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Relationship Between Weights Measured by Permanent Truck Scales and Golden River Weigh-In-Motion Scales

by

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in cooperation with
Kentucky Transportation Cabinet
Commonwealth of Kentucky

and

Federal Highway Administration
US Department of Transportation

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16. Abstract

The Division of Planning purchased a Golden River Weigh-in-Motion system. The first assignment was to determine the optimum calibration setting for operating each weigh mat. The second assignment was to determine the sensitivity of the weigh data. The third assignment was to develop appropriate relationships to adjust the dynamic data to equivalent static data.

A series of correlation efforts established the appropriate calibration factor for each weigh mat. Then the mats were installed at a site on I 64 in Shelby County and data were collected for over 1,600 trucks. From these data, it became evident that equations to adjust dynamic loads to equivalent static loads should be developed for individual axle locations on the truck rather than the gross weight as recommended by the manufacturer. The primary reason was that the steering axle's dynamic load was approximately 70 percent of the static axleload. The discrepancy is due to the torque transmitted from the engine to the drive axles which partially lifts the steering axle off the pavement. Therefore, equations were developed for:

1. Steering Axle
2. Single Drive Axle
3. Single Axle on Trailer
4. Drive Tandem Axles
5. Trailer Tandem Axles
6. Drive Tridem Axles
7. Trailer Tridem Axles

Observations of truck dynamics combined with literature review indicated that dynamic axleloads are affected by:

1. Engine torque,
2. Temperature of rigid pavements,
3. Location of axle on truck,
4. Pavement roughness rather than pavement type, and
5. Suspension system between truck frame and axles.

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EXECUTIVE SUMMARY

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

A Golden River weigh-in-motion (WIM) system has been purchased by the Division of Planning, Kentucky Transportation Cabinet. Among the questions asked at the time of purchase were:

- What calibration number should be used?
- Will the calibration number change as a function of:
    - a. Individual weigh mat,
    - b. Pavement type, and/or
    - c. Different highways?
- How are WIM data to be converted to equivalent static truck scale values?

A research study was initiated in an attempt to answer as many of the questions as possible.

SENSITIVITY ANALYSES USING DATA FROM ONE WEIGH MAT

Calibration Factors

The manufacturer's literature suggested calibration factors for each of the two weigh mats based upon vehicle gross weight. To verify the manufacturer's recommended calibration factor, calibration factors were chosen to extend 20 units above and below the manufacturer's recommended value and recommendations made that data be collected at intervals of 10 units (for example, 167, 177, 187 (manufacturer's recommended value), 197, and 207). A WIM site was selected where the permanent truck scale could not be seen. The permanent truck scale was located approximately 1 mile beyond the WIM site.

The predominant truck on Kentucky interstate pavements is the Class 9 truck--a 5-axle semitrailer truck. Depending upon the route, Class 9 trucks may exceed 60 percent of the truck population. Therefore, data could be collected rather rapidly because of the high percentage. Data were collected for Class 9 trucks using both WIM and permanent truck scales in sufficient quantities to provide matching of approximately 200 to 300 trucks from both sets of scale data. Comparison of WIM versus static scale data for the steering axle (Figure 1) revealed significant differences. Therefore, data were analyzed by axle location on the vehicle rather than by gross vehicle weight. Scatter in the data suggested that the ratio of static to WIM axleloads might prove more meaningful. Figures 2 and 3 illustrate variations in the ratios of static axleload to WIM axleload as a function of WIM trailer tandem axleload and calibration factor. Figure 4 shows data for drive tandems using the same calibration factor value as for Figure 3. Note the reduced scatter in ratio values in Figure 4 compared to Figure 3. An average ratio was calculated for the drive tandem and trailer tandem for each calibration factor value. A regression between average ratio and calibration factor was calculated for each mat and the calibration factor was calculated for a ratio of 1.00 as shown in Figure 5 for mat A. Figure 6 illustrates the same analyses based upon gross weight. Similar comparisons were made for the second mat and the results were similar.

Figures 1-4 suggested that investigations for converting WIM data to equivalent static data should be based upon axle group and by location on the vehicle rather than by gross load. For verification of the assumption, data were collected at a site on an asphaltic concrete pavement section on I64 in Shelby County. After setting the calibration factor value for mat A (serial number 1051), data were collected by both WIM and permanent truck scales until approximately 1,600 trucks in Classes 4 through 12 had been correlated.

Figure 5 represents the average static to WIM ratios for both drive and tandem axles at each of five calibration factor values for approximately 200 Class 9 trucks each. A best fit polynomial regression equation also is shown. The five factor values were chosen as equally above and below the value recommended by the manufacturer who based it upon gross load. Tandem axles of Class 9 trucks are the most common axle arrangement and account for the greatest proportion of accumulated pavement fatigue. An arithmetic mean of the ratios shown in Figure 1 for steering axles translates into a mean WIM weight that is approximately 70 percent of the respective static mean weight. Fatigue caused by the steering axle is not as great as that for tandem axle groups. Thus, the calibration factor best fitting the means of the ratios for the tandem axles was chosen for collecting future data. The calibration factor of 180 provided a best fit ratio of 1.0 and that factor was used to collect data at the Shelbyville and Elizabethtown sites. Using the same methodology, a value of 195 was chosen for the second weigh mat.

Because the above procedure produced a regression equation fitting between the two sets of tandems, the data had to be adjusted by individual weigh mat to reflect the observed difference. The following steps were used.

1. The first task is to adjust the data to minimize the impact of errors in the electronic calibration of the WIM pads. If the pads are properly calibrated, then

$$\Sigma(1/N)(Si/Wi) = 1 \quad \text{.......................} \quad 1$$

in which N is the number of tandem axles weighed on Class 9 trucks, Si is the static weight of the ith tandem axle, and Wi is the corresponding WIM weight. If some error remains following electronic calibration, an adjustment factor, k, can be developed such that

$$\Sigma(1/kN)(Si/Wi) = 1 \tag{2}$$

Data from the two flexible pavement sites were combined and four values of k were determined for each combination of two pads and two pavement types (flexible and rigid).

2. WIM loads for all axle types and all truck types were adjusted to reduce the effect of initial calibration error as follows:

$$W' = kW \tag{3}$$

   in which W' is the adjusted axleload, k is the appropriate adjustment factor for the pad-pavement type combination, and W is the unadjusted axleload as originally recorded.

3. The relationship between WIM and static axleloads seems to be very complex and depends on a host of factors such as road roughness, type of suspension system, wheel base, truck aerodynamics, etc. For a variety of reasons including incomplete information, detailed relationships could not be developed in this study. Type of pavement (flexible or rigid) was used as a surrogate for pavement related effects such as road roughness. The combination of truck and axle types was used as a surrogate for the important truck related effects.

   WIM-to-static conversion equations were thus developed for each possible combination of pavement type and truck/axle type. Regression analyses of trailer tandem data of Class 9 trucks were performed for:

$$\text{Static axleload} = a + b^*(\text{WIM axleload}) + c(\text{WIM axleload})^2, \tag{4}$$

$$\text{Static axleload} = d + e(\text{WIM axleload}), \text{ and} \tag{5}$$

$$\text{Static axleload} = f + g^*(\log (W')). \tag{6}$$

   in which a, b, c, d, e, f, and g are calibration constants and log(W') is the common logarithm of the adjusted WIM axleload.

4. Because some truck types were poorly represented in the available

database--that is, the sample size was small--calibrations similar to the above were repeated without separate consideration of truck type. That is, conversion equations were developed for each possible combination of the two pavement types and the seven axle types.

Future calibration of weigh mats may be performed using a simplifed procedure presented in Appendix A. The major simplification is the required number of matched weighings.

Drift in calibration factor value may occur with time and may be a function of deterioration of materials in the mat and/or changes in electronic characteristics. Appendix B contains a procedure to monitor drift by analyzing steering axle data.

WIM Versus Static

Figure 7 illustrates the relationship between WIM and static axleload data for the steering axle. The heavier axleloads are known to be associated with large dump trucks (Classes 5 and 6) hauling from limestone quarries and which have wide flotation tires on that axle. Note that the WIM axleload is approximately 70 percent of the static axleload. This relationship was noted during an earlier investigation at a WIM site located just beyond the crest of a vertical curve on a rigid pavement and the WIM site was within view of the permanent truck scale. Often there was sufficient truck traffic at the permanent truck scale to cause a backup of trucks to form on the shoulder of the mainline pavement. As the trucks came over the top of the hill, drivers would see the backlog of trucks and take their foot off the gas pedal and the front of the truck could be seen to drop in elevation.

Comparisons of static to WIM axleloads for four-tired single axles are shown in Figures 8 and 9 for drive and trailer axles, respectively. Similarly, the relationships for drive and trailer tandems are shown in Figures 10 and 11, respectively. In Figures 8-11, there is a grouping of data for relatively low WIM axleloads corresponding to much higher static axleloads. These data groups suggest the possibility of axles bouncing over the capacitance pad because they are relatively unloaded while the static scales would capture the total load. In Figure 8, there is the possibility that the torque between the tire and pavement surface is causing a resultant force located at a different angle compared to single axles not subjected to torque such as on trailers.

Torque involves a horizontal force vector such that the total force vector is not in a strictly vertical direction. In Figure 10, the slope of data points for drive tandems is flatter than the slope shown in Figure 11 (trailer tandems) which suggests again that torque is reducing the vertical component (Figure 10) compared to tandems on trailers. Figures 12 and 13 contain data for drive and trailer tridems, respectively, but definitive conclusions are not justified due to scarcity of data. Static weight is the equivalent of a dead weight plus a dynamic force vector having a value of zero. It is dangerous to conclude that the sum of the dynamic weights of all axles should equal the sum of the static weights as measured by static truck scales. The road profile combined with suspension systems may cause the axle to be in an upward or downward motion as it passes over the weigh mat. It is reasonable to conclude that the sum of the weights should be nearly equal.

Analyses of WIM Data

Figures 14 and 15 contain the same data sets shown in Figures 10 and 11, respectively, except the difference in the WIM recorded data for each axle is expressed as a percent difference. The data groupings suggest the possibility of the effects of various suspension systems, but there are no data to confirm such suspicions. Gillespie determined the dynamic effects of three suspension systems as shown in Figure 16 (1). For the torsion bar suspension, there are approximately 2.5 cycles of dynamic force per second. The number of cycles per second increased to 3.5 and 10 for four-leaf and walking-beam suspensions, respectively. In addition, the range of dynamic force appears to be approximately the same for the torsion bar and four-leaf suspensions, but there is a much larger variation for the walking-beam suspension. Unfortunately, the capacitance pad weigh systems did not provide any data output of dynamic force variations for each axle.

The data were separated into sets for the first and second axles for both the drive and trailer tandems as shown in Figures 17-20, respectively. Figure 17 shows that the data tend to separate into small groups that might be a function of type of axle suspension. Regression analyses were made for each axle location within the tandem. Equations for each axle were evaluated at 1,000-lb increments and the resulting data points are shown in Figures 21 and 22 for drive and trailer tandems, respectively.

Figures 23-25 present WIM axleload data for the first, middle, and last axle within the drive tridem versus total WIM tridem load. The majority of vehicles were in Class 7. For these vehicles, the air-lift suspension axle is the leading axle in the tridem and is reflected by the wider scatter in data. Similarly, Figures 26-28 are for tridems on trailers, but the scarcity of data precludes any definitive conclusions for trailer tridems. Figures 29 and 30 illustrate the evaluated regression equations for individual axle locations in the same manner as Figures 21 and 22 for tandems.

Vehicle Velocity

Figures 31-39 present the relationship between vehicle velocity and vehicle gross load for Vehicle Classes 4 through 12 respectively. Data for Vehicle Classes 5, and 8 through 11 (Figures 32, 35 through 38) suggest the possibility of a relationship between gross load and vehicle velocity.

The ratios of static gross load to WIM gross load for all vehicle classes were combined and sorted into ranges of gross load. The ratio versus vehicle velocity was plotted for each vehicle in its load range as shown in Figures 40-45. Regression analyses performed for each set of data are presented in Figures 40-45. The middle line is the mean fit to the data and the upper and lower lines correspond to plus and minus one standard error, respectively. Figures 40-45 show that as the load increases, the relationship between ratio of gross loads becomes a constant regardless of vehicle velocity.

GENERAL ANALYSES

Invalid Data Entry

The WIM mats were installed approximately one mile ahead of each of three permanent truck scale installations. Data were validated for non-zero axleloads for those axles requiring data. For example, the computer program for operating the permanent scale and recording of data, counts the number of axles in the axle group, divides the total weight by the number of axles in the assembly and records the result by axle location. Thus, the recorded axleload for each axle must be equal for a multiple axle assembly. The WIM data record contains axle spacings permitting verification of the number of axles and non-zero entries for each appropriate axle. Table 2 contains the number of trucks for which WIM and static scale data were matched at each site and the number and percentage of trucks for which the data records were deleted due to an inappropriate entry of a zero or unequal data entries for each axle of the group.

Static Truck Scale Sites

For permanent scale installations, improper placement of the truck may result in a portion of a tire resting on the scale frame instead of being entirely on the platform. Also, observations indicate the way the truck is stopped on the scale may affect the recorded weight. In Figure 11, the few data points located below the mass of data could have resulted from either zero entries or in the case of a tire being partially on the scale frame.

Weigh-In-Motion Sites

The two WIM mats were placed approximately 200 feet apart which would permit a driver to be riding the edge stripe of one mat and move toward the center of the next mat or vice versa. Figure 46 is a recreation of the manufacturer's figure showing that the sensitivity of the capacitance signal is variable for approximately the first 15 inches from each end of the mat. Thus, for a tire partially, or entirely, traversing within the first 15 inches, the recorded WIM axleload is too low as indicated by a few data points positioned above the mass of data in Figure 11. No hard data have been collected for determining the traveling position of the truck in the lane. However, from observations, the tires on the right side of over 25 percent of the trucks are located within 15 inches of the pavement-shoulder joint. Thus, the WIM pads may not be measuring the total dynamic loads.

Regression Equations

Figure 47 illustrates the evaluated regression equations given previously. Initial analyses were made for the first two equations previously and statistics indicated that the best results were obtained using Equation 1. However, Figure 47 shows that the polynomial equation reaches a maximum static weight that is below measured values. Equation 3 best fits the data in the region of lesser axleloads but has an increasing bend that predicts a static value that is too low compared to the data in the upper region and used to obtain the regression equation constants. Therefore, equation 2 was chosen as the most realistic representation.

Regression equations were obtained for the adjusted data for the respective axle group. Regression equations were obtained by pavement type for each axle group for each vehicle classification. For the vast majority of trucks, the axle groups may be sorted into one of seven major groups:

1. steering
2. single drive axle
3. single trailer axle
4. drive tandem axles
5. trailer tandem axles
6. drive tridems, and
7. trailer tridems.

In addition, data for each vehicle classification were sorted by axle group, combined into a respective data set, and the respective seven regression equations were obtained. For those vehicle classifications for which there were insufficient data to obtain statistically reliable equations, the appropriate equations from the seven above will be utilized. Numerical values for the constants for the axle groups for Class 9 trucks are listed in Table 3. Numerical values for the constants for all regression equations are presented in Appendix C. A discussion is given to help interpret some of the statistics included in the tables.

INITIAL USES OF WIM DATA

Some of the immediate uses of EAL data estimated from WIM data are:

1. EAL estimation for the traffic stream on that pavement.
2. Comparison of estimated EALs for pavements in the same highway system and various highway systems.
3. Analyze the WIM data for AADT and vehicle classification purposes and to add to the HPMS data files accordingly.
4. Using data from WIM sites on the same highway system, calculate an average EAL per truck for each site and multiply those averages by vehicle classification for other sites where vehicle classification, and AADT have been collected but for which WIM data are not, or will not, be available.
5. Use estimated EAL from WIM data coupled with AADT and vehicle classification data for similar sites as input for initial and overlay pavement thickness designs.

OTHER FACTORS INFLUENCING WIM DATA

Pavement Roughness

Gillespie (5) presented a paper on modeling truck dynamic loads with respect to the interaction between truck dynamics and pavement loading. He stated, "Although the nonuniformity force repeats with each revolution of the wheels on the truck, its point of application along the road is random. This contrasts with the dynamic loads excited by road roughness, which being triggered by the roughness, always repeat in the same locations along the road." Zuieback, et al, (6) state, "The dynamic weight measured by a WIM scale is determined by the dynamic response of the vehicle system to the pavement roughness....A literature survey ... showed that the vast majority of relevant information from the literature focused on the ride quality of tractor-trailers and did not address the wheel/pavement interaction and damping distance problems. The problem of selecting the most important factors is compounded by the non-linear relationship between road roughness and many other factors which contribute to the dynamic wheel load." Zuieback also discusses the effects ofjointed concrete pavement in relation to road roughness. The objectives of Zuie-back's (6) study were:

1. determine the accuracy of WIM systems installed in pavements, and
2. determine the length and smoothness of an approach section of pavement to meet the accuracy tolerances set in those pavements with roughness which would otherwise result in accuracies poorer than set in 1. above for axle weight, gross weight, axle spacing, and wheel base length.

The last objective recognizes that pavement roughness will affect dynamic loads and are reflected in the data recorded by WIM sensing equipment.

As stated earlier, one of the objectives of Zuieback's study was to determine the approach length that is needed to be smooth for the least variation in WIM data. However, there are very practical problems with requiring smooth approaches to WIM sites, primarily scheduling and financial. In Kentucky, the HPMS Monitoring Guide will require 30 WIM sites to be monitored each year and each site is to be activated on a three-year cycle. The requirement of a smooth approach would present very real scheduling and financial problems that may become prohibitive. Change in pavement roughness with time should be monitored. By monitoring pavement roughness, a correlation might be made with change in dynamic loading, rate of change in pavement rougness, rate of change in accumulated EAL as a function of traffic volume and pavement roughness, rate of change in pavement serviceability, and pavement serviceability rating.

Measuring and quantifying pavement roughness could be scheduled so that changes in roughness could be taken into account. Exact roughness may not be required but relative changes would permit:

1. adjusting WIM data to some "standard" roughess value to permit comparison of accumulated EAL for similar pavements in the same highway system,
2. comparing the rate of change in accumulated EAL for one pavement to estimate the rate of change and/or serviceability of another similar pavement for which WIM data are not available, and
3. similar types of comparisons between highway systems.

Correlating pavement roughness with mean WIM data may indicate that separate calibration factors are not required by pavement type but that pavement type is reflected in pavement roughness.

Suspension Systems

The roughness of rigid pavements changes rapidly with changes in exposure to solar heat. Vertical movement of the tractors of Class 9 trucks were observed to change markedly with increasing hour of the day. Prior to 11 am, no unusual vertical movement was noted. However, by 12 noon all of those tractors were observed to have an increase in vertical movement. By 3 pm, it was only a matter of degree of movement. To prove the point, a video camera was taken to the site and a tape was made that includes clock time as a part of the video image. One of the easier ways to monitor vertical movement is to compare the top of the exhaust stack with the top of the trailer. Any vertical movement is magnified at that location.

Gillespie (1,5) indicates that there are four distinct types of suspension systems, namely:

1. four-leaf spring assembly,
2. torsion bar,
3. walking beam, and
4. air bag.

Each has its own dynamic frequency characteristics and each is affected by pavement roughness. It appears that the walking beam may be the type that is affected the most by pavement roughness. Correlating WIM and static scale data with type of suspension might permit identifying patterns of differential axleload distributions as indicated in Figures 14, 15, 19, and 20. If a pattern could be identified, more appropriate adjustment factors might be developed for calculating the increase in EAL as a function of suspension type. If desired, it might be possible to monitor the change in useage of suspension types by the trucking industry and the corresponding changes to the rate of accumulating EAL. This might become important when considering thinner pavements on lower levels of highway systems.

Other Factors

Little is known about the dynamic effects of increasing tire contact pressures, type of tire construction, number of tires on the axle, aerodynamic wind deflectors, cab location with respect to the steering axle, and tractor frame length upon front-to-rear rotations. The new "set-back" style of "cab-over" places the driver ahead of the steering axle and the engine and transmission closer to the steering axle. What is the difference between the axleloads and the effects of dynamics between the two styles of "cab-overs"?

SUMMARY

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7. Tridem Trailer Axles

Relationships illustrated herein are applicable to any WIM system using Golden River weigh mats. Some of the relationships may be applicable to installations using other sensor equipment but may require adjustment.

Observations of truck dynamics combined with literature review indicated that dynamic axleloads are affected by:

1. Engine torque,
2. Temperature of rigid pavements,
3. Location of axle on truck,
4. Pavement roughness rather than pavement type, and
5. Suspension system between truck frame and axles.

RECOMMENDATIONS

WIM sites should be selected for both directions for the permanent truck scale sites at London (I 75) and on I 71. Pavement roughness measurements should be requested for 0.1 mile ahead of each new site and for the three sites where WIM data have been collected to date. It is recommended that the roughness measurements for the I 75 London and I 71 sites be evaluated and ranked. If one direction has a roughness index that is smoother and/or rougher than for the three sites already sampled, WIM installation(s) should be made at that site(s) and data should be col-lected for 200 Class 9 trucks per site. It should be possible to make a correlation between measured roughness and the mean WIM weight for each truck scale site. The correlation would permit the development of an adjustment factor to relate WIM data collected anywhere with a companion roughness measurement to a chosen standard roughness value.

If the above recommendation is accepted, the type of suspension on the different axle groups also should be identified at the truck scale site and recorded. The suspension data could be listed on a separate sheet and identified by the ID number assigned as part of the WIM data record. By recording the type of suspension, it may be possible to develop signature patterns, correlations, and adjustment factors to account for the various suspensions.

FUTURE RESEARCH

Future analyses of WIM data should be made to determine ways to:

1. analyze the traffic stream to obtain vehicle classification counts,
2. estimate average EAL per vehicle classification and accumulated EAL for vehicle classification,
3. accumulate EALs for that pavement,
4. use the calculated average EAL per vehicle classification for a given route, calculate an estimated accumulated EAL for another route using the recorded AADT and vehicle classification data, and
5. estimate additional EALs caused by uneven load distribution between axles within that group.

Further desireable refinements and relationships include:

1. effects of increased tire contact pressure and the associated reduced contact area,
2. development and correlation of increasing rate of EAL per truck within a given vehicle classification, and
3. development and correlation of the effects of various types of suspension systems.

Research requiring development of equipment and/or analysis techniques are:

1. Installation of some type of tape sensor to indicate that a tire has traversed the weigh mat at some point less that 15" from the end of the mat. It would be desireable if the sensor and recording equipment had the ability to specify where the tire was located. Either that data should be rejected, or adjusted for location within the 15". However, this last adjustment would require additional data collection and analysis.
2. Install other tape sensors to permit determination of where the truck was in relation to either the shoulder pavement joint or the centerline joint. This capability would permit analyzing the traffic stream for lateral distribution of the vehicles within that lane. These same tapes might be used to determine the number of tires on the axle and the tire width. Coupling vehicle speed as measured by the speed loops with these data and analyzing the time the tires contact and leave the tapes would permit calculating the tire contact length and thus tire contact area and contact pressure.

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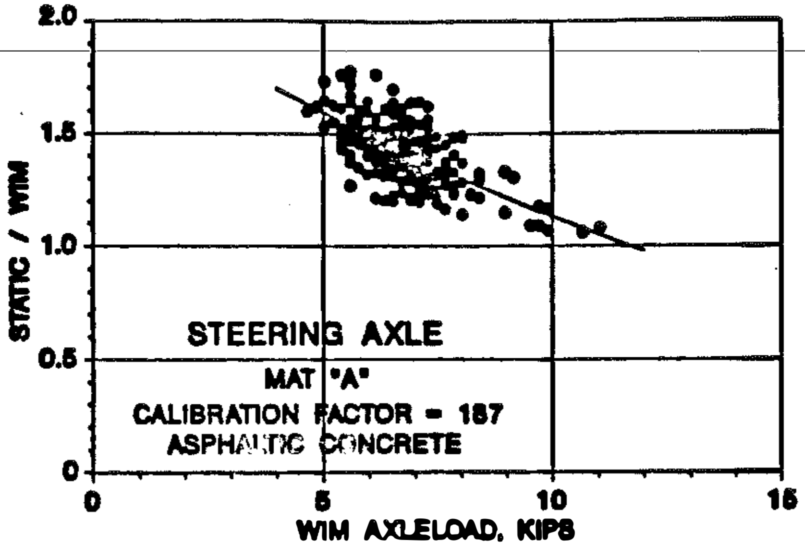


FIGURE 1. WIM AXLELOAD VERSUS RATIO OF STATIC AXLELOAD TO WIM AXLELOAD FOR STEERING AXLES.

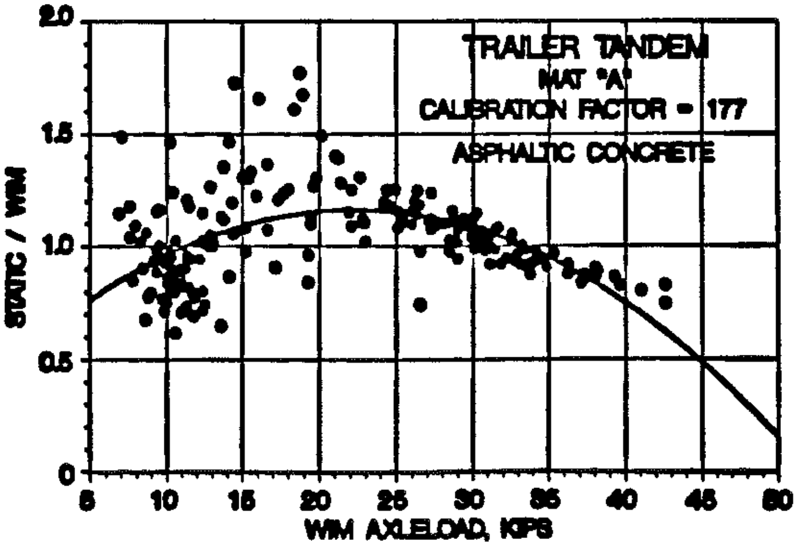


FIGURE 2. WIM AXLELOAD VERSUS RATIO OF STATIC AXLELOAD TO WIM AXLELOAD FOR TRAILER TANDEM AXLES FOR CALIBRATION FACTOR OF 177.

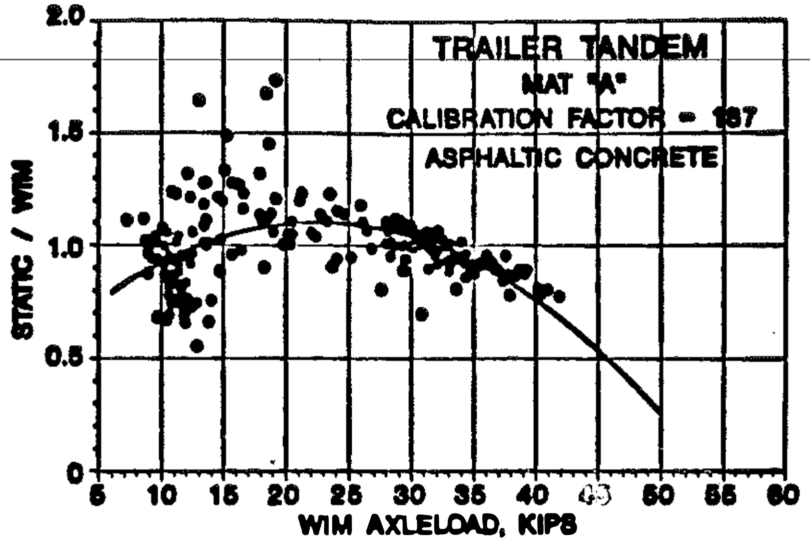


FIGURE 3. WIM AXLELOAD VERSUS RATIO OF STATIC AXLELOAD TO WIM AXLELOAD FOR TRAILER TANDEM AXLES FOR CALIBRATION FACTOR OF 187.

