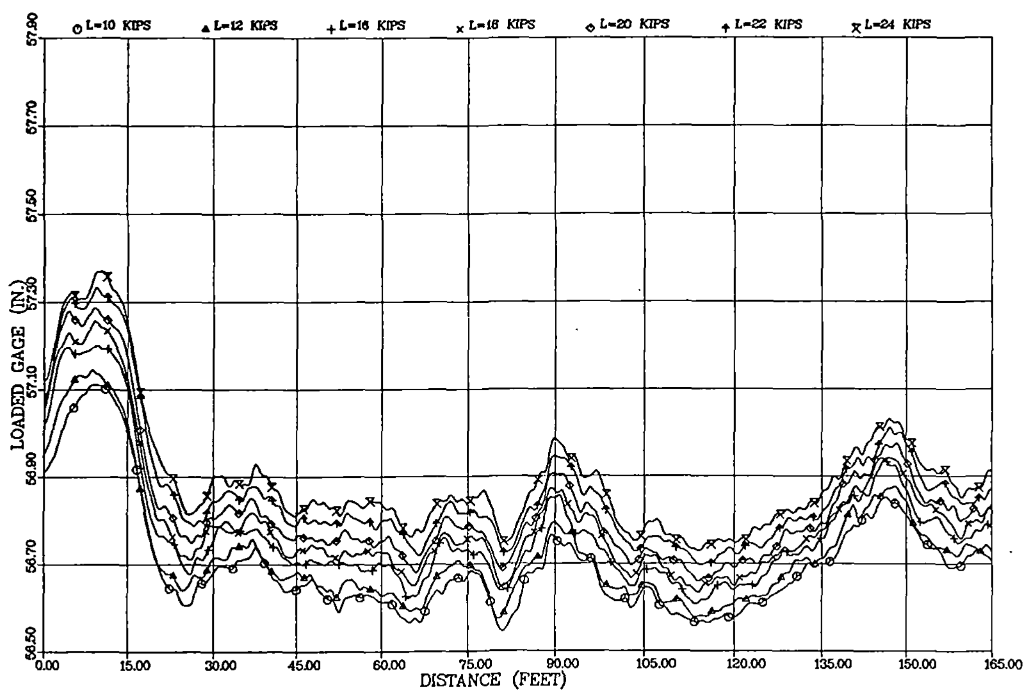

Exhibit **A2.** Loaded Gage Distance History, 5-Degree Curve, (Section 3(2)),Concrete Ties, V=39 Kips.

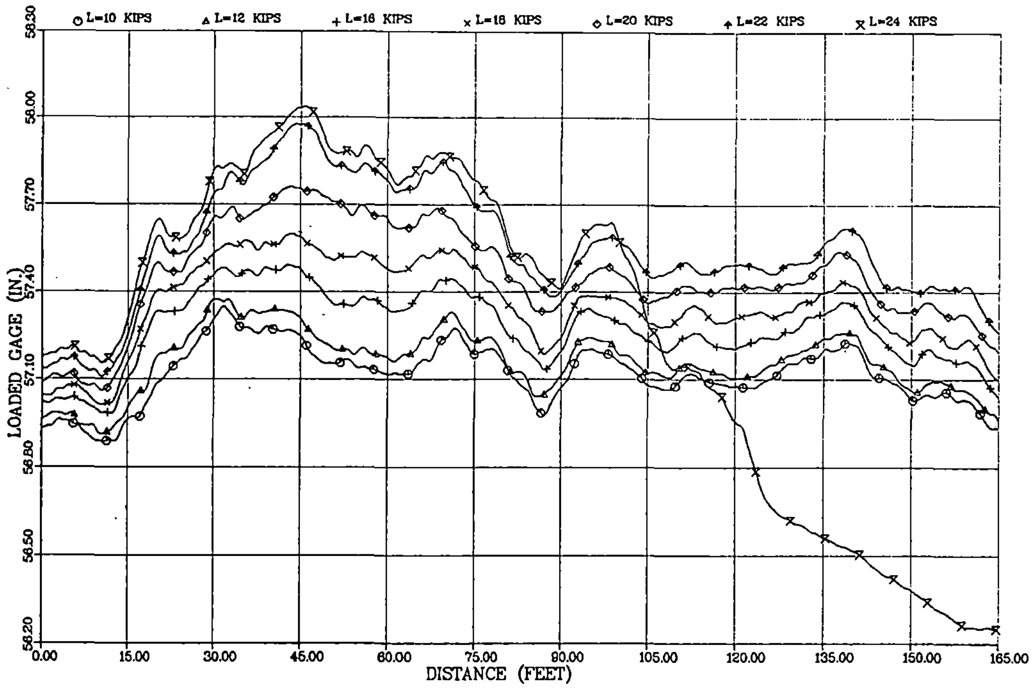

Exhibit **A3.** Loaded Gage Distance History, 5-Degree Curve (Section 3(3)),Wood Ties/4-Cut Spikes, V=39 Kips.

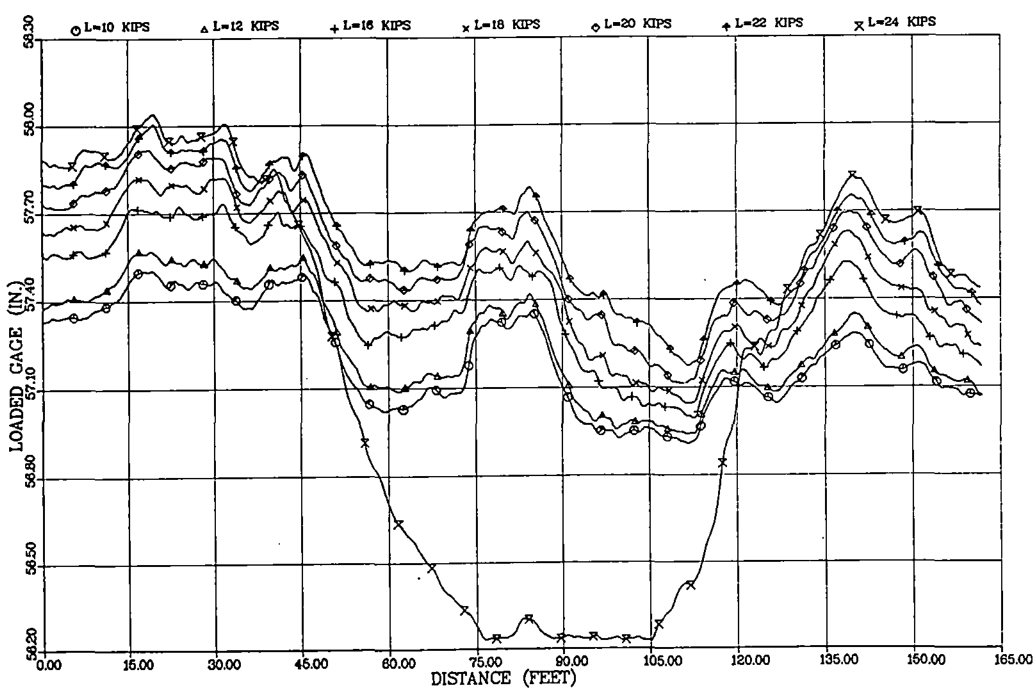

Exhibit **A4.** Loaded Gage Distance History, 5-Degree Curve (Section 7F), Glue Laminated Ties/4-Cut Spikes, V=39 Kips.

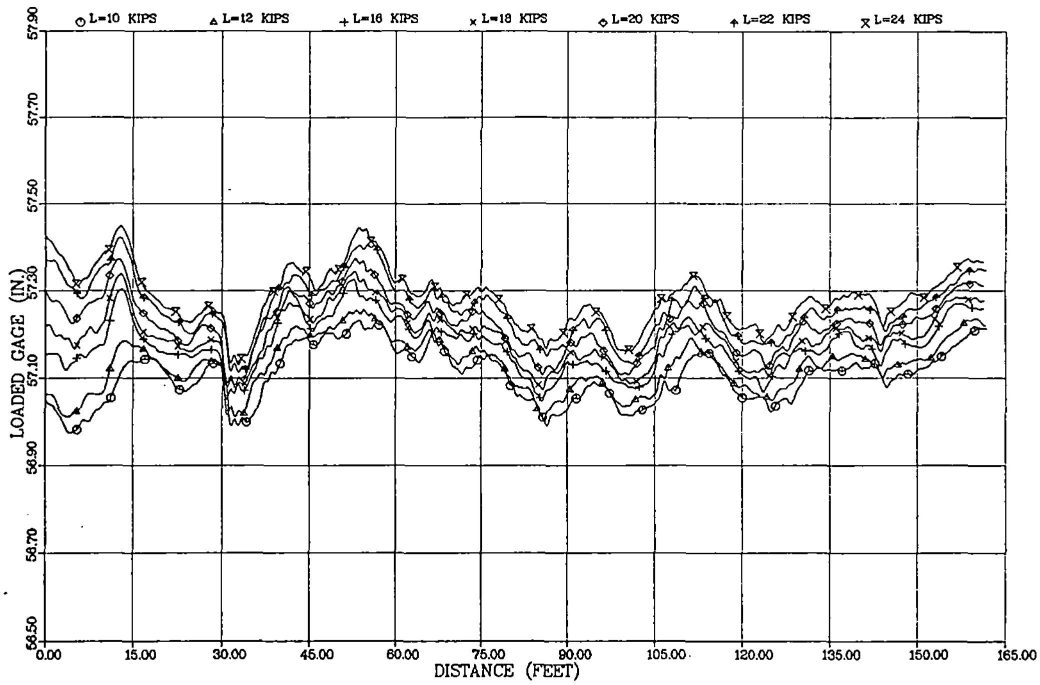

Exhibit **A5.** Loaded Gage Distance History, 5-Degree Curve, (Section 7C),Wood Ties/Pandrol Fasteners, V=39 Kips.

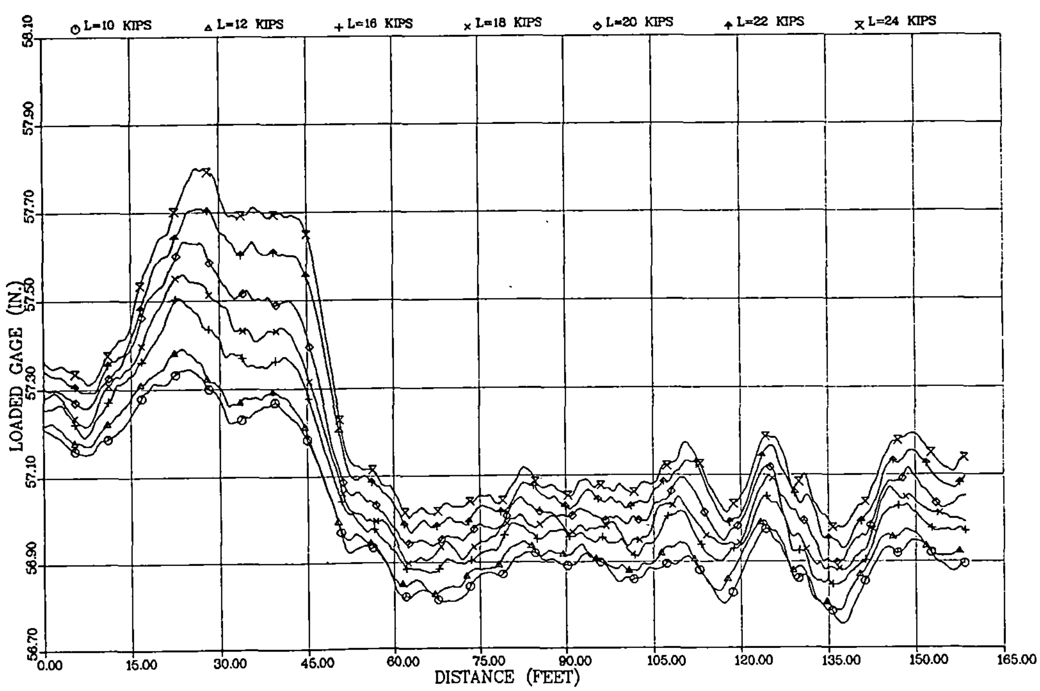

Exhibit **A6.** Loaded Gage Distance History, 5-Degree Curve, (Section 7E), Wood Ties/Elastic Spikes, V=39 Kips.

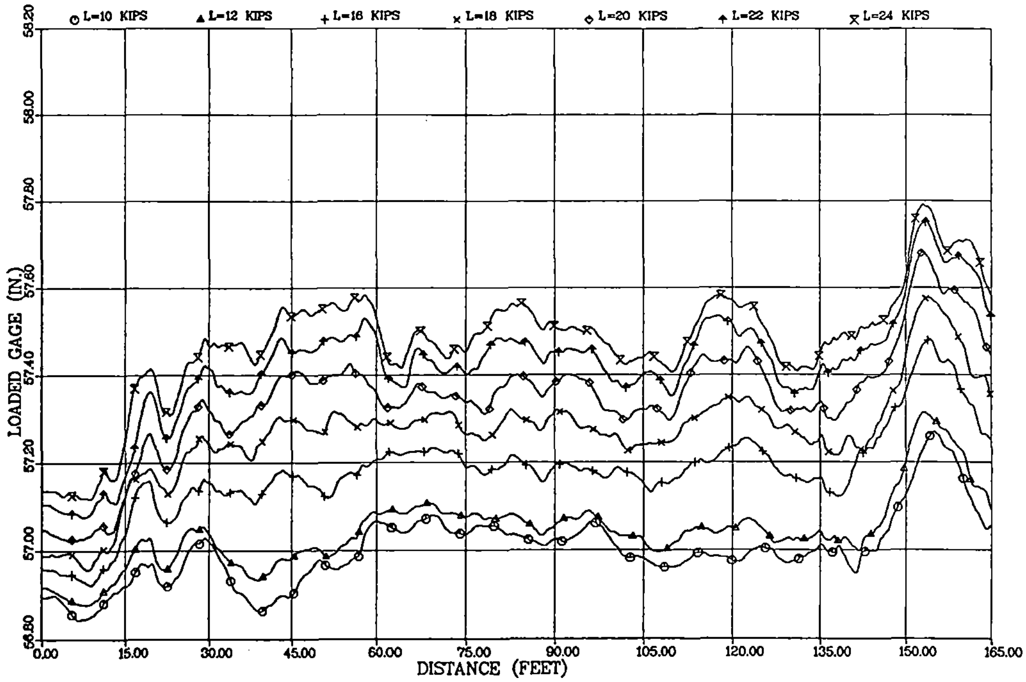

Exhibit **A7.** Loaded Gage Distance History, 5-Degree Curve (Section 7A(2)),Wood Ties/4-Cut Spikes, V=39 Kips.

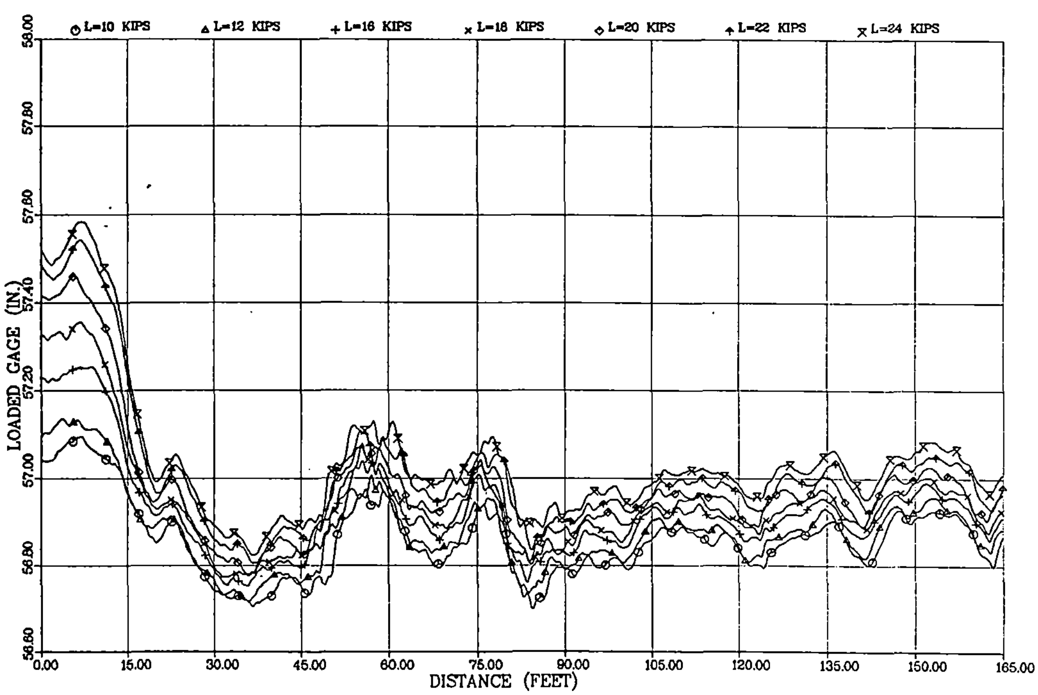

Exhibit **A8.** Loaded Gage Distance History, 5-Degree Curve (Section 7D), Wood Ties/McKay Fasteners, V=39 Kips.

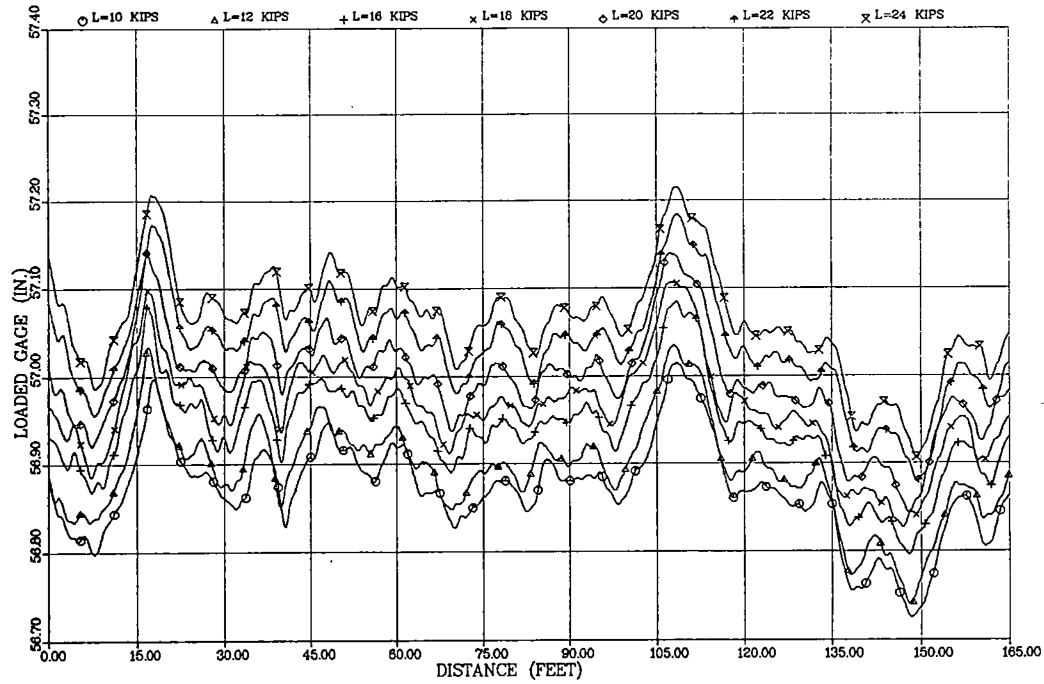

Exhibit A9. Loaded Gage Distance History, 6-Degree Curve, (Section 25A), Wood Ties/Pandrol Fasteners, V=39 Kips.

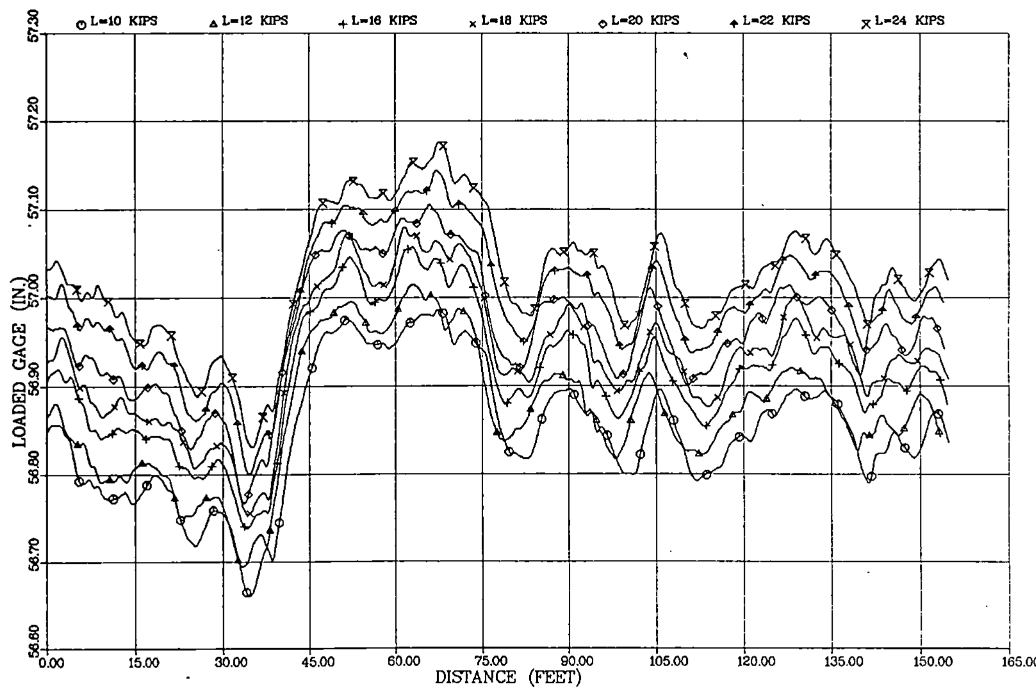

Exhibit A10. Loaded Gage Distance History, 6-Degree Curve, (Section 25B), Wood Ties/Pandrol Fasteners, V=39 Kips.

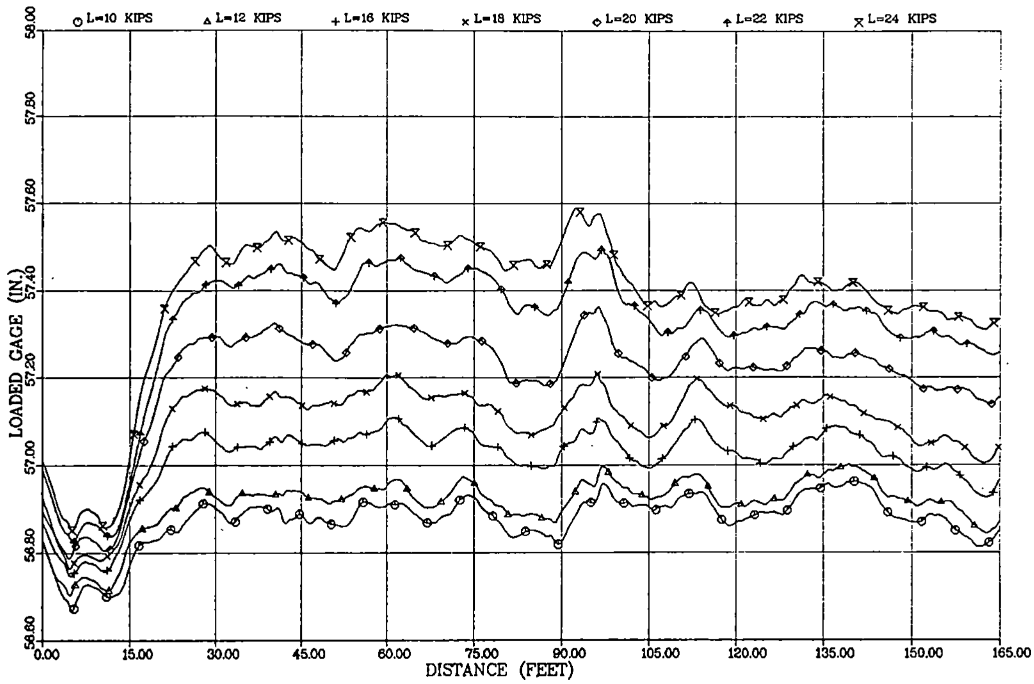

Exhibit **A11.** Loaded Gage Distance History, 6-Degree Curve, (Section 25CDE), Wood Ties/4-Cut Spikes, V=39 Kips.

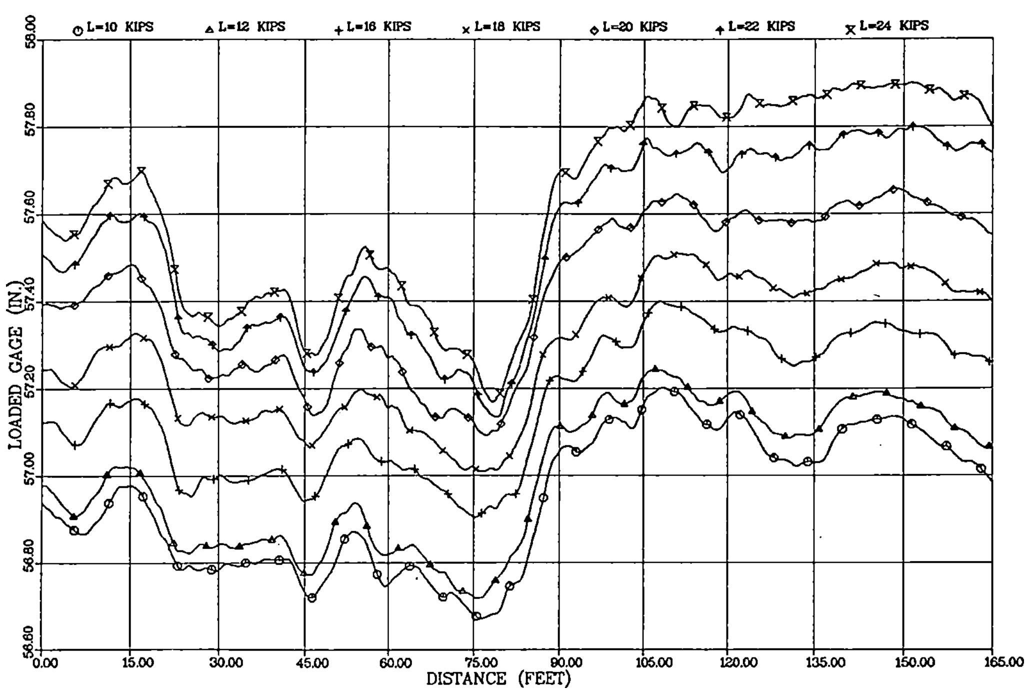

Exhibit **A12.** Loaded Gage Distance History, 6-Degree Curve, (Section 25FGH), Wood Ties/4-Cut Spikes, V=39 Kips.

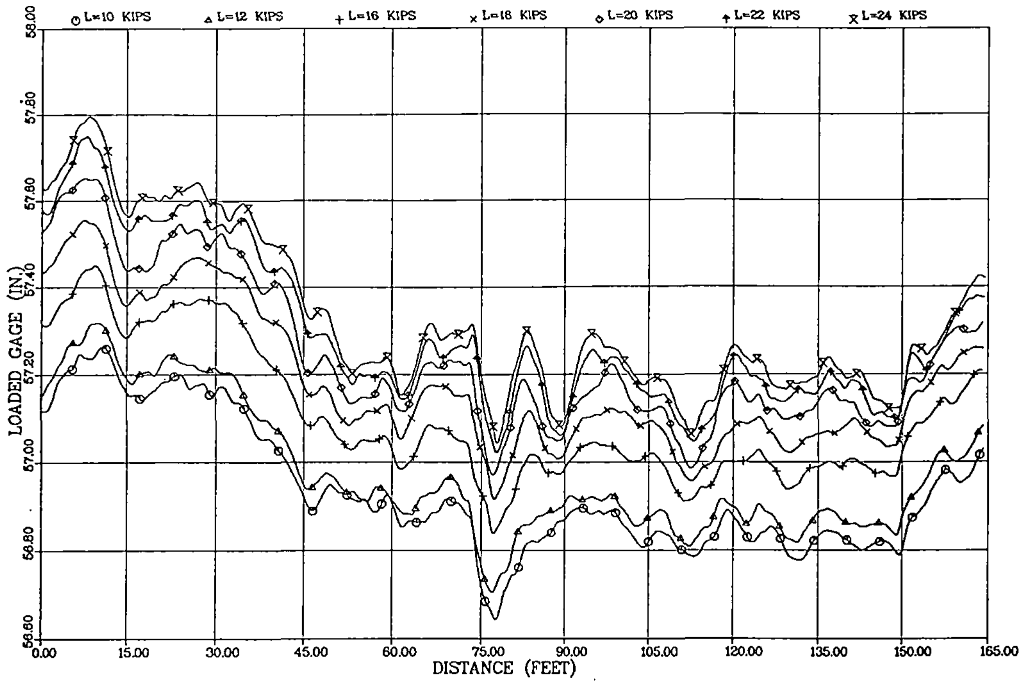

Exhibit **A13.** Loaded Gage Distance History, 6-Degree Curve, (Section 25I), Wood Ties/4-Cut Spikes, V=39 Kips.

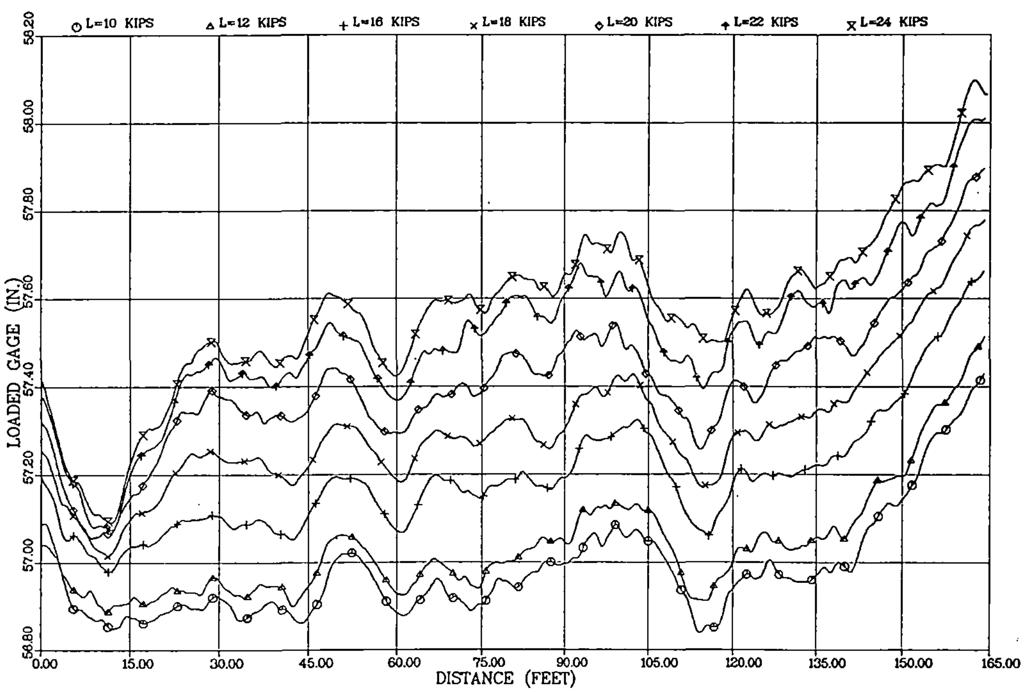

Exhibit **A14.** Loaded Gage Distance History, 6-Degree Curve, (Section 25J), Wood Ties/4-Cut Spikes, V=39 Kips.

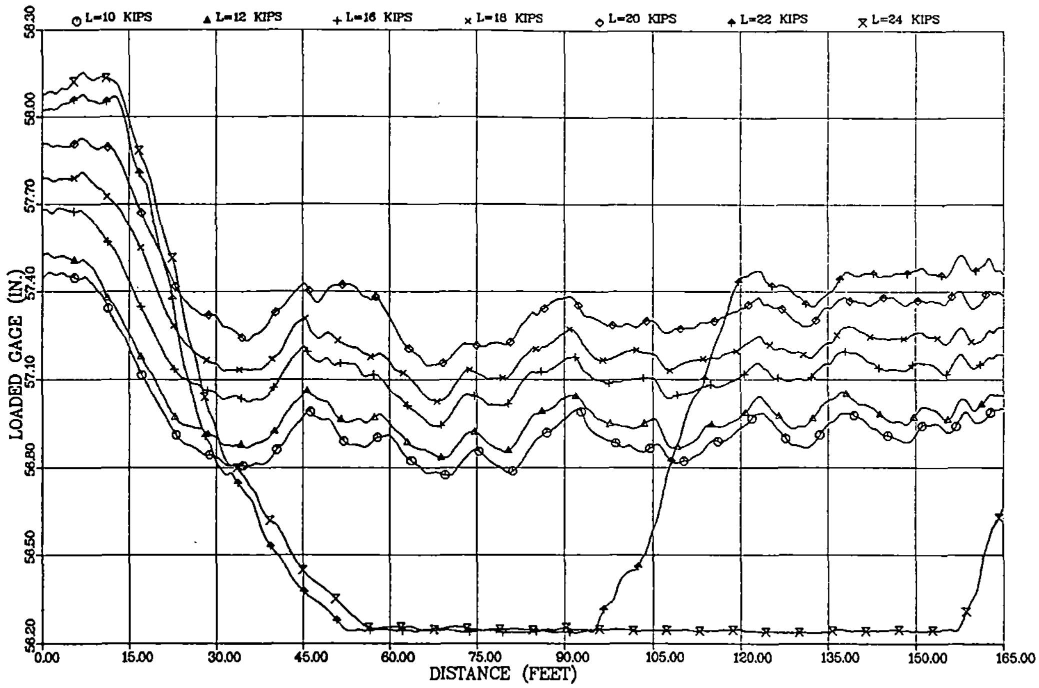

Exhibit **A15.** Loaded Gage Distance History, 6-Degree Curve (Section 25KLMNO), Wood Ties/4-Cut Spikes, V=39 Kips.

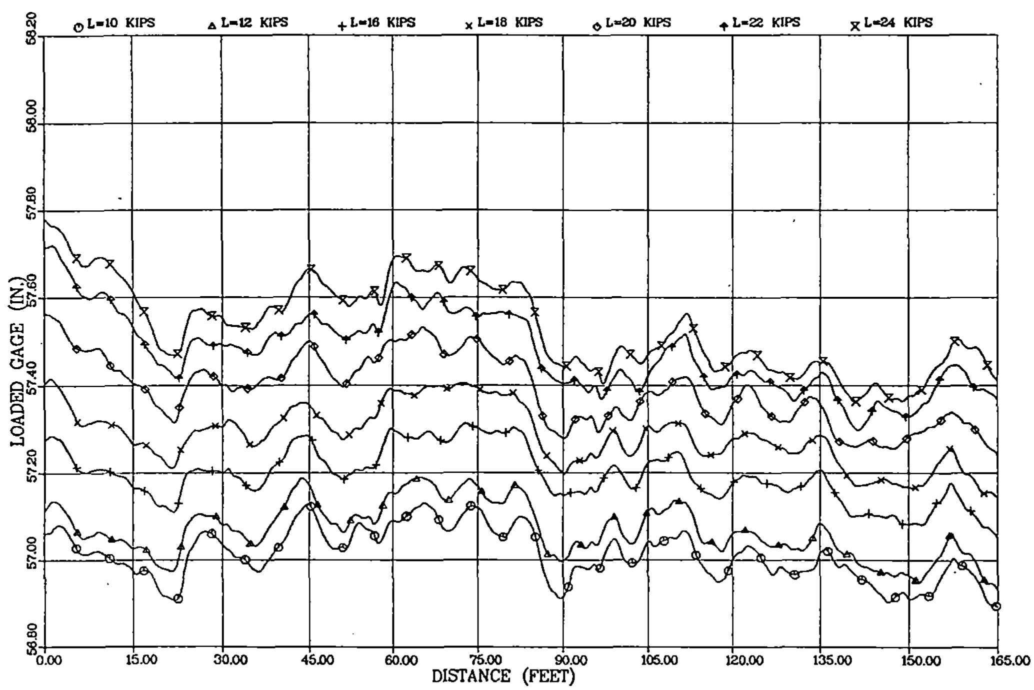

Exhibit **A16.** Loaded Gage Distance History, 6-Degree Curve, (Section 25PQ), Wood Ties/4-Cut Spikes, V=39 Kips.

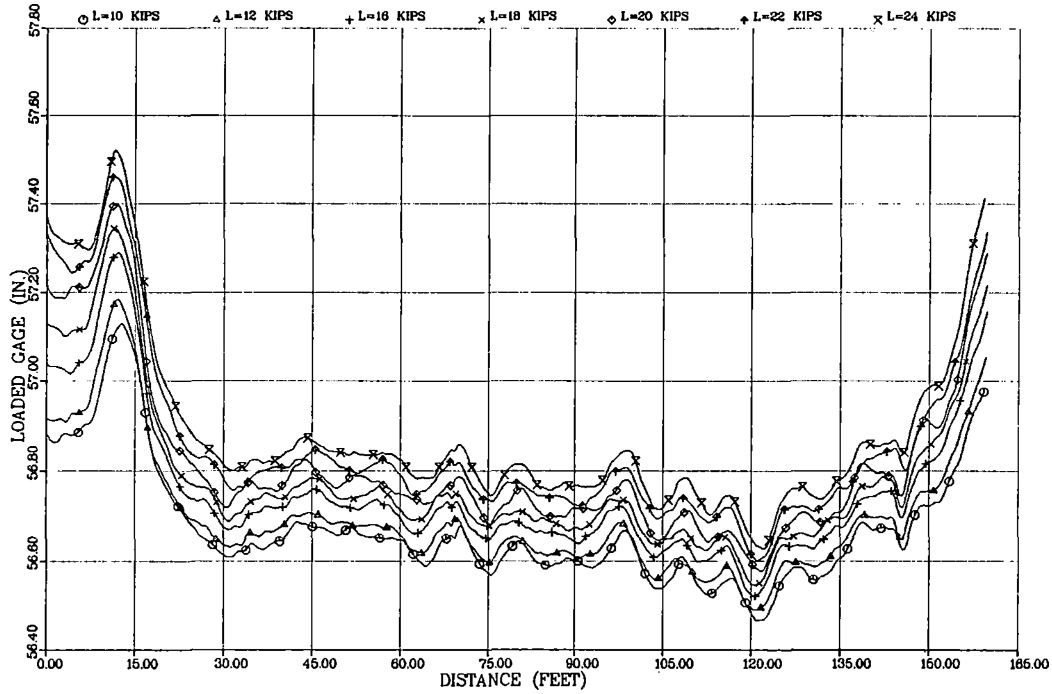

Exhibit A17. Loaded Gage Distance History, 6-Degree Curve, (Section 25R), Wood Ties/Pandrol Fasteners, V=39 Kips.

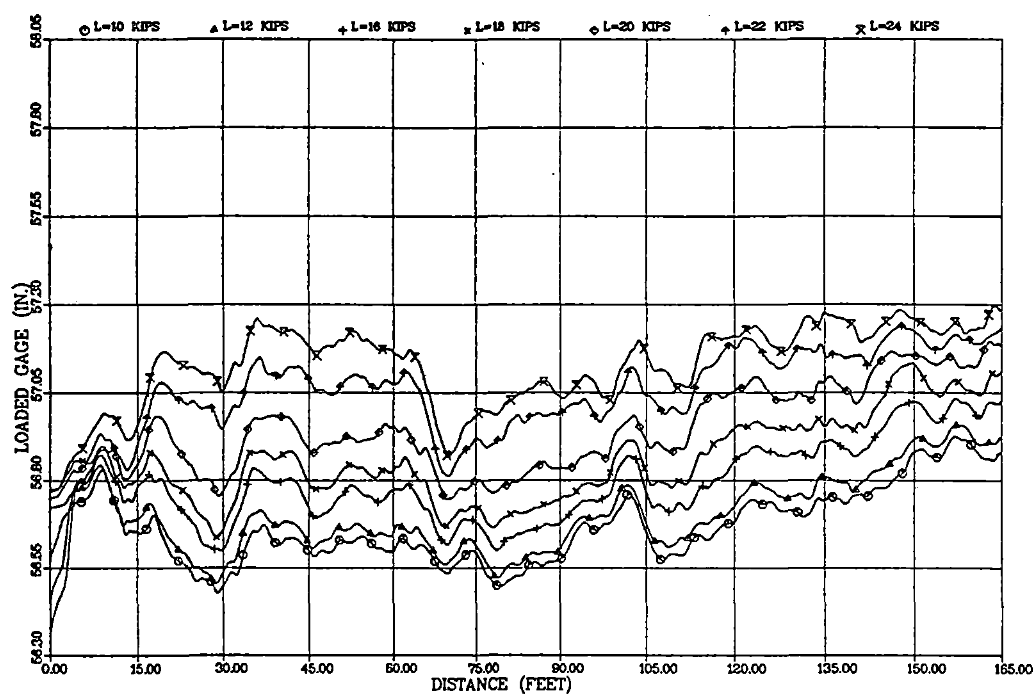

Exhibit A18. Loaded Gage Distance History, Tangent Track (Section 29), Wood Ties/Pandrol Fasteners, V=39 Kips.

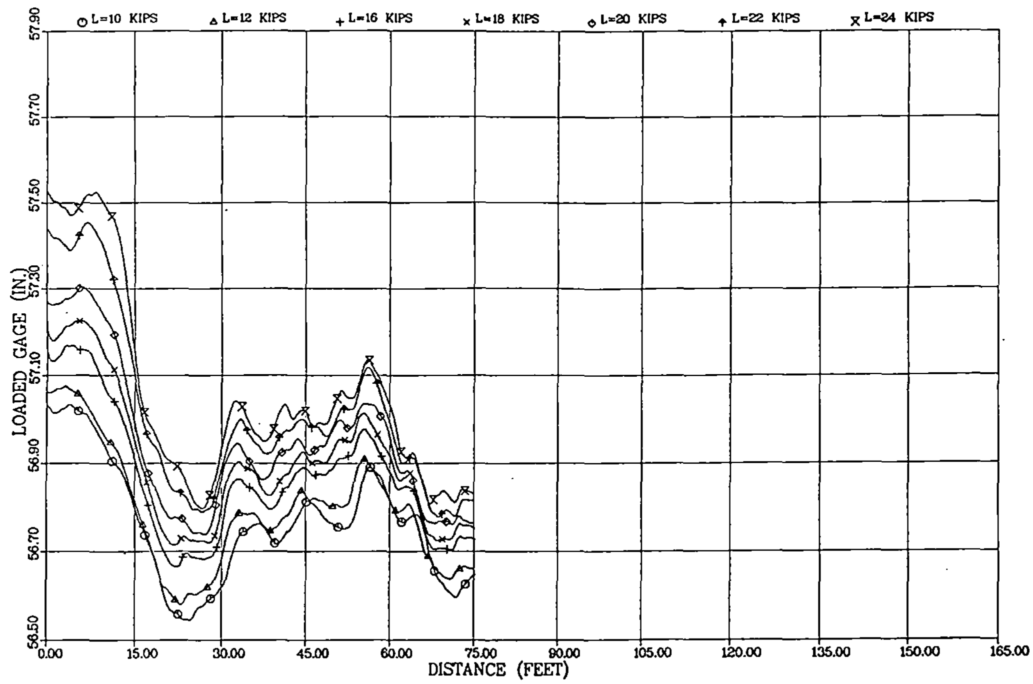

Exhibit A19. Loaded Gage Distance History, 5-Degree Curve (Section 31(1)), Azobe Ties/5-Cut Spikes, V=39 Kips.

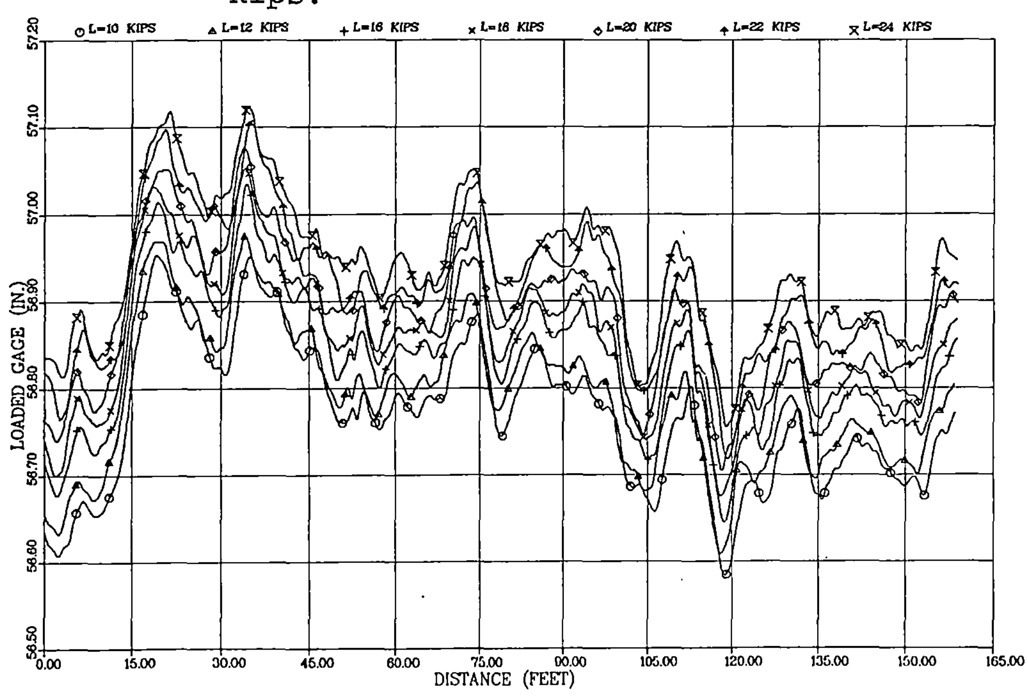

Exhibit A20. Loaded Gage Distance History, 5-Degree Curve (Section 31(2)), Azobe Ties/Elastic Spikes, V=39 Kips.

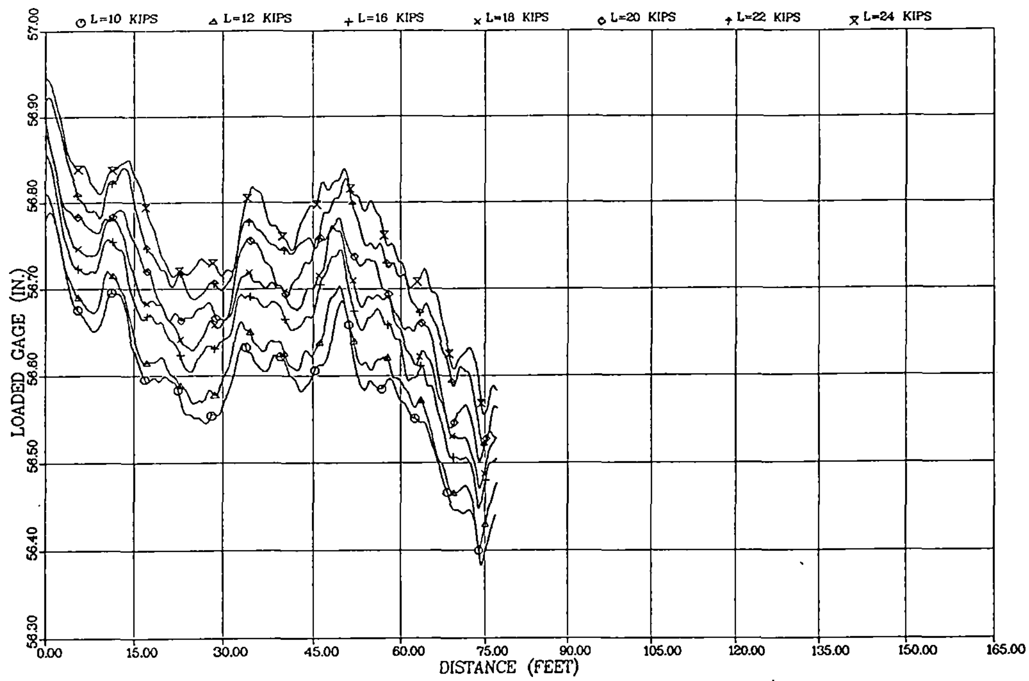

Exhibit **A21.** Loaded Gage Distance History, 5-Degree Curve (Section 31(3)), Azobe Ties/Pandrol Fasteners, V=39 Kips.

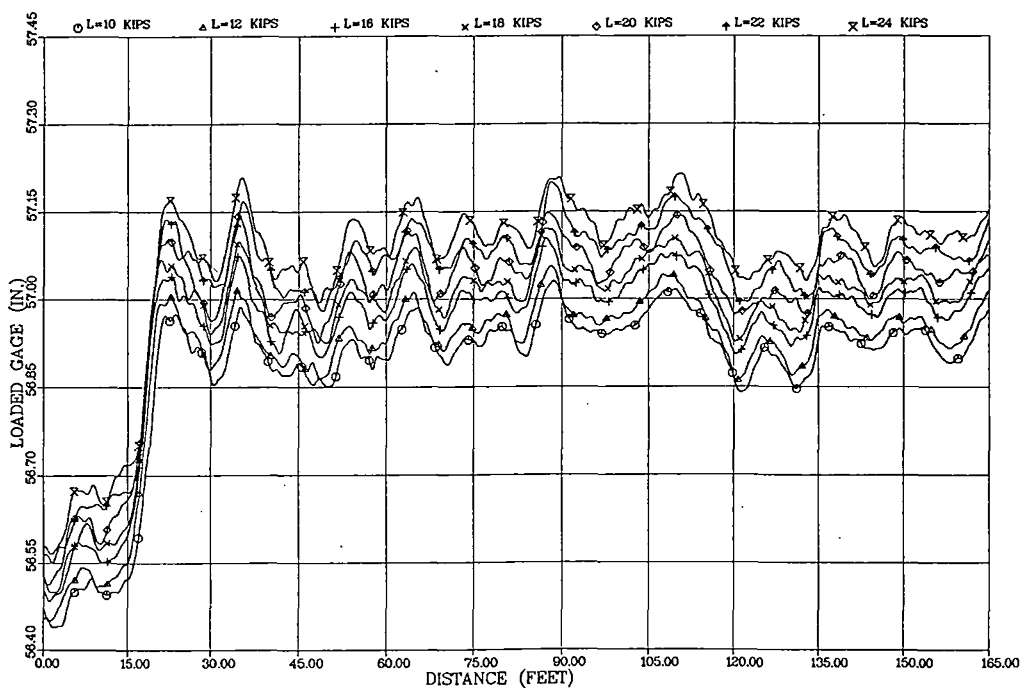

Exhibit **A22.** Loaded Gage Distance History, 5-Degree Curve, (Section 31(4)), Concrete Ties, V=39 Kips.

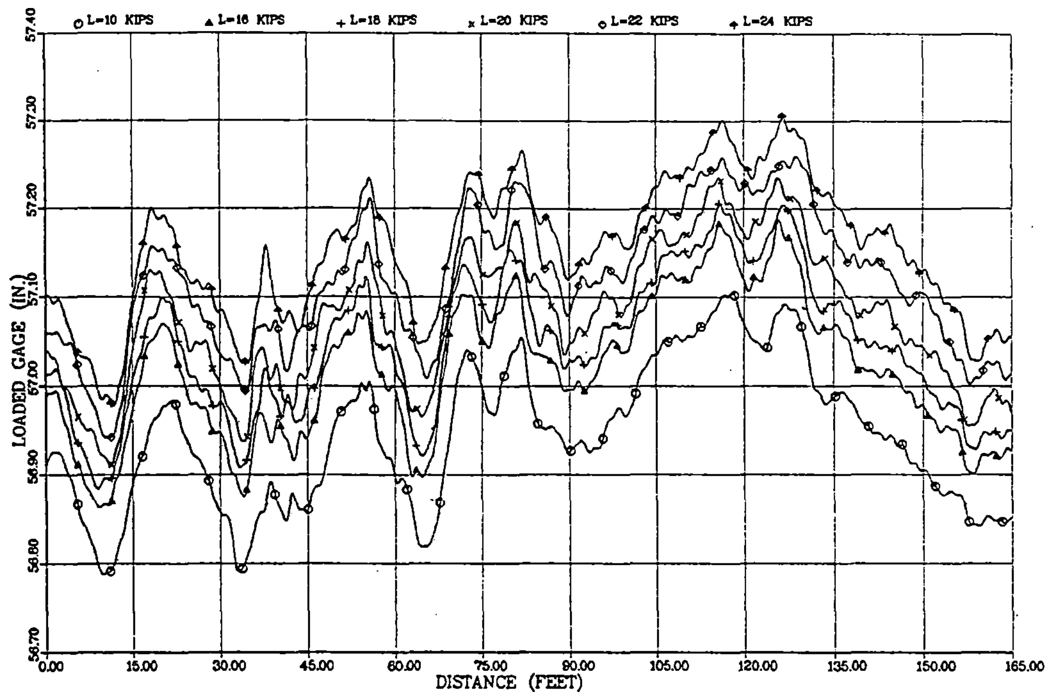

Exhibit A23. Loaded Gage Distance History, Tangent Track (Section 33), Concrete Ties-Wood/Pandrol-Wood/4-Cut Spikes Grouped, V=39 Kips.

9.2 Appendix-B Average Magnitude Plots

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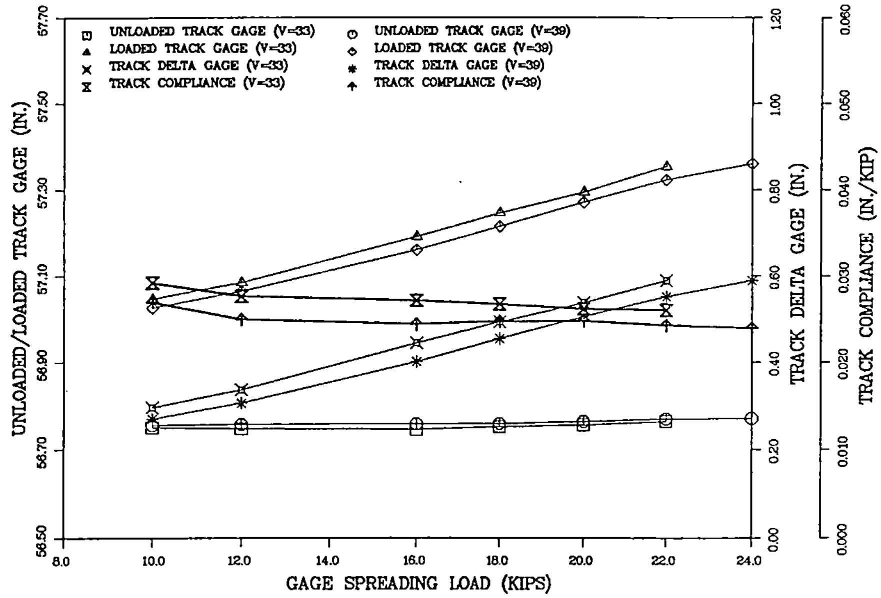

Exhibit B1. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Spreading Load, 5-Degree Curve(Section 3(1)), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

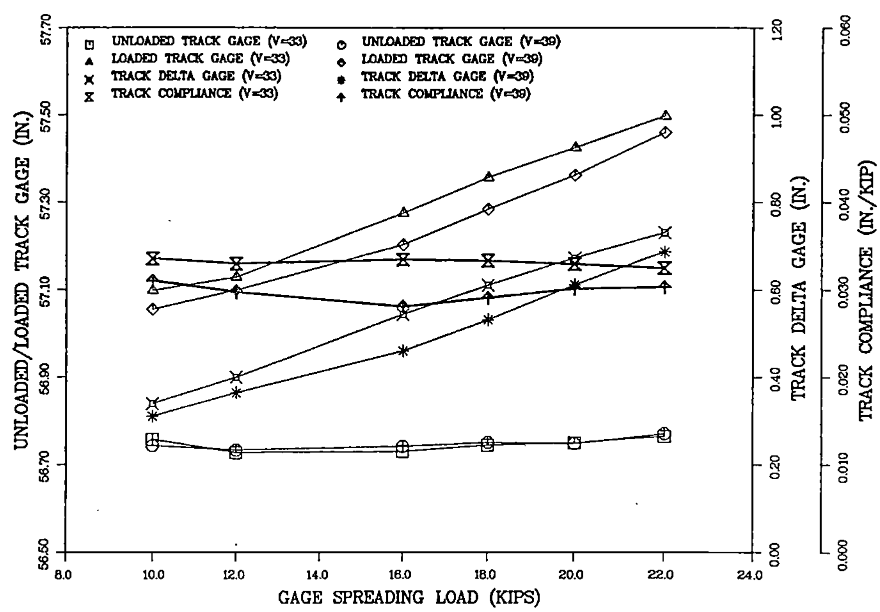

Exhibit B2. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Spreading Load, 5-Degree Curve(Section 3(3)), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

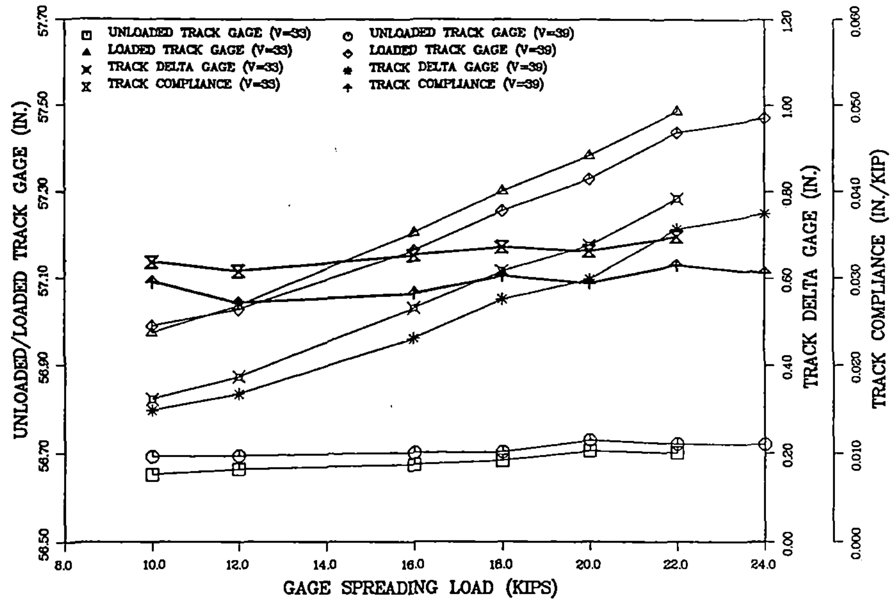

Exhibit B3. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Spreading Load, 5-Degree Curve(Section 7A(2)), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

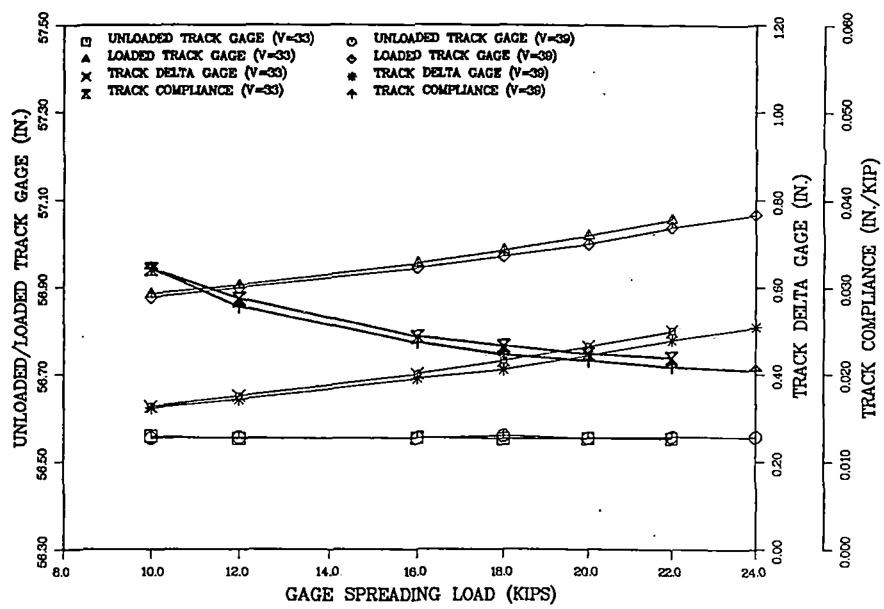

Exhibit B4. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Spreading Load, 6-Degree Curve(Section 25A), Wood Ties/Pandrol Fasteners, V=33 and 39 Kips.

