DEVELOPMENT OF AN IMPROVED VEHICULAR LOADING CHARACTERIZATION ASSOCIATED WITH THE GAGE STRENGTH OF TRACK

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EXECUTIVE SUMMARY

This report describes the development and application of a simplified technique for presenting vehicular loading information in a consistent and uniform manner. The load data, both lateral (L) and vertical (V), is used to develop a "loading severity", value (5), with which the level of loading can be equated with the associated level of damage to the track, as defined by a given rail head deflection. Specifically, it addresses the gage retaining strength of the track structure, in general, and the tie-fastener-rail system, in particular. This is done by means of a linear relationship $S=L-\mu V$ where μ is the effective friction coefficient between the rail and the tie.

Data were taken from five sets of fie1d and laboratory tests of track gage widening, used to validate this relationship and to determine the effective friction coefficient for conventional track. The linear relationship between lateral (L) and vertical (V) loads indicates that the equation shown above is a good approximation to the equivalent levels of loading. Examination of the test data and analysis of the effective friction for the numerous individual tests in the five series shows a normal effective friction distribution, with a mean value of 0.4 and a standard deviation of 0.1.

ACKNOWLEDGEMENTS

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The authors would like to thank Messrs. G. J. Ewenson of CP Rail and A. W. Worth of CN Rail Engineering for their important work on this methodology, as well as Messrs. William Chang and George Marathias for their invaluable assistance in processing the AAR's track laboratory data.

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1.0 INTRODUCTION

The capability of matching train behavior with the capacity or strength of the track has up until recently been based upon the subjective judgment of both rolling stock designers and track engineers. Recently, significant amounts of information have been obtained on both the loads that trains and individual cars apply to the track and on the load-carrying capacity of the track structure. However, the data has usually been presented in such a broad range of formats that comparisons of the applied loads with the track's ability to resist these loads has been extremely difficult, if not impossible.

Recent studies on the effect of loads on the gage widening behavior of track have provided much information about this critical form of track behavior. However, since the track's behavior is dependent upon both the lateral and vertical loads, and their ratio, there appeared to be an infinite number of load combinations which would cause identical gage widening behavior for track of given strength. If these infinite series of lateral (L) and vertical (V) load combinations could be equated to a single variable, a "track loading severity" value, then the confusion caused by use of the three variables, L, V and L/V, would be eliminated.

This report presents the derivation and use of a simplified linear relationship that was developed under the Track Strength Characterization Program. Data were taken from five different sets of field tests, in which the strength of the track structure was measured by the displacement of a rail head under various combinations of lateral and vertical loads. These data were used to develop and validate the postulated "track loading severity" relationship, which in turn permits a more effective presentation of track strength data, in a format which permits better correlation with the corresponding vehicular loading information.

2.0 ANALYSIS

In order to develop a relationship between the loads applied to a track structure and the corresponding gage widening behavior, the transmission of the applied vertical and lateral loads from the rail head to the ties was examined. This can be seen in the free body diagram of a rail, shown in Figure 1.

The following assumptions are made:

(1) The rail weight is negligible, when compared to the vertical and lateral applied forces.
(2) Coulomb friction exists between the rail, tie plates, and
(3) The rail length is long enough to dissipate the lateral and vertical shear reactions, as well as the bending moments and torsional reactions.

The sum of the forces in the vertical (y) direction gives:

$$\sum_{i=1}^{a} N_i = N = V \qquad (1)$$

where:

N = Sum of the normal forces from all of the associated tie plates, and
V = Applied vertical force at the rail head.

Summing the forces in the lateral (x) direction gives:

$$\sum_{i=1}^{a} S_i + \sum_{i=1}^{a} \mu_i N_i - L = 0 \qquad (2)$$

where:

S_i = Rail-fastener lateral force developed at the j" tie plate (See Figure 1),
N_i = Normal vertical force at the i^{th} tie plate, and
μ_i = Friction coefficient between the i^{th} tie and the rail.

Using the following definitions:

$$S = \sum_{i=1}^{a} S_i \text{ and } \mu = \frac{1}{N} \sum_{i=1}^{a} \mu_i N_i \qquad (3)$$

then substituting Equations (1) and (3) into (2) gives:

$$L = S + \mu V \qquad (4)$$

where:

μ = Effective friction coefficient between the rail, tie plates and ties.

Equation (4) can also be written as:

$$S = L - \mu V$$

where: S is a direct measure of the loading of the rail-fastener system,* i.e., a fastener loading severity value.

3.0 TEST DATA

In order to validate the relationship developed in the previous Section, test data from five different gage widening tests were analyzed. These tests involved the application of combined lateral and vertical loads, and measurements of the corresponding lateral movements of the rail head.

The tests examined were:

1. Main line gage widening tests on Southern Railways (1),*
2. Static and dynamic gage widening tests at the Transportation Test Center (2),
3. Secondary track gage widening tests on Southern Railway (3),
4. Main, secondary and yard track tests on Canadian National Railways (4), and
5. Full-scale laboratory tests of track gage widening at the AAR's Track Laboratory (5).

Data were also taken from full-scale laboratory tests of lateral track shift (6) and analyzed. In these tests, the gage was mechanically prevented from widening and consequently the track displaced laterally.

In all of the above tests, both the vertical and lateral loads were varied so as to apply different load combinations to the track and the corresponding lateral rail head displacements

* The general relationship also appears to hold for the tie-ballast system: $S' = L - \mu' V$ were S' is the tie ballast loading severity value and μ' is the effective friction coefficient between the ties and the ballast.

* The numbers in square brackets [] pertain to the references listed in section 8.0 of this report.

were measured. In order to reduce these data, the load levels that produced equivalent lateral railhead deflections were plotted, as shown in Figure 2. In all cases, the lateral-vertical load relationship that resulted in constant railhead deflection was a straight line. Thus, it could be concluded that all of the load combinations that produced the same amount of railhead deflection were of equivalent severity. Making use of the linear relationship: $L = S + \mu V$ or $S = L - \mu V$, a track loading severity va1ue could then be obtained.

4.0 RESULTS

The test data from both the laboratory and field tests were plotted in the format shown in Figure 2, with each curve representing a line of constant rail head deflection. Thus, each lateral and vertical load combination produced an equivalent amount of rail head deflection and an equi\'21ent amount of track "damage."' As can be seen from Figure 2 and the data curves in Appendix A, this lateral-vertical load relationship for constant railhead deflection is a straight line, the slope of which is the effective friction coefficient, μ between the rail and the associated tie plates and ties. The intercept on the vertical axis (Figure 2) is the lateral force resisted by the rail-fastener system in the absence of any applied vertical load.

The linear relationship also appears to apply when the lateral forces are plotted against the vertical forces at constant rail *base* deflection, as shown in Figure 3. This is to be expected since the rail head merely amplifies the corresponding motion of the base through rotation or twist.

Data from Reference 6, which was developed from the AAR's lateral track shift tests, were also plotted in the same way. These plots are shown in Figure 4. These relationships are also linear, but the effective friction coefficients, μ', are higher than those measured in the various gage widening tests. This indicates that gage widening would occur before the lateral movement or a conventional wood cross tie track.

Percentage distribution curves for the effective friction coefficients are shown in Figures 5 through 9. Figure 5, which shows the distribution of the data from the AAR's Track Laboratory tests [5] indicates a double peak, with a mean value of 0.31 and a standard deviation of 0.12. Figure 6 shows the distribution of all of the other test data exclusive of the Track Laboratory tests. The mean value is 0.39 and the standard deviation is 0.13. The distribution from all of the test data is shown in Figure 7, which shows a mean value of approximately 0.4. However, these data include friction values derived from low levels of lateral force (which were probably insufficient to develop full friction), as well as friction values from the track shift tests. Removal of these data from the distribution gives the plot shown in Figure 8, which shows a mean value of 0.40 and a standard deviation of 0.10. Note that over 41 % of the effective friction values were between 0.35 and 0.45 and 67.6% were between 0.3 and 0.5.

