Measurement of Wheel Wander Under Live Traffic Conditions

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ABSTRACT: A critical parameter to measure for any type of pavement structural analysis is the precise location of the applied load. Under live traffic conditions the placement is random (termed wheel wander) and is important to characterize since it defines the transverse location and severity of pavement distress. As more test roads are built with embedded instrumentation to support the calibration and implementation of mechanistic-empirical (M-E) pavement design, the load placement relative to the instrumentation must be determined. Also, it is necessary to assess whether the wheel wander under test conditions is representative of open-access facilities. In this research, a lateral-position measurement system, comprised of independent axle sensing strips, was installed at the National Center for Asphalt Technology (NCAT) Test Track to measure wheel wander of the traffic. The Test Track is a 1.7 mile (2.7 kilometer) cooperative research test road trafficked by five tractor-trailers operated by ten drivers over two shifts per day. This paper details the lateral-position measurement system, the installation process, the calibration process and the algorithms to compute lateral offset. Data collected over two trucking shifts are presented, comprised of over 3,000 axle passes, and indicate a normal distribution of wheel wander at the Test Track having a standard deviation of 8.6 in. (21.8 cm), consistent with measurements made at open-access facilities.

KEY WORDS: Wheel wander, accelerated pavement testing, pavement strain.

1 INTRODUCTION

Wheel wander, or the lateral distribution of wheel loads, is a natural phenomenon observed on public-access roadways. Various vehicle types, individual driving habits, wind effects, mechanical alignment of trailers and other factors all contribute to the randomness of wheel wander (Buiter et al., 1989). Further, Blab and Litzka (1995) identified lane width, vehicle speed, existing cross-sectional rut-depth and vehicle width as critical factors in the amount of wander. Figure 1 illustrates an example of a normally-distributed wheel wander pattern collected in Michigan, which is representative of many open-access facilities (Stempihar et al., 2005).

From a pavement design and performance perspective, wheel wander is critical since it dictates where the loads are placed and the frequency with which a point in the pavement is loaded. Further, in the absence of wheel wander, pavement damage is much more severe and premature. This has been observed under heavy-vehicle simulators when wheel wander is removed. It was also observed at the WESTRACK experiment where robotically-driven trucks initially trafficked test sections with little or no wheel wander (Epps et al., 2002). In reality, field studies conducted over a number of years indicate that wheel wander tends to be normally distributed with a standard deviation ranging from 8 to 24 in. (20 to 61 cm) (Buiter et al., 1989; Timm, 1996; Stempihar et al., 2005). The level of variance depends primarily upon the route and the respective lane width (Buiter et al., 1989).

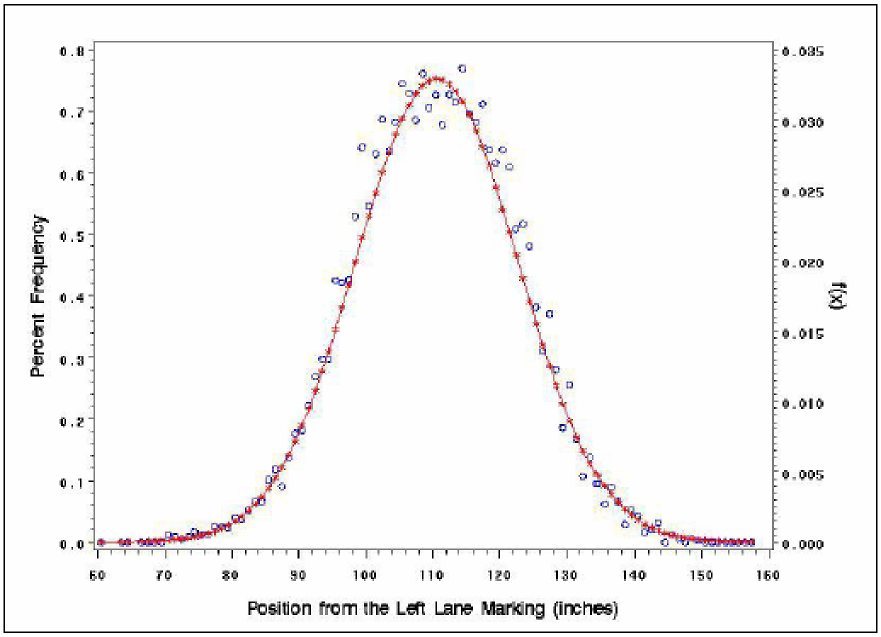


Figure 1: Measured wheel wander in Michigan (Stempihar et al., 2005).