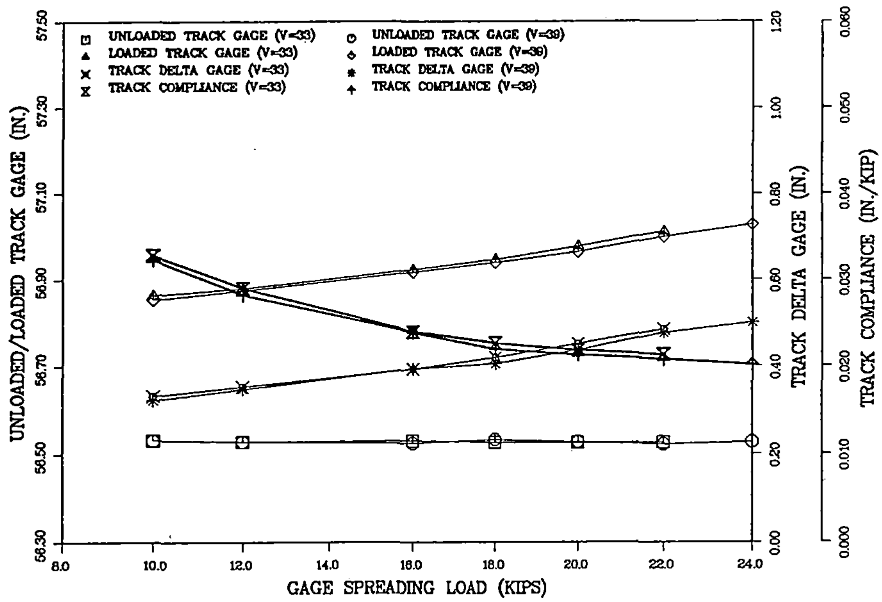

Exhibit B5. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Spreading Load, 6-Degree Curve(Section 25B), Wood Ties/Pandrol Fasteners, V=33 and 39 Kips.

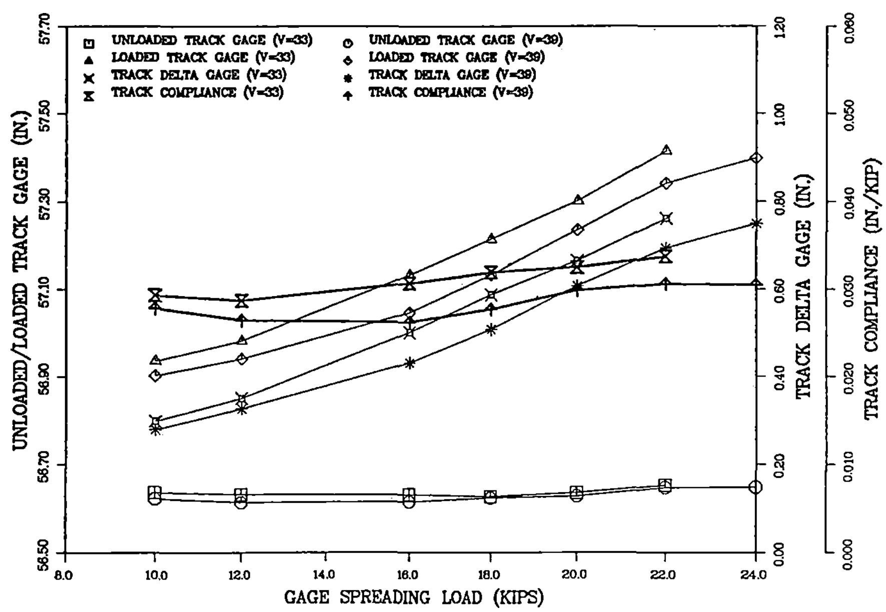

Exhibit B6. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Spreading Load, 6-Degree Curve(Section 25CDE), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

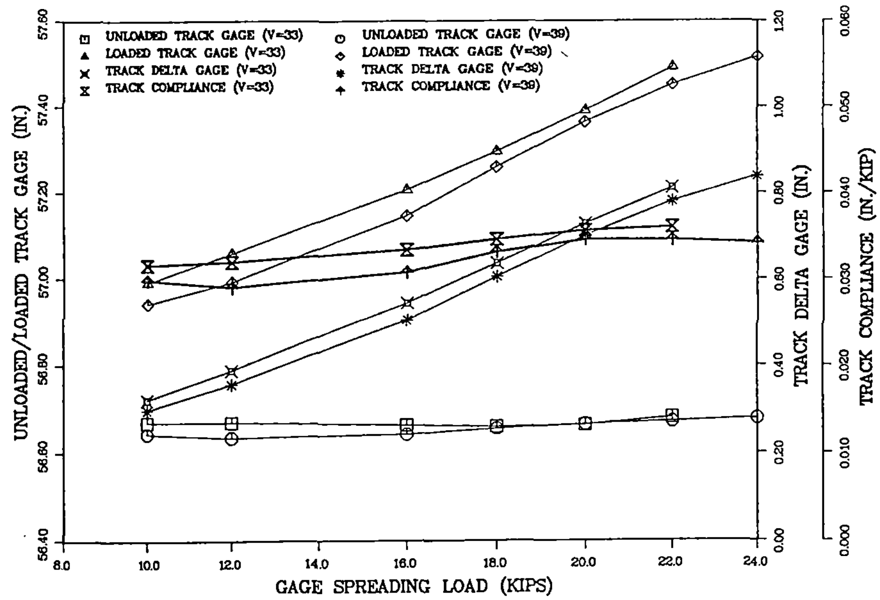

Exhibit B7. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Spreading Load, 6-Degree Curve(Section 25FGH), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

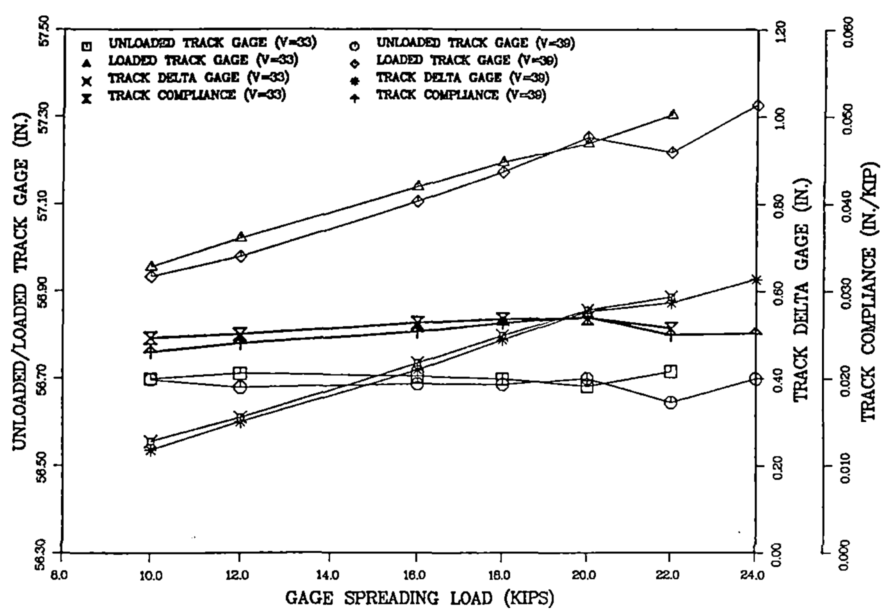

Exhibit B8. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Spreading Load, 6-Degree Curve(Section 25I), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

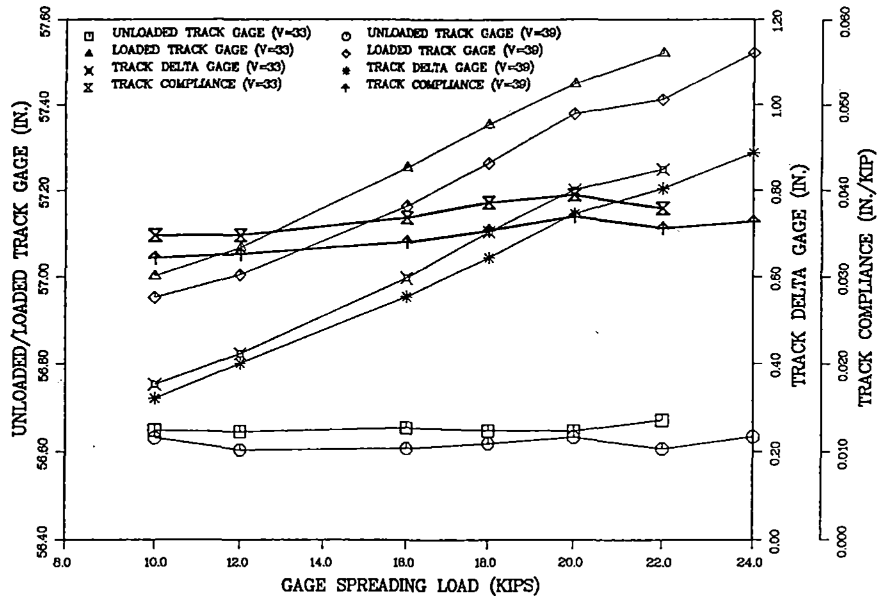

Exhibit B9. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Spreading Load, 6-Degree Curve(Section 25J), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

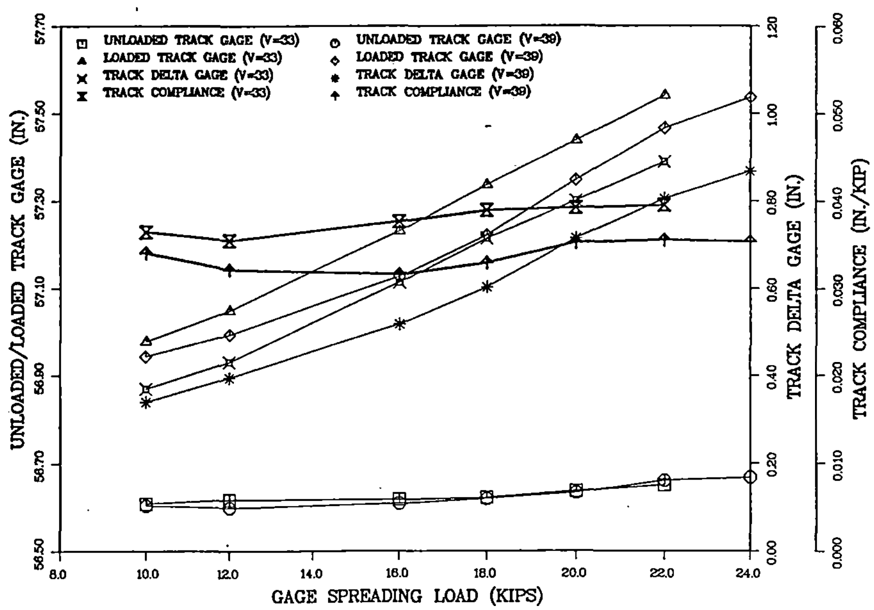

Exhibit B10. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Spreading Load, 6-Degree Curve(Section 25KLMNO), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

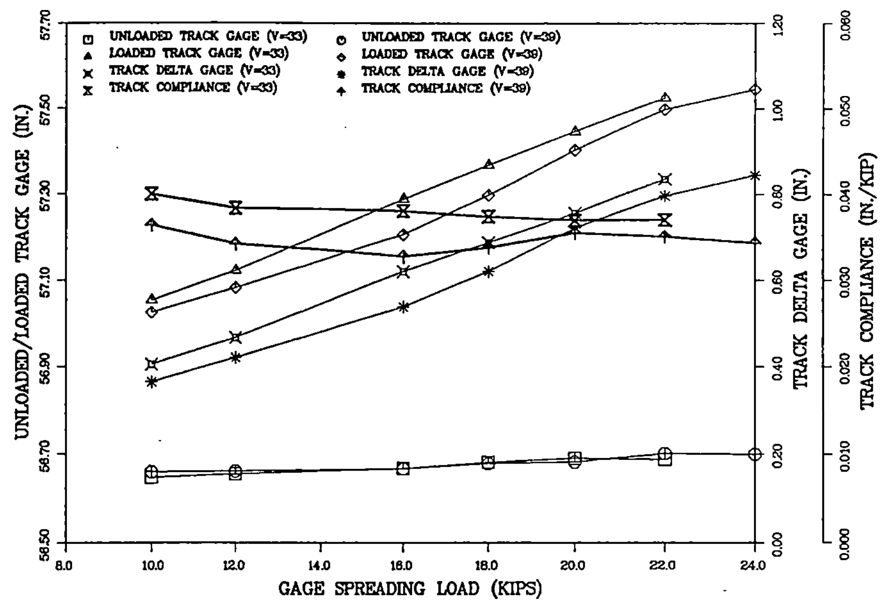

Exhibit B11. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Spreading Load, 6-Degree Curve(Section 25PQ), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

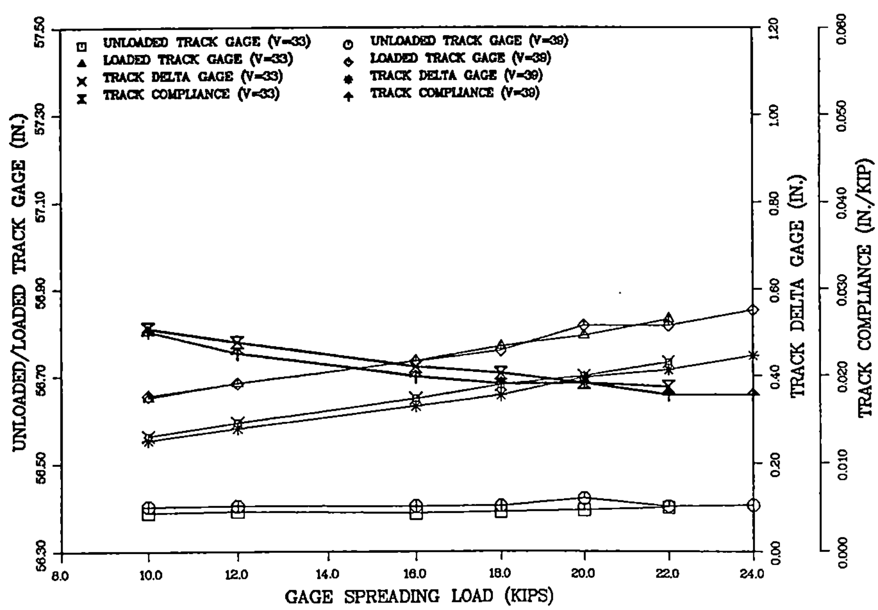

Exhibit B12. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Spreading Load, 6-Degree Curve(Section 25R), Wood Ties/Pandrol Fasteners, V=33 and 39 Kips.

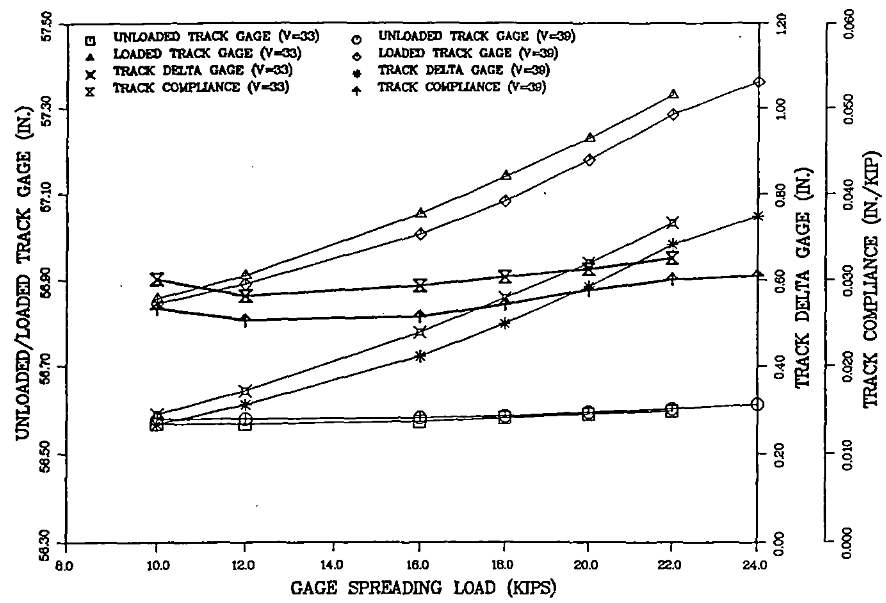

Exhibit B13. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Spreading Load, Tangent Track(Section 29), Wood/Pandrol, V=33 and 39 Kips.

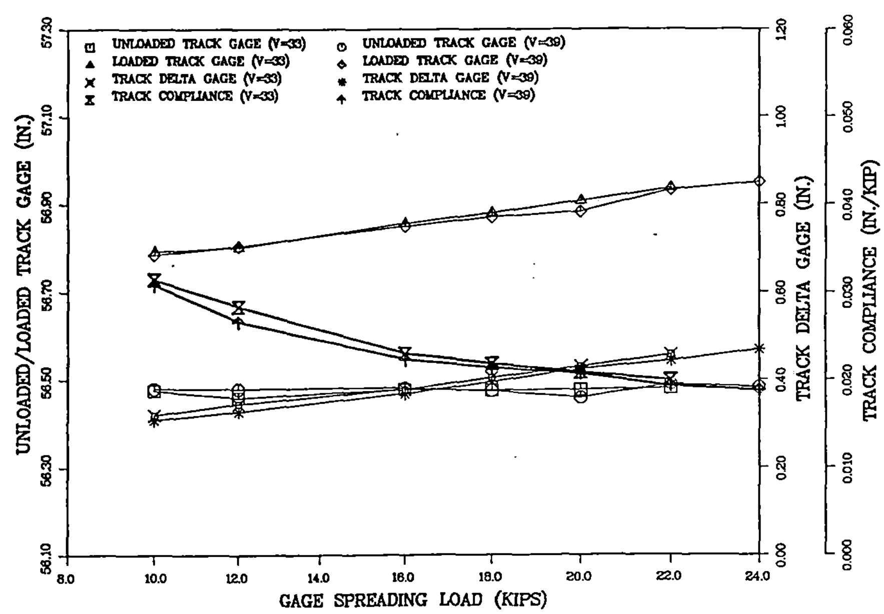

Exhibit B14. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Spreading Load, 5-Degree Curve(Section 31(2)), Azobe Ties/Elastic Spikes, V=33 and 39 Kips.

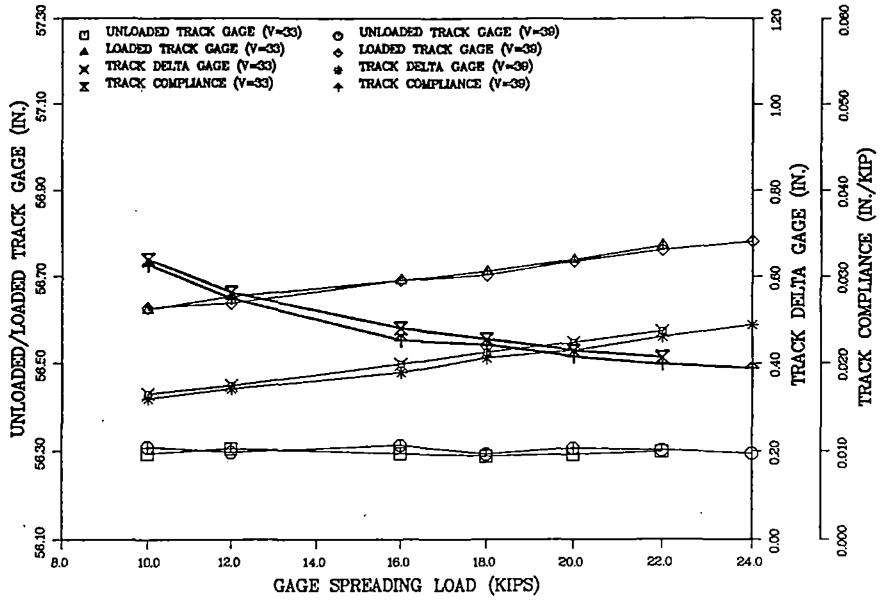

Exhibit B15. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Spreading Load, 5-Degree Curve(Section 31(3)), Azobe Ties/Pandrol Fasteners, V=33 and 39 Kips.

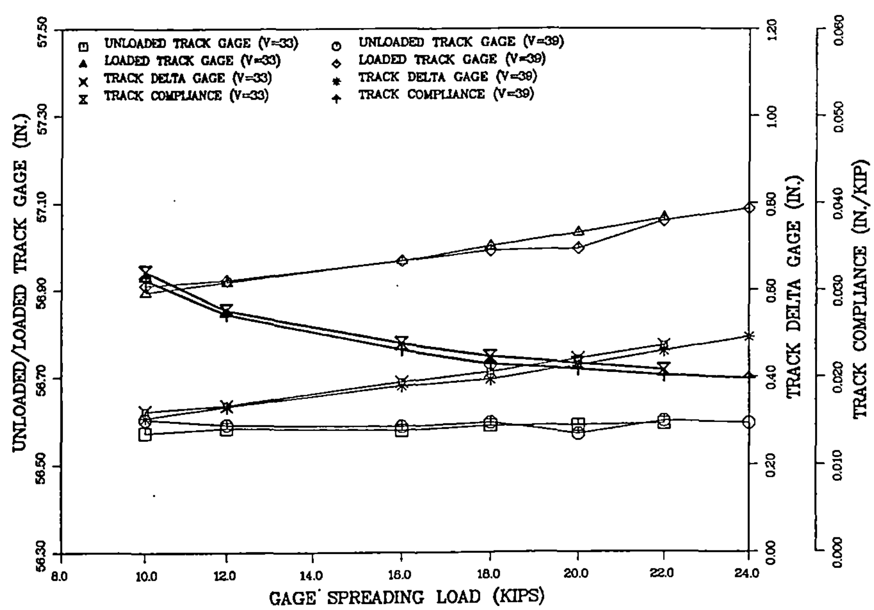

Exhibit B16. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Spreading Load, 5-Degree Curve(Section 31(4)), Concrete Ties, V=33 and 39 Kips.

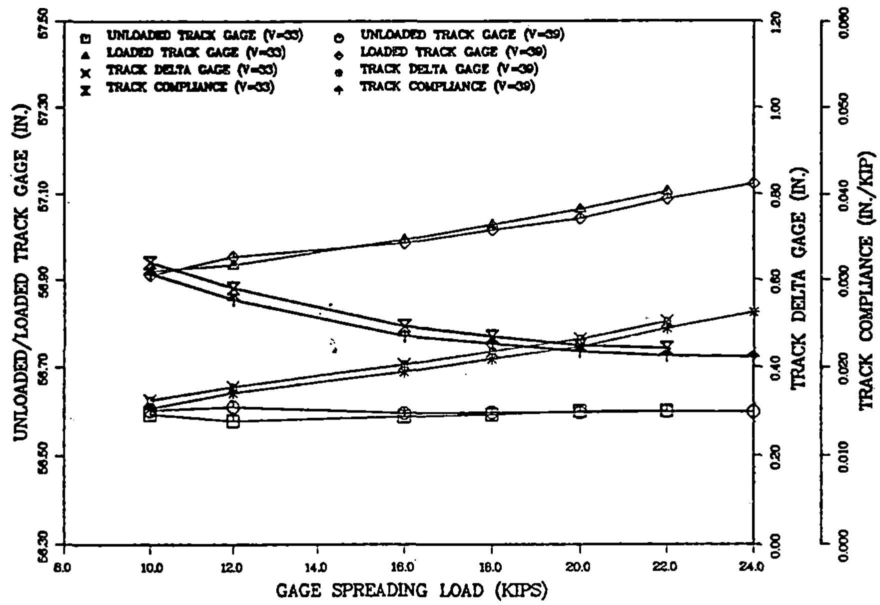

Exhibit B17. Unloaded, Loaded and Delta Gages, and Track Compliance versus Gage Spreading Load, Tangent Track(Section 33), Concrete Ties-Wood/Pandrol-Wood/4-Cut Spikes Grouped. V=33 and 39 Kips.

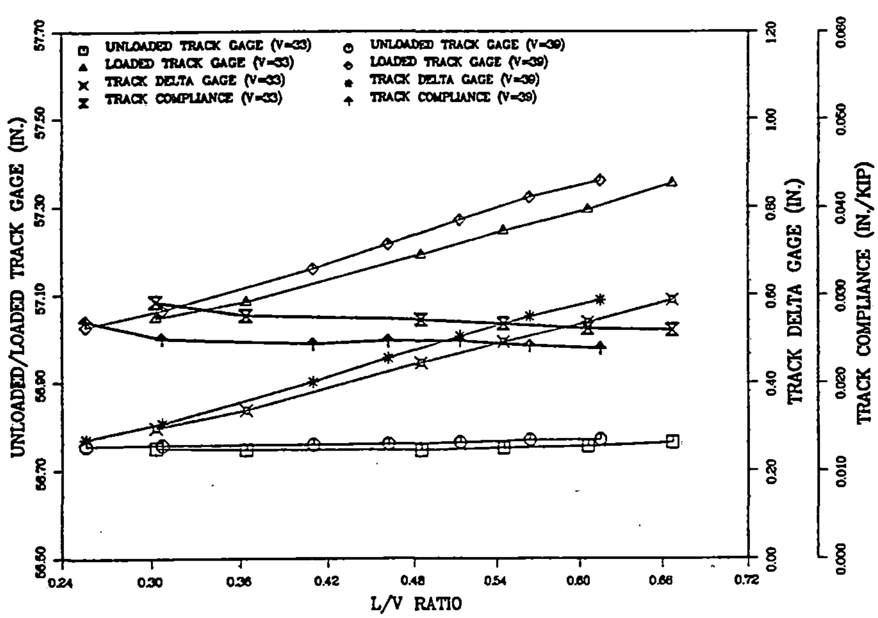

Exhibit B18. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 5-Degree Curve(Section 3(1)), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

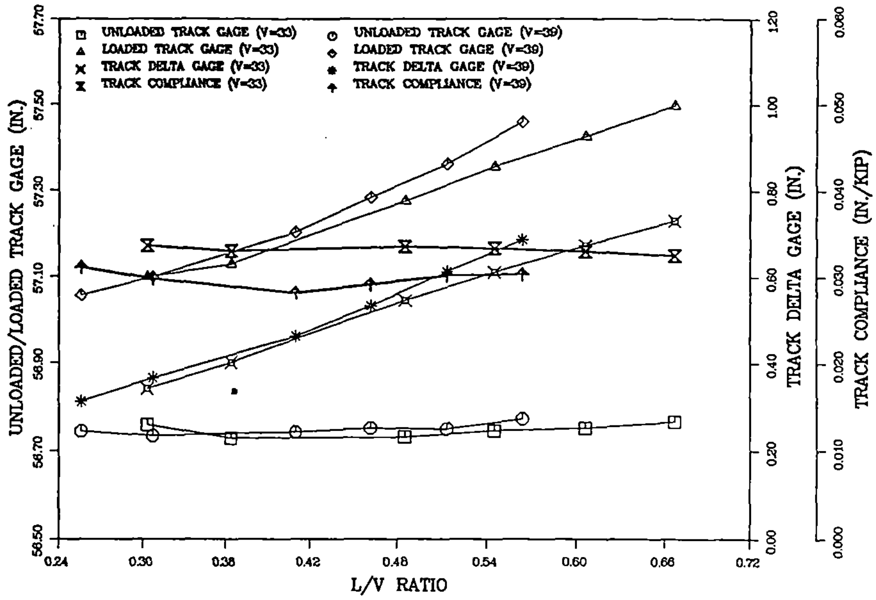

Exhibit B19. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 5-Degree Curve(Section 3(3)), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

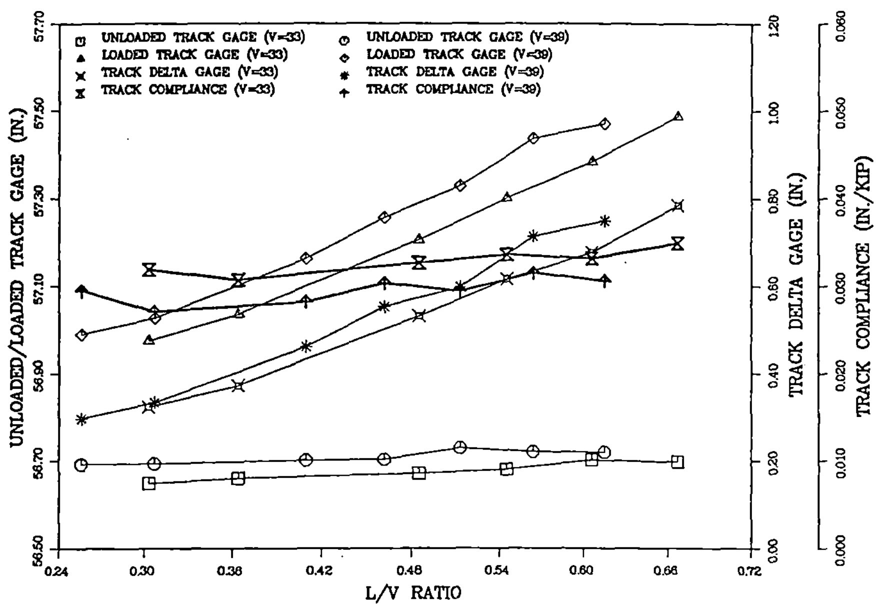

Exhibit B20. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 5-Degree Curve(Section 7A(2)), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

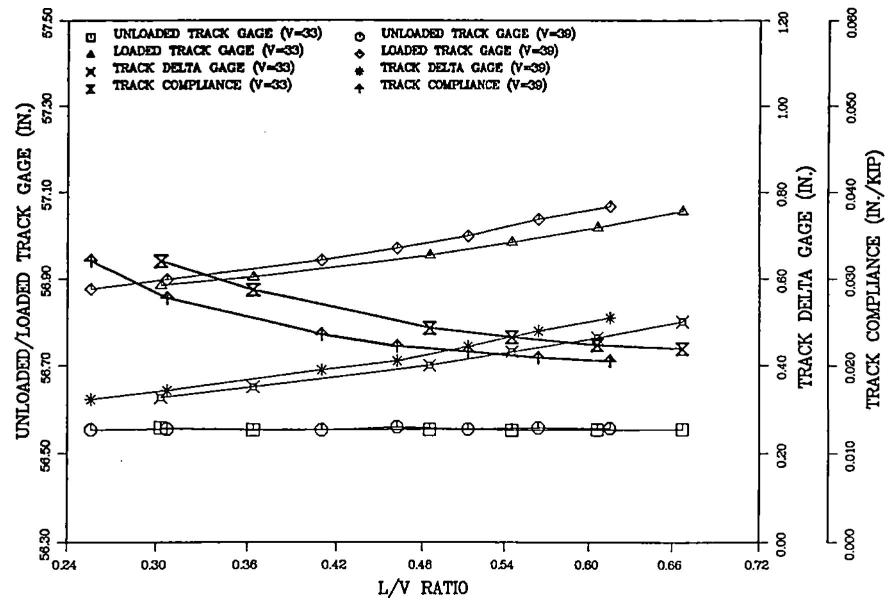

Exhibit B21. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 6-Degree Curve(Section 25A), Wood Ties/Pandrol Fasteners, V=33 and 39 Kips.

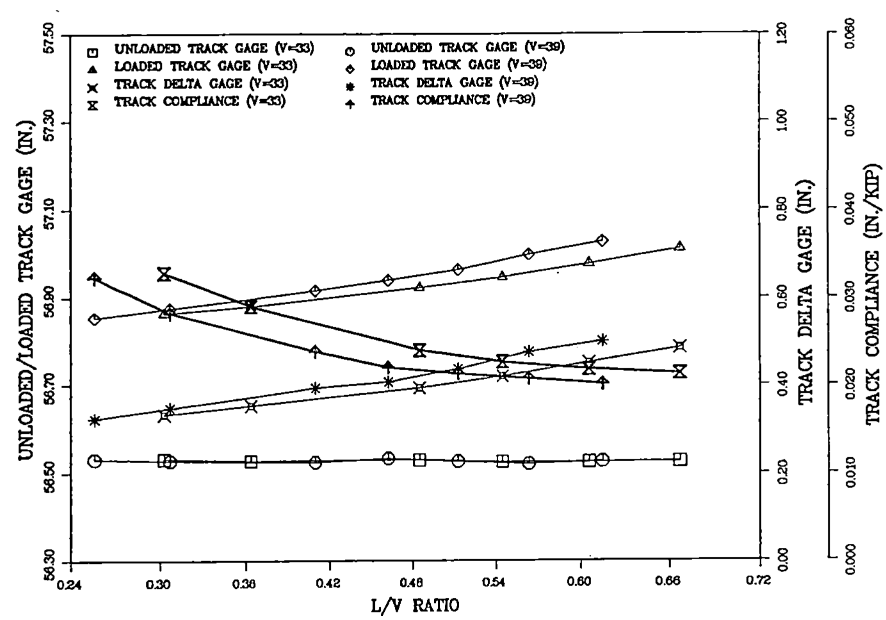

Exhibit B22. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 6-Degree Curve(Section 25B), Wood Ties/Pandrol Fasteners, V=33 and 39 Kips.

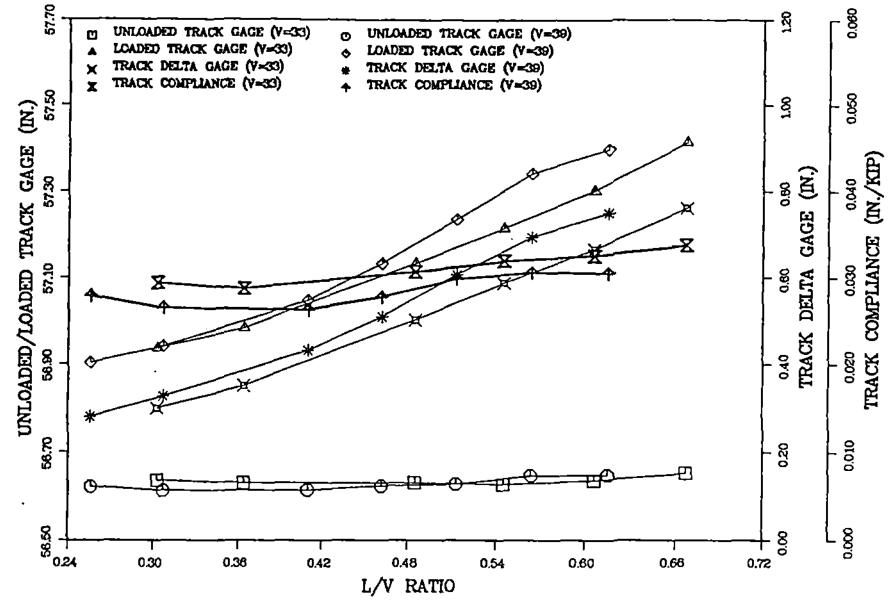

Exhibit B23. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 6-Degree Curve(Section 25CDE), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

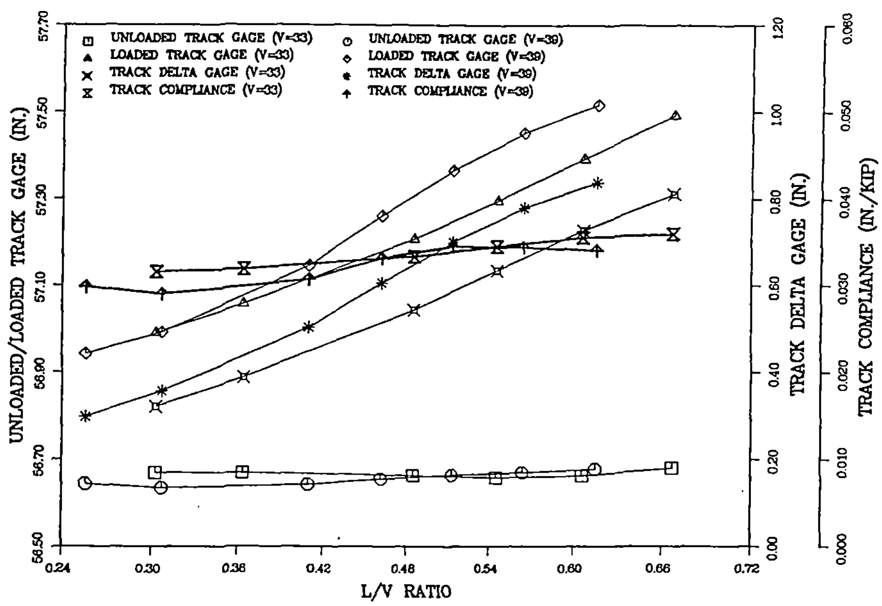

Exhibit B24. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 6-Degree Curve(Section 25FGH), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

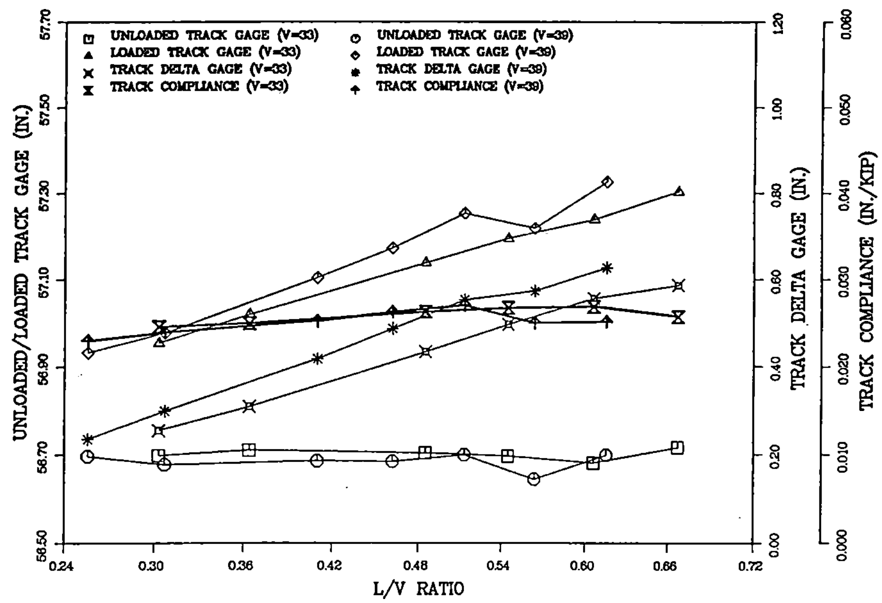

Exhibit B25. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 6-Degree Curve(Section 25I), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

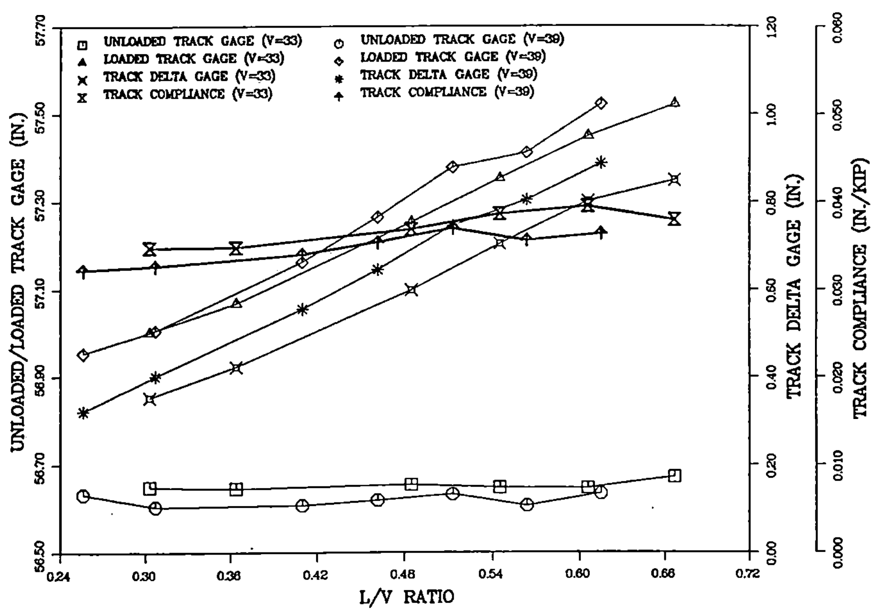

Exhibit B26. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 6-Degree Curve(Section 25J), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

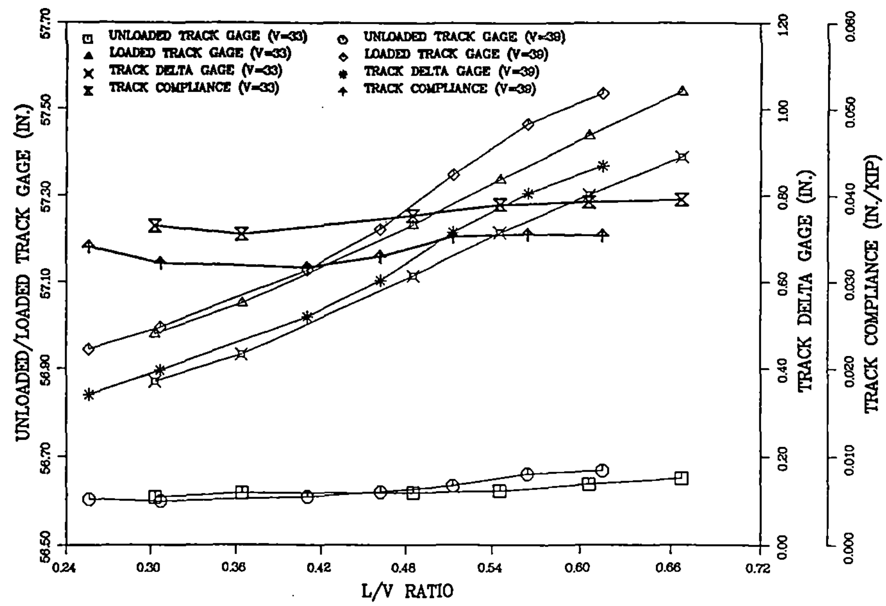

Exhibit B27. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 6-Degree Curve(Section 25KLMNO), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

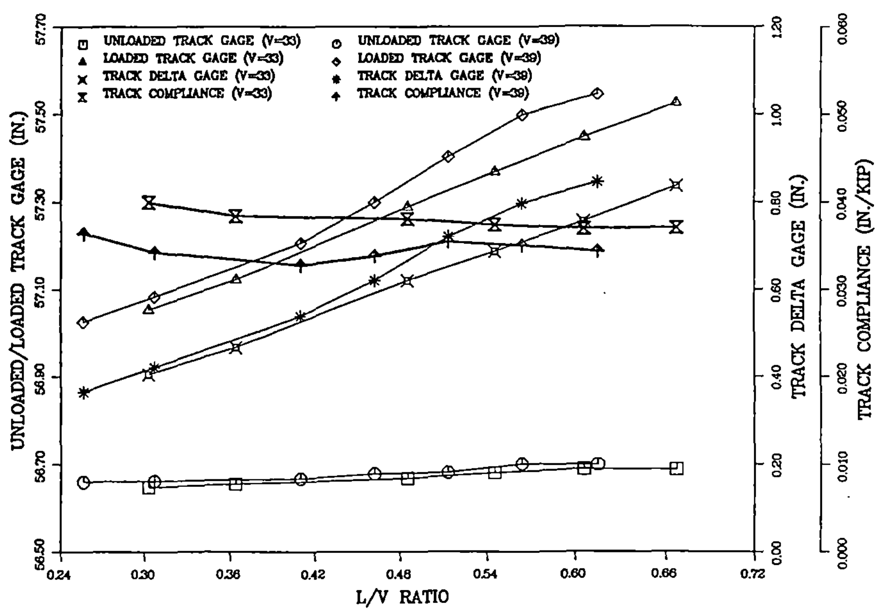

Exhibit B28. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 6-Degree Curve(Section 25PQ), Wood Ties/4-Cut Spikes, V=33 and 39 Kips.

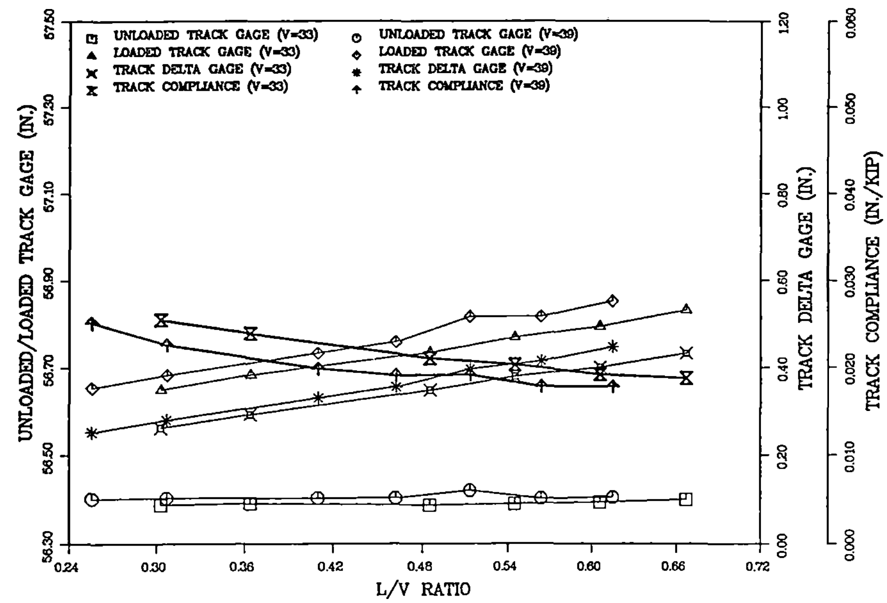

Exhibit B29. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 6-Degree Curve(Section 25R), Wood Ties/Pandrol Fasteners, V=33 and 39 Kips.

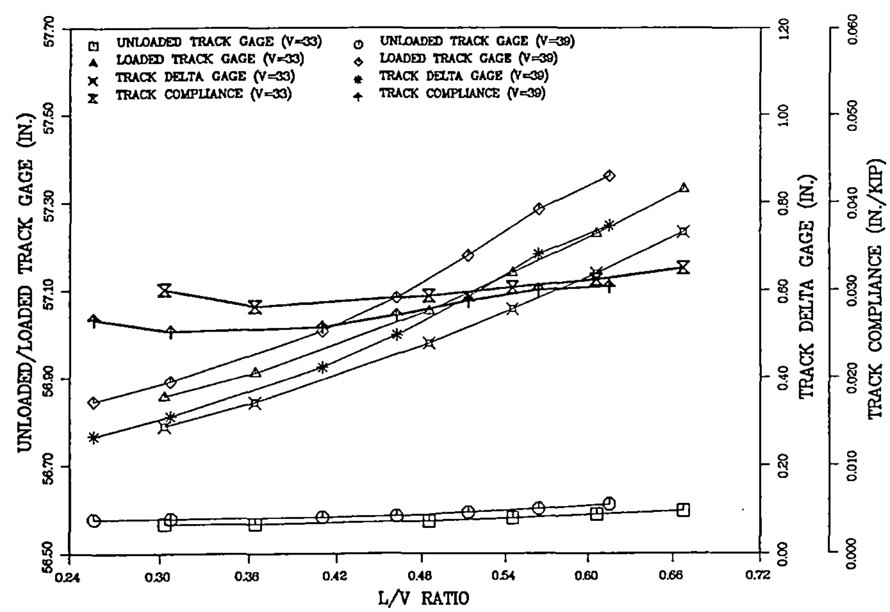

Exhibit B30. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, Tangent Track(Section 29), Wood Ties/Pandrol Fasteners, V=33 and 39 Kips.

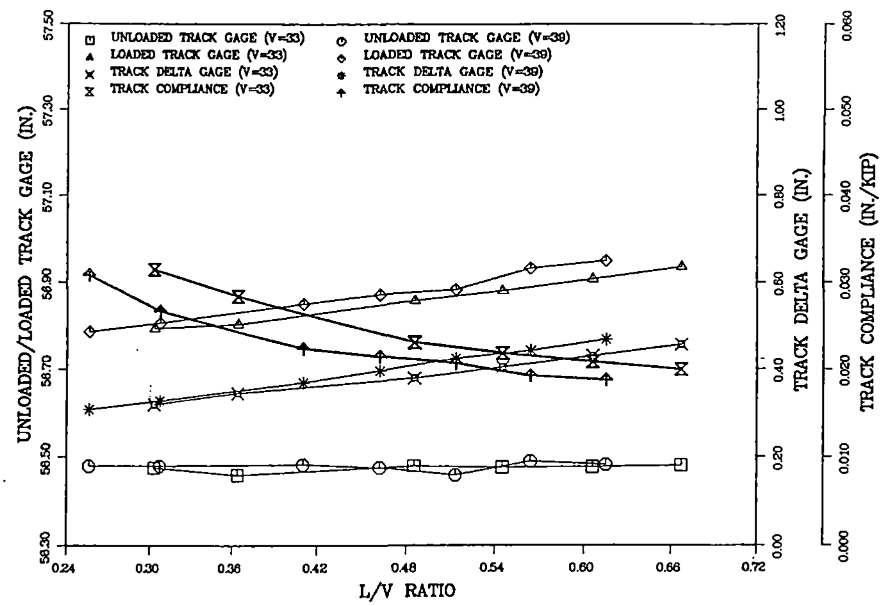

Exhibit B31.. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 5-Degree Curve(Section 31(2)), Azobe Ties/Elastic Spikes, V=33 and 39 Kips.

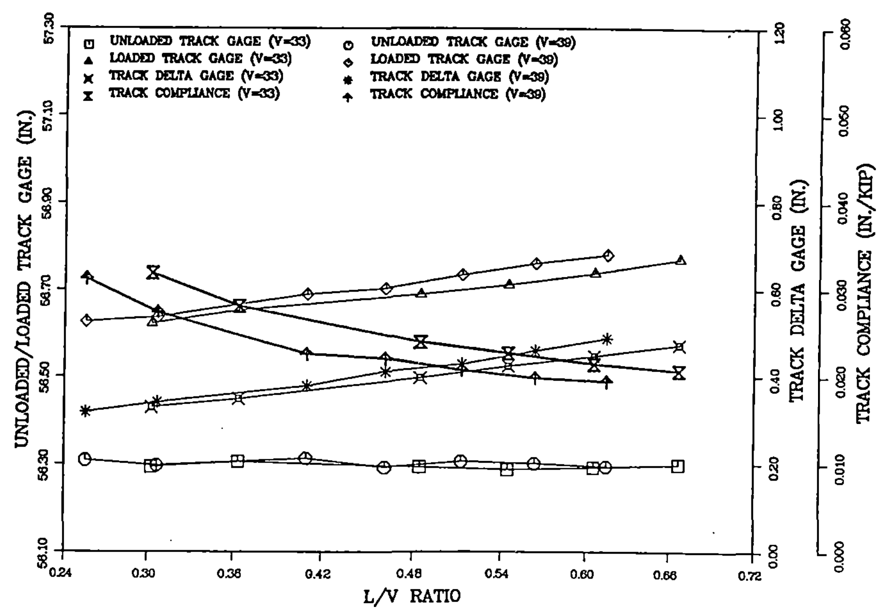

Exhibit B32. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 5-Degree Curve(Section 31(3)), Azobe Ties/Pandrol Fasteners, V=33 and 39 Kips.

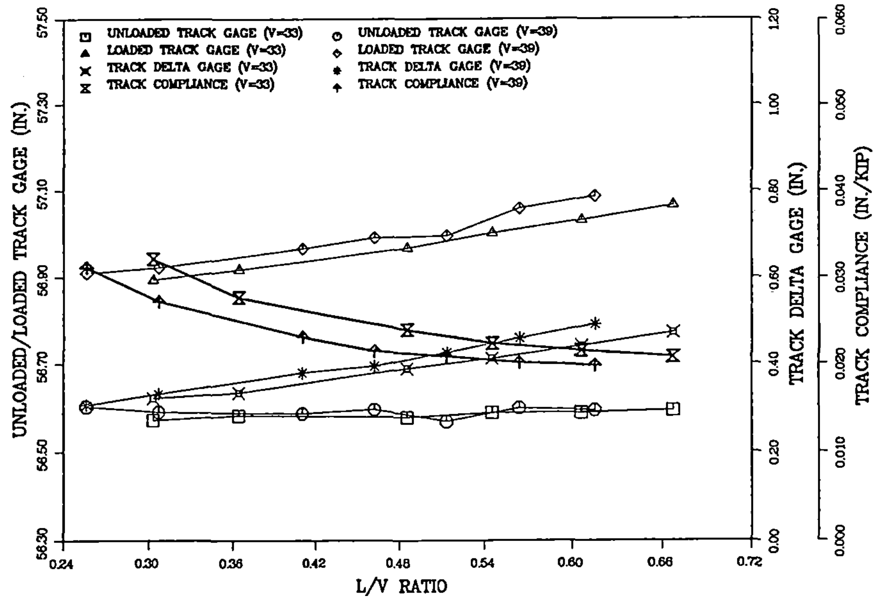

Exhibit B33. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, 5-Degree Curve(Section 31(4)), Concrete Ties, V=33 and 39 Kips.

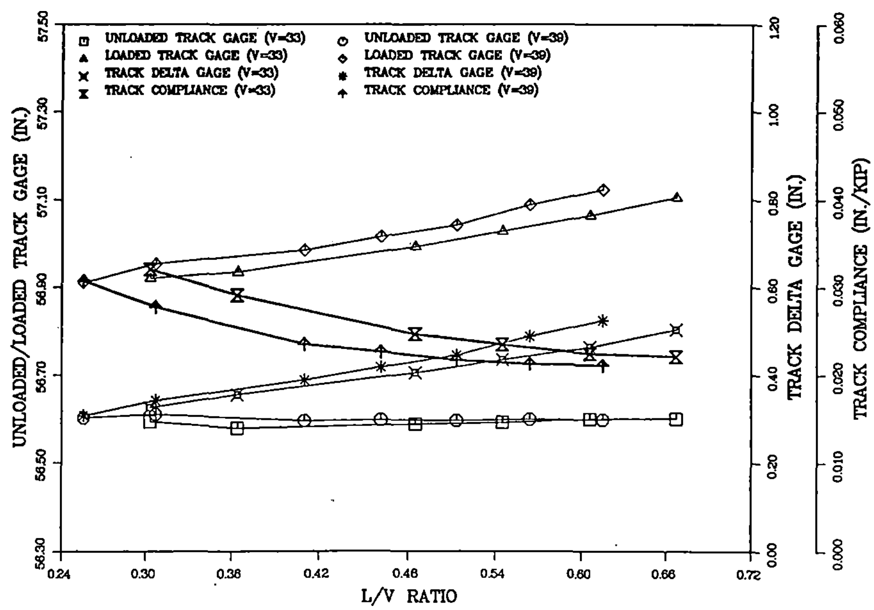

Exhibit B34. Unloaded, Loaded and Delta Gages, and Track Compliance versus L/V Ratio, Tangent Track(Section 33), Concrete Ties-Wood/Pandrol-Wood/Cut Spikes Grouped, V=33 and V=39 Kips.append b-add

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9.3 Appendix-C Percentage Level Exceedance Plots With Respect To Gage Widening Loads

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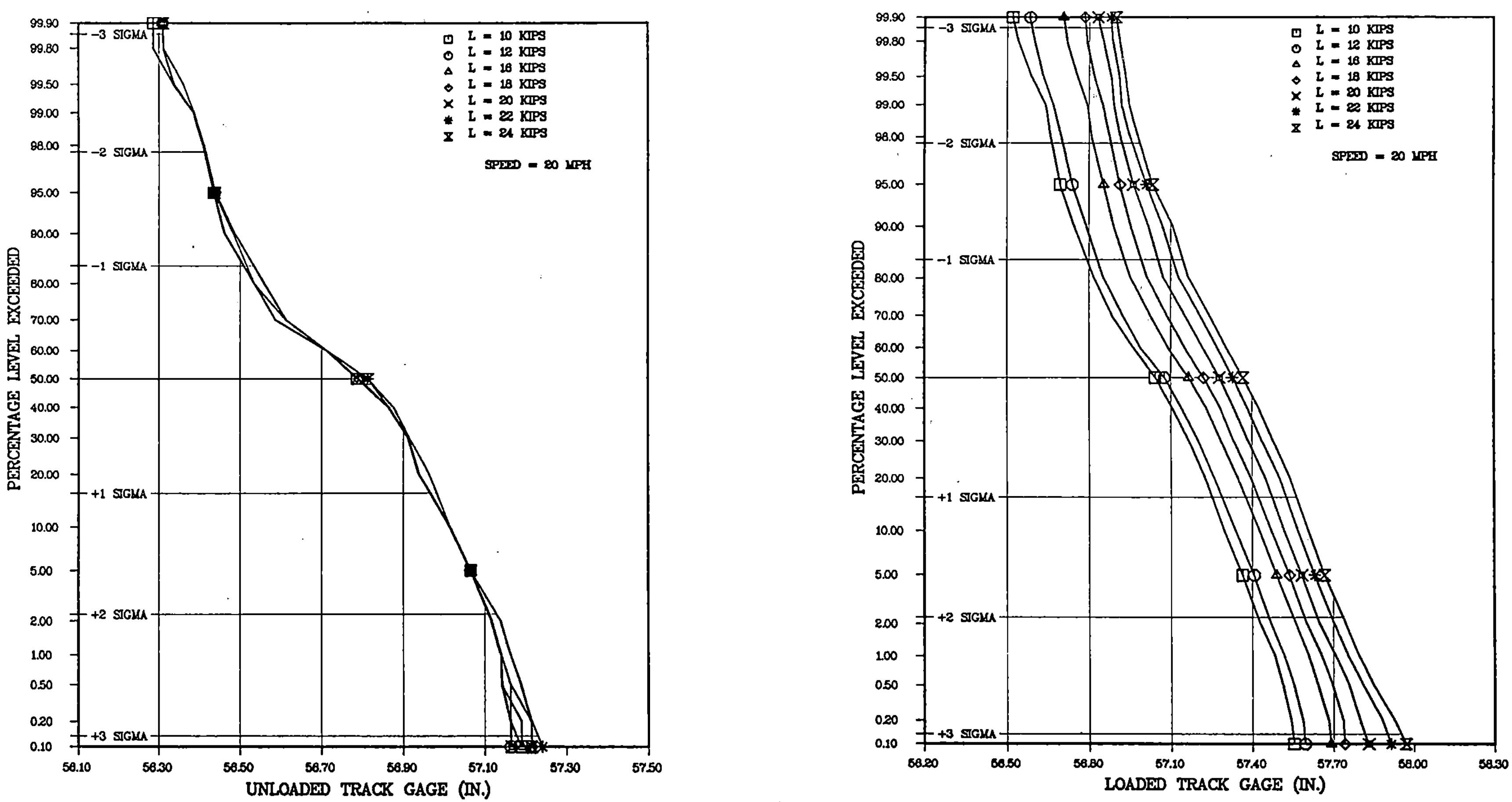
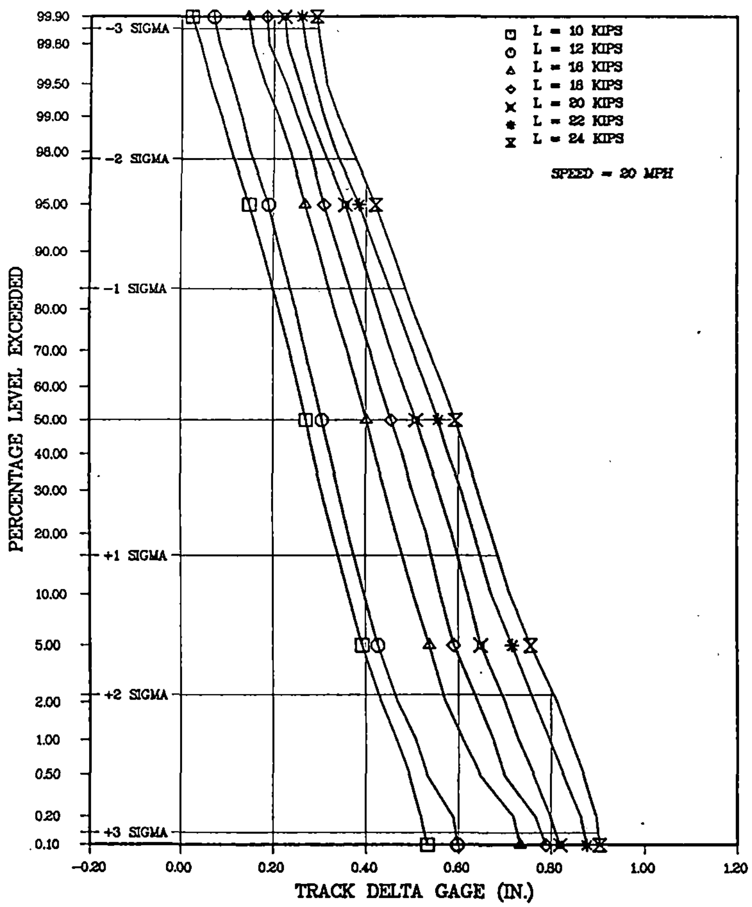


Exhibit **C1.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 3(1)), Wood Ties/ 4-Cut Spikes. V=39 Kips.