The distribution for values or effective friction coefficient, exclusive of the CN data, Track Shift Test data and low values of μ (from the very low rail deflection curves) is shown in Figure 9. The mean value or effective friction coefficient for these data is 0.40, with a standard deviation of 0.096. This curve shows that 75.4% of the friction values occurred between 0.3 and 0.5.

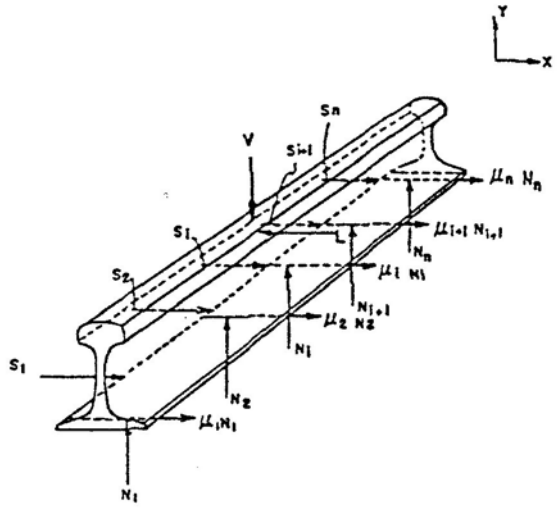

Figure 1. Free Body Diagram of a Rail.

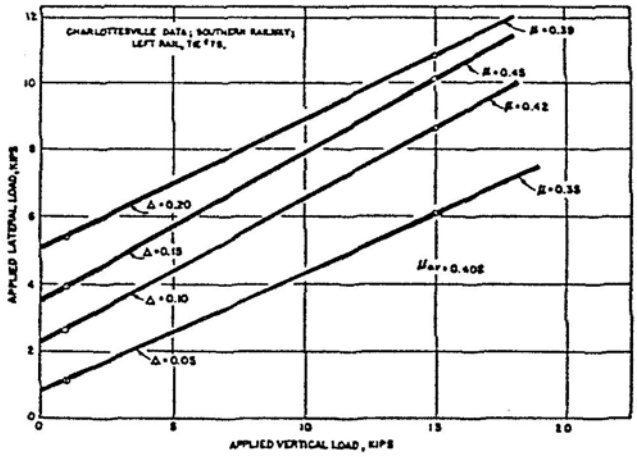

Figure 2. Applied Lateral vs. Applied Vertical Loads, for Constant Railhead Deflection (Δ). Data From the Southern Railway Tests at Charlottesville Va.

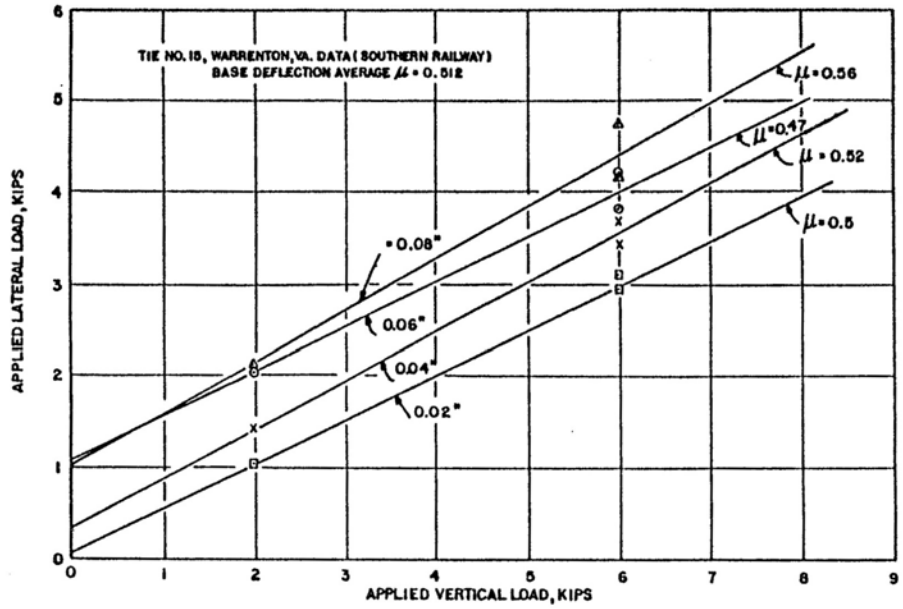

Figure 3. Applied Lateral vs. Applied Vertical Loads, for Constant Railbase Deflection. Data from the Southern Railway Tests at Warrenton, Va.

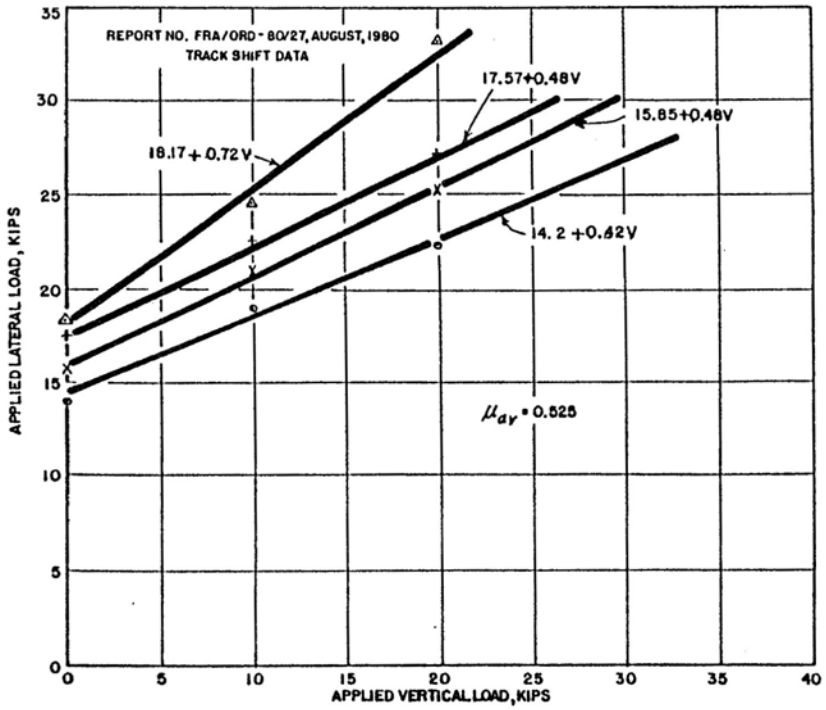

Figure 4. Applied Lateral vs. Applied Vertical Loads, for Constant Lateral Track Deflection. Data From the AAR's Lateral Track Shift Tests.

5.0 DISCUSSION OF RESULTS

The test data examined in this report show a high degree of linearity when lateral *vs.* vertical load curves are plotted for given values of rail head deflection. However, a considerable

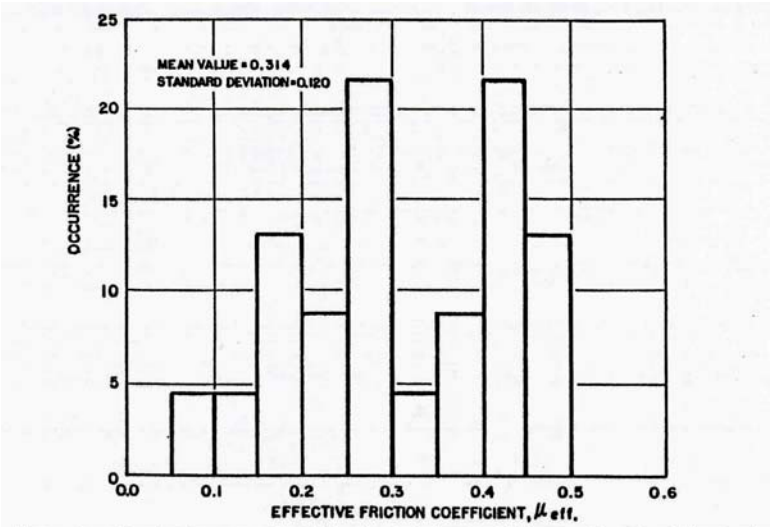

Figure 5. Distribution Curve for Effective Friction Coefficients, from the AAR's Track Laboratory Test Data.

amount of dispersion was present in the applied lateral load curves for no applied vertical load. Since these points did not involve development of friction forces, they were excluded from the final plots.

