ASSESSING APPROPRIATE LOADING CONFIGURATION IN ACCELERATED PAVEMENT TESTING

Thomas Byron [(1)], Bouzid Choubane [(1)], and Mang Tia [(2)]

[(1)] Florida Dept. of Transportation
Materials Research Park
5007 N.E. 39th Avenue
Gainesville, FL 32609
Phone: (352) 955-6302
Fax: (352) 955-6345
E-mail: tom.byron@dot.state.fl.us
E-mail: bouzid.choubane@dot.state.fl.us

[(2)] Civil and Coastal Engineering Dept.
University of Florida
Gainesville, FL 32611
Phone: (352) 392-9537 x1463
Fax: (352) 392-1660
E-mail: mtia@ce.ufl.edu

Paper submitted for presentation at the 2003 Transportation Research Board Annual Meeting and subsequent publication in the Transportation Research Record

ABSTRACT

The need for faster and more practical evaluation methods under closely simulated in-service conditions prompted several transportation agencies, including the Florida Department of Transportation (FDOT), to consider accelerated pavement testing (APT). APT is generally defined as a controlled application of a realistic wheel loading to a pavement system simulating long-term, in-service loading conditions. This allows the monitoring of a pavement system's performance and response to accumulation of load damage within a much shorter time frame. APT can produce early, reliable and beneficial results.

Accelerated loading may be performed to include a number of possible loading configurations (uni- or bi-directional loading, with or without wheel wander, different wheel wander incremental steps, etc.). However, in order to obtain meaningful results, it is essential to determine a realistic APT simulation of actual in-service loading. Currently, uni-directional loading, without any wheel wander, is generally used, particularly for rut evaluation. It is thought that such a loading configuration would be more efficient for accelerated pavement testing purposes. This may be true in terms of efficiency, but its effectiveness and appropriateness to simulate actual in-service truck loading still remain unclear. Consequently, the present study was initiated primarily to assess and determined a more realistic APT simulation of actual in-service loading conditions.

This paper presents a description of the testing program, the data collection effort and the subsequent analyses and findings.

INTRODUCTION

The evaluation and validation of new/emerging pavement technologies and innovative concepts require assessing their in-service long-term performance. In-service assessment requires the consideration of the interaction between traffic loading, materials properties, and environmental effects. The primary disadvantage of such an evaluation approach is the extensive time period required to obtain potentially meaningful results. Additionally, it is often difficult, impractical, and/or expensive to obtain or account for all the data and information required from in-service experimental set ups.

The need for faster and more practical evaluation methods under closely simulated in-service conditions prompted the Florida Department of Transportation (FDOT) to consider accelerated pavement testing (APT). APT is generally defined as a controlled application of a realistic wheel loading to a pavement system simulating long-term, in-service loading conditions. This allows the monitoring of a pavement system's performance and response to accumulation of damage within a much shorter time frame. APT can produce early, reliable and beneficial results while improving pavement technology and understanding/prediction of pavement systems performance.

BACKGROUND

Florida's APT Facility

Florida's Accelerated Pavement Testing and Research program is housed within the new State Materials Research Park in Gainesville. The testing site consists of 8 linear test tracks with each test track measuring 150 feet long and 12 feet wide. Two additional test tracks were designed with water table control capabilities within the supporting base and subgrade layers. The accelerated loading is performed using a Heavy Vehicle Simulator (HVS), Mark IV model. The HVS is electrically powered (using external electric power source or electricity from an on-board diesel generator), fully automated, and mobile. The HVS functionality has recently been enhanced to include automated laser profiling and test track temperature control capabilities.

HVS Loading Capabilities

HVS can apply wheel loads between 7 and 45 kips (using dual or super-single tires) along a 30-foot test strip within any given test track. The effective test segment within this test span is approximately 20 feet in length. The remaining 5 feet, at either end of the test strip, allows the load wheel to reach programmed parameters controlling load and speed levels. Depending on the loading method, the wheel may be loading and accelerating at one end while unloading and decelerating at the other. These five-foot sections are referred to as the acceleration/deceleration zones. A chain-driven carriage system provides for uni- or bi-directional load application with or without wander to the test track.

In the uni-directional testing mode, the wheel gets loaded at the start of an acceleration/ deceleration zone, and is then accelerated until it reaches the pre-set parameters within that zone length (5 feet). The wheel travels at those set parameters along the testing path (20 feet) of the track. Thereafter, it is unloaded and decelerated within the other acceleration/deceleration zone. At this point, the machine picks up and carries the load wheel off the pavement back to the beginning of the test strip for another pass. This motion is fluid and continuous. As a result, the test strip gets one loaded pass in one direction. The HVS can apply approximately 14,500-loaded uni-directional passes during a normal 24-hour operation.

In the bi-directional testing mode, the HVS wheel is in constant contact with the pavement surface. Thus, the wheel simply travels back and forth on the test track (including acceleration/deceleration zones) under a loaded condition. Since the load wheel remains loaded in both directions, one round trip is in essence two loaded passes. Therefore, during a normal 24-hour operations, the HVS can apply approximately 29,000-loaded bi-directional passes.