Wheel wander is a critical issue pertaining to the validity of research underway at the National Center for Asphalt Technology (NCAT) Test Track. Since the Test Track is meant to simulate open-access facilities, it is imperative that realistic wheel wander patterns be applied during testing. A number of factors could lead to non-realistic wheel wander at the Test Track. First, the traffic consists of only two types of test vehicles, triple trailers and a standard box trailer, so the randomness of different vehicle types has been effectively reduced. Second, the driver pool consists of ten drivers over two shifts per day, further reducing the natural randomness found on open-access roads. Third, because the Test Track is a closed loop, there is potential that the repetitive environment will cause the trucks to track consistently along the same line.

Another important consideration for the Test Track, and other live traffic pavement testing facilities with embedded instrumentation, is determining the lateral placement of loads relative to the gauges. The Test Track has a number of test sections with strain gauges installed at the bottom of the hot-mix asphalt layer to measure strain under dynamic loading (Timm et al., 2004). There are gauges centered along the outside wheelpath in addition to gauges offset 24 in. (61 cm) to the left and right of the outside wheelpath, respectively. It is critical to understand the wheel wander pattern in relation to the placement of the gauges since the lateral offset will greatly affect the strain response reading on each gauge.

1.1 Objectives

To address the issues described above, the objectives of this study included:

1. Devise a means of accurately measuring the lateral placement of wheel loads.
2. Characterize the wheel wander pattern at the NCAT Test Track and compare it against open-access facilities.
3. Assess the effect of wheel placement on measured pavement response.

1.2 Scope

A lateral positioning system, consisting of axle sensing strips, was assembled and installed at the NCAT Test Track. Calibration studies were conducted to verify the measurements, and five hours of live traffic data were collected and analyzed. Data were also collected from embedded strain gauges in a test section to establish a relationship between strain and lateral offset. This paper describes the system, governing equations, calibration and results of the live testing.

2 LATERAL POSITIONING SYSTEM – GENERAL APPROACH

Though many approaches to measuring wheel wander are available, ranging from precision cameras to Global Positioning Systems (GPS), it was decided to implement a system similar to that used at the Minnesota Road Research Project (Chadbourn et al., 1999). The system consists of three embedded axle sensing strips in a precise geometric arrangement that enable the measurement of lateral wheel position. The sensors are made of a resistive material sensitive to pressure and enclosed in a semi-rigid casing that is impervious to moisture. Under no-load conditions, the resistance of each sensor exceeds 10 MΩ. Upon application of pressure from a passing wheel, the resistance is dramatically reduced to between 2 and 50 kΩ. This system was relatively inexpensive (less than $2000) and was compatible with the existing data acquisition equipment in use at the Test Track (Timm et al., 2004). Also, the system was relatively easy to install, calibrate and execute wheel wander studies.

The key to the lateral position system is the geometric arrangement of the axle sensing strips, shown schematically in Figure 2. In addition to the sensors and pavement markings, the figure indicates a particular wheel track, at a lateral offset of y′. Further, Figure 2 shows the corresponding time stamps (t_1, t_2 and t_3) when each sensor records the passage of the wheel. Using the precisely measured geometry of the sensor arrangement, in addition to the accurately measured time stamps, the lateral offset of the wheel is determined by (Timm and Priest, 2005):

$$y' = \tan\alpha\left[\frac{x}{t_3 - t_1}\cdot(t_2 - t_1) - f\right] \quad (1)$$