Although the track shift data showed the same linearity information, it was removed from the final distribution curve because it did not measure the effective friction between the rail and the ties, but rather was a measure of the friction between the ties and the ballast.

The friction coefficients obtained from the CN Data [4] were much higher than those obtained from the AAR and other tests. In the CN tests, the rails were jacked apart directly under the axles of loaded cars, and thus frictional forces were also developed at the wheel/rail interface points. To determine the effective friction coefficient values on the same basis with the other test data, the CN values were divided by two (an estimate only).

The low value of effective friction coefficient, e.g., (those less than 0.2) were discarded from the final distribution curve, because the lateral forces were insufficient to overcome static friction.

The data from all of the references cited in this report were reduced by plotting L versus V graphs for given values of lateral rail head deflections. Some curves of L versus V were also plotted using given values of rail base deflections.

From the various curves of L versus V (see the Appendix), a best straight line fit produced values of μ_{eff} and S. using Equation 4. A summary of the μ_{eff} values of these curves is shown in Figure 9.

6.0 CONCLUSIONS

1. Measured track strength and loading data ha\"e demonstrated that a linear relationship exists between the lateral and vertical loads applied to the rail head, for any given rail head lateral deflection. The data fits the equation:

$$L = S + \mu V$$

2. On a plot of lateral load, L, versus vertical load, V, the force, S, applied to the rail fastening system (the force which causes track gage deterioration) is the intercept on the L axis, while the slope of the line is the effective friction, μ between the rail, tie plates and ties.

3. A realistic value for effective friction coefficient is $\mu = 0.4$, with a standard deviation $\alpha = 0.1$ (for the limited amount of data analyzed in this report, the effective friction between rail and ties fell in the range of 0.3 to 0.5, 75% of the time).

4. With the equation: $S = L - \mu V$ established and validated, it becomes a powerful tool for equating lateral and vertical wheel-rail loads, in terms of the net lateral force applied to the rail fastening system (See Table 1). All of the lateral and vertical wheel/rail loading combinations shown in Table 1 have developed the same lateral rail head deflection, and, therefore, the same net lateral force on the rail fastening system. They are, therefore, of equivalent severity as far as track gage widening is concerned.

5. Being able to correlate the three variables: L, V and L/V in terms of one variable, S, which is directly related to the gage strength of the track, is considered to be breakthrough for characterization of the entire vehicle loading/track strength regime in North America.

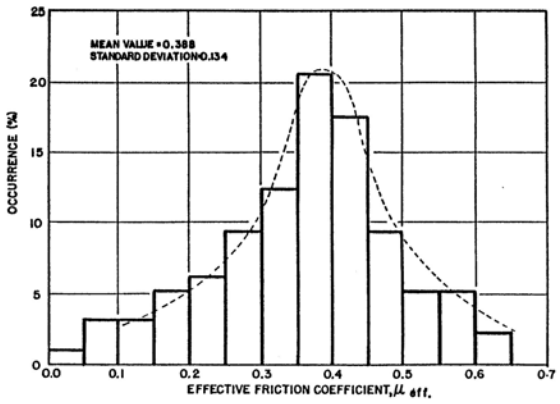

Figure 6. Distribution Curve for Effective Friction Coefficients, from All Test Data, Except the AAR's Track Laboratory Tests.

6. It is clear from Table 1 that lateral loading by itself is a poor indicator of track loading severity, because lateral loads ranging from 11 to 27 kips produced the smack loading on the rail fastening system. The L/V ratio by lisle is also a poor indicator, because it ranged from 0.6 to 2.2 for the same not result. It should be noted that the L/V ratio is useful for evaluation of wheel climbing tendencies, but has limited value for the evaluation of track gage strength.

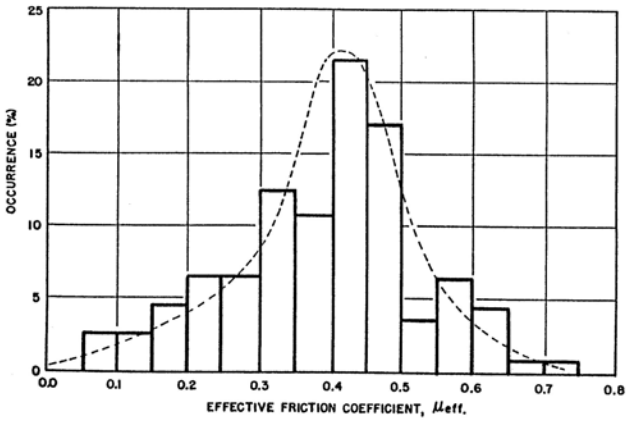

Figure 7. Distribution Curve for Effective Friction Coefficients, from All Test Data.

TABLE 1.
Calculated Fastener loading Severity Values, for an Assumed Value of Effective Friction Coefficient and Various Combinations of Applied Lateral and Vertical Loads.
For μ = 0.4 (assumed value), S = L - 0.4V

Lateral Wheel Load, L (kips)	Vertical Wheel Load, V (kips)	L/V Ratio	μV = 0.4V (kips)	Net Lateral Force on Rail Fastenings, S (kips)
11	5	2.20	2	9
13	10	1.30	4	9
15	15	1.00	6	9
17	20	0.85	8	9
19	25	0.76	10	9
21	30	0.70	12	9
23	35	0.66	14	9
25	40	0.63	16	9
27	45	0.60	18	9

Note: All of the above load combinations produce an equivalent amount of railhead deflection and hence an equivalent level of damage to the track.

7.0 RECOMMENDATIONS

The simplified method described herein can be used to compare future track test information. The effective value of μ = 0.4, with a standard deviation of 0.1, can be used to determine track conditions from information obtained from track strength investigations. This technique could be verified and updated as new information is gathered.

1. For correlations of vehicle loading with track gage strength, the equation: $S = L - \mu V$, should be used to define loading in terms of *one* "loading severity" variable S, i.e., the resultant lateral force which must be resisted by the rail fastening system instead of the *two* variables, L and V, which have been used in the past.

2. While data in this report has indicated an effective friction value of 0.4 is most appropriate, it seems prudent, in view of the scatter encountered, to analyze wheel loadings in terms of a range of friction values, such as:

$S = L - 0.2V$
$S = L - 0.3V$
$S = L - 0.4V$
$S = L - 0.5V$

In this manner, data that is analyzed now may be interpolated at any time in the future to reflect possible changes in the most appropriate value of friction.

3. Data from previous loading measurement tests (which have been preserved on tape) should be re-analyzed, in order to develop histograms or cumulative probability curves of S.

8.0 REFERENCES

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2. Harrison, H., Forry, M., and Tuten, J., Letter Report for Technical Task Directive No.8, Item 3, Deflection and Stiffness, Battelle-Columbus Laboratories.
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5. Choros, J., Zarembski, A. M., and Gitlin, I., "Laboratory Investigation of Track Gauge Widening Characteristics," Federal Railroad Administration Report FRA/ORD-80/33, August 1980.
6. Choros, J., Zarembski, A. M., and Gitlin, I., "Laboratory Investigation of Lateral Track Shift," Federal Railroad Administration Report FRA/ORD-80/27, August 1980.