In both uni- or bi-directional testing modes, wheel wander is also an option. With the wheel wander option, the HVS has the capability to apply a load across a centerline width of up to 30 inches after a full loading cycle. When wander is considered, the actual loaded footprint width on the test track is the programmed wander plus the loading tire width. For instance, using a 12-inch wide super-single, specifying (or programming) zero or 30-inch wander will respectively result in a 12- or 42-inch wide footprint on the pavement. Additionally, the increments (or steps) of wander per wheel pass are pre-set and adjustable. This provides for the capability to adjust the number of passes needed to produce a given wander. For example, in a uni-directional loading, a specified 4-inch wander in two-inch increment will be achieved in a cycle of three wheel passes (0, 2, then 4 inches), whereas the same amount of wander (4 inches) in one-inch increment will require five passes to make a full cycle (0, 1, 2, 3, and 4 inches) of wheel loading.

Thus, when using an HVS in an APT experiment, several loading configurations are possible. A number of current APT programs specify the use of uni-directional loading with no wander, particularly for rut evaluation. It was thought that such a loading configuration would be more efficient for accelerated pavement testing purposes. This may be true in terms of efficiency, but its effectiveness and appropriateness to simulate actual in-service truck loading still remain unclear. The present study was, therefore, initiated primarily to assess and determined a more realistic APT simulation of actual in-service loading configurations.

Initial Experiment

The first experiment in Florida's APT program was initially designed to address the effects of polymer modifiers on the performance of fine-graded Superpave mixes. One mix included a virgin binder meeting the requirements of PG 67-22, while the other contained a polymer-modified binder meeting those of PG 76-22. Both respective mixes contained the same effective binder content, aggregate components and gradation. The mixes were designed for 10-30 million ESALs, using the standard Superpave mix design methodology. This required that all volumetric properties, aggregate consensus properties, and moisture susceptibility meet the Superpave criteria.

The respective Superpave mixes were placed in two, two-inch lifts to construct seven distinct test tracks (or lanes) while complying with all the standard FDOT construction, materials, and in-place (as constructed) specifications and methods. The supporting layers consist of a 10.5-inch limerock base over a 12-inch limerock stabilized subgrade. During placement of all these layers (both asphalt and supporting layers), all standard FDOT density requirements and acceptance criteria were applicable. A substantial array of thermocouples was placed during construction to allow for temperature monitoring at the asphalt/base interface and at a 2-inch depth in the asphalt. Test track surface thermocouples were mounted after construction. Each track was subsequently divided into three replicate testing sections for a total of 21 possible test sections. The intent of these three replicate sections within each track was to allow for a statistically sound experiment design.

As previously described, the HVS allows for a number of possible loading combinations. Therefore, it was deemed essential, during the planning phase of the above study, to first determine a realistic APT simulation protocol in order to obtain meaningful results. To this end, several test sections were subsequently solely dedicated to conduct an assessment of various loading configurations. The findings of this assessment are summarized herein. One has to note that the APT loading configuration appropriateness was addressed to consider rutting performance only. In addition, the load applied on all test sections was through a super-single tire loaded to 9000 lbs.

LOADING CONFIGURATION ASSESSMENT

Uni- vs. Bi-Directional Loading

A comparison of the respective effects of both loading directions (uni- and bi-directions) without wheel wander was first conducted. Intuitively, one would expect different pavement performance under these two testing conditions. Respective ruts resulting from these two APT loading conditions were manually measured using a straight edge laid transversely across the rut footprint as shown in Figure 1. Daily measurements were taken at five fixed locations along each test track section for each predetermined number of load passes. These five measurements were then averaged to determine a single rut value for a corresponding number of loaded passes. Measurements were taken at the deepest level, not at the top of the tread pattern.

As illustrated in Figure 2, the subsequent monitoring indicated that the rut developed substantially faster in the uni-directional mode. Over the course of a 100,000-pass comparison, the uni-directional loading caused the rut to develop at a rate of approximately 65 percent greater than that of the bi-directional loading when analyzed on a per-pass basis. Thus, every loaded pass in the uni-directional mode induced approximately 65 percent more rut than a loaded pass in the bi-directional mode. During the bi-directional testing the average high temperature measured at a 2-inch depth in the pavement was 32.1° C with an average low of 20.4° C. During the uni-directional testing, the temperature monitoring indicated an average high of 29.7° C and an average low of 19.0° C. Therefore, although the temperatures were close, the uni-directional loading caused a significantly greater rate of rutting while at a slightly lower temperature. One could hypothesize that the bi-directional mode resulted in relatively lower rutting rate in this case because its loading was applied in a more "kneading"-like fashion, thus relatively strengthening the internal mix structure. Considering that this kneading action is not actually observed on in-service pavements, uni-directional testing would seem to most closely simulate the loading directional effects of real-world traffic.