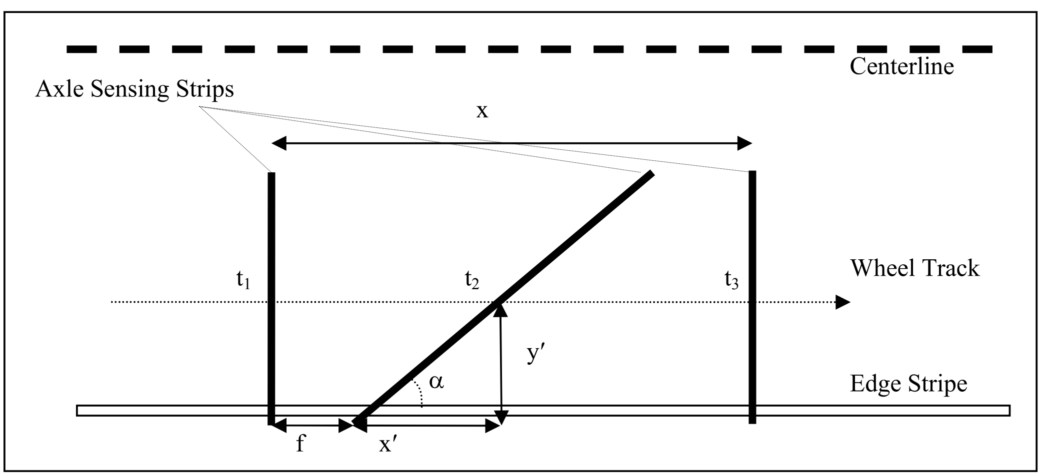


Figure 2: Arrangement of axle sensing strips.

3 SENSOR INSTALLATION AND CALIBRATION

The installation procedure consisted of precisely locating the sensor locations using stringlines. The first and third sensor (Figure 2) were spaced 96 in. (244 cm) apart. The diagonal sensor was centered between the two at an angle of 46°. Slots were cut using a concrete saw to accommodate the sensors and cleaned with brushes to remove debris. A sand-epoxy mixture, provided by the manufacturer, was used to anchor the sensors in each slot, and the sensor cables were connected into a roadside box for data acquisition. Figure 3 illustrates the completed installation. Further installation details have been documented elsewhere (IRD, 2003; Timm and Priest, 2005).

Figure 3: Final sensor installation.

The system required a simple calibration test to check the accuracy of the installation, data collection and calculation procedures. To accomplish this task, five readings were taken with a passenger car. A line of fine sand was placed parallel to and just past the third sensor so that the offset distance, from the edgestripe to the center of the tire, could be physically measured by the marks in the sand. These measurements were then compared to the computed offset, and the results are presented in Figure 4. It was concluded that the system is very accurate and is a nearly perfect representation of physical measurements as indicated by the nearly 1:1 slope and high coefficient of determination (R^2).

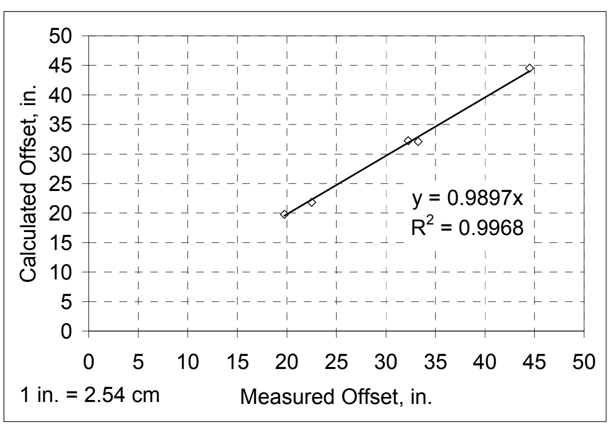
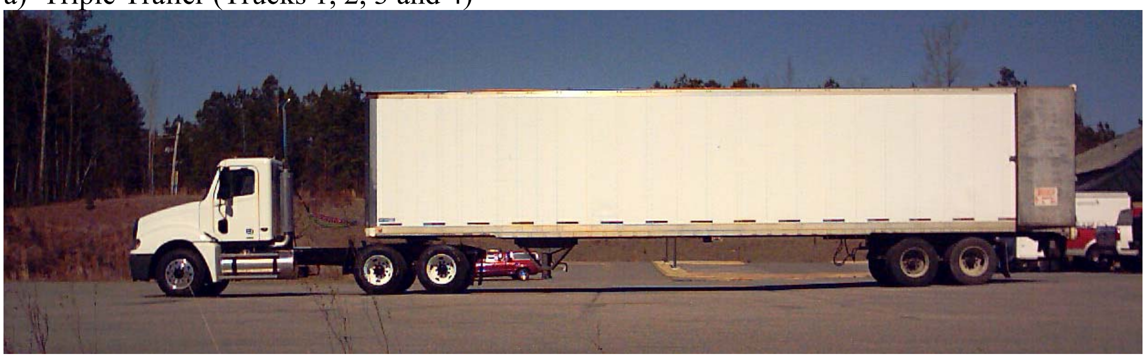