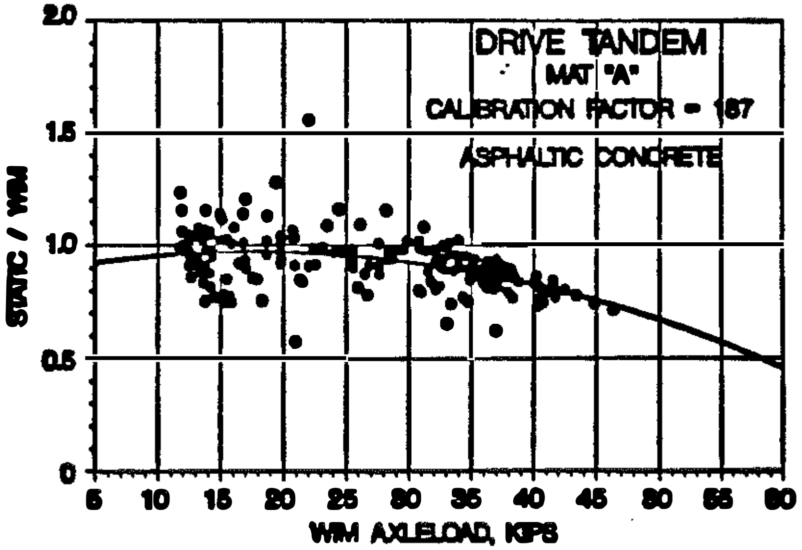


FIGURE 4. WIM AXLELOAD VERSUS RATIO OF STATIC AXLELOAD TO WIM AXLELOAD FOR DRIVE TANDEM AXLES FOR CALIBRATION FACTOR OF 187.

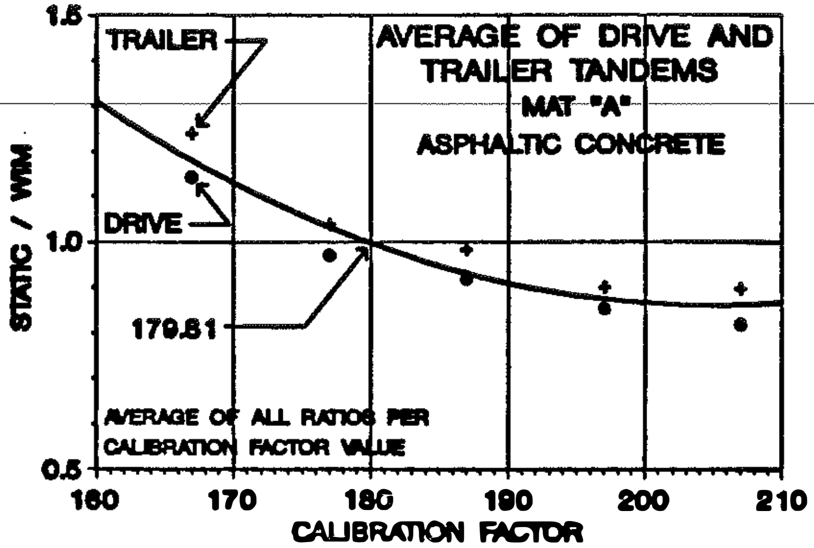


FIGURE 5. RELATIONSHIP BETWEEN CORRELATION FACTOR AND RATIO OF STATIC AXLELOAD TO WIM AXLELOAD TO DETERMINE BEST CALIBRATION FACTOR VALUE.

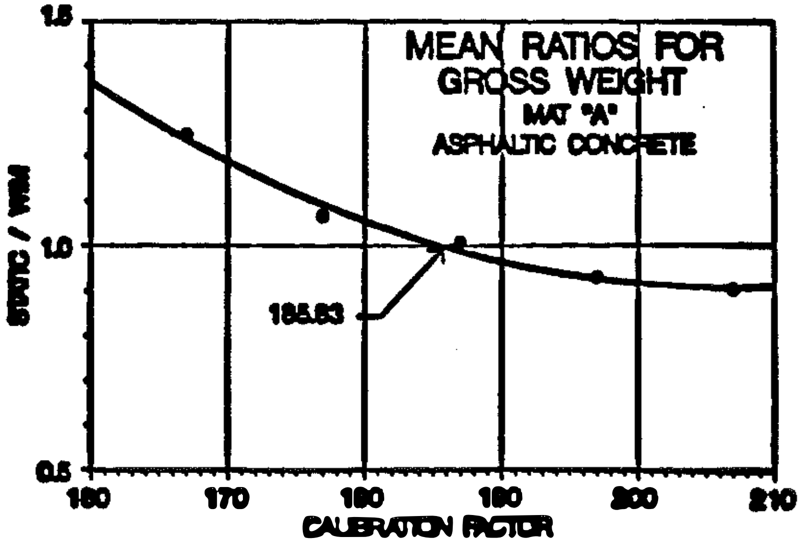


FIGURE 6. CALIBRATION FACTOR VERSUS RATIO OF STATIC GROSS LOAD TO WIM GROSS LOAD.

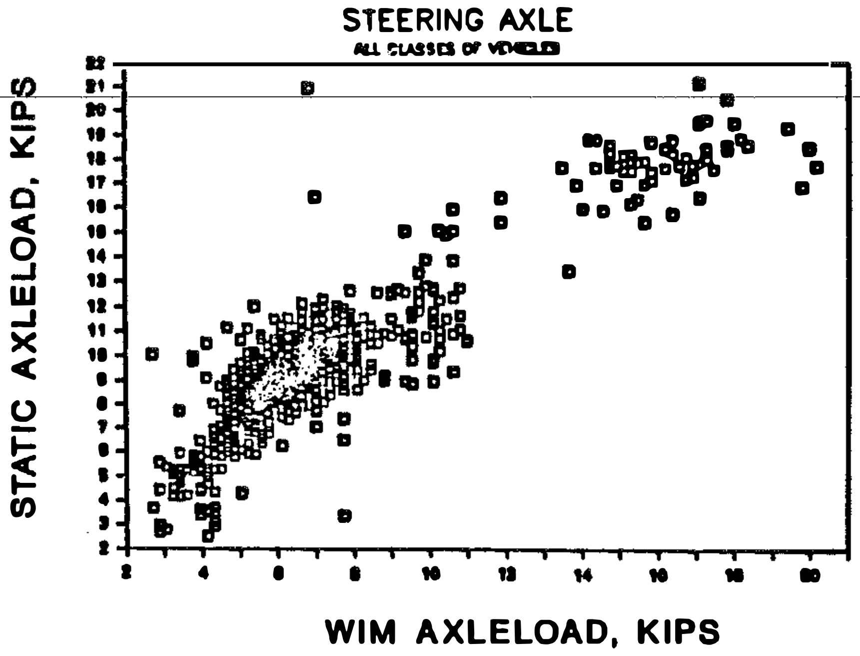


FIGURE 7. WIM AXLELOAD VERSUS STATIC AXLELOAD FOR STEERING AXLE

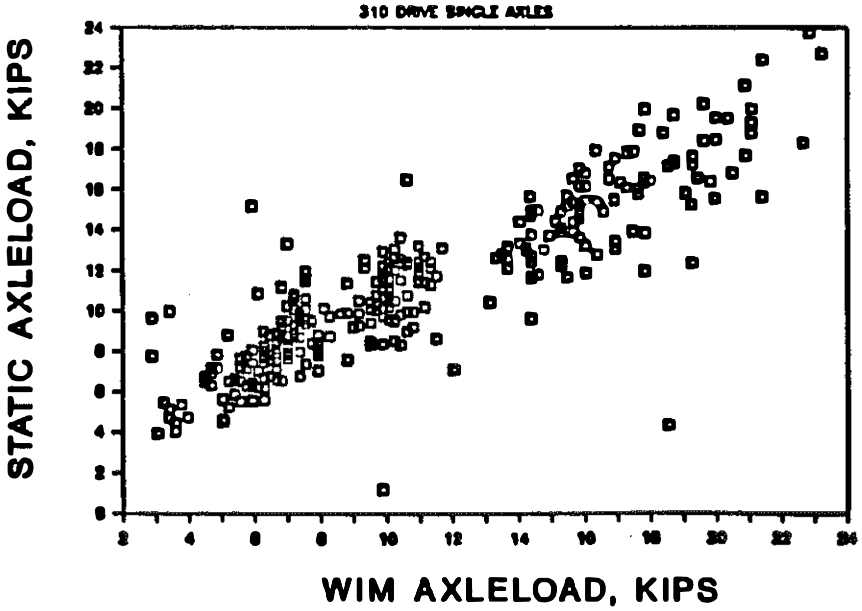


FIGURE 8. WIM AXLELOAD VERSUS STATIC AXLELOAD FOR DRIVE SINGLE AXLES.

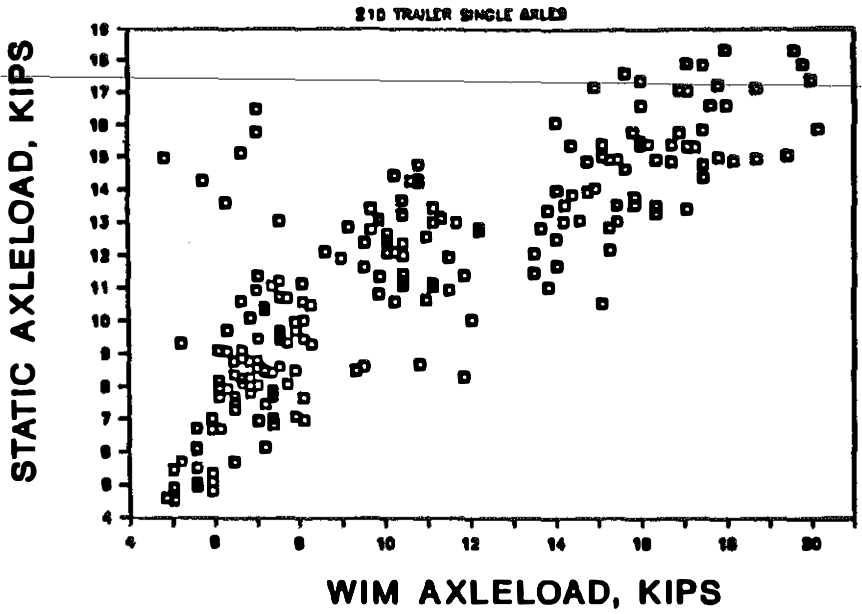


FIGURE 9. WIM AXLELOAD VERSUS STATIC AXLELOAD FOR TRAILER SINGLE AXLES.

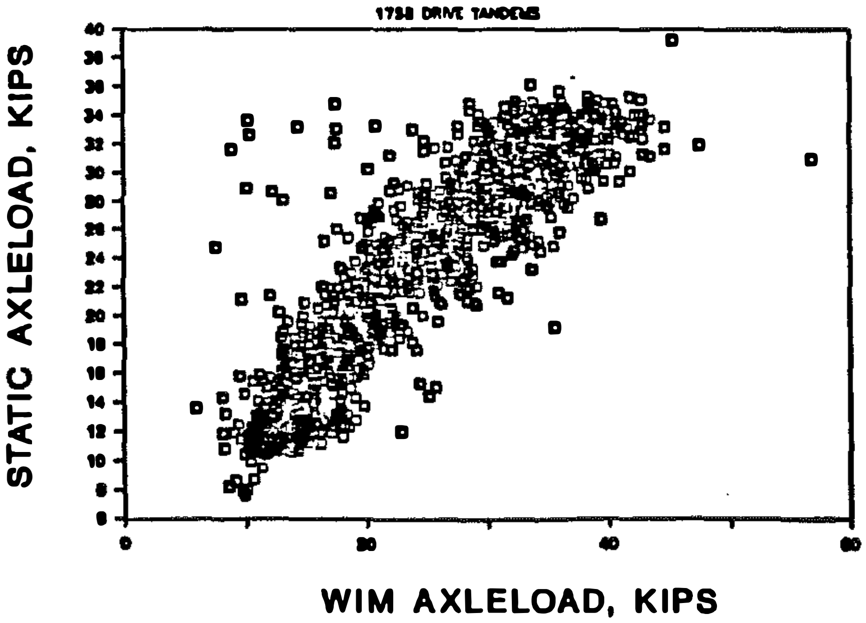


FIGURE 10. WIM AXLELOAD VERSUS STATIC AXLELOAD FOR DRIVE TANDEM AXLES.

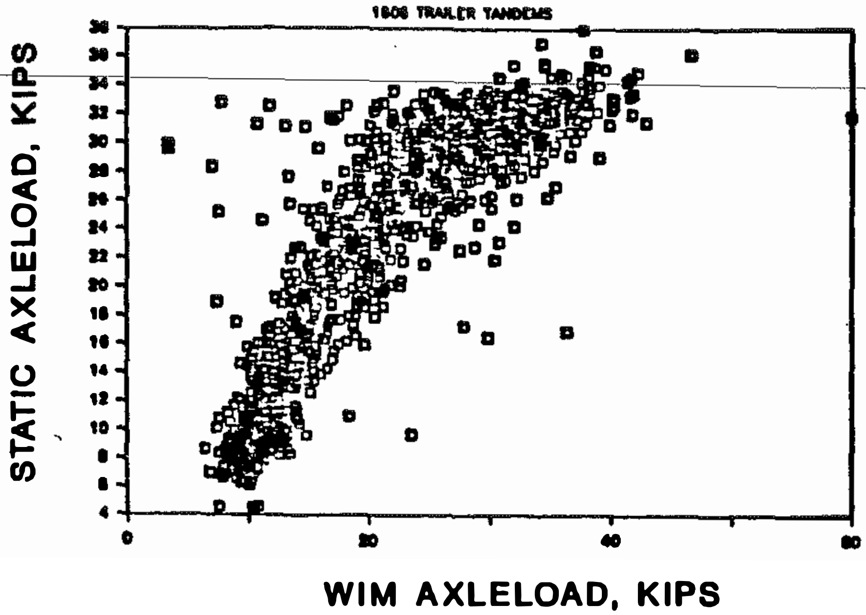


FIGURE 11. WIM AXLELOAD VERSUS STATIC AXLELOAD FOR TRAILER TANDEM AXLES.

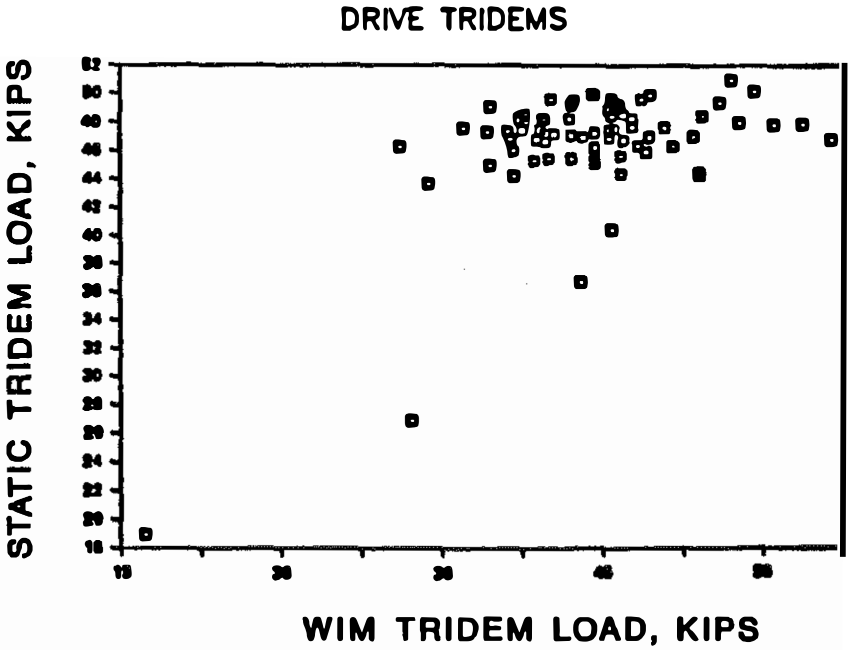


FIGURE 12. WIM TRIDEM LOAD VERSUS STATIC TRIDEM LOAD FOR DRIVE TRIDEM AXLES.

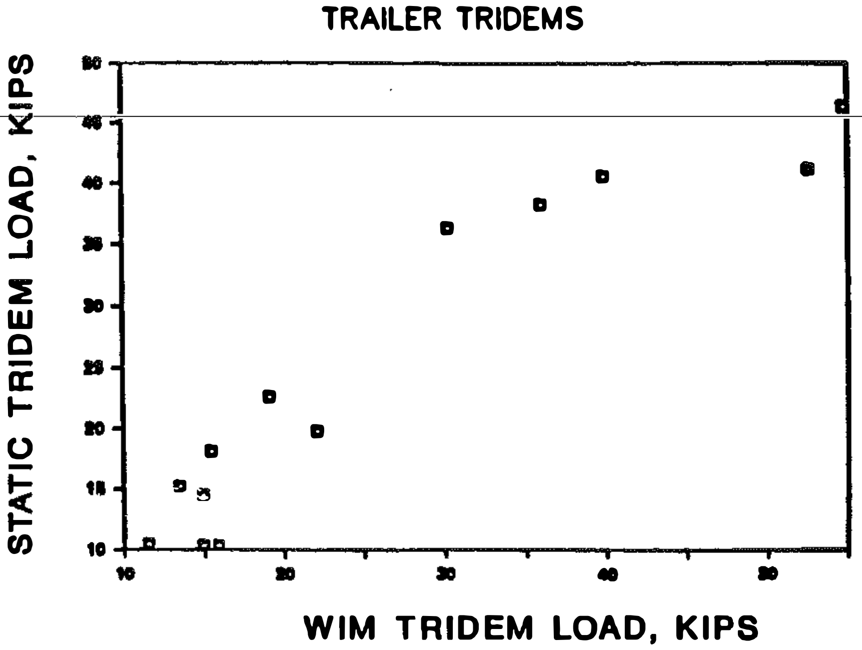


FIGURE 13. WIM TRIDEM LOAD VERSUS STATIC TRIDEM LOAD FOR TRAILER TRIDEM AXLES.

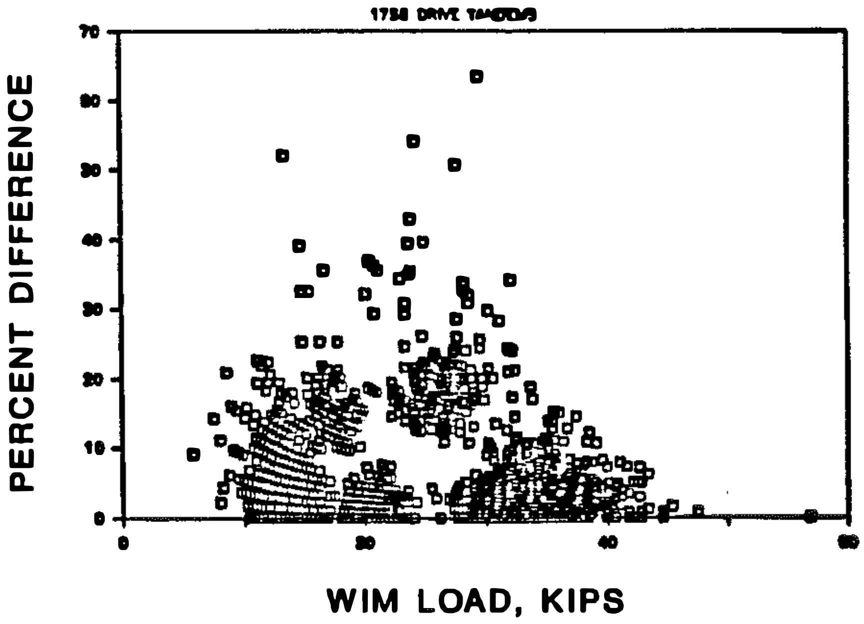


FIGURE 14. WIM LOAD VERSUS PERCENT DIFFERENCE FOR DRIVE TANDEM AXLES.

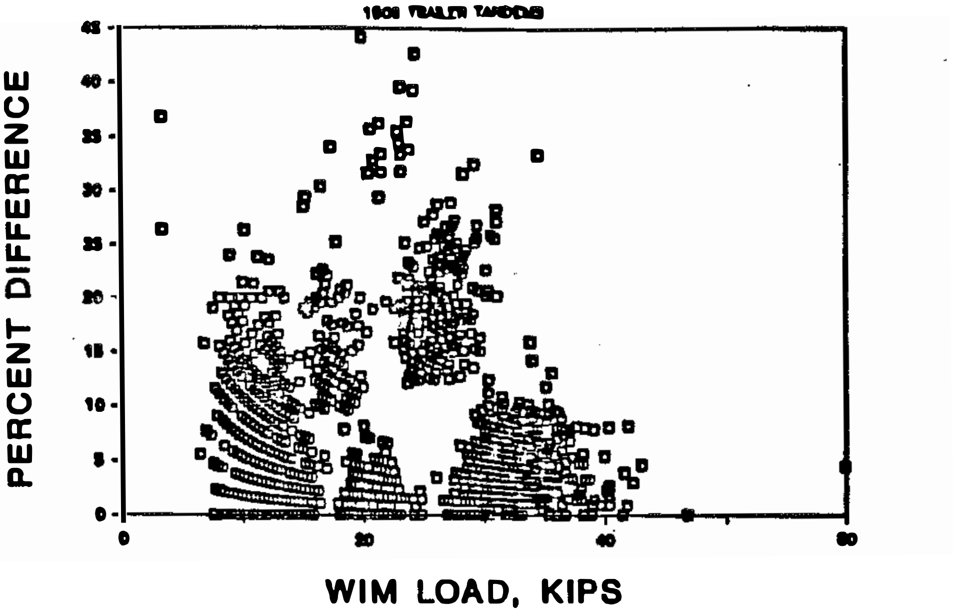


FIGURE 15. WIM LOAD VERSUS PERCENT DIFFERENCE FOR TRAILER TANDEM AXLES.

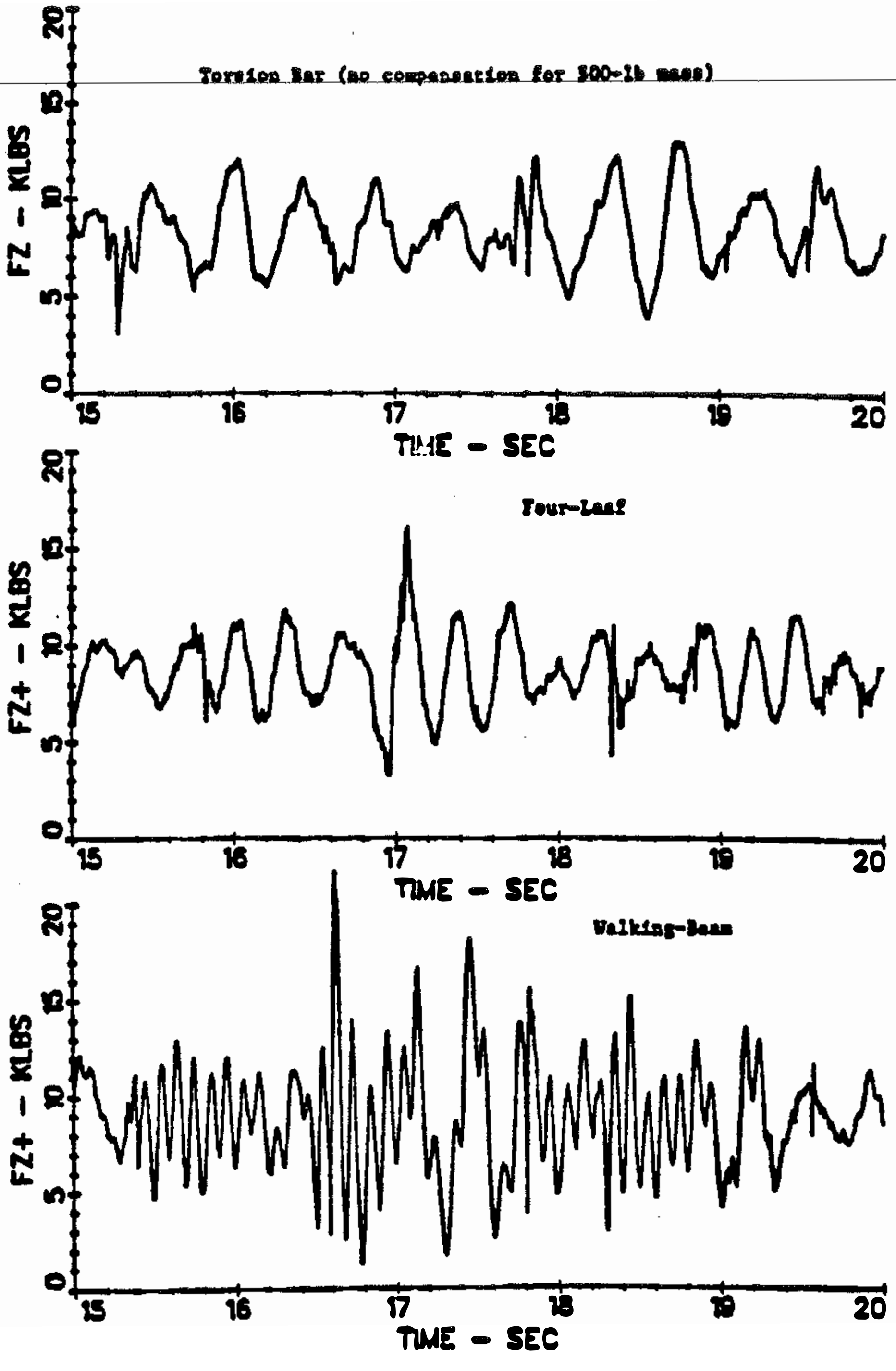


FIGURE 16. COMPARISON OF THREE VEHICLE RESPONSES TO THE SAME ROAD INPUT, REF. GILLESPIE'S FIGURE 57.

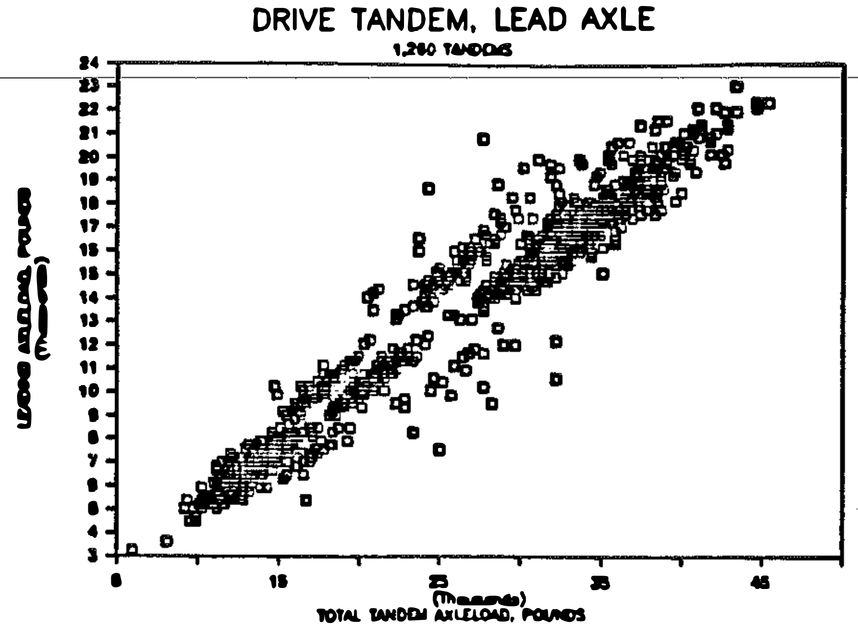


FIGURE 17. TOTAL TANDEM AXLELOAD VERSUS FIRST AXLELOAD FOR DRIVE TANDEM AXLE GROUP.