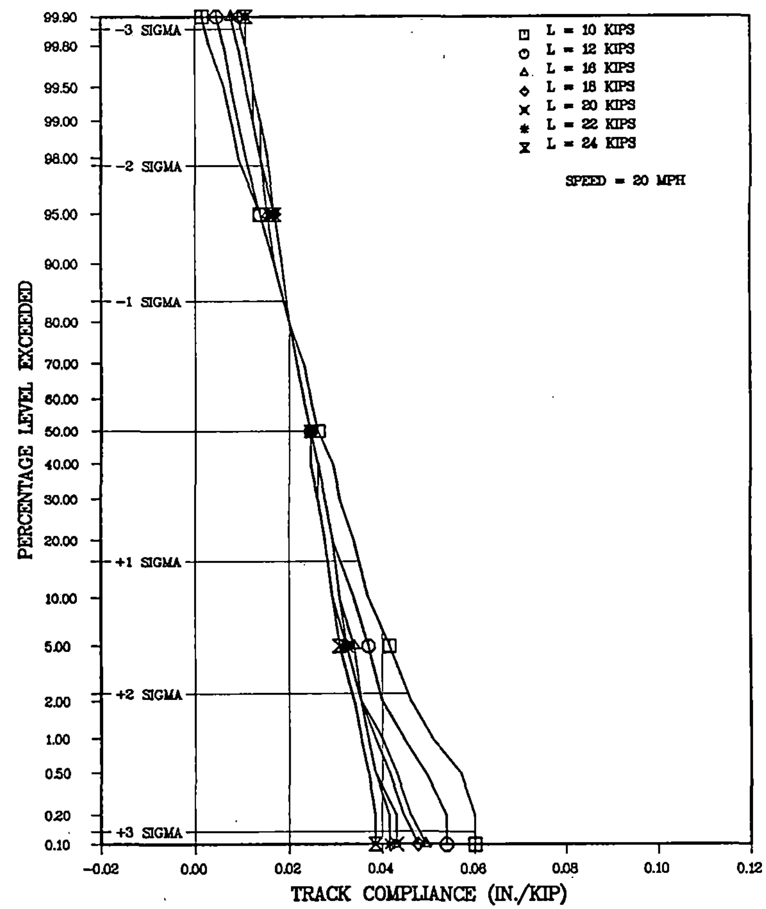
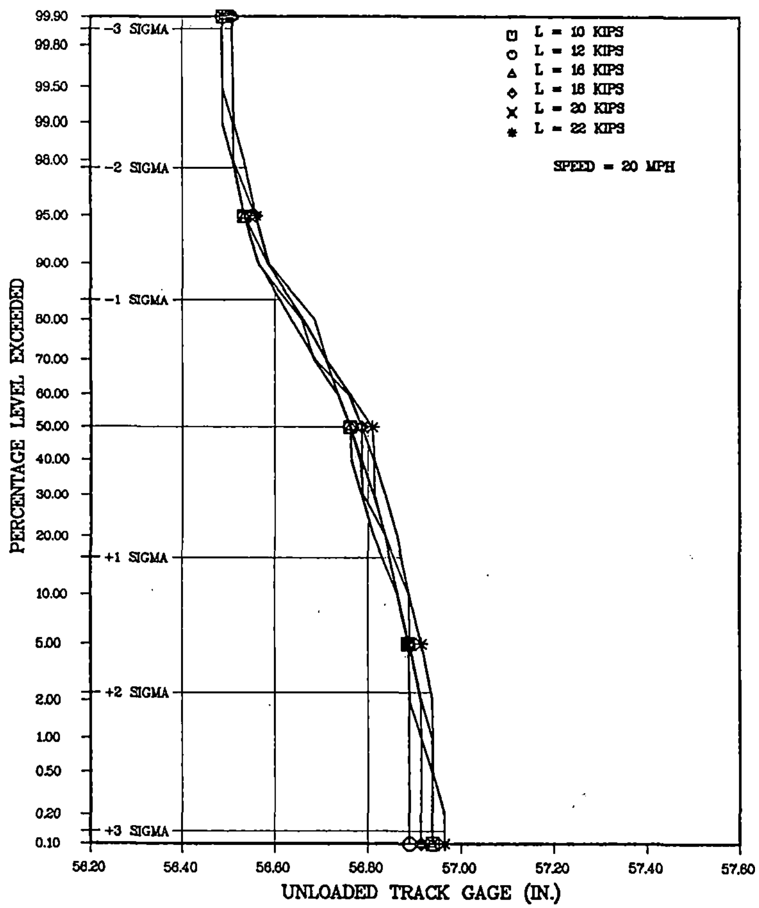


Exhibit **C2.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 3(1)), Wood Ties/4-Cut Spikes, V=39 Kips.



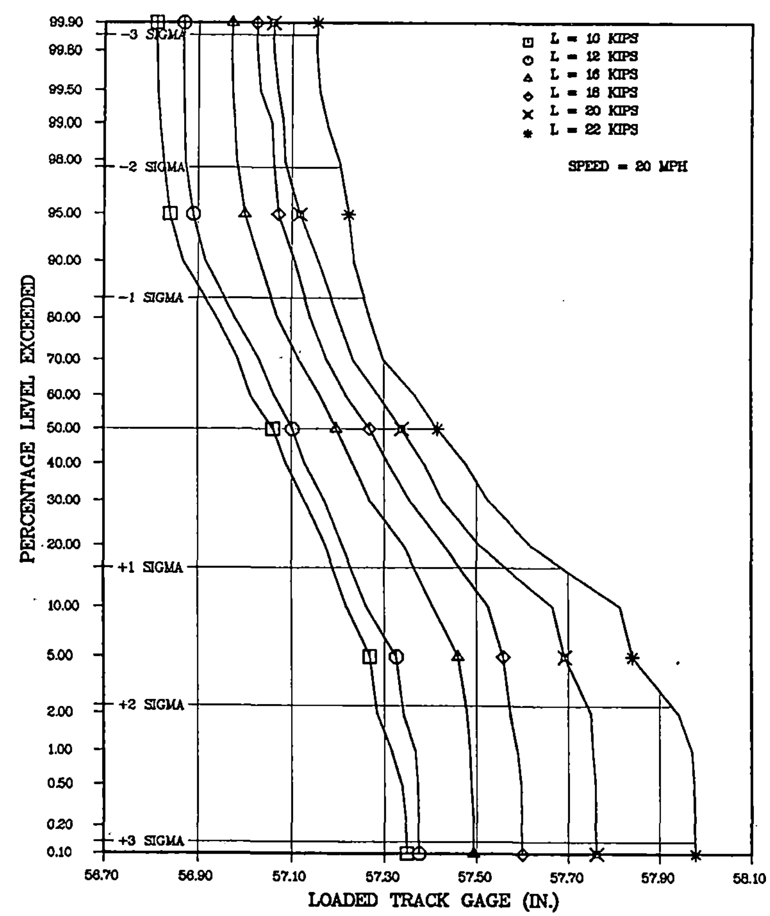
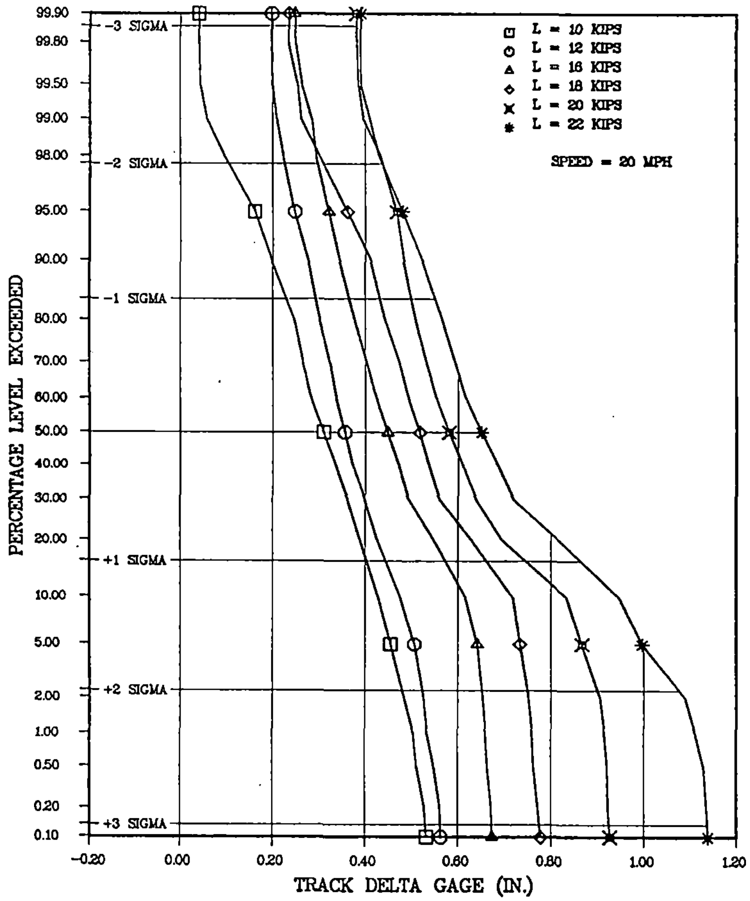


Exhibit **C3.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 3(3)), Wood Ties/ 4-Cut Spikes, V=39 Kips.



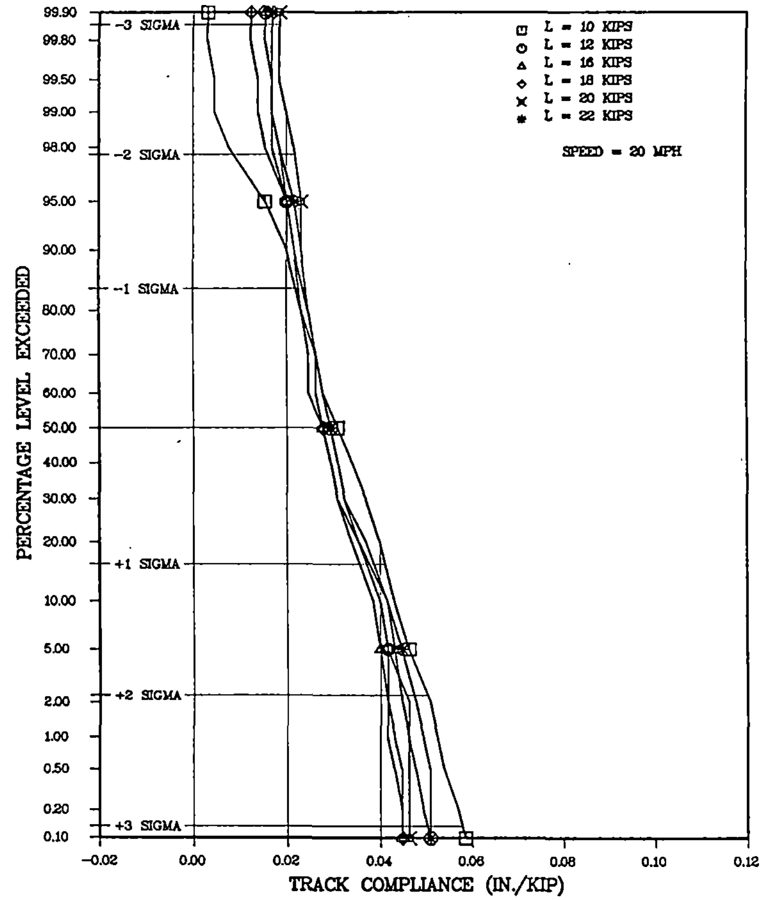
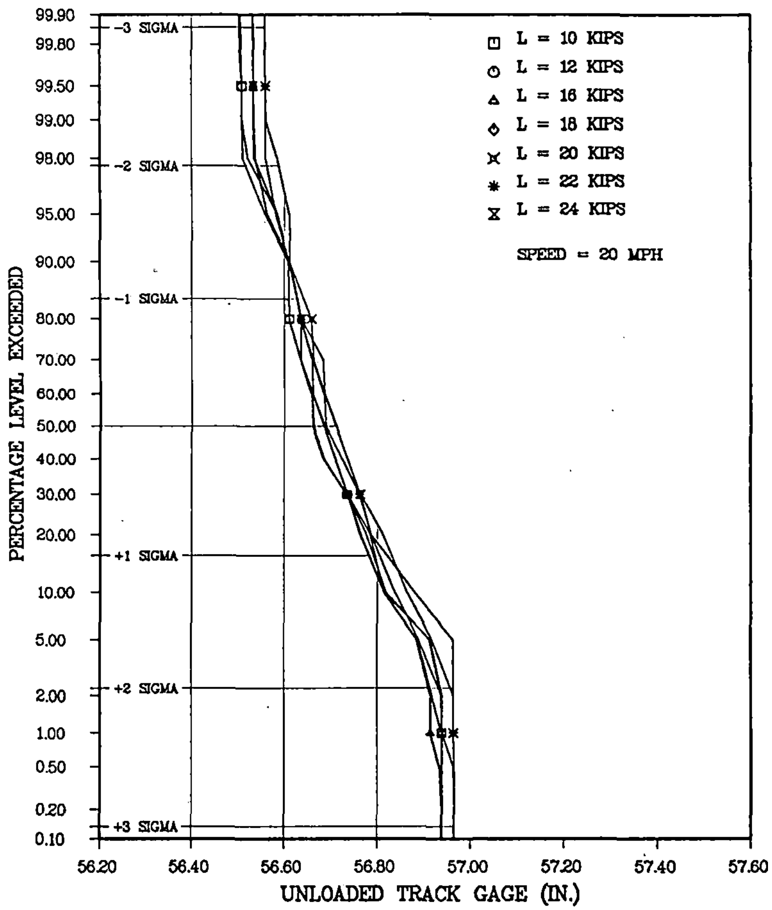


Exhibit **C4.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 3(3)), Wood Ties/ 4-Cut Spikes, V=39 Kips.



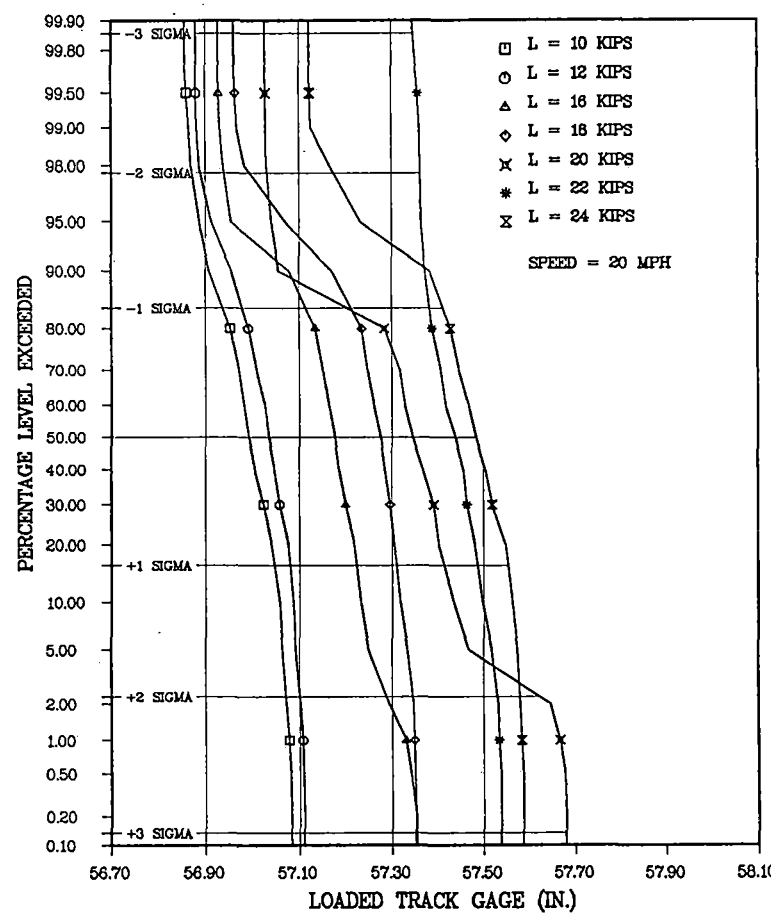


Exhibit **C5.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 7(A2)), Wood Ties/4-Cut Spikes, V=39 Kips.

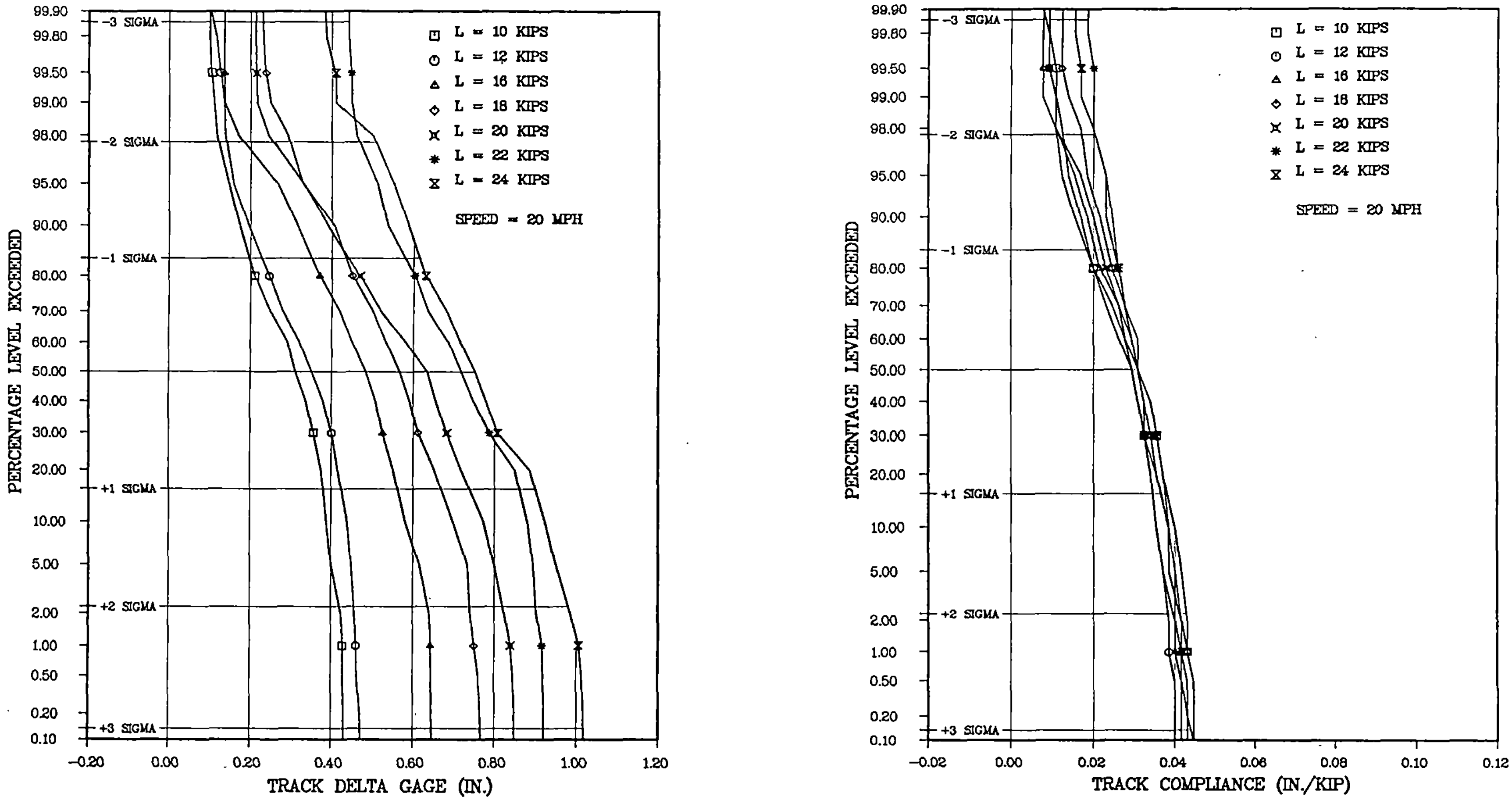


Exhibit **C6.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 7(A2)), Wood Ties/4-Cut Spikes, V=39 Kips.

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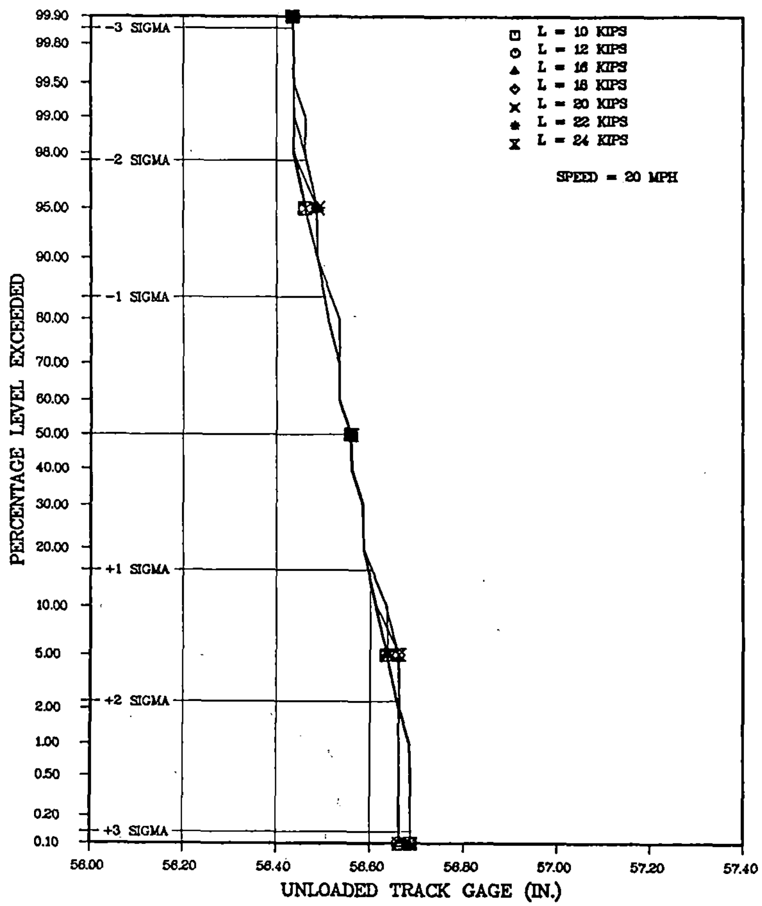


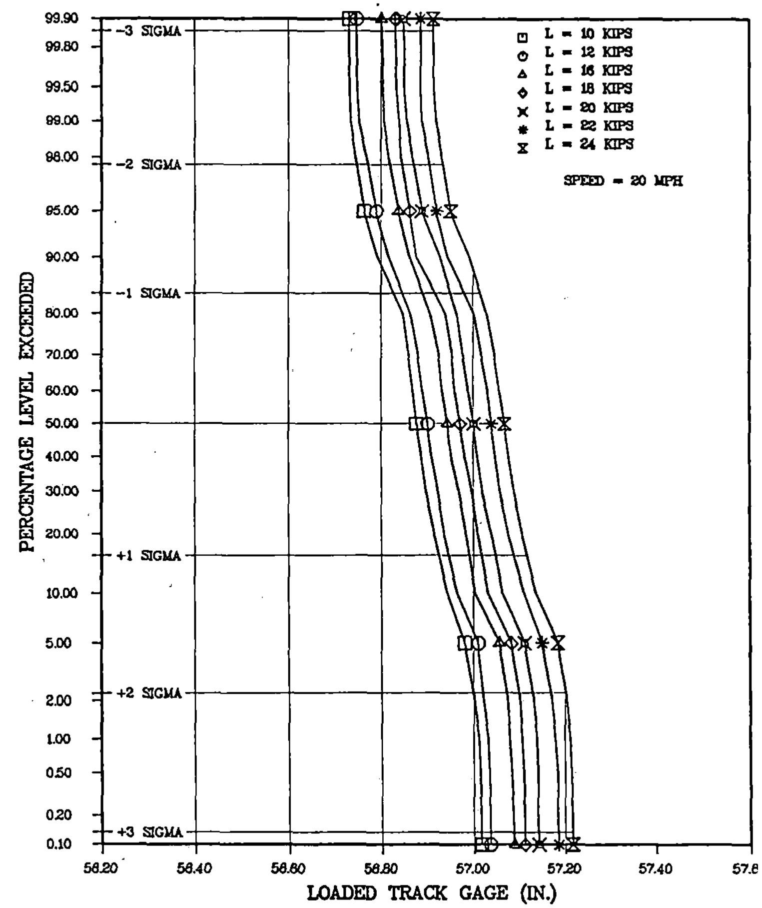
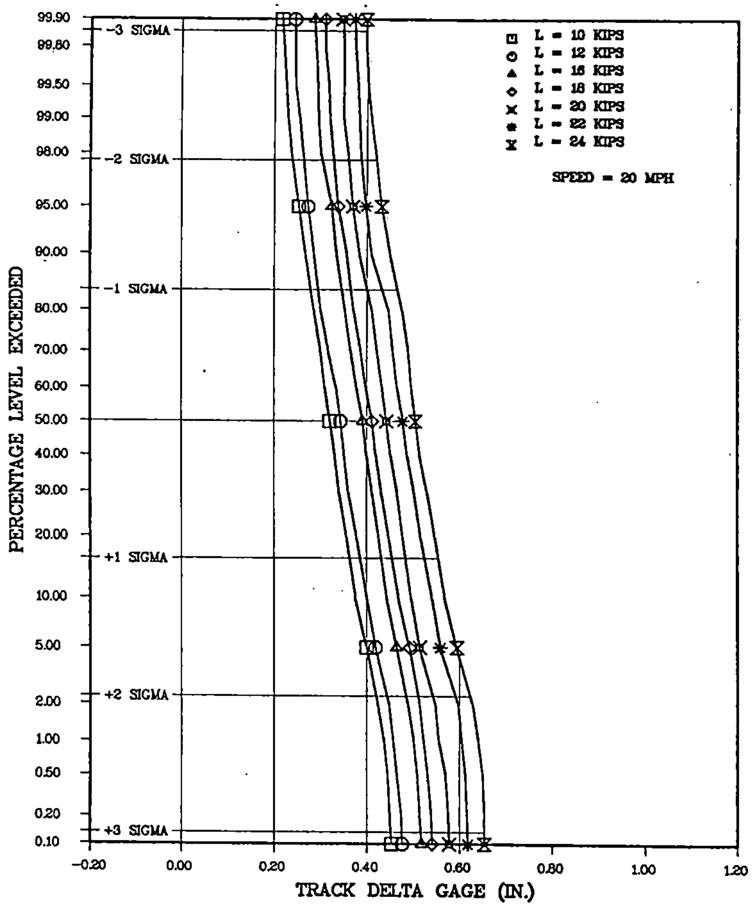


Exhibit **C7.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 6-Degree Curve(Section 25A), Wood Ties/ Pandrol Fasteners, V=39 Kips.



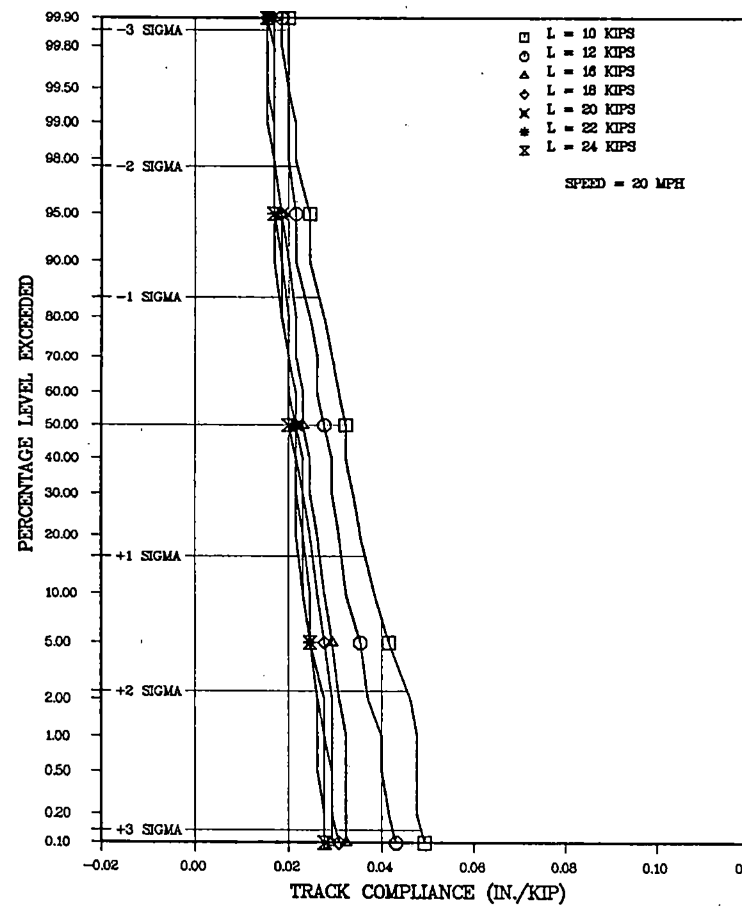
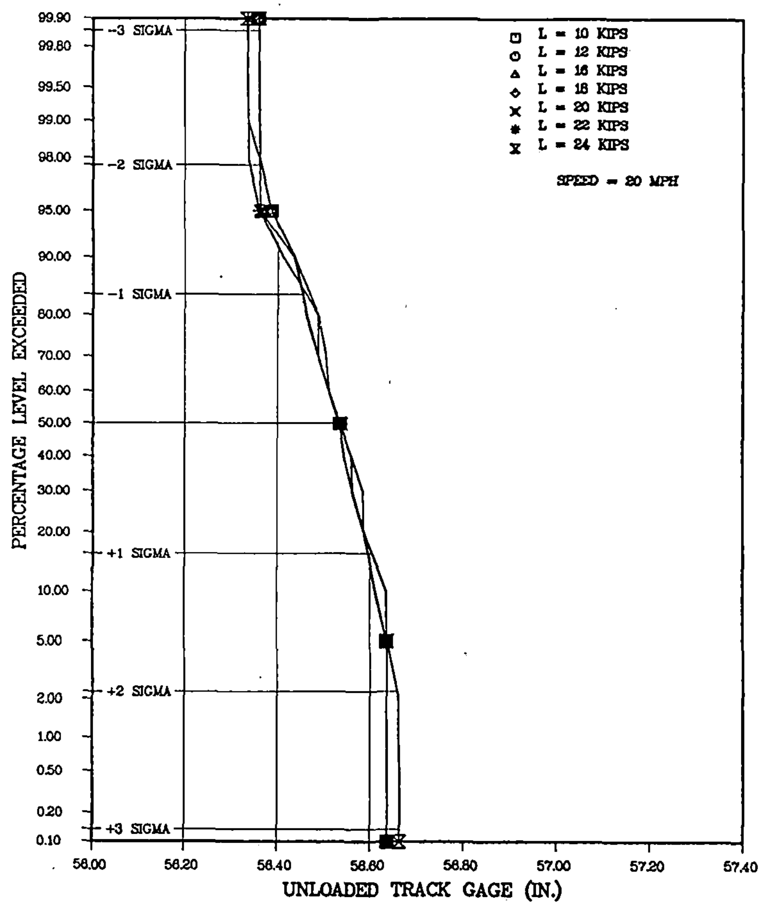


Exhibit **C8.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 6-Degree Curve(Section 25A), Wood Ties /Pandrol Fasteners, V=39 Kips.



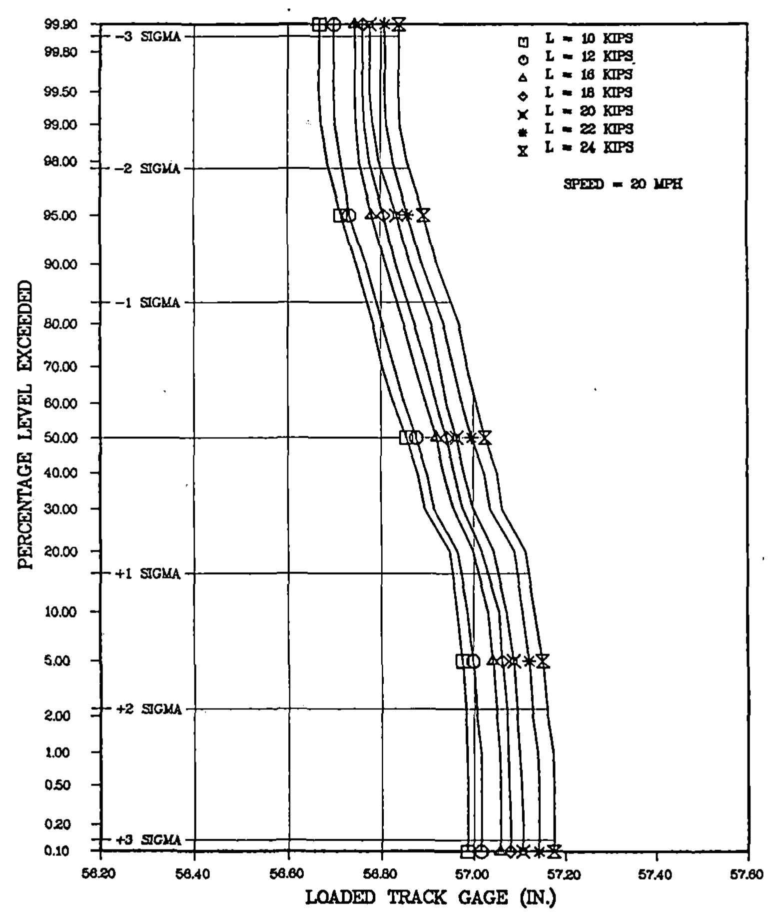
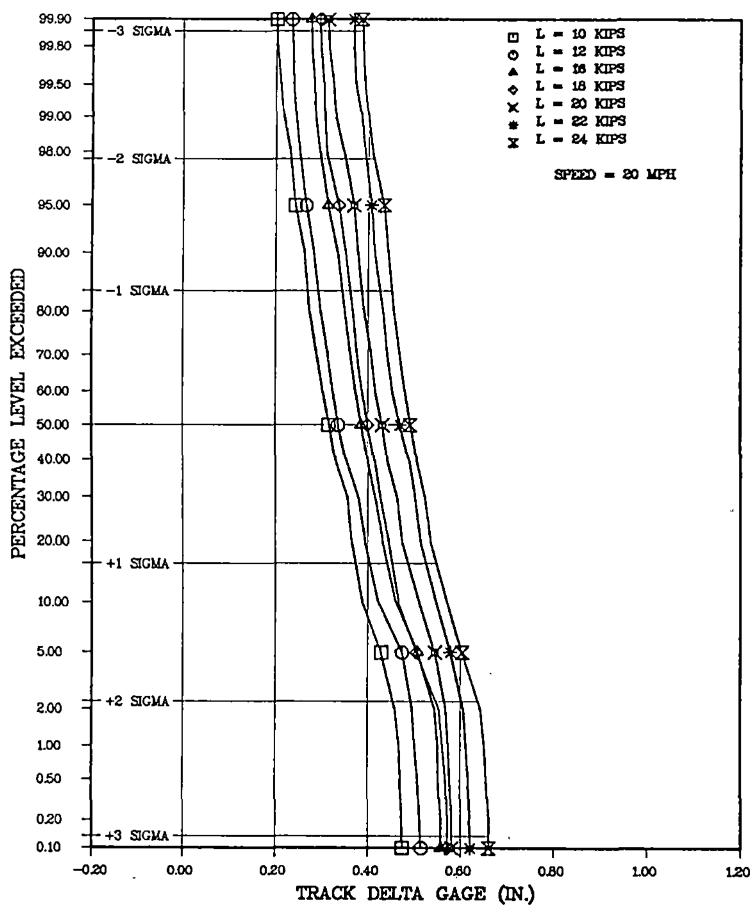


Exhibit **C9.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 6-Degree Curve(Section 25B), Wood Ties/ Pandrol Fasteners, V=39 Kips.



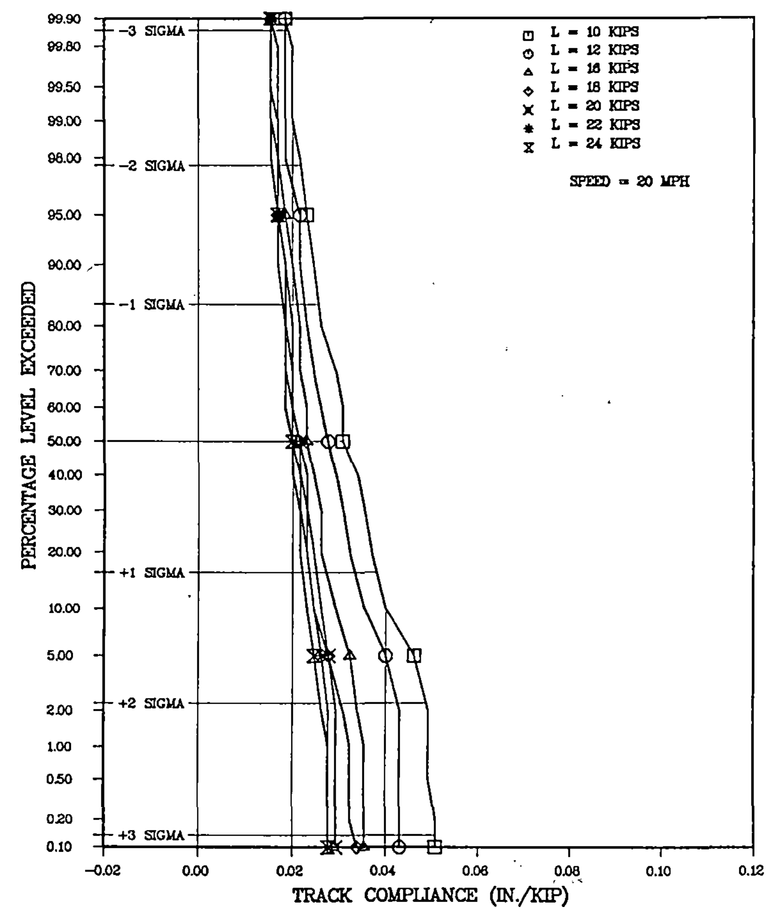
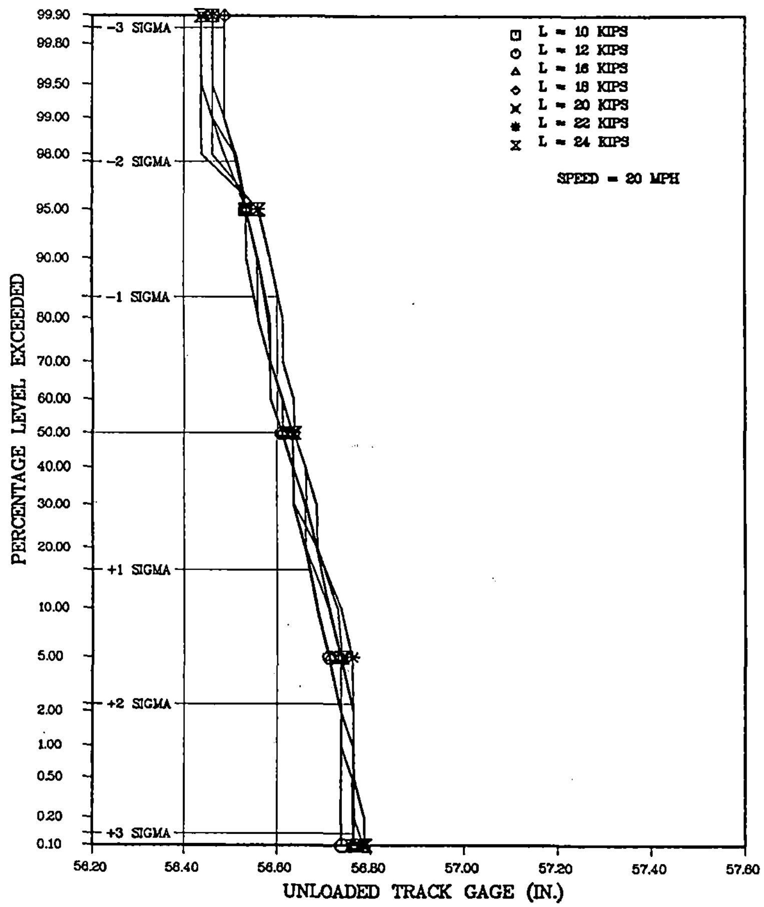


Exhibit **C10.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 6-Degree Curve(Section 25B), Wood Ties/ Pandrol Fasteners, V=39 Kips.



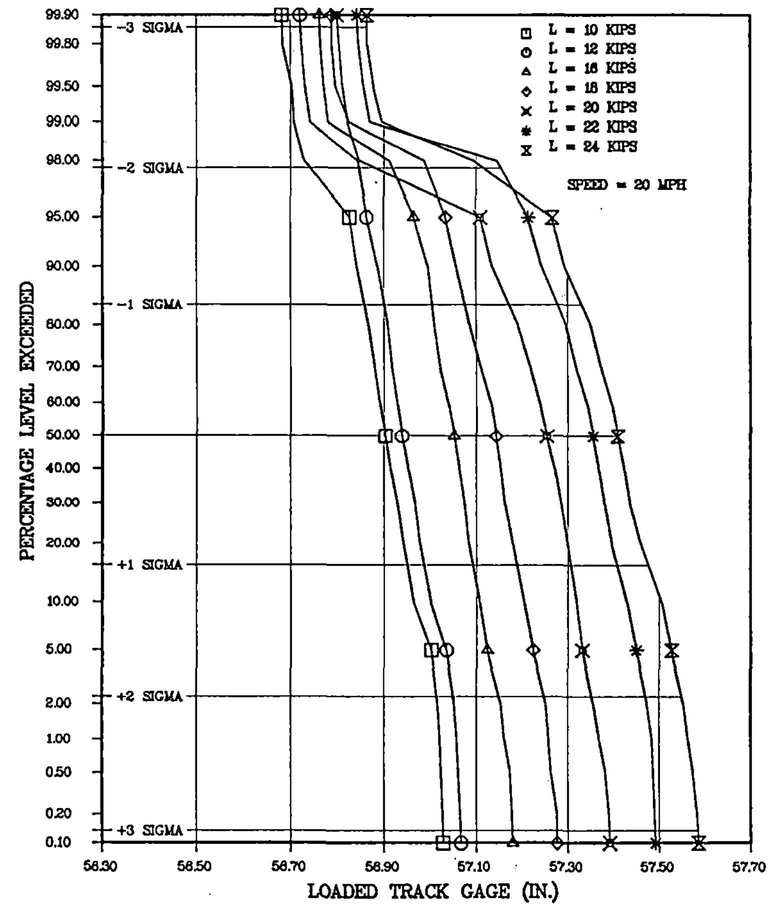
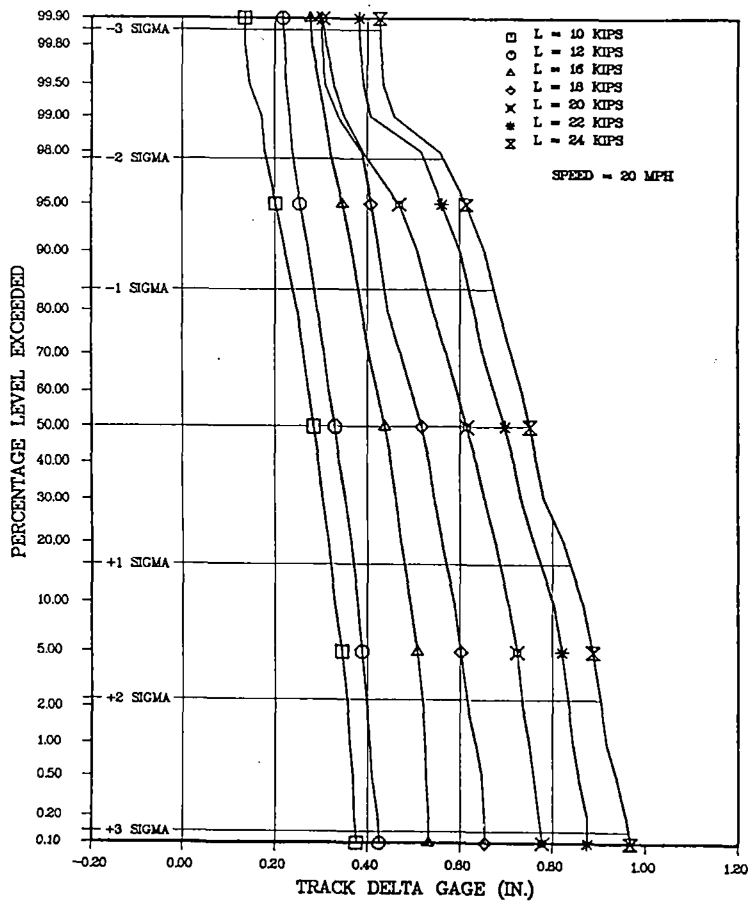
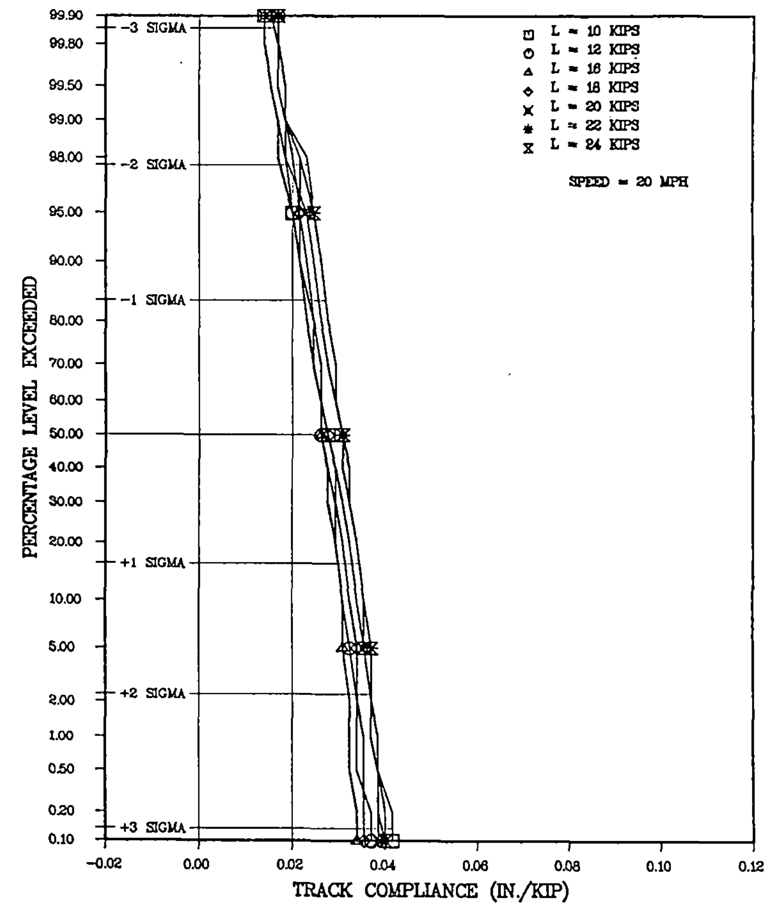


Exhibit **C11.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 6-Degree Curve(Section 25CDE), Wood Ties/ 4-Cut Spikes, V=39 Kips.





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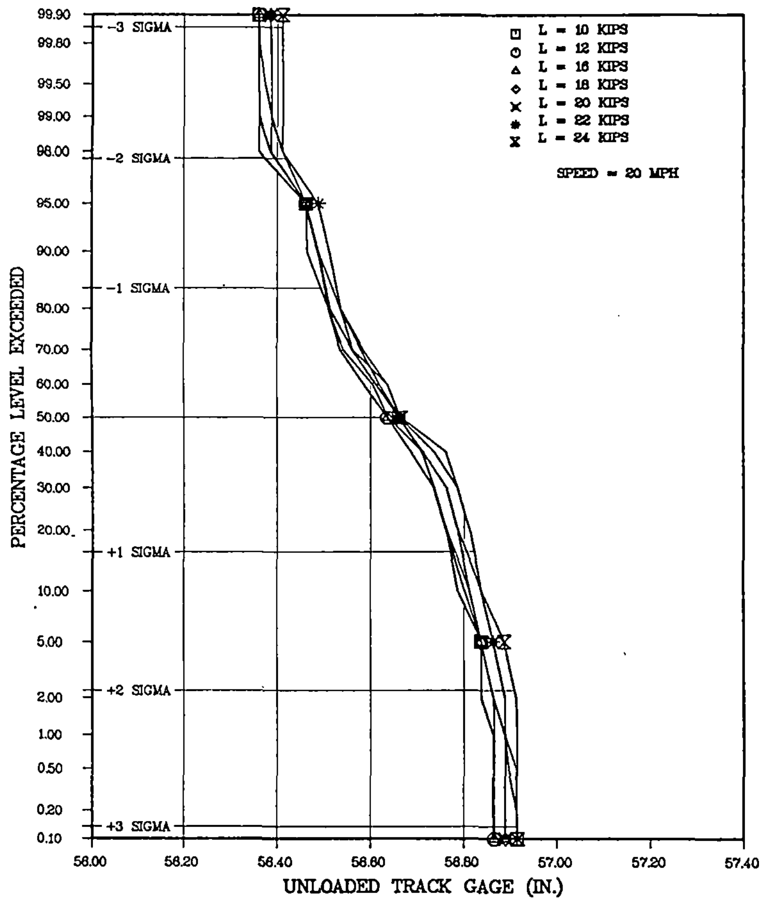


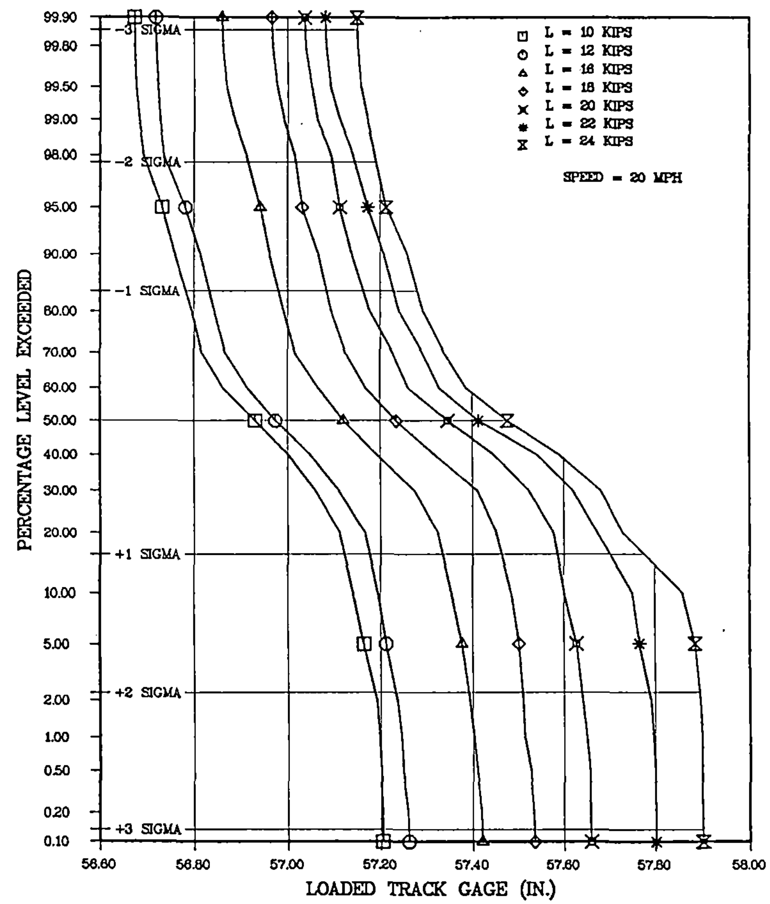


Exhibit **C13.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 6-Degree Curve(Section 25FGH), Wood Ties/ 4-Cut Spikes, V=39 Kips.

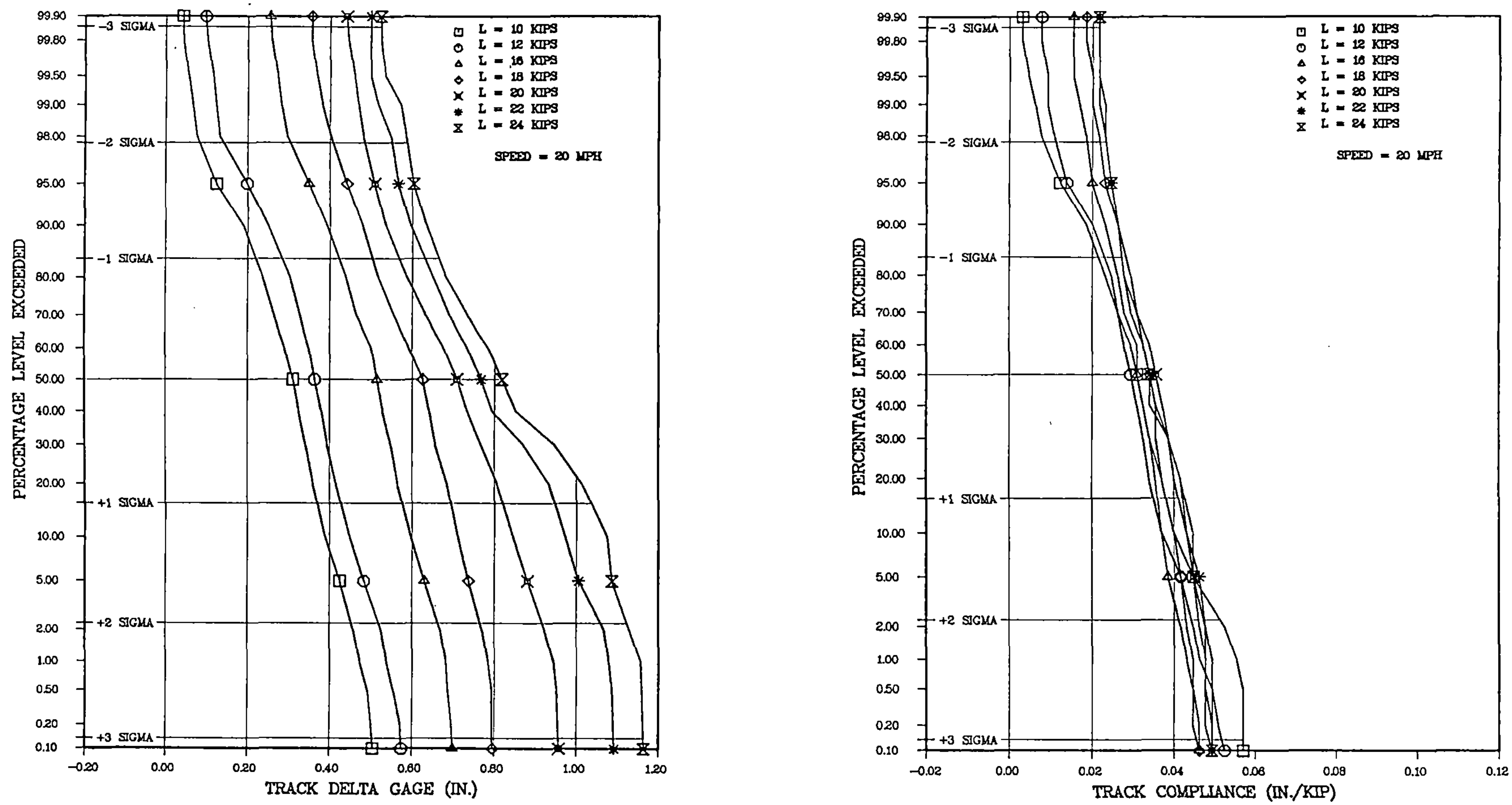


Exhibit **C14.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 6-Degree Curve(Section 25FGH), Wood Ties/4-Cut Spikes, V=39 Kips.

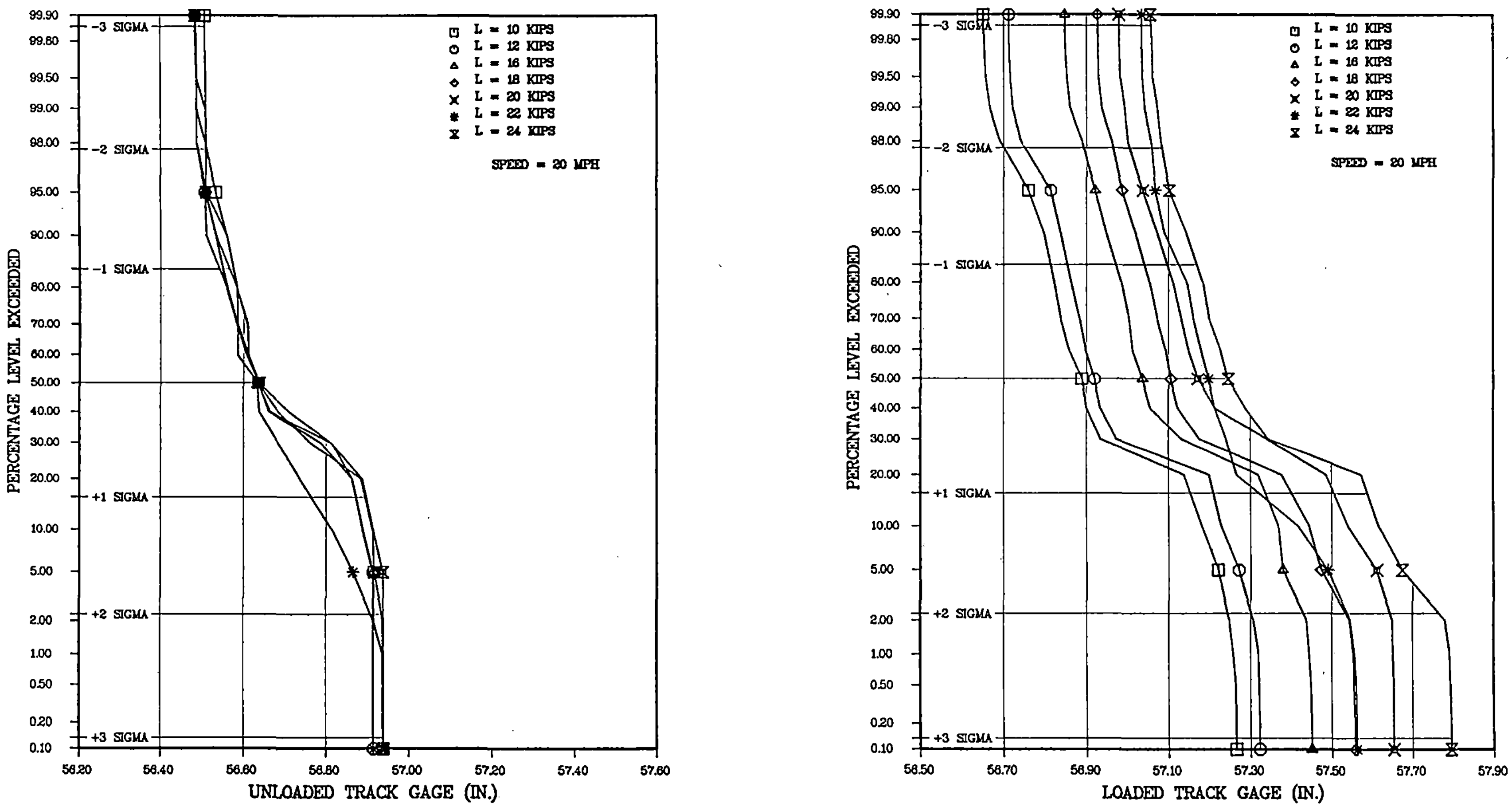
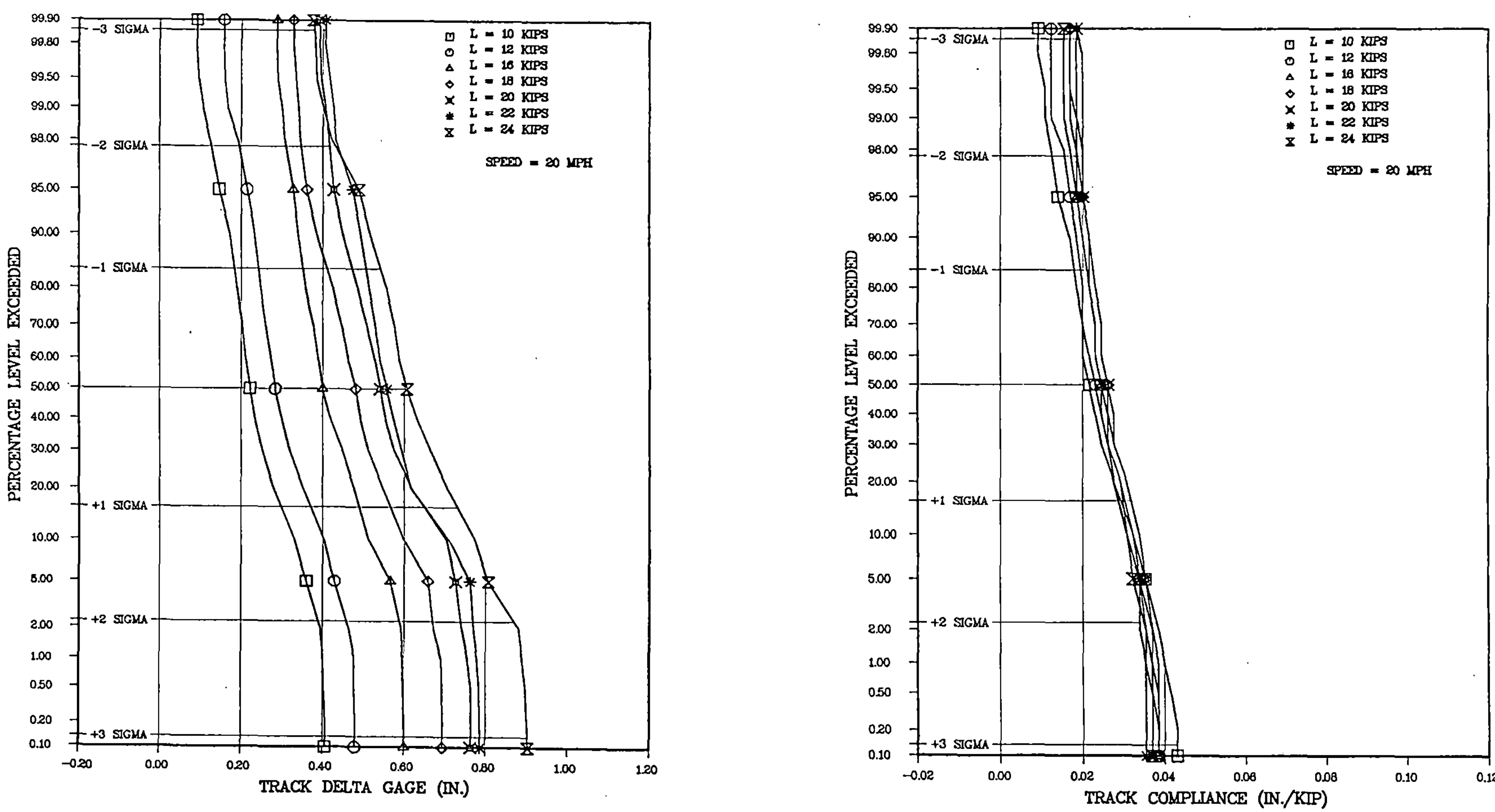


Exhibit **C15.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 6-Degree Curve(Section 25I), Wood Ties/ 4-Cut Spikes, V=39 Kips.