Rut profiles also developed differently. In the bi-directional mode, the tire never leaves the pavement surface. Thus, for the "no wheel wander" case, any given point on the tire hits the exact same spot on the asphalt surface with every pass. As a result, the rut profile was simply the tire tread pattern pressed into the asphalt. In the uni-directional mode, however, the tire leaves the ground after each pass and will continue to spin so that there is variability in how the tire tread contacts the pavement. The uni-directional rut profile developed as a series of longitudinally parallel high and low "lines" along the rut footprint seemingly corresponding to the general tire tread pattern. These observations are shown in Figure 3. Additionally, there were distinct visual cues that the respective pavement-tire interactions were also different. During the uni-directional mode of testing, a deposit rapidly built up where the wheel touched down at the beginning of each pass. A photographic illustration of such a build up removed from the track is given in Figure 4. Meanwhile, the pavement aggregate in the rut footprint looked worn as if "scrubbed clean". It was initially thought that the build up consisted of displaced asphalt binder. Further laboratory analysis showed that the subject build up was virtually all rubber with an immeasurable amount of binder material. In addition, considerable rubber build up also occurred on the raised tread portion of the tire, and visible wear on the "sharp" corners of the tire tread was apparent. It was estimated that as much as 25 percent of the tread depth was worn away at very localized areas of the tire after the 100,000-pass test. As a result, the uni-directional, without wander, loading mode simulation appeared to place considerable wearing forces on both the tire and the pavement that may not necessarily be indicative of real-world traffic loading.

Effect of Wheel Wander

The next series of tests were conducted to evaluate the effects of wheel wander on pavement-tire interactions. Both bi- and uni-directional testing modes with 4-inch total wheel wander, in two-inch increment, were used. The HVS had a default wander step increment of 2 inches built into the software and this value was initially used for this testing.

All the effects previously described for the no wander testing were again apparent but to a lesser extent. It should be noted that these tests were carried out during the months of December and January when the ambient temperatures became much lower. The uni-directional test was conducted first with an average high temperature of 20.7° C and low of 14.6° C monitored at the 2-inch depth in the asphalt. The corresponding average temperatures for the bi-directional test were 19.7° C for the high and 9.2° C for the low. These low temperatures greatly reduced the rate of rutting regardless of the testing mode used. Consequently, performing a rut-per-pass comparison analysis based solely on loaded passes in this case would not have been meaningful or significant for all practical purposes.

Pavement-Tire Tread Interaction During Uni-directional Testing

Throughout the course of the testing, it appeared that the tire tread pattern had an impact on the pavement deformation patterns. For uni-directional loading especially, the pattern formed on the pavement seemed to match very closely with the general tread pattern. This is in terms of the tire contact areas with the pavement surface during a full revolution of the tire. The same observation applied to both with and without wheel wander testing. As a result, an attempt was made to determine what effect, if any, the tire tread patterns may have on the pavement deformation during uni-directional testing. It was also intended to determine the appropriate amount of wander increment that would result in a realistic "Bell curve"-shaped (or smoother) transverse profile of subsequent rut comparable to those observed on in-service roadways.

A print of a sample of a tire tread contact area with the pavement surface under a 9000-pound loaded wheel was first made. The pavement-tire contact area for this print was randomly selected to minimize the potential for sampling error or bias when a full tire rotation is considered. The layout of such a tread pattern is shown in Figure 5. In the process of mapping the tire tread, it was observed that, although very close, the tread pattern was not completely symmetrical across the width of the tire, nor was it exactly repetitive tangentially around the tire. The differences in symmetry and repetitive pattern were on the order of hundredths of inches. For the purpose of this investigation, as a close approximation, symmetry was assumed across the tire width.

Using MicroStation and Excel, a subroutine was developed to quantify the level of pavement-tire contact. The width of the tire-pavement contact print was first divided into strips, illustrated in Figure 6, based on the specific tread geometry in contact with the pavement surface. The majority of the strips reduce to a series of trapezoids with the following geometry:

$L2_i$

y2

Δh = strip width = y2 – y1

y1

$L1_i$

The remaining strips (strips 5, 18 and 30) amount to a collection of opposing triangles as follows:

$L2_j$

y2

Δh = strip width

y1

$L1_i$

Defining the y-axis across the width of the print and the x-axis tangentially, the amount of pavement-tire linear contact, at any given y-location, is determined by summing the length of the lines in the x-direction that fall on the tread pattern. Except for strip 1 ($0 \le y \le 1.07$ inch), which is in the 100 percent contact range, a line drawn tangentially at any other location ($1.07 < y \le 6.0$ inches) will fall both on the tread pattern (contact) and in the gaps between the tread (no contact).

The equation to determine the amount of linear contact, in percent, across the series of trapezoidal shapes, in a given strip, reduces to the sum of the lengths of the lines through all the trapezoids at a given y-location ($y1 \le y < y2$):

$$\left[\frac{\sum L1_i - \left(\left(\frac{\sum L1_i - \sum L2_i}{\Delta h}\right) * (y - y1)\right)}{L}\right] * (100)$$

where:

- y = contact location along y axis;
- $L1_i$ = length of bottom side of trapezoid i in the strip;
- $L2_i$ = length of upper side of trapezoid i in the strip;
- L = total length of the print of contact area;
- $\Delta h = y2 - y1 =$ strip width;
- y1 = y-value at the bottom of the strip; and
- y2 = y-value at the top of the strip.