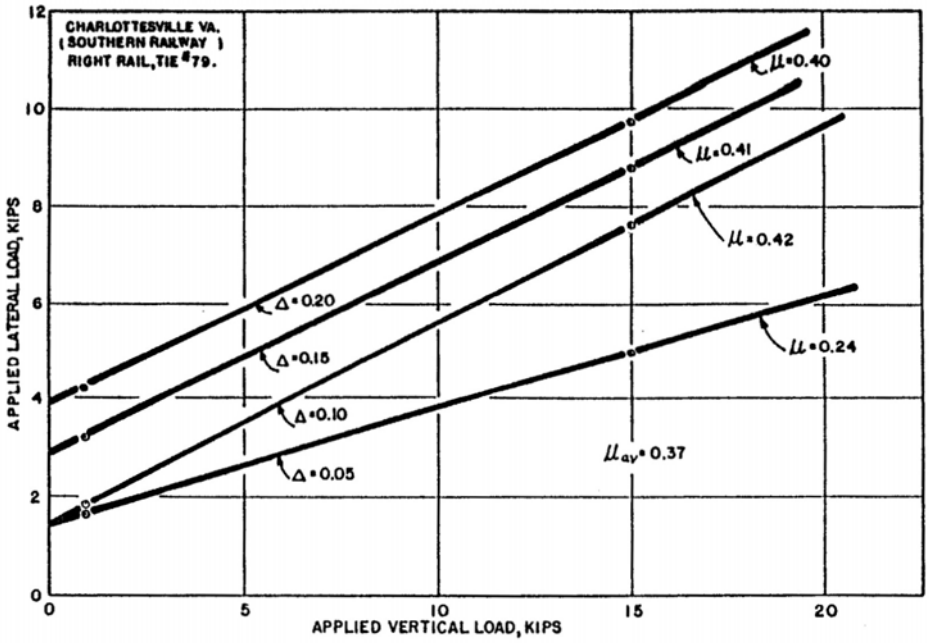

Figure A.1 Data from Southern Railway Tests at Charlottesville, Va. Right Rail at Tie No. 79.

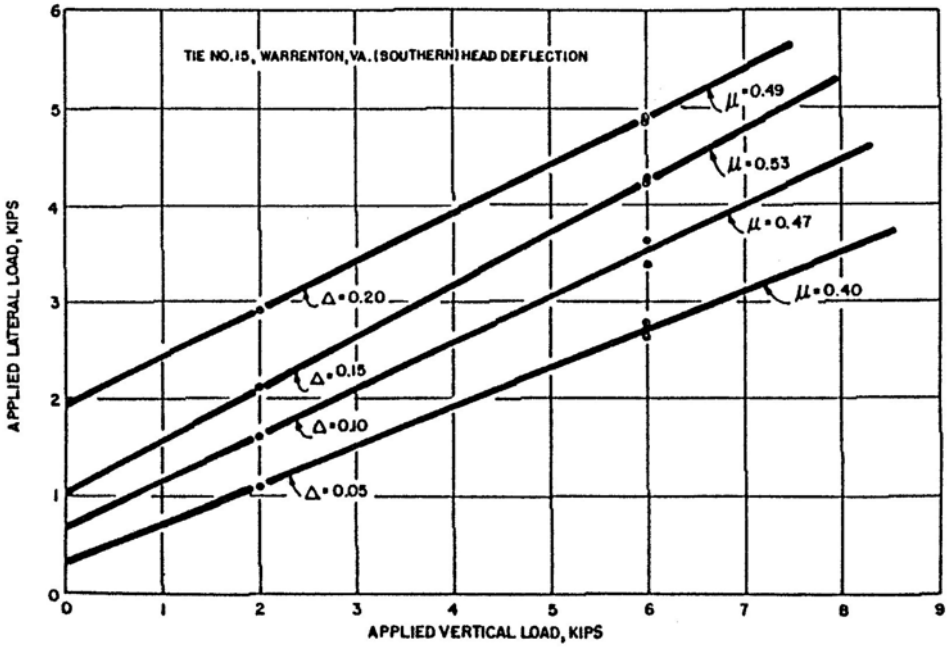

Figure A.2 Data from Southern Railway Tests at Warrenton, Va. Rail Head Deflections at Tie No. 15.

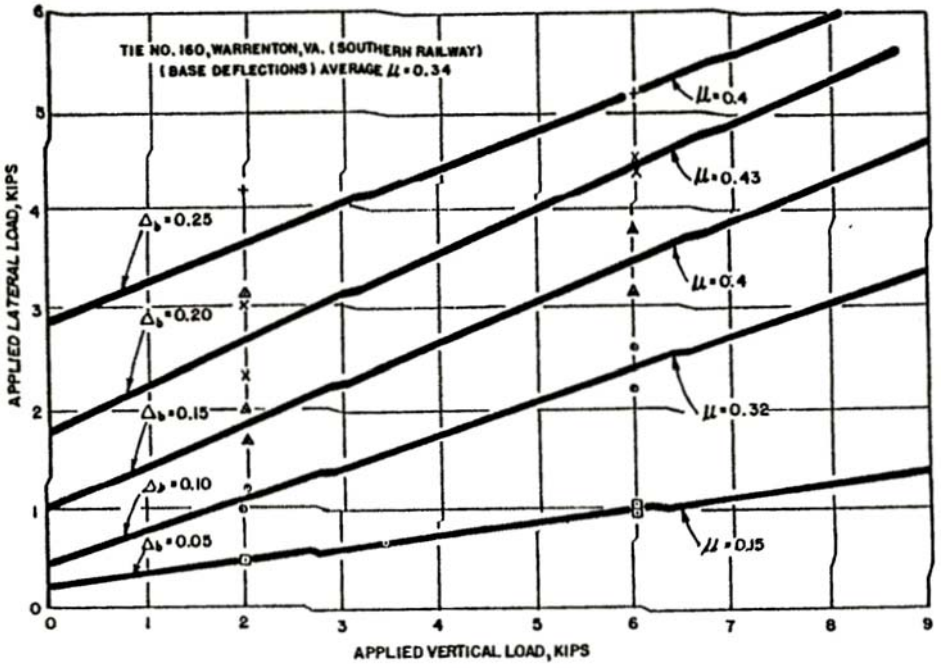

Figure A.3 Data from Southern Railway Tests at Warrenton, Va. Rail Base Deflections at Tie No. 160.

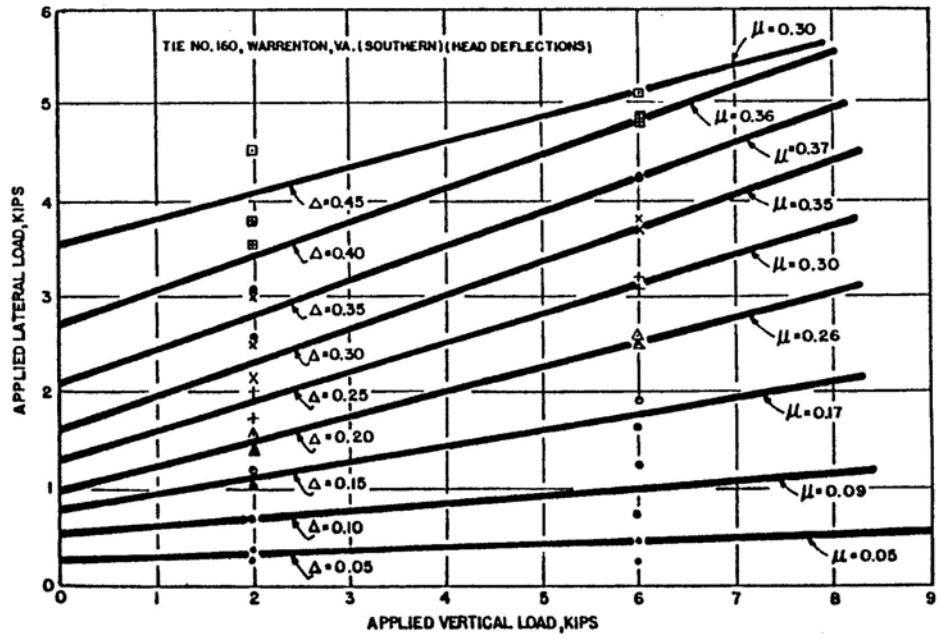

Figure A.4 Data from Southern Railway Tests at Warrenton, Va. Rail Head Deflections at Tie No. 160.