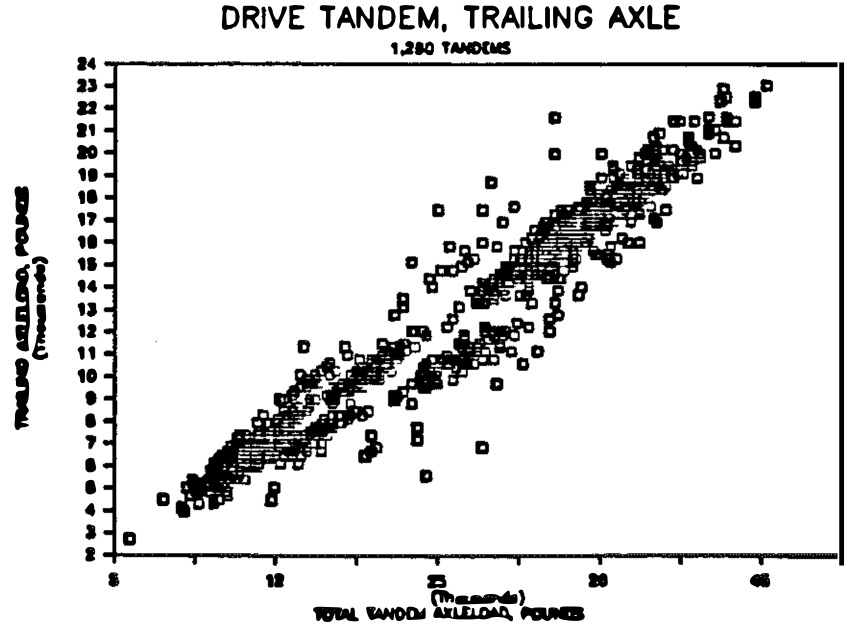


FIGURE 18. TOTAL TANDEM AXLELOAD VERSUS TRAILING AXLELOAD FOR DRIVE TANDEM AXLE GROUP.

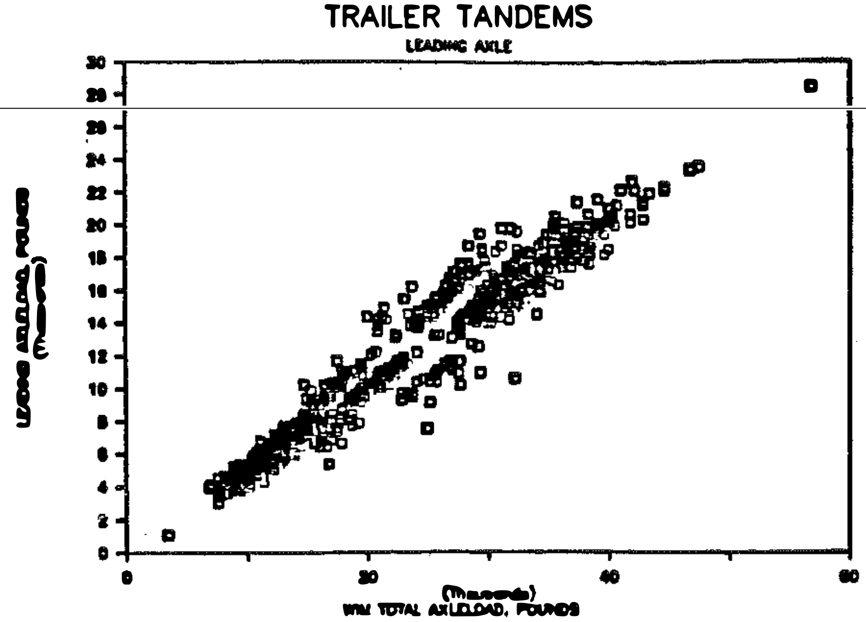


FIGURE 19. TOTAL TANDEM AXLELOAD VERSUS LEADING AXLELOAD FOR TRAILER TANDEM AXLE GROUP.

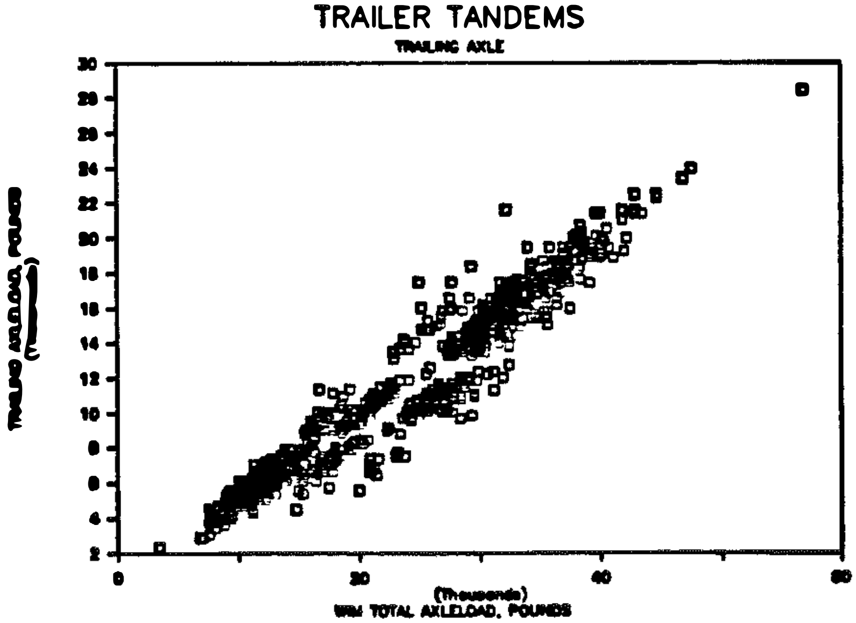
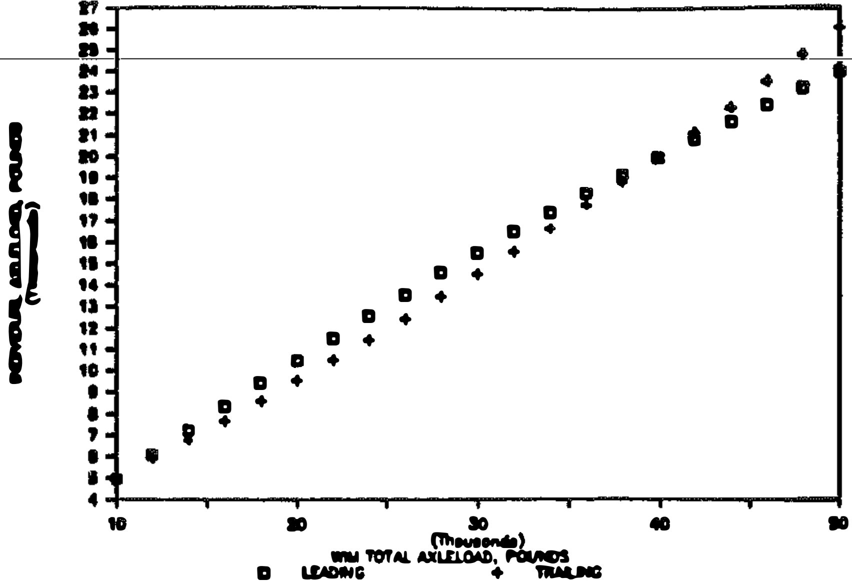
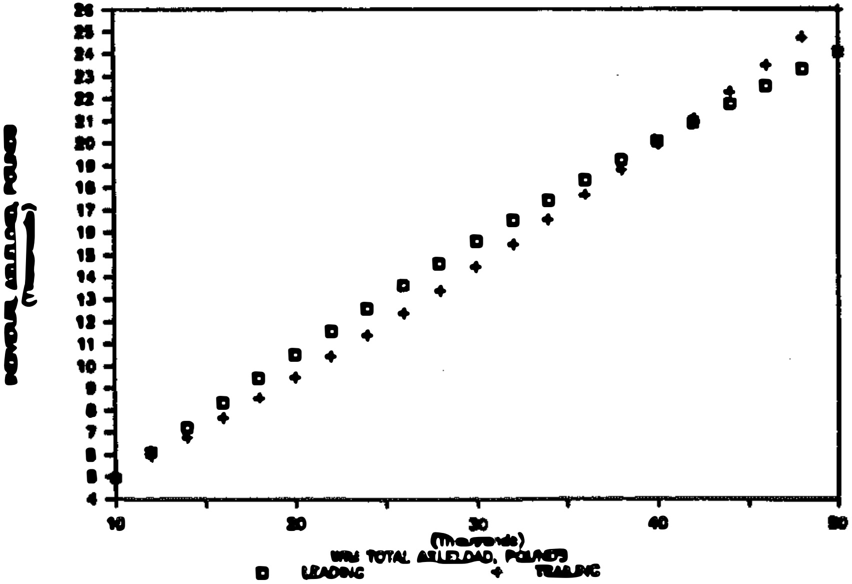


FIGURE 20. TOTAL TANDEM AXLELOAD VERSUS TRAILING AXLELOAD FOR TRAILER TANDEM AXLE GROUP.


DRIVE TANDEMS

COMPARISON OF REGRESSION EQUATIONS

FIGURE 21. COMPARISON OF REGRESSION EQUATIONS FOR RESPECTIVE AXLES IN DRIVE TANDEM GROUP.


TRAILER TANDEMS

COMPARISON OF REGRESSION EQUATIONS

FIGURE 22. COMPARISON OF REGRESSION EQUATIONS FOR RESPECTIVE AXLES IN TRAILER TANDEM GROUP.

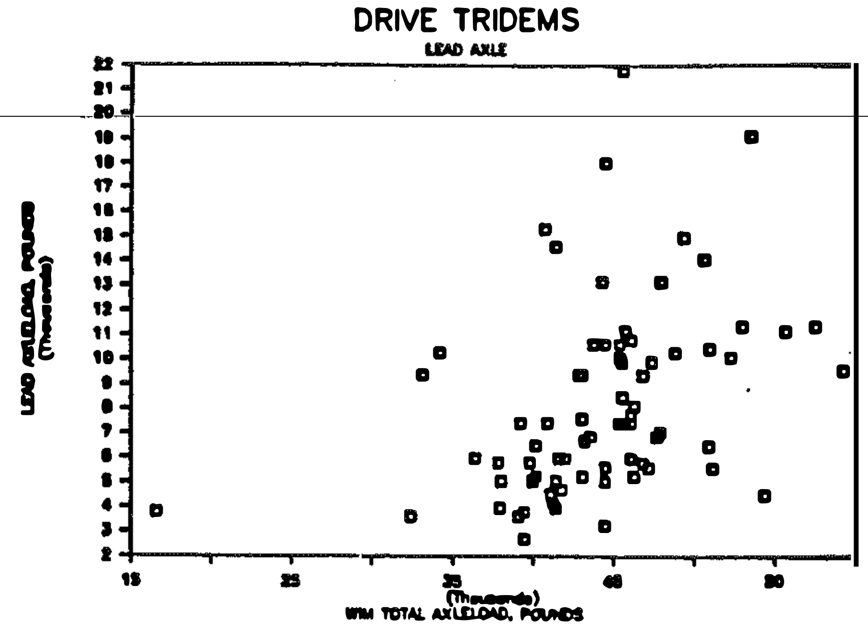


FIGURE 23. RELATIONSHIP BETWEEN WIM TOTAL TRIDEM LOAD VERSUS LEADING AXLELOAD FOR DRIVE TRIDEM GROUP.

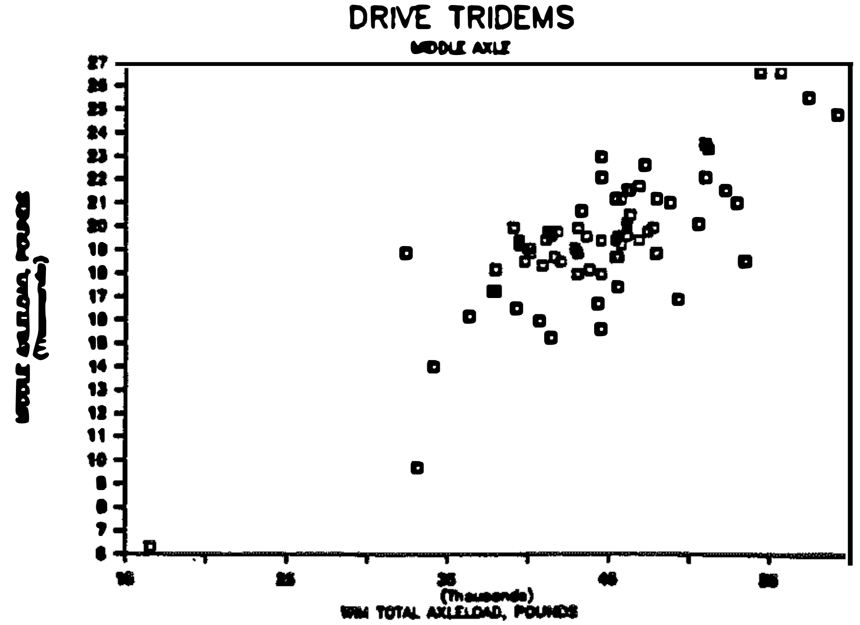


FIGURE 24. RELATIONSHIP BETWEEN WIM TOTAL TRIDEM LOAD VERSUS MIDDLE AXLELOAD FOR DRIVE TRIDEM GROUP.

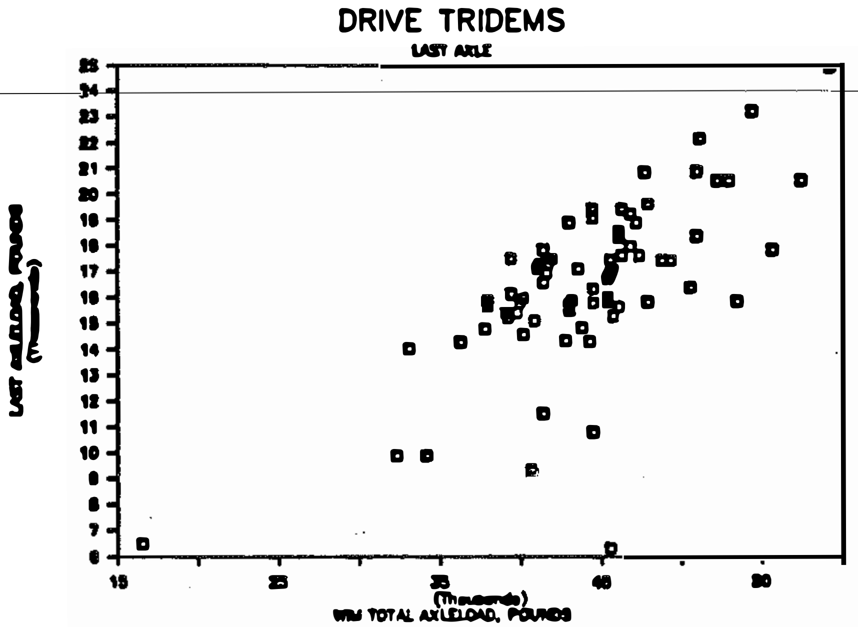


FIGURE 25. RELATIONSHIP BETWEEN WIM TOTAL TRIDEM LOAD VERSUS TRAILING AXLELOAD FOR DRIVE TRIDEM GROUP.

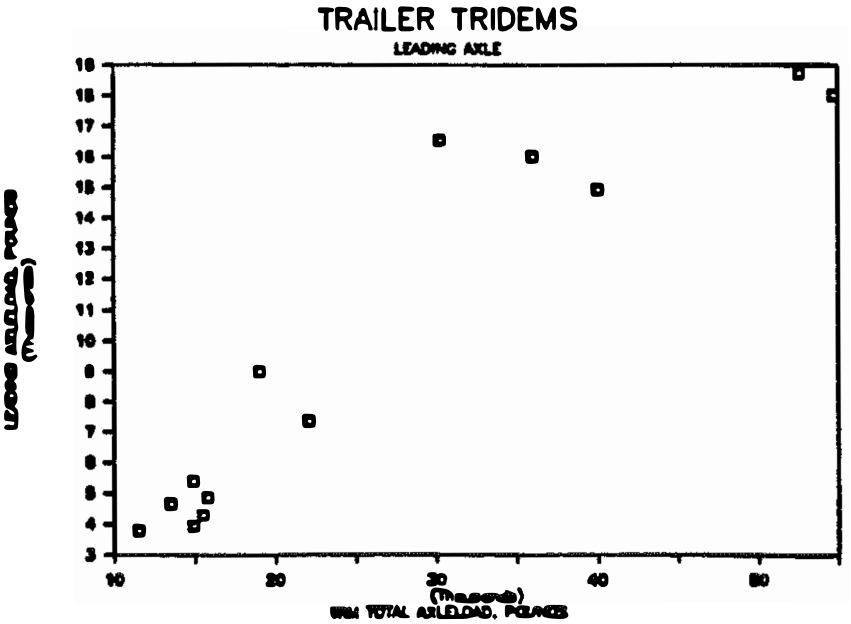


FIGURE 26. RELATIONSHIP BETWEEN WIM TOTAL TRIDEM LOAD VERSUS LEADING AXLELOAD FOR TRAILER TRIDEM GROUP.

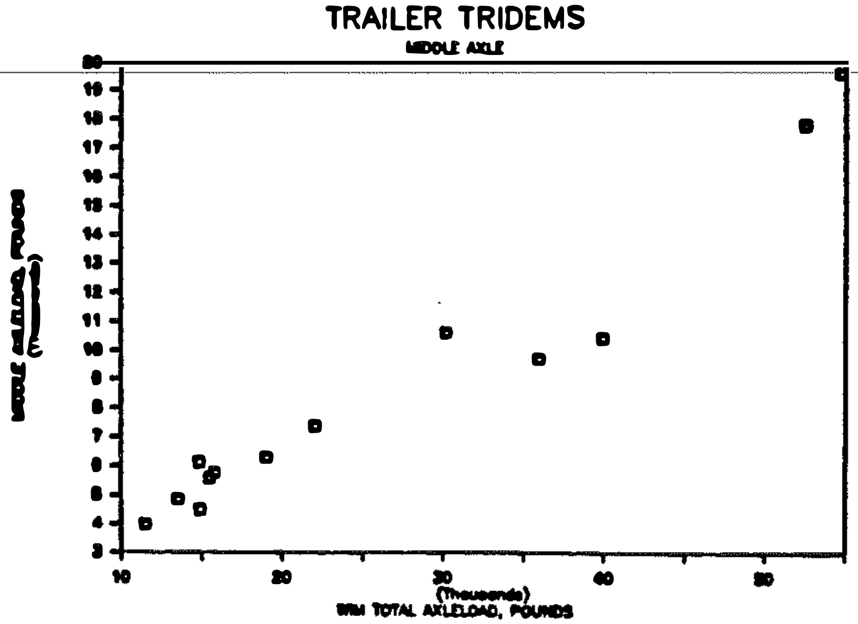


FIGURE 27. RELATIONSHIP BETWEEN WIM TOTAL TRIDEM LOAD VERSUS MIDDLE AXLELOAD FOR TRAILER TRIDEM GROUP.

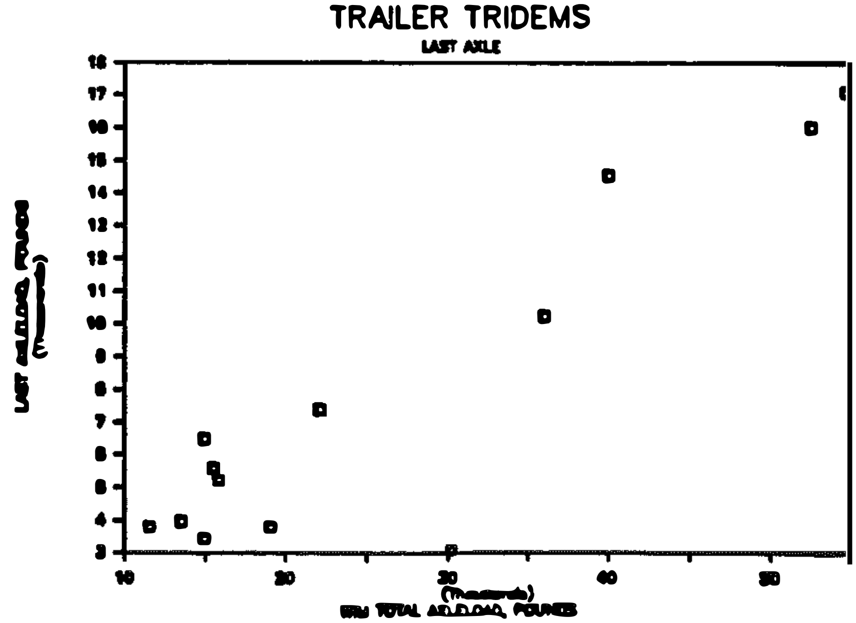


FIGURE 28. RELATIONSHIP BETWEEN WIM TOTAL TRIDEM LOAD VERSUS TRAILING AXLELOAD FOR TRAILER TRIDEM GROUP.

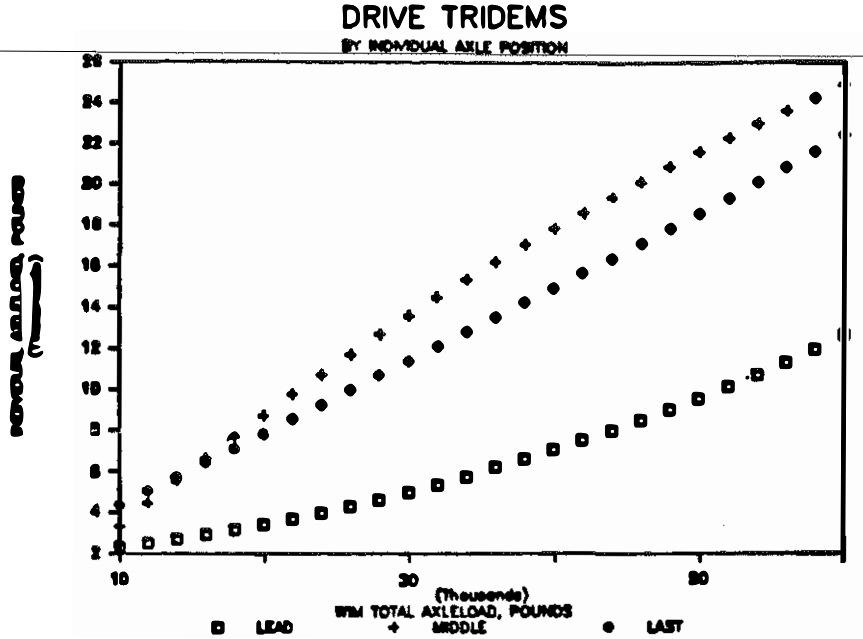


FIGURE 29. COMPARISON OF REGRESSION EQUATIONS BY AXLE POSITION VERSUS WIM TRIDEM LOAD FOR DRIVE TRIDEM GROUP.

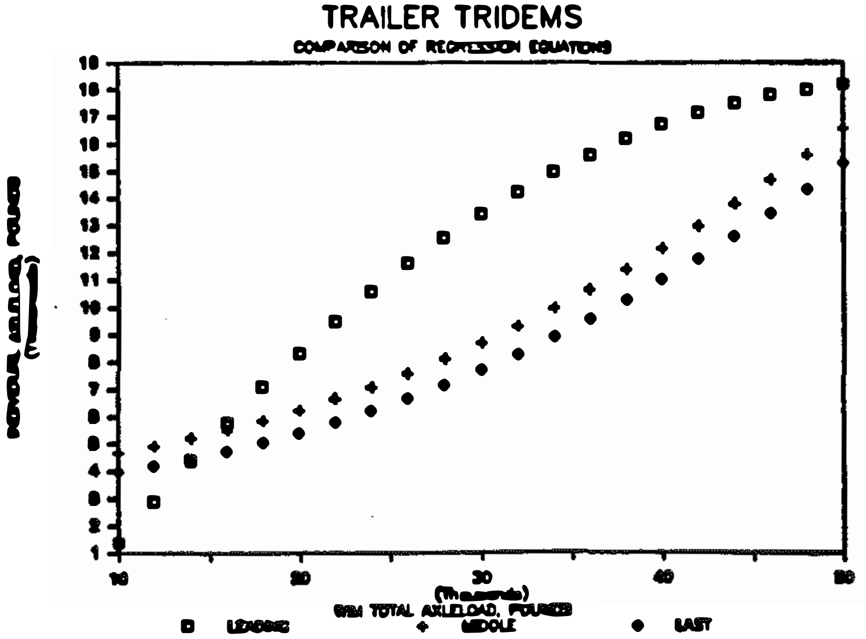


FIGURE 30. COMPARISON OF REGRESSION EQUATIONS BY AXLE POSITION VERSUS WIM TRIDEM LOAD FOR TRAILER TRIDEM GROUP.

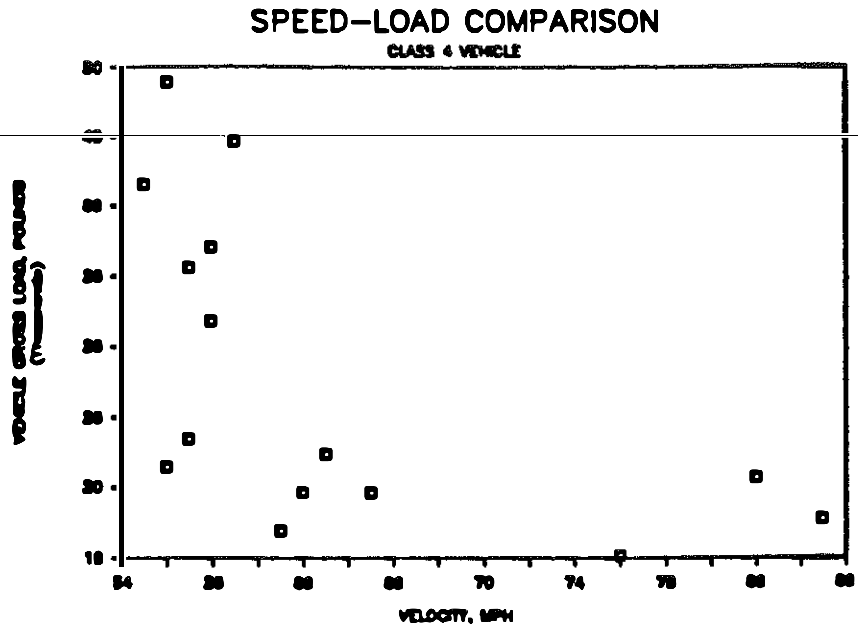


FIGURE 31. VEHICLE VELOCITY VERSUS VEHICLE GROSS LOAD FOR CLASS 4 VEHICLE.