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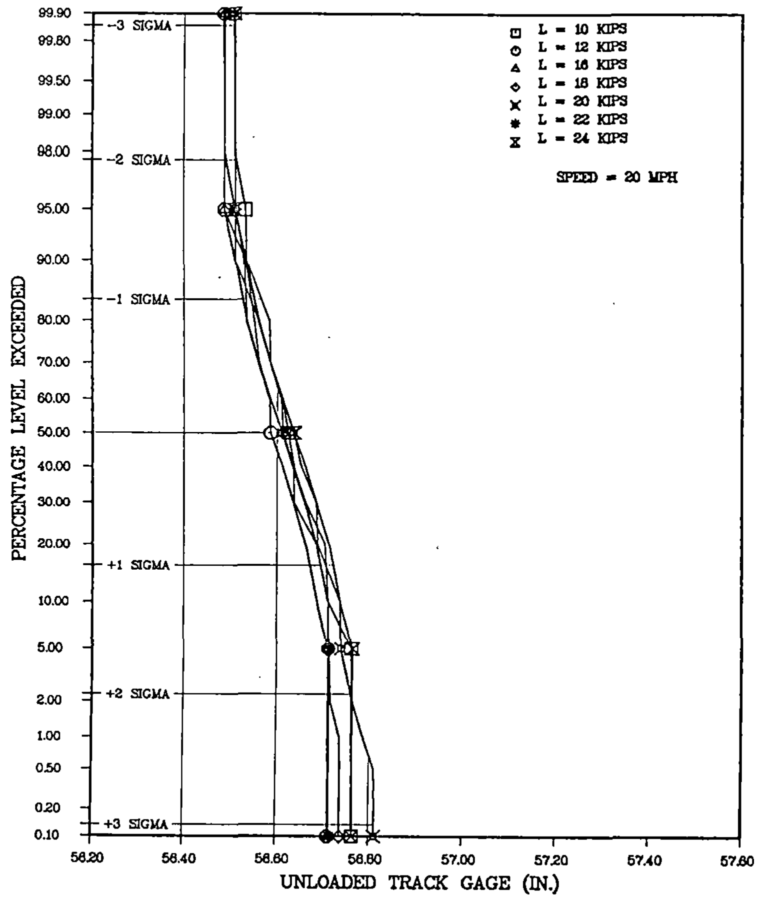


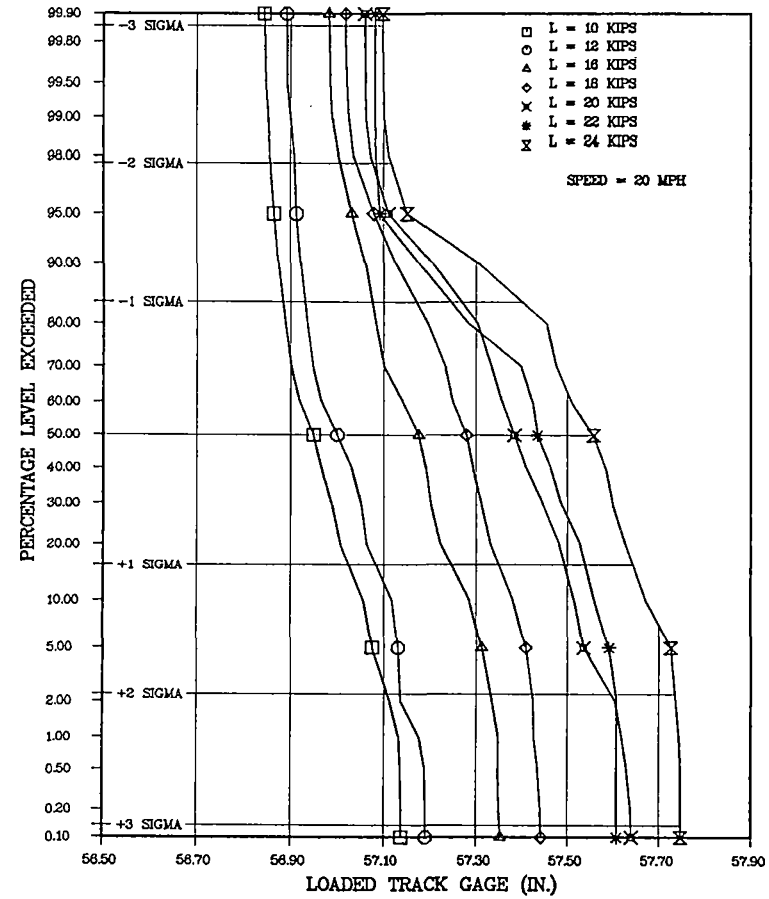


Exhibit **C17.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 6-Degree Curve(Section 25J), Wood Ties/4-Cut Spikes, V=39 Kips.

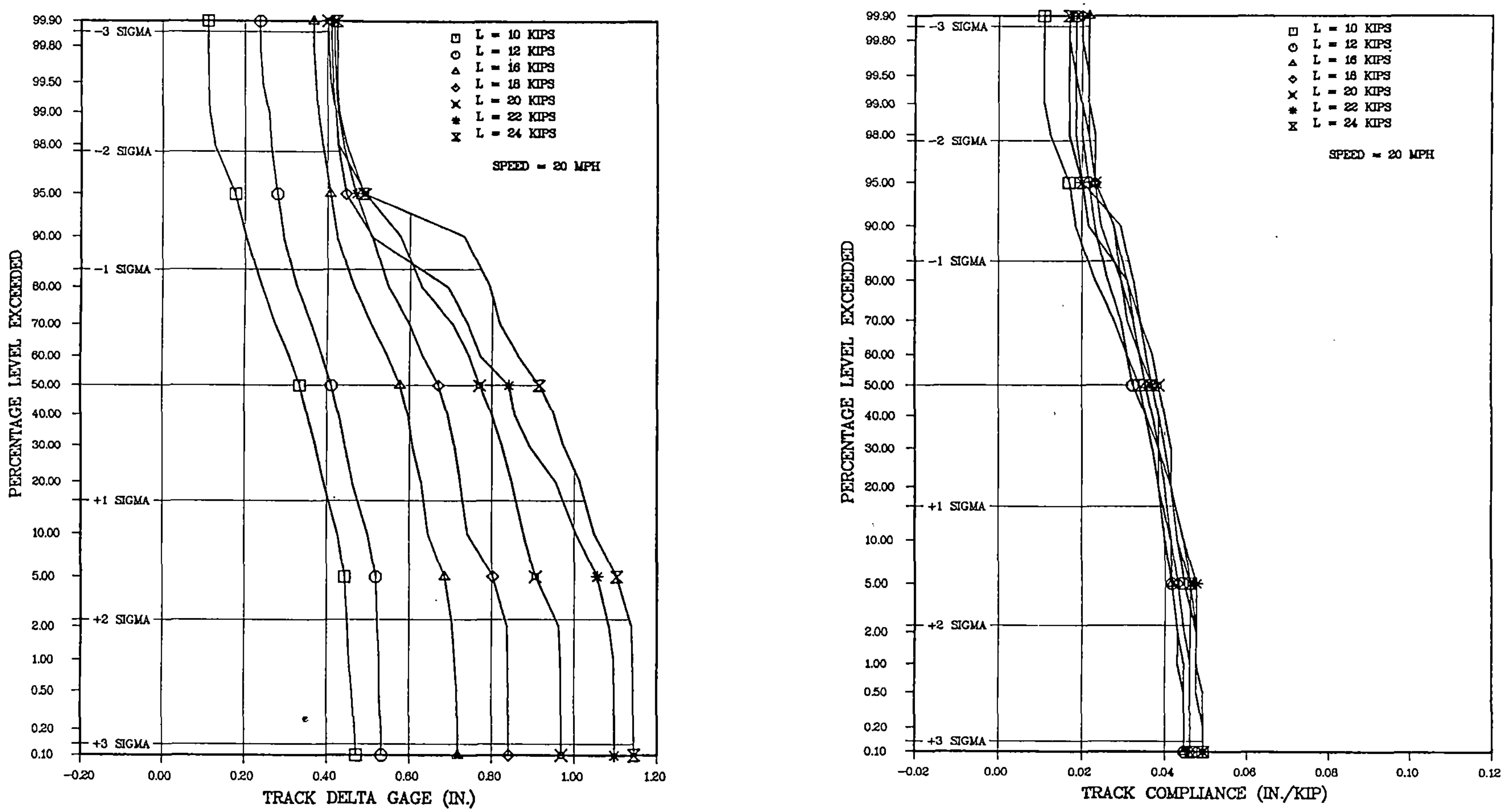


Exhibit **C18.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 6-Degree Curve(Section 25J), Wood Ties/4-Cut Spikes, V=39 Kips.

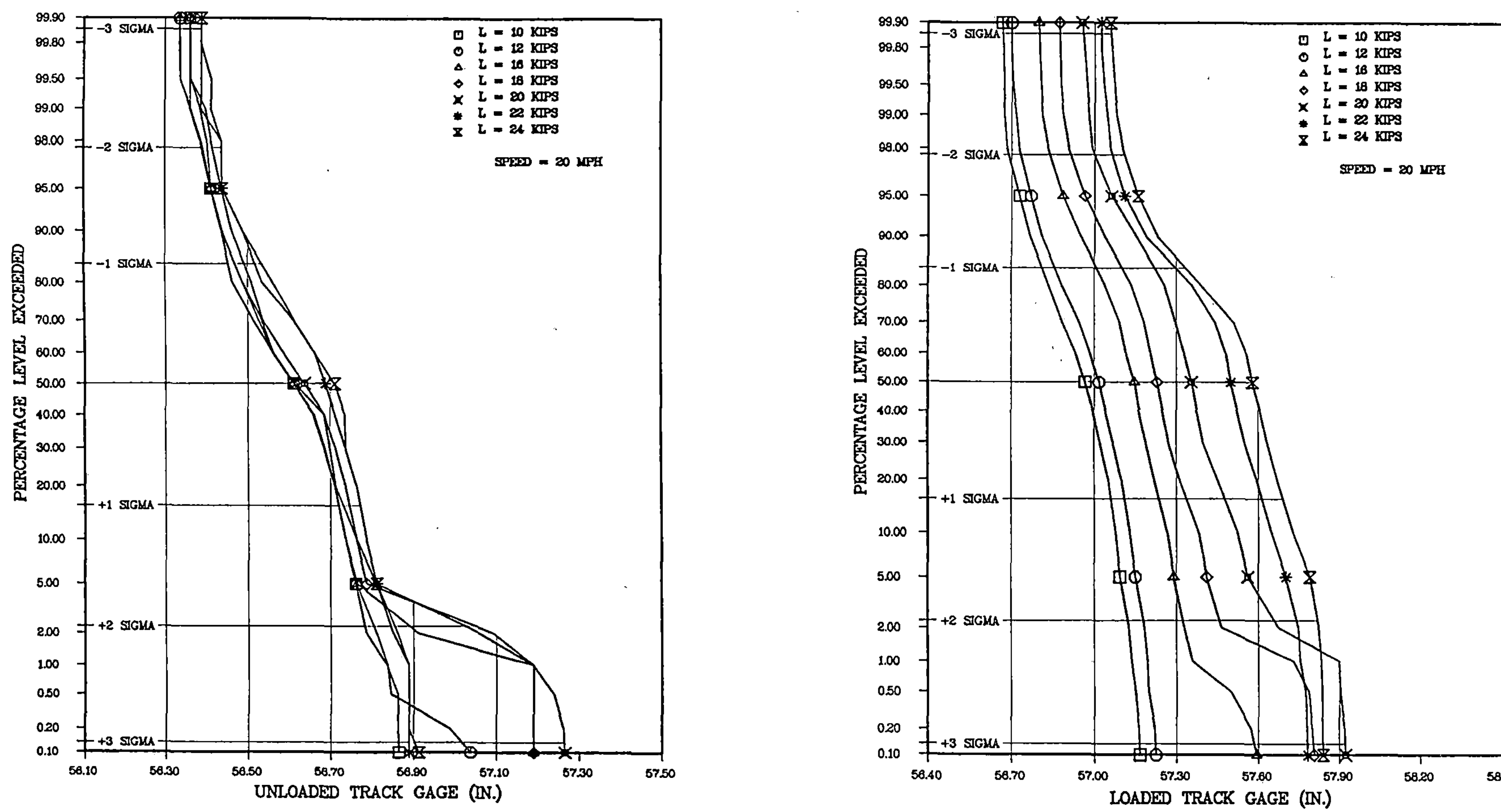
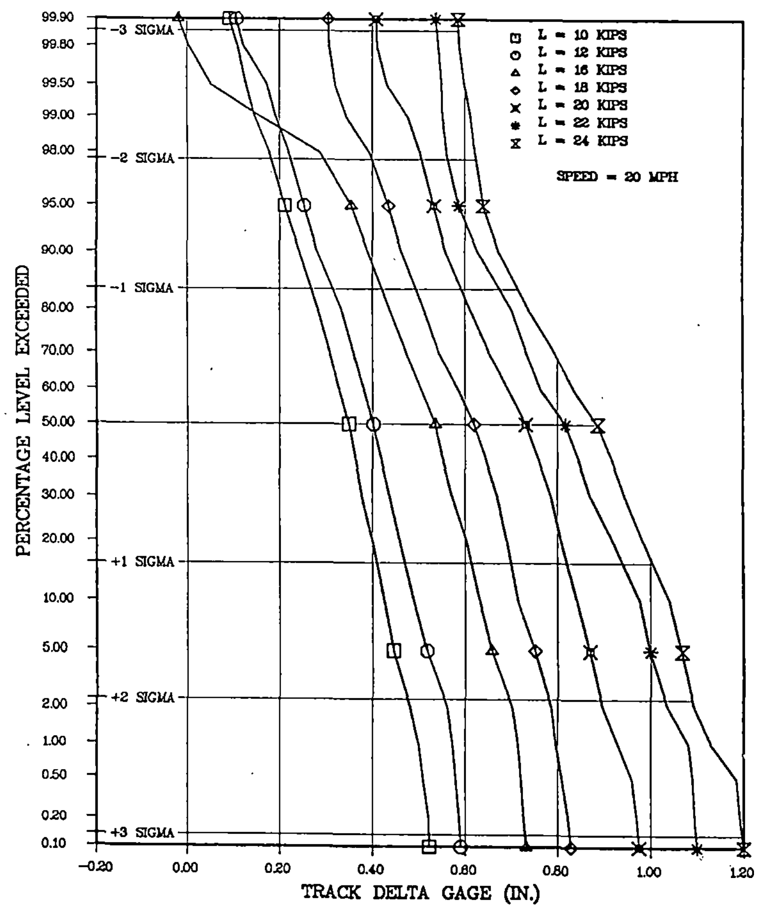


Exhibit **C19.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 6-Degree Curve(Section 25KLMNO), Wood Ties/4-Cut Spikes, V=39 Kips.



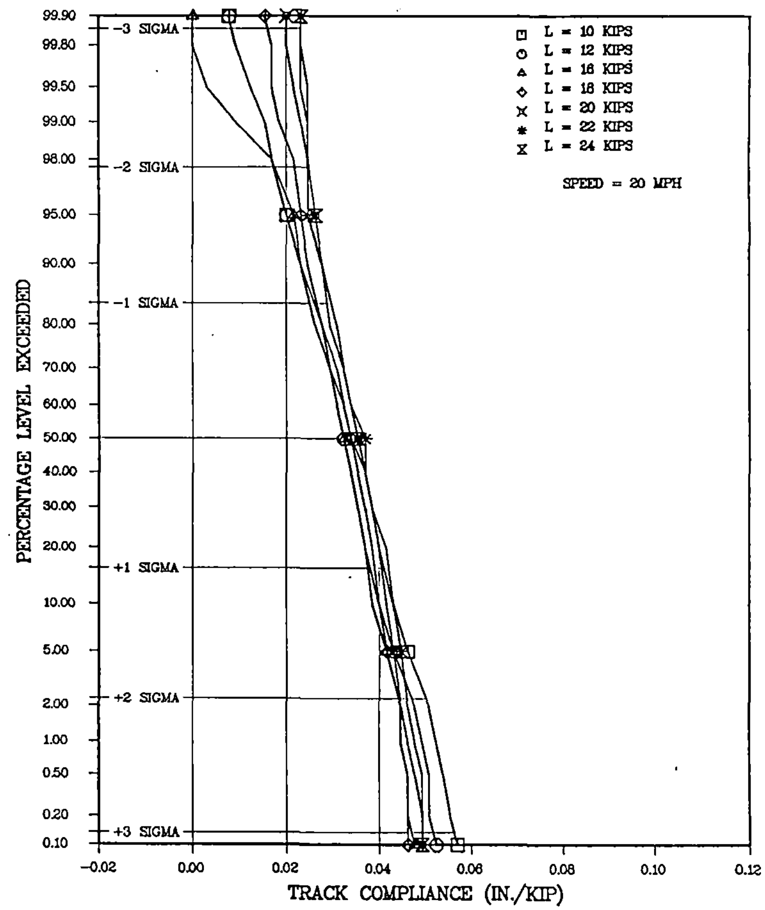


Exhibit **C20.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 6-Degree Curve(Section 25KLMNO), Wood Ties/ 4-Cut Spikes, V=39 Kips.

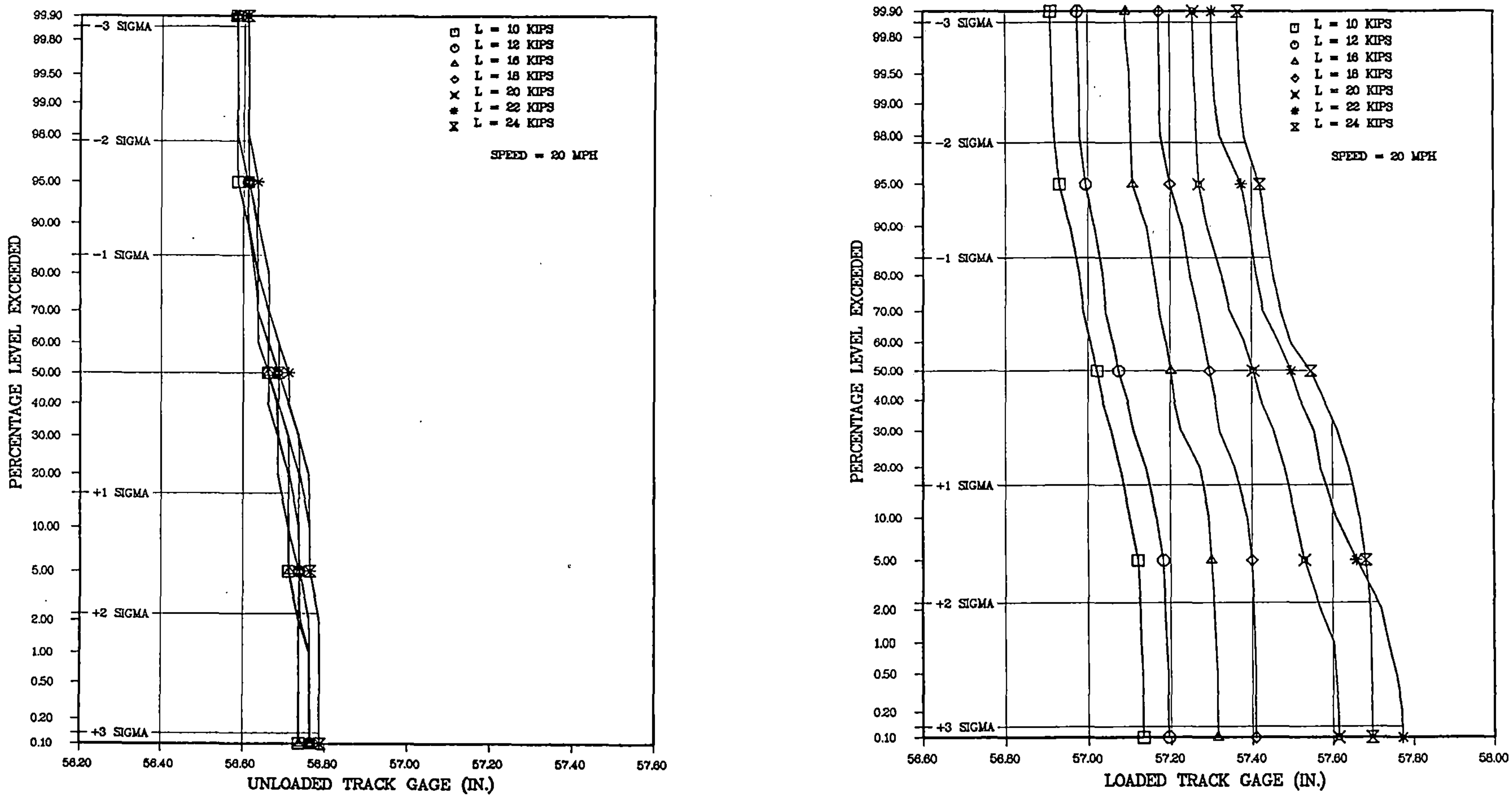


Exhibit **C21.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 6-Degree Curve(Section 25PQ), Wood Ties/4-Cut Spikes, V=39 Kips.

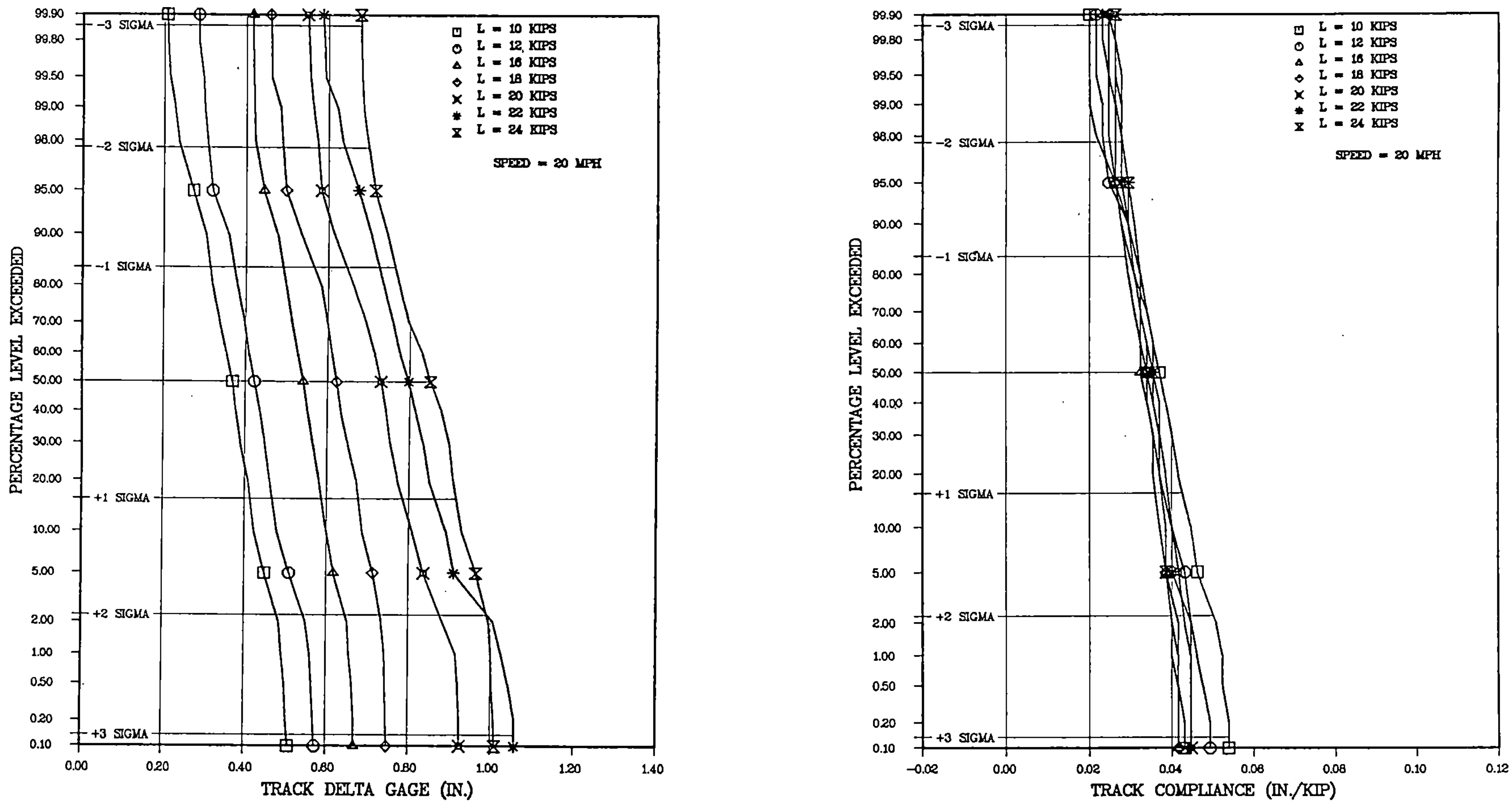
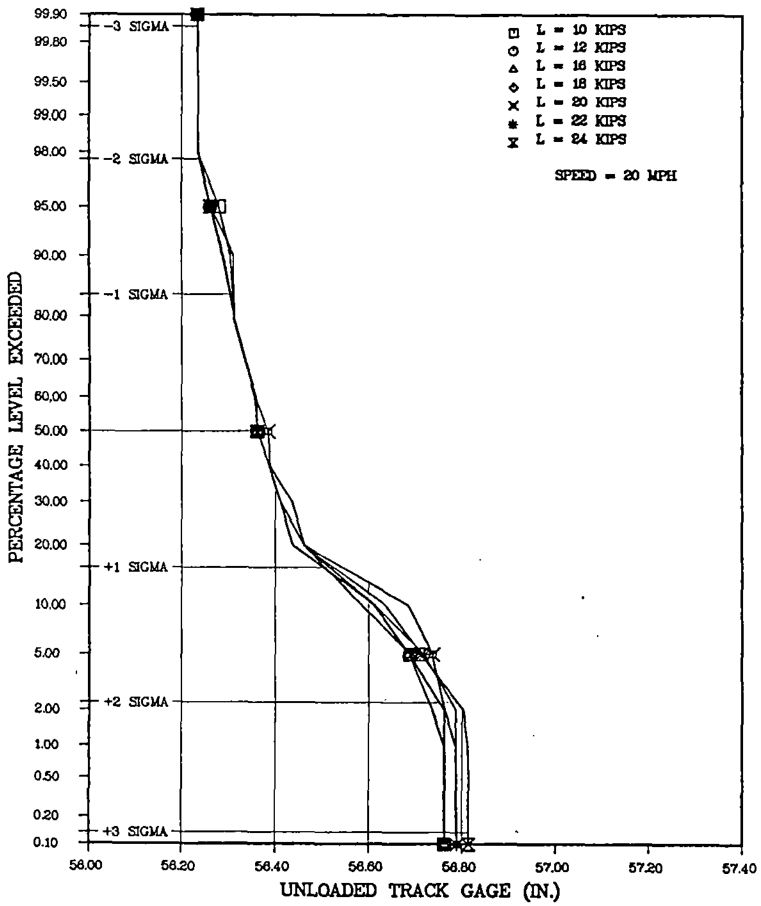


Exhibit **C22.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 6-Degree Curve(Section 25PQ), Wood Ties/4-Cut Spikes, V=39 Kips.



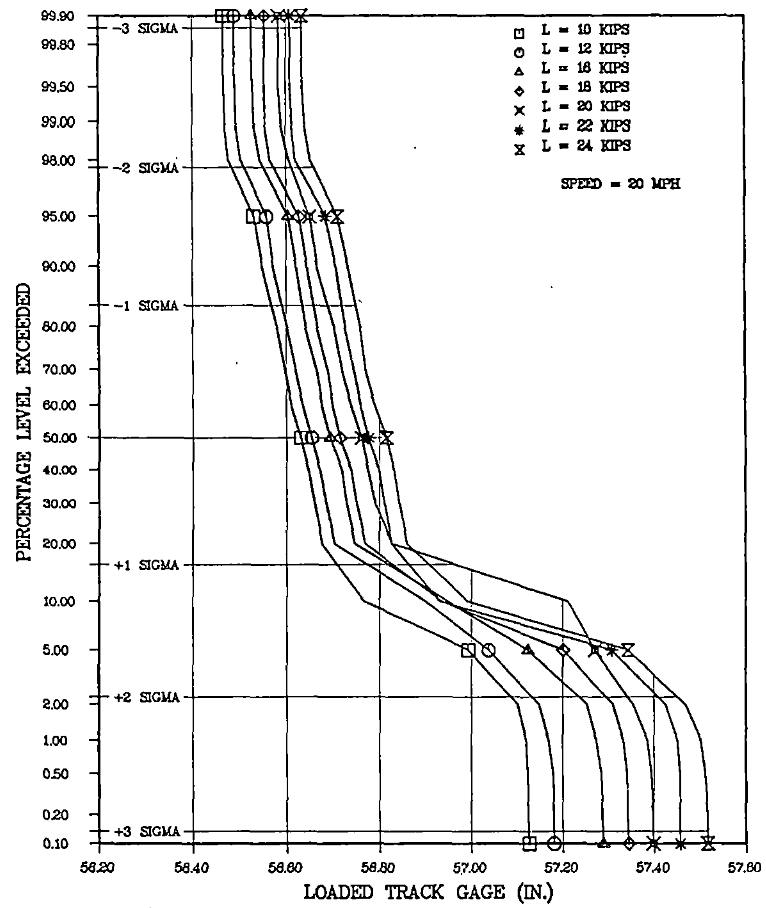
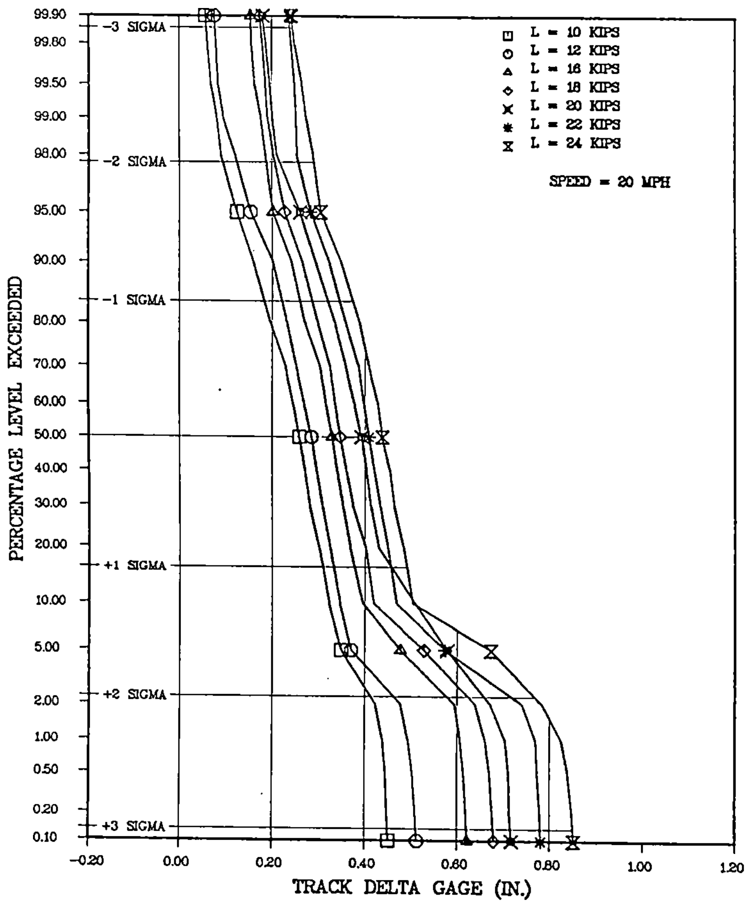
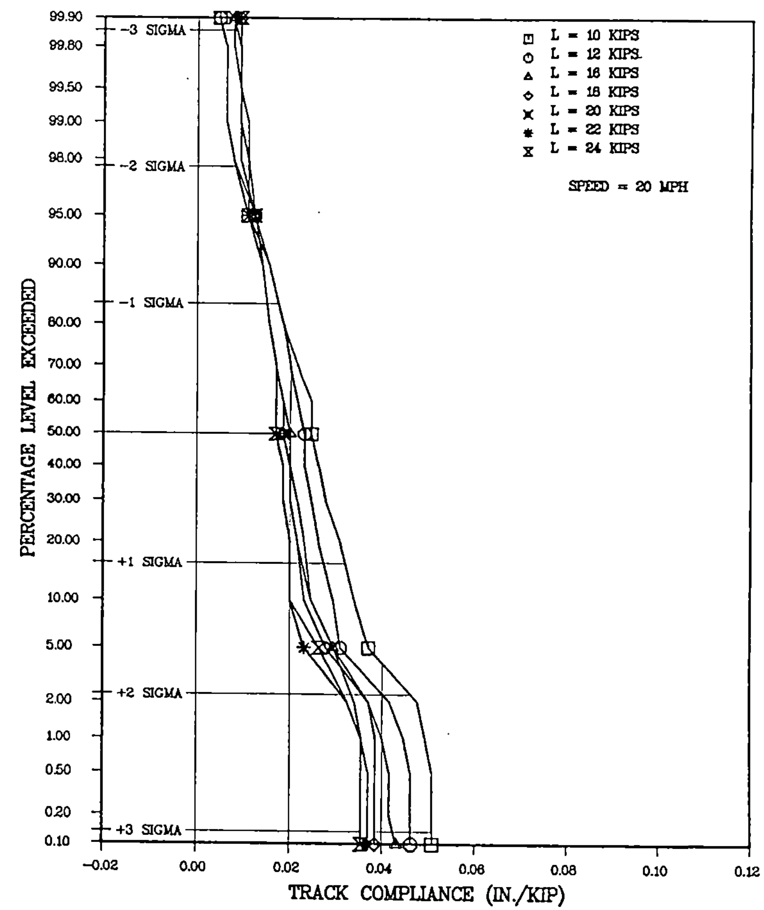


Exhibit **C23.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 6-Degree Curve(Section 25R), Wood Ties/Pandrol Fasteners, V=39 Kips.





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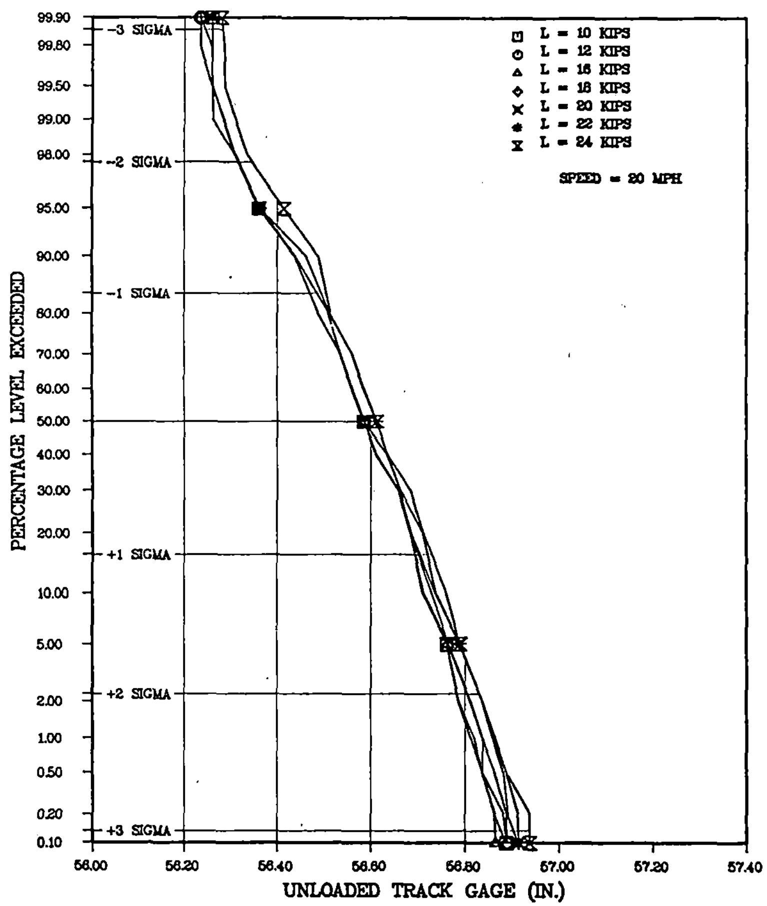


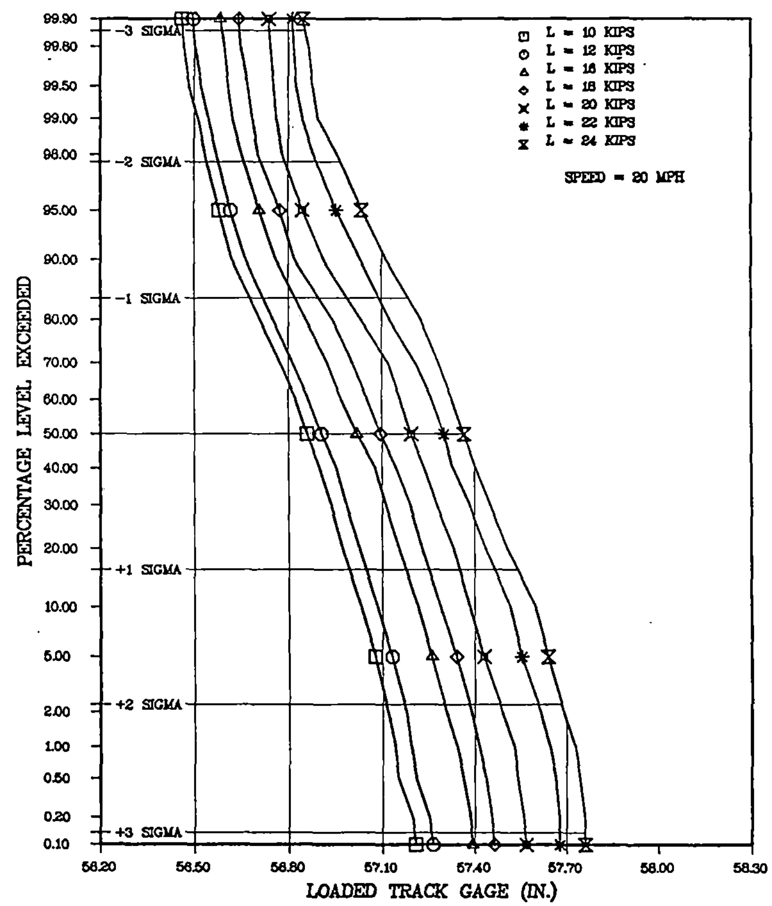
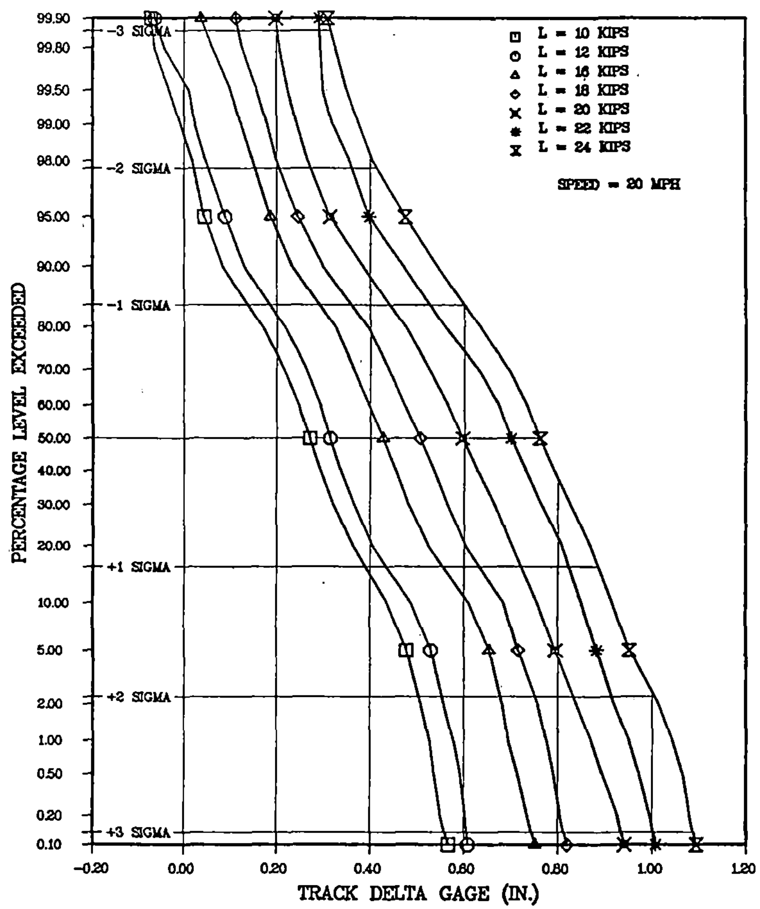


Exhibit **C25.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, Tangent Track(Section 29), Wood Ties/ Pandrol Fasteners, V=39 Kips.



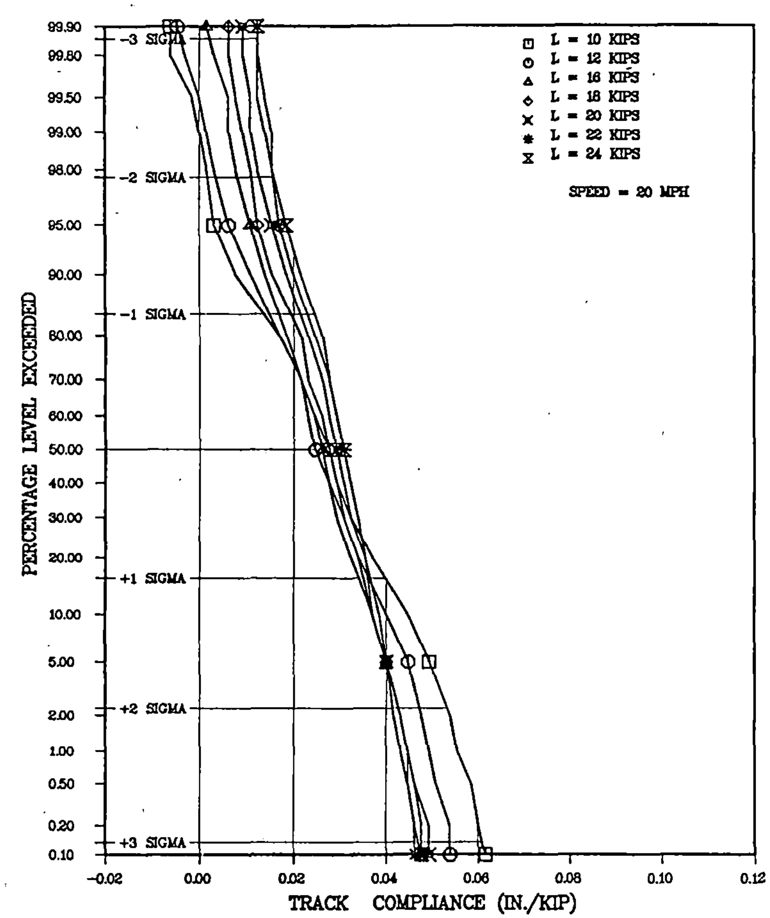
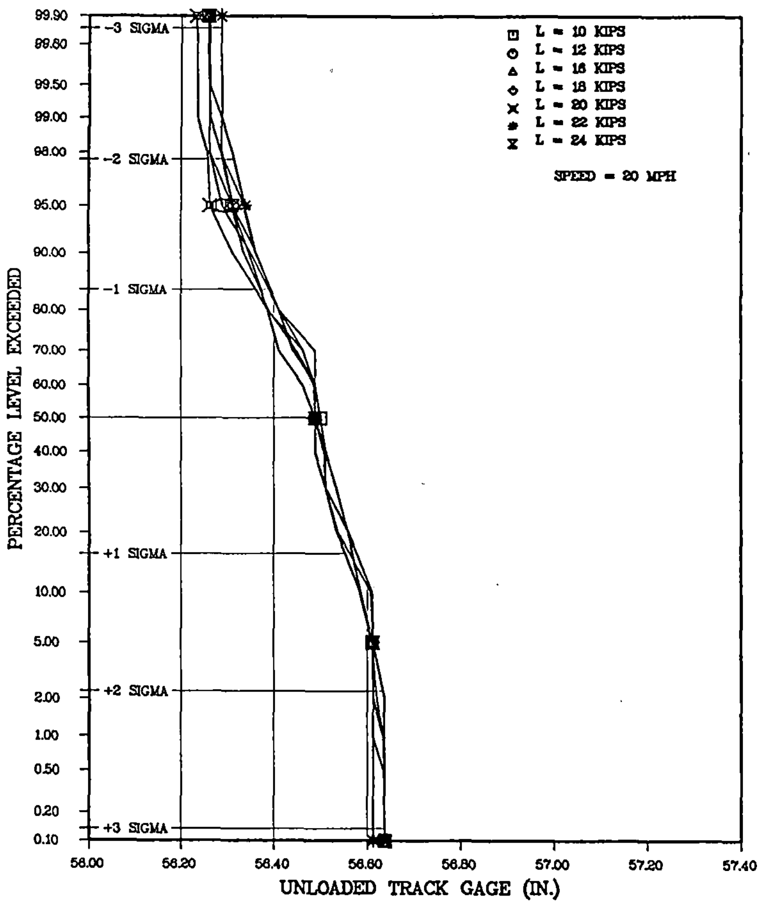


Exhibit **C26.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, Tangent Track(Section 29), Wood Ties/ Pandrol Fasteners, V=39 Kips.



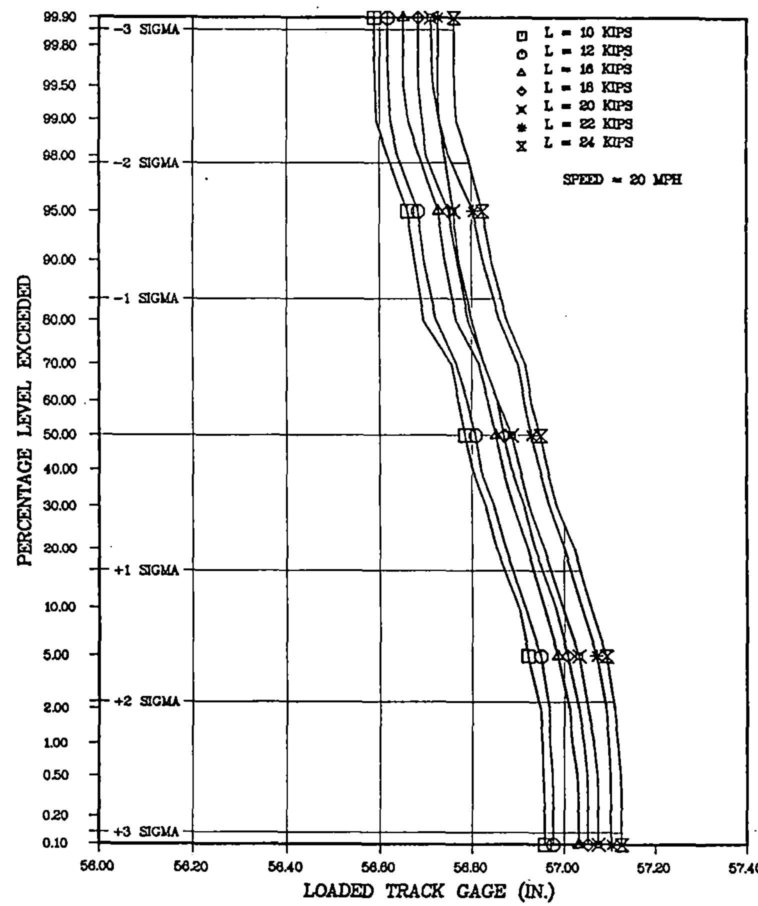
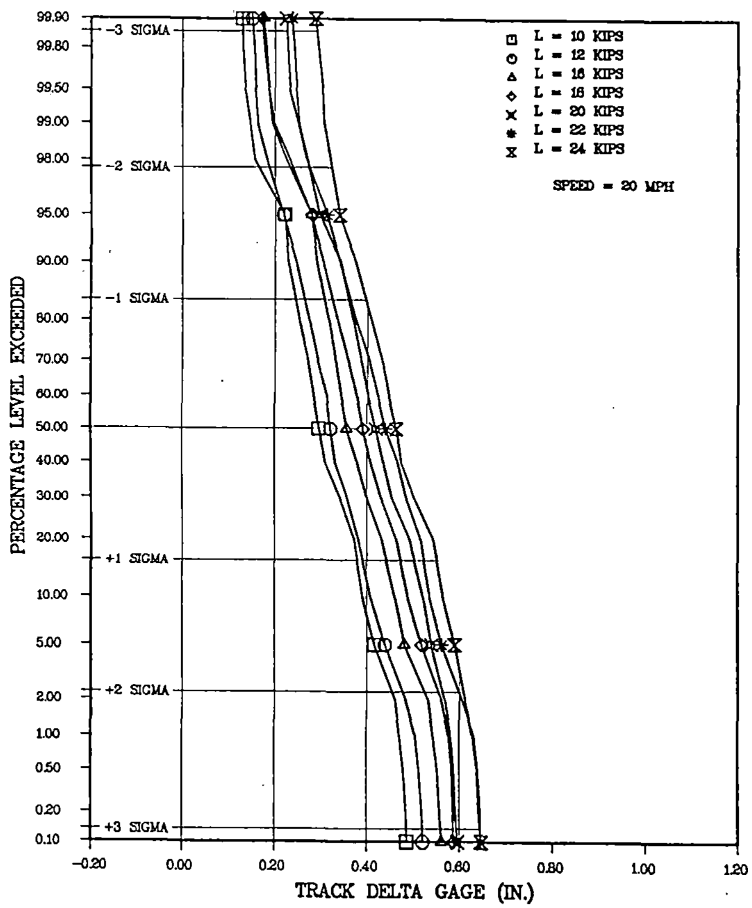


Exhibit **C27.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 31(2)), Azobe Ties/Elastic Spikes, V=39 Kips.



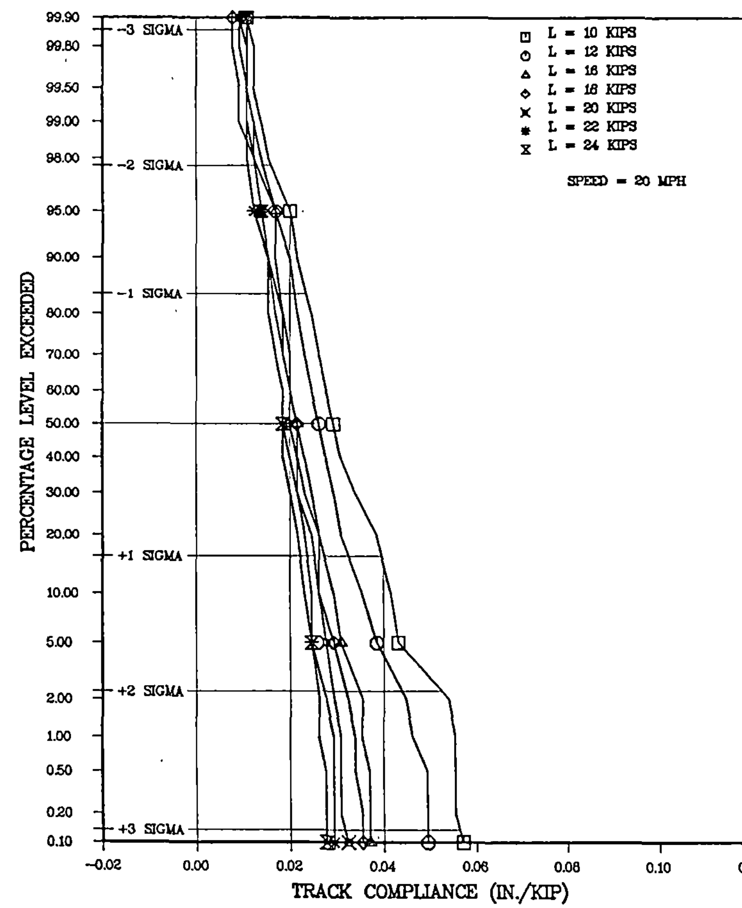
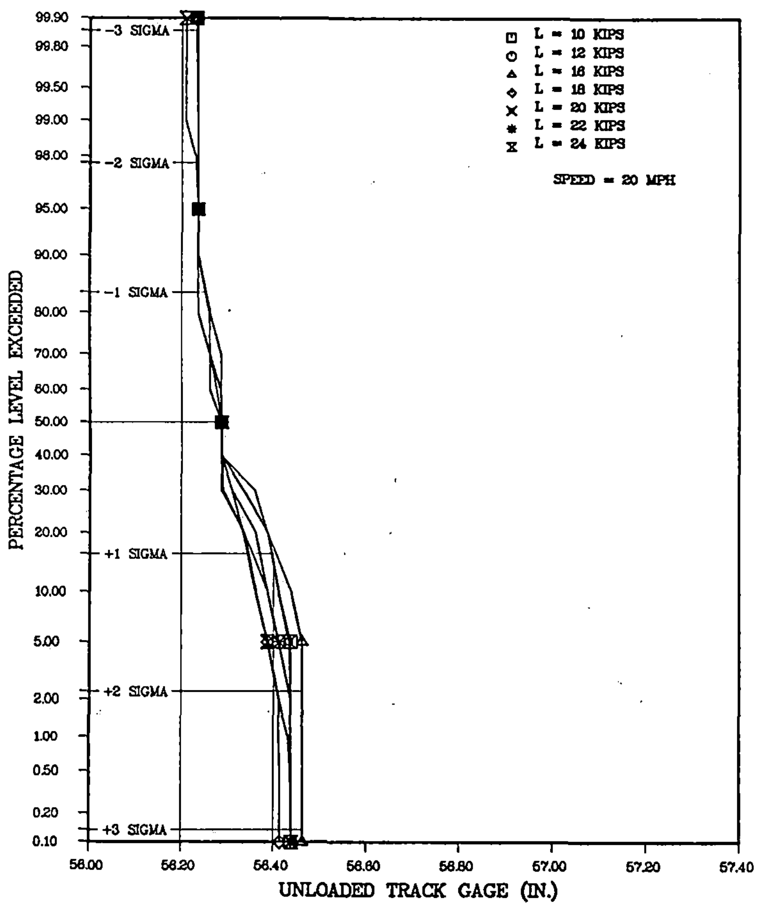


Exhibit **C28.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 31(2)), Azobe Ties/ Elastic Spikes, V=39 Kips.



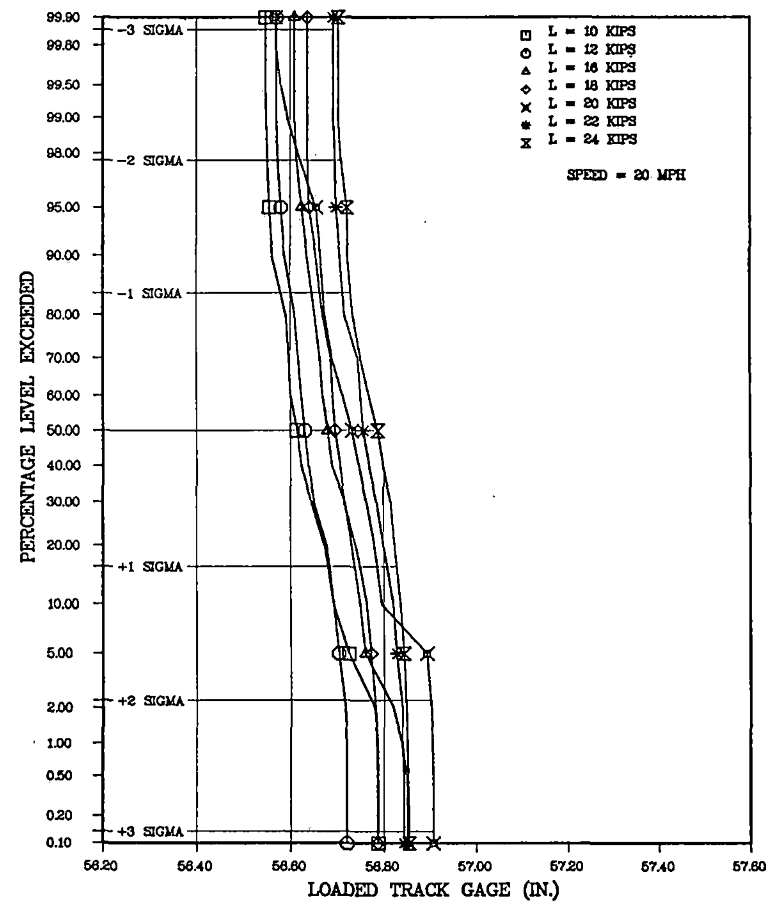


Exhibit **C29.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 31(3)), Azobe Ties/Pandrol Fasteners, V=39 Kips.

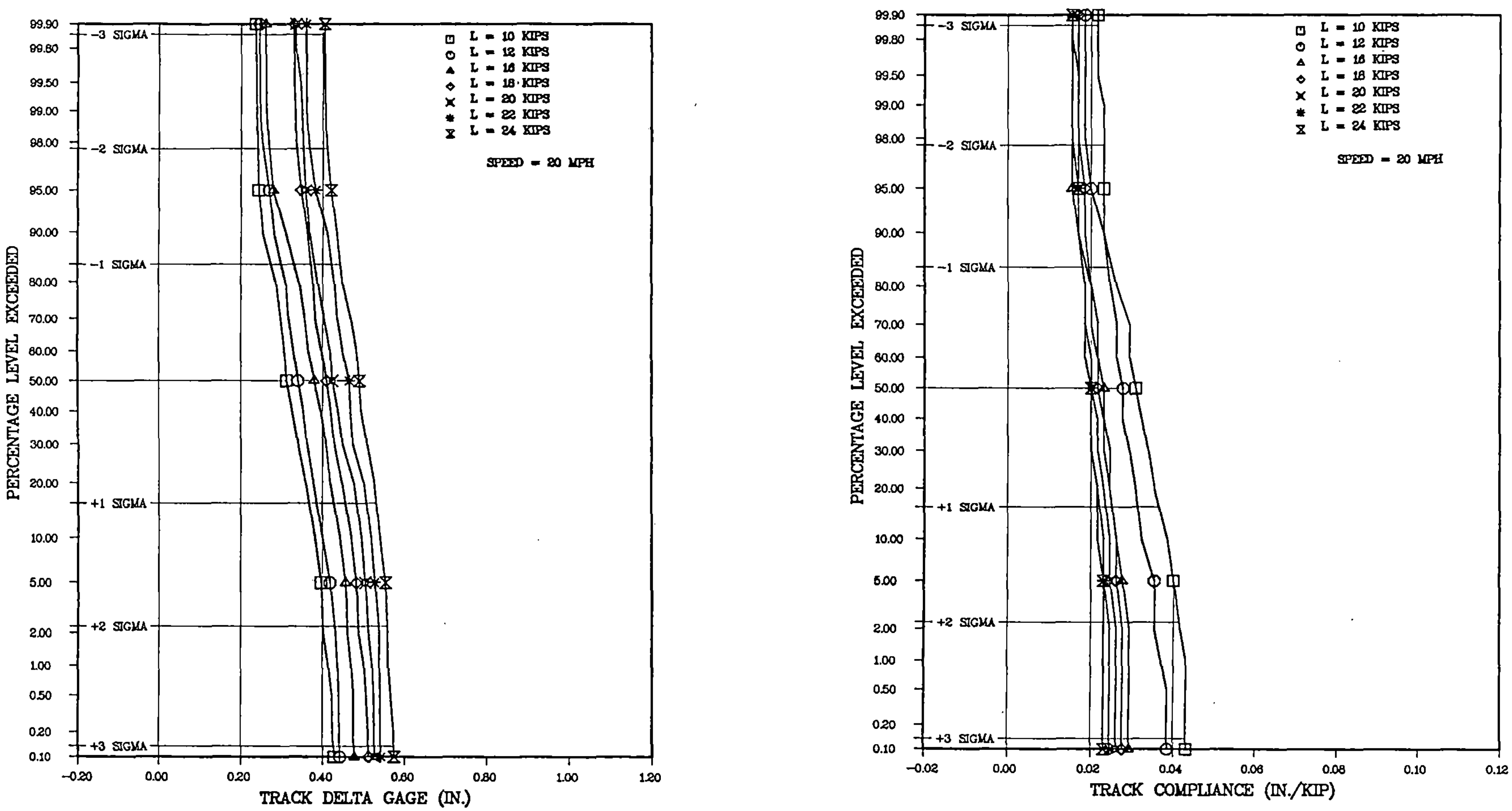


Exhibit **C30.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 31(3)), Azobe Ties/ Pandrol Fasteners, V=39 Kips.