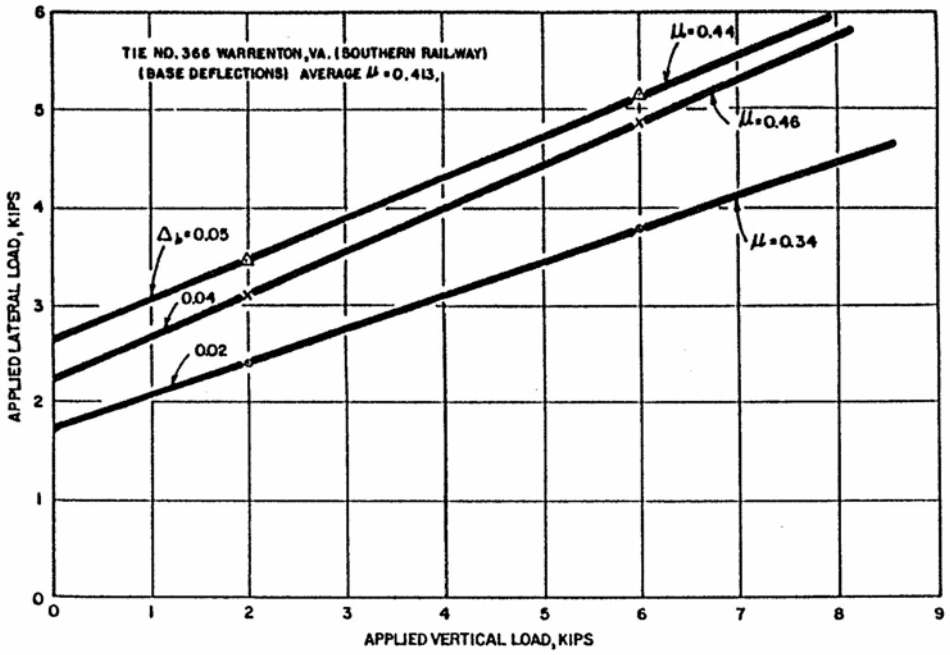

Figure A.5 Data from Southern Railway Tests at Warrenton, Va. Rail Base Deflections at Tie No. 366.

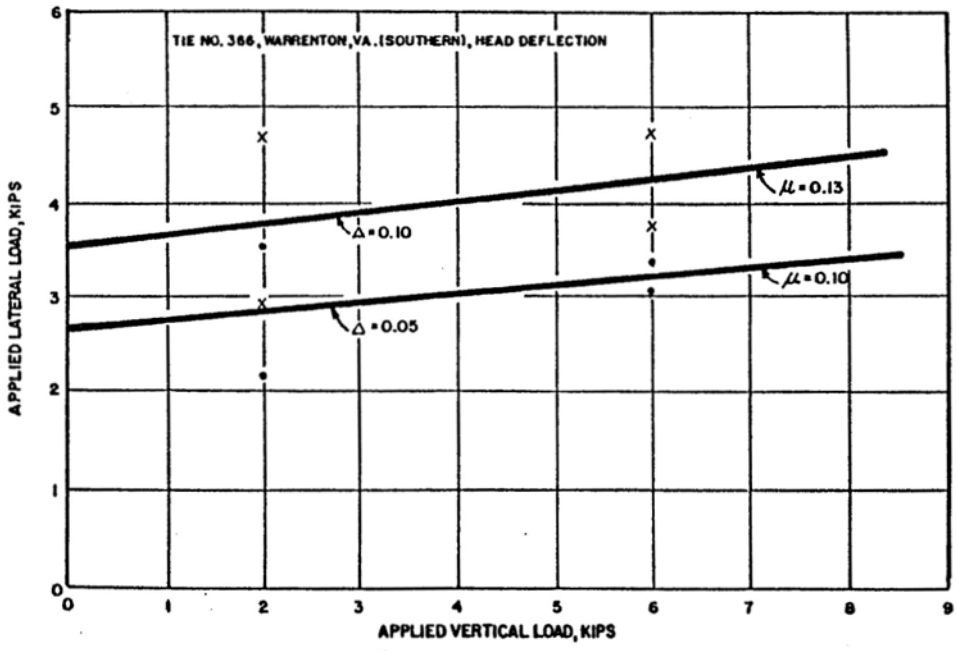

Figure A.6 Data from Southern Railway Tests at Warrenton, Va. Rail Head Deflections at Tie No. 366.

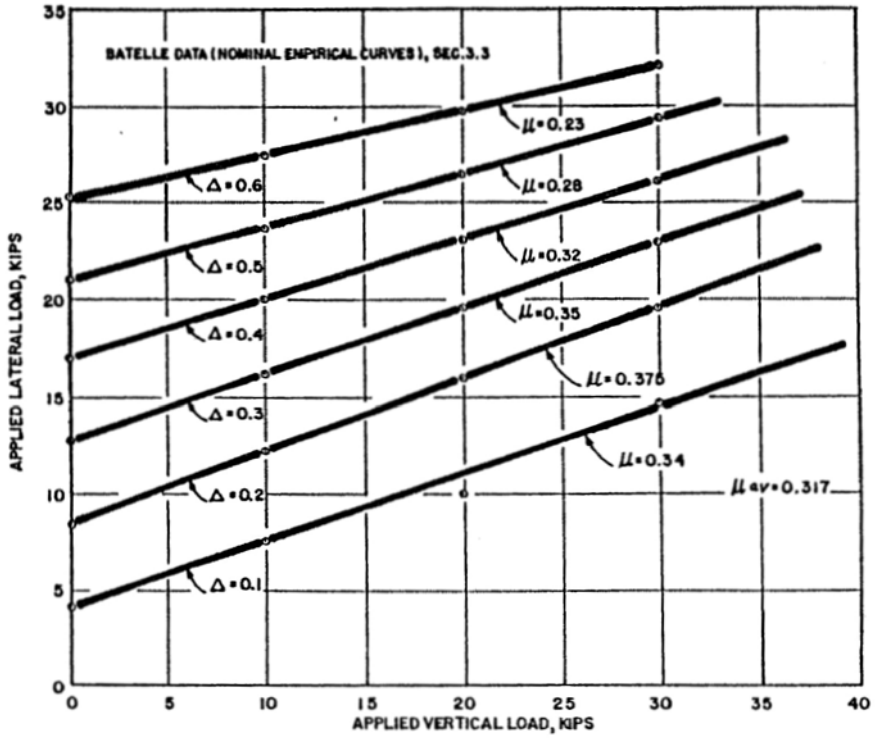

Figure A.7 Data from Transportation Test Center, Section 3.3.

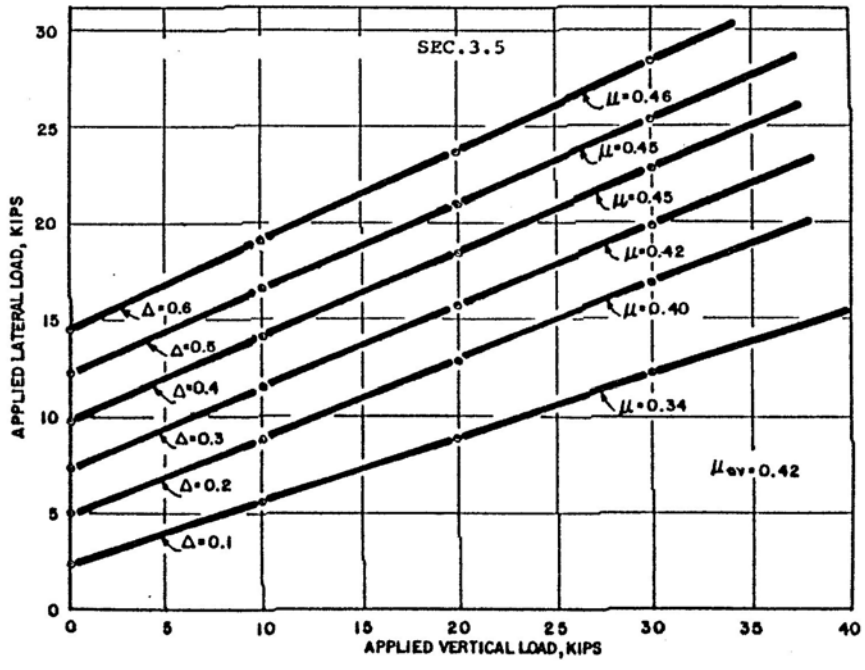

Figure A.8 Data from Transportation Test Center, Section 3.5.