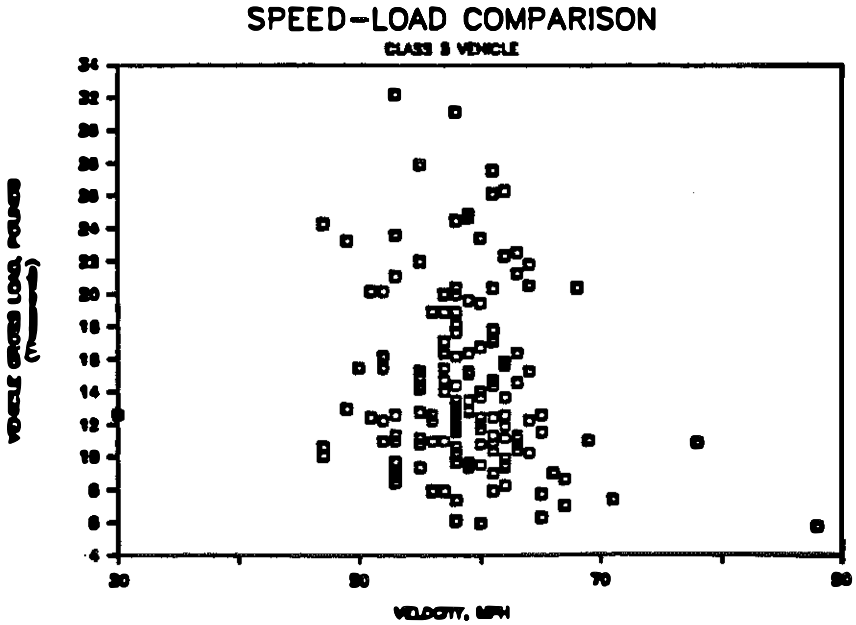


FIGURE 32. VEHICLE VELOCITY VERSUS VEHICLE GROSS LOAD FOR CLASS 5 VEHICLE.

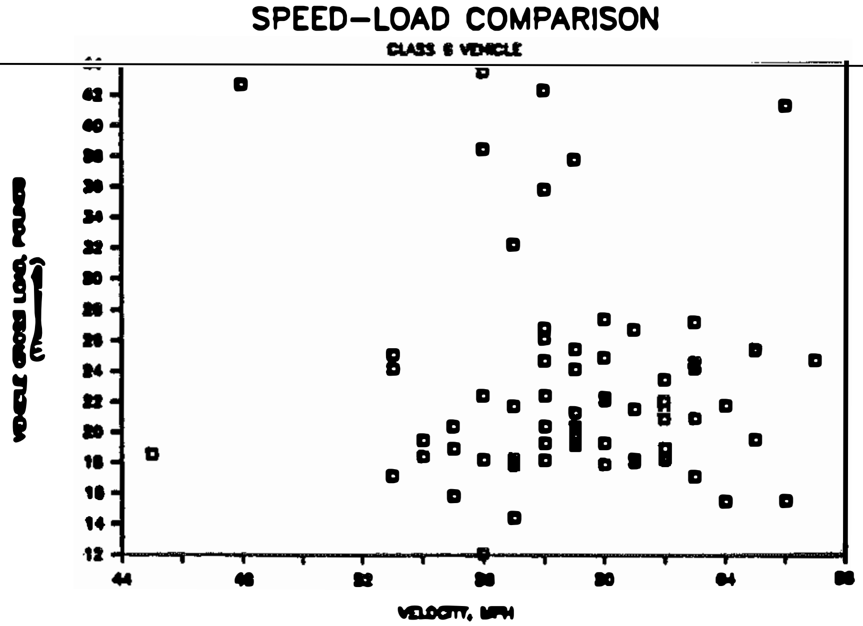


FIGURE 33. VEHICLE VELOCITY VERSUS VEHICLE GROSS LOAD FOR CLASS 6 VEHICLE.

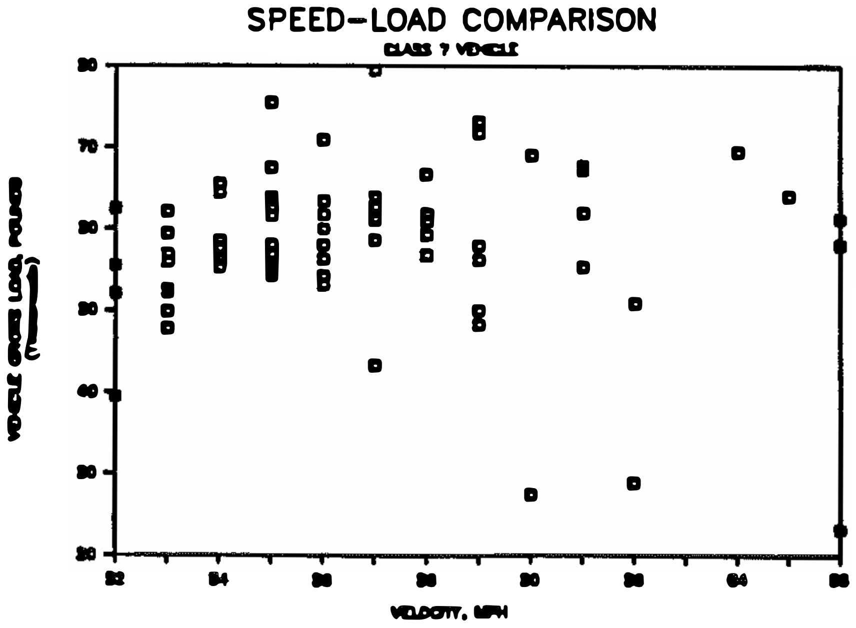


FIGURE 34. VEHICLE VELOCITY VERSUS VEHICLE GROSS LOAD FOR CLASS 7 VEHICLE.

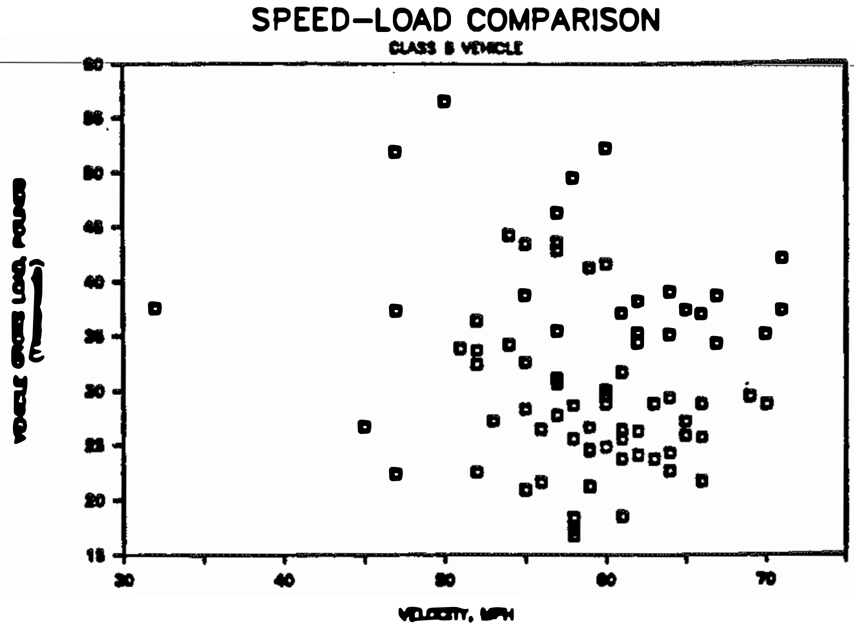


FIGURE 35. VEHICLE VELOCITY VERSUS VEHICLE GROSS LOAD FOR CLASS 8 VEHICLE.

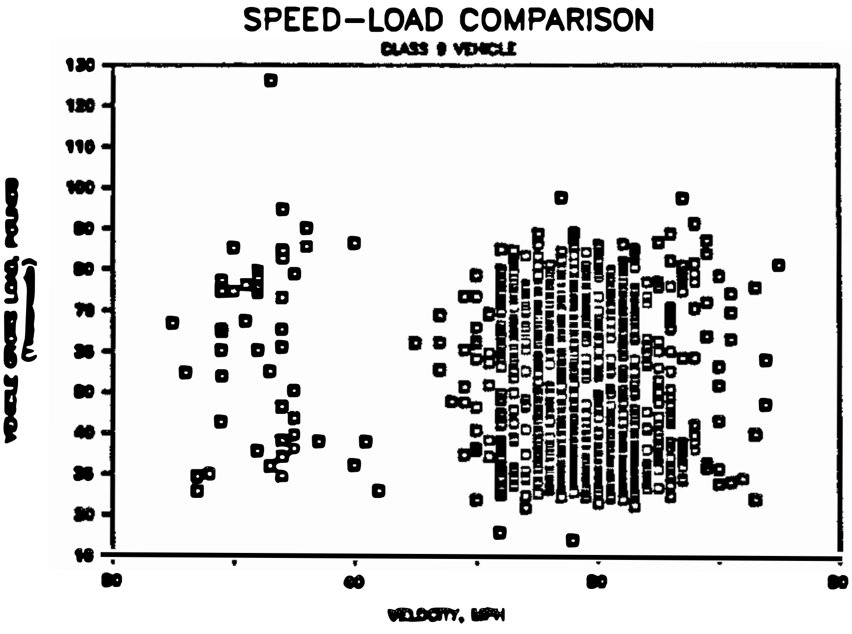


FIGURE 36. VEHICLE VELOCITY VERSUS VEHICLE GROSS LOAD FOR CLASS 9 VEHICLE.

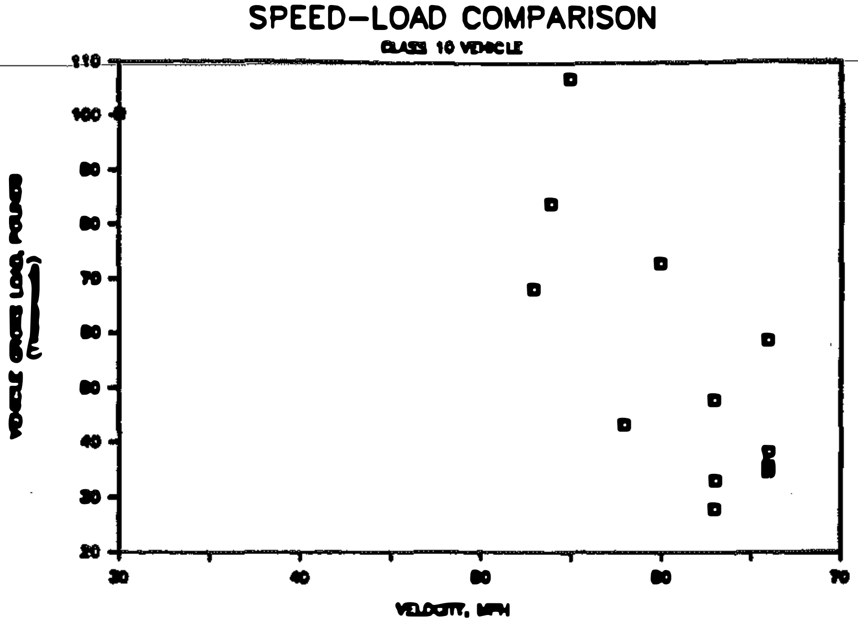


FIGURE 37. VEHICLE VELOCITY VERSUS VEHICLE GROSS LOAD FOR CLASS 10 VEHICLE.

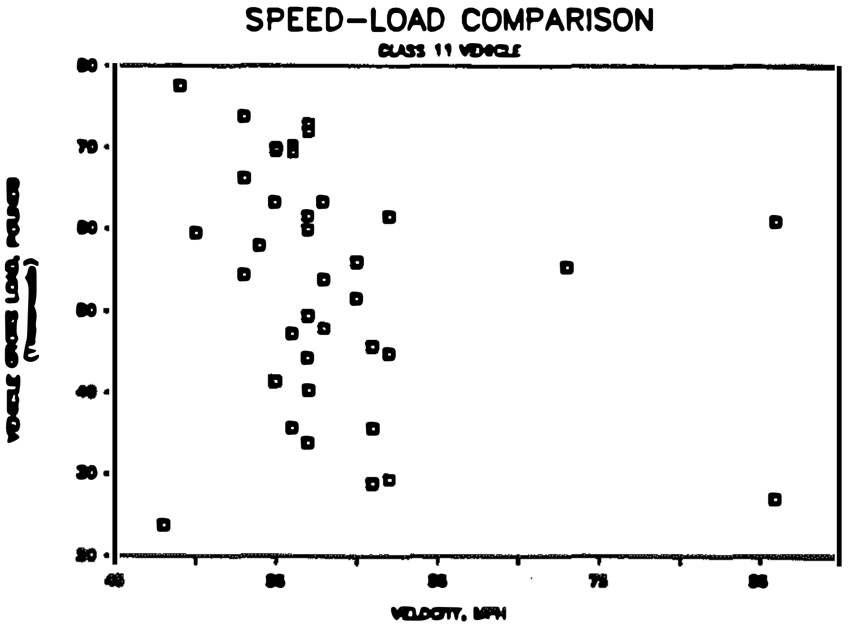


FIGURE 38. VEHICLE VELOCITY VERSUS VEHICLE GROSS LOAD FOR CLASS 11 VEHICLE.

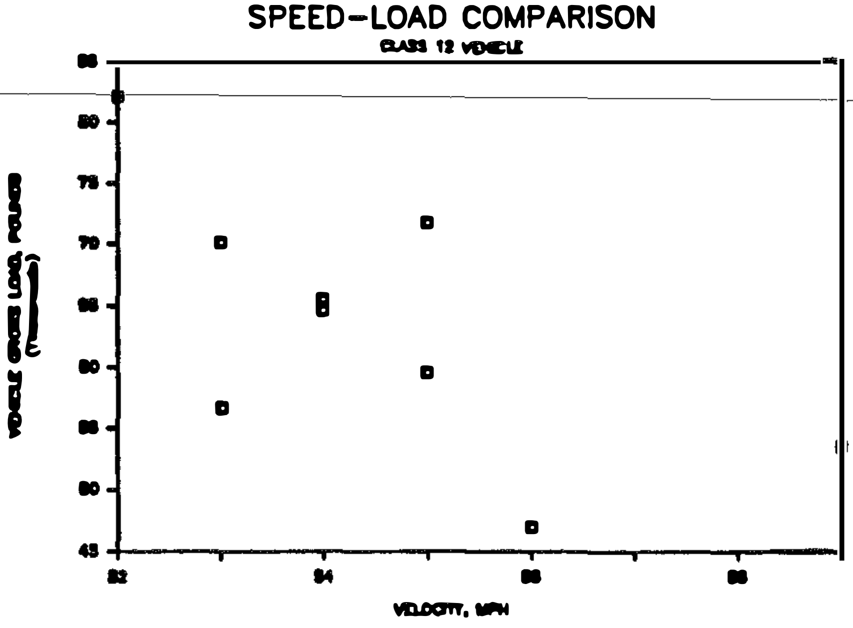


FIGURE 39. VEHICLE VELOCITY VERSUS VEHICLE GROSS LOAD FOR CLASS 12 VEHICLE.

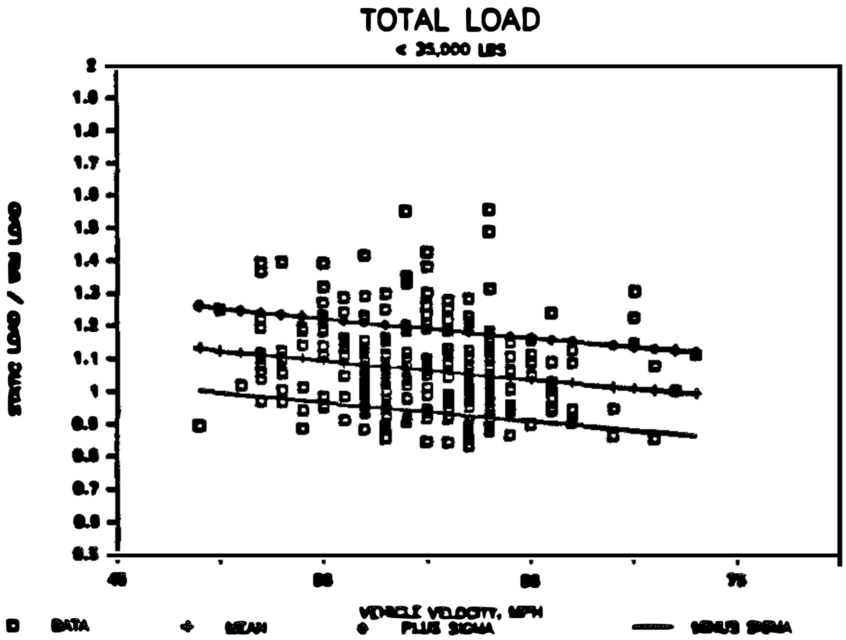


FIGURE 40. VEHICLE VELOCITY VERSUS RATIO OF STATIC LOAD TO WIM LOAD FOR GROSS LOADS < 35,000 POUNDS.

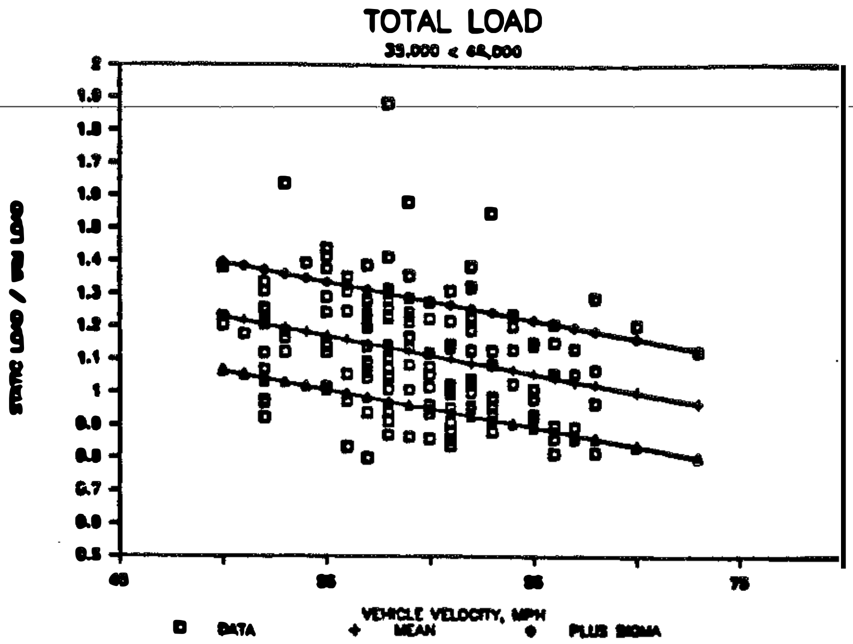


FIGURE 41. VEHICLE VELOCITY VERSUS RATIO OF STATIC LOAD TO WIM LOAD FOR GROSS LOADS OF 35,000 TO < 45,000 POUNDS.

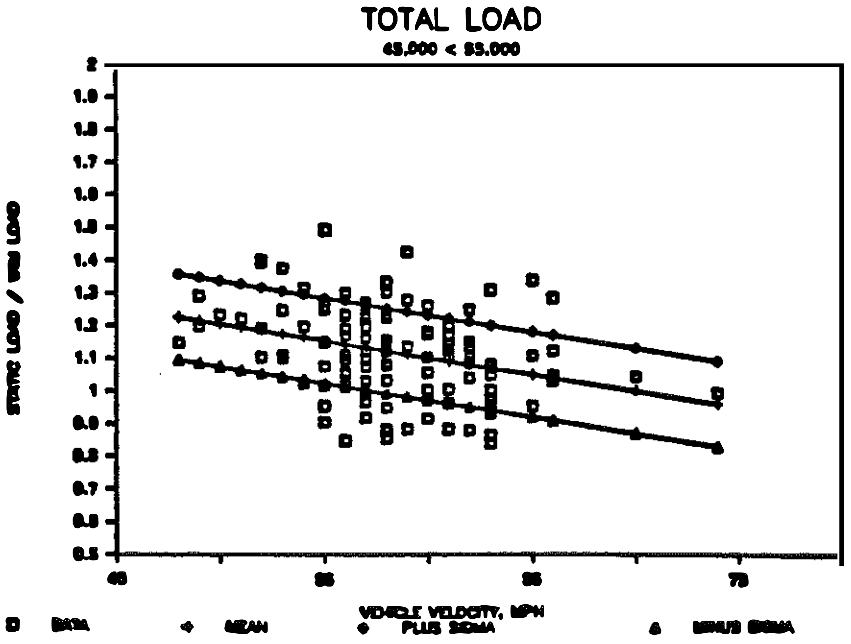


FIGURE 42. VEHICLE VELOCITY VERSUS RATIO OF STATIC LOAD TO WIM LOAD FOR GROSS LOADS OF 45,000 TO < 55,000 POUNDS.

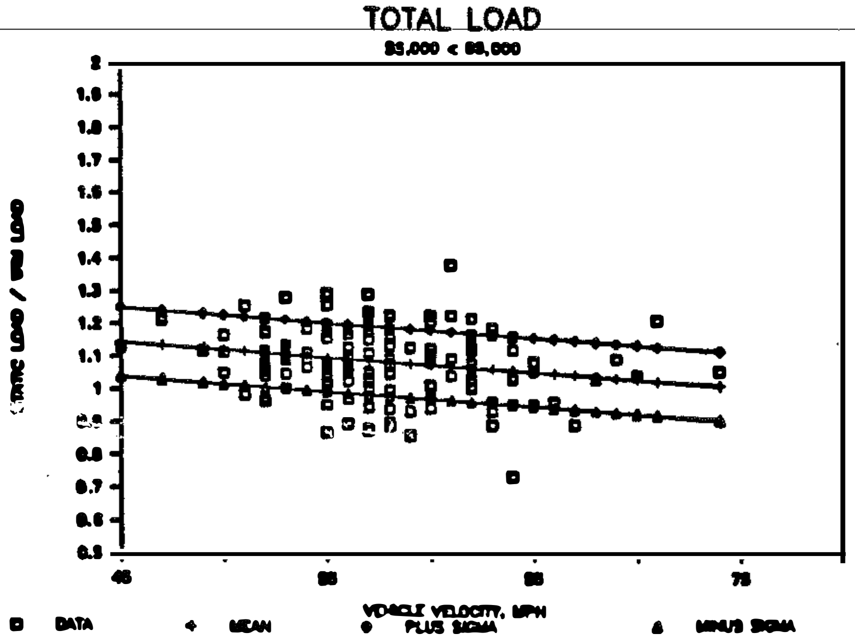


FIGURE 43. VEHICLE VELOCITY VERSUS RATIO OF STATIC LOAD TO WIM LOAD FOR GROSS LOADS OF 55,000 TO < 65,000 POUNDS.

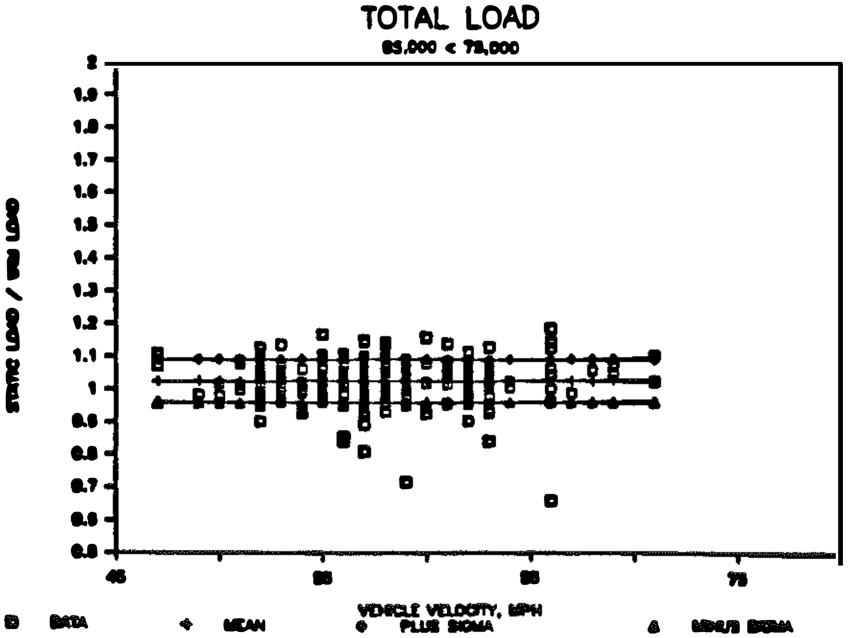


FIGURE 44. VEHICLE VELOCITY VERSUS RATIO OF STATIC LOAD TO WIM LOAD FOR GROSS LOADS OF 65,000 TO < 75,000 POUNDS.

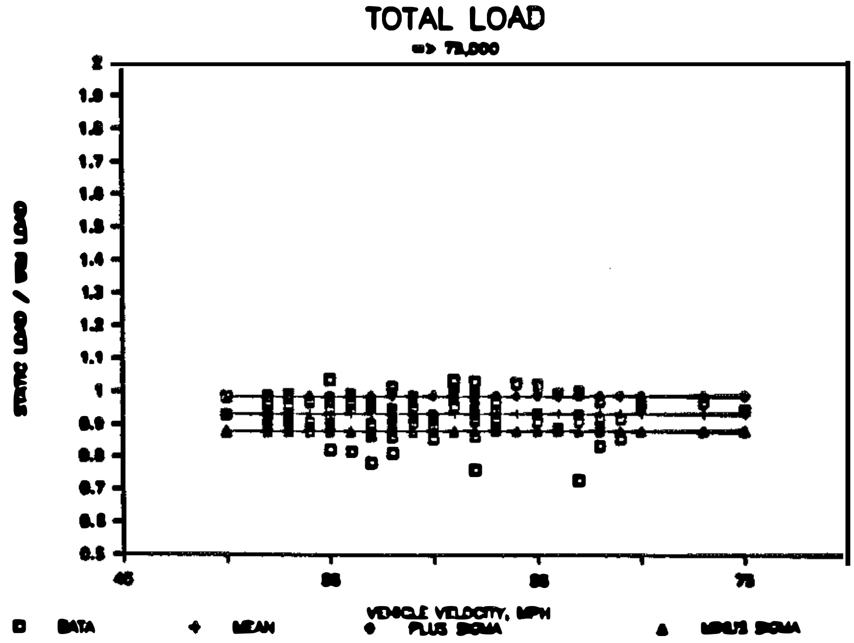


FIGURE 45. VEHICLE VELOCITY VERSUS RATIO OF STATIC LOAD TO WIM LOAD FOR GROSS LOADS OVER 75,000 POUNDS.