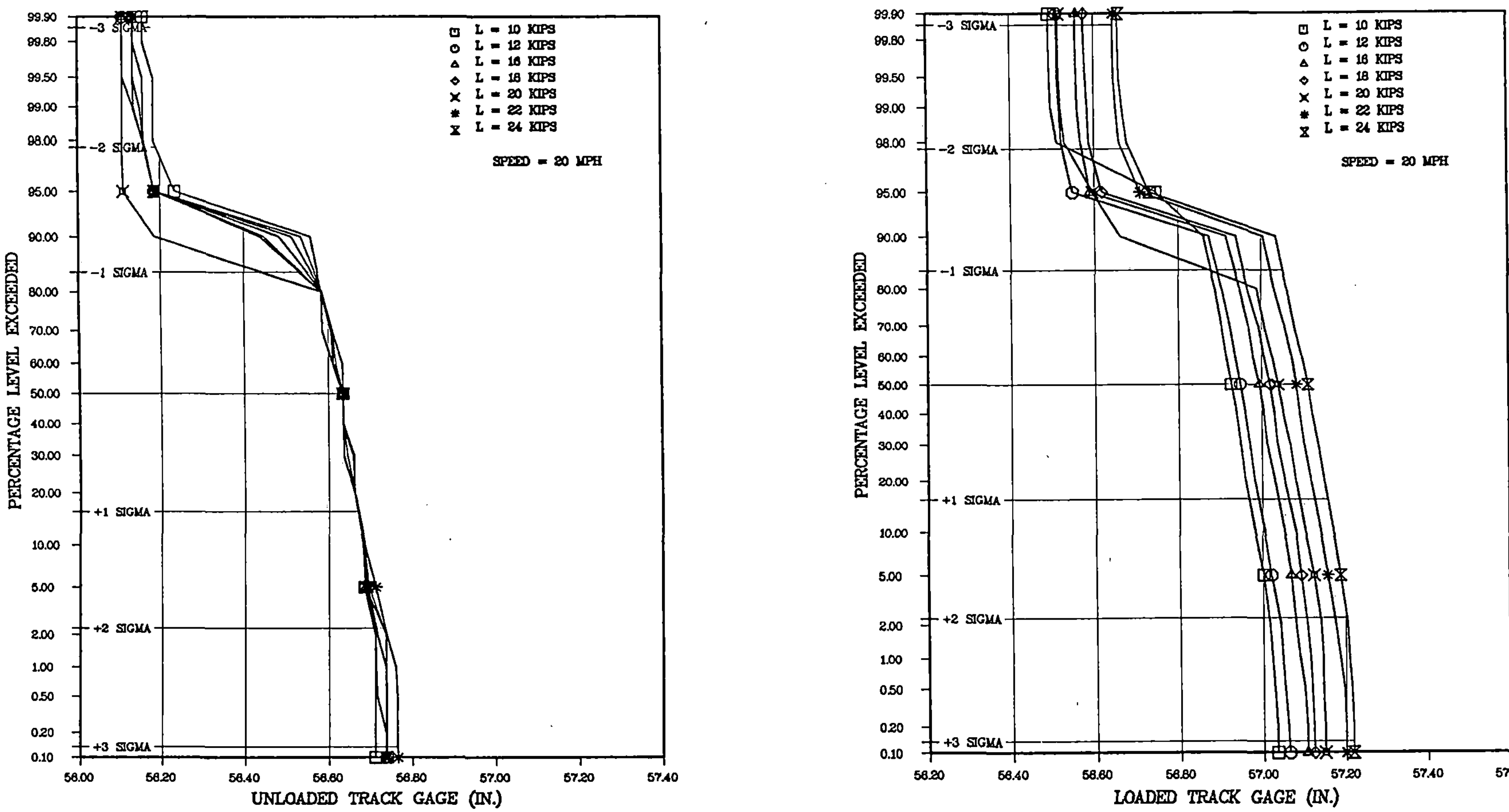
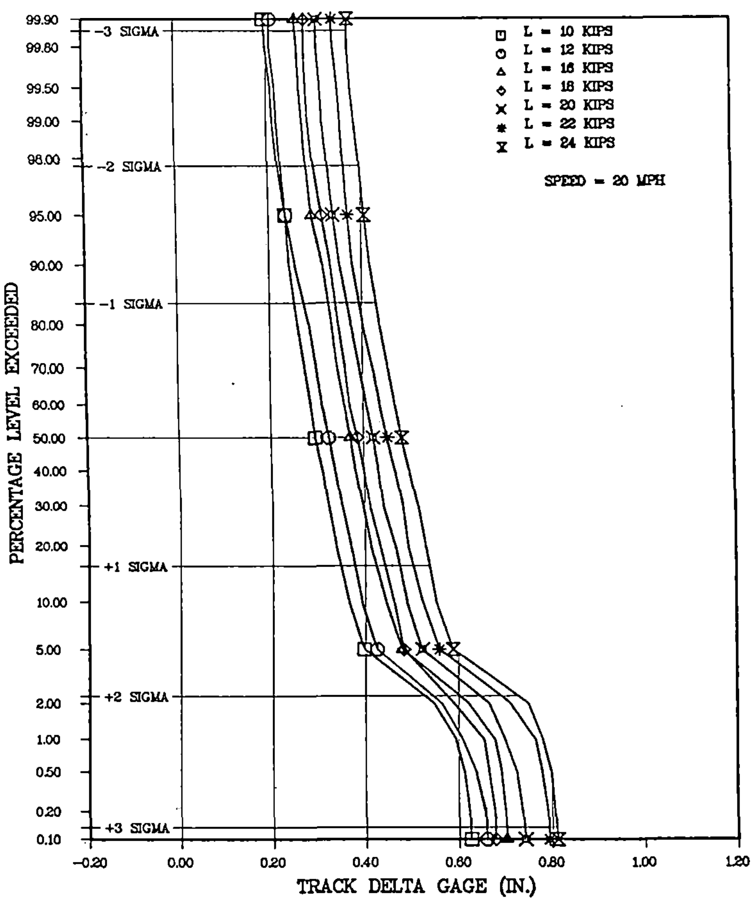


Exhibit **C31.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 31(4)), Concrete Ties, V=39 Kips.



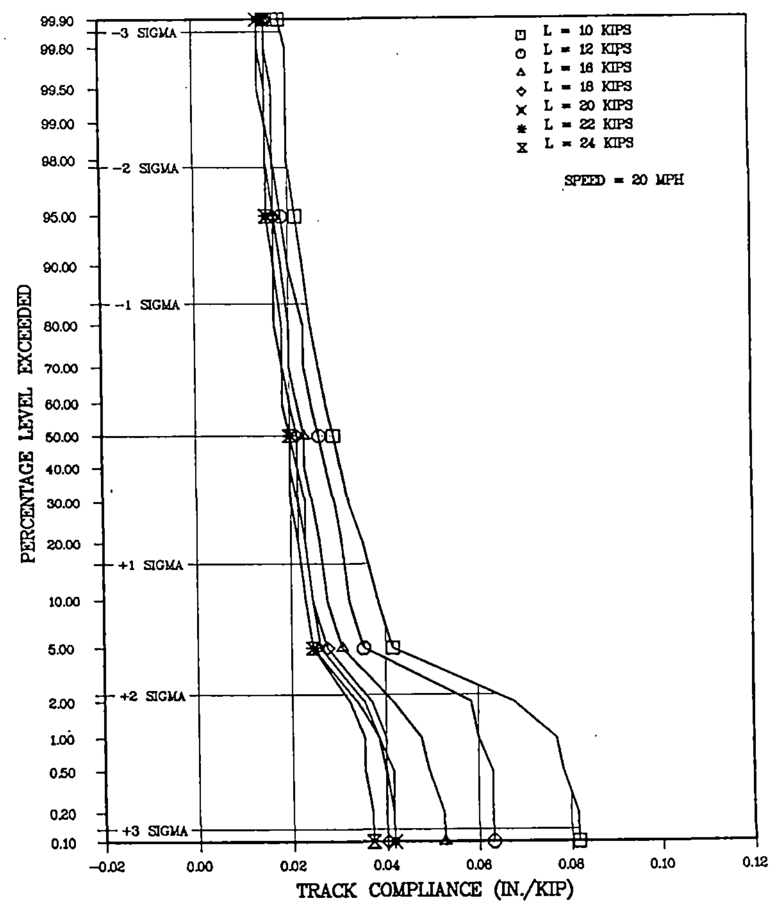


Exhibit **C32.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 31(4)), Concrete Ties, V=39 Kips.

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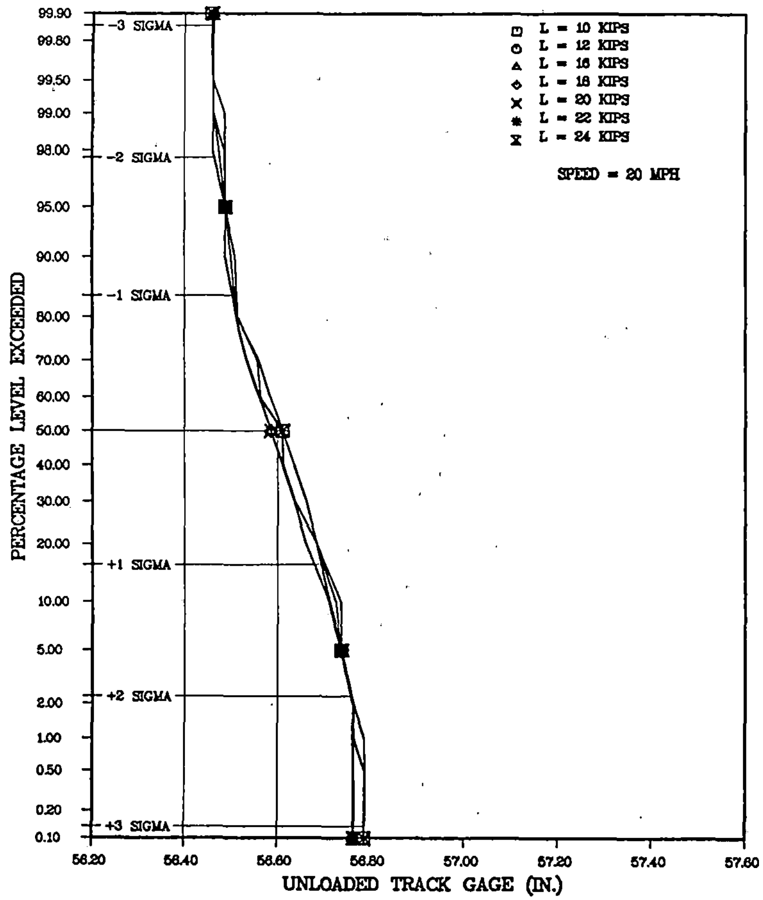


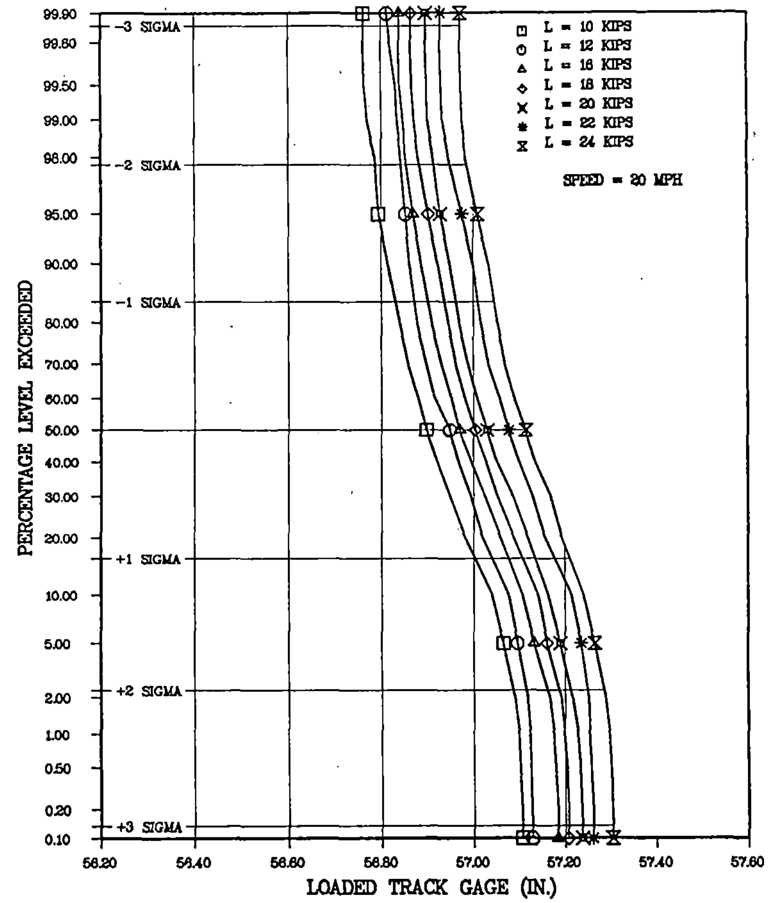
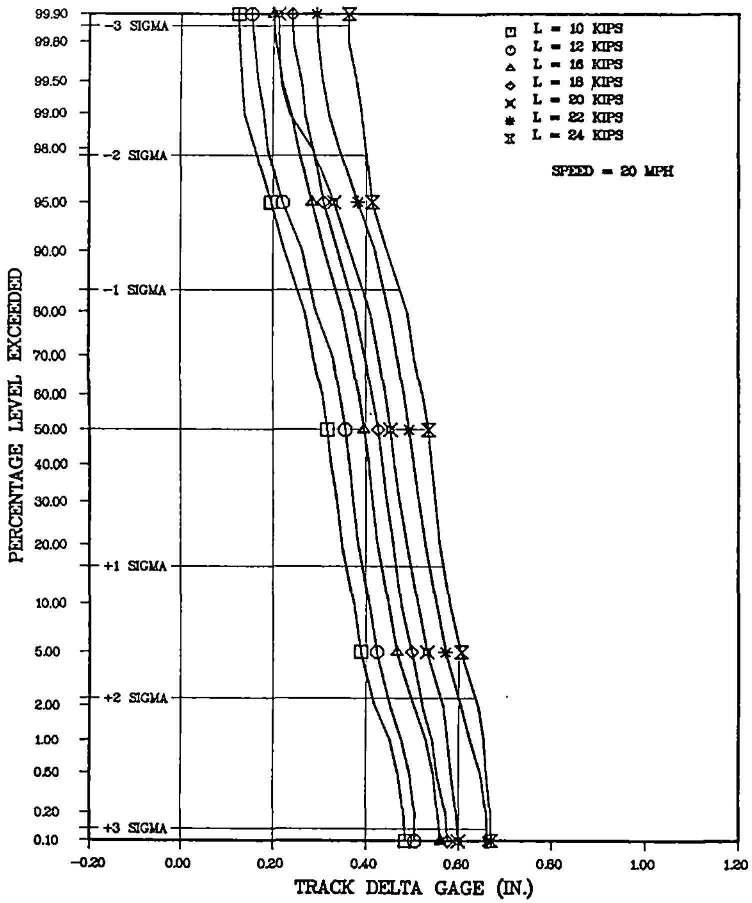


Exhibit **C33.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, Tangent Track(Section 33), Concrete Ties-Wood/ Pandrol-Wood/4-Cut Spikes Grouped, V=39 Kips.



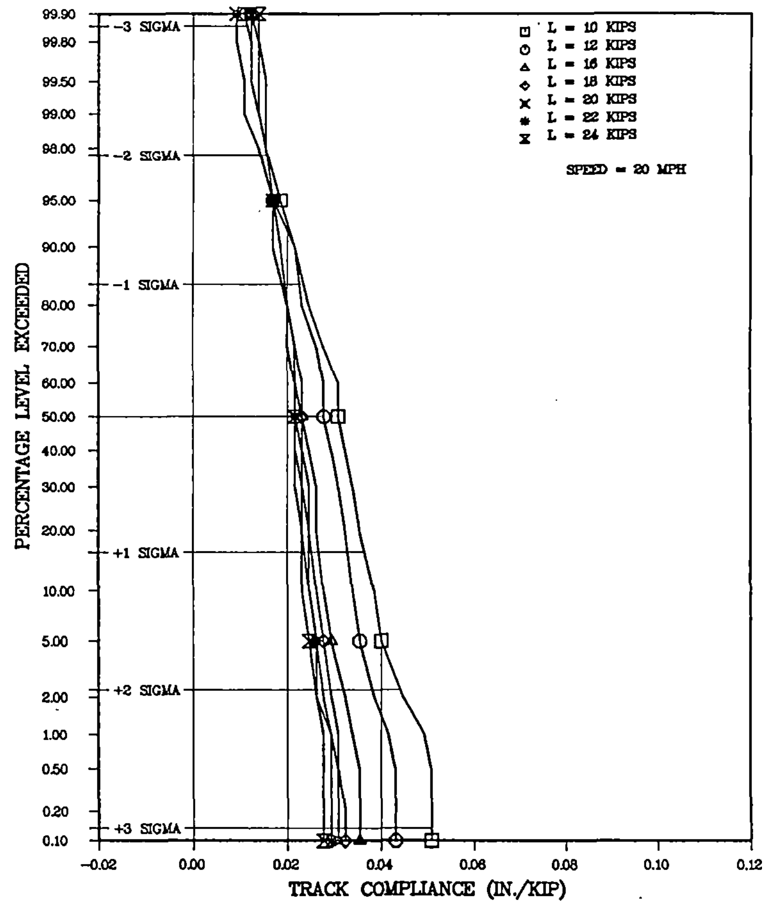


Exhibit **C34.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, Tangent Track(Section 33), Concrete Ties-Wood/Pandrol-Wood/4-Cut Spikes Grouped, V=39 Kips.

9.4 Appendix-D Percentage Level Exceedance Plots With Respect To Tie/Fastener Type

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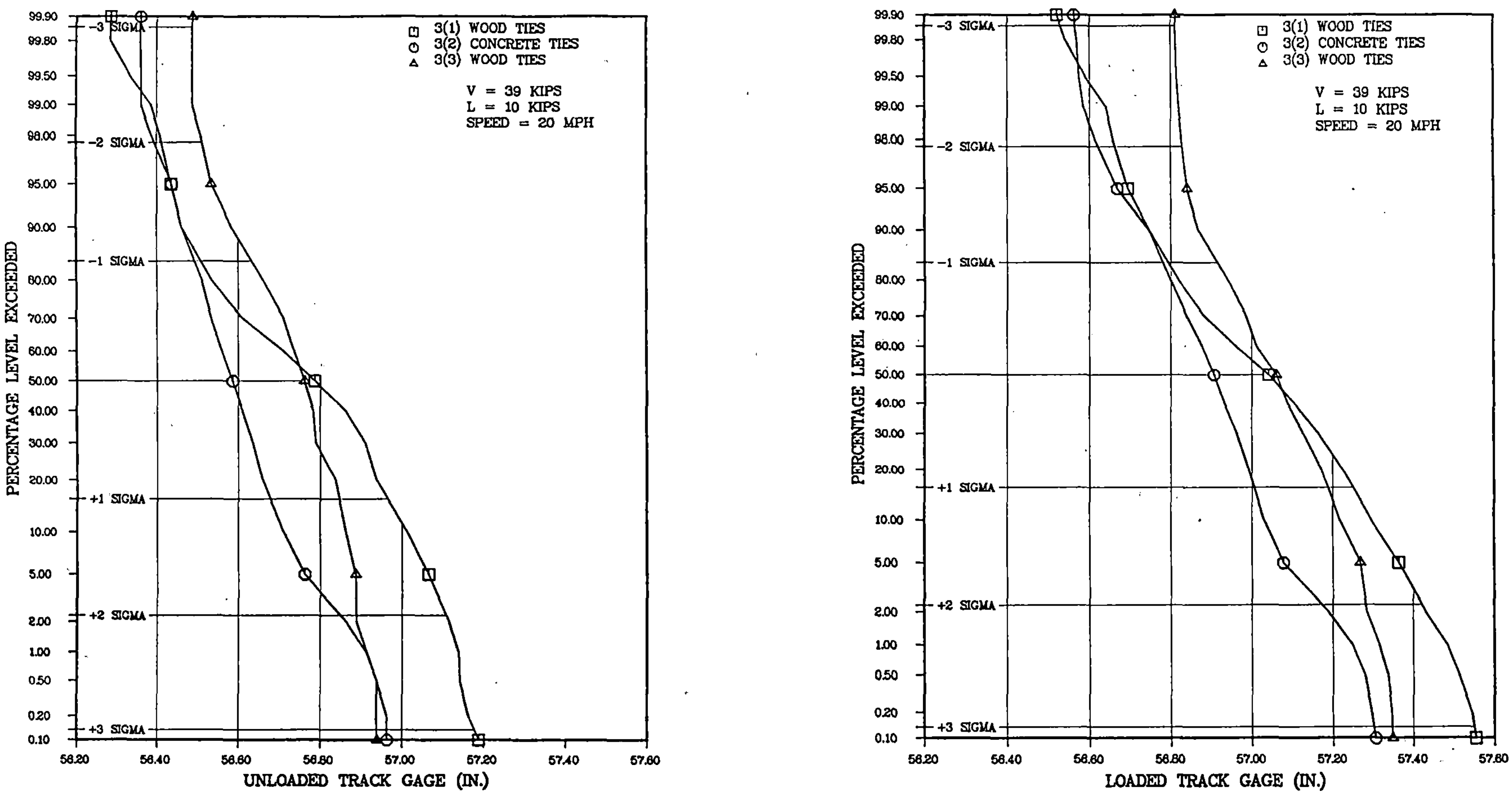
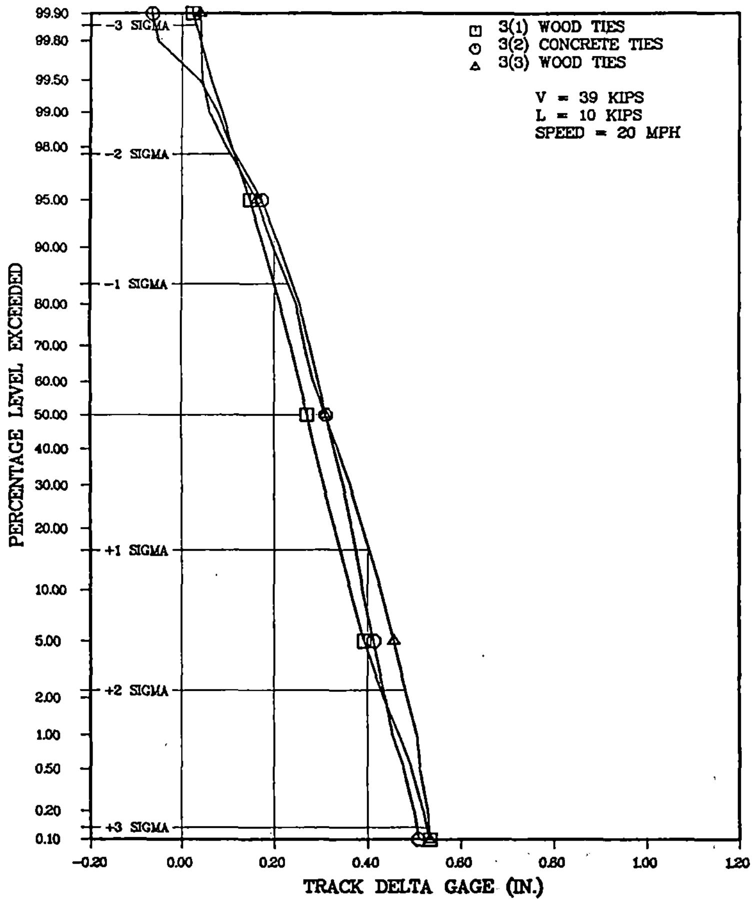


Exhibit **D1.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 3), All Segments, L=10 Kips and V=39 Kips.



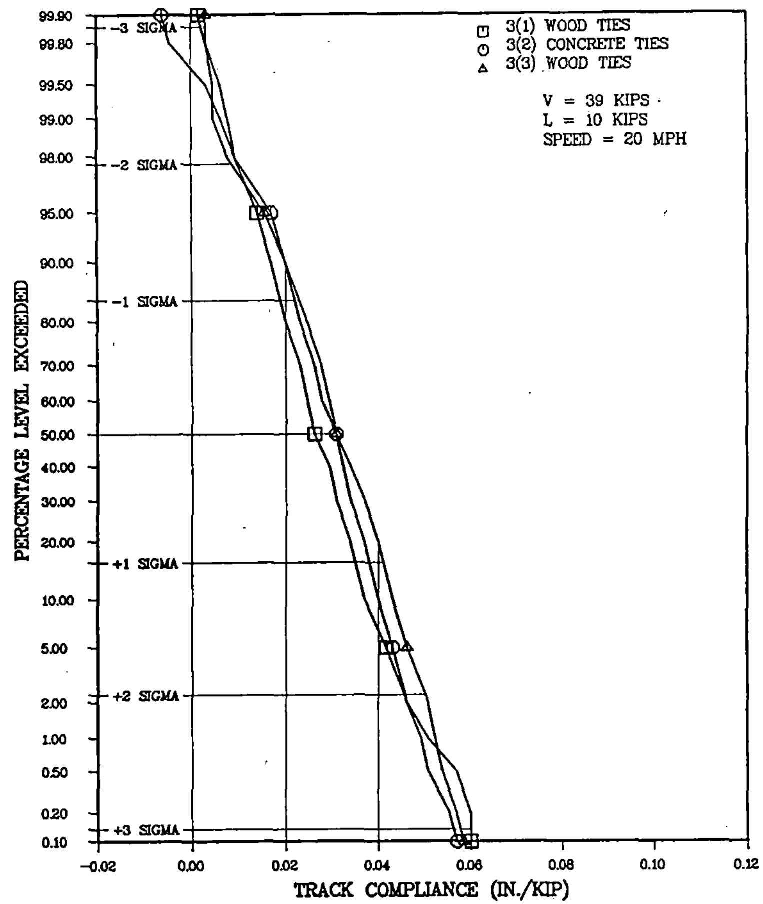


Exhibit **D2.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 3), All Segments, L=10 Kips and V=39 Kips.

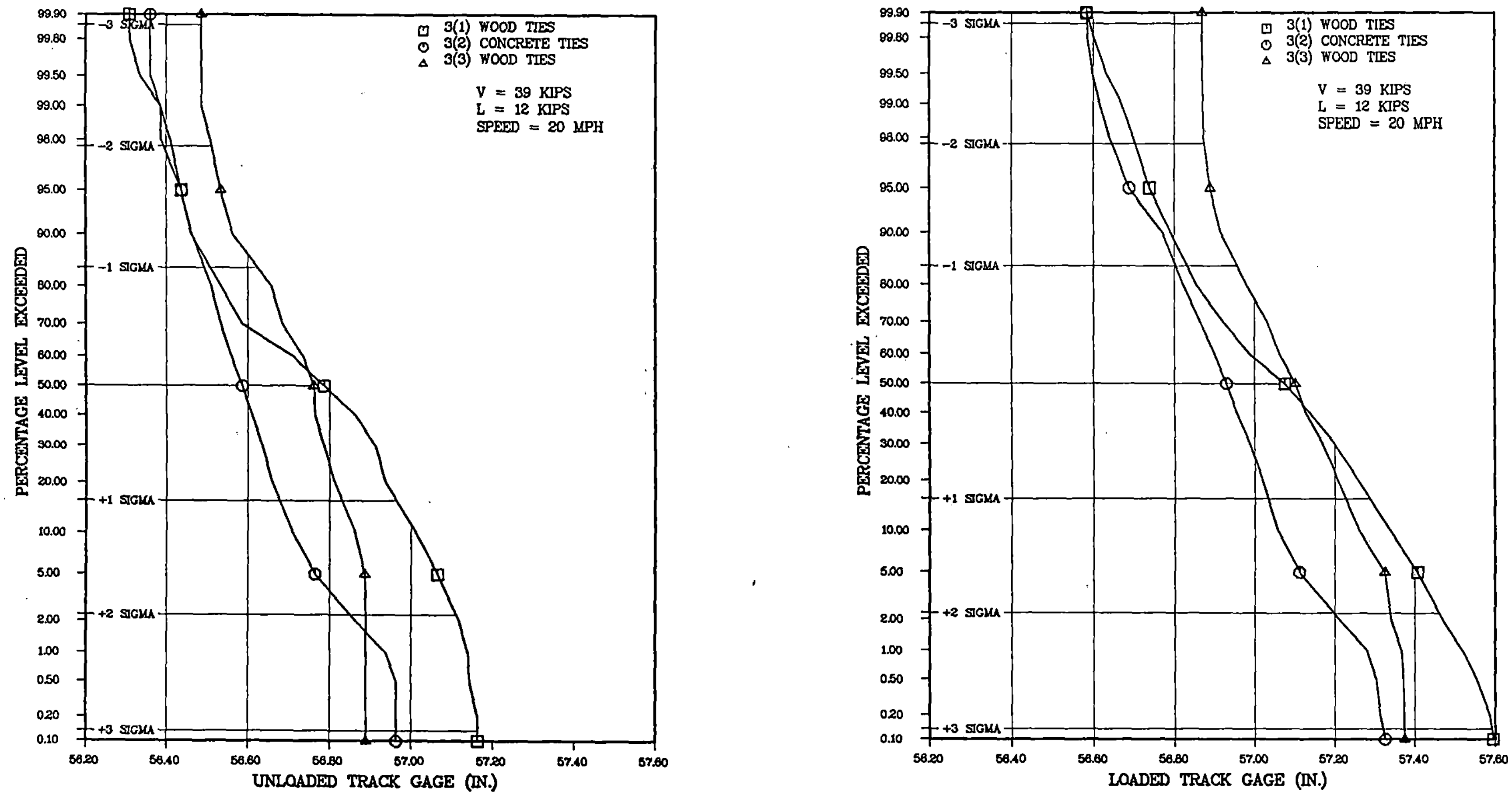


Exhibit **D3.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 3), All Segments, L=12 Kips and V=39 Kips.

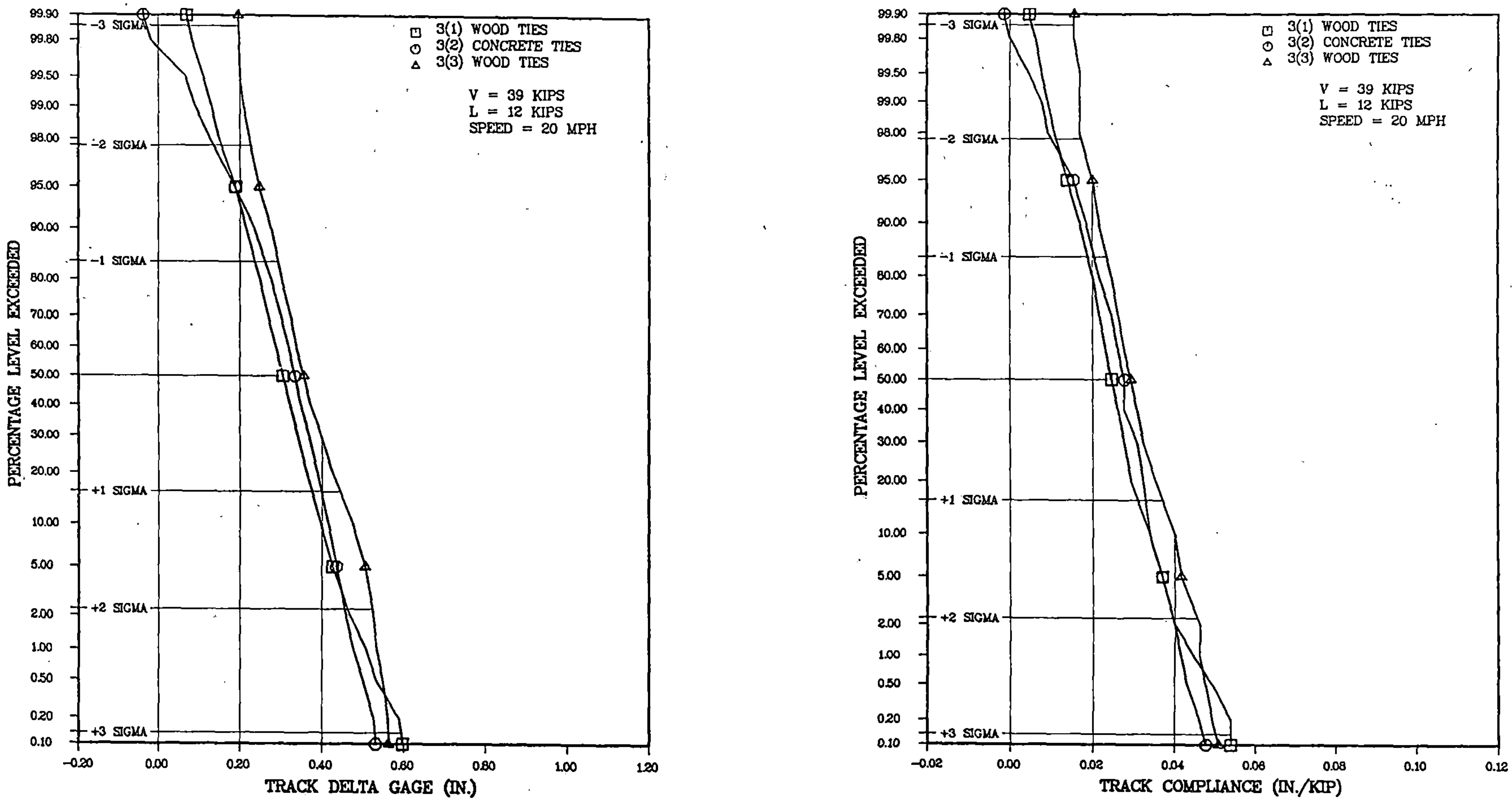
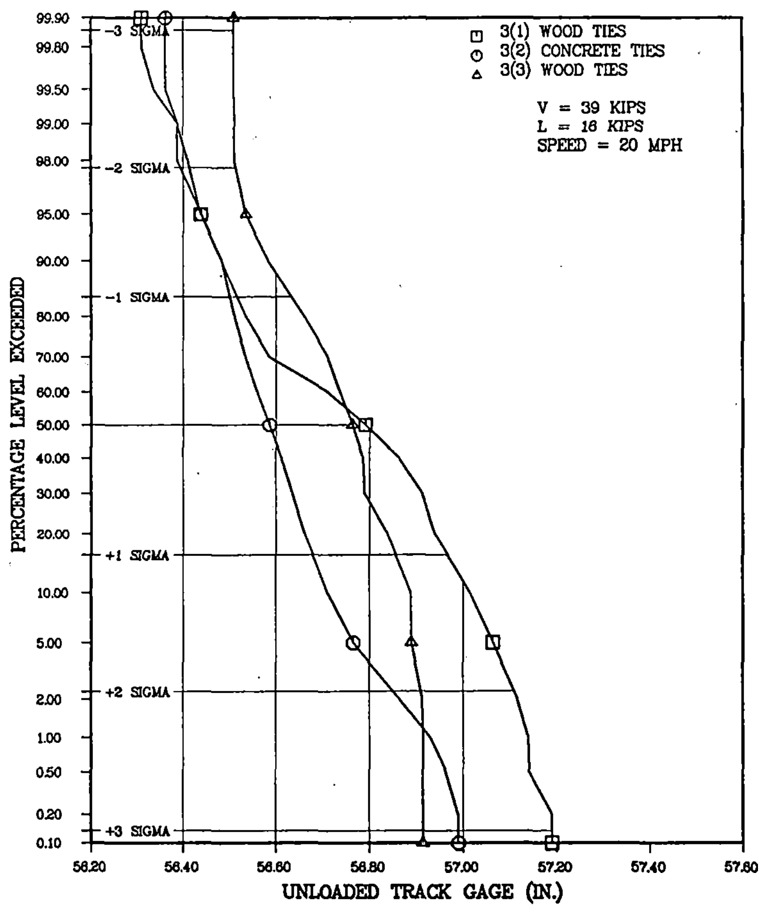
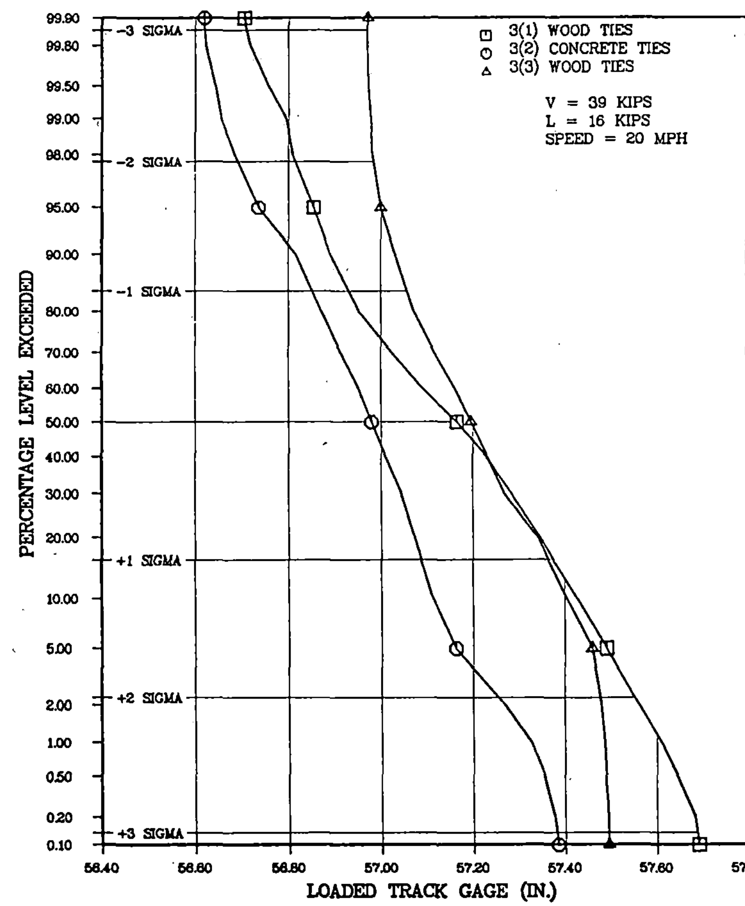


Exhibit **D4.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 3), All Segments, L=12 Kips and V=39 Kips.





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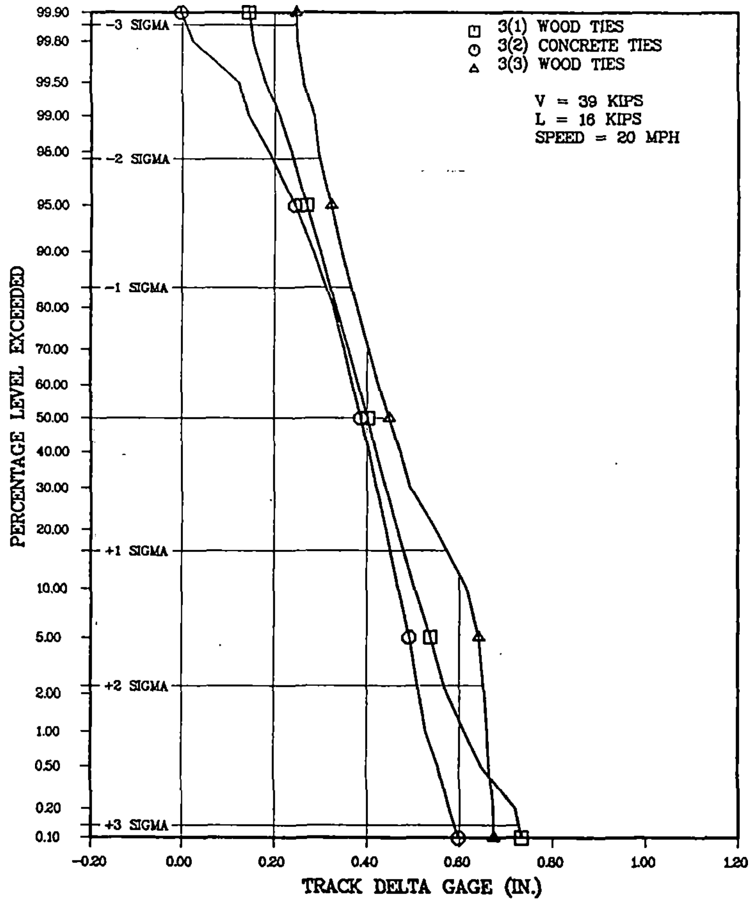


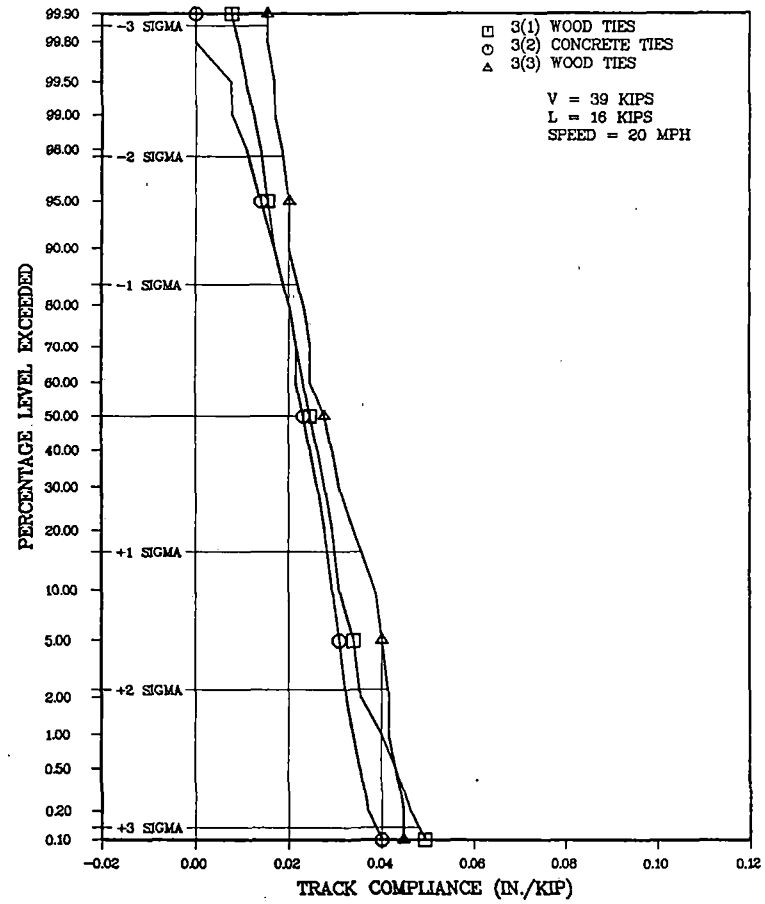


Exhibit **D6.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 3), All Segments, L=16 Kips and V=39 Kips.

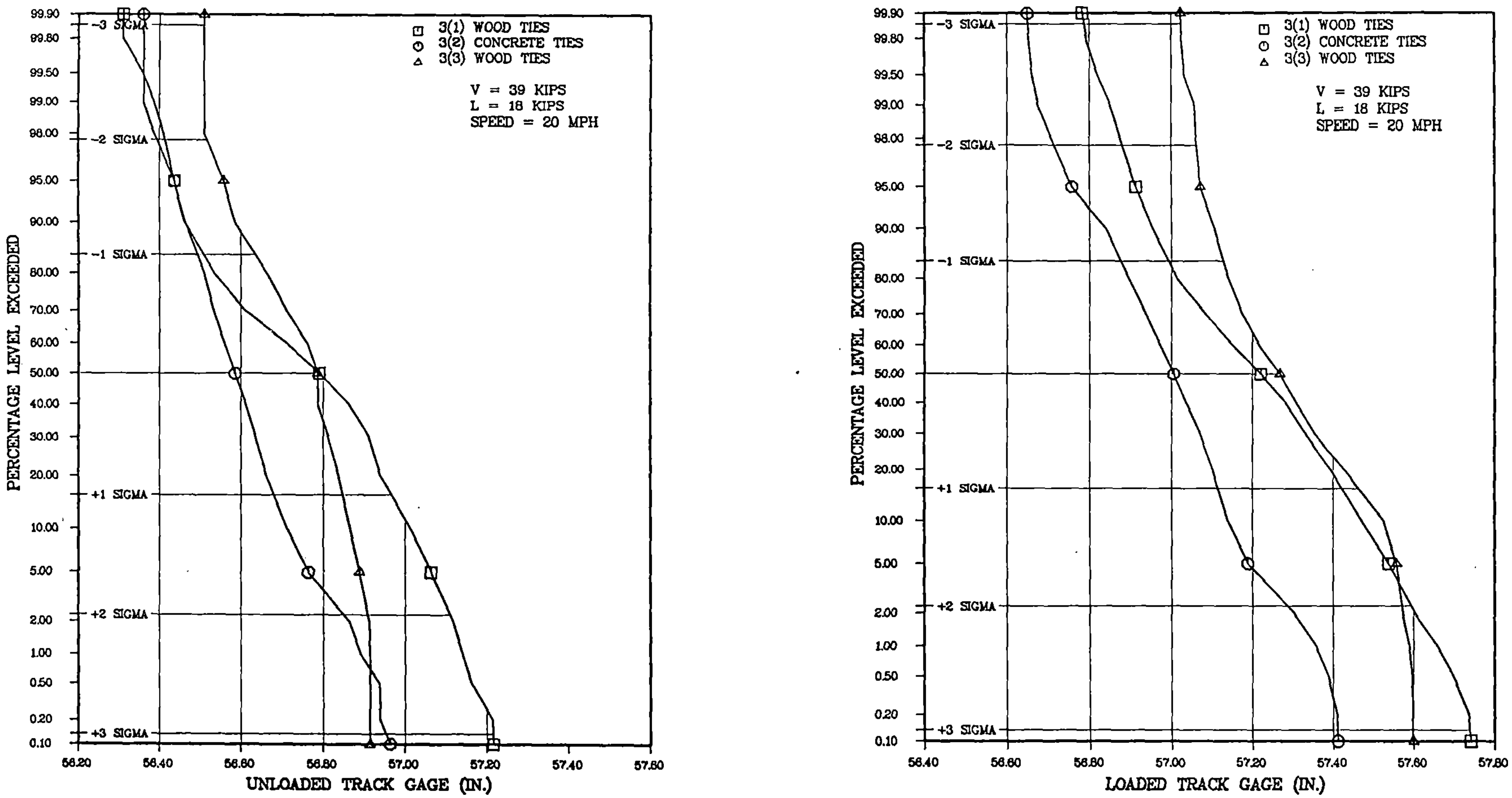


Exhibit **D7.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 3), All Segments, L=18 Kips and V=39 Kips.

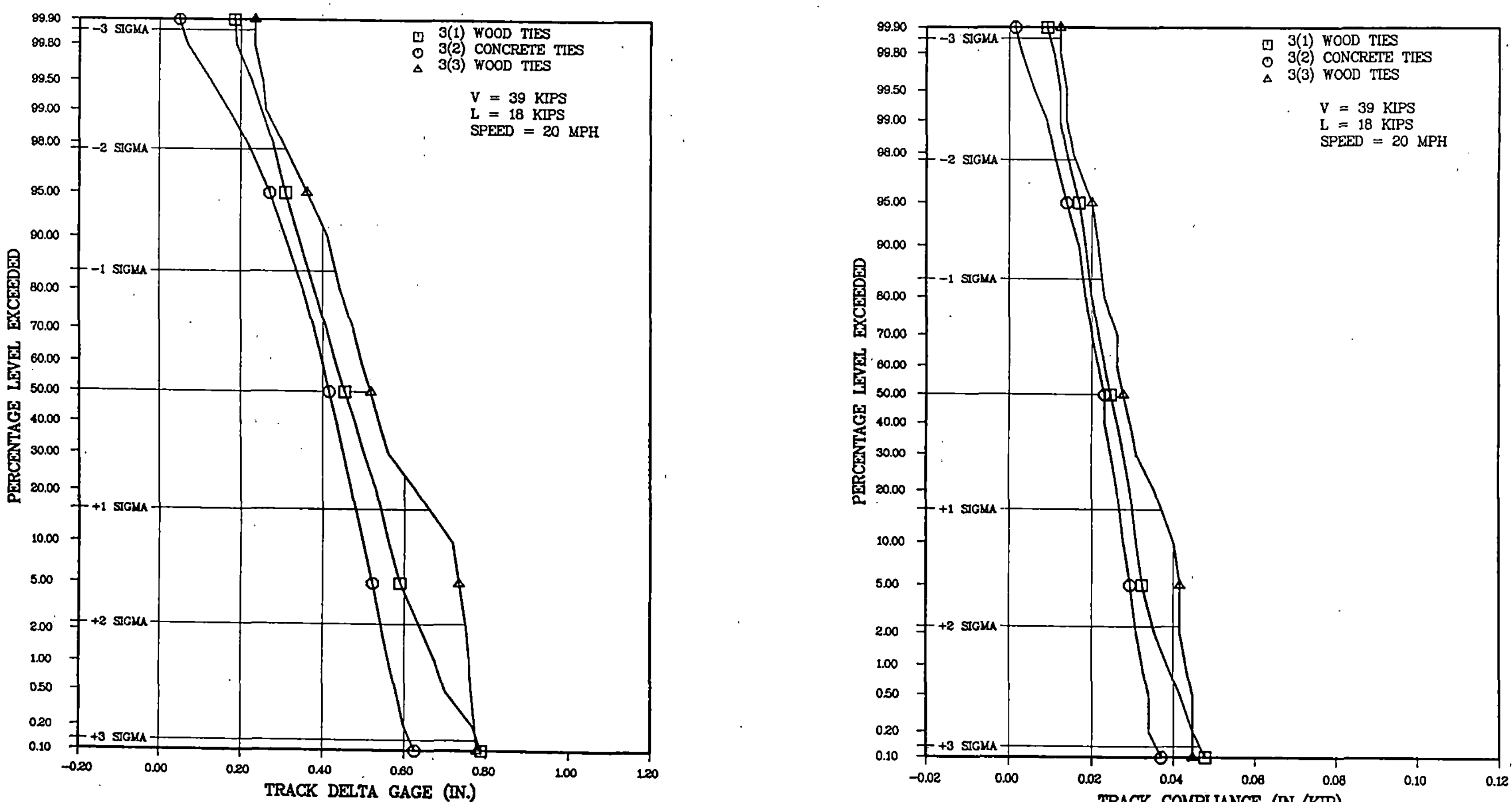
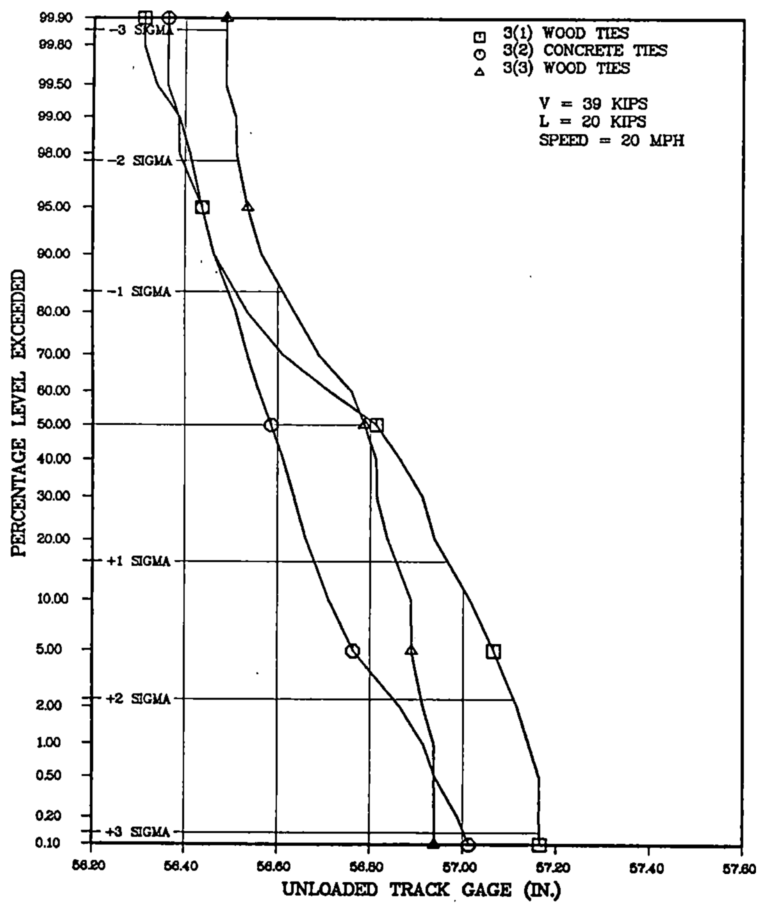
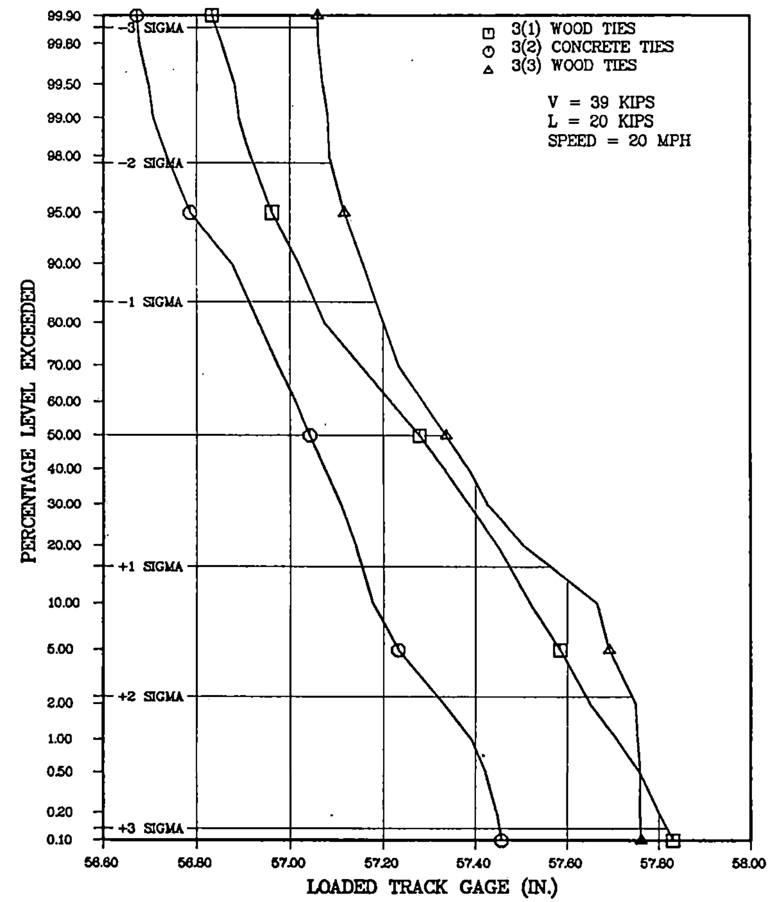


Exhibit **D8.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 3), All Segments, L=18 Kips and V=39 Kips.





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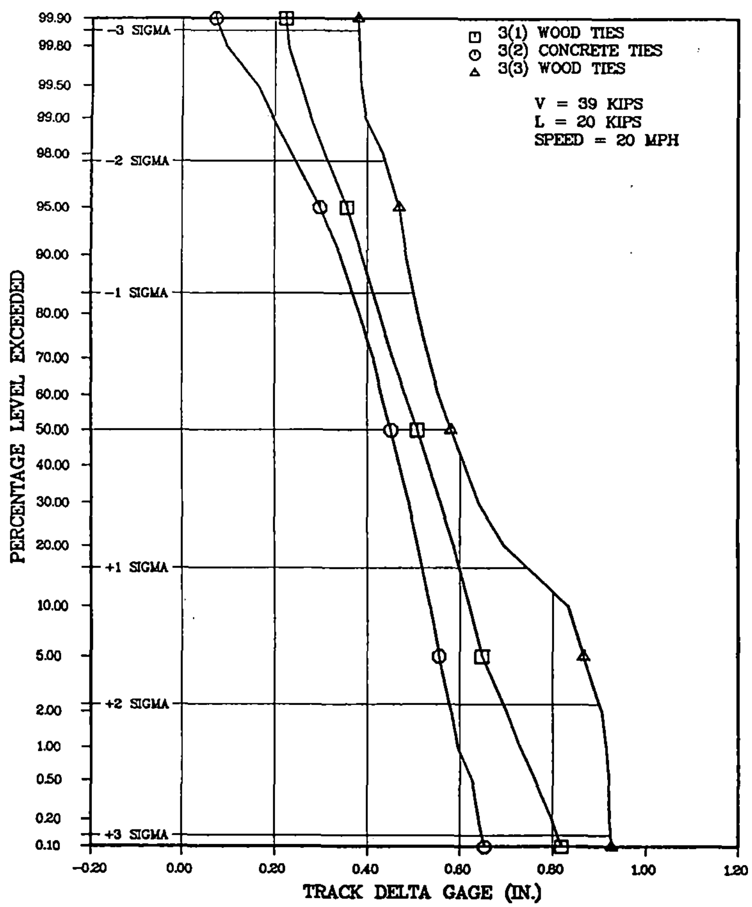


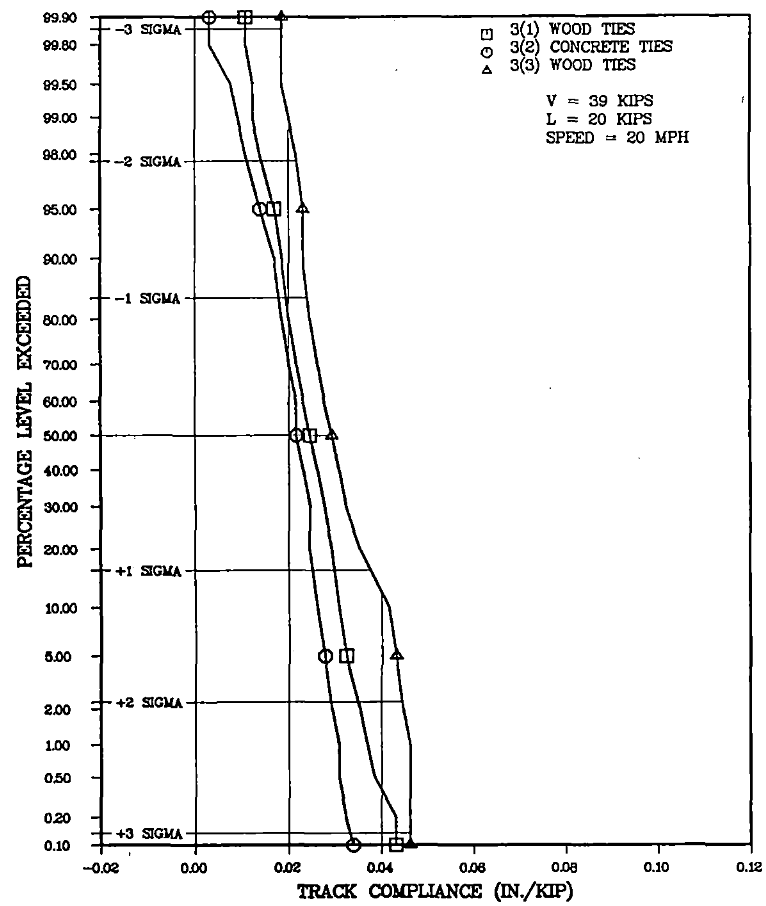
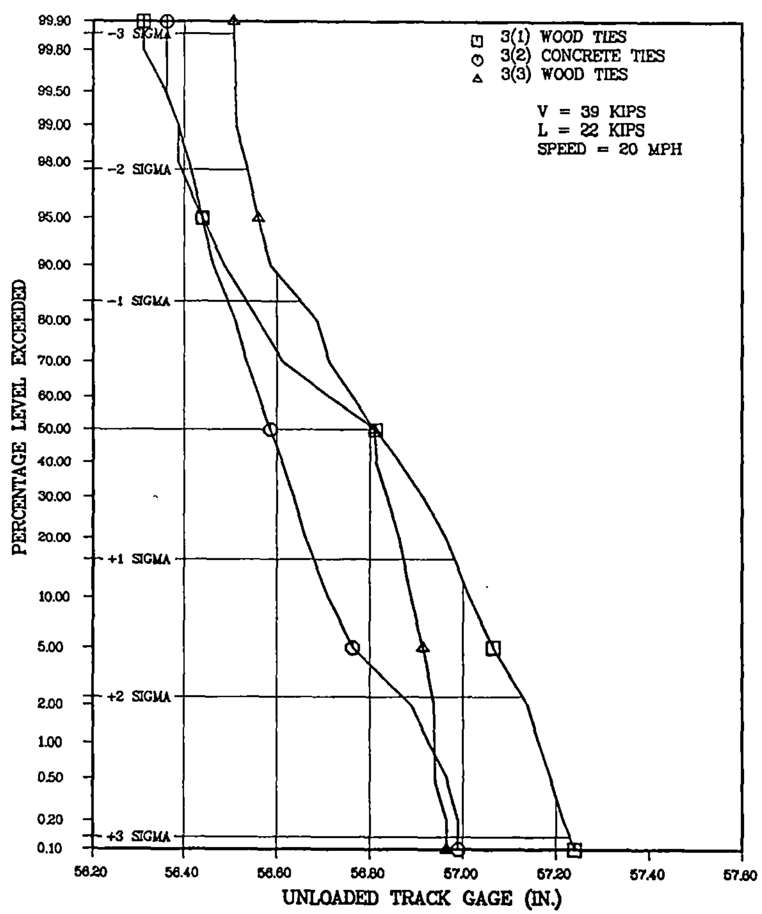


Exhibit **D10.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 3), All Segments, L=20 Kips and V=39 Kips.