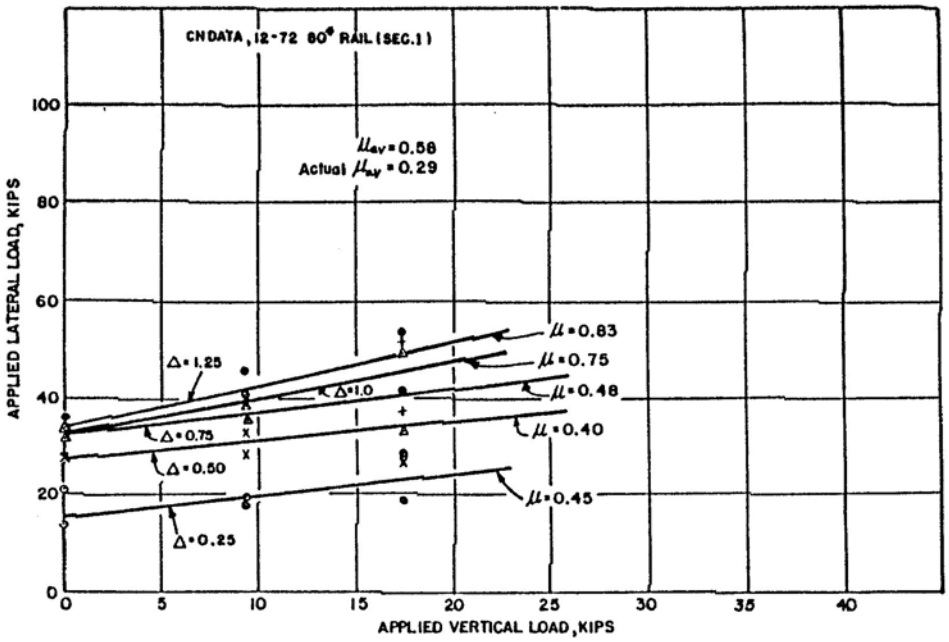

Figure A.9 Canadian National Data. Section 1, 80# Rail.

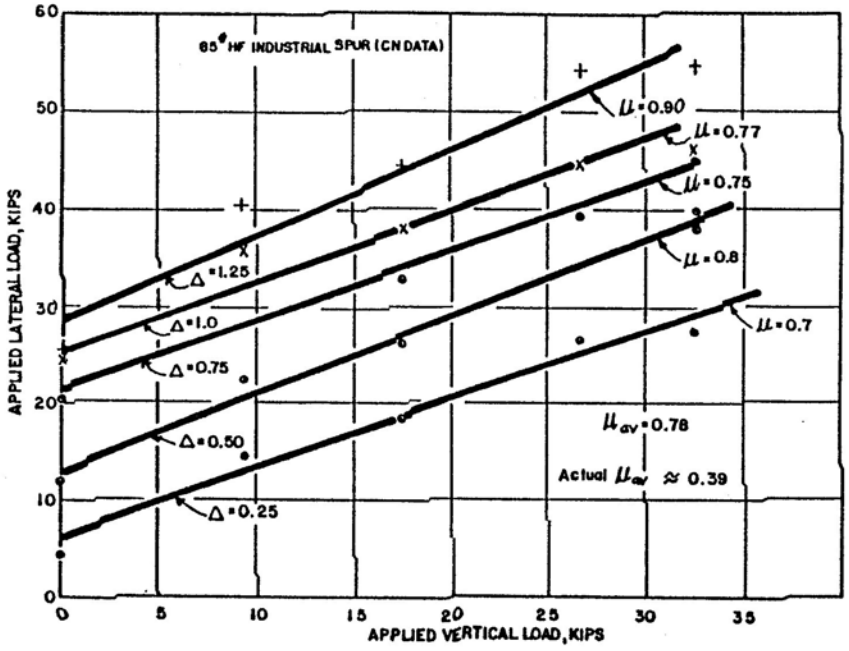

Figure A.10 Canadian National Data. Industrial Spur, 85# HF Rail.

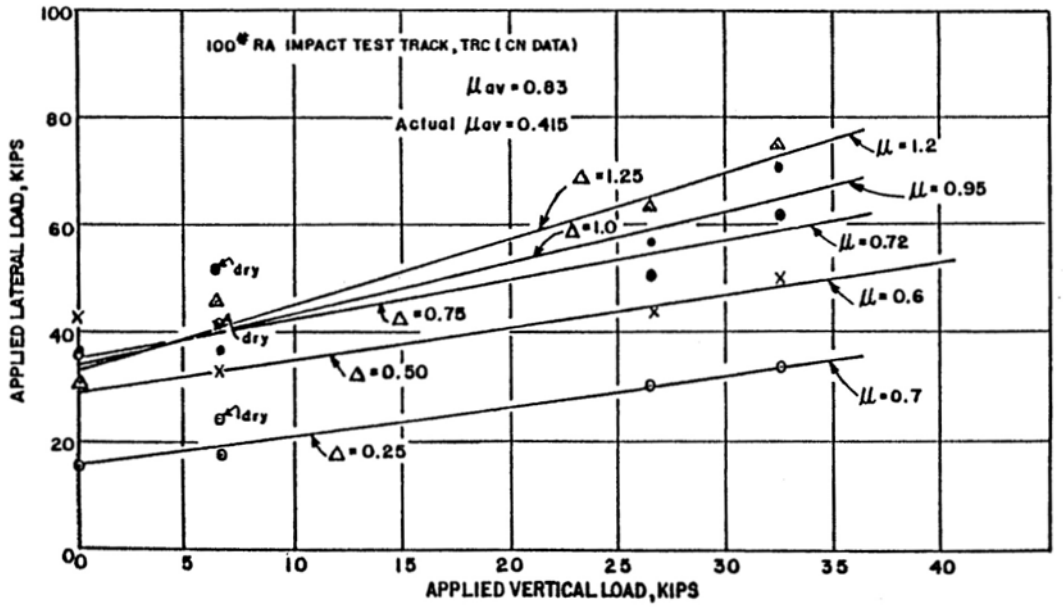

Figure A.12 Canadian National Data. Impact Test Track, T.R.C., 100# RA Rail.

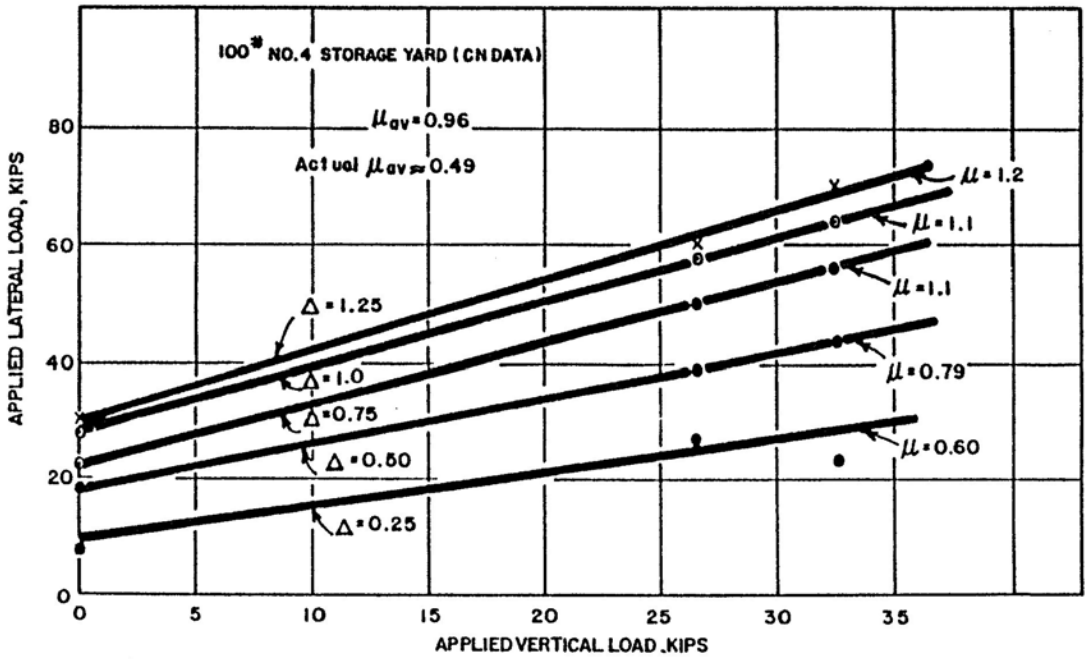

Figure A.11 Canadian National Data. Storage Yard, No. 4, 100# Rail.