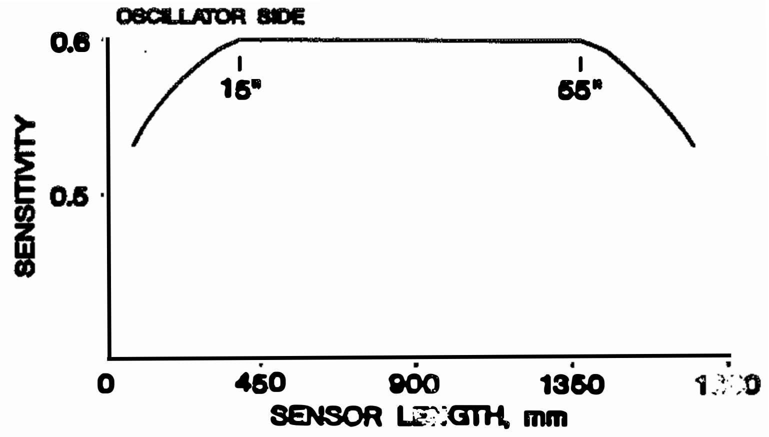


FIGURE 46. AN APPROXIMATE REPRODUCTION OF THE SENSITIVITY OF THE ELECTRICAL SIGNAL FROM THE WEIGH MAT AS A FUNCTION OF MAT LENGTH.

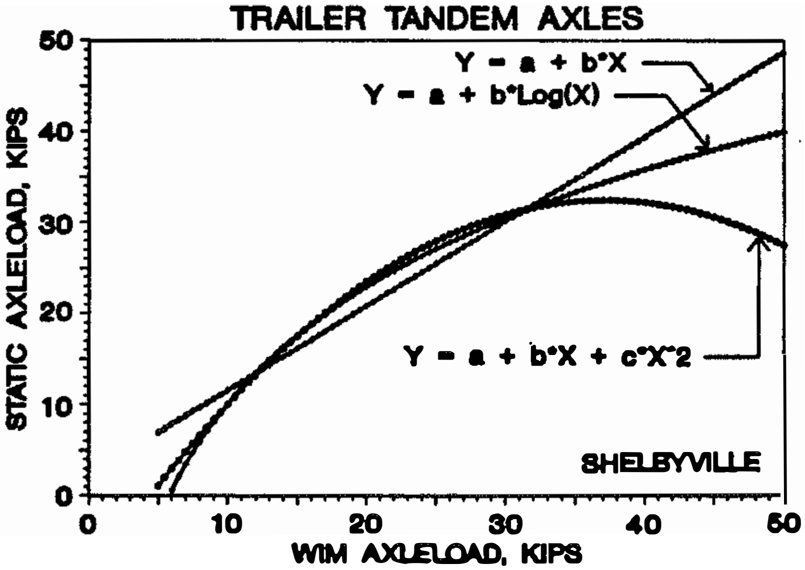


FIGURE 47. COMPARISON OF THREE REGRESSION EQUATIONS FITTED TO THE STATIC AND WEIGH-IN-MOTION AXLELOADS.

TABLE I. POLYNOMIAL COEFFICIENTS TO ADJUST WEIGH-IN-MOTION DATA TO EQUIVALENT STATIC SCALE VALUE BY AXLE LOCATION ON VEHICLE

EQUATION FORMAT: $Y = a + bX + cX^2$

		DRIVE AXLE		
	STEERING	SINGLE	TANDEM	TRIDEM
c	-0.000021689	0.0000061306	-0.0000141751	-0.0000306725
b	1.3313494303	0.5710284024	1.5035340031	3.0087359324
a	1641.3641617	4135.5077939	-3930.5004888	-25467.820407
STANDARD ERROR	1051.6604504	1903.6409725	2548.9995497	3064.8081838
R^2	0.7808836423	0.7777160252	0.9006533335	0.7505157055
F RATIO	2872.4109067	435.59435727	5697.8320442	108.297660387
NUMBER OF OBSERVATIONS	1615	252	1260	75

	TRAILER AXLE		
	SINGLE	TANDEM	TRIDEM
c	-0.0000359639	-0.0000243245	-0.0000195474
b	1.577666216	2.0031561485	2.114225245
a	-1067.2289242	-8415.7658813	-12941.477115
STANDARD ERROR	1513.6248287	2687.908828	3414.8376245
R^2	0.8307419998	0.910573402	0.9466890612
F RATIO	346.02388608	6068.683808	88.789381854
NUMBER OF OBSERVATIONS	144	1195	13

TABLE 2. NUMBER OF TRUCKS WEIGHED AT EACH SITE AND NUMBER OF ERRONEOUS OBSERVATIONS

LOCATION	TOTAL NUMBER OF OBSERVATIONS	NUMBER OF ERRONEOUS OBSERVATIONS	PERCENT
ELIZABETHTOWN	4,354	29	0.67
SHELBYVILLE	4,418	44	1.00
GEORGETOWN	3,869	39	1.00

TABLE 3. STATISTICAL VALUES FOR REGRESSION EQUATION CONSTANTS FOR CLASS 9 VEHICLES

AXLE GROUP	a	b	N	R^2
	FLEXIBLE PAVEMENT			
STEERING AXLE	5470.4395	0.6158783	6675	0.3581
DRIVE TANDEM	5141.1544	0.7388733	6673	0.8179
TRAILER TANDEM	3035.2880	0.8658488	6381	0.8430
	RIGID PAVEMENT			
STEERING AXLE	5549.9561	0.6071582	2781	0.2938
DRIVE TANDEM	4265.1512	0.7948960	2780	0.8311
TRAILER TANDEM	1647.5577	0.9202749	2600	0.8097

APPENDIX A

ESTABLISHMENT OF SAMPLE SIZE FOR ELECTRONIC CALIBRATION OF GOLDEN RIVER WEIGH-IN-MOTION MATS

UK UNIVERSITY
OF KENTUCKY

COLLEGE OF ENGINEERING

KENTUCKY TRANSPORTATION CENTER
TRANSPORTATION RESEARCH BUILDING
533 S. LIMESTONE STREET
LEXINGTON, KENTUCKY 40506-0043

April 7, 1989

H.2.123

Mr. Don Ecton, P.E.
Director
Division of Planning
Frankfort, KY 40622

SUBJECT: Establishment of Sample Size for Electronic Calibration of Golden River Weigh-In-Motion Mats

Dear Don:

Attached is a copy of the above written discussion for your use to calibrate the new mats.

Please contact me if you have any questions.

Sincerely,

John A Deacon

John A. Deacon
Associate Director

Attachment

cc: Rob Bostrum

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An Equal Opportunity University

ESTABLISHMENT OF SAMPLE SIZE FOR ELECTRONIC CALIBRATION OF GOLDEN RIVER WEIGH-IN-MOTION MATS

John A. Deacon
April 5, 1989

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1. Calibration Strategy

Weigh-in-motion mats can be electronically calibrated several different ways. The technique examined herein involves use of a spectrum of on-the-road vehicles rather than a single test vehicle of known loading. Field data are collected which enable fitting a quadratic equation to the mean values of static/WIM axle load ratios obtained at several different calibration settings as follows:

$$\text{Mean Static/WIM Axle Load} = a + b(CS) + c(CS)^2 \qquad (1)$$

in which CS is the calibration setting. The recommended setting or calibration factor, CF, is that which corresponds to a mean static/WIM ratio of one from the calibrated quadratic equation or:

$$CF = \frac{-b \pm [b^2 - 4(a-1)(c)]^{0.5}}{2(a-1)} \qquad (2)$$

Accuracy of the calibration is potentially a function of the number of calibration settings, the range between the largest and smallest calibration settings, and the number of axles weighed at each setting.

2. Original Calibration

The original Kentucky calibration was based on weights of tandem axles of 5-axle tractor-semitrailers. This axle remains a logical choice for calibration purposes. It is the most frequently occurring axle on major trucking highways and is the type most responsible for the bulk of pavement wear.

Five trial calibration settings of the WIM equipment were used, covering a range on the calibration scale of approximately 40 calibration units. To calibrate each pad, approximately 1,000 trucks were weighed, 200 at each calibration setting.

An original calibration for mat "A" is summarized in Figure 5 of "Dynamic Forces Versus Static Weights--Highway Design" by Herbert F. Southgate, October 1988. The quadratic calibration equation is given approximately as follows:

$$\text{Mean Static/WIM Axle Load} = 10.08163 - 0.089681(CS) + 0.0002179(CS)^2 \qquad (3)$$

in which CS is the calibration setting. The recommended calibration factor, that yielding a mean static/WIM axle load of one, was 179.81.

3. Evaluation of Calibration Procedures

The best calibration procedure is one that minimizes the calibration cost while providing an acceptable level of accuracy. For the calibration strategy investigated herein, calibration cost is best reduced by reducing the number of trucks weighed. Unfortunately, the number of trucks can not be reduced without sacrificing accuracy.

The "true" calibration factor, that which on average yields static weights of tandem axles which equal their WIM weights, is indeterminable. There is always some error due to limited sample size and randomness. One acceptable measure of the likely magnitude of error is the standard deviation of the calibration factor.

4. Computation of Standard Deviation of Calibration Factor

The standard deviation of the calibration factor can not be directly measured. It can be estimated with acceptable accuracy either by computer simulation or from a confidence interval band about the line of regression. For the analysis reported herein, simulation was used.

Static/WIM weight ratios for individual tandem axles were assumed to be normally distributed with a mean given by Eq. 3 and a standard deviation of 0.2. This standard deviation was typical of measured quantities. For one mat at three sites and a second mat at one site, the standard deviations ranged from 0.179 to 0.226 (computed from an average of about 3,000 axles in each case). In the simulations reported herein, static/WIM weight ratios were generated by conventional techniques using a computer-driven random number generator. Following simulation of the required number of weight ratios and computation of their mean value at each calibration setting, a least squares procedure was used to fit a quadratic equation (Eq. 1) to the data: the best-fit equation was then solved to determine the calibration factor (Eq. 2). The process was repeated until the number of simulations was sufficient to enable a reasonably accurate estimate of both the mean and the standard deviation of the calibration factor.

5. Results from the Simulation

After considerable experimentation, a minimum of 200 simulations was found to be necessary to yield reasonably stable estimates of the standard deviation of the calibration factor: estimates reported herein were developed from either 200 or 400 simulations. Even then, results, although interpretable, sometimes demonstrate inconsistencies.

Three calibration variables were investigated, the number of trucks (or axles) weighed, the number of calibration settings, and the range between the maximum and minimum calibration settings. Preliminary investigations suggested that the number of trucks and the range of calibration settings were most important.

As expected, the accuracy of the simulated calibrations increased with increases in the number of trucks used for the calibration (Table 1 and Figure 1). The effect rather significantly diminishes for larger samples, however. For example, no real advantage seems to be gained by increasing the sample size from 1,000 to 2,500 trucks.

The calibration range markedly influenced the calibration accuracy: the error observed with a 40-point range was only about one-half that observed with a 30-point range. Generalization of this finding suggests that a range greater than 40 points should be used in field calibrations. However, possible nonlinearities and loss in accuracy of the equipment over a broad range in settings could negate the apparent statistical advantage. Lack of detailed knowledge of the equipment--particularly over a broad range of calibration settings--prevents a recommendation for extension of the range of calibration settings.

For a constant range in calibration settings and a constant number of vehicles, the number of different calibration settings has no measurable effect on calibration accuracy (Table 2).

6. Significance of Standard Deviation of Calibration Factor

With a 40-point calibration range and five initial settings, the calibration procedure investigated herein can reasonably be expected to yield standard deviations of the calibration factor of the order of magnitude of 1.0. Assuming that the calibration factor is normally distributed, the 95-percent confidence interval for mat "A" is approximately 179.81 ± 2 or 177.81 to 181.81. From Eq. 3, the corresponding range in the static/WIM ratio is 1.025 to 0.979, a range of about ± 2.2 percent from the mean.

Whether such a range is significant from the viewpoint of EAL forecasts is judgmental. Because of the "4th" power relationship, a 2.2-percent greater load induces added wear of approximately 9 percent, a not insignificant quantity. Fortunately, the error is as likely to be negative as positive: with several mats in service, the EAL-forecast model should not be unduly biased one way or the other. Further mitigating any adverse effects of calibration inaccuracy is the fact the EAL model uses data obtained from a multi-year period, sufficiently long that multiple recalibrations will likely have been performed on each mat. Positive and negative errors are expected to cancel each other.

7. Recommendations

Doubling the sample size from approximately 1,000 5-axle tractor-semitrailers to 2,000 has been recommended to achieve increased accuracy in the calibration process. The analyses reported herein suggest that such a doubling of effort would only marginally improve calibration accuracy. Such marginal improvements would be expected to have insignificant impact on the ability to generate accurate design EALs for pavement design purposes.

More importantly, it is unlikely that halving the sample size from 1,000 to 500 trucks would have a discernible impact on the accuracy of design estimates providing the WIM mats are recalibrated when necessary. At the same time, considerable savings both in time and money could be realized by such a reduction. A sample size of 500 5-axle tractor-semitrailer trucks is, therefore, recommended for future calibration of Golden River weigh-in-motion mats.

Alternate schemes, other than the one investigated herein, are available for the calibration of WIM equipment. The possibility that one or more of these schemes could achieve greater accuracy with decreased calibration expense seems worthy of future investigation. Three of the most promising possibilities are (1) to employ a test vehicle of known weight, (2) to continuously calibrate mats in service to a vehicle/axle type of expectedly stable load, or (3) to develop a microcomputer-based field system capable of searching quickly for an optimal calibration point. Only in the latter case would paired observations be required from both WIM mats and static scales. The remaining two alternatives would not routinely require static measurements.

TABLE 1

EFFECT OF SAMPLE SIZE AND RANGE OF CALIBRATION SETTINGS ON RELIABILITY OF CALIBRATION[a]

Number of Trucks Weighed	Standard Deviation of Calibration Factor	
	30-Unit Range	40-Unit Range
200[b]	2.201	1.404
250	2.034	1.310
400[b]	2.020	1.092
500	2.125	1.019
600[b]	2.139	0.988
750	1.966	0.935
800[b]	1.854	0.927
1,000[b]	1.900	0.903
1,200[b]	1.823	0.840
1,250	1.981	0.880
1,500	1.876	0.829
1,750	1.755	0.763
2,000	1.769	0.784
2,250	1.863	0.772
2,500	1.751	0.828

[a] Five calibration settings were used: the middle setting was 180.

[b] 400 simulations.

TABLE 2

EFFECT OF NUMBER OF SETTINGS ON RELIABILITY OF CALIBRATION[a]

Number of Settings	Standard Deviation of Calibration Factor
3	0.834
4	0.843
5	0.887
6	0.779
7	0.821
8	0.913
9	0.910

[a] 1,000 trucks weighed and 400 simulations. The middle calibration setting was 180.

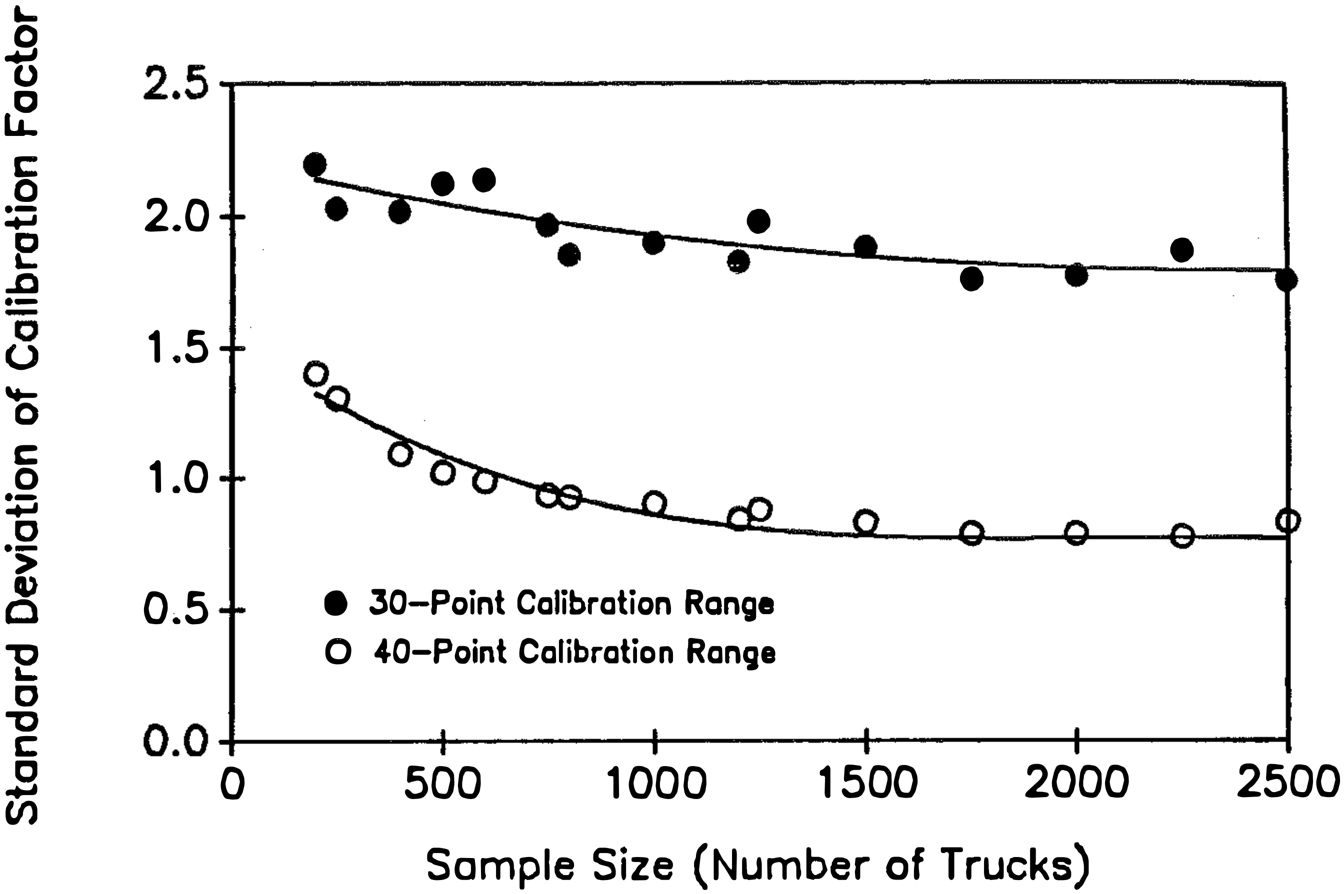

Figure 1. Effect of Sample Size on Reliability of Calibration

APPENDIX

LISTING OF QUICKBASIC 4.5 COMPUTER CODE

7

```
DECLARE SUB LINFIT (X(), Y(), COEF(), NOSET%)
DECLARE SUB CRAMER (A(), Z(), COEF(), IERR%)
DECLARE SUB DETERM (SUM, B())
DEFSNG A-Z
'   SIMULATION TO EVALUATE ALTERNATE STRATEGIES FOR ELECTRONIC
'   CALIBRATION OF GOLDEN RIVER WEIGH-IN-MOTION PADS
'
'   JOHN A. DEACON
'   KENTUCKY TRANSPORTATION CENTER
'   APRIL 2, 1989

'   NOSIM       Number of Simulations
'   NOSET       Number of Settings of Calibration Constant for Each
Simulation
'   ISETTING    Initial Value of Calibration Constant
'   INCREMENT   Increment of Calibration Constant
'   SIZE        Number of Axles to Weigh for Each Setting
'   TRUE        True Value of Calibration Constant

RANDOMIZE TIMER
DIM SHARED X(60), Y(60)
DIM SHARED A(3, 3), B(3, 3), Z(3), COEF(3)
1 CLS
PRINT "         SIMULATION TO EVALUATE ALTERNATE STRATEGIES FOR
ELECTRONIC"
PRINT "              CALIBRATION OF GOLDEN RIVER WEIGH-IN-MOTION PADS"
PRINT
PRINT "                       KENTUCKY TRANSPORTATION CENTER"
PRINT "                             APRIL 2, 1989"
PRINT
INPUT "Number of Simulations to be Performed                  ", NOSIM%
IF NOSIM% < 2 THEN NOSIM% = 2
INPUT "Number of Settings of Calibration Constant             ", NOSET%
IF NOSET% < 3 THEN NOSET% = 3
INPUT "Initial Value of Calibration Constant                  ", ISETTING
INPUT "Increment of Calibration Constant Between Settings     ", INCREMENT
INPUT "Number of Tandem Axles to be Weighed for Each Setting ", SIZE%
INPUT "Standard Deviation in Static/WIM Ratio                 ", DEV
TRUE = 179.81
PRINT "Assumed True Value of Calibration Constant"; TAB(54); TRUE
PRINT
BEEP
PRINT "                        COMPUTATIONS PROCEEDING"
PRINT
OX = 0
OX2 = 0
DIFF = 9999
NBR = 0
FOR IIII% = 1 TO NOSIM%
    FOR III% = 1 TO NOSET%
        X(III%) = ISETTING + (III% - 1) * INCREMENT
        IF ABS(X(III%) - TRUE) < DIFF THEN DIFF = ABS(X(III%) - TRUE)
```

```
        TEMPSY = 0
        YMEAN = 10.08163 - .089681 * X(III%) + .0002179 * X(III%) ^ 2
        FOR II% = 1 TO SIZE%
                SSUM = 0!
                FOR I% = 1 TO 12
                    SSUM = SSUM + RND
                NEXT I%
            TEMPY = YMEAN + DEV * (SSUM - 6!)
            TEMPSY = TEMPSY + TEMPY
        NEXT II%
        Y(III%) = TEMPSY / SIZE%
    NEXT III%



CALL LINFIT(X(), Y(), COEF(), NOSET%)
CA = COEF(3)
CB = COEF(2)
CC = COEF(1) - 1!
IF (CB ^ 2! - 4! * CA * CC) > 0! THEN
        CF1 = (-CB + (CB ^ 2! - 4! * CA * CC) ^ .5) / (2! * CA)
        CF2 = (-CB - (CB ^ 2! - 4! * CA * CC) ^ .5) / (2! * CA)
        IF ABS(TRUE - CF1) < ABS(TRUE - CF2) THEN CF = CF1 ELSE CF = CF2
        NBR = NBR + 1
ELSE
        CF = 0
END IF
PRINT "Simulation "; IIII%; "  Calibration "; CF

OX = OX + CF
OX2 = OX2 + CF ^ 2
NEXT IIII%
STDDEV = ((OX2 - (OX ^ 2) / NBR) / (NBR - 1)) ^ .5
MEAN = OX / NBR
CLS
PRINT "CALIBRATION PROCEDURE"
PRINT
PRINT "     Number of Settings of Calibration Constant            "; NOSET%

PRINT "     Number of Axles Weighed for Each Setting              "; SIZE%
PRINT "     Increment Between Settings of Calibration Constant    ";
INCREMENT
PRINT
PRINT
PRINT "MEASURES OF EFFECTIVENESS"
PRINT
PRINT "     True Calibration Constant                             "; TRUE
PRINT "     Mean of Calibration Constant                          "; MEAN
PRINT "     Standard Deviation of Simulated Calibration Constant  "; STDDEV

PRINT "     Interval Between True Constant and Nearest Setting    "; DIFF
PRINT "     Standard Deviation in Static/WIM Ratio                "; DEV
```

```
PRINT "     Number of Successful Simulations                    "; NBR
PRINT
PRINT
LPRINT CHR$(12)
LPRINT TAB(60); DATE$
LPRINT
LPRINT "CALIBRATION PROCEDURE"
LPRINT
LPRINT "     Number of Settings of Calibration Constant          ";
NOSET%
LPRINT "     Number of Axles Weighed for Each Setting            "; SIZE%

LPRINT "     Increment Between Settings of Calibration Constant  ";
INCREMENT
LPRINT
LPRINT
LPRINT "MEASURES OF EFFECTIVENESS"
LPRINT
LPRINT "     True Calibration Constant                           "; TRUE
LPRINT "     Mean of Calibration Constant                        "; MEAN
LPRINT "     Standard Deviation of Simulated Calibration Constant ";
STDDEV
LPRINT "     Interval Between True Constant and Nearest Setting  "; DIFF
LPRINT "     Standard Deviation in Static/WIM Ratio              "; DEV
LPRINT "     Number of Simulations                               "; NBR
LPRINT
PRINT "     Strike Y to Continue, N to Terminate      "
TRASH$ = ""
2 TRASH$ = INKEY$
IF TRASH$ = "" THEN GOTO 2
TRASH$ = UCASE$(TRASH$)
IF TRASH$ = "Y" THEN GOTO 1
CLS

END

SUB CRAMER (A(), Z(), COEF(), IERR%)
SHARED TRUE%
FOR I% = 1 TO 3
    FOR J% = 1 TO 3
        B(I%, J%) = A(I%, J%)
    NEXT J%
NEXT I%
CALL DETERM(SUM, B())
DETER = SUM
IF (DETER = 0) THEN
    IERR% = TRUE%
    PRINT "ERROR--MATRIX SINGULAR "
ELSE
    FOR J% = 1 TO 3
        FOR I% = 1 TO 3
            B(I%, J%) = Z(I%)
```

```
            IF (J% > 1) THEN B(I%, J% - 1) = A(I%, J% - 1)
        NEXT I%
        CALL DETERM(SUM, B())
        COEF(J%) = SUM / DETER
    NEXT J%
END IF
END SUB

SUB DETERM (SUM, B())
SUM = B(1, 1) * (B(2, 2) * B(3, 3) - B(3, 2) * B(2, 3))
SUM = SUM - B(1, 2) * (B(2, 1) * B(3, 3) - B(3, 1) * B(2, 3))
SUM = SUM + B(1, 3) * (B(2, 1) * B(3, 2) - B(3, 1) * B(2, 2))
END SUB

SUB LINFIT (X(), Y(), COEF(), NOSET%)
SUMX = 0
SUMY = 0
SUMXY = 0
SUMX2 = 0
SUMY2 = 0
SUMX3 = 0
SUMX4 = 0
SUM2Y = 0
FOR K% = 1 TO NOSET%
    SUMX = SUMX + X(K%)
    SUMY = SUMY + Y(K%)
    SUMXY = SUMXY + X(K%) * Y(K%)
    SUMX2 = SUMX2 + X(K%) ^ 2
    SUMY2 = SUMY2 + Y(K%) ^ 2
    SUMX3 = SUMX3 + X(K%) ^ 3
    SUMX4 = SUMX4 + X(K%) ^ 4
    SUM2Y = SUM2Y + X(K%) ^ 2 * Y(K%)
NEXT K%
A(1, 1) = NOSET%
A(2, 1) = SUMX
A(1, 2) = SUMX
A(3, 1) = SUMX2
A(1, 3) = SUMX2
A(2, 2) = SUMX2
A(3, 2) = SUMX3
A(2, 3) = SUMX3
A(3, 3) = SUMX4
Z(1) = SUMY
Z(2) = SUMXY
Z(3) = SUM2Y
CALL CRAMER(A(), Z(), COEF(), IERR%)
END SUB
```

APPENDIX B

PROCEDURE TO CHECK GOLDEN RIVER WEIGH-IN-MOTION SYSTEM FOR DRIFT IN CALIBRATION FACTOR VALUE

APPENDIX B

The Shelbyville data set was sorted by vehicle class and the steering axleload data extracted to determine the number of weighings required to reach a fairly stable value. The arithmetic average was obtained as shown in Table B1 and illustrated in Figure B1. Based on these data, the average WIM weight should be taken for at least 900 to 1000 trucks to determine if there has been any significant shift in the calibration factor.

Whenever a relationship can be developed to adjust the WIM data for the roughness of the approach, the recorded WIM weights should be adjusted to a chosen roughness value. Then, a specified number of steering axles for Class 9 trucks could be deleted from the beginning of the data set and the same number added after the last record. Such a procedure provides a "running" average that can be used to compare with values listed below.