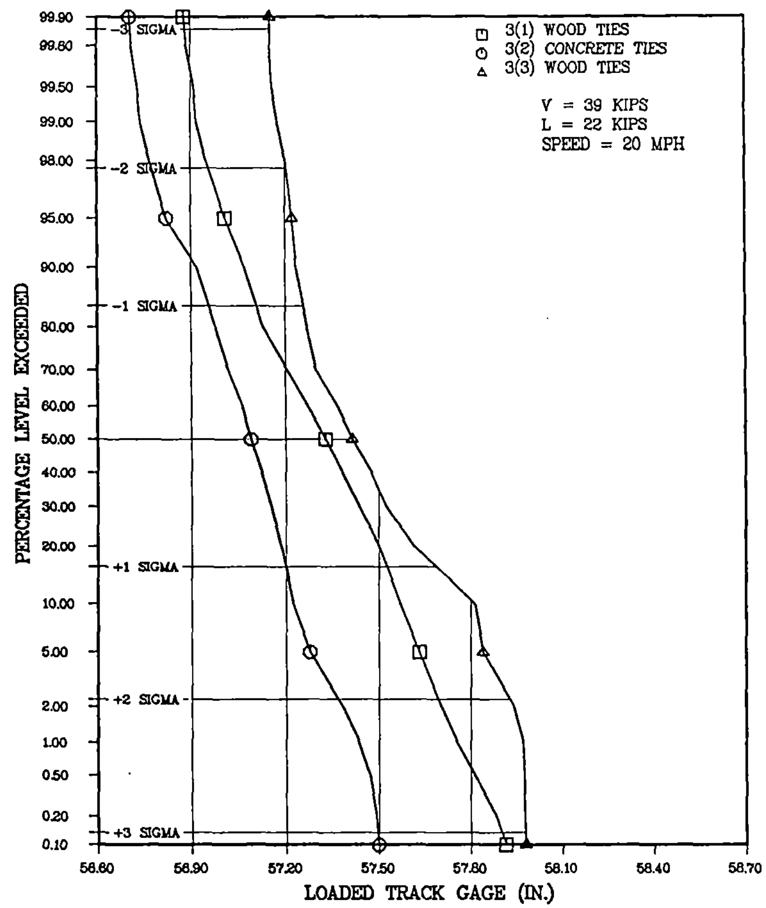
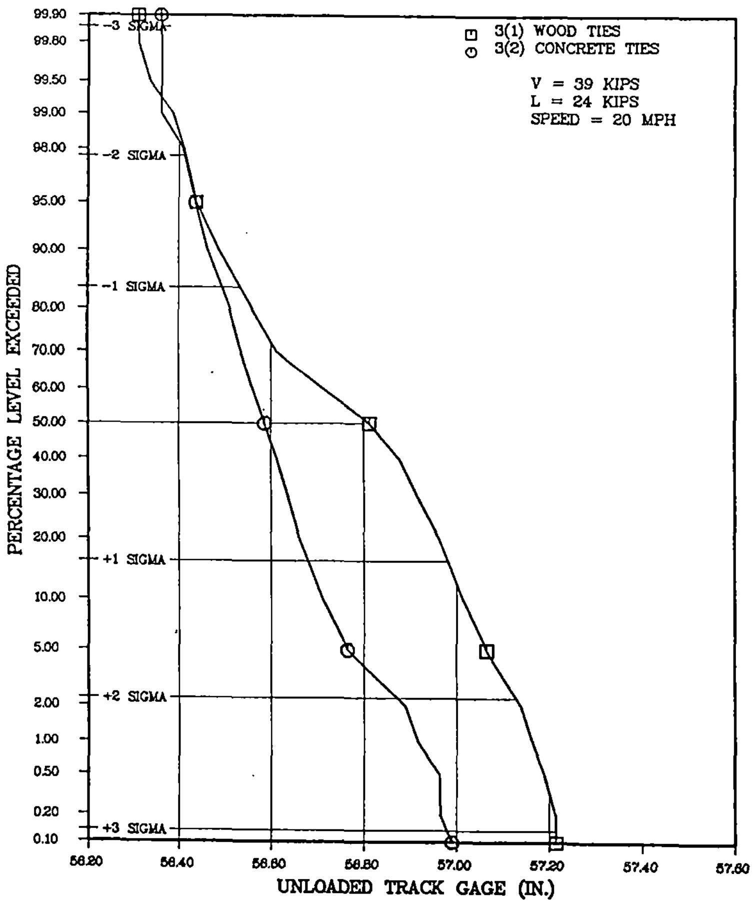


Exhibit **D11.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 3), All Segments, L=22 Kips and V=39 Kips.



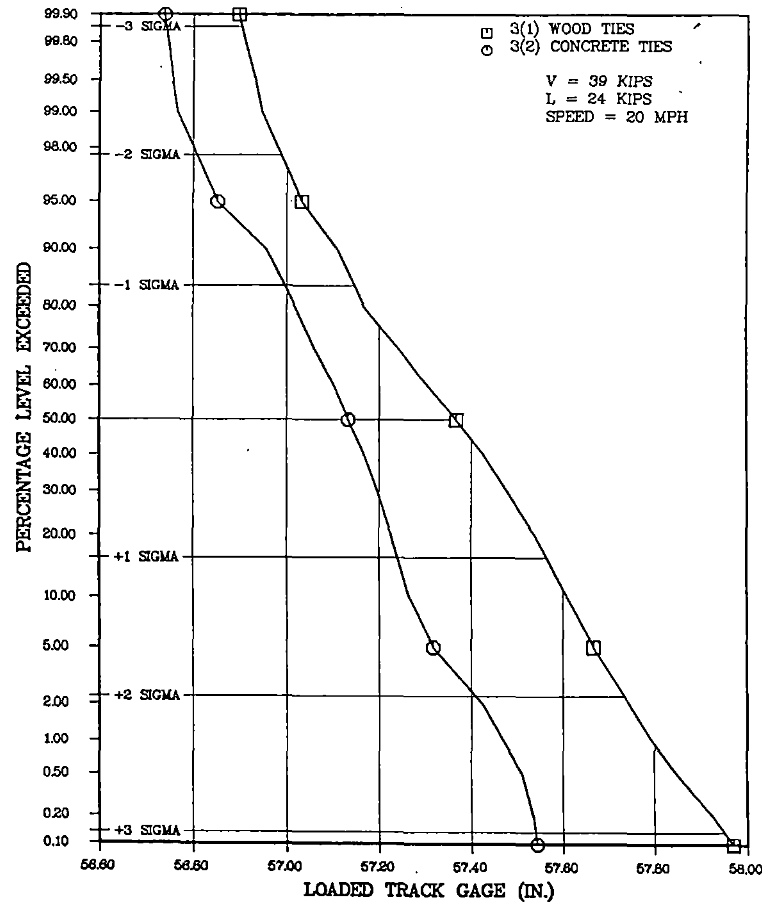
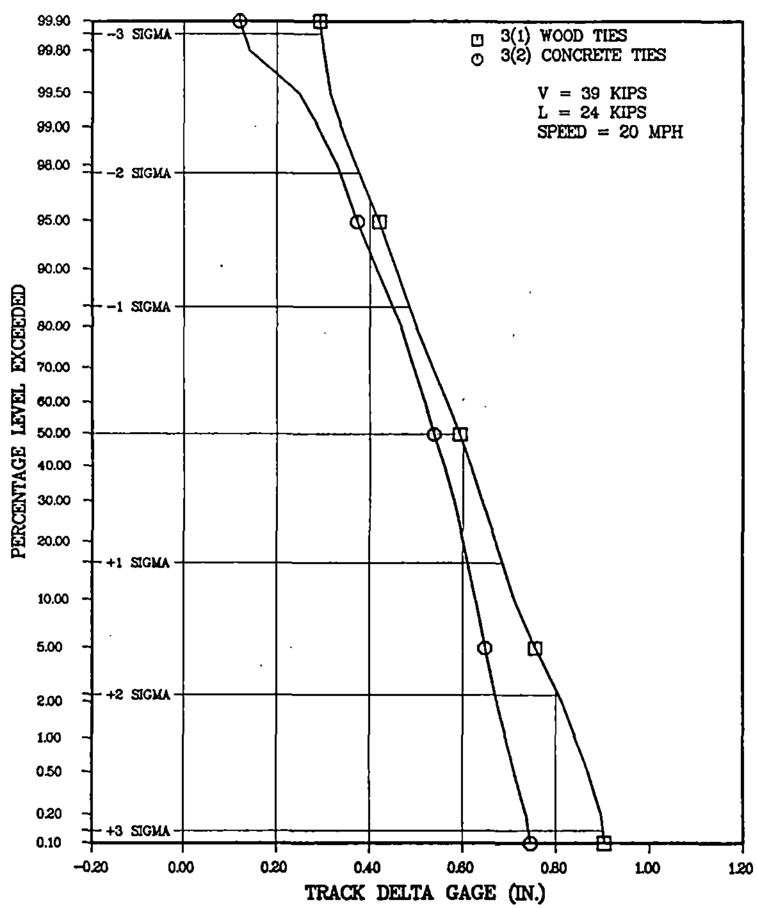


Exhibit **D12.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 3), All Segments, L=24 Kips and V=39 Kips.



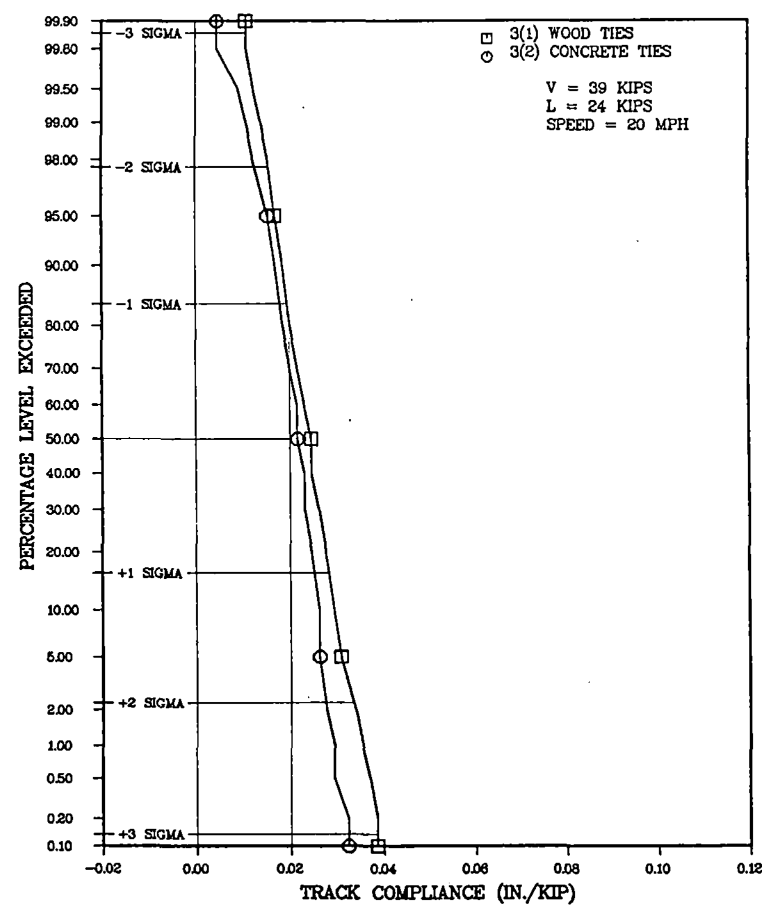


Exhibit **D13.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 3), All Segments, L=24 Kips and V=39 Kips.

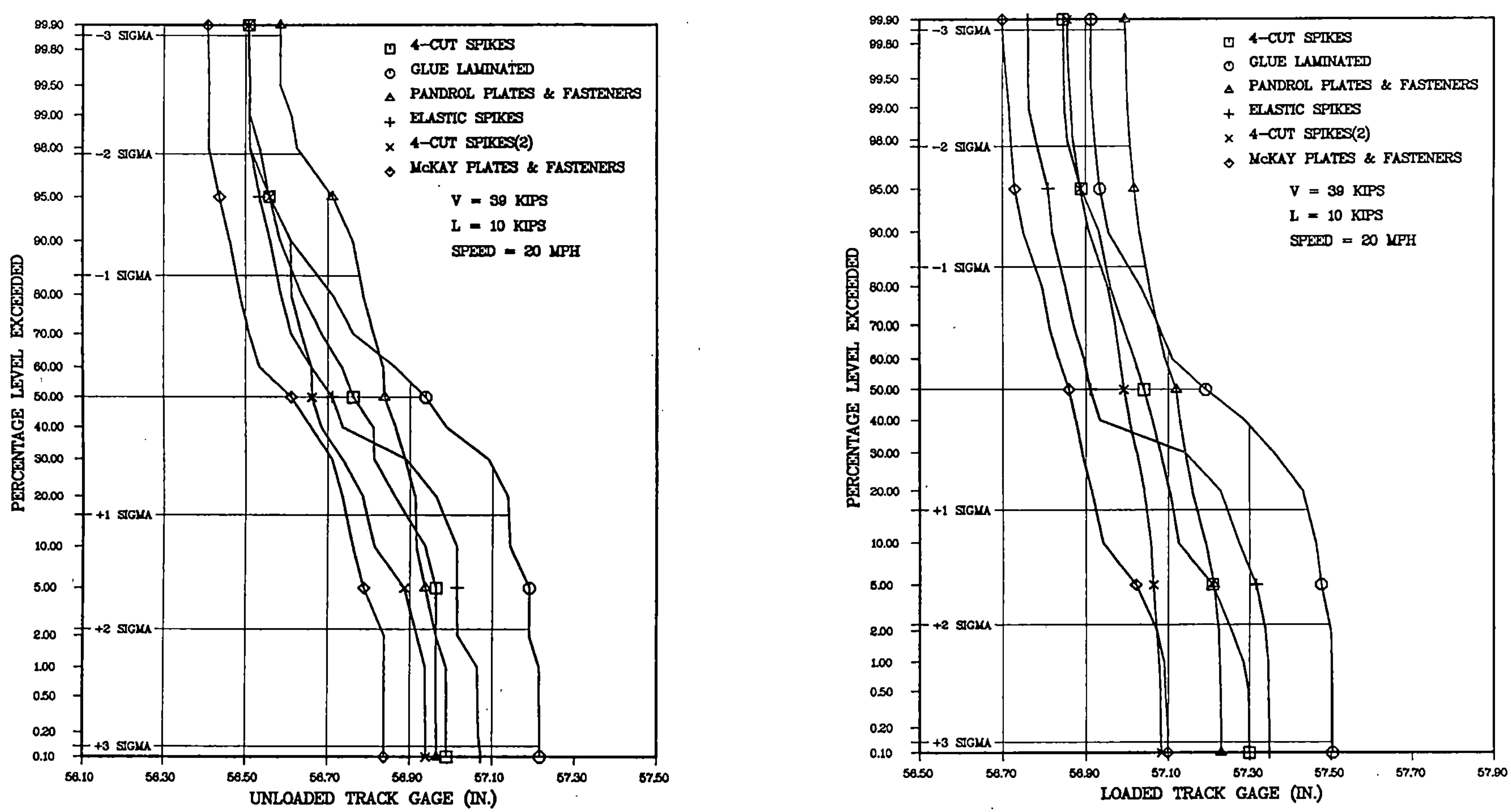
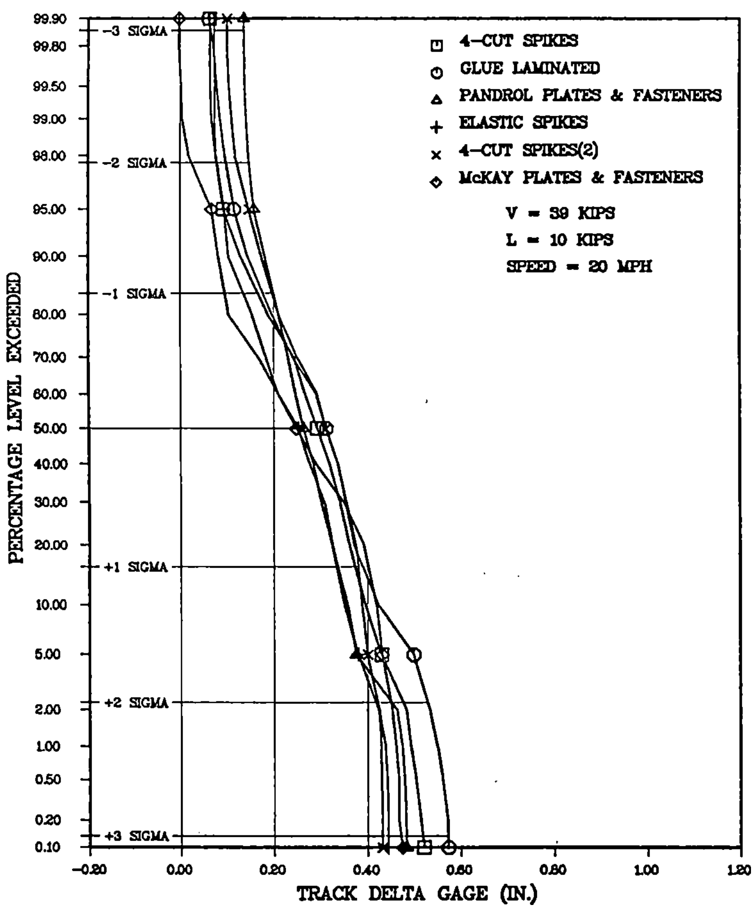


Exhibit **D14.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 7), All Segments, L=10 Kips and V=39 Kips.



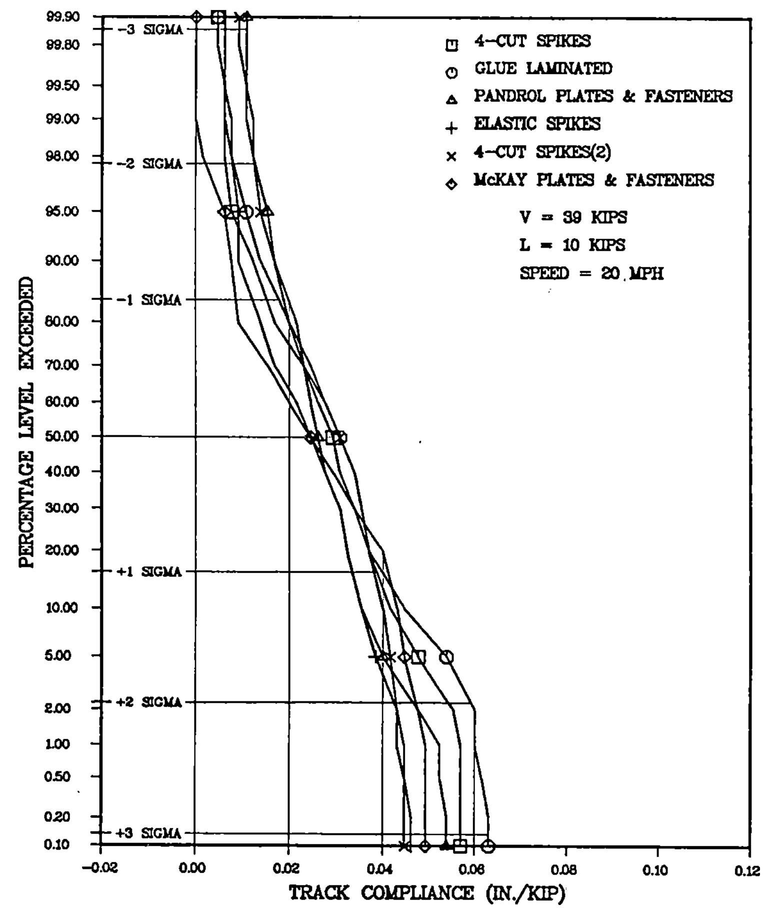


Exhibit **D15.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 7), All Segments, L=10 Kips and V=39 Kips.

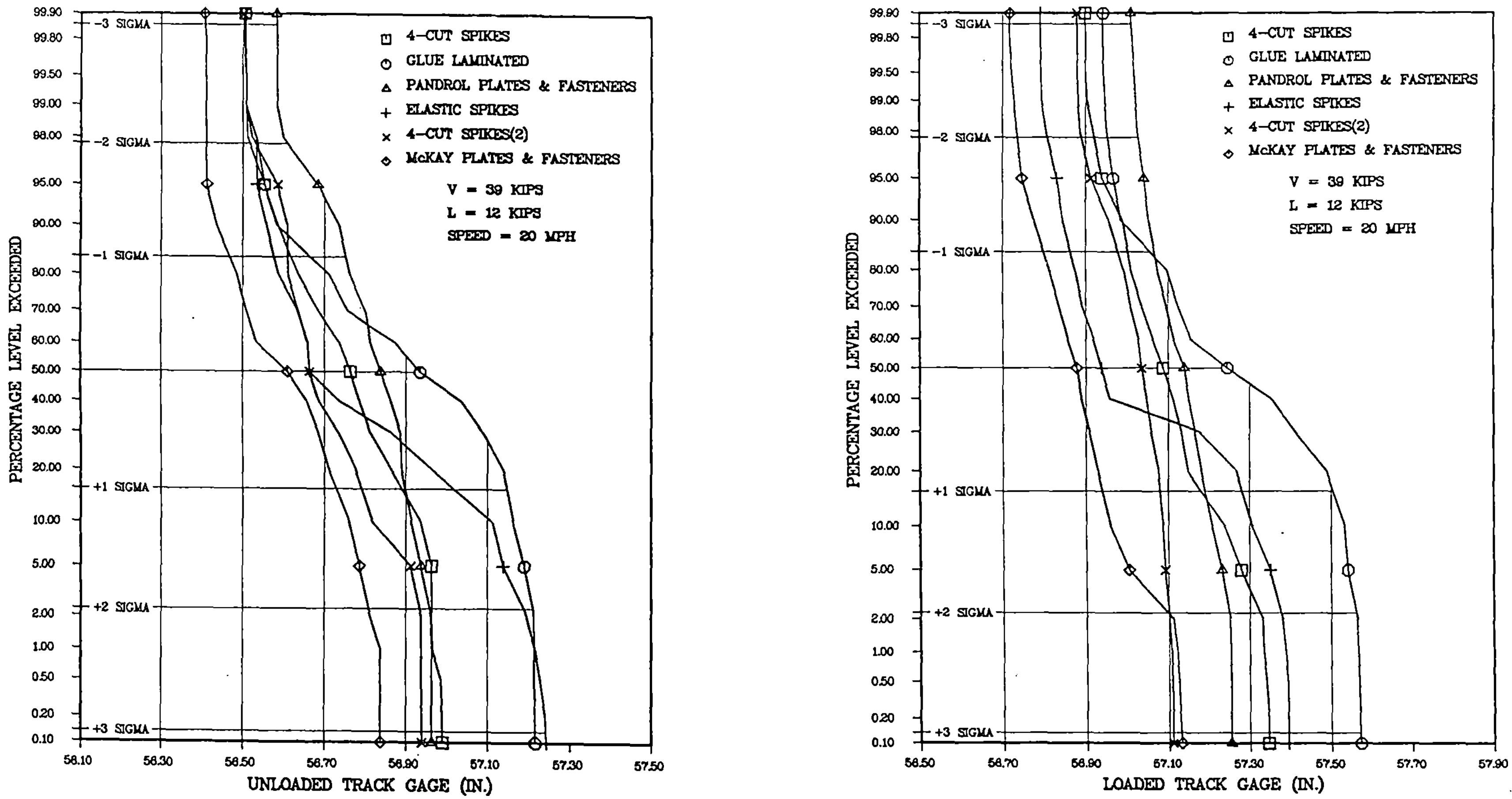
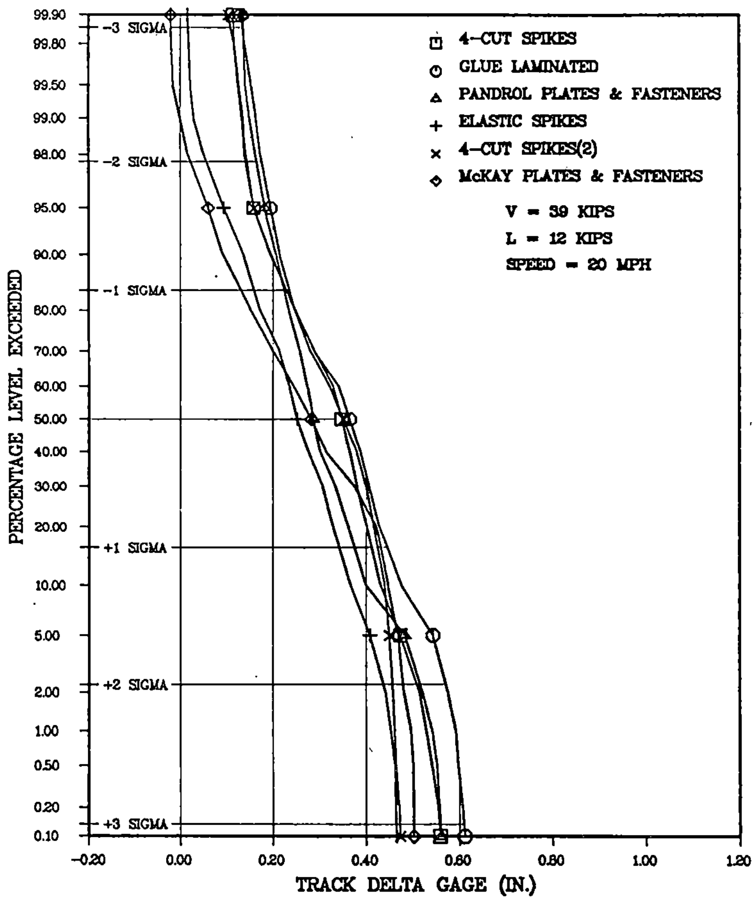


Exhibit **D16.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 7), All Segments, L=12 Kips and V=39 Kips.



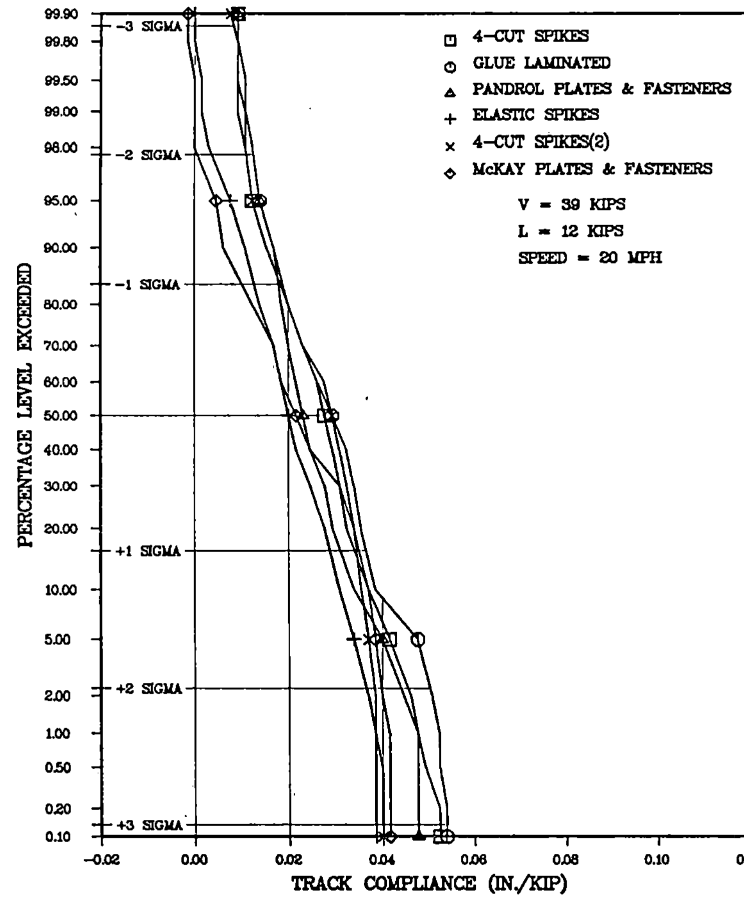
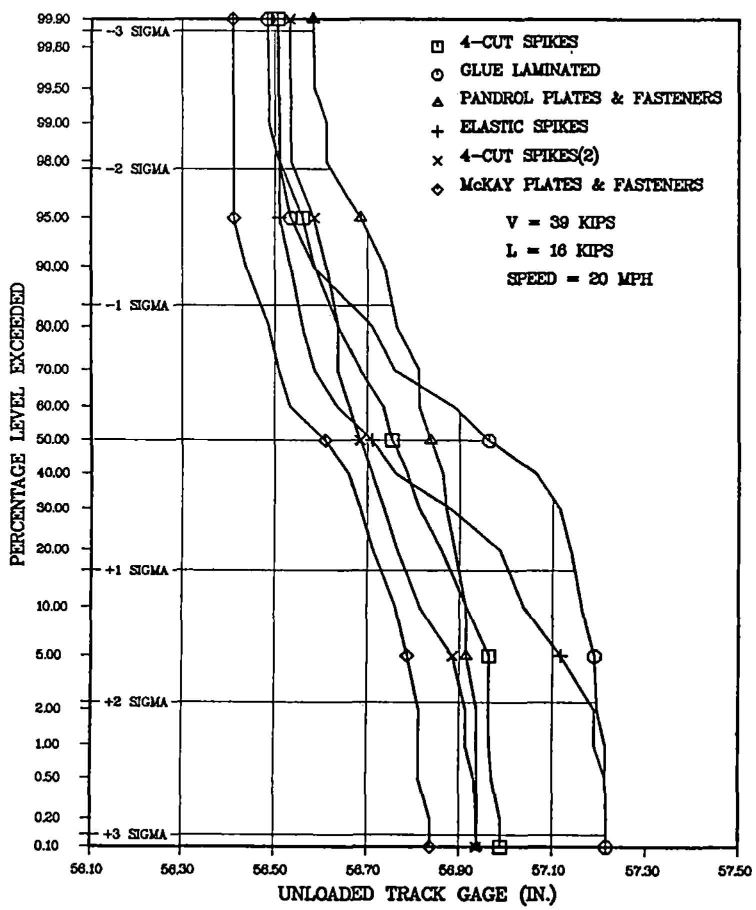


Exhibit **D17.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 7), All Segments, L=12 Kips and V=39 Kips.



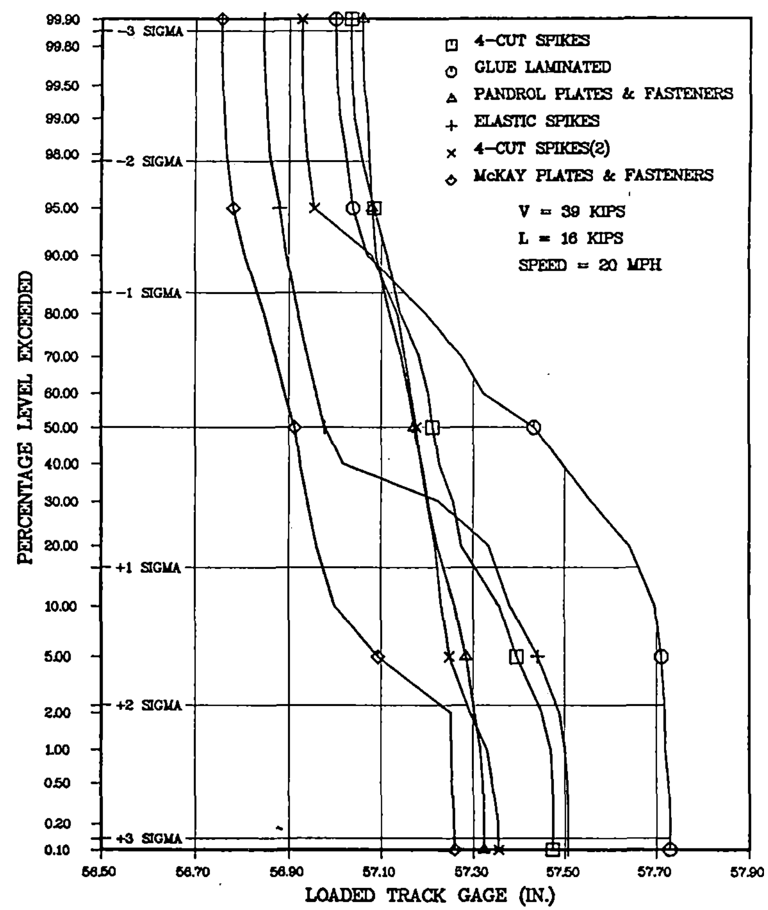
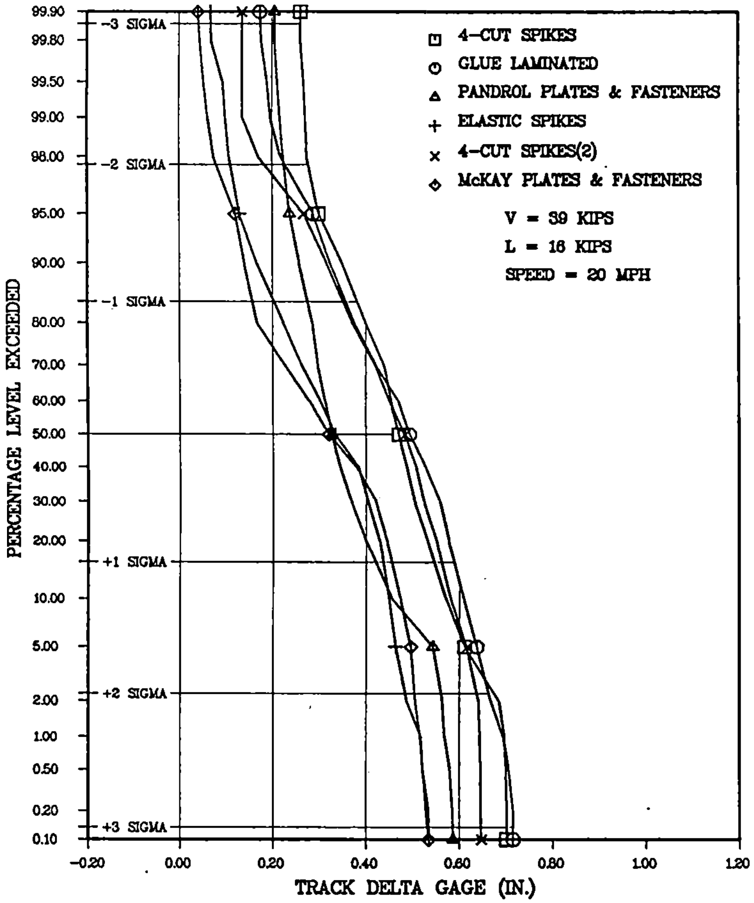


Exhibit **D18.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 7), All Segments, L=16 Kips and V=39 Kips.



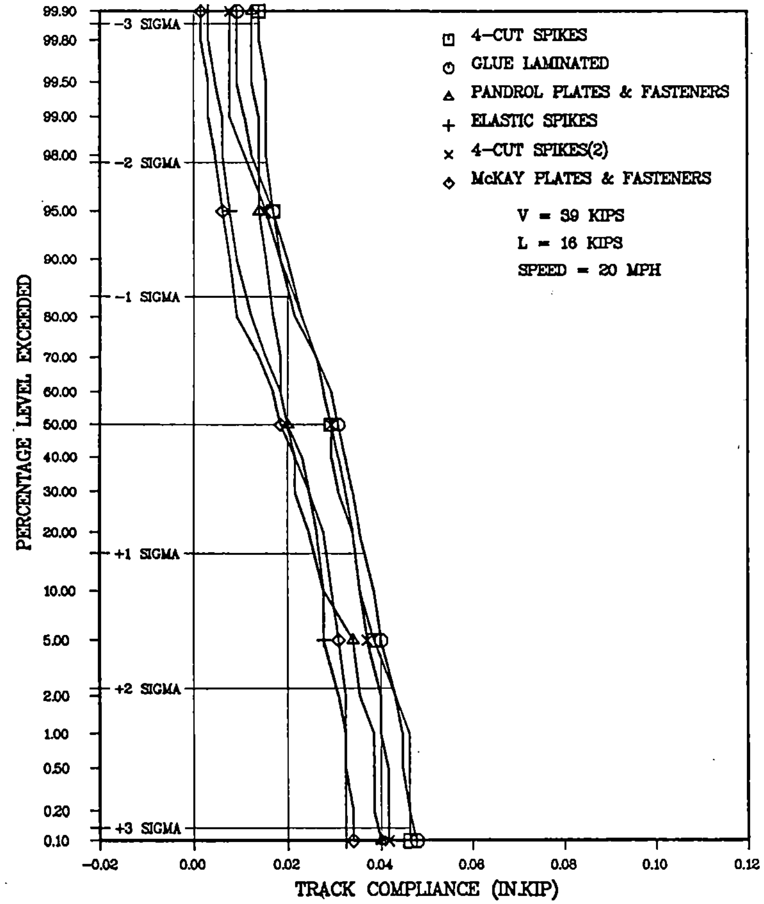


Exhibit **D19.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 7), All Segments, L=16 Kips and V=39 Kips.

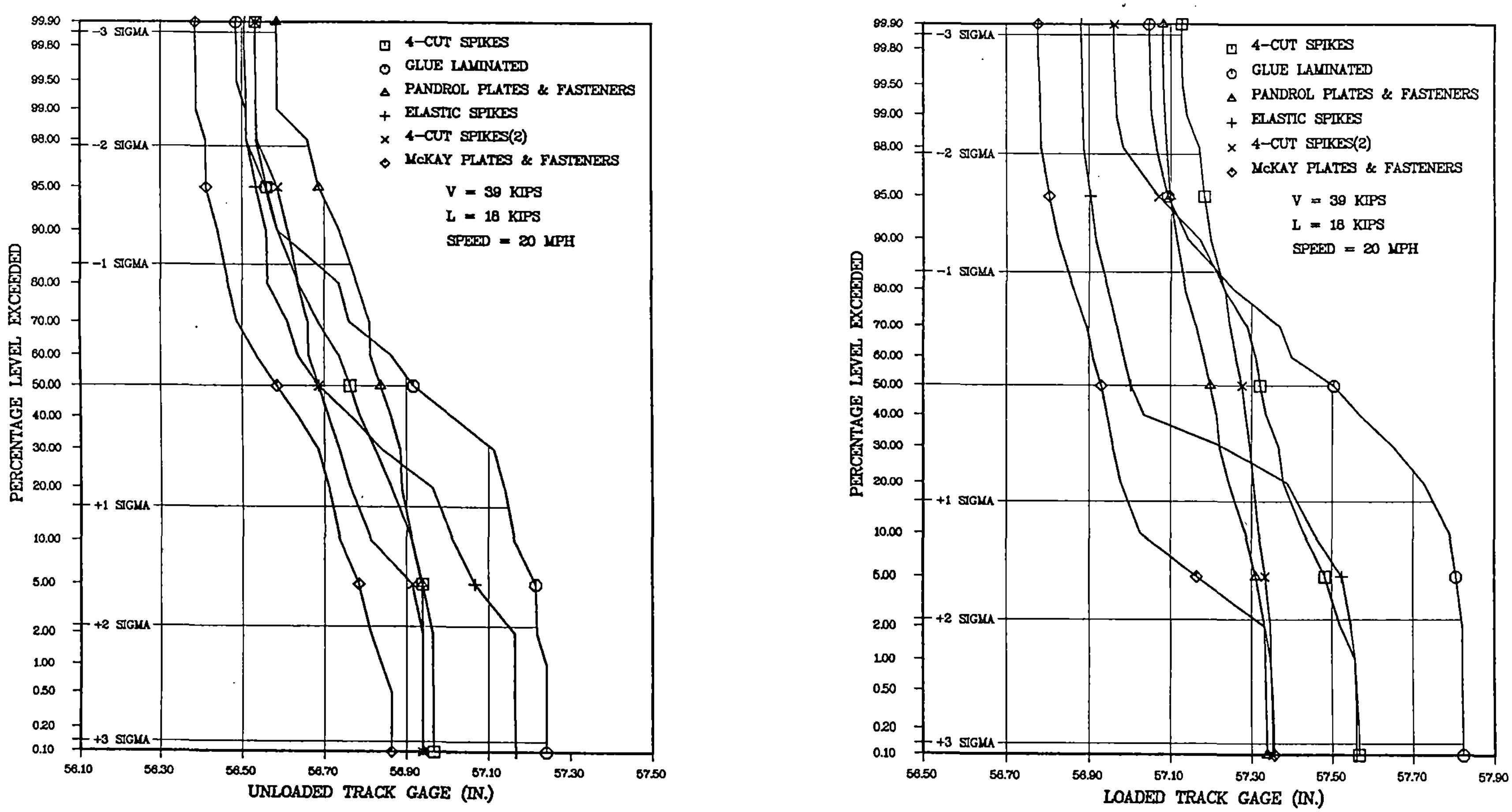
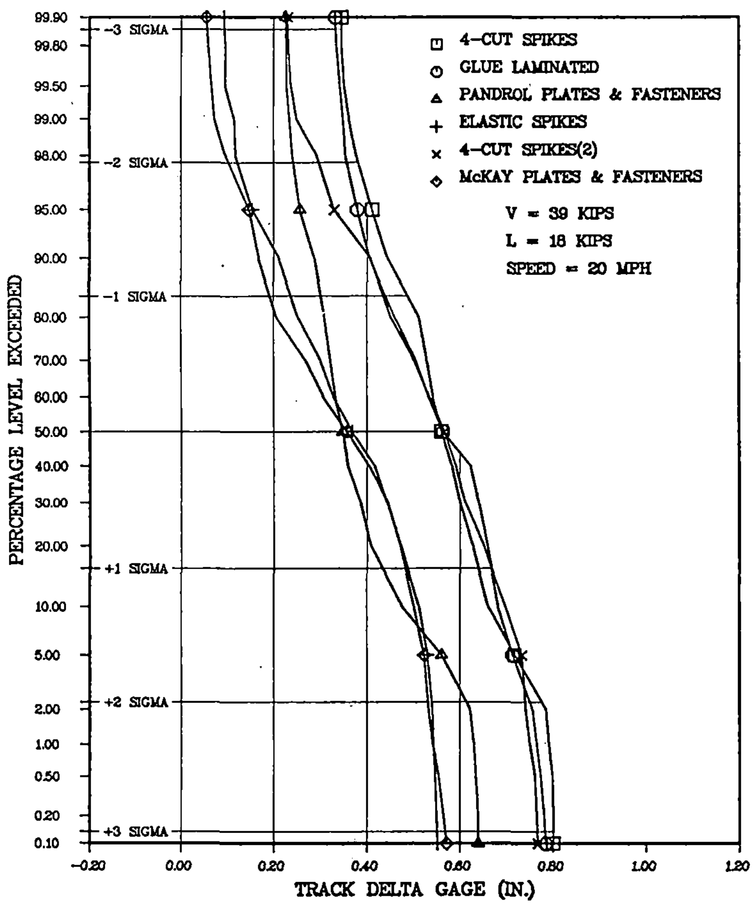


Exhibit **D20.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 7), All Segments, L=18 Kips and V=39 Kips.



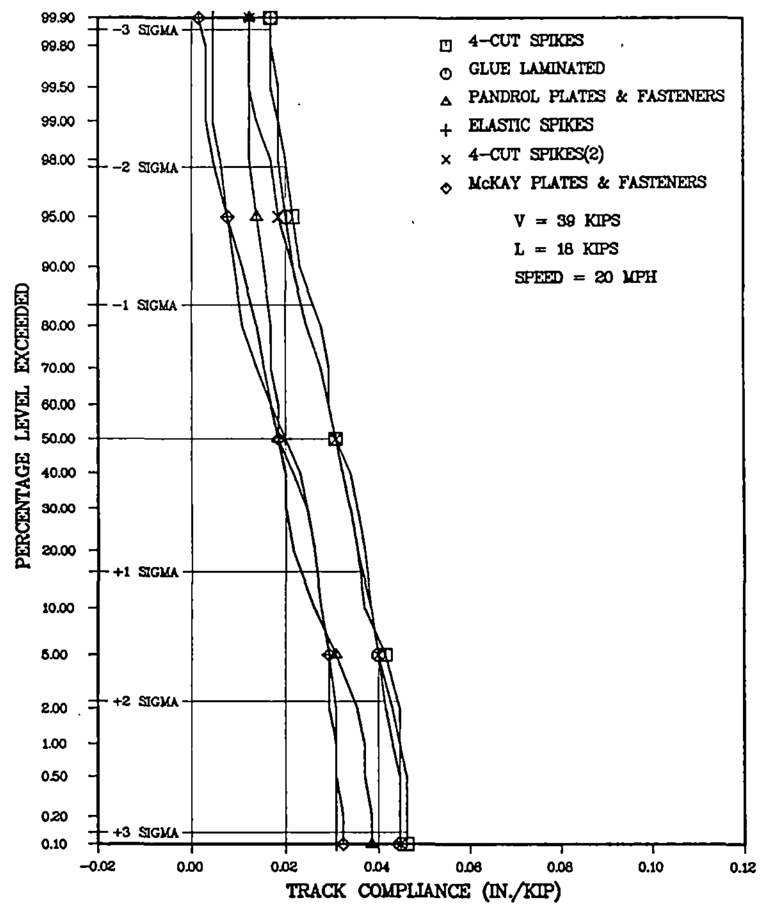
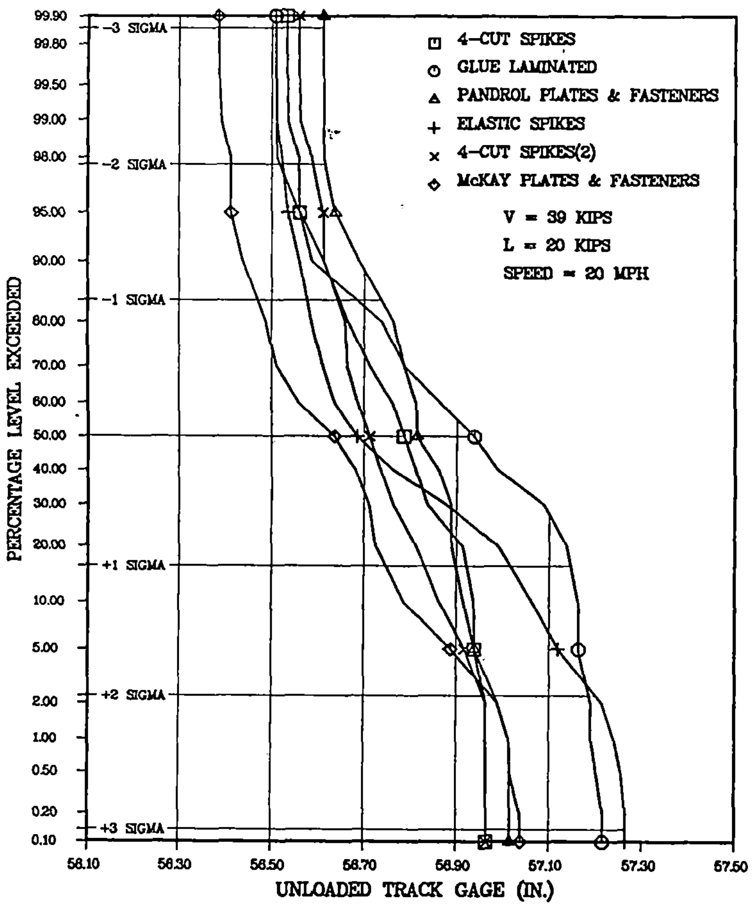


Exhibit **D21.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 7), All Segments, L=18 Kips and V=39 Kips.



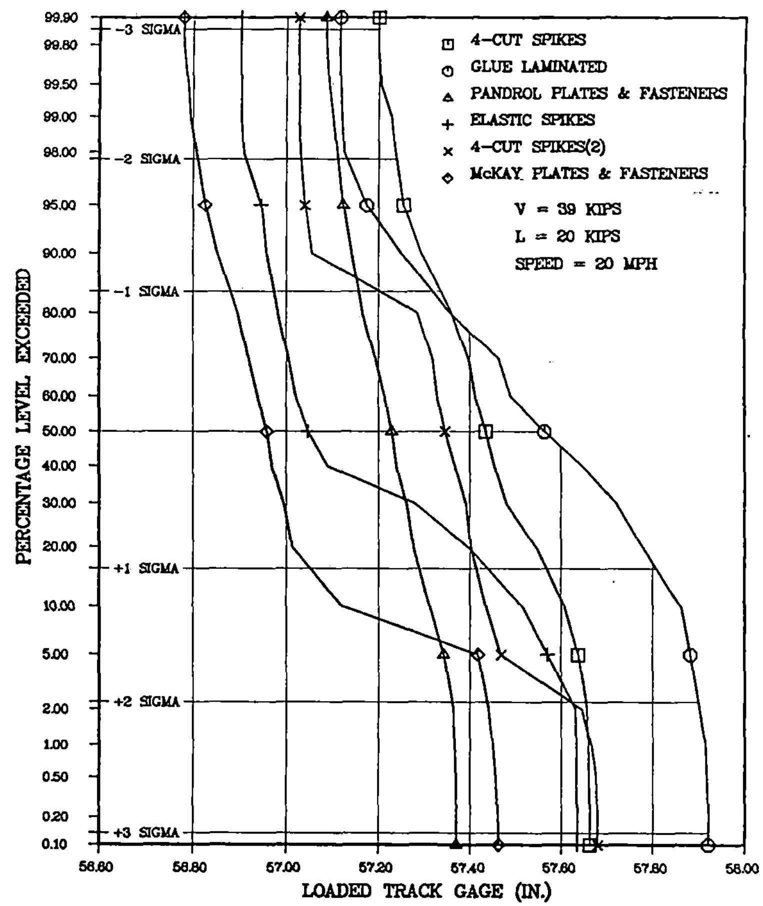
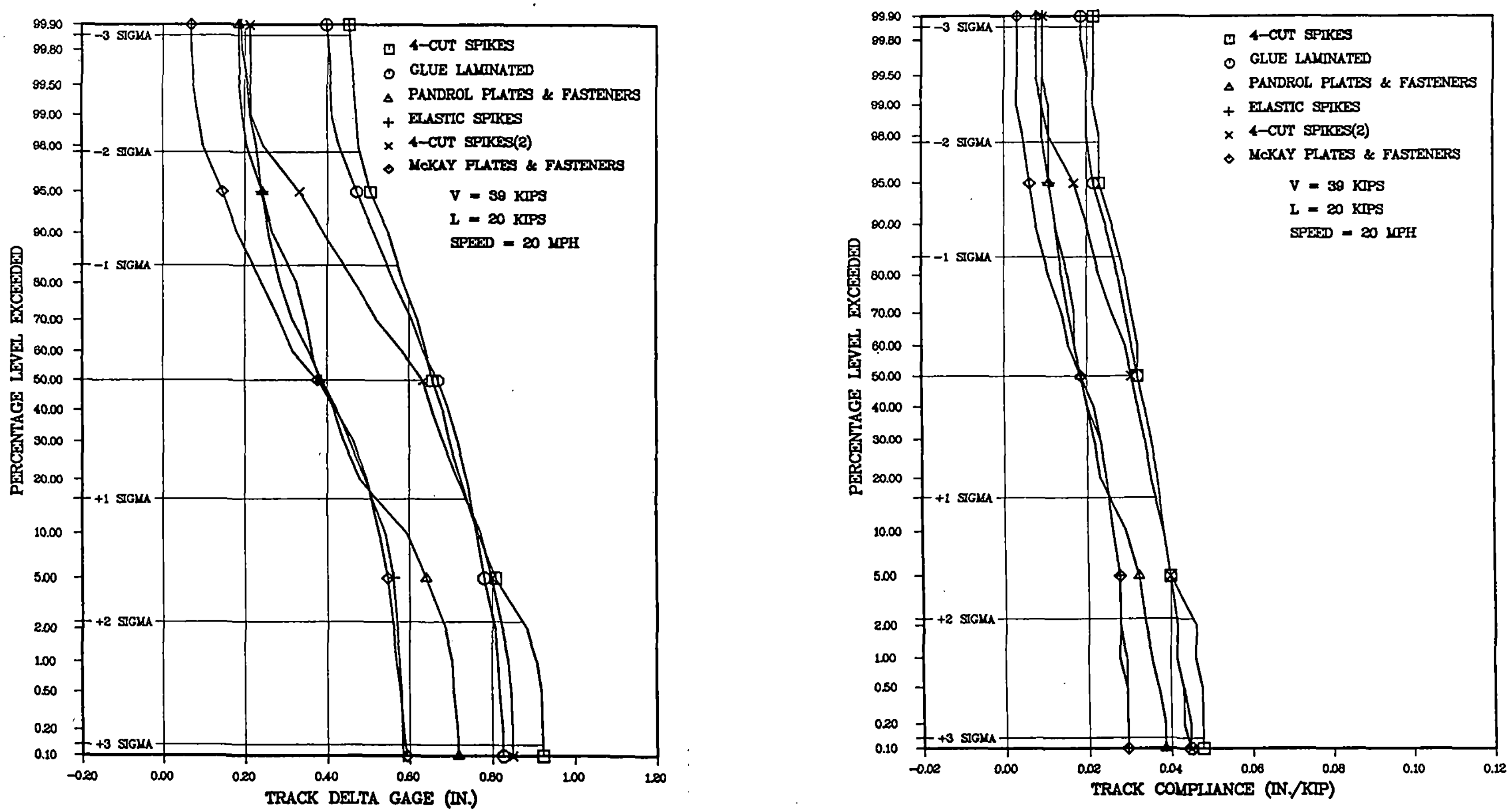


Exhibit **D22.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 7), All Segments, L=20 Kips and V=39 Kips.



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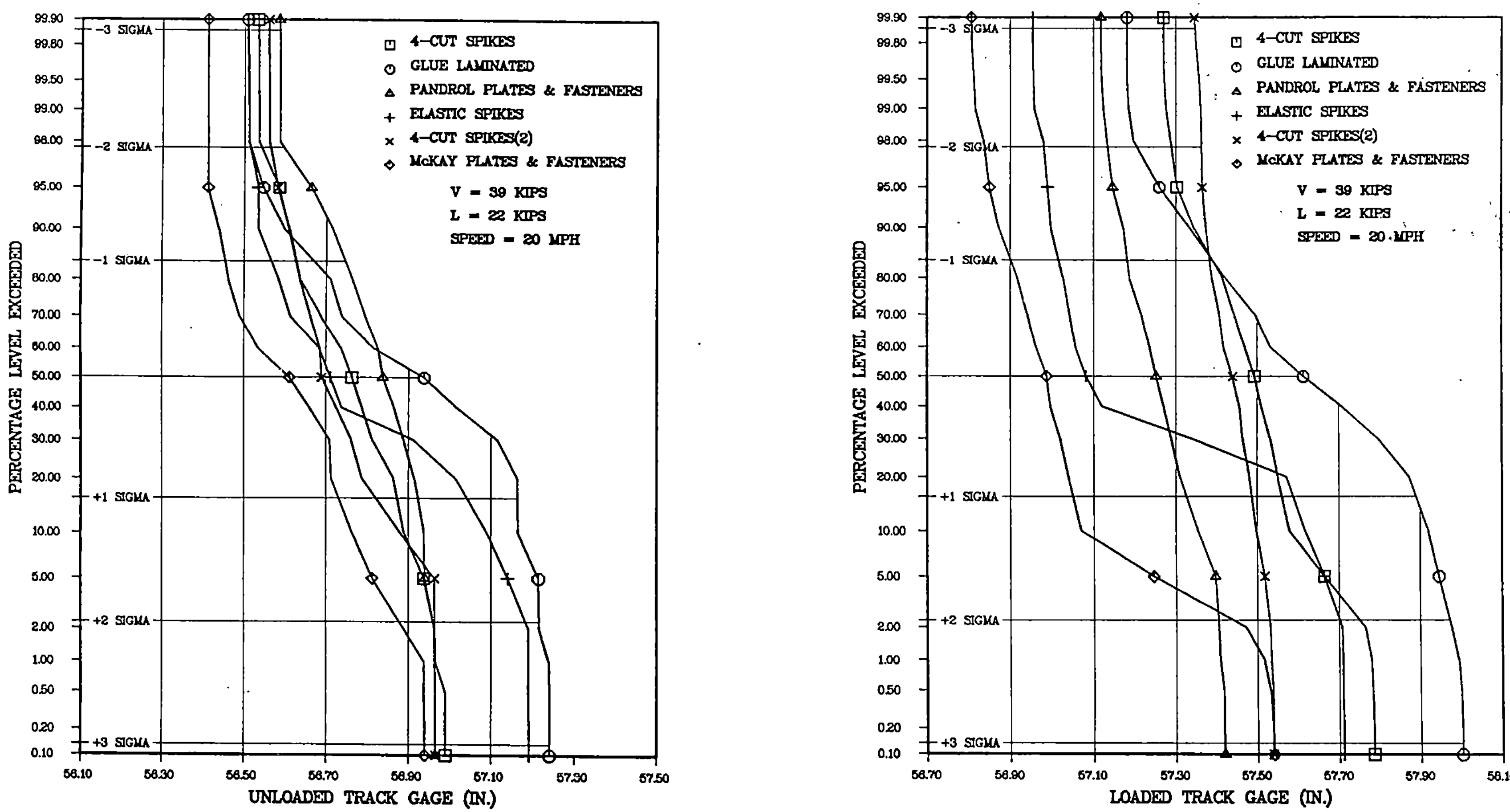
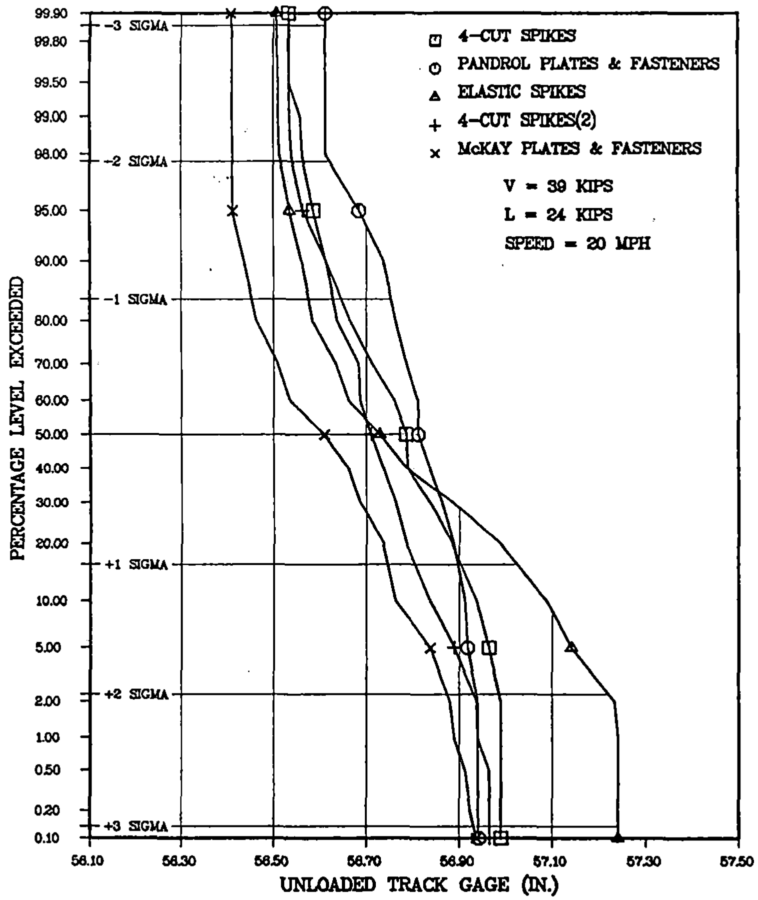


Exhibit **D24.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 7), All Segments, L=22 Kips and V=39 Kips.