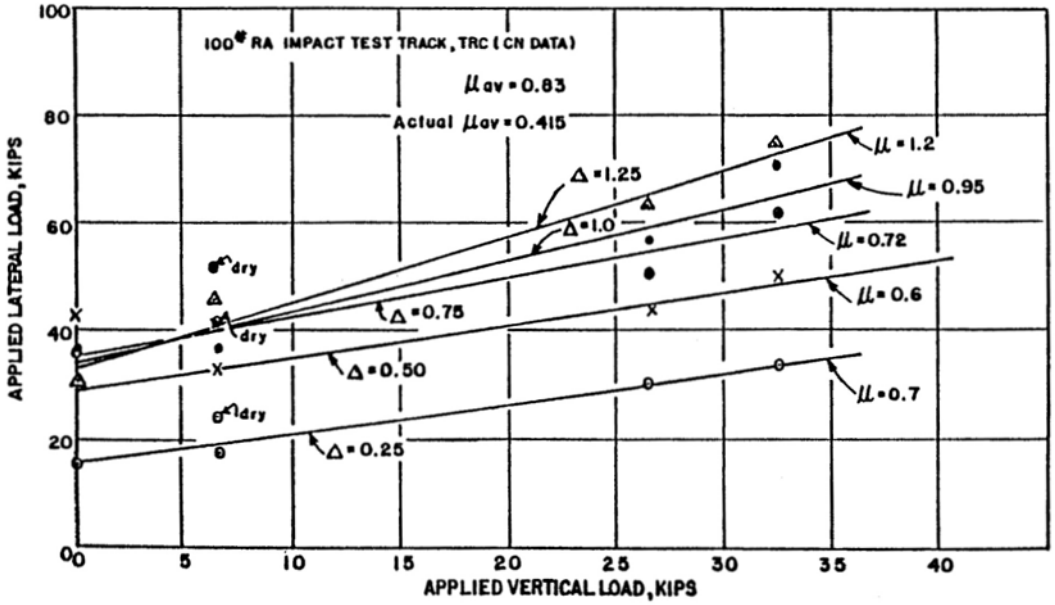

Figure A.12 Canadian National Data. Impact Test Track, T.R.C., 100# RA Rail.

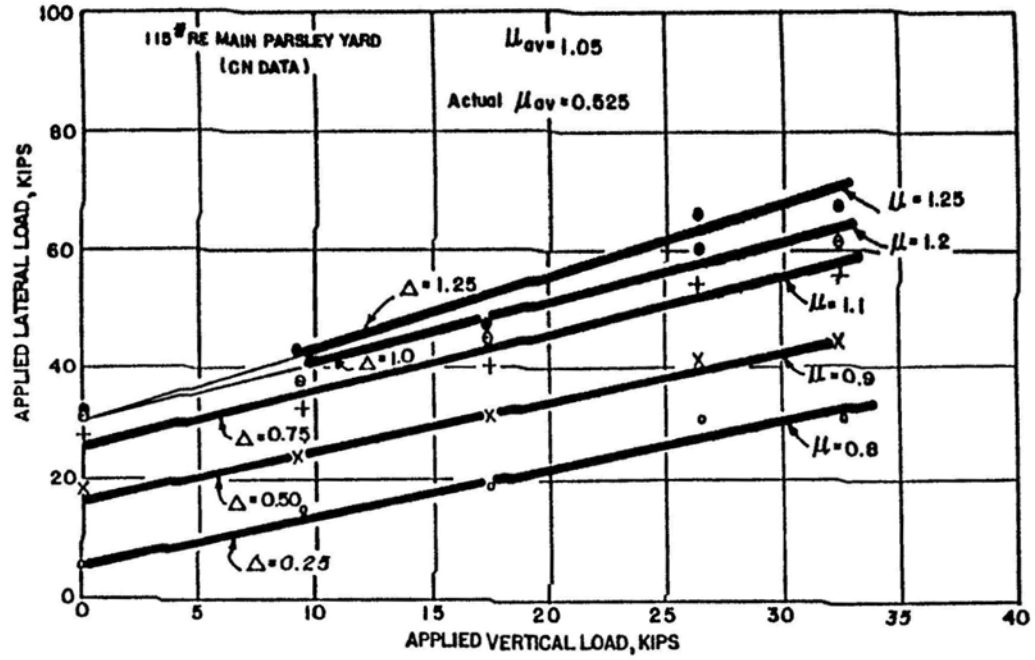

Figure A.13 Canadian National Data. Main Parsley Yard, 115# RE Rail.

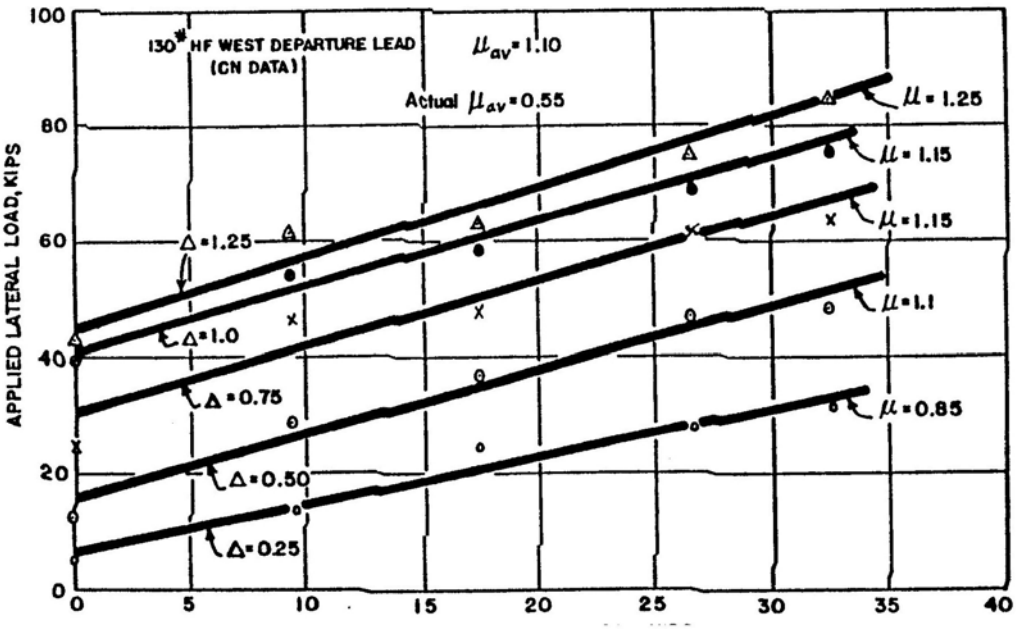

Figure A.14 Canadian National Data. West Departure Lead, 130# HF Rail.