TABLE B1. AVERAGE STEERING AXLELOAD

TRUCK NUMBER	AXLELOAD, POUNDS	
	STATIC	WIM
1 - 100	7653.8	5475.6
1 - 200	9214.7	6800.4
1 - 300	8894.9	6463.8
1 - 400	9407.4	7046.1
1 - 500	9607.6	7188.8
1 - 600	9572.7	7044.3
1 - 700	9570.1	6956.5
1 - 800	9545.9	6919.6
1 - 900	9525.8	6850.6
1 - 1000	9520.2	6813.0
1 - 1100	9523.6	6798.9
1 - 1200	9508.4	6760.4
1 - 1300	9486.0	6727.8
1 - 1400	9472.3	6705.6
1 - 1500	9451.8	6685.0

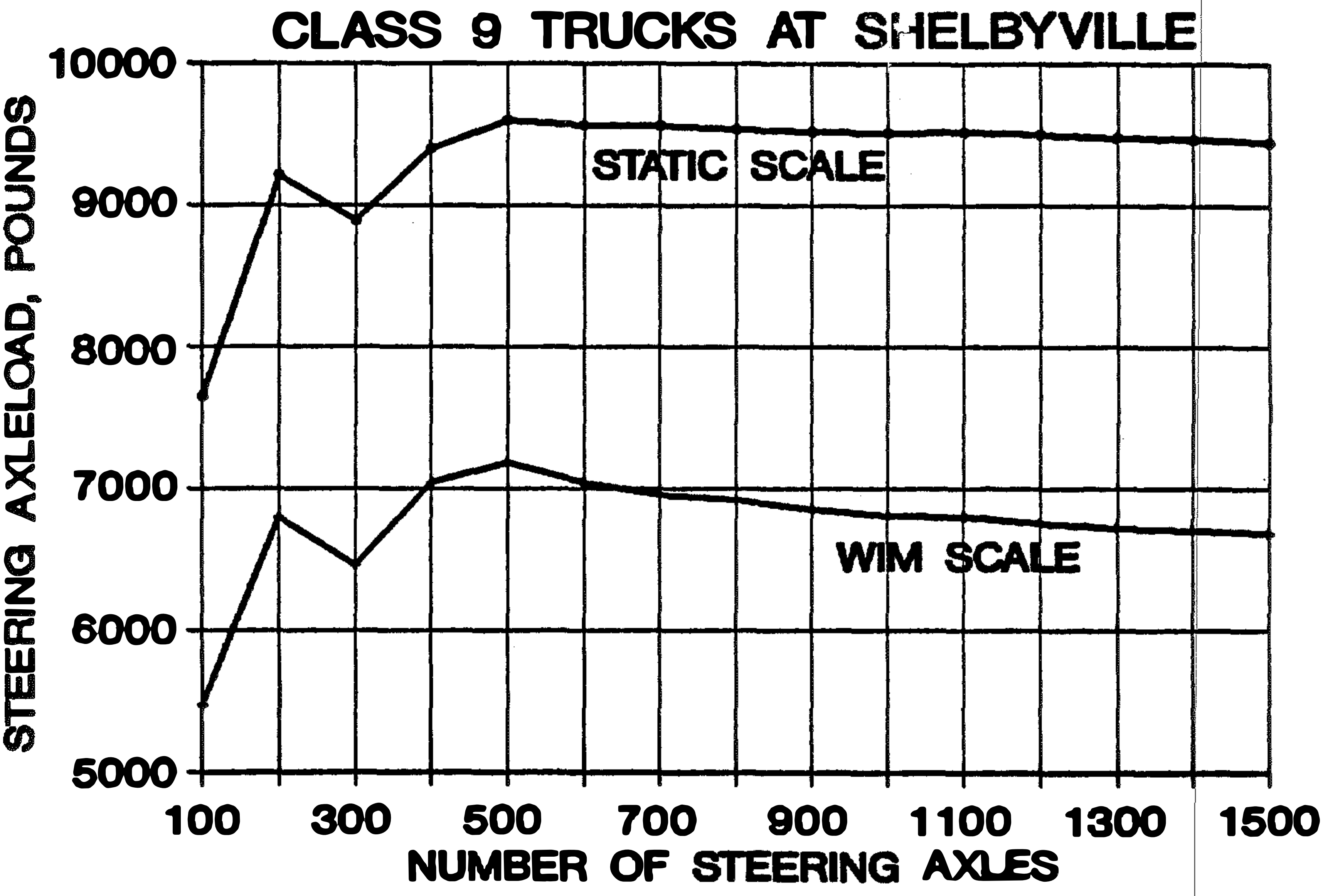

FIGURE B1. AVERAGE STEERING AXLELOAD

APPENDIX C

LIST OF TABLES

STATISTICAL ANALYSES AND INTERPRETATIONS

For a T distribution, at least 30 degrees of freedom are required in order to be assured that there is no significant bias due to the lack of a representative set of data. The reference for this is "Table III. Percentiles of the t Distribution", "Introduction to Probability and Statistics", by B. W. Lindgren and G. W. McElrath, The Macmillan Company, New York, 1959.

The number of degrees of freedom is one less than the number of observations. Therefore, there must be a minimum of 31 observations to have 30 degrees of freedom without causing a statistical bias. To be on the conservative side, it is recommended that the number of observations should be in the range of 50 to 100 before considering the regressions to be reliable for general use within individual vehicle class. Thus in Table C2, the regressions for Class 4, and trailer single and drive tandem axles for Class 8 are not recommended for use. Class 10 must be considered as marginal at best. For Table C3, Class 4, Class 7, and the trailer single and drive tandem axle regressions should not be used. Class 12 must be considered marginal. For these vehicle classifications, the regressions by axle location given in Table C1 should be used.

TABLE C1. STATISTICAL VALUES FOR REGRESSION EQUATION CONSTANTS FOR SEVEN BASIC AXLE GROUPS

Y = a + b*X

AXLE GROUP	a	b	N	R^2
FLEXIBLE PAVEMENT				
STEERING	3557.2423	0.8932135	8699	0.6938
DRIVE SINGLE	3076.3085	0.735836	1404	0.8392
TRAILER SINGLE	2939.1856	0.720307	2167	0.7945
DRIVE TANDEM	4890.9914	0.7463315	7088	0.825
TRAILER TANDEM	2926.9924	0.8693042	6735	0.8473
DRIVE TRIDEM	38041.8808	0.2044157	186	0.1166
TRAILER TRIDEM	4947.4293	0.8634991	67	0.7682
RIGID PAVEMENT				
STEERING	3864.2167	0.8619752	3823	0.5814
DRIVE SINGLE	2972.9051	0.7179301	696	0.7828
TRAILER SINGLE	3503.9253	0.7393744	1402	0.6666
DRIVE TANDEM	4055.0787	0.8017253	3075	0.8339
TRAILER TANDEM	1611.5815	0.9220579	2746	0.8128
DRIVE TRIDEM	37421.673	0.2192902	44	0.3029
TRAILER TRIDEM	15454.4334	0.6378718	131	0.5585

TABLE C2. STATISTICAL VALUES FOR REGRESSION EQUATION CONSTANTS FOR EACH AXLE GROUP WITHIN EACH VEHICLE CLASSIFICATION FOR FLEXIBLE PAVEMENT

$Y = a + b*X$

AXLE GROUP	a	b	N	R^2
CLASS 4				
STEERING	6788.6556	0.5663658	36	0.7053
DRIVE TANDEM	5657.5083	0.7152323	36	0.8066
CLASS 5				
STEERING	487.1305	1.2892328	594	0.687
DRIVE SINGLE	3231.6993	0.7116072	594	0.8168
CLASS 6				
STEERING	4309.4401	0.8275233	229	0.7614
DRIVE TANDEM	2433.9743	0.7948671	227	0.7299
CLASS 7				
STEERING	5594.2217	0.7810228	196	0.7614
DRIVE TRIDEM	39193.7413	0.1794698	184	0.0881
CLASS 8				
STEERING	2945.6937	0.9251754	379	0.4059
DRIVE SINGLE	3358.8703	0.7061323	356	0.7337
TRAILER SINGLE	1629.9582	0.8242531	24	0.7042
DRIVE TANDEM	156.2411	0.946768	20	0.7872
TRAILER TANDEM	1849.699	0.9049906	354	0.7709
CLASS 9				
STEERING	5470.4395	0.6158783	6675	0.3581
DRIVE TANDEM	5141.1544	0.7388733	6673	0.8179
TRAILER TANDEM	3035.288	0.8658488	6381	0.843
CLASS 10				
STEERING	7202.5787	0.289908	51	588
DRIVE TANDEM	4904.6994	0.7554978	51	0.846
TRAILER TRIDEM	6298.4814	0.8232144	51	0.7129
CLASS 11				
STEERING	5416.5672	0.6012531	457	0.2622
DRIVE SINGLE	3167.4828	0.7434655	454	0.7846
TRAILER SINGLE	3456.9877	0.6812423	1314	0.775
CLASS 12				
STEERING	6317.8591	0.3738969	82	0.1919
DRIVE TANDEM	11651.298	0.4402026	81	0.5326
TRAILER SINGLE	4198.3254	0.6297903	243	0.7349

TABLE C3. STATISTICAL VALUES FOR REGRESSION EQUATION CONSTANTS FOR EACH AXLE GROUP WITHIN EACH VEHICLE CLASSIFICATION FOR RIGID PAVEMENT

Y = a + b*X

AXLE GROUP	a	b	N	R^2
CLASS 4				
STEERING	723.1975	1.3097741	13	0.4836
DRIVE TANDEM	1023.4462	0.8288069	11	0.6573
CLASS 5				
STEERING	318.9998	1.3234121	246	0.608
DRIVE SINGLE	2740.3059	0.7448936	246	0.7684
CLASS 6				
STEERING	4171.2673	0.7238139	101	0.4414
DRIVE TANDEM	657.6015	0.903561	101	0.6669
CLASS 7				
STEERING	12252.2638	0.3157259	39	0.3291
DRIVE TRIDEM	38105.0161	0.2054489	39	0.3298
CLASS 8				
STEERING	2839.8418	0.9638416	164	0.6456
DRIVE SINGLE	2990.323	0.6926076	151	0.724
TRAILER SINGLE	4004.4395	0.5858458	16	0.438
DRIVE TANDEM	8268.4698	0.5930186	8	0.4182
TRAILER TANDEM	306.8368	1.022011	147	0.7281
CLASS 9				
STEERING	5549.9561	0.6071582	2781	0.2938
DRIVE TANDEM	4265.1512	0.794896	2780	0.8311
TRAILER TANDEM	1647.5577	0.9202749	2600	0.8097
CLASS 10				
STEERING	5596.3381	0.5808657	130	0.3811
DRIVE TANDEM	12516.977	0.5331612	125	0.67028
TRAILER TRIDEM	16991.0172	0.5965314	126	0.5063
CLASS 11				
STEERING	5891.7357	0.5388247	298	0.1769
DRIVE SINGLE	4059.8911	0.6595216	295	0.5582
TRAILER SINGLE	3767.2177	0.7175486	870	0.6304
CLASS 12				
STEERING	6311.7652	0.3951383	51	0.1365
DRIVE TANDEM	9992.0783	0.5066399	50	0.4455
TRAILER SINGLE	2686.2628	0.785251	150	0.7029

LIST OF FIGURES

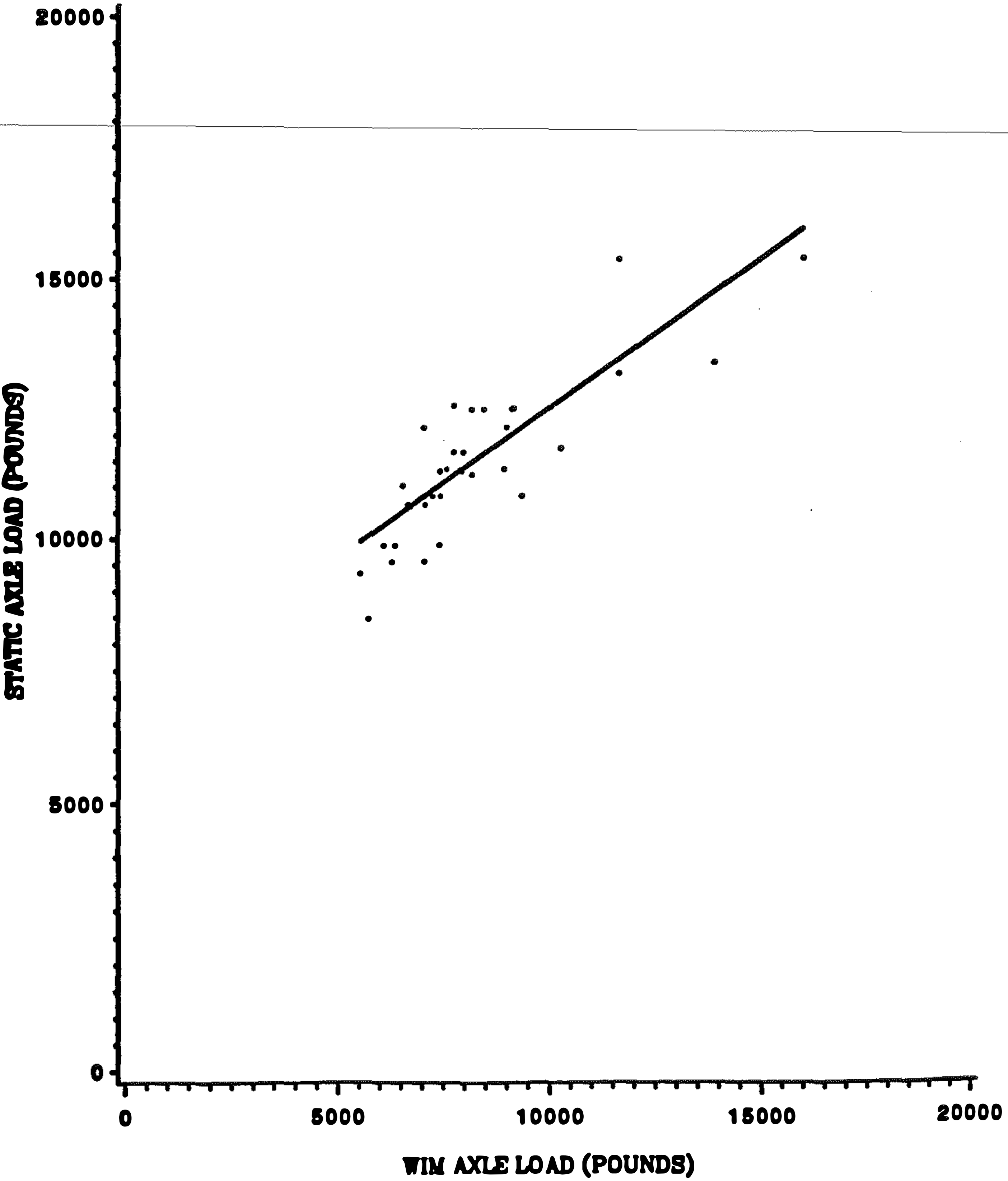

FIGURE C1. RELATION BETWEEN STATIC AND WIM AXLELOADS -- STEERING AXLE, FLEXIBLE PAVEMENT, VEHICLE CLASS NO. 4.

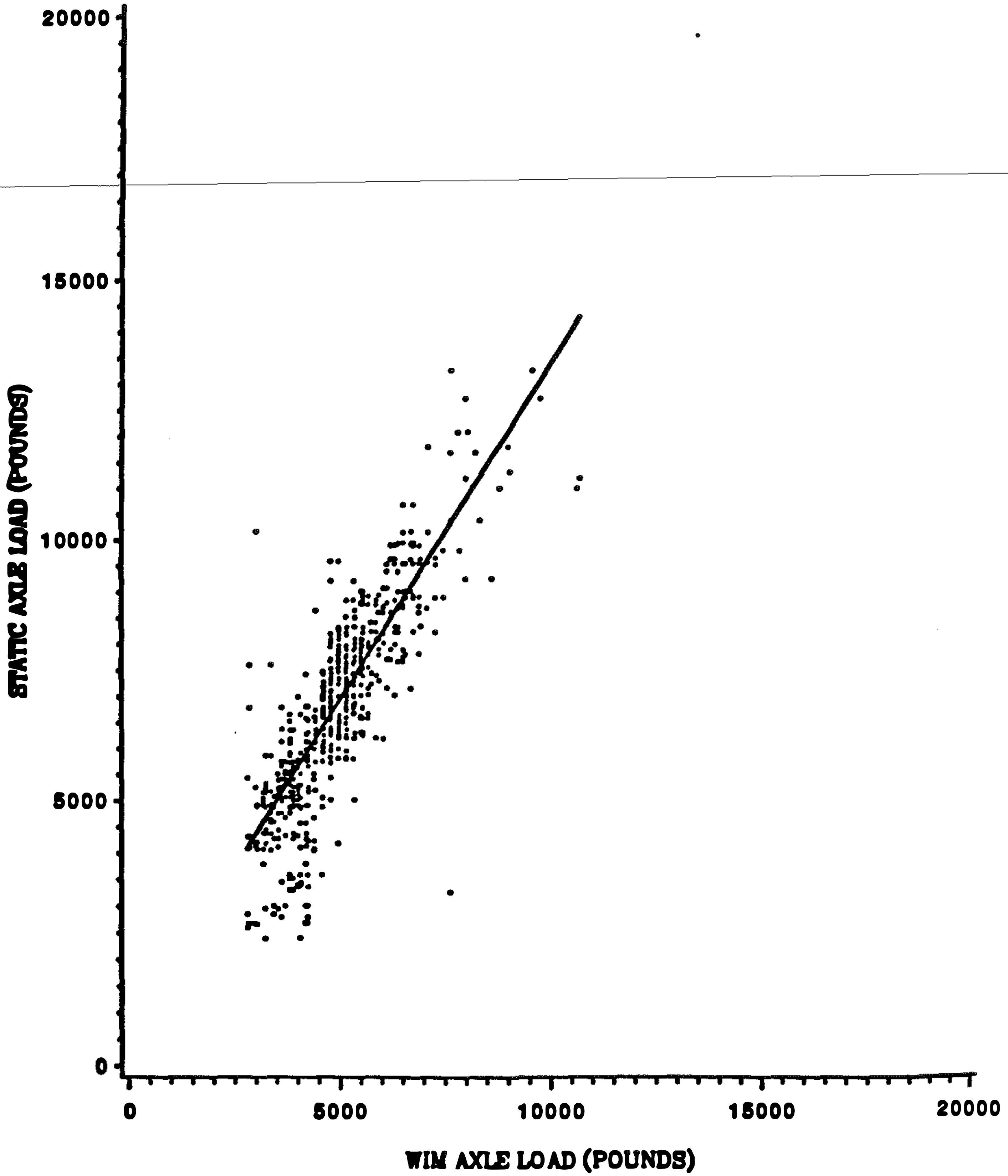

FIGURE C2. RELATION BETWEEN STATIC AND WIM AXLELOADS -- STEERING AXLE, FLEXIBLE PAVEMENT, VEHICLE CLASS NO. 5.

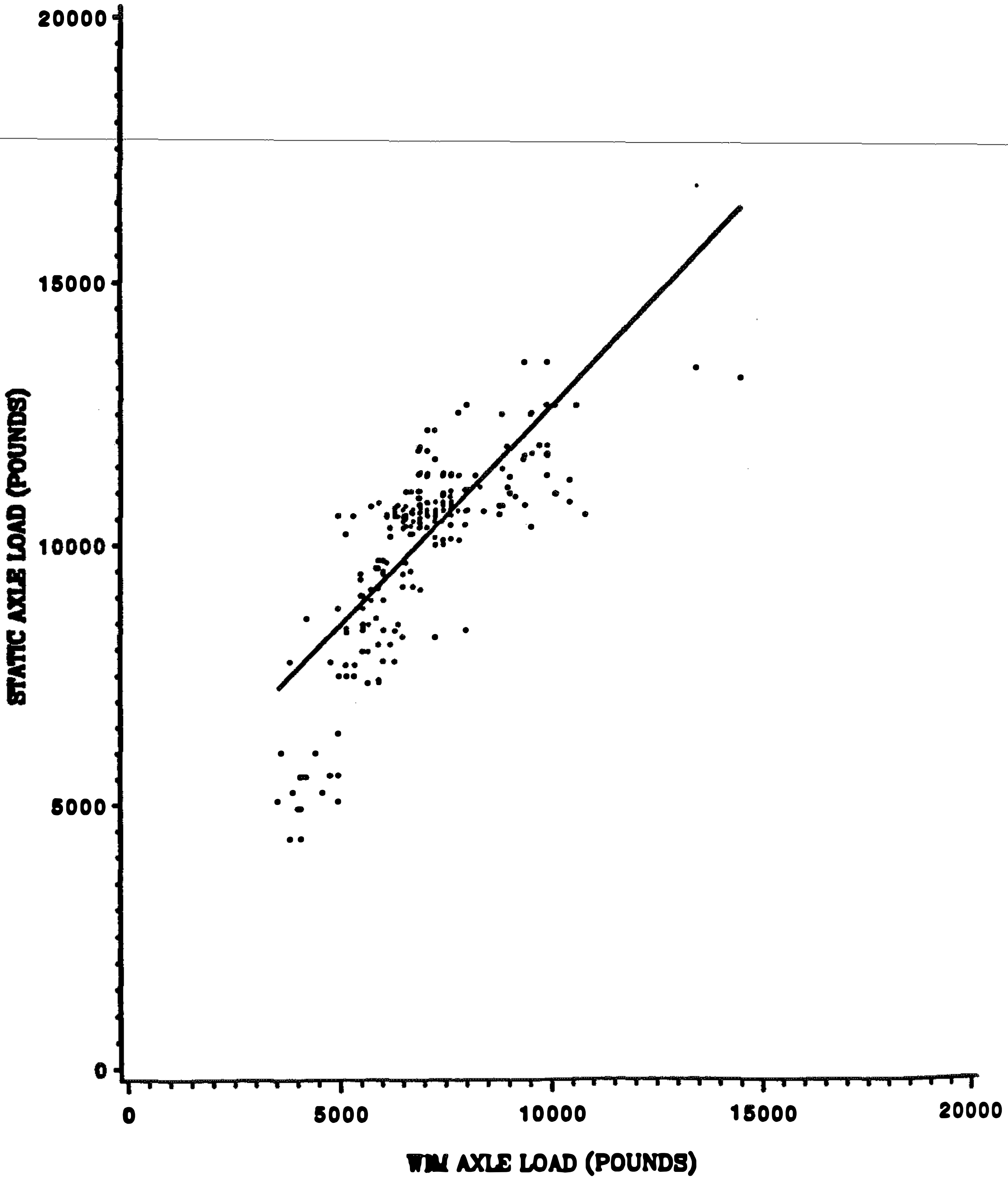

FIGURE C3. RELATION BETWEEN STATIC AND WIM AXLELOADS -- STEERING AXLE, FLEXIBLE PAVEMENT, VEHICLE CLASS NO. 6.

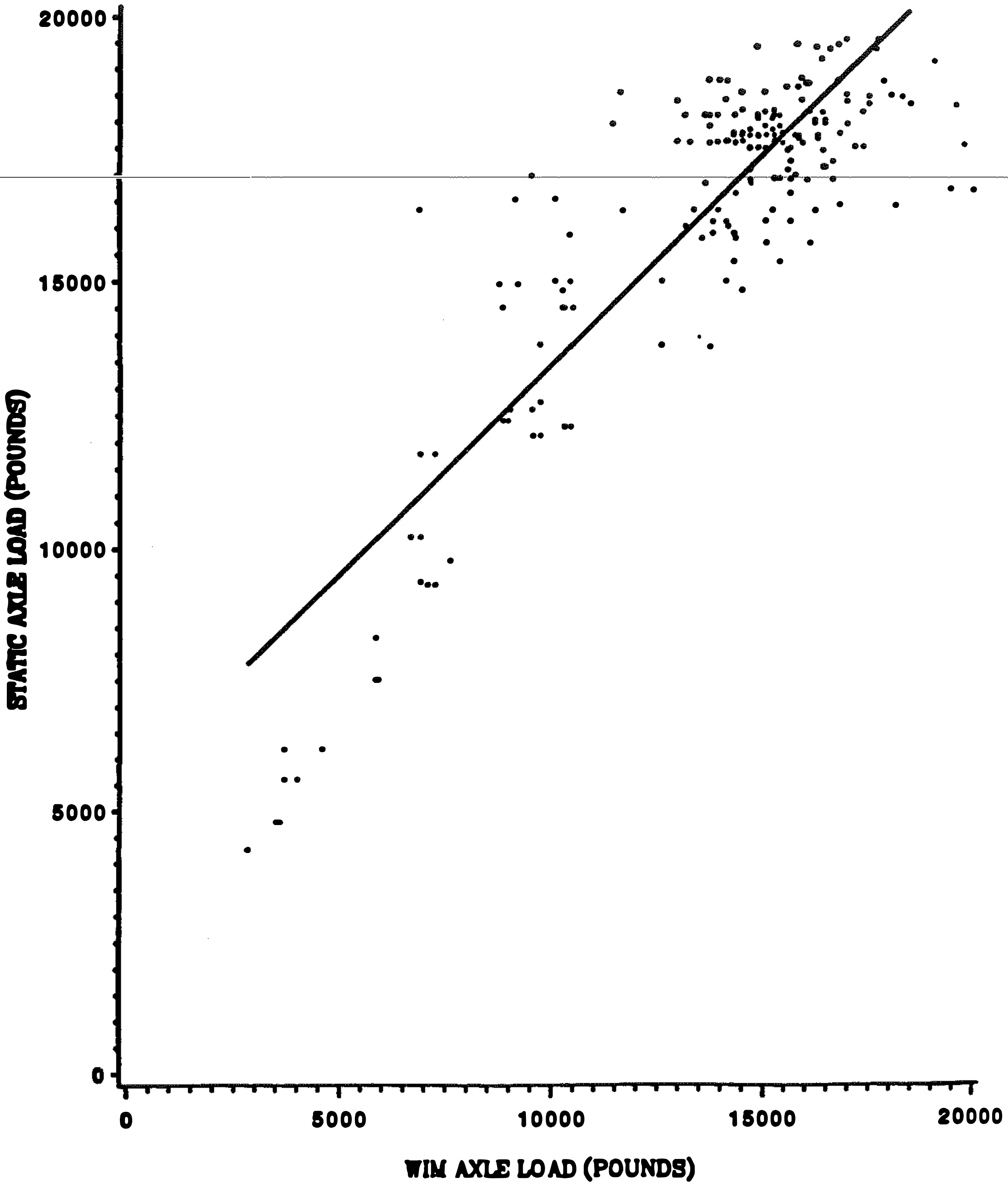

FIGURE C4. RELATION BETWEEN STATIC AND WIM AXLELOADS -- STEERING AXLE, FLEXIBLE PAVEMENT, VEHICLE CLASS NO. 7.