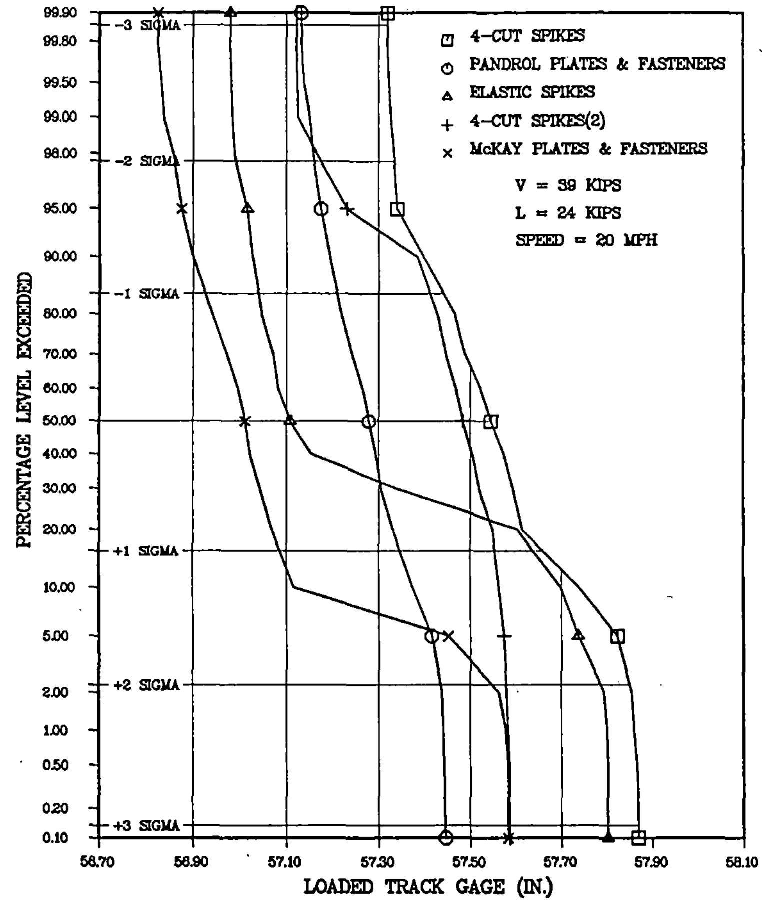


Exhibit **D25.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 7), All Segments, L=24 Kips and V=39 Kips.

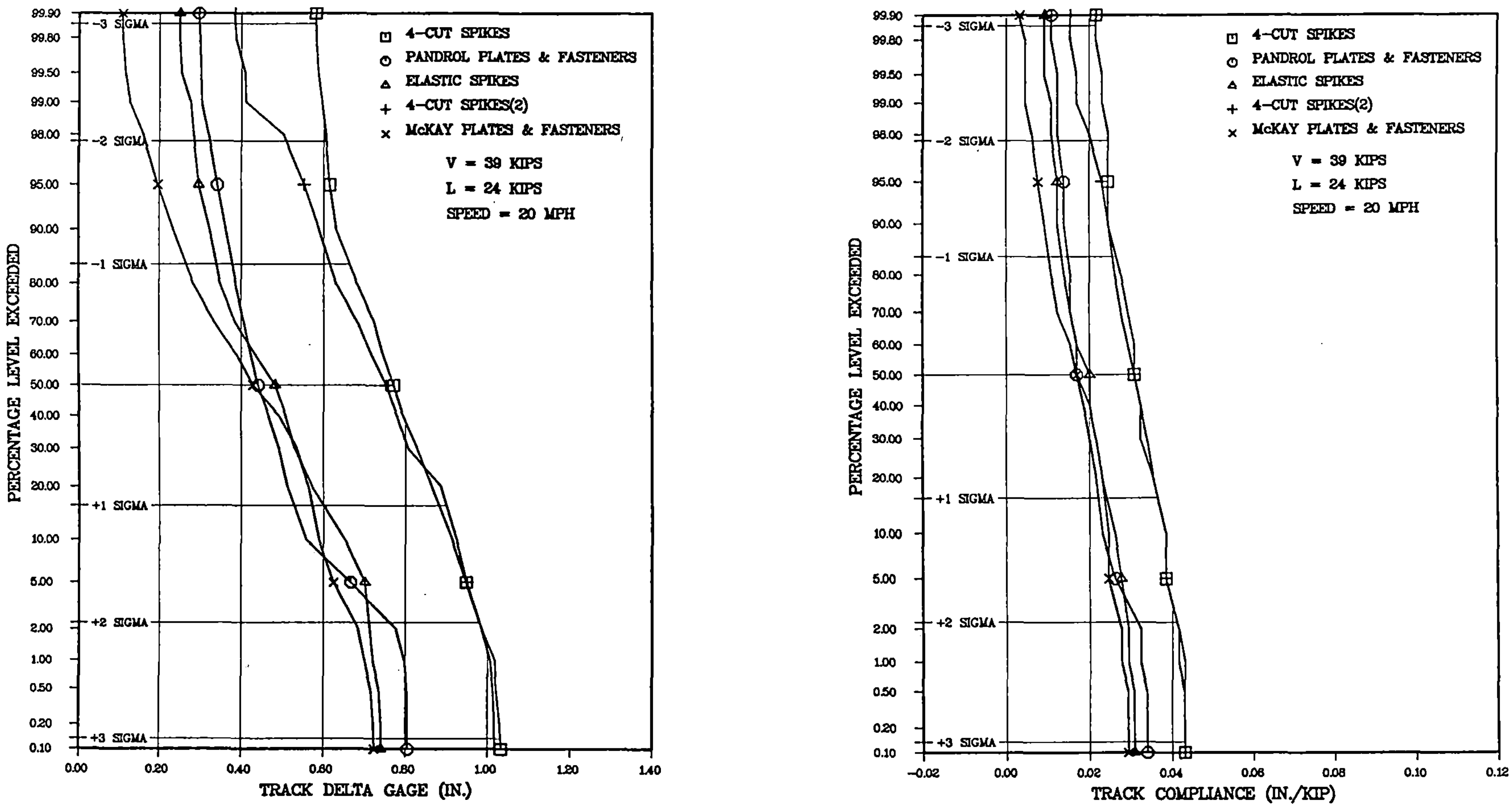


Exhibit **D26.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 7), All Segments, L=24 Kips and V=39 Kips.

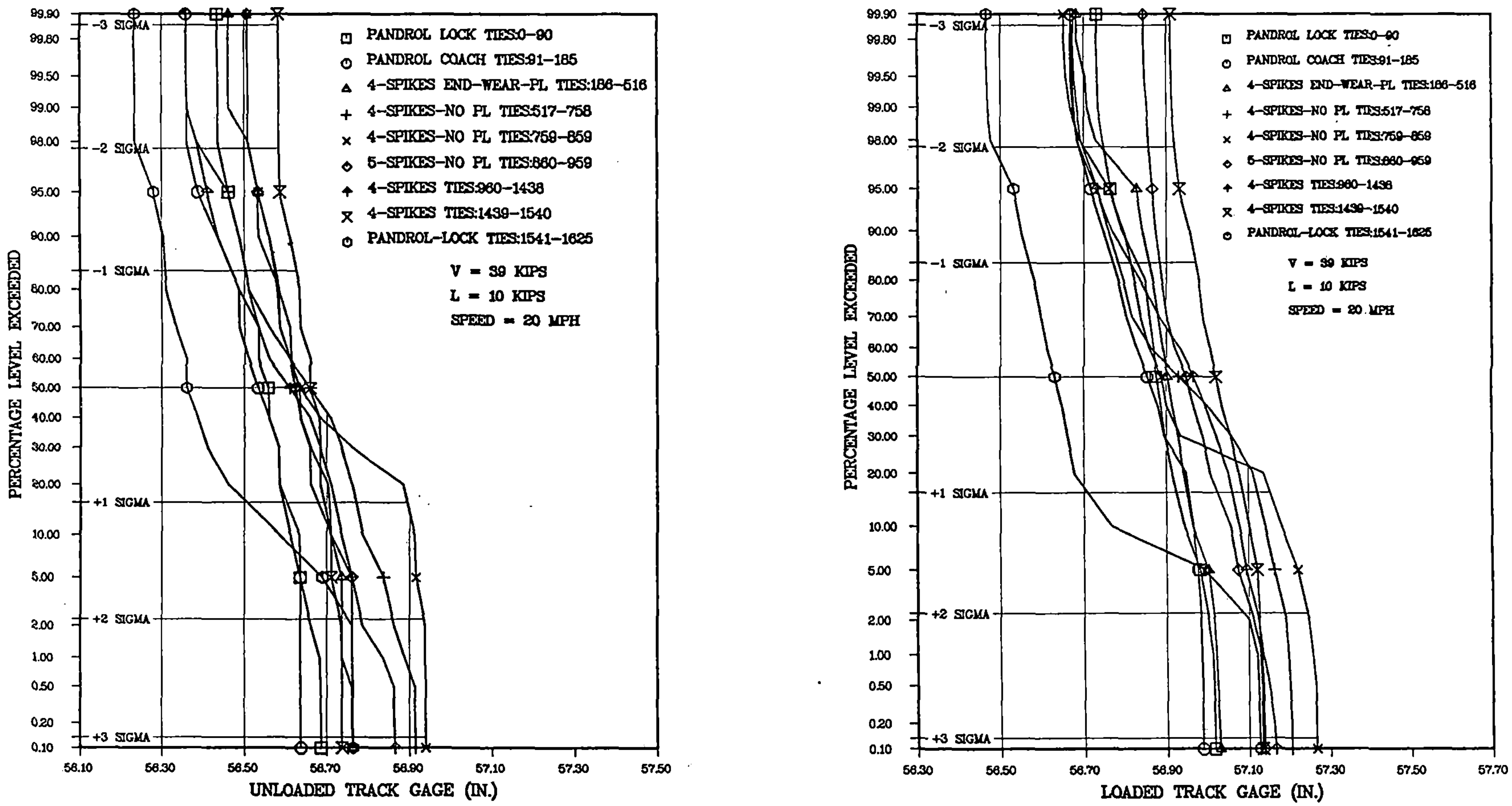
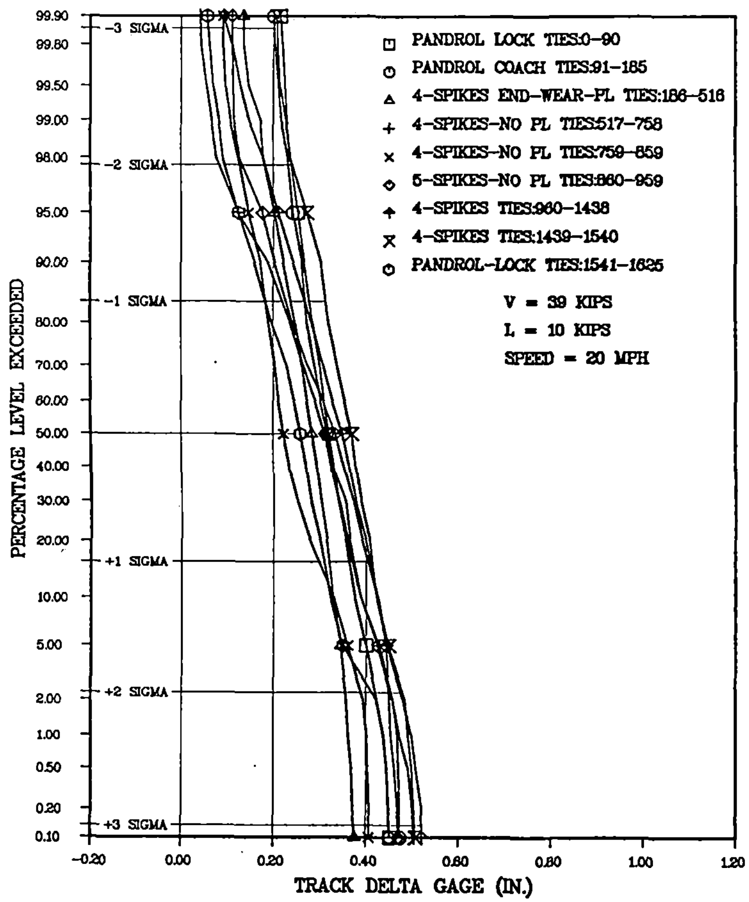


Exhibit **D27.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 6-Degree Curve(Section 25), All Segments, L=10 Kips and V=39 Kips.



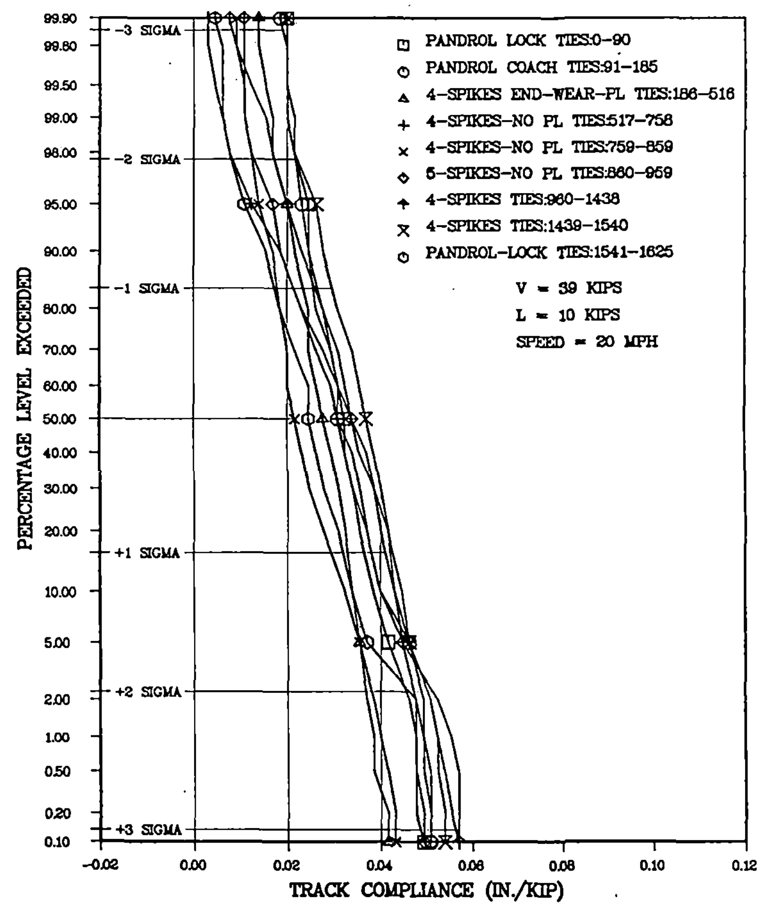
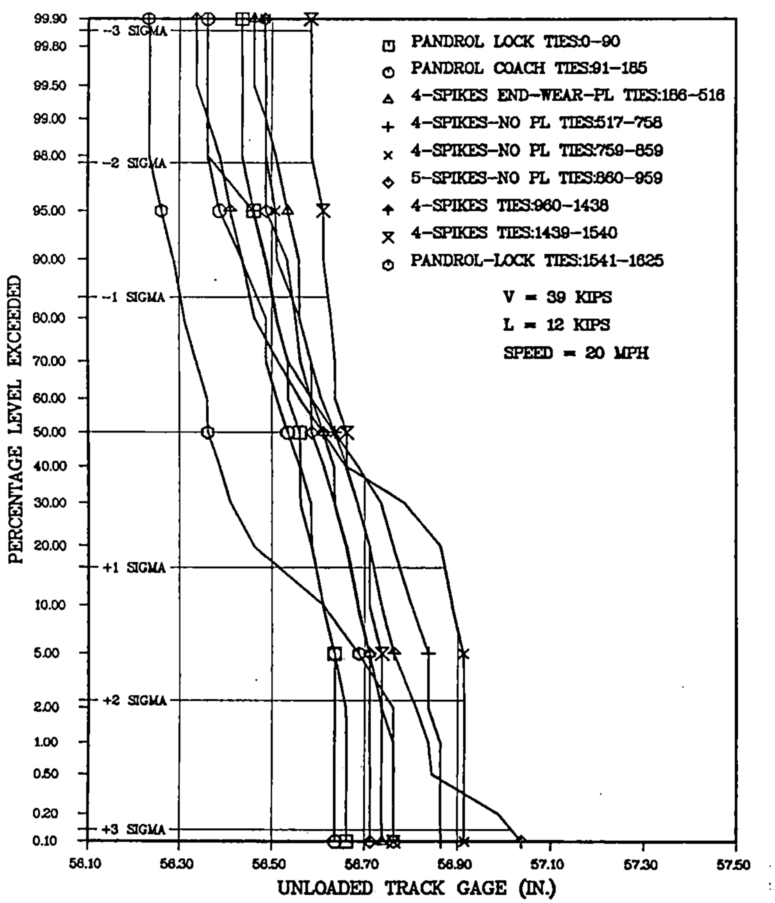


Exhibit **D28.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 6-Degree Curve(Section 25), All Segments, L=10 Kips and V=39 Kips.



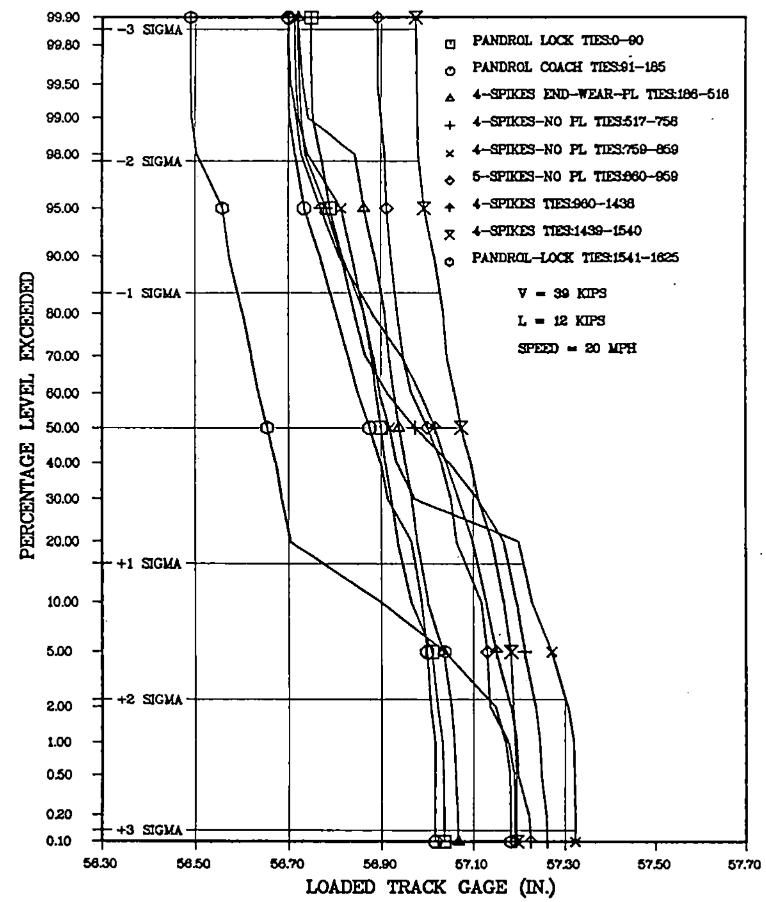


Exhibit **D29.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 6-Degree Curve(Section 25), All Segments, L=12 Kips and V=39 Kips.

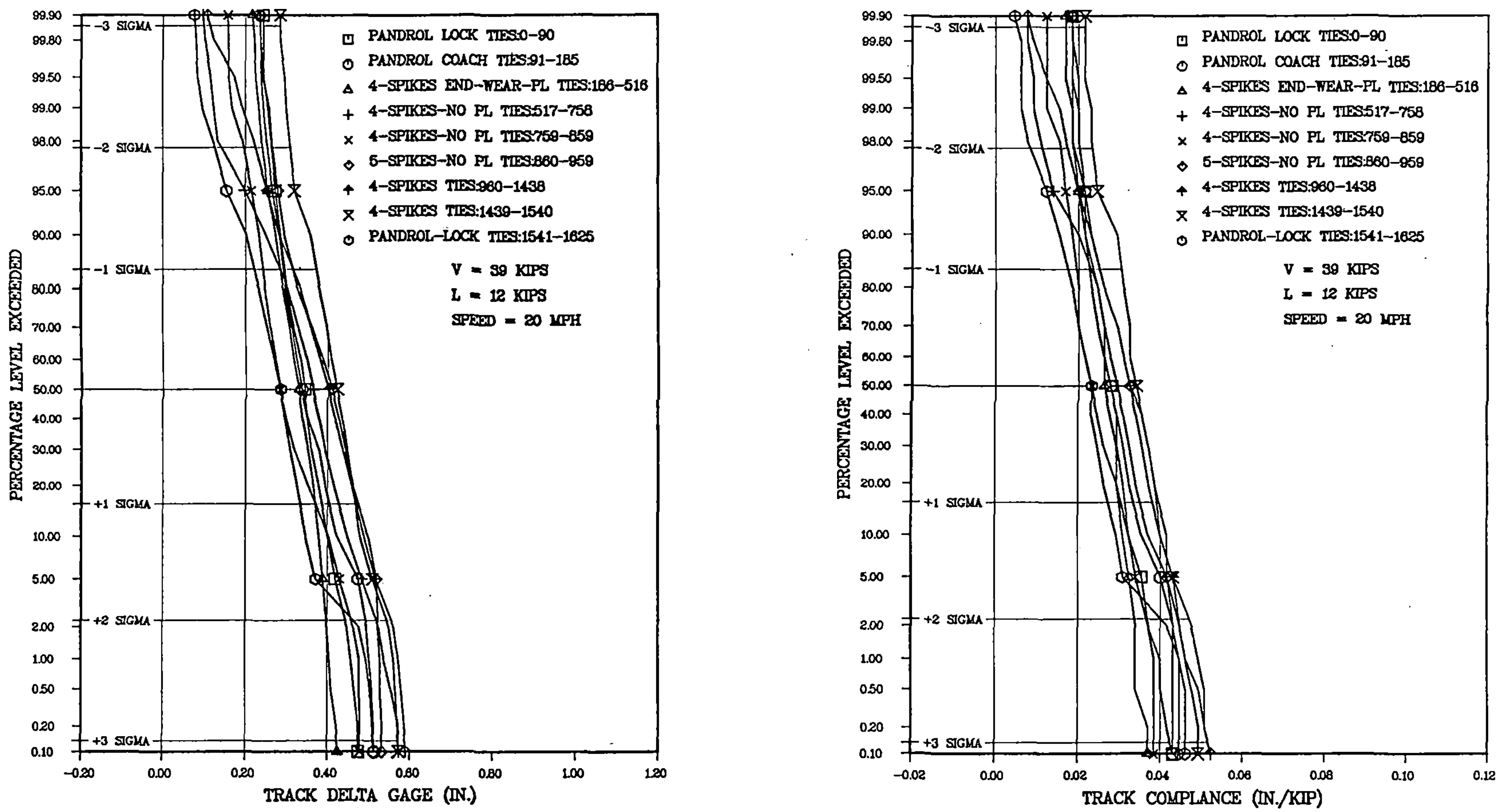
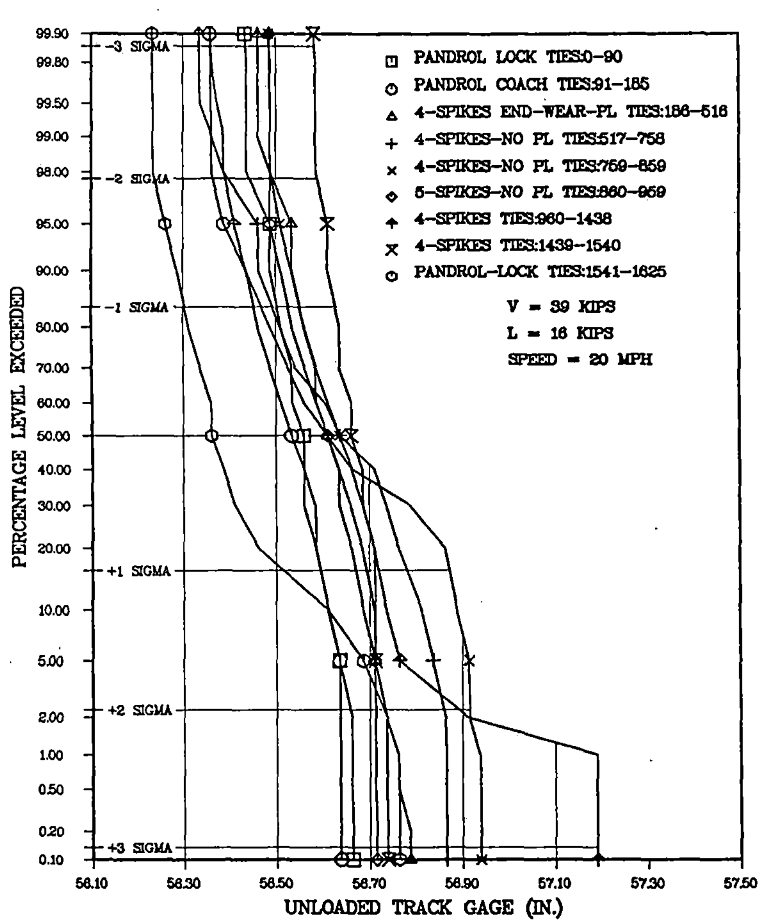


Exhibit **D30.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 6-Degree Curve(Section 25), All Segments, L=12 Kips and V=39 Kips.



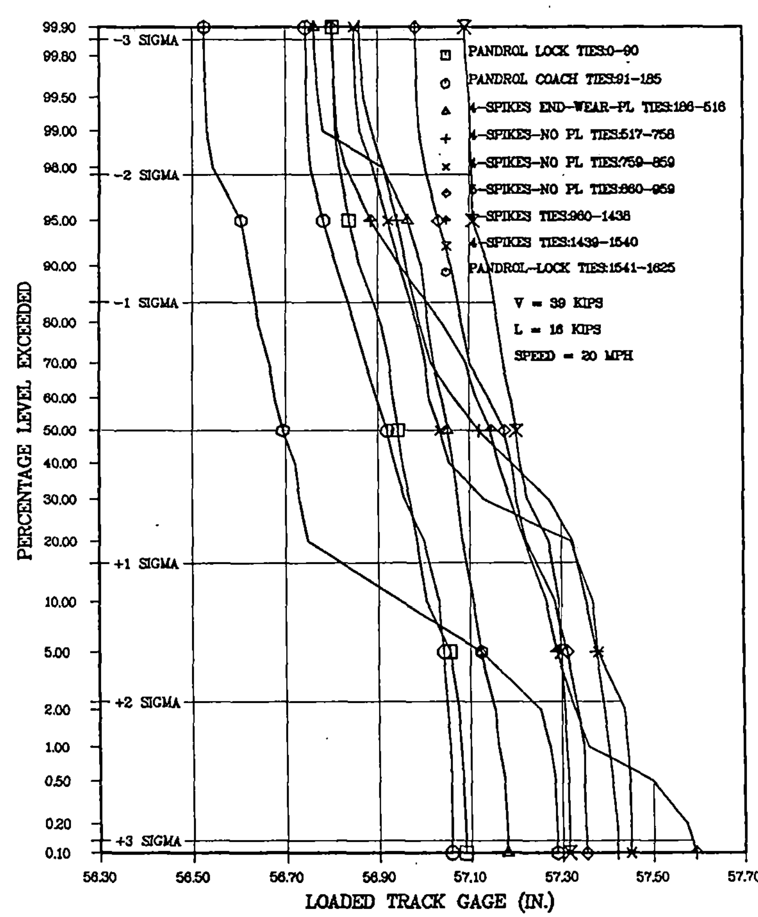
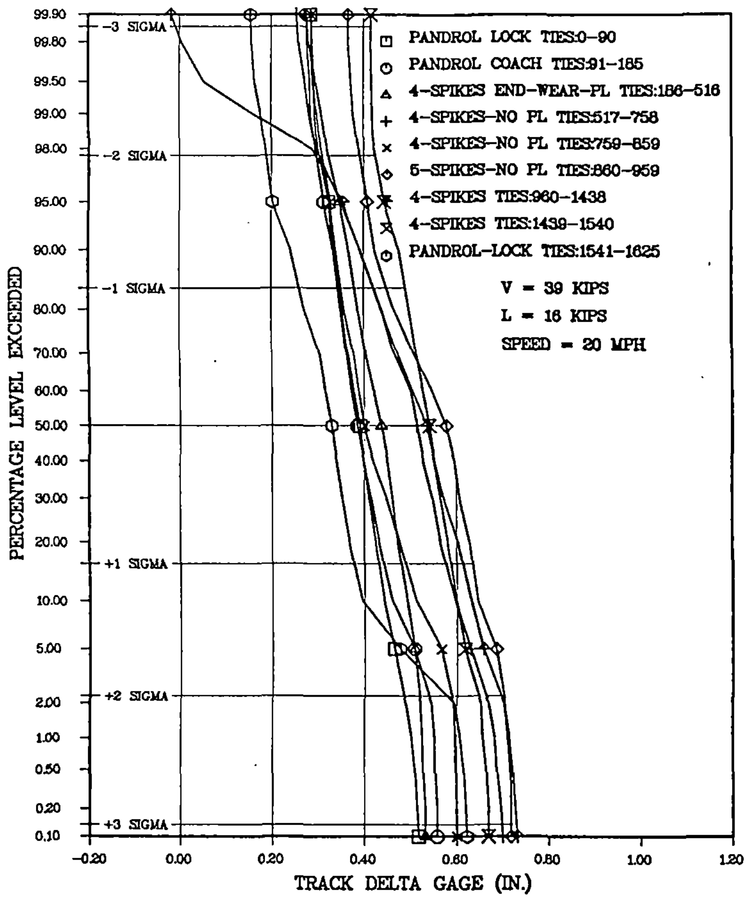


Exhibit **D31.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 6-Degree Curve(Section 25), All Segments, L=16 Kips and V=39 Kips.



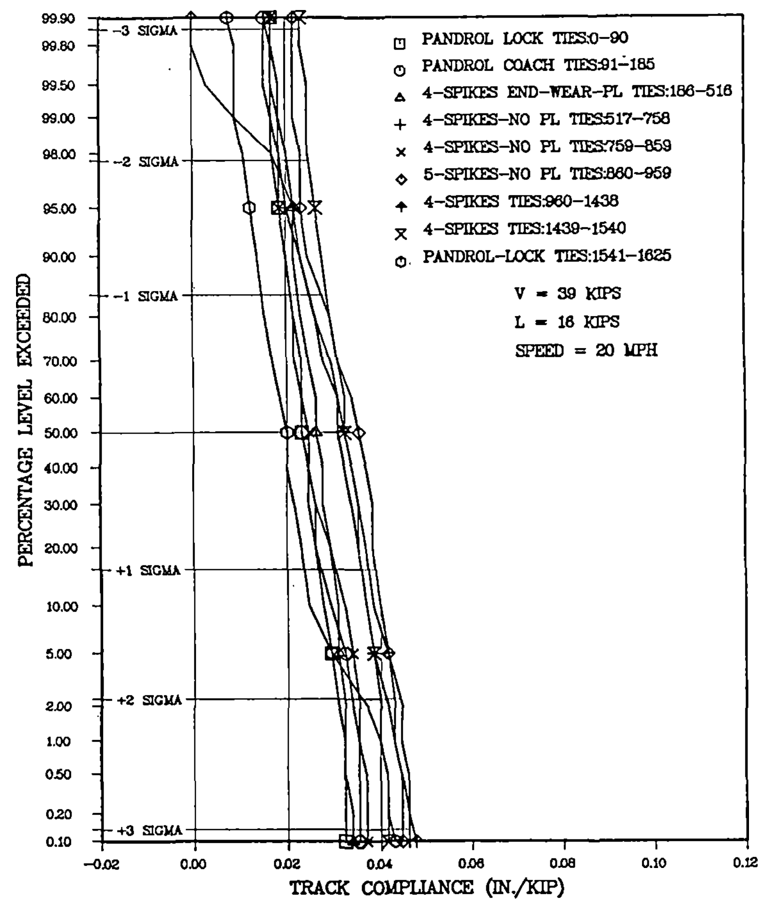


Exhibit **D32.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 6-Degree Curve(Section 25), All Segments, L=16 Kips and V=39 Kips.

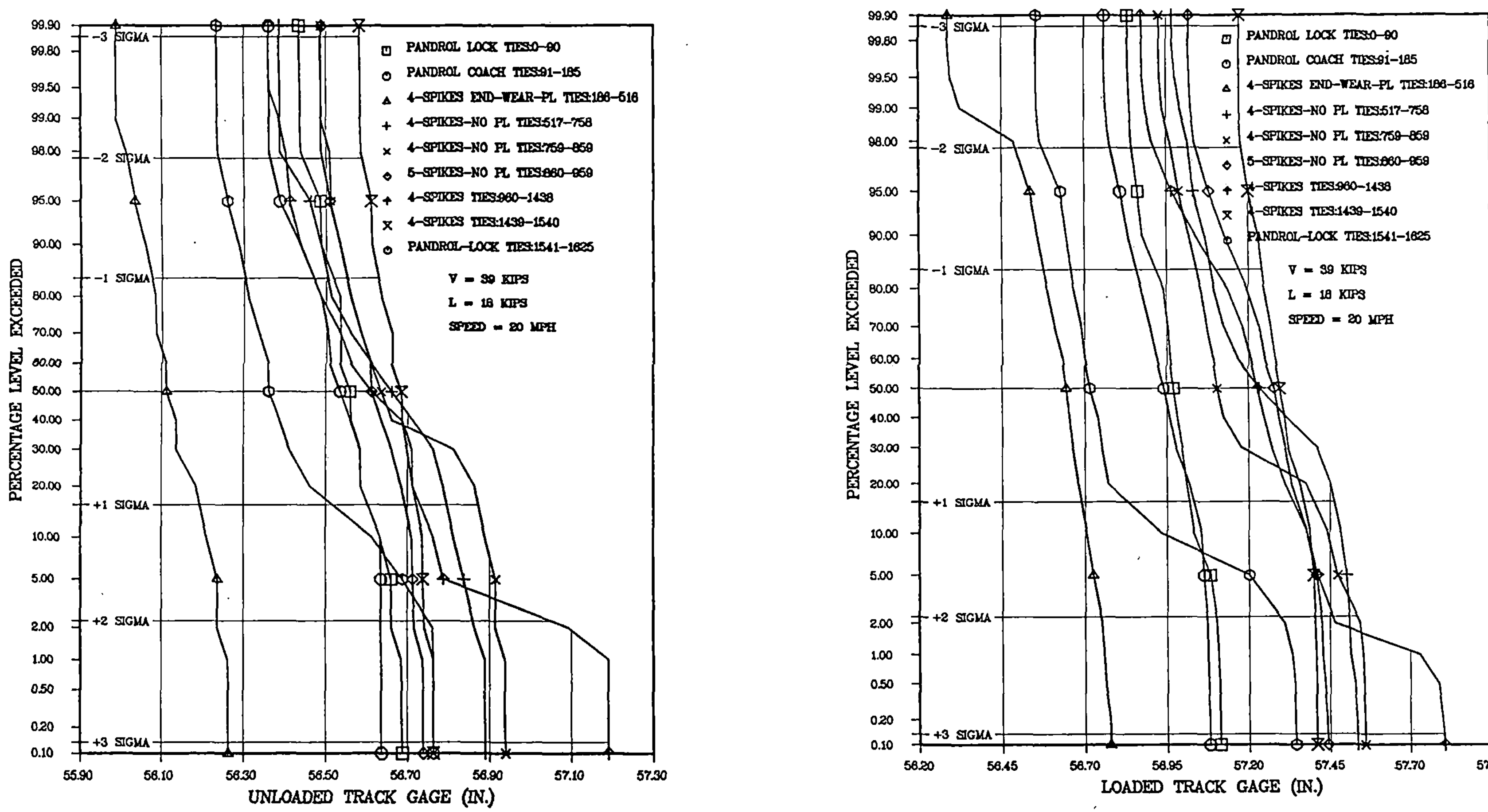
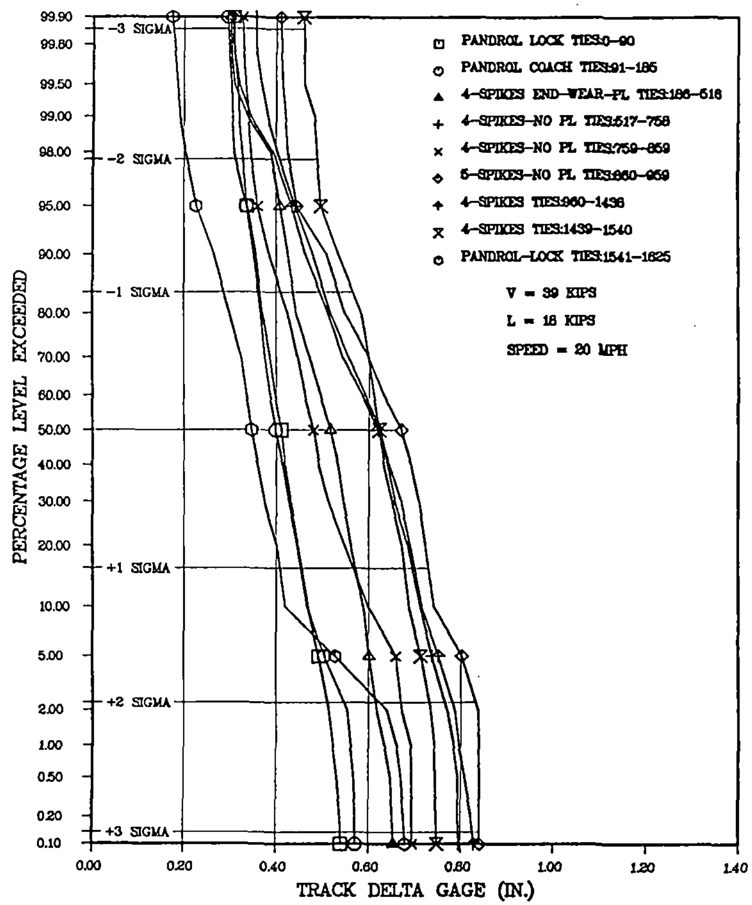


Exhibit **D33.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 6-Degree Curve(Section 25), All Segments, L=18 Kips and V=39 Kips.



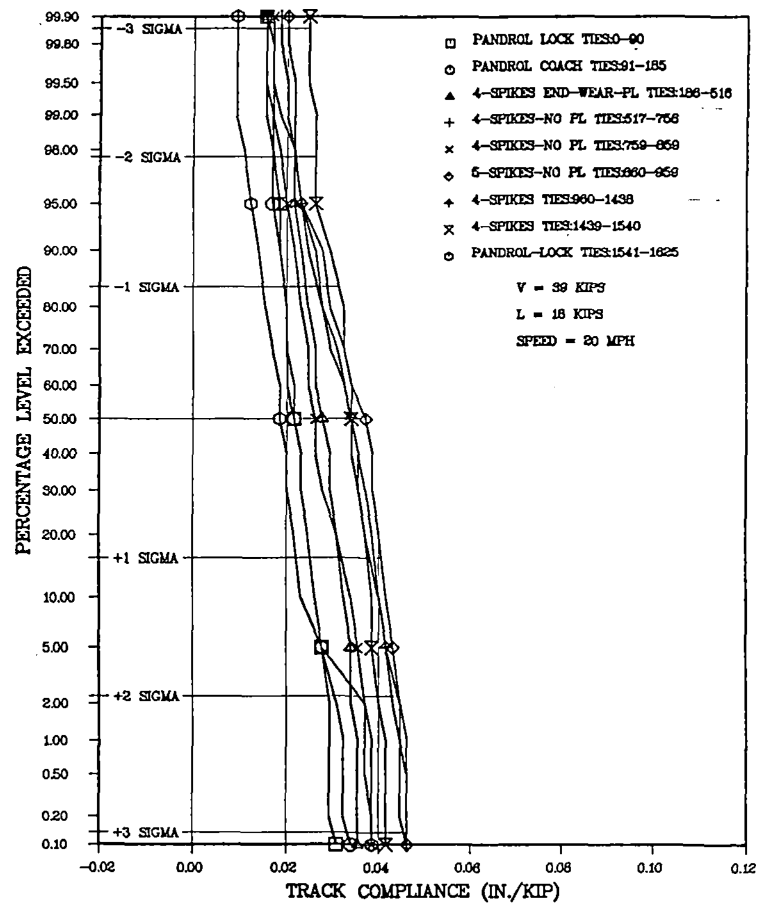
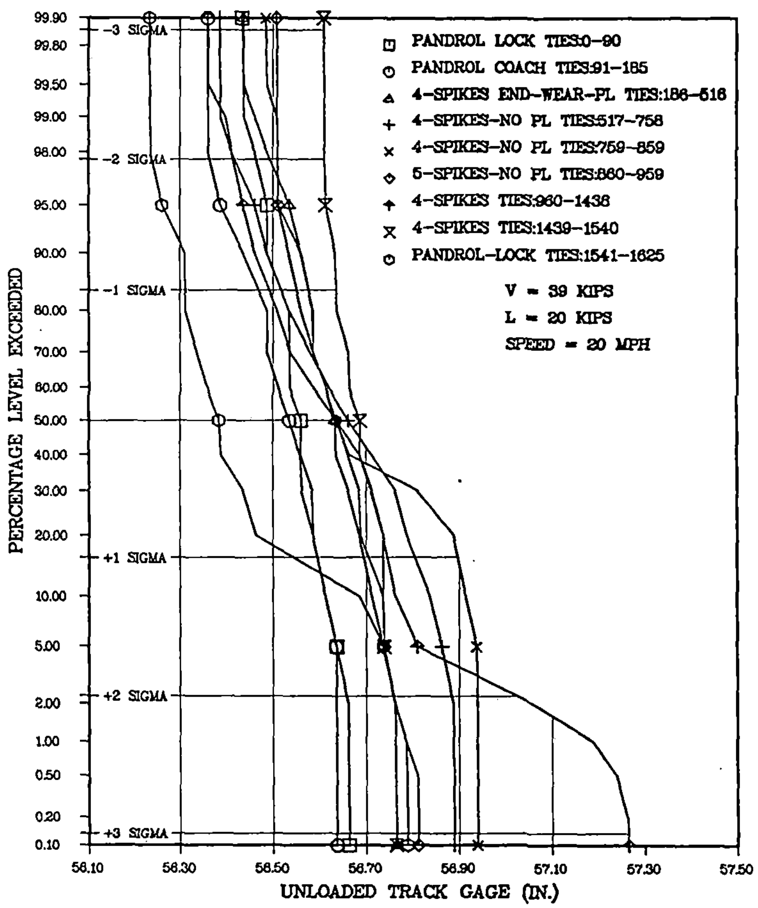


Exhibit **D34.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 6-Degree Curve(Section 25), All Segments, L=18 Kips and V=39 Kips.



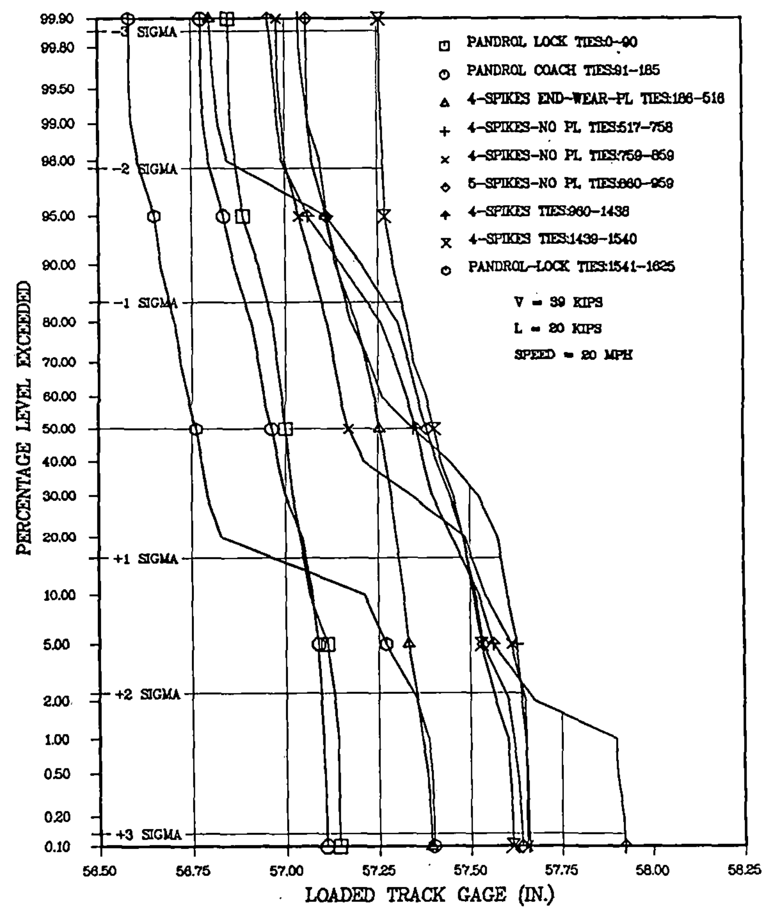
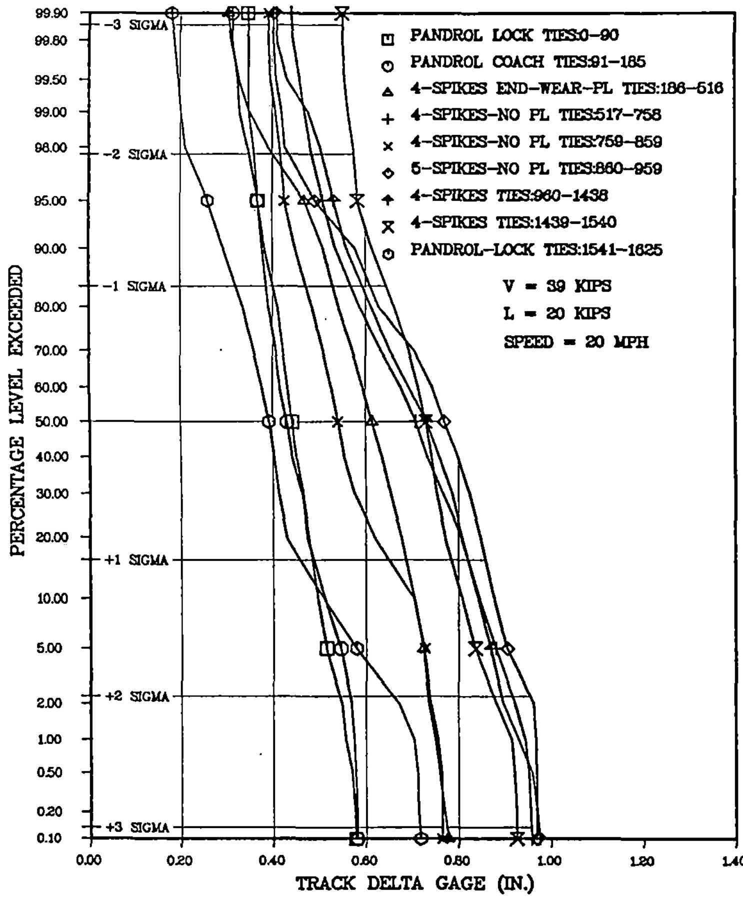


Exhibit **D35.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 6-Degree Curve(Section 25), All Segments, L=20 Kips and V=39 Kips.



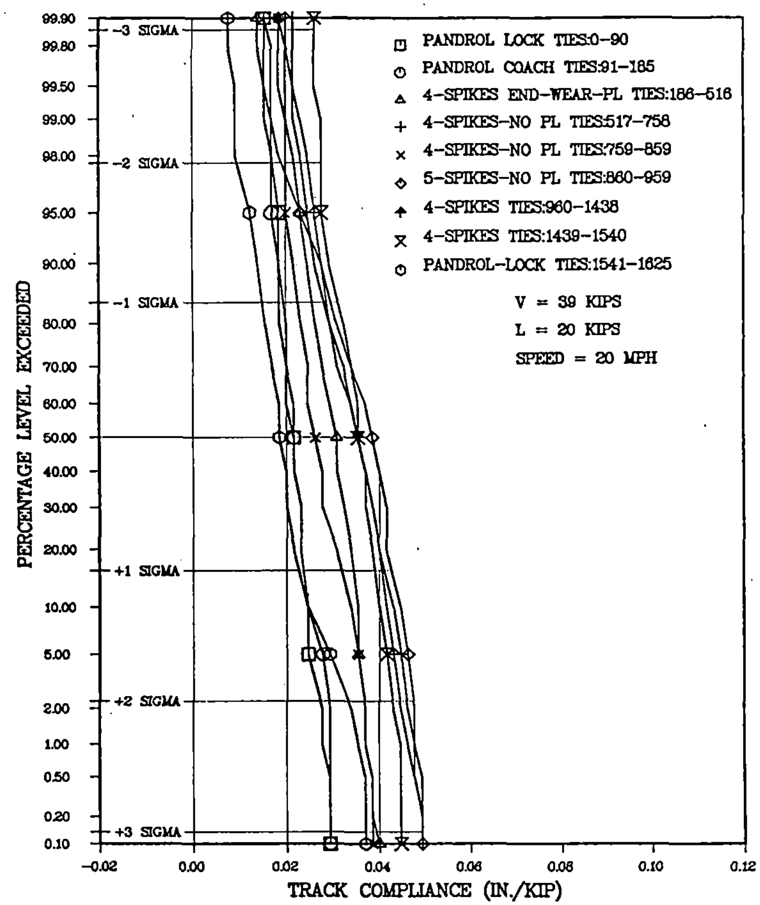
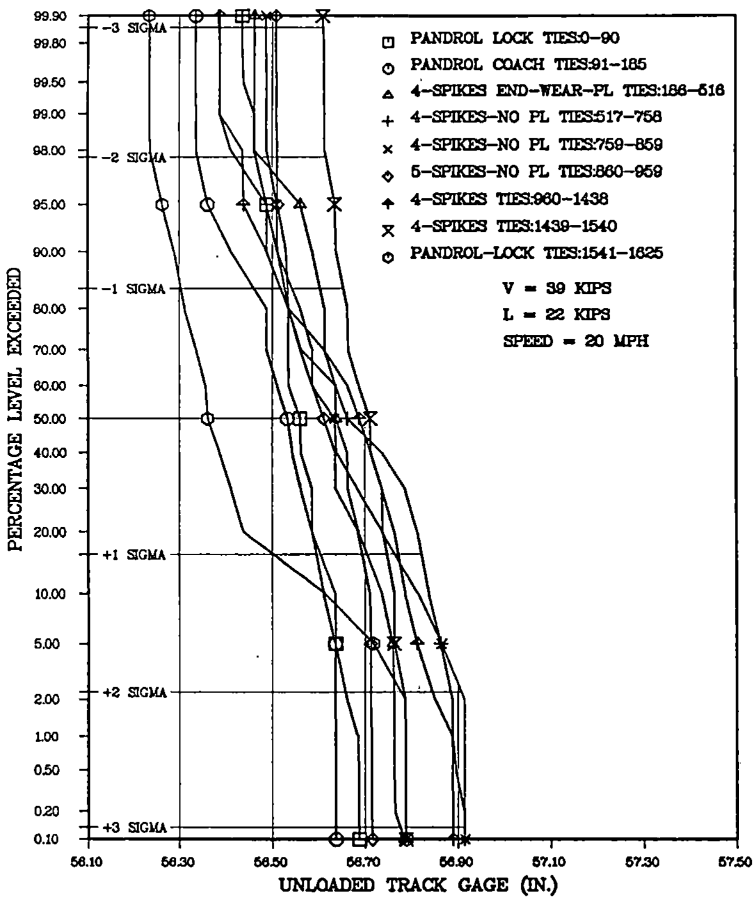


Exhibit **D36.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 6-Degree Curve(Section 25), All Segments, L=20 Kips and V=39 Kips.



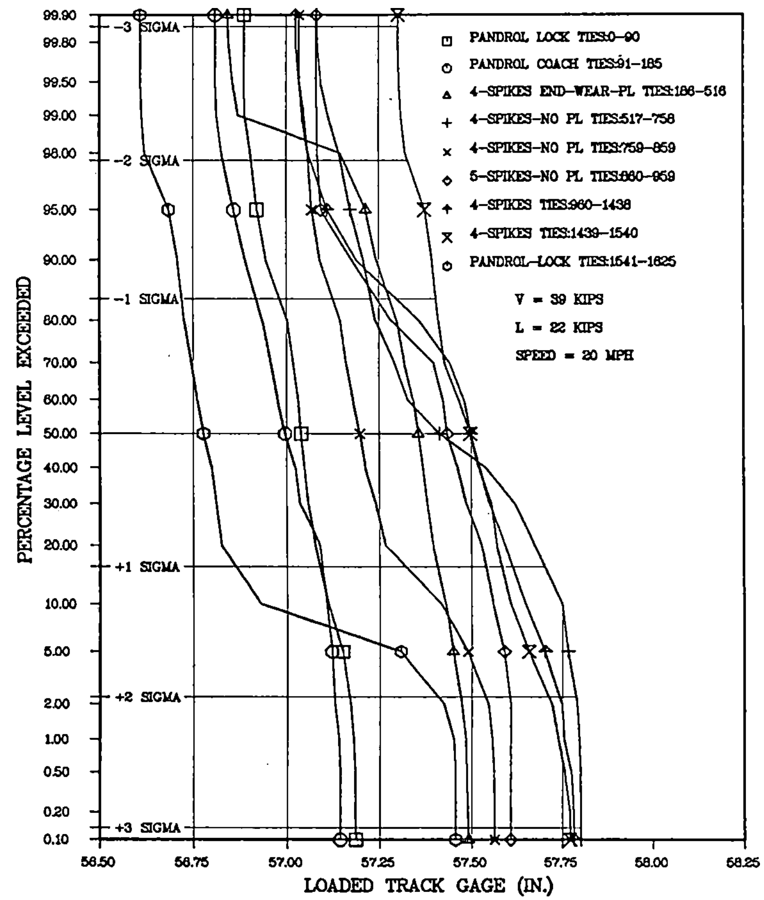
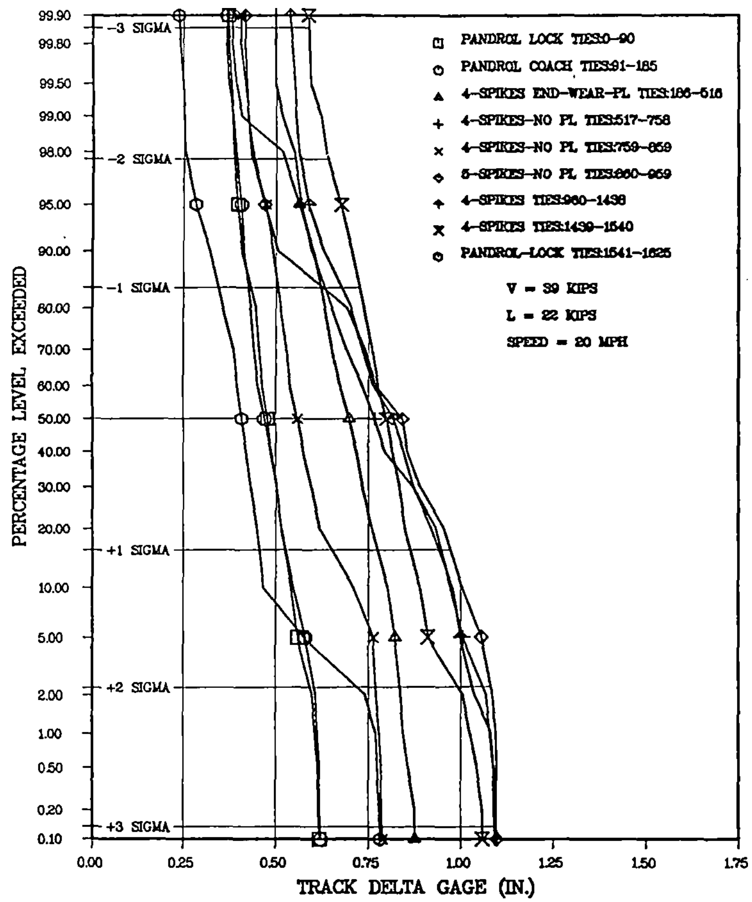


Exhibit **D37.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 6-Degree Curve(Section 25), All Segments, L=22 Kips and V=39 Kips.



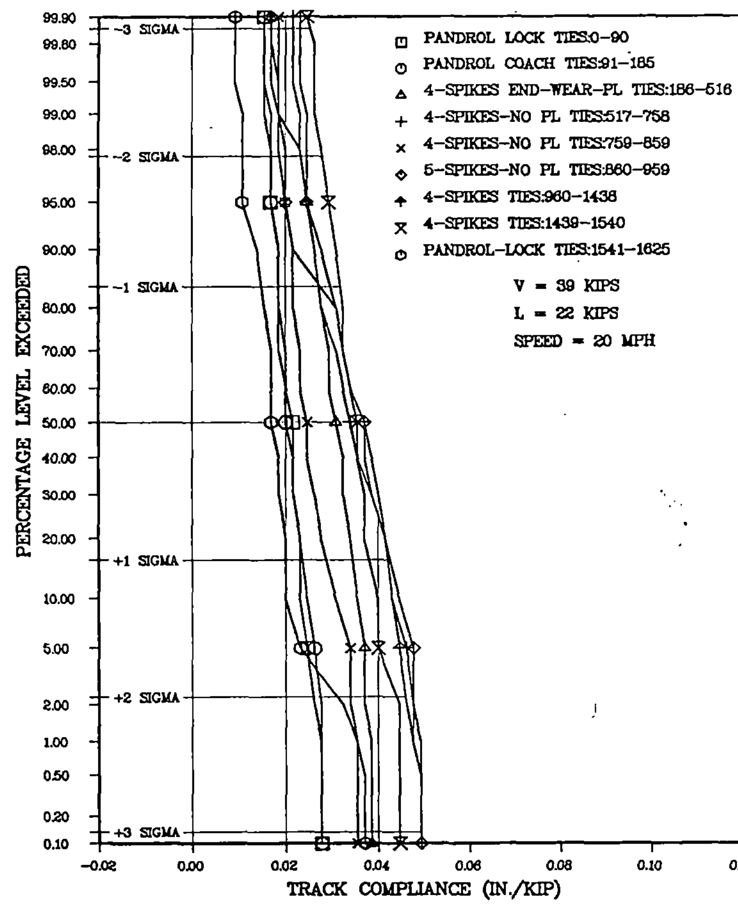
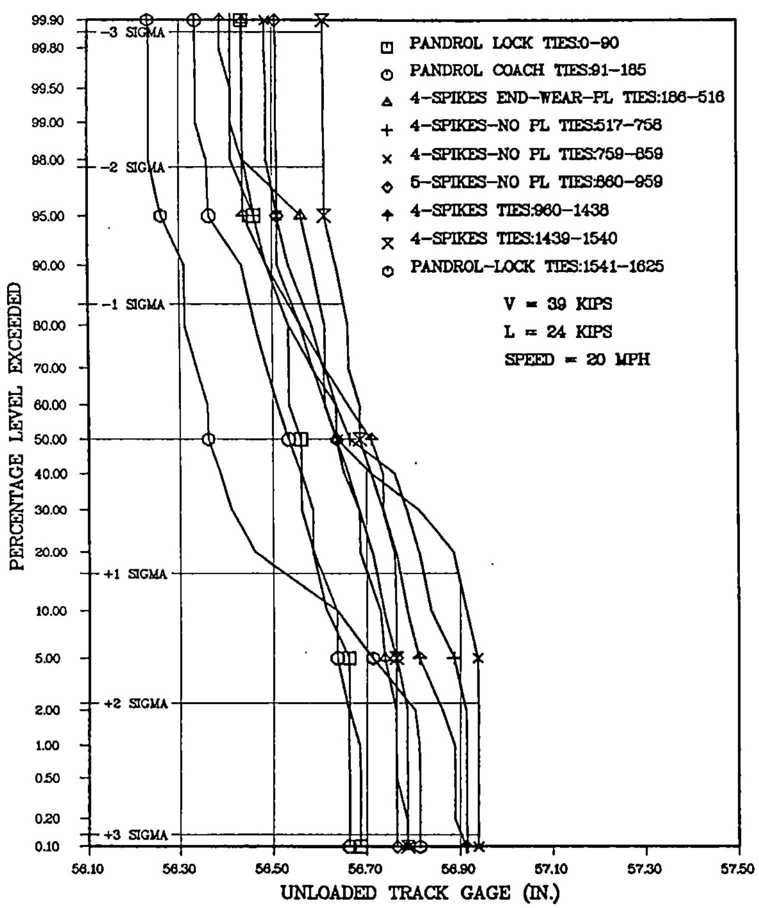


Exhibit **D38.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 6-Degree Curve(Section 25), All Segments, L=22 Kips and V=39 Kips.