In the triangle shapes case, the equation was developed based on the combined contribution from the upward and downward facing groups of triangles (for all upward facing triangles, L2 = 0, for all downward facing triangles, L1 = 0). Thus, the percent of linear contact, at any given y-location (for $y1 \le y < y2$), is determined using the following equation:

$$\left[\frac{\left[\sum L1_i - \left(\left(\frac{\sum L1_i - 0}{\Delta h}\right) * (y - y1)\right)\right] + \left[0 - \left(\left(\frac{0 - \sum L2_j}{\Delta h}\right) * (y - y1)\right)\right]}{L}\right] * (100)$$

where:

> y = contact location coordinate along y-axis;
> $L1_i$ = length of bottom side of upward facing triangle i in the strip;
> $L2_j$ = length of upper side of downward facing triangle j in the strip;
> L = total length of the print of contact area;
> $\Delta h = y2 - y1$ = strip width;
> y1 = y-value at the bottom of the strip; and
> y2 = y-value at the top of the strip.

The percent of linear contact along a tire width between a tire and a pavement surface as determined in this investigation is given in Figure 7. A contact of 100 percent means that a particular strip within the tire width is in continuous contact through a full rotation, while 0 percent contact means that a particular strip never touches the pavement in a full rotation. In the present case, the super-single contact with the pavement ranged from 19 to 100 percent along the tire width. In addition, the high and low contact regions of the tire tread were along the same respective locations as the low and high points in the actual rut profile on the test track sections. This "wavy" pattern is also an indication that the test section was not uniformly loaded across the tire width.

Effects of Wheel Wander

A similar experiment was also conducted using a 4-inch total wheel wander, with a 2-inch increment. Using uni-directional loading, the first pass had the left edge of the tire running longitudinally down the left edge (or the "zero line") of the test strip. The next pass moved two inches to the right so that the left edge is now running down the two-inch line. Finally, on the last pass, the wheel moved two more inches to the right putting its left edge on the four-inch line. The end result, with a 12-inch wide tire, was a 16-inch wide rut footprint (wander plus tire width) that took three passes (or legs) to complete. The results of the tire-pavement contact analysis in such an instance are summarized in Figure 8. This figure shows that the resulting transverse rut profile from this loading configuration had also somewhat of a "wavy" pattern. This indicates that the two-inch step increment with a 4-inch total wheel wander did very little to reduce the effect of the tread pattern.

Thereafter, with a four-inch wander, the testing objective became one of attempting to determine an appropriate wander incremental step that would make the pavement-tire tread contact area, within a test section, as smooth as possible. The intent was to minimize the transverse "wave" patterns of the resulting deformations. This investigation included both the possibility of adjusting the step increment as well as adjusting the number and order of passes at each step (increment). The number of passes at each step is programmable in the HVS control software. The software also allows full control of the number and order of the individual legs (or passes) within a specified total wheel wander while using different wander incremental steps. It is possible, for instance, to run x-number of 2-inch legs followed by y-number of 0-inch legs followed by z-number of 4-inch legs – or any other combination to make a complete wander cycle. It turned out that no appreciable improvement in contact curve smoothness could be attained adjusting the number and/or the order in which the legs were run in a wander cycle with a two-inch increment.

The next effort was to focus solely on the step increment assuming the legs were run in order and only once for a full wander cycle. Looking at the initial pavement-tire tread contact plot of Figure 7, it was first thought that a step increment that would put the low contact points squarely on top of the preceding high contact points would generate a smoother curve. The distance between the low points and the adjacent high points was estimated to be on average 0.89 inch. Therefore, a subsequent analysis was conducted using a 0.89-inch incremental step for a total wheel wander done with 5 legs over 3.56 inches (0, 0.89, 1.78, 2.67, and 3.56 inches). The resulting amounts of total contact across the test width are summarized in Figure 9. It can be seen from this Figure that this latter case gives a considerably smoother contact curve than does the two-inch step increment. However, as various step increments were analyzed, it was further determined that a one-inch step increment with 5 legs generated the smoothest contact curve for a four-inch wander. As a result of the analysis, the next tests were conducted with four-inch wander and one-inch step increment. Figure 10 shows a comparative pavement-tire contact as determined using a one- and two-inch incremental step, respectively. The one-inch increment virtually eliminated the series of parallel high and low lines that ran longitudinally down the rut footprint in the two-inch step test. This was especially true for the center 6 or 7 inches of the footprint. The one-inch step also eliminated the rubber deposited along the track as well as that that accumulated on the tire. There is still some rubber deposit left where the tire touches down but this appears to be unavoidable and similar to an aircraft tire touching down on landing. As a result of the tire tread contact study, the one-inch step increment testing parameter was adopted as the standard and has been used since. The rut profile has remained "smooth" even under elevated testing temperatures that have greatly accelerated and exaggerated the rut profile development. Also as a result of this experience, it is understood that a thorough tire tread investigation will need to be done any time the tire brand and/or type is changed. This is strongly recommended for others using this type of pavement testing equipment. This may become very interesting with the use of the standard dual–wheel axle where not only the tire tread but also the gap between tires will come into play over the width of the programmed wander.