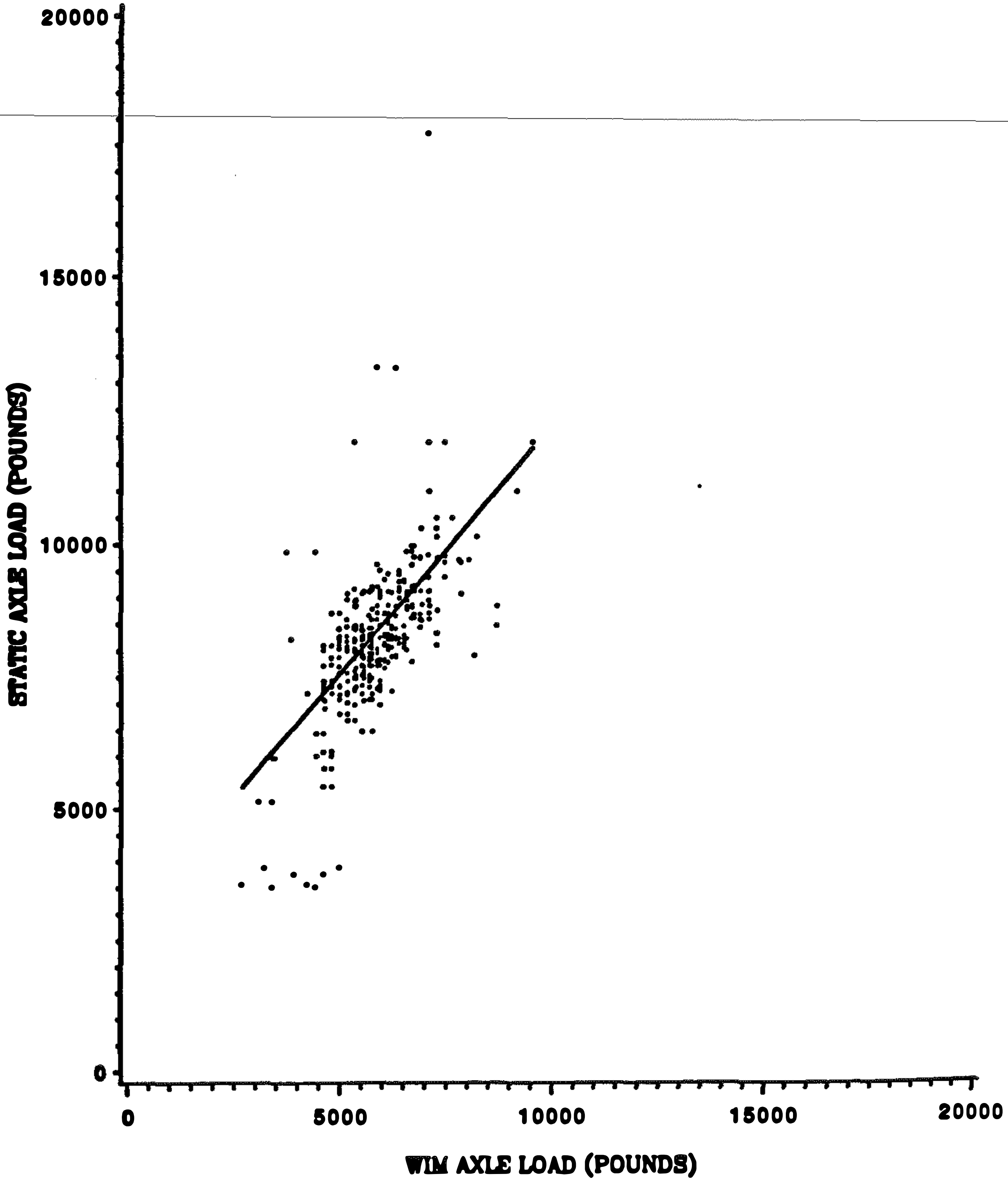

FIGURE C5. RELATION BETWEEN STATIC AND WIM AXLELOADS -- STEERING AXLE, FLEXIBLE PAVEMENT, VEHICLE CLASS NO. 8.

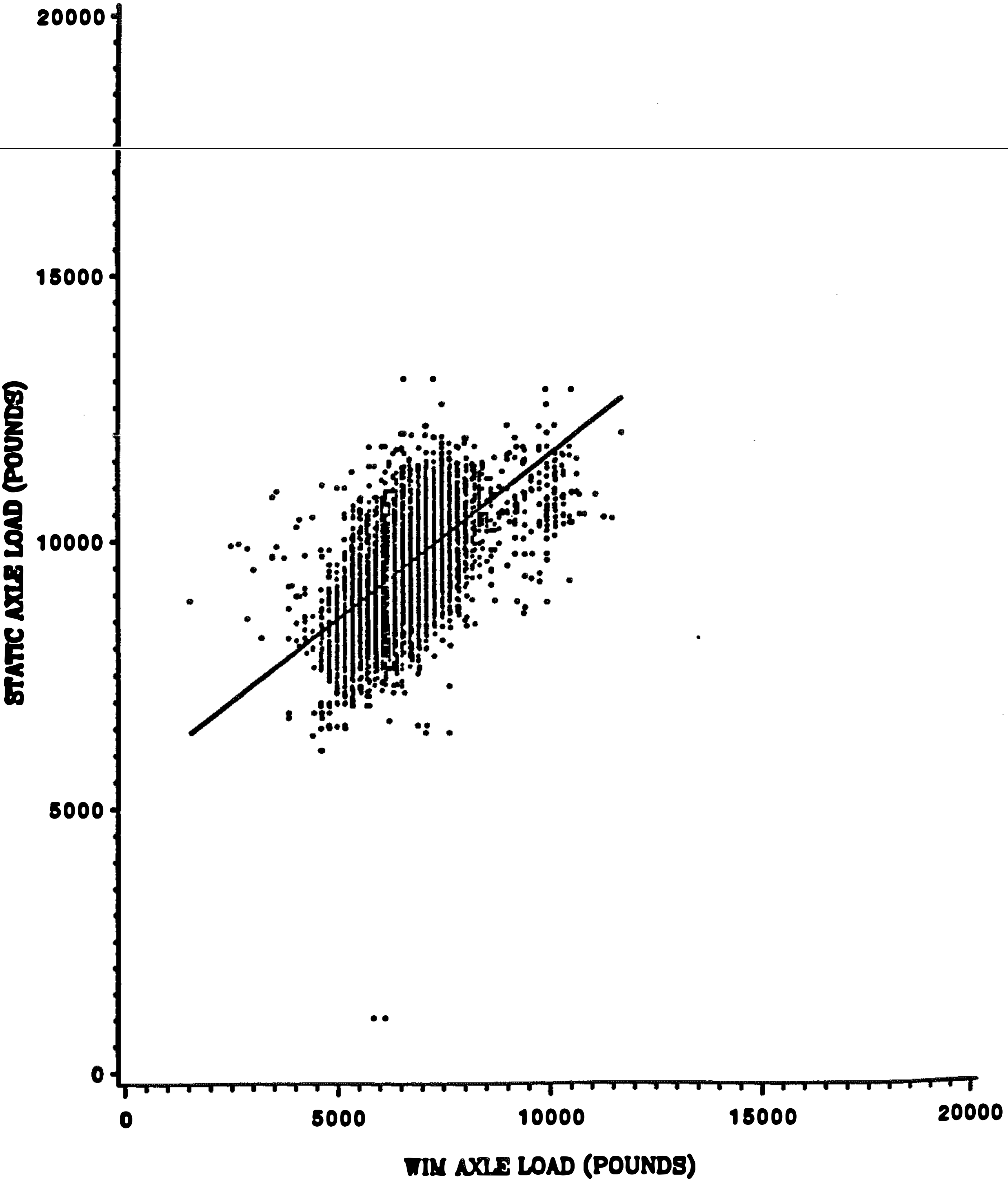

FIGURE C6. RELATION BETWEEN STATIC AND WIM AXLELOADS -- STEERING AXLE, FLEXIBLE PAVEMENT, VEHICLE CLASS NO. 9.

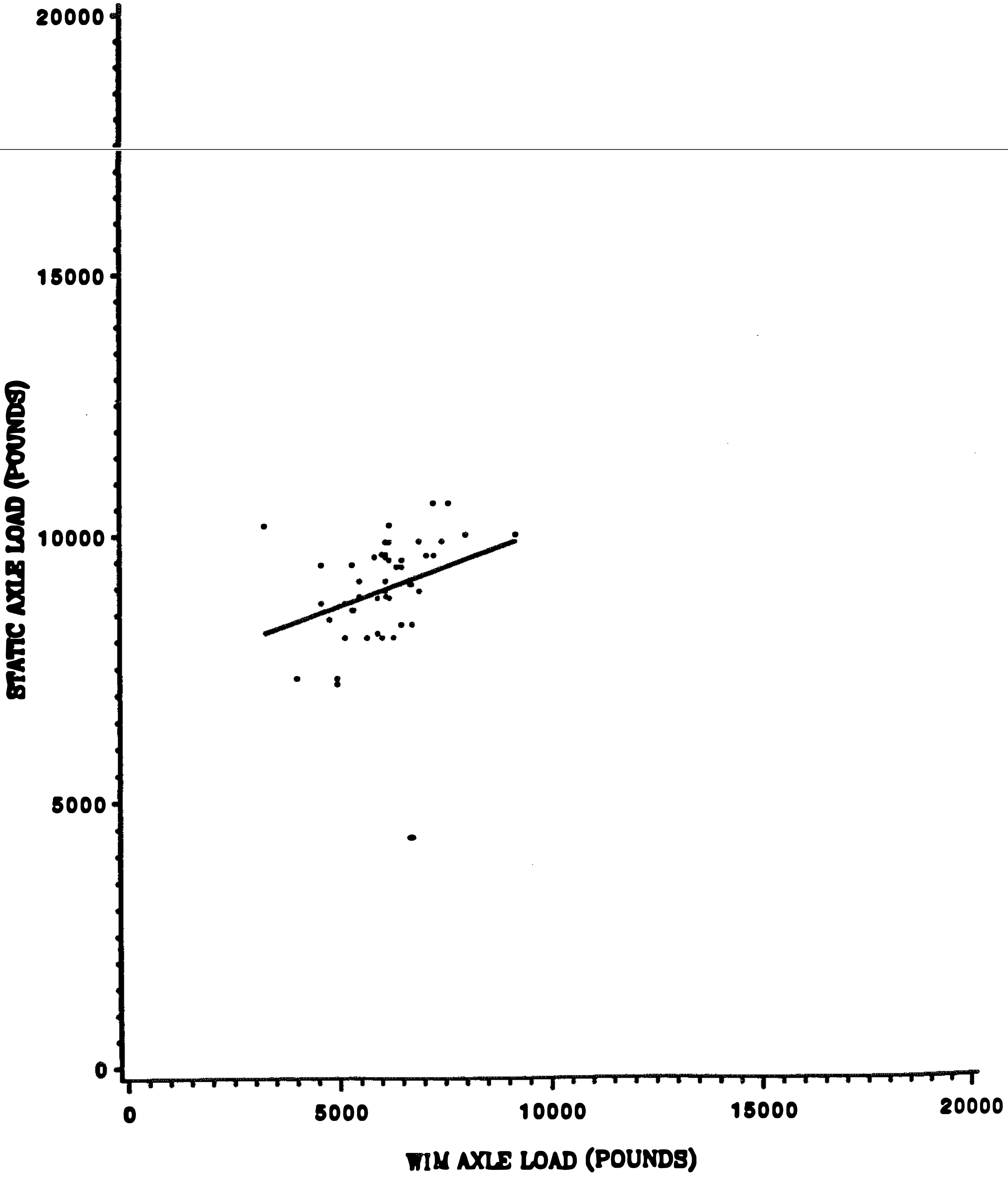

FIGURE C7. RELATION BETWEEN STATIC AND WIM AXLELOADS -- STEERING AXLE, FLEXIBLE PAVEMENT, VEHICLE CLASS NO. 10.

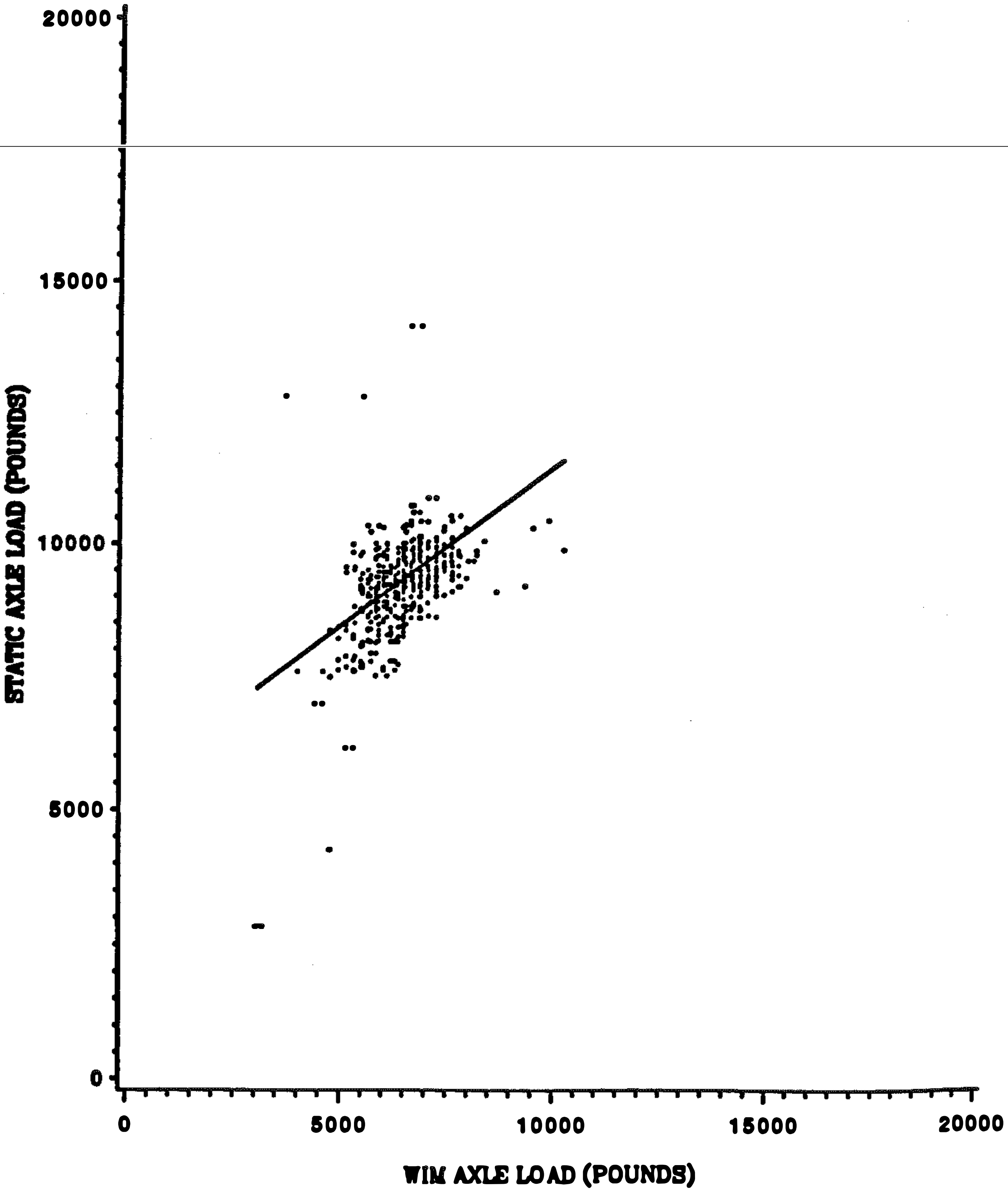

FIGURE C8. RELATION BETWEEN STATIC AND WIM AXLELOADS -- STEERING AXLE, FLEXIBLE PAVEMENT, VEHICLE CLASS NO. 11.

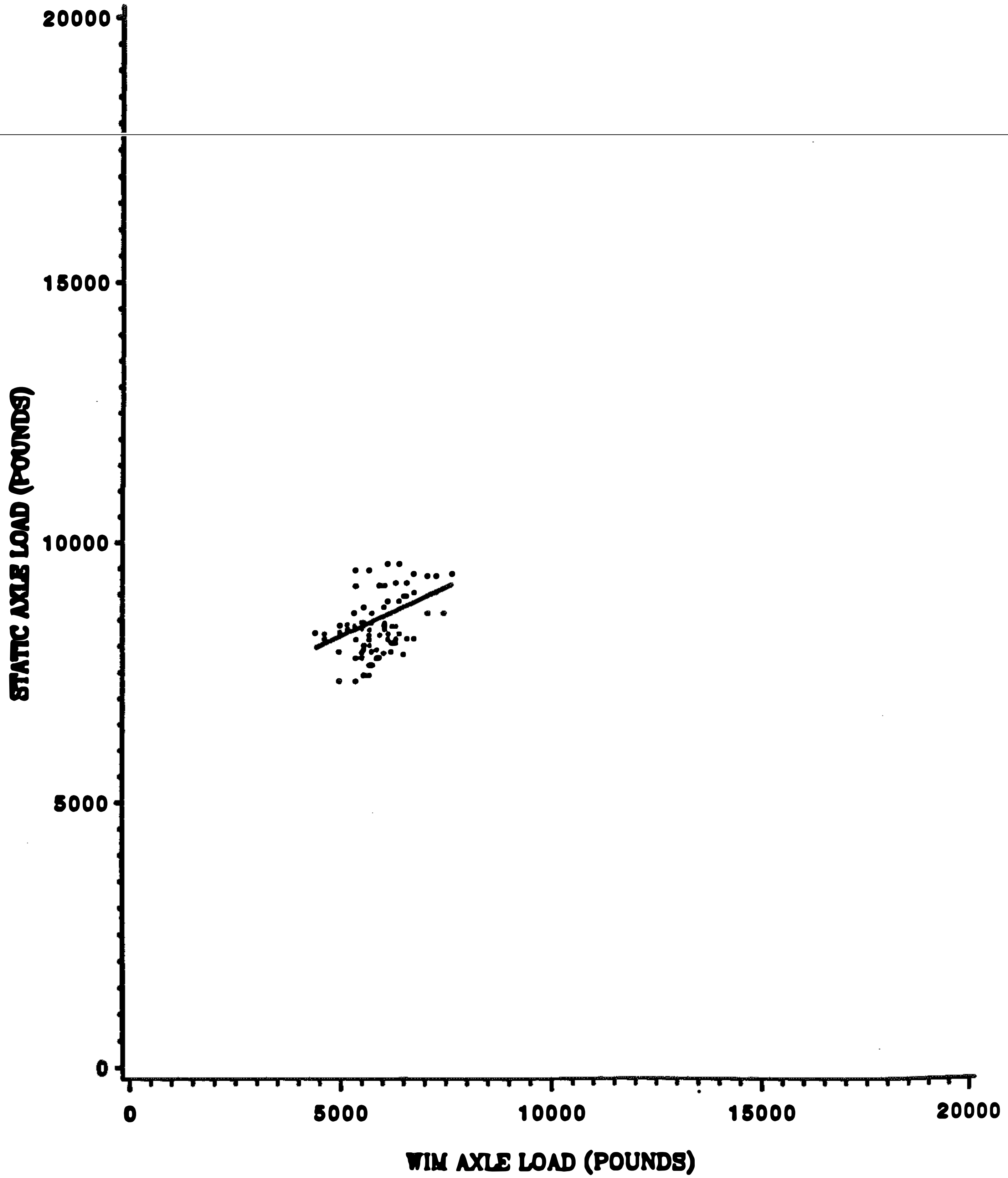

FIGURE C9. RELATION BETWEEN STATIC AND WIM AXLELOADS -- STEERING AXLE, FLEXIBLE PAVEMENT, VEHICLE CLASS NO. 12.

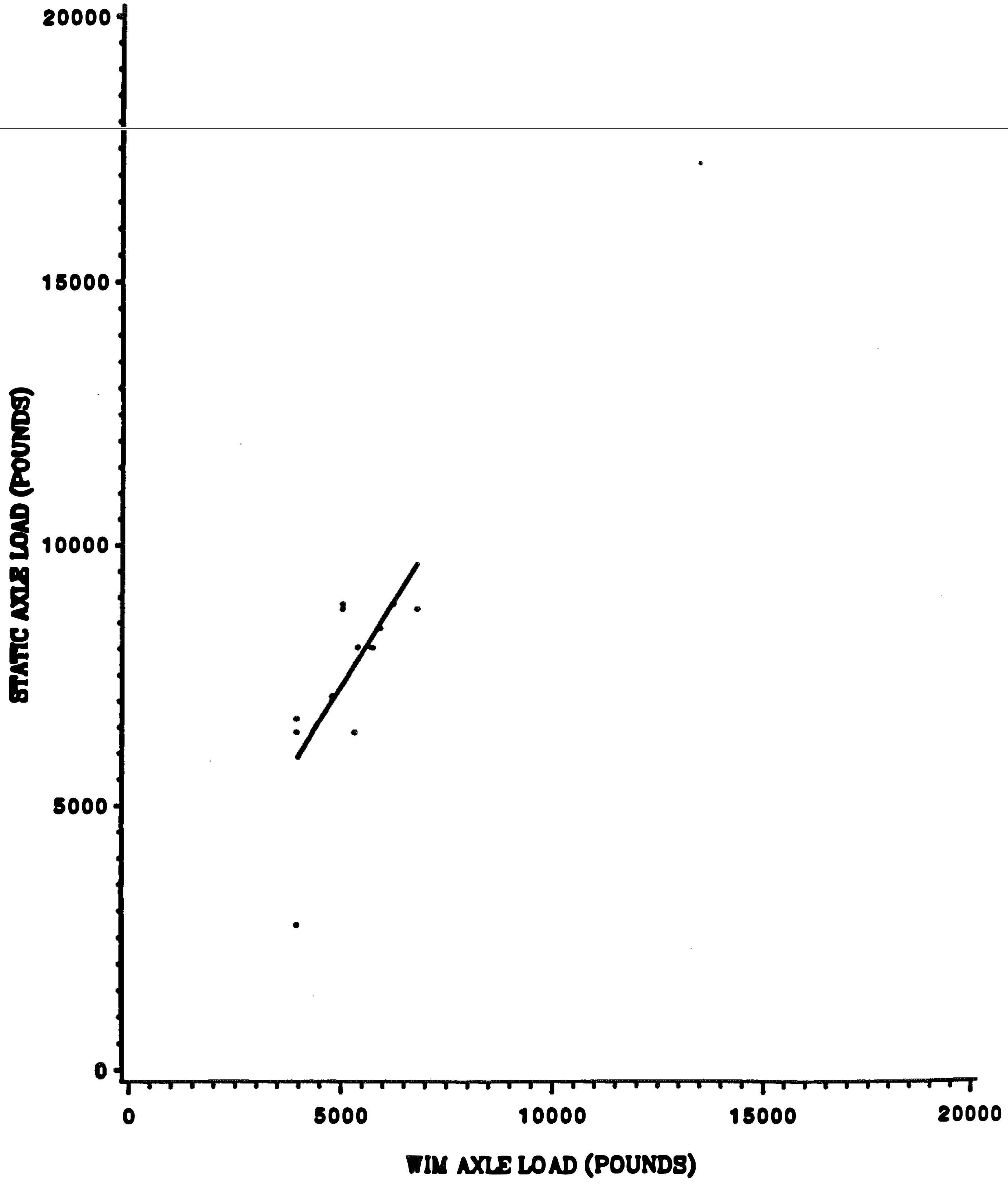

FIGURE C10. RELATION BETWEEN STATIC AND WIM AXLELOADS -- STEERING AXLE, RIGID PAVEMENT, VEHICLE CLASS NO. 4.

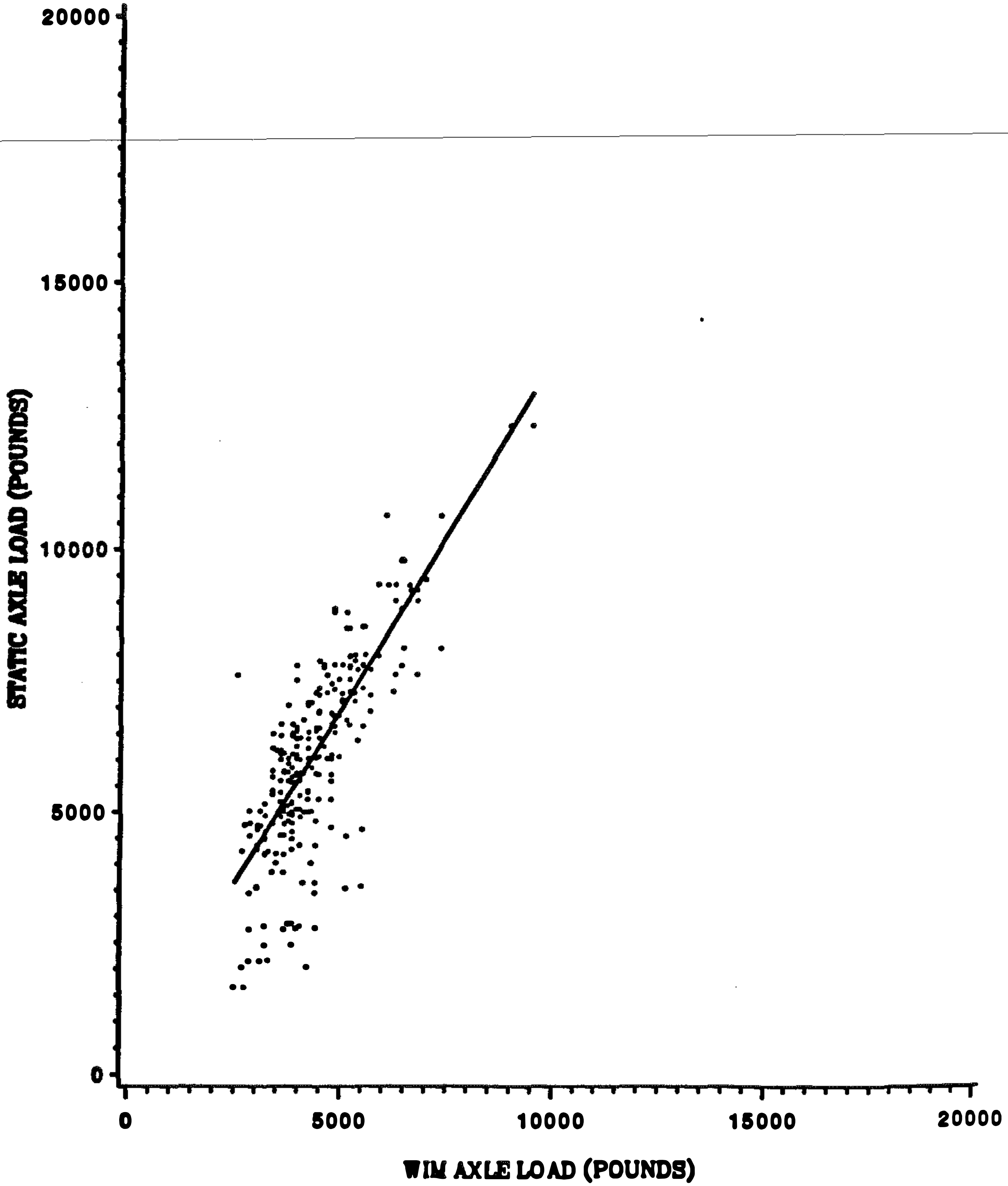

FIGURE C11. RELATION BETWEEN STATIC AND WIM AXLELOADS -- STEERING AXLE, RIGID PAVEMENT, VEHICLE CLASS NO. 5.