Figure 4: Calibration data.

4 WHEEL WANDER INVESTIGATION

After the system had been installed, checked and calibrated, data were collected over a 2.5 hour period from both a morning and afternoon shift on July 21, 2004. Two truck types were included in the study; a triple-trailer configuration (8 axles/truck) and a standard box-trailer configuration (5 axles/truck). Figures 5 (a) and (b) show the two test vehicles which were operated at 45 mph (72 kmh) during the tests. The data were examined from three perspectives. First, all axles were considered together to determine the overall wheel wander pattern. Second, the axles were identified separately on each of the individual vehicles (i.e, steer axle, second axle, third axle, etc.). Finally, the data were used with measured strain data to determine the effect of offset on strain response.

a) Triple Trailer (Trucks 1, 2, 3 and 4)



b) Box Trailer (Truck 5)

Figure 5: Test vehicles.

4.1 Wheel Wander of All Axles

Histograms were generated from the wheel position data and are pictured in Figure 6. The data are divided into the morning and afternoon shift, with the average and standard deviation of each distribution noted in the figure. In total, the two histograms represent 3,410 axle hits, and it can be concluded that both distributions follow an approximately normal distribution, which is consistent with other wheel wander studies (Buiter et al., 1989; Stempihar et al., 2005).

When comparing the standard deviation measured at the Test Track to other studies (Buiter et al., 1989; Timm, 1996; Stempihar et al., 2005), it is on the lower end of the 8 – 24 in. (20-61 cm) scale. However, considering the limited number of vehicles and drivers at the Test Track, it can be concluded that the wheel wander reasonably approximates that of open-access facilities.

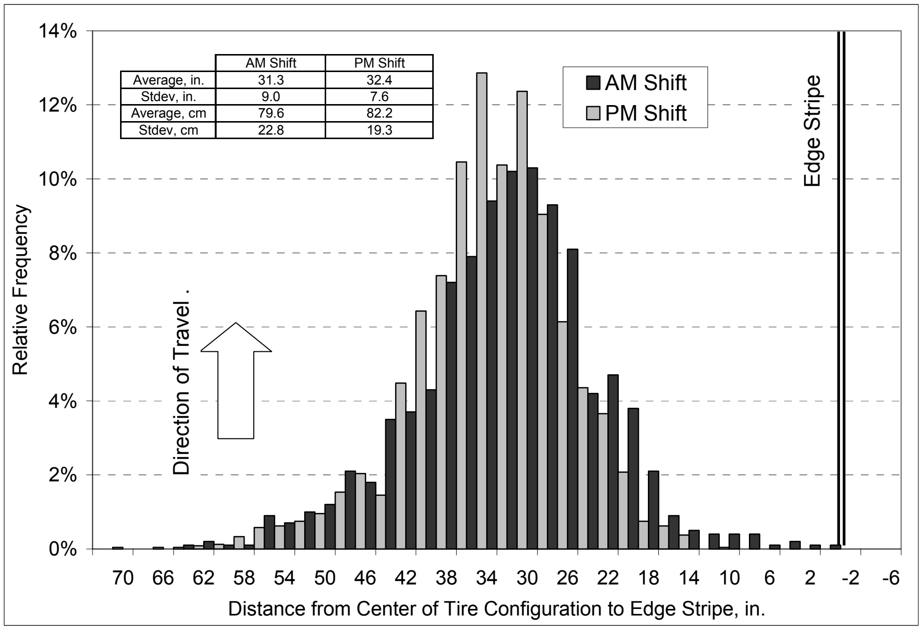


Figure 6: Statistical summary of wheel wander data.