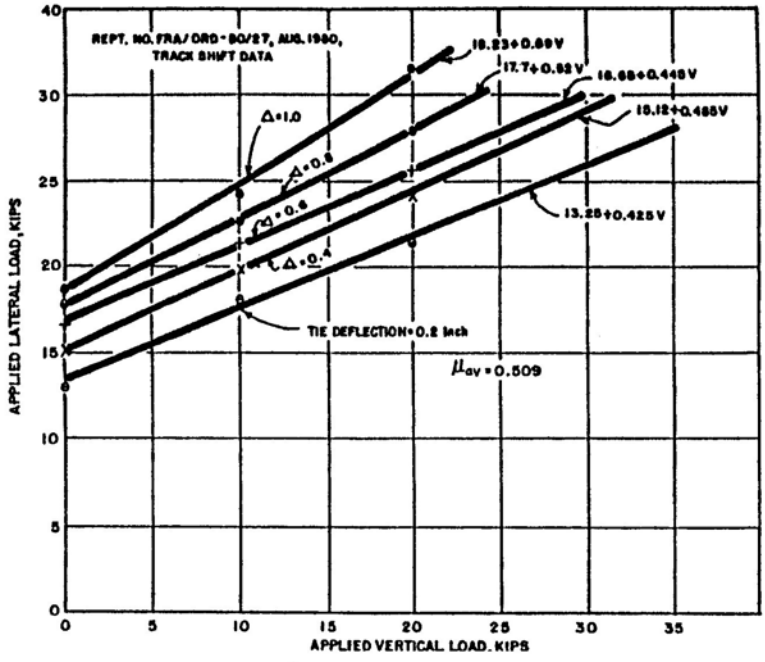

Figure A.15 Track Shift Test Data, from AAR's Track Laboratory Tests

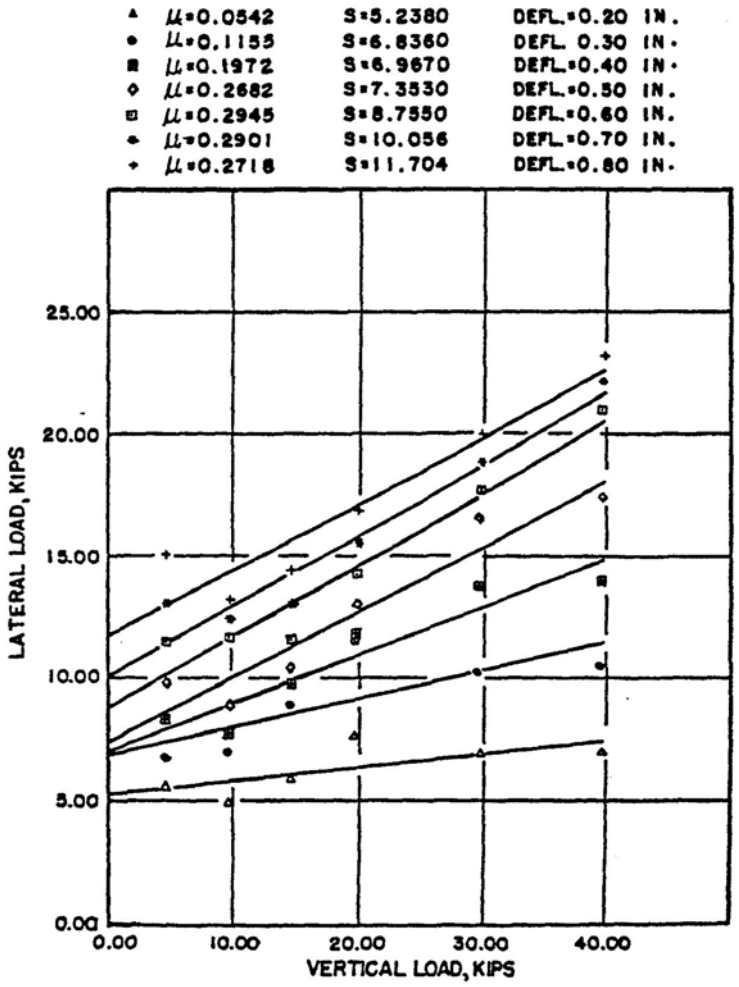

Figure A.16 Rail Deflections for Various Applied Lateral and Vertical Loads. AAR's Track Laboratory Gage Widening Tests.

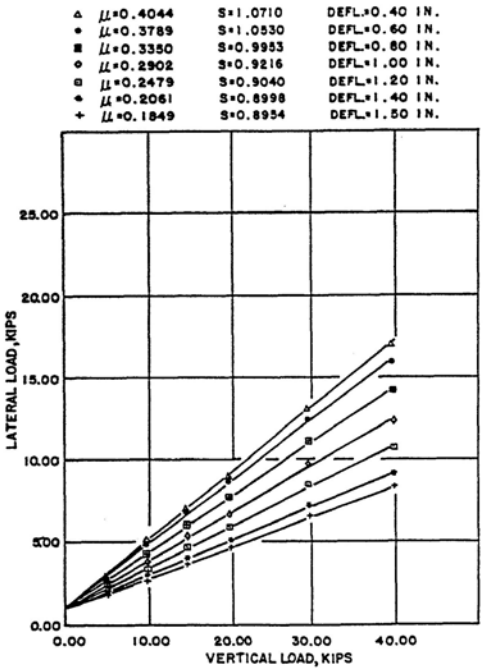

Figure A.17 Rail Deflections for Various Applied Lateral and Vertical Loads. AAR's Track Laboratory Gage Widening Tests.

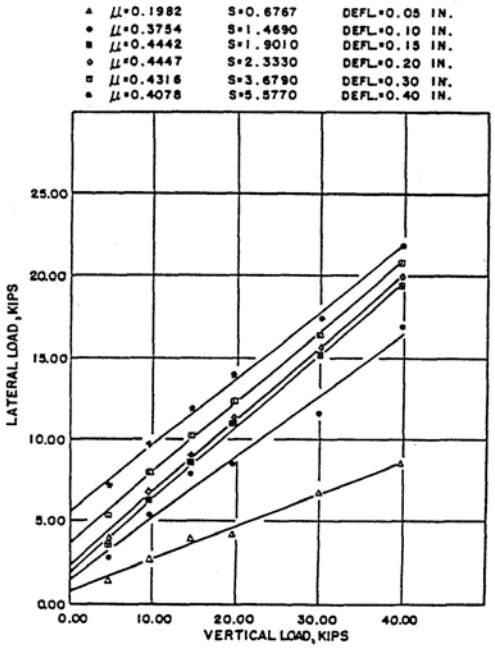

Figure A.18 Rail Deflections for Various Applied Lateral and Vertical Loads. AAR's Track Laboratory Gage Widening Tests.

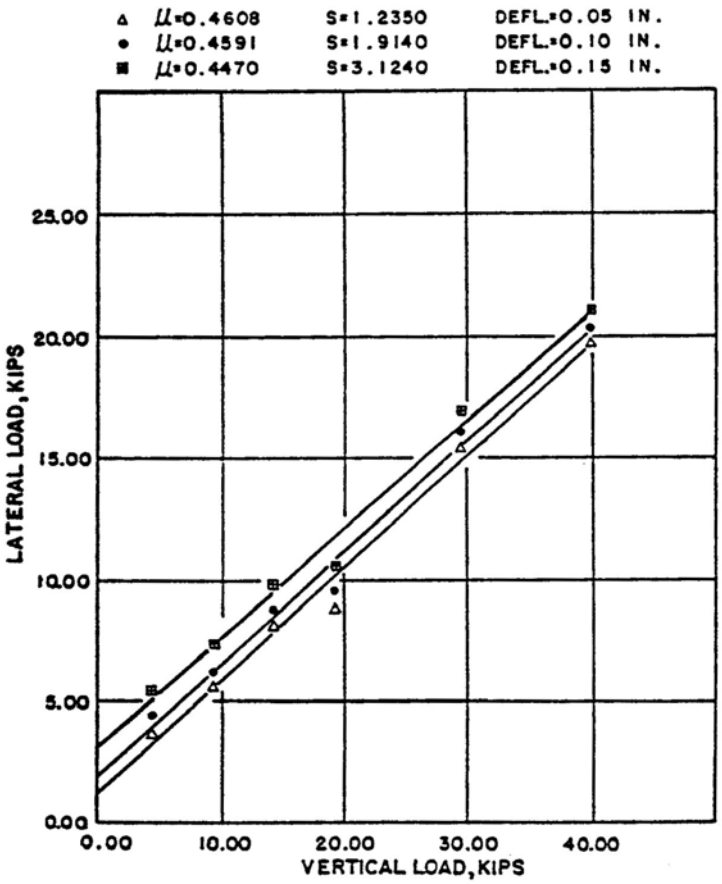

Figure A.19 Rail Deflections for Various Applied Lateral and Vertical Loads. AAR's Track Laboratory Gage Widening Tests.