CONCLUSIONS

The present study was conducted primarily to assess the different possible loading combinations for accelerated pavement testing. The intent was to determine a more realistic APT simulation of actual in-service loading configuration. Within the test range, the findings indicated the following:

- Although the pavement temperatures were close during this evaluation, when the wheel wander was not considered, the rut developed significantly faster in the uni-directional than in the bi-directional mode. After 100,000-passes, the uni-directional loading caused the rut to develop at a rate of approximately 65 percent greater than that of the bi-directional loading when analyzed on a per-pass basis. During the bi-directional testing the average high temperature measured at a 2-inch depth in the pavement was 32.1° C with an average low of 20.4° C. During uni-directional testing, the monitoring of the corresponding temperatures indicated an average high of 29.7° C and average low of 19.0° C. Therefore, the uni-directional loading caused a significantly greater rate of rutting while at a slightly lower temperature.
- When the wheel wander was not considered, the uni-directional mode appeared to place considerable wearing forces on both the tire and the pavement. It was estimated that as much as 25 percent of the tread depth was worn away at very localized locations on the tire after 100,000 passes.
- Throughout the course of the testing, it appeared that the tire tread pattern had an impact on the pavement deformation patterns. For uni-directional loading especially, the pattern formed on the pavement seemed to match very closely the general tire tread pattern. The observation held true for both with and without wheel wander testing.
- For a given type of tire tread, when wheel wander option was considered, each of the various wander increments considered differently affected the tire-pavement contact across the test track width.
- The present findings also show the importance of using wheel wander for rut testing purposes for more realistic and meaningful results. It is also important to use an appropriate wander incremental step in order to eliminate the transverse "wavy" pattern due to tire treads.
- It is recommended that, in order to determine an appropriate loading configuration, a thorough pavement-tire tread investigation be conducted any time the tire brand and/or type is changed.

ACKNOWLEDGMENTS

The authors would like to acknowledge Steve Ross (FDOT), Stephan Budricks and Charles Moore (Dynatest) for their diligent efforts and contributing knowledge.

LIST OF FIGURES

FIGURE		PAGE
1	Illustration of rut measurement using a straight edge.	12
2	A comparative illustration of respective rut measurements resulting from uni- and bi-directional modes of loading.	13
3	A photographic illustrations of respective rut profiles resulting from bi- and uni-directional modes of loading.	14
4	A photographic illustration of rubber build up removed from a test section.	15
5	Lay Out of Tire Tread Patterns.	16
6	Illustration of Tire Tread Strips.	17
7	Amounts of tire-pavement contact as measured along the tire width during uni-directional loading mode without a wheel wander.	18
8	Total amount of tire-pavement contact as measured along the test width during uni-directional loading mode with a 4-inch wheel wander in a 2-inch increment.	19
9	Total amount of tire-pavement contact as measured along the test width during uni-directional loading mode with a 3.56-inch wheel wander in a 0.89-inch increment.	20
10	Total amount of tire-pavement contact as measured along the test width during uni-directional loading mode with a 4-inch wheel wander, in a 1- and 2-inch increments respectively.	21

FIGURE 1 Illustration of rut measurement using a straight edge.