4.2 Wheel Wander by Truck and Axle

The data summarized in Figure 6 were further divided by truck and axle number on each truck. Figures 7 and 8 indicate the average offset from the edge stripe, in addition to the variability of the wheel placement around the average, for each axle on each truck in the morning and afternoon shifts, respectively. For example, according to Figure 7, the average offset of the steer axle on Truck 1 is approximately 24 inches (61 cm) with about 95% (two standard deviations) of the offsets within 20 inches (51 cm) of the average.

Figures 7 and 8 indicate that the drivers are very consistent in the placement of the steer axle. The average offset, between all drivers, was between 20 and 30 inches (51 and 76 cm). However, what does vary greatly is the tracking of the trailing axles on each vehicle. For example, the trailing axles on Truck 1 gradually track closer to the edge stripe. Conversely, the trailing axles on Truck 4 are generally consistent along the length of the trailer train. It must also be noted that regardless of the driver, the trailer trains tend to track similarly between the morning and afternoon shifts. This is logical since the tracking of the trailing axles is primarily a function of the trailer alignment rather than the driving pattern.

Figures 7 and 8 also show the placement of the embedded strain gauges relative to the edgestripe and the lateral offset of each axle. For example, the axles on Truck 1 tend to travel primarily between the gauges centered on the wheelpath and gauges offset 24 in. (61 cm) to the right of the wheelpath center. The effect of the relative offset between axle placement and strain response is explored below.

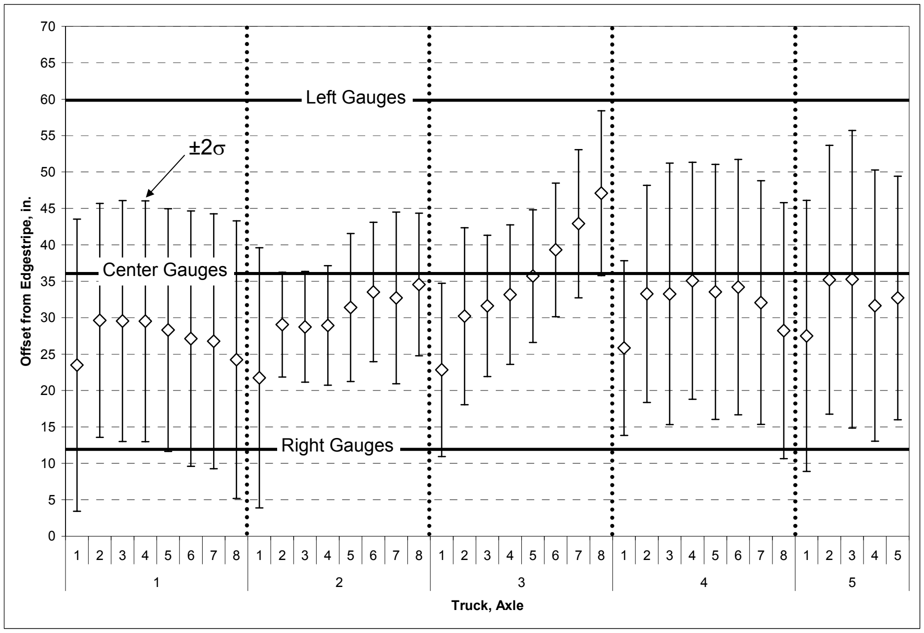


Figure 7: Wheel wander – AM shift.