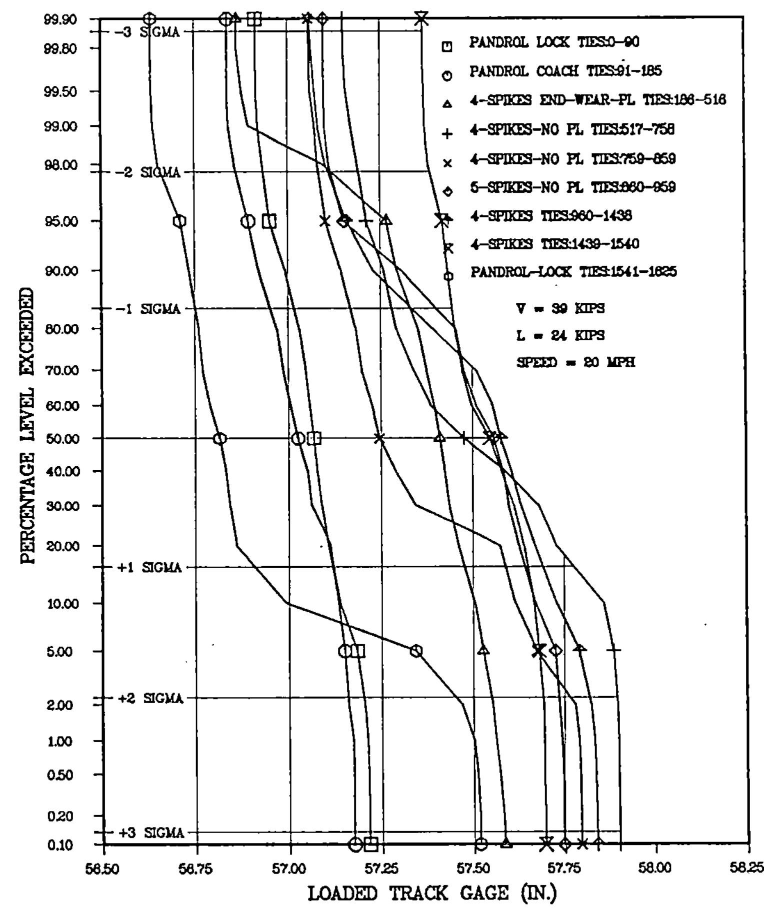


Exhibit **D39.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 6-Degree Curve(Section 25), All Segments, L=24 Kips and V=39 Kips.

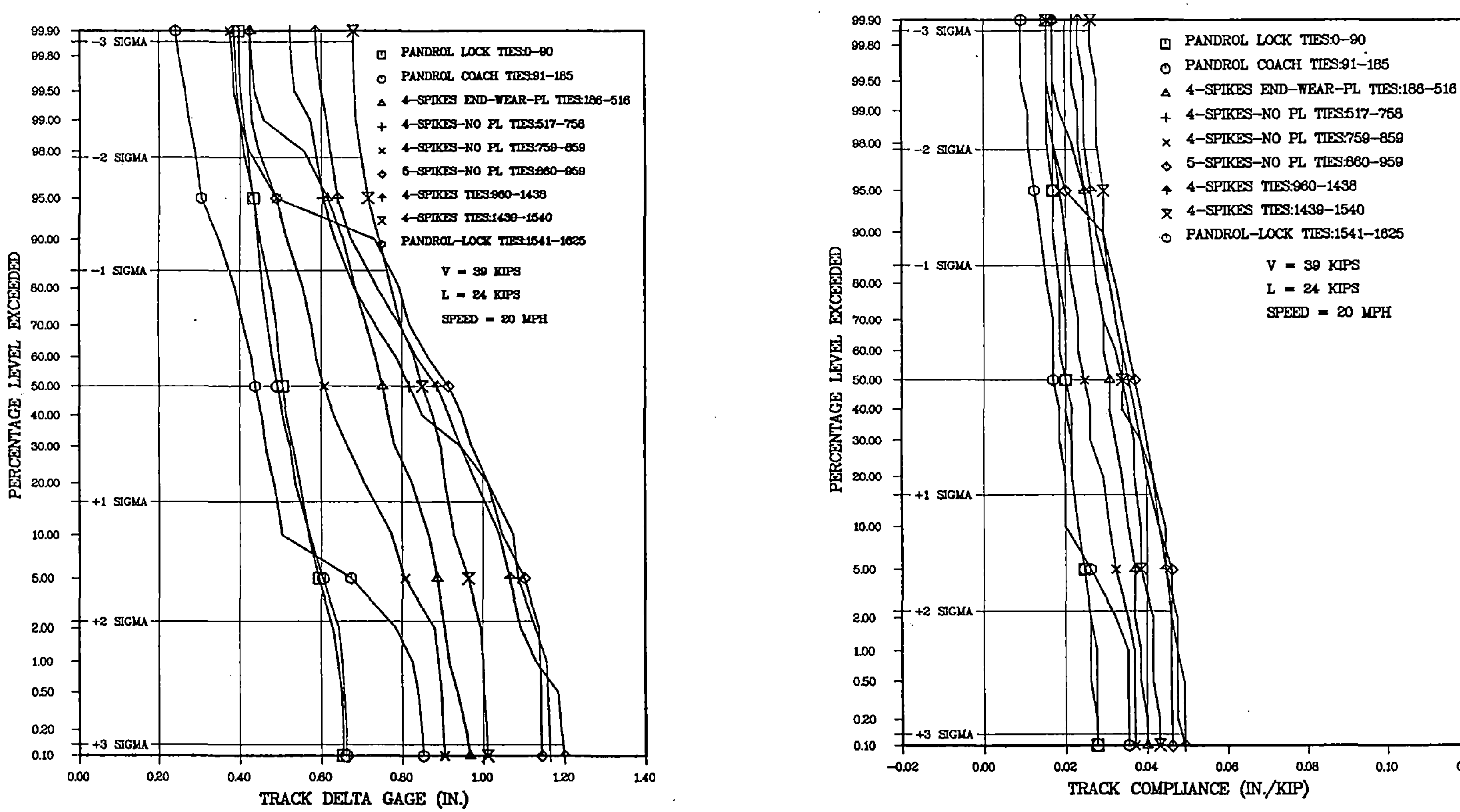


Exhibit **D40.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 6-Degree Curve(Section 25), All Segments, L=24 Kips and V=39 Kips.

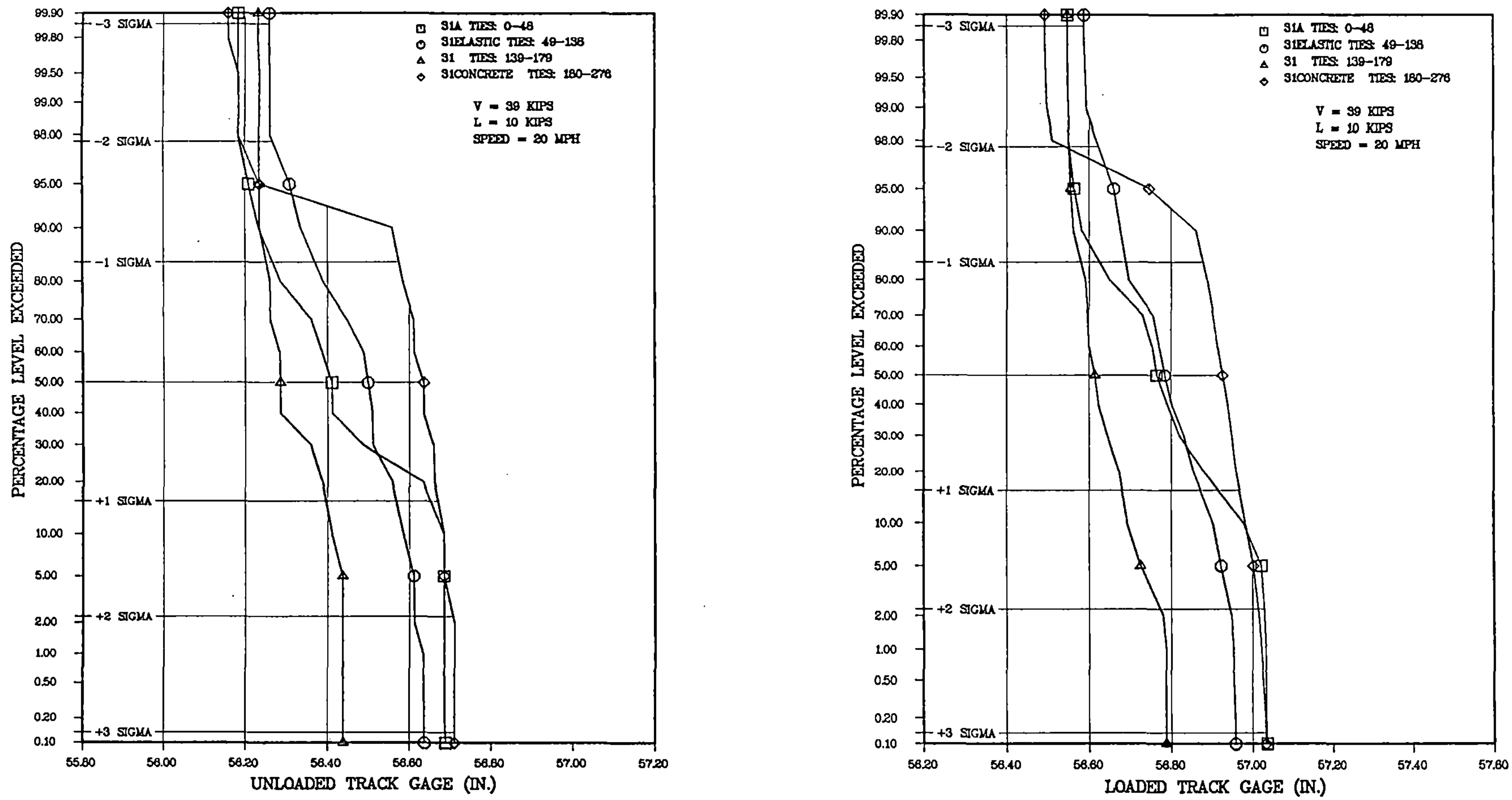


Exhibit **D41.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 31), All Segments, L=10 Kips and V=39 Kips.

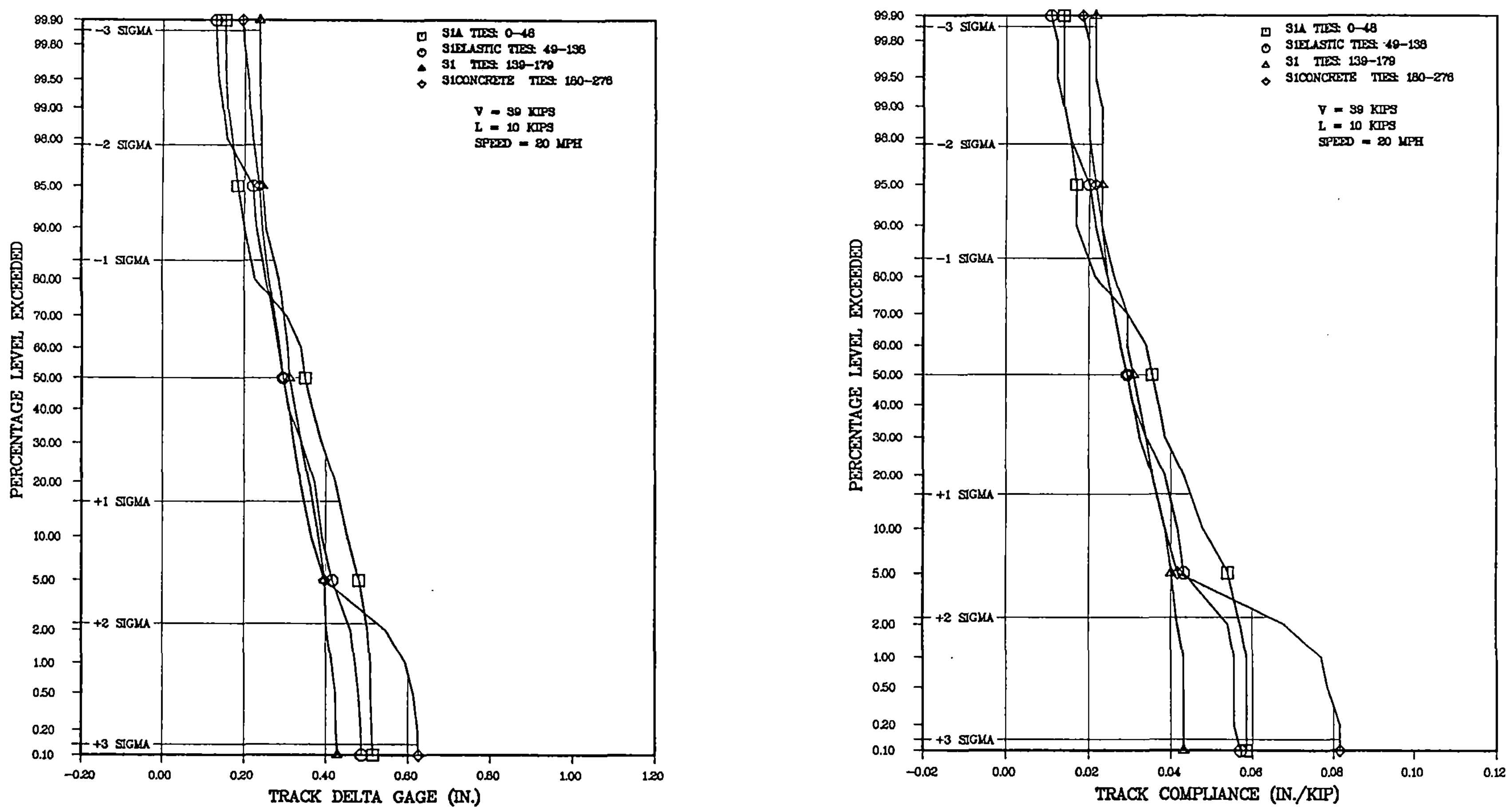
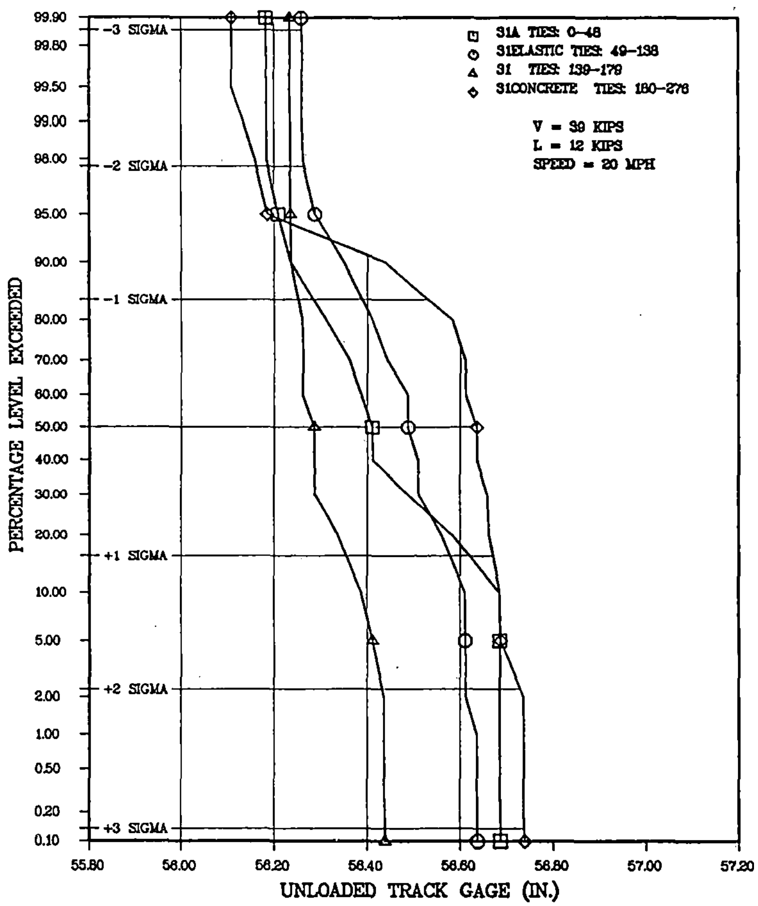


Exhibit **D42.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 31), All Segments, L=10 Kips and V=39 Kips.



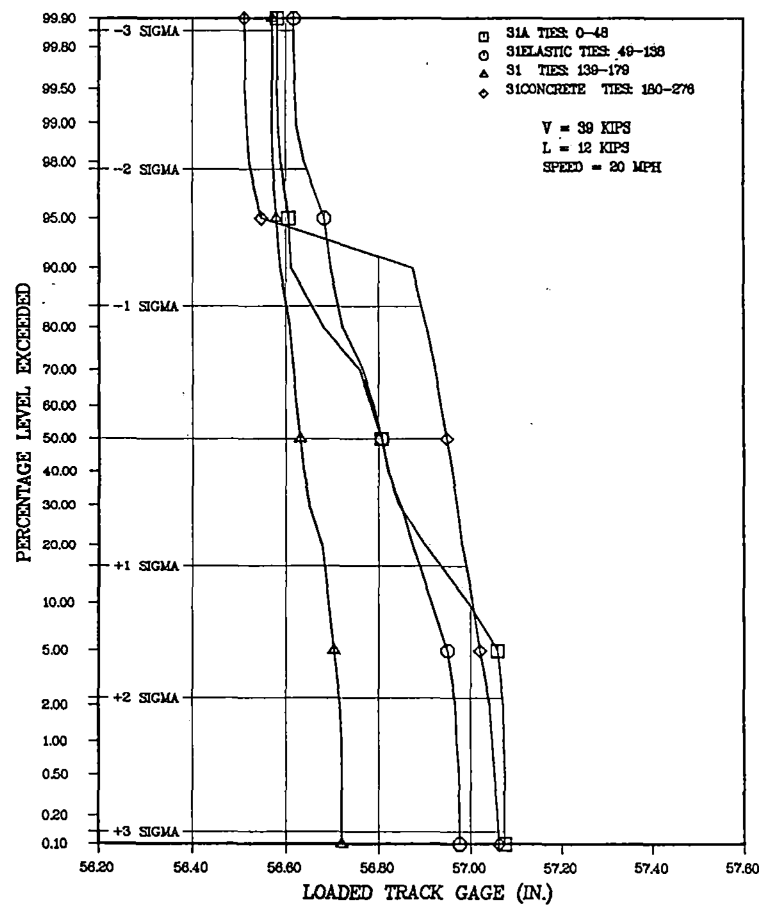
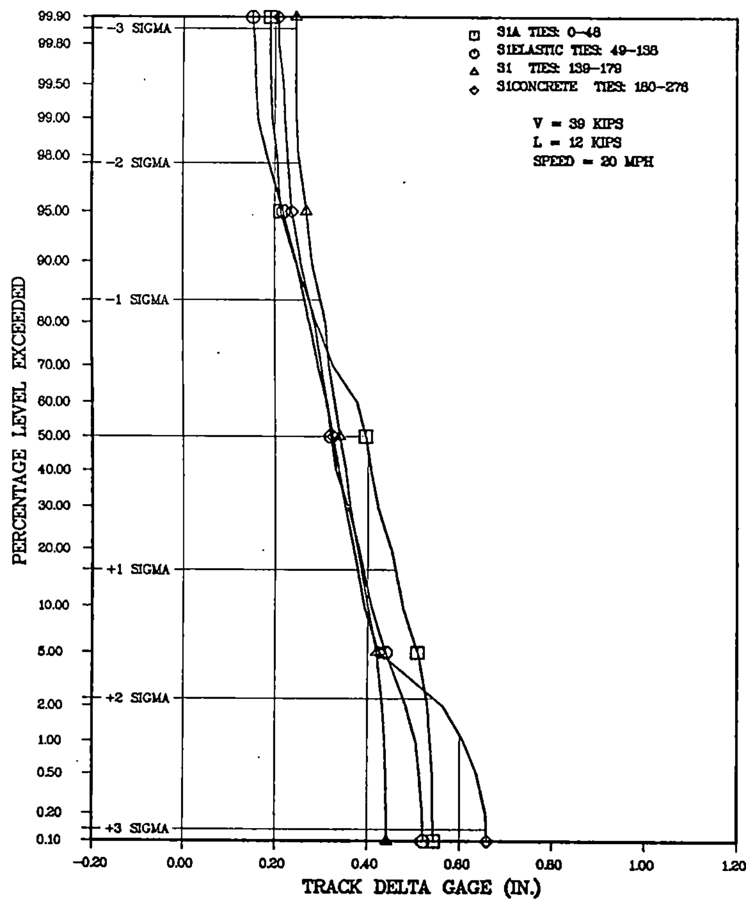


Exhibit **D43.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 31), All Segments, L=12 Kips and V=39 Kips.



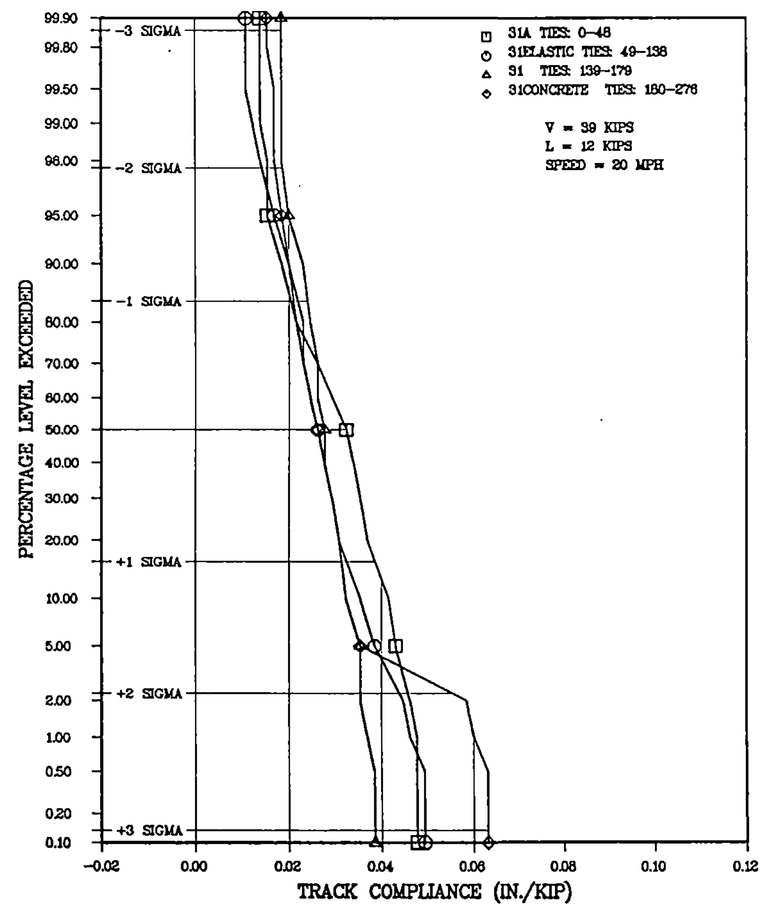
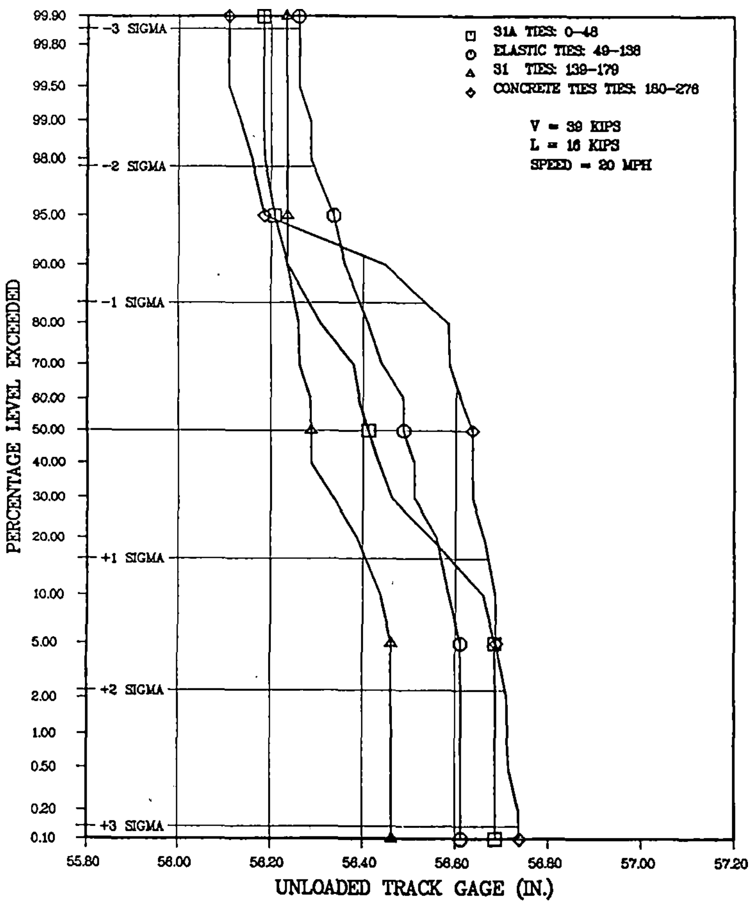


Exhibit **D44.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 31), All Segments, L=12 Kips and V=39 Kips.



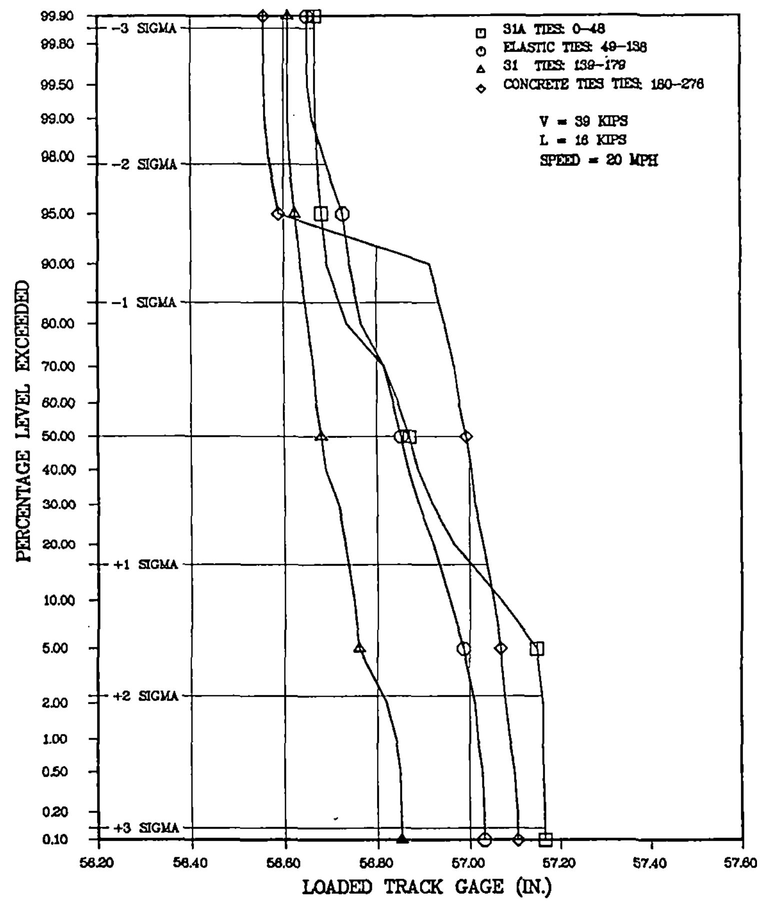
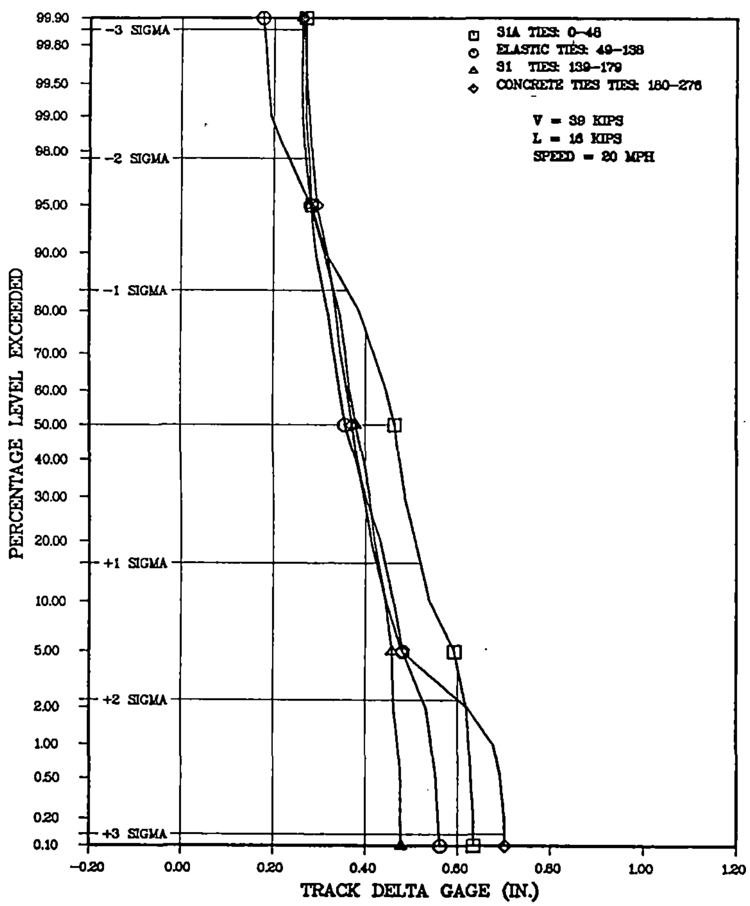


Exhibit **D45.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 31), All Segments, L=16 Kips and V=39 Kips.



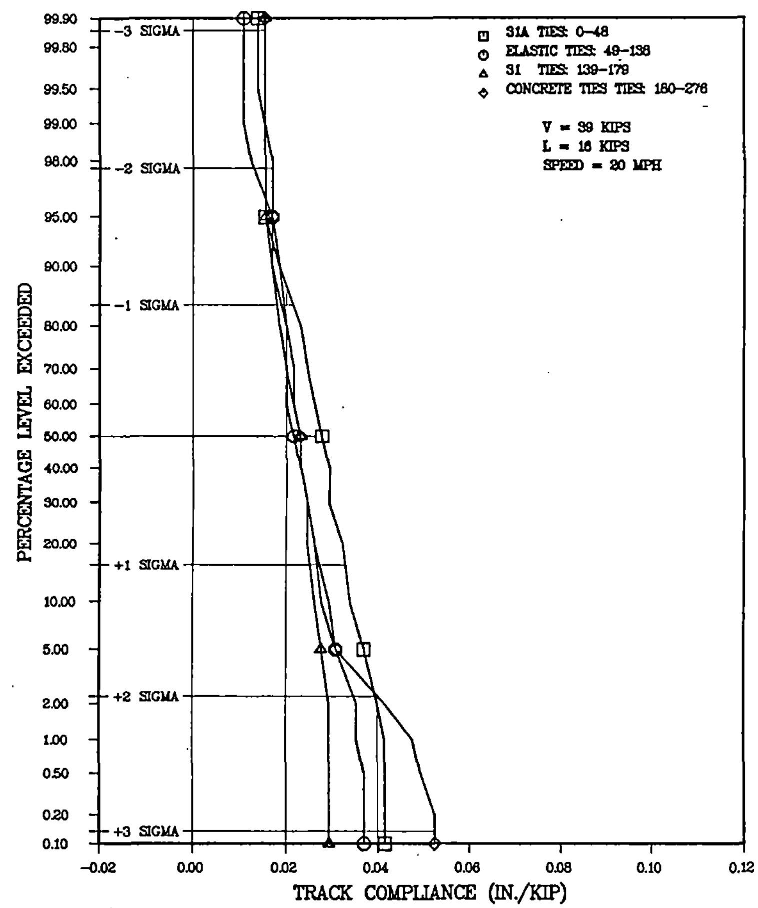


Exhibit **D46.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 31), All Segments, L=16 Kips and V=39 Kips.

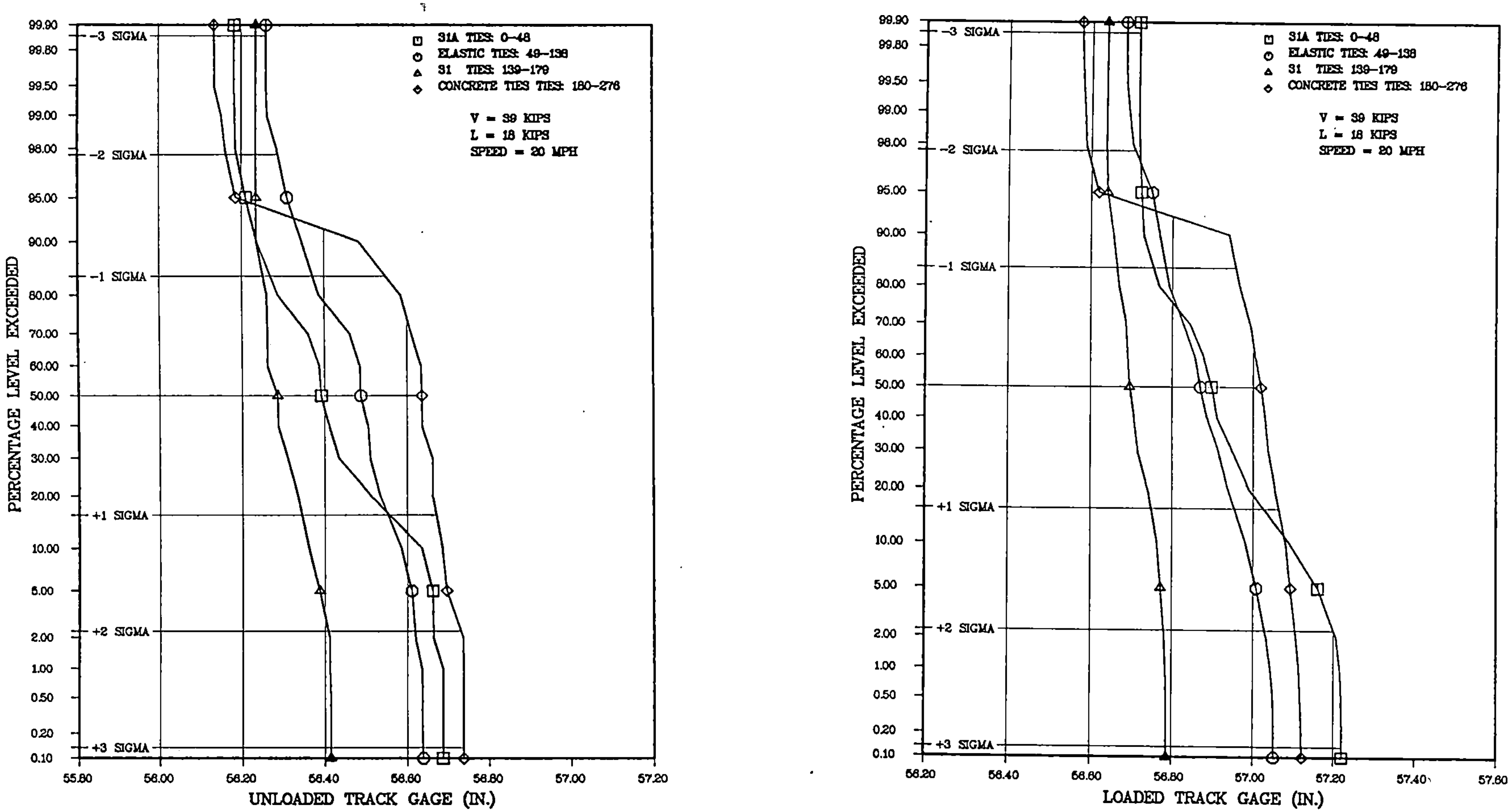
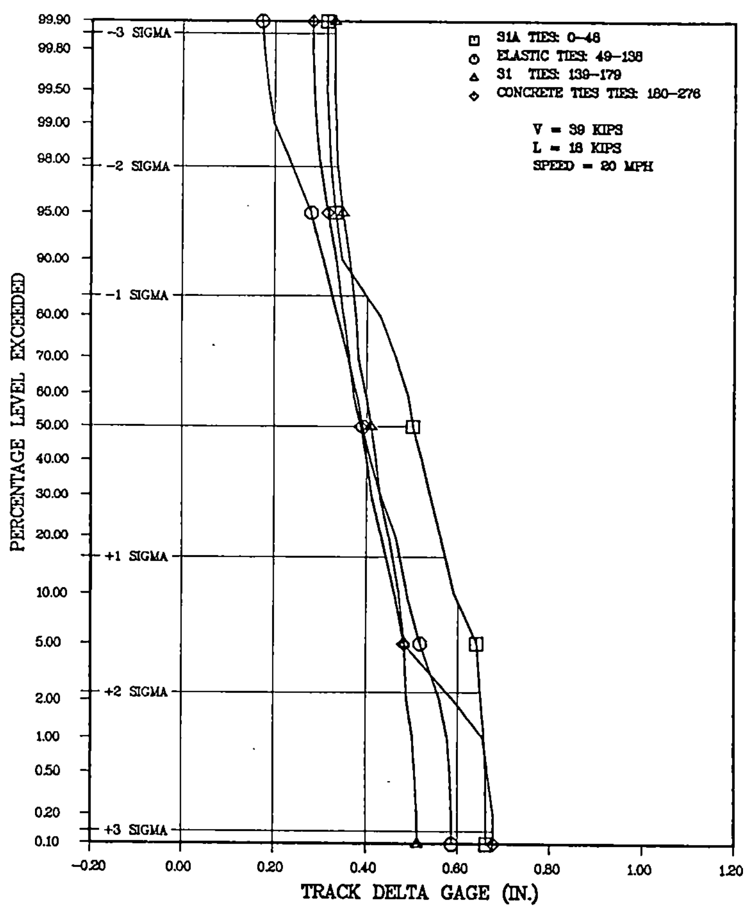


Exhibit **D47.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 31), All Segments, L=18 Kips and V=39 Kips.



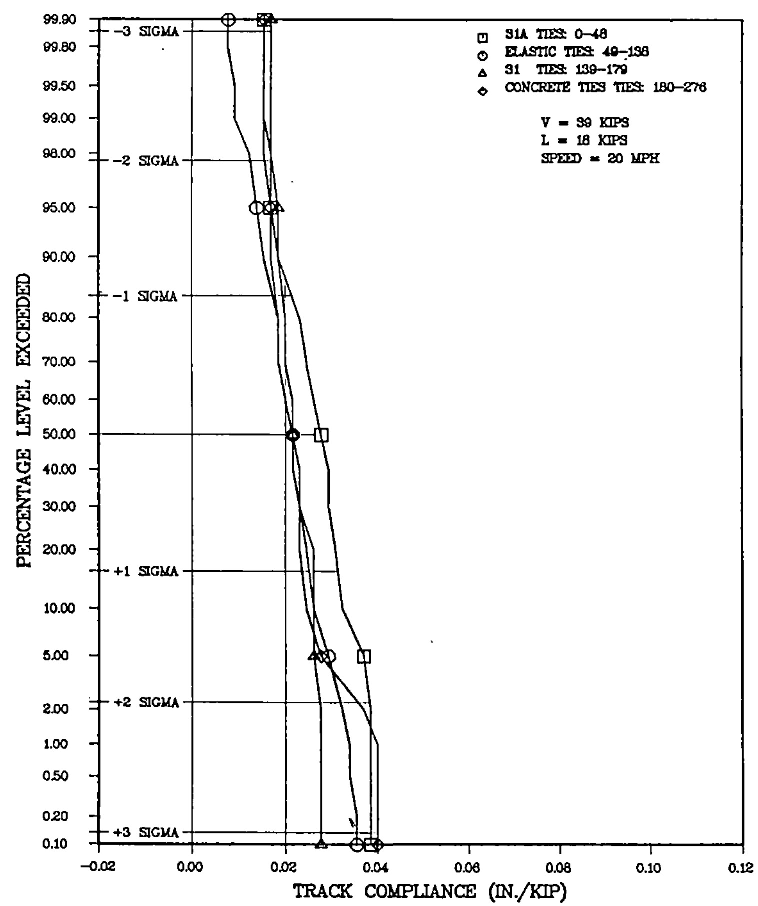


Exhibit **D48.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 31), All Segments, L=18 Kips and V=39 Kips.

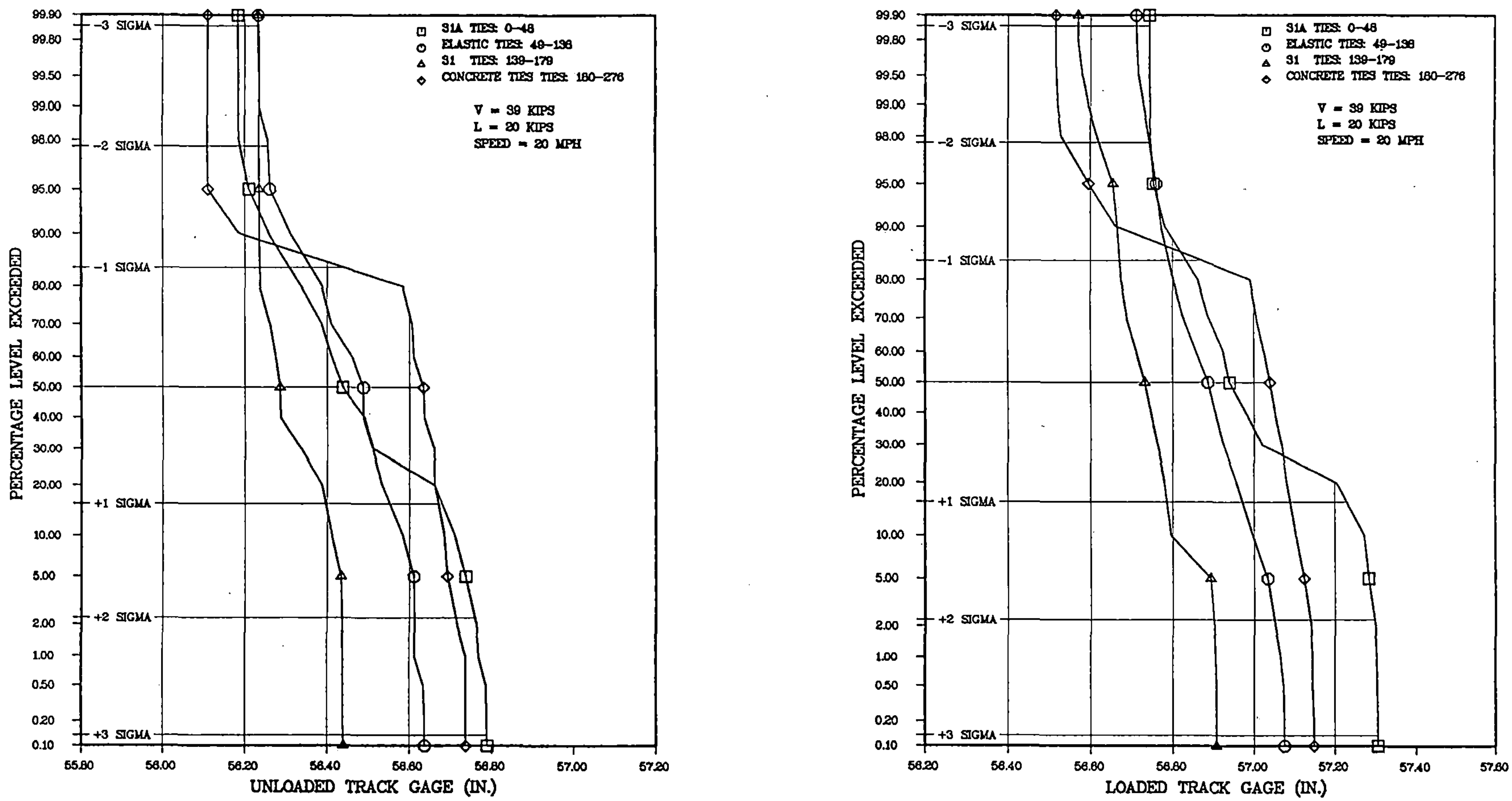
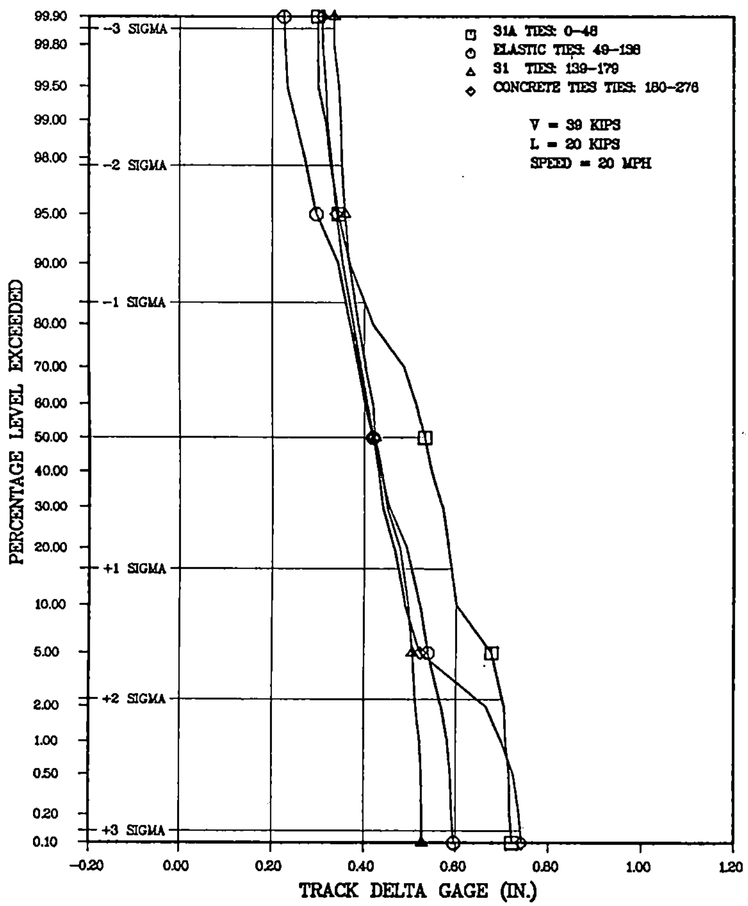


Exhibit **D49.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 31), All Segments, L=20 Kips and V=39 Kips.



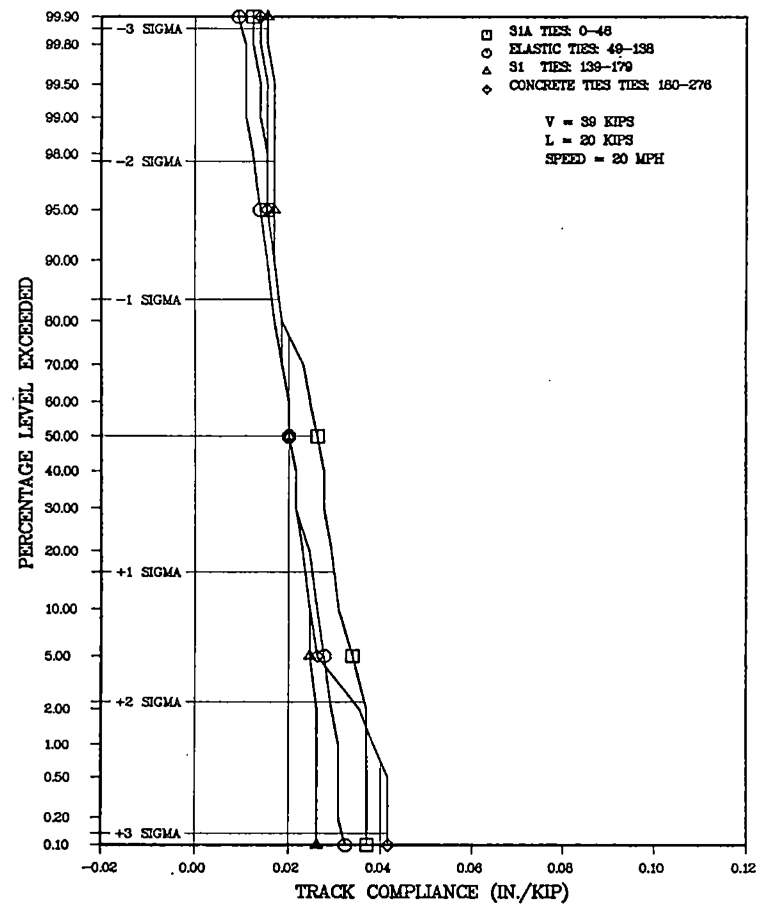


Exhibit **D50.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 31), All Segments, L=20 Kips and V=39 Kips.

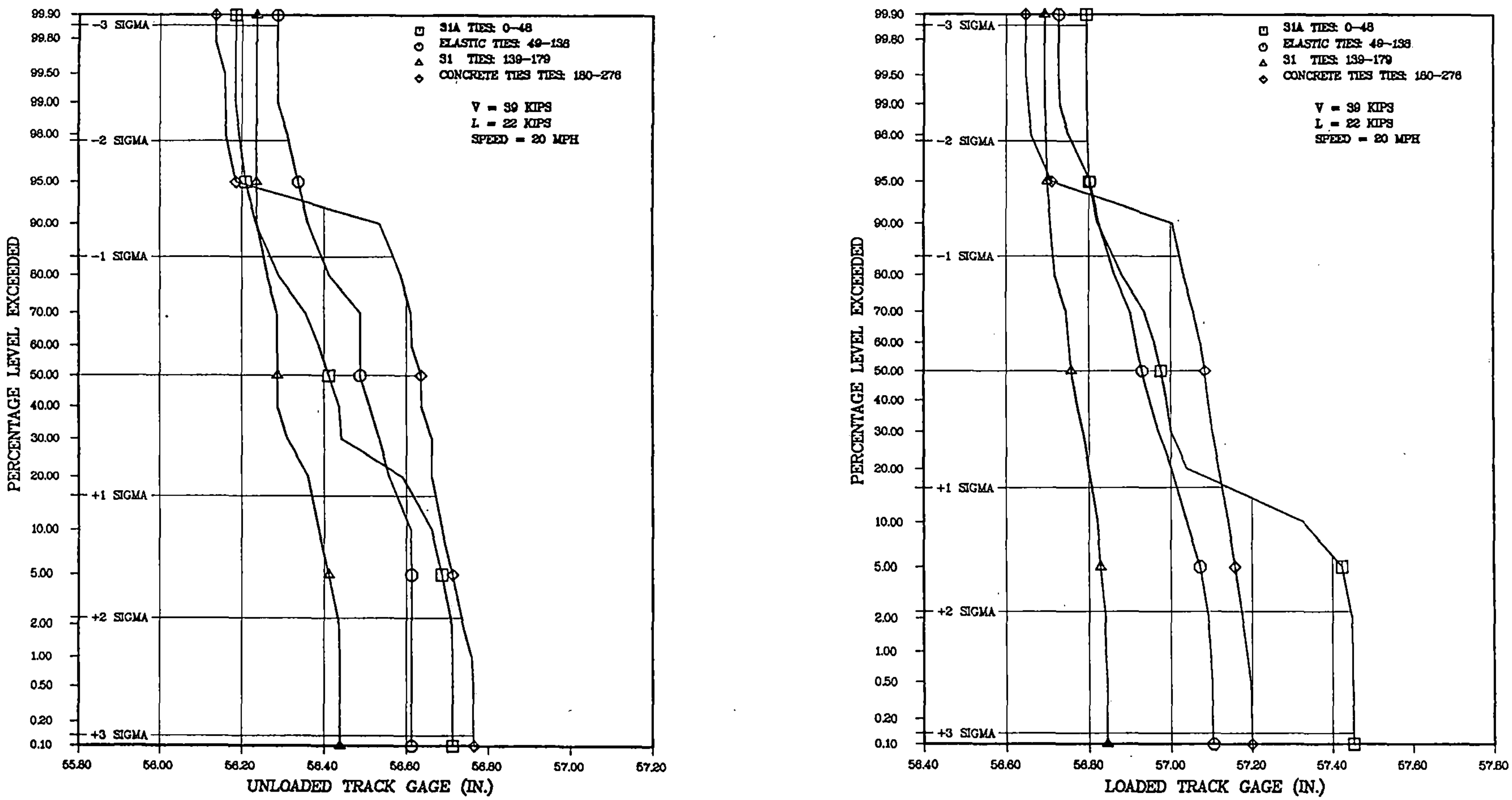
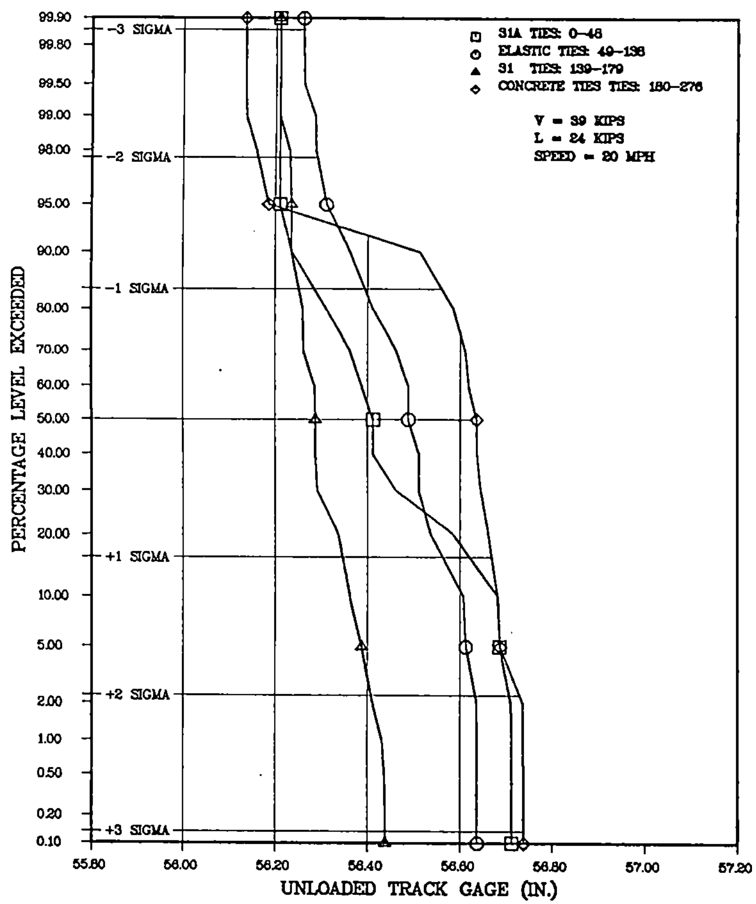


Exhibit **D51.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 31), All Segments, L=22 Kips and V=39 Kips.



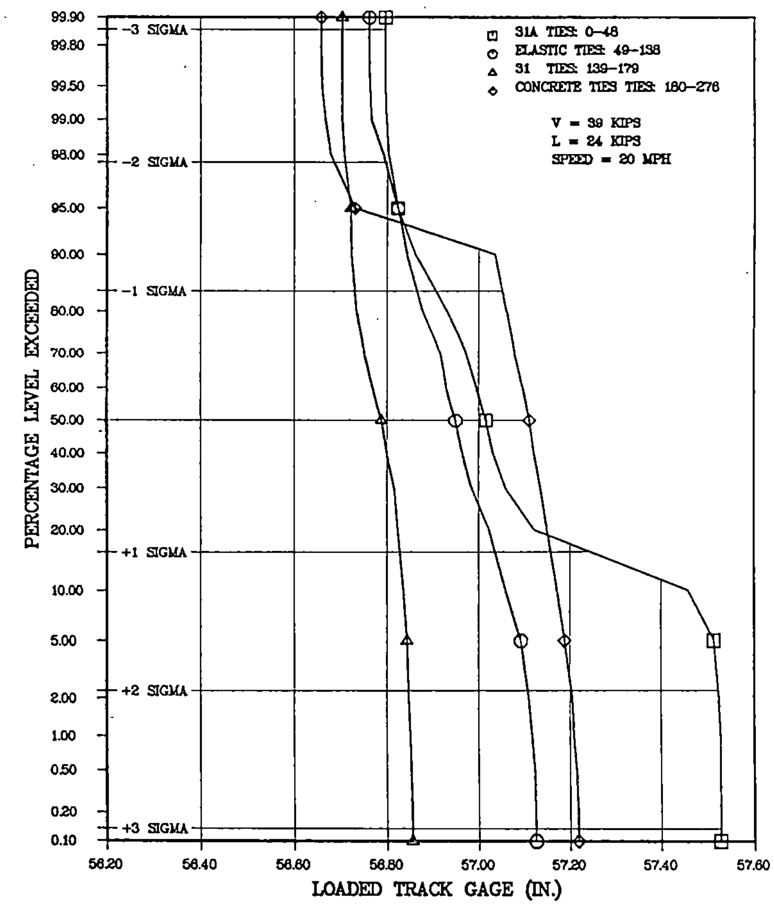
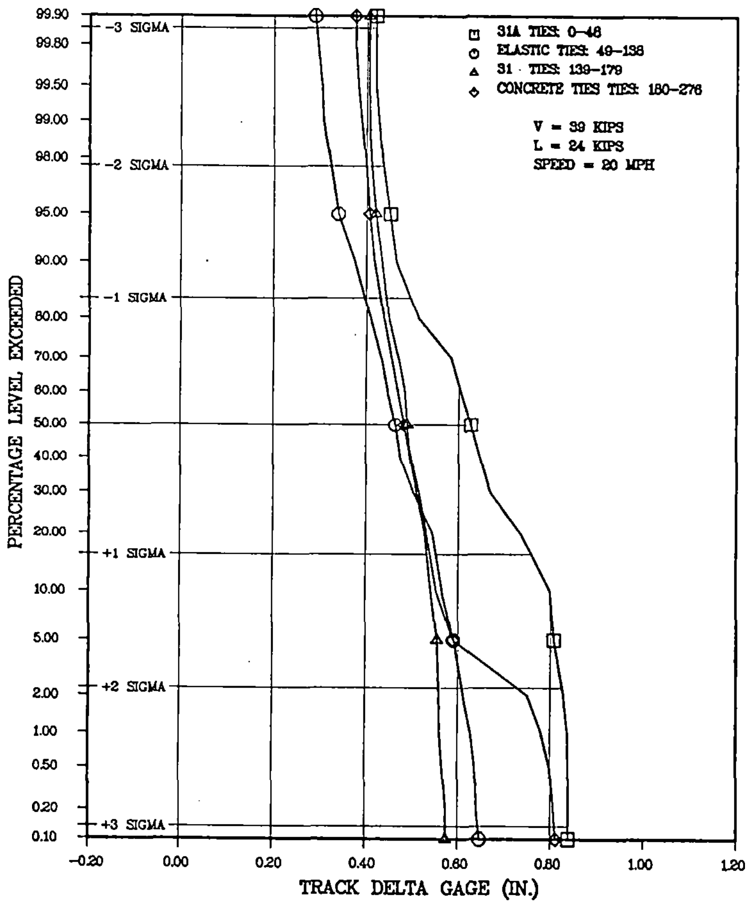


Exhibit **D52.** Percentage Level Exceedances of Unloaded and Loaded Track Gage, 5-Degree Curve(Section 31), All Segments, L=24 Kips and V=39 Kips.



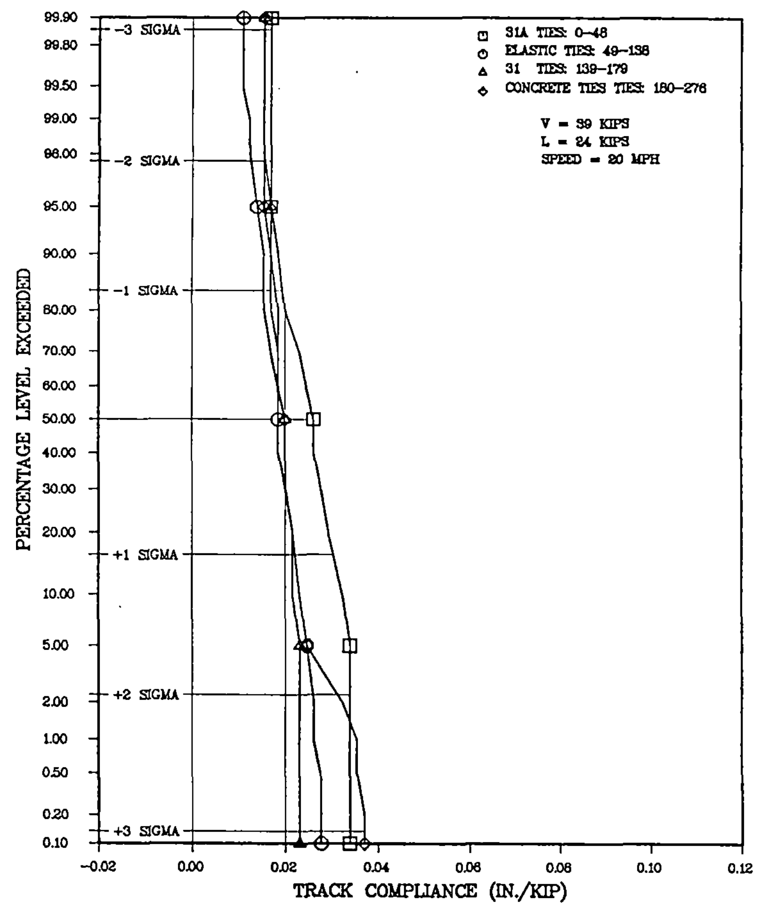


Exhibit **D53.** Percentage Level Exceedances of Track Delta Gage and Track Compliance, 5-Degree Curve(Section 31), All Segments, L=24 Kips and V=39 Kips.

Heavy Axle Load Track Gage Widening Tests by Using the Track Loading Vehicle, 1994
AAR, Satya P Singh, Anne B Hazell, Semih F Kalay

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