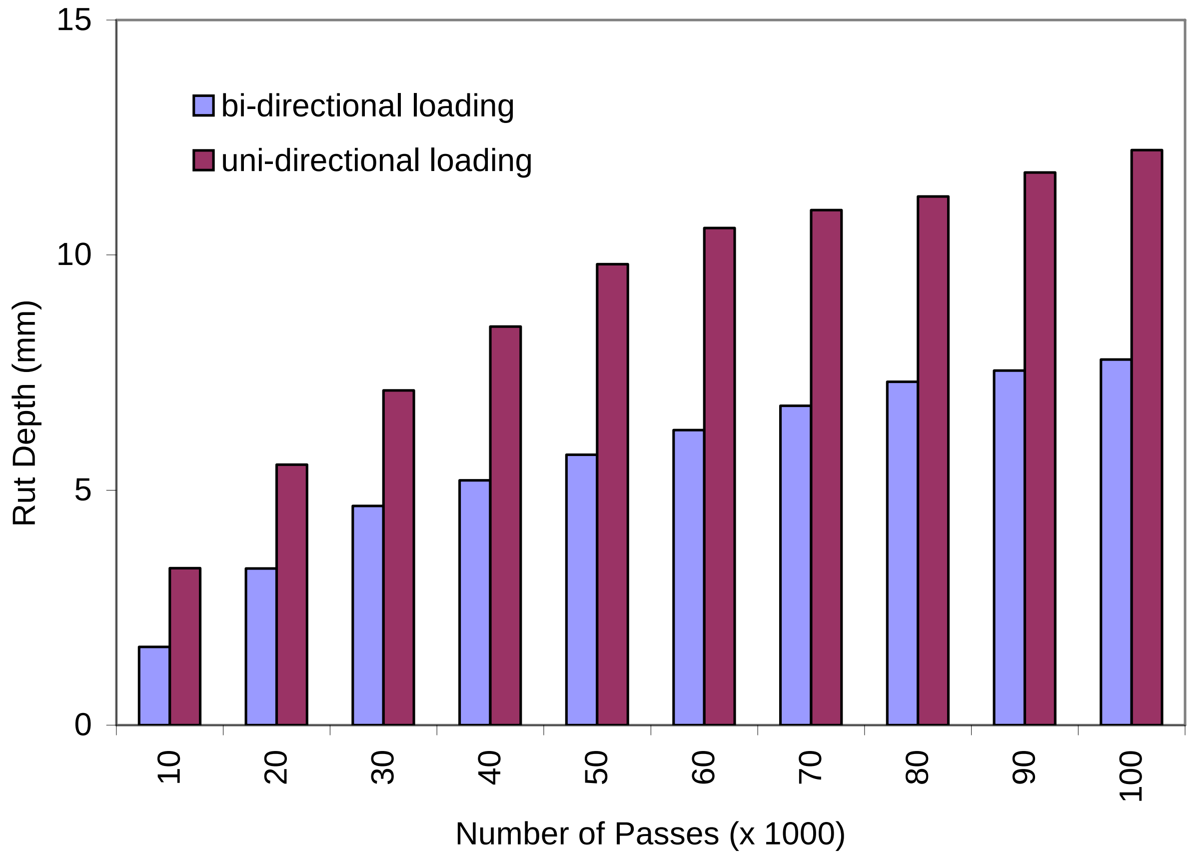
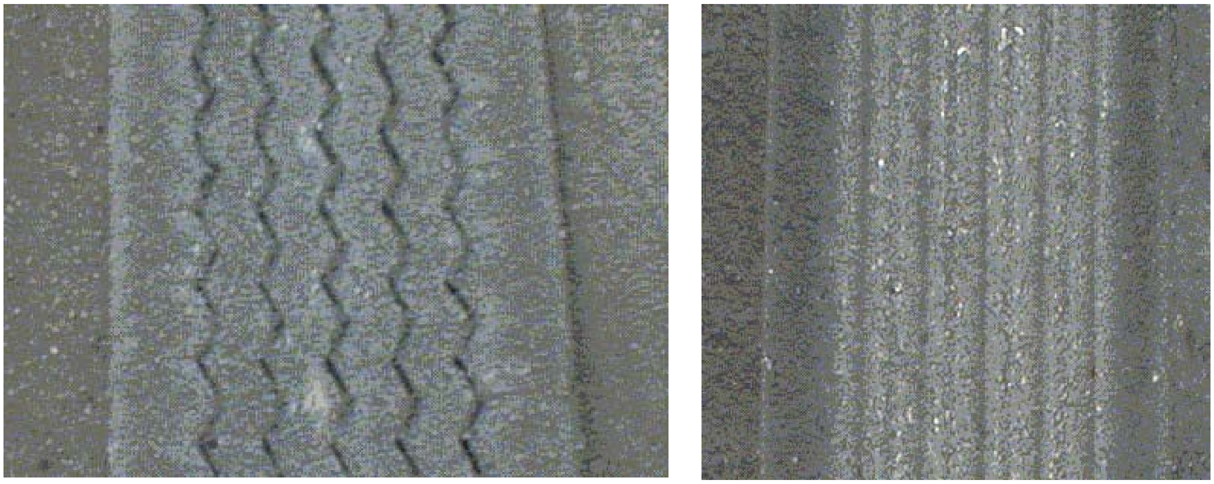


FIGURE 2 A comparative illustration of respective rut measurements resulting from uni- and bi-directional modes of loading.



(a) Bi-directional loading (b) Uni-directional loading

FIGURE 3 Photographic illustrations of respective rut profiles resulting from bi- and uni-directional loading modes.

FIGURE 4 A photographic illustration of rubber build up removed from a test section.