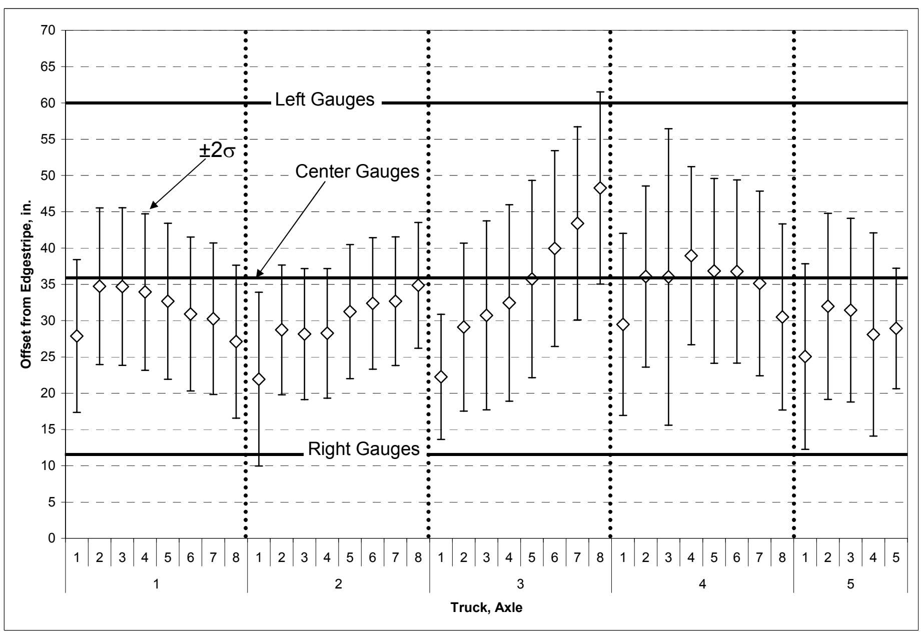


Figure 8: Wheel wander - PM shift.

4.3 Effect of Wheel Wander on Measured Strain

It has been observed that despite identically loaded single axles (20 kip (89 kN) per axle), the measured strain tends to increase or decrease through a given truck pass as demonstrated in Figure 9. The figure shows three strain traces from gauges oriented with traffic at each lateral offset, with a line connecting the peaks of the trailing single axles (axles 4 through 8). The measured strain from the right gauge clearly decreases with each axle, the center gauge reading increases with each single axle while the left gauge increases only slightly.

Figure 9: Dynamic strain traces.

While the effect of wheel wander on measured strain response is evident from a qualitative perspective in Figure 9, there is a need to quantify this effect to fully understand and assess the relationship. To accomplish this, dynamic strain data from an instrumented test section were plotted against the measured average offset using the lateral positioning system. The test section consisted of 7 in. (18 cm) of HMA over 6 in. (15 cm) of unbound granular base on subgrade soil. The embedded strain gauges in the test section were approximately 800 ft (244 m) from the lateral positioning system. Though this is a considerable distance, it was hypothesized that the wheel wander measured at the location of the lateral positioning system was representative throughout the test sections in the straightaway. Also, this study did not attempt to link individual wheel pass offsets and strain response, but rather average responses over multiple readings.

Dynamic strain measurements were obtained for three passes of Trucks 1 – 4 during the morning shift. The trailing single axles (axles 4 – 8), which are loaded equally, were used in the analysis to isolate the effect of strain versus offset. The average strain per axle for each gauge was determined over the three passes. The offset between each gauge location and average lateral wheel offset was determined. Figure 10 illustrates the effect of average wheel placement on measured strain response for each truck. Clearly, there is a characteristic relationship as shown by the regression models. Trucks 1, 2 and 4 all exhibited similar linear trends and R^2 values. Truck 3, however, exhibited much different behavior. The reason for this is not immediately evident, but it is interesting to note that the wheel wander shown for this truck (Figure 7) is clearly different from the other four triple-trailer sets where each of the trailing axles tracks farther away from the edgestripe. Further investigation of this trailer train is certainly warranted.