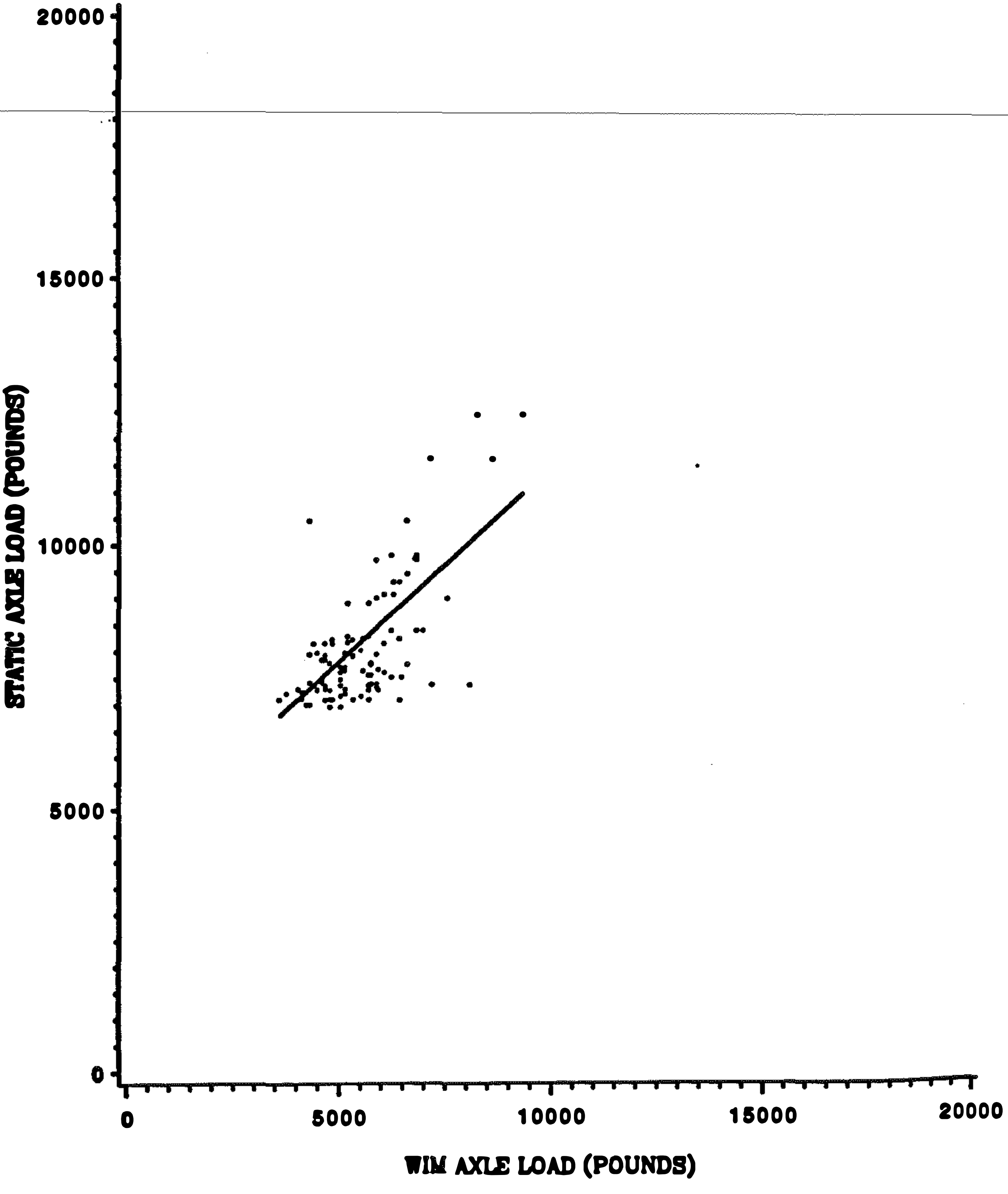

FIGURE C12. RELATION BETWEEN STATIC AND WIM AXLELOADS -- STEERING AXLE, RIGID PAVEMENT, VEHICLE CLASS NO. 6.

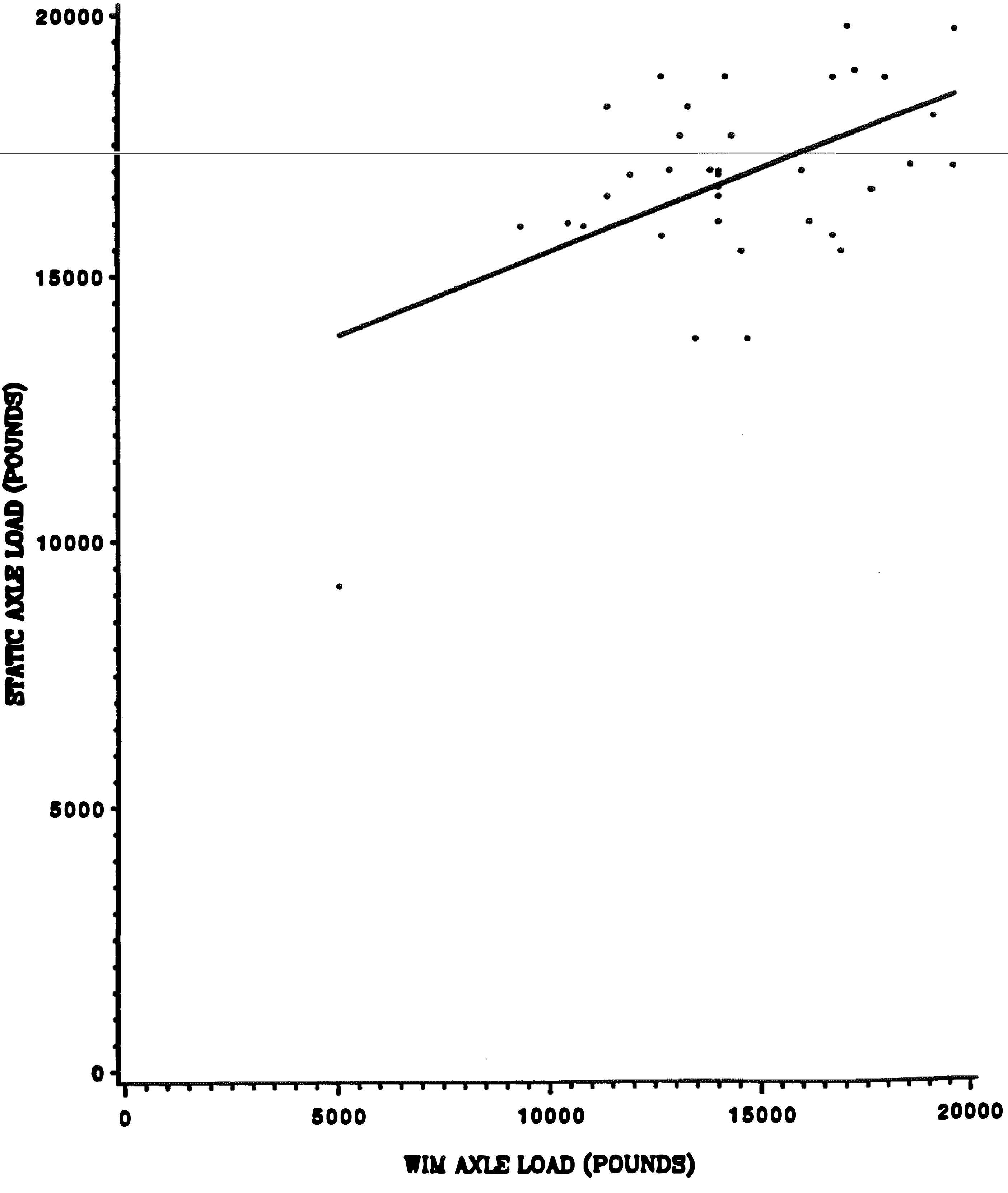

FIGURE C13. RELATION BETWEEN STATIC AND WIM AXLELOADS -- STEERING AXLE, RIGID PAVEMENT, VEHICLE CLASS NO. 7.

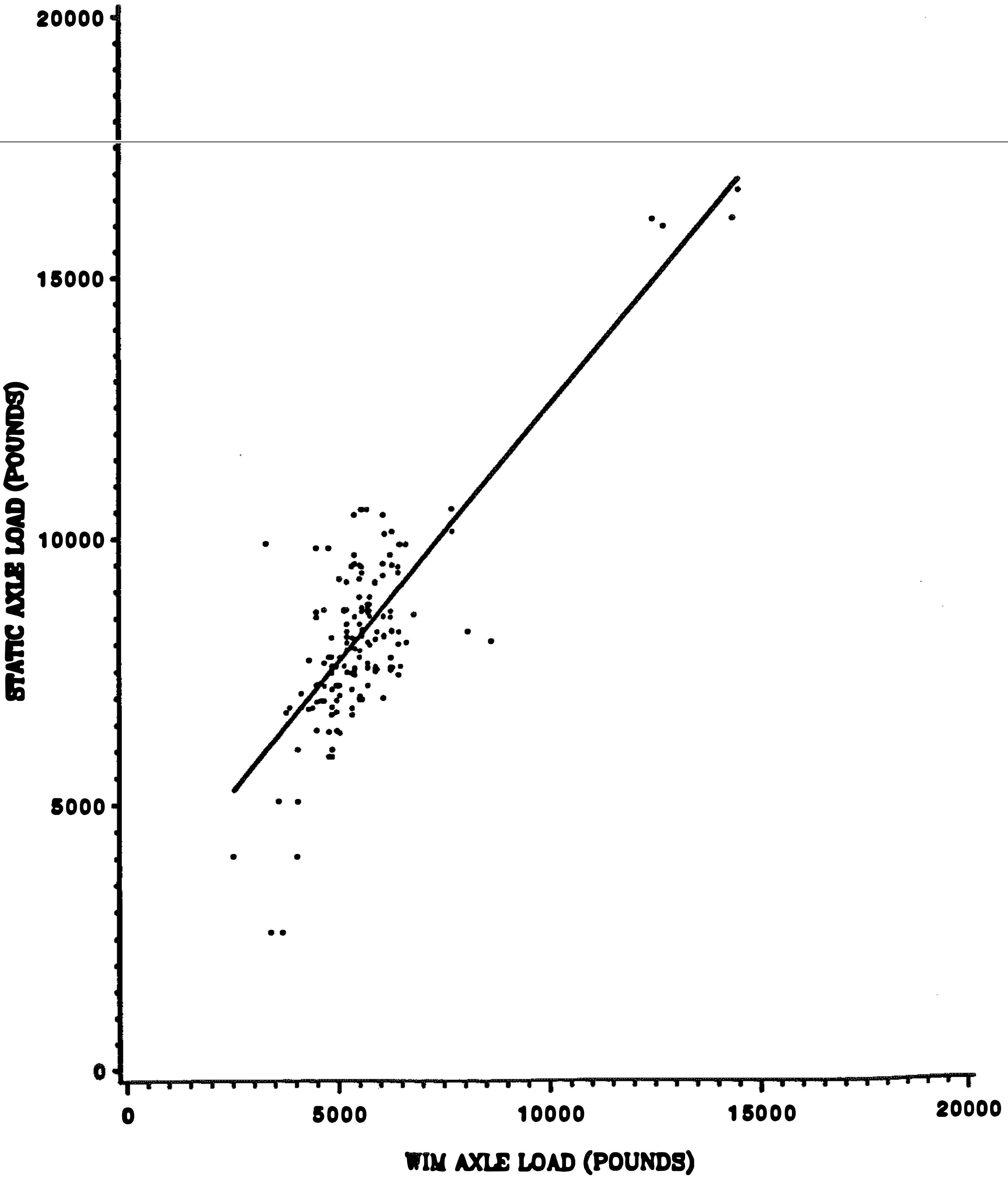

FIGURE C14. RELATION BETWEEN STATIC AND WIM AXLELOADS -- STEERING AXLE, RIGID PAVEMENT, VEHICLE CLASS NO. 8.

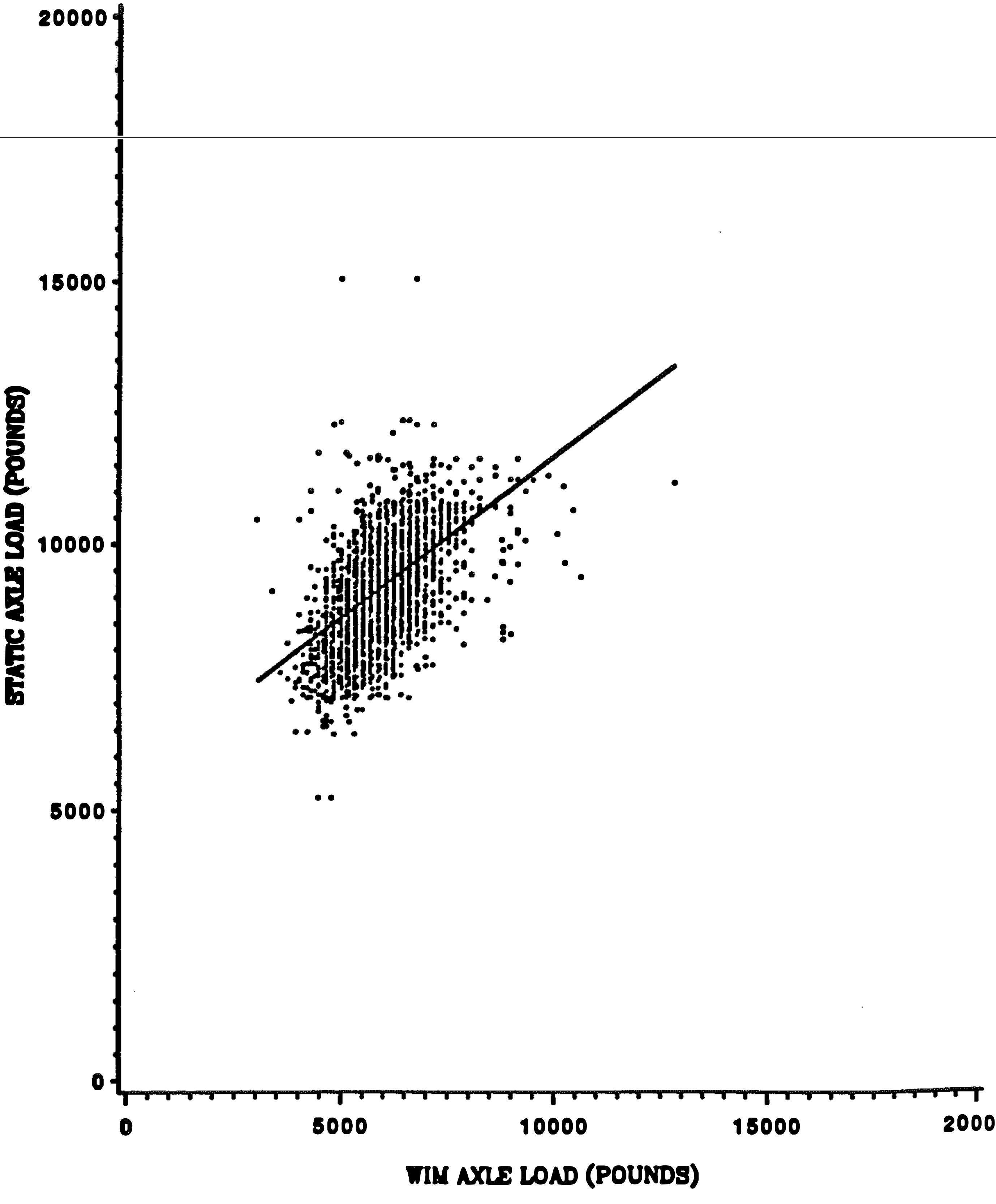

FIGURE C15. RELATION BETWEEN STATIC AND WIM AXLELOADS -- STEERING AXLE, RIGID PAVEMENT, VEHICLE CLASS NO. 9.

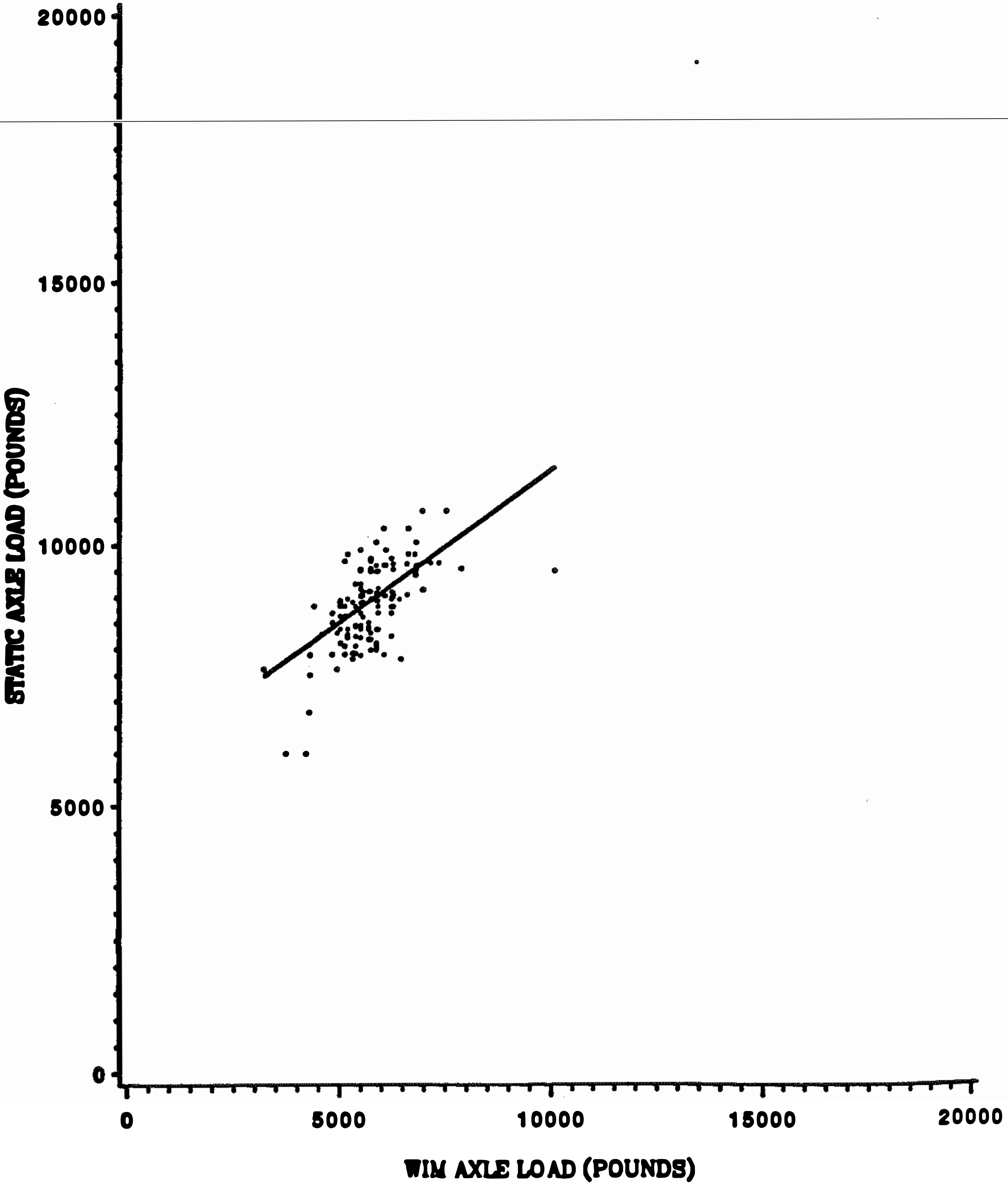

FIGURE C16. RELATION BETWEEN STATIC AND WIM AXLELOADS -- STEERING AXLE, RIGID PAVEMENT, VEHICLE CLASS NO. 10.

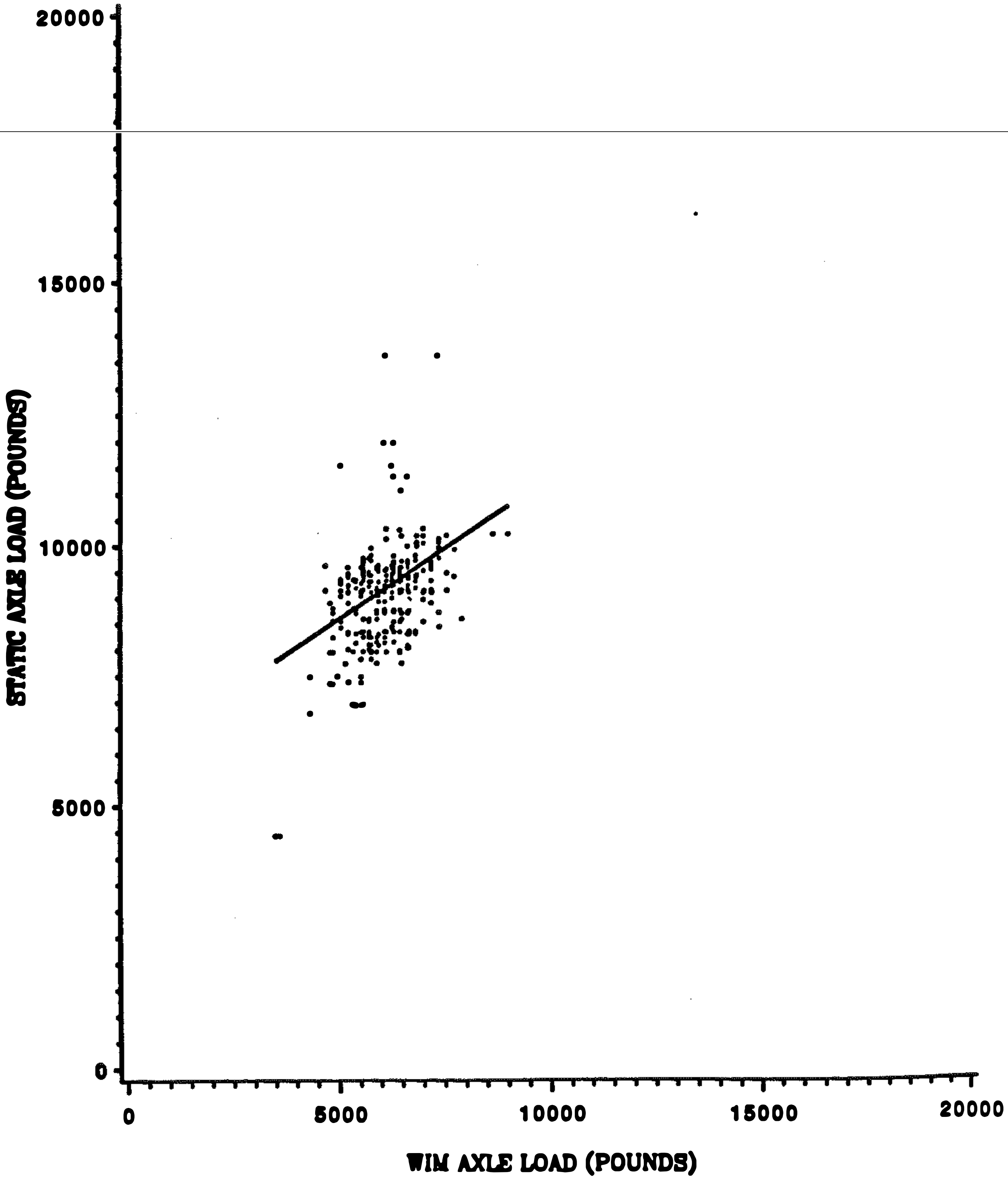

FIGURE C17. RELATION BETWEEN STATIC AND WIM AXLELOADS -- STEERING AXLE, RIGID PAVEMENT, VEHICLE CLASS NO. 11.

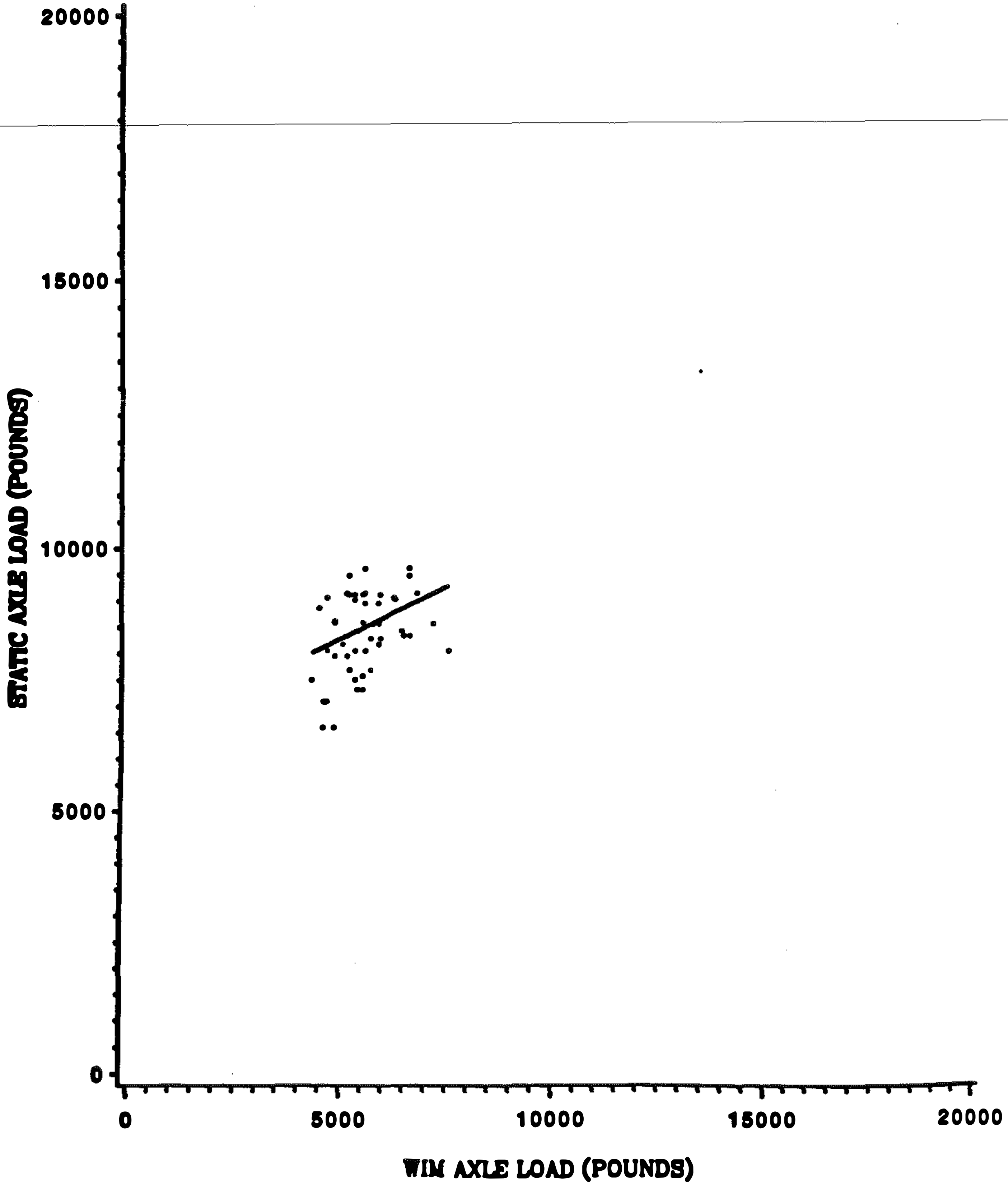

FIGURE C18. RELATION BETWEEN STATIC AND WIM AXLELOADS -- STEERING AXLE, RIGID PAVEMENT, VEHICLE CLASS NO. 12.