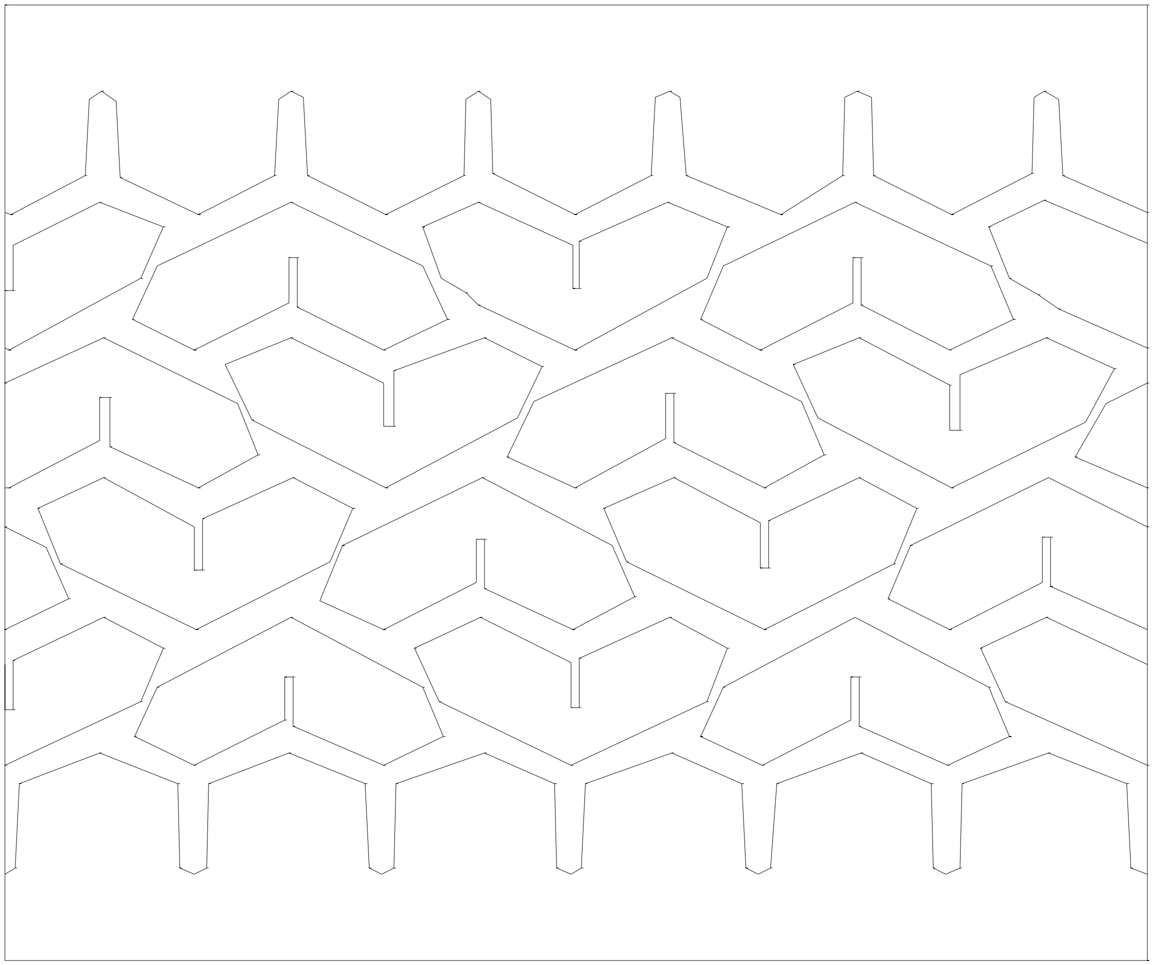


FIGURE 5 Lay Out of Tire Tread Patterns.

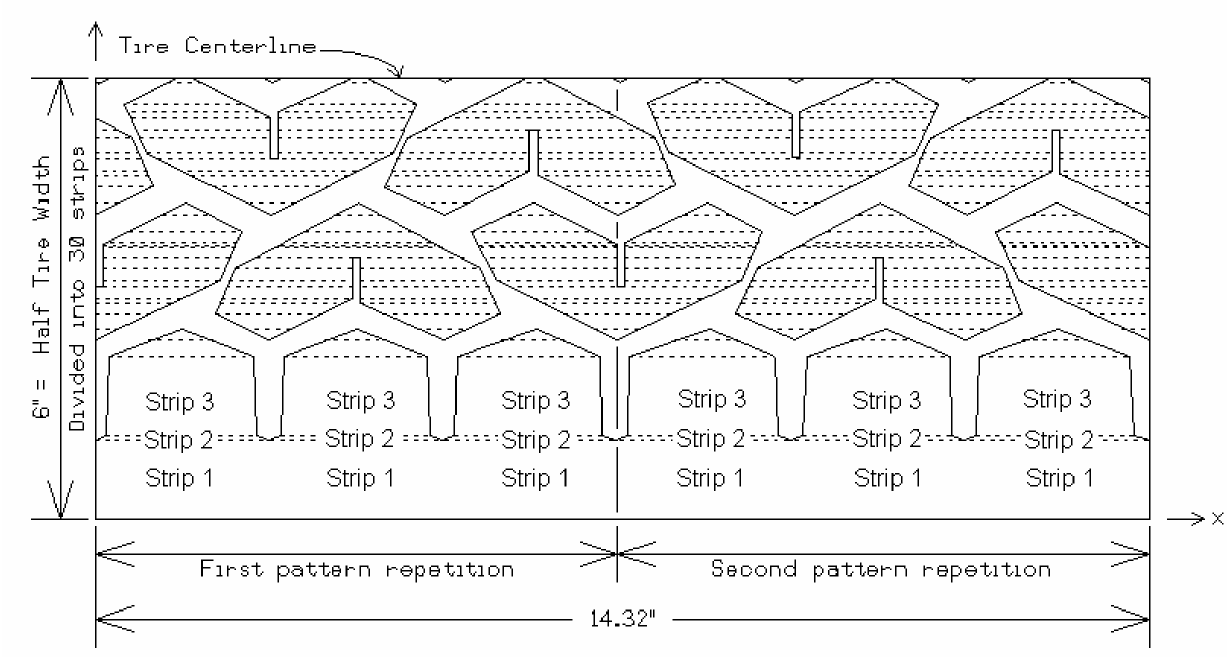


FIGURE 6 Illustration of Tire Tread Strips.