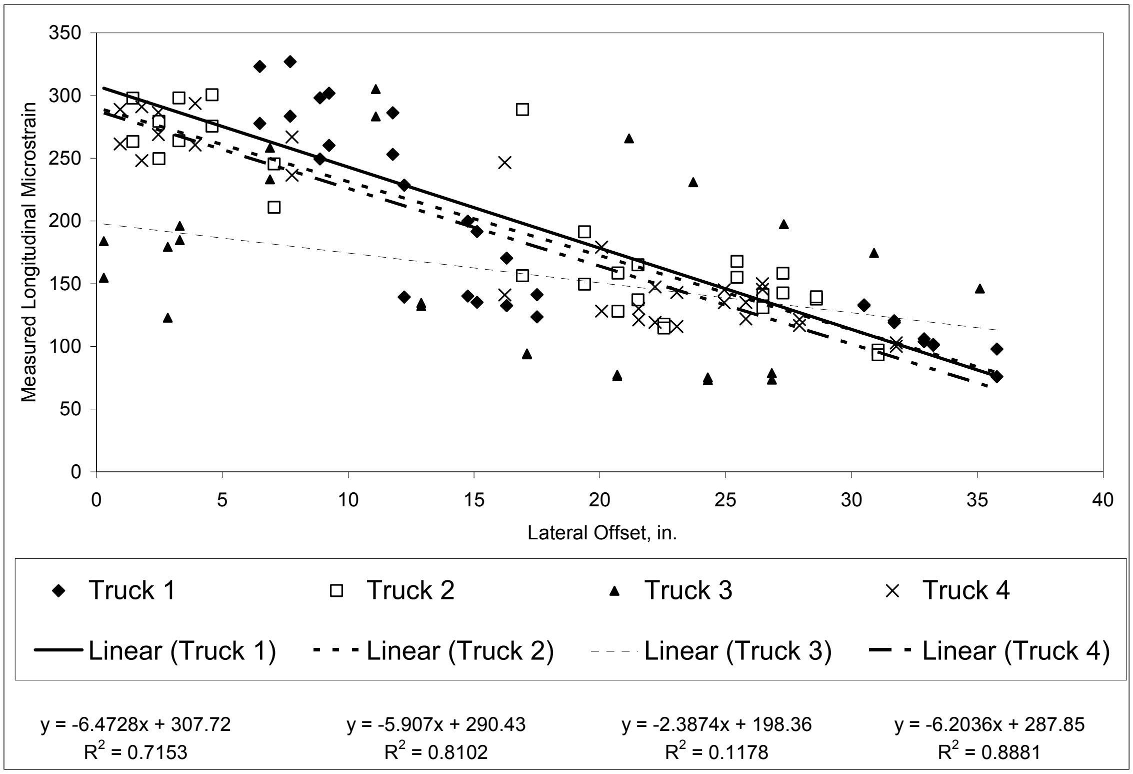


Figure 10: Effect of lateral offset on strain response.

The information in Figure 10 is critical to the proper interpretation of the live strain data collected as part of the long-term pavement study at the Test Track. Since the test sections are subjected to traffic with wheel wander, it is impossible to always have a "direct hit" (i.e., zero offset between load and gauge) on the embedded instrumentation. The methods outlined above, with the results plotted in Figure 10, may be used to estimate the maximum pavement strain despite not having "direct hits" on the gauges in every truck pass.

5 CONCLUSIONS AND RECOMMENDATIONS

Wheel wander is an important parameter to measure and characterize since it has a direct impact on pavement response and performance. Based on the findings of this study, the following conclusions and recommendations can be made:

1. The lateral-positioning system used at the NCAT Test Track is a simple, yet effective and accurate means of measuring lateral offset of wheel loads. This system could also be installed on open-access facilities.
2. The disadvantage of the lateral positioning system at the NCAT Test Track is that the location is permanent. Therefore, results from the sensors must be extrapolated to other test sections. Other systems should be considered that can be moved between sections.
3. The measured wheel wander at the Test Track is comparable to that of open-access facilities, though its variation tends toward the lower end of the scale reported from the literature.
4. Each vehicle and driver has a unique wheel wander pattern which should be considered in pavement response data collection and processing.

5. Wheel wander data are critical in estimating the maximum pavement response under dynamic traffic loads. The methods described in this paper can be applied to other sections at the Test Track and may also be applied to other full-scale testing facilities.

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