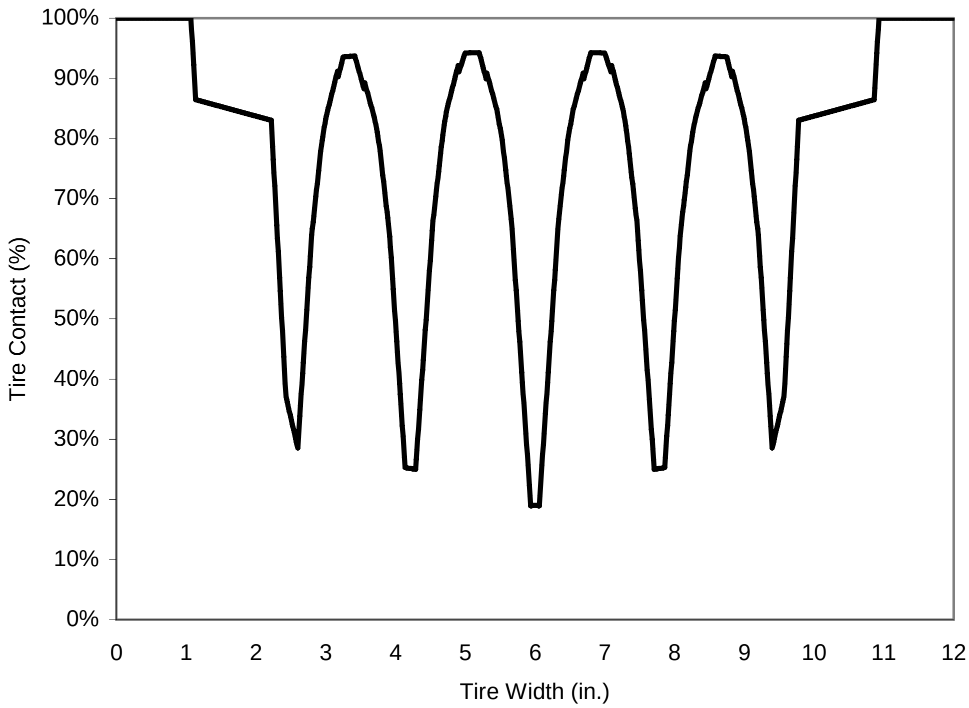


FIGURE 7 Amounts of tire-pavement contact as measured along the tire width

during uni-directional loading mode without a wheel wander.

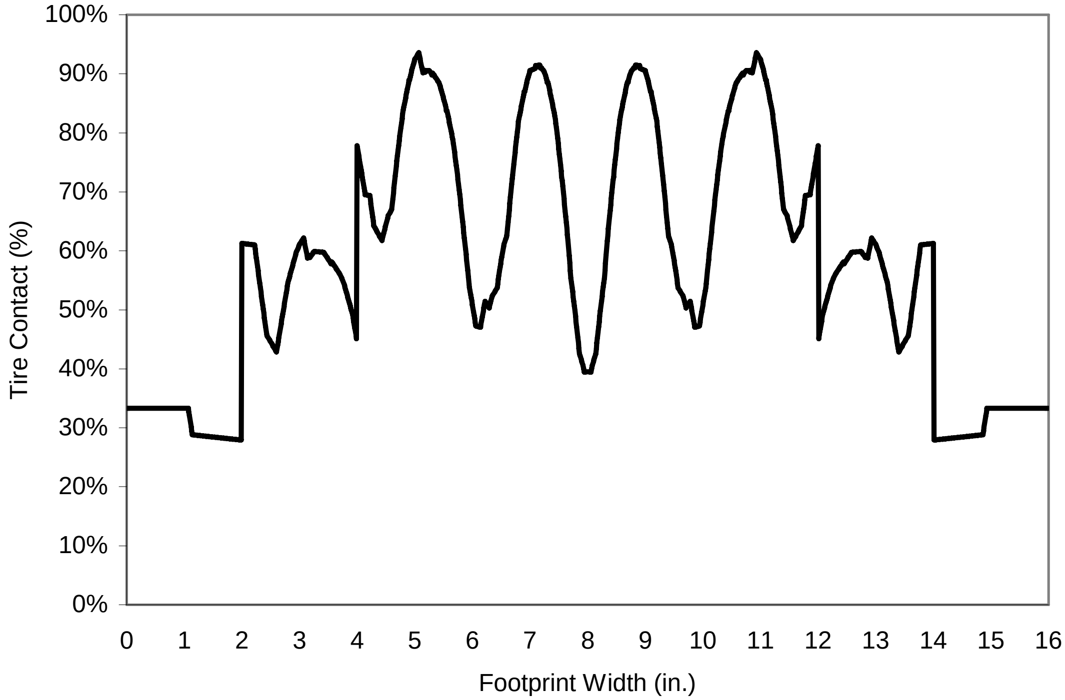


FIGURE 8 Total amount of tire-pavement contact as measured along the test width during uni-directional loading mode with a 4-inch wheel wander in a 2-inch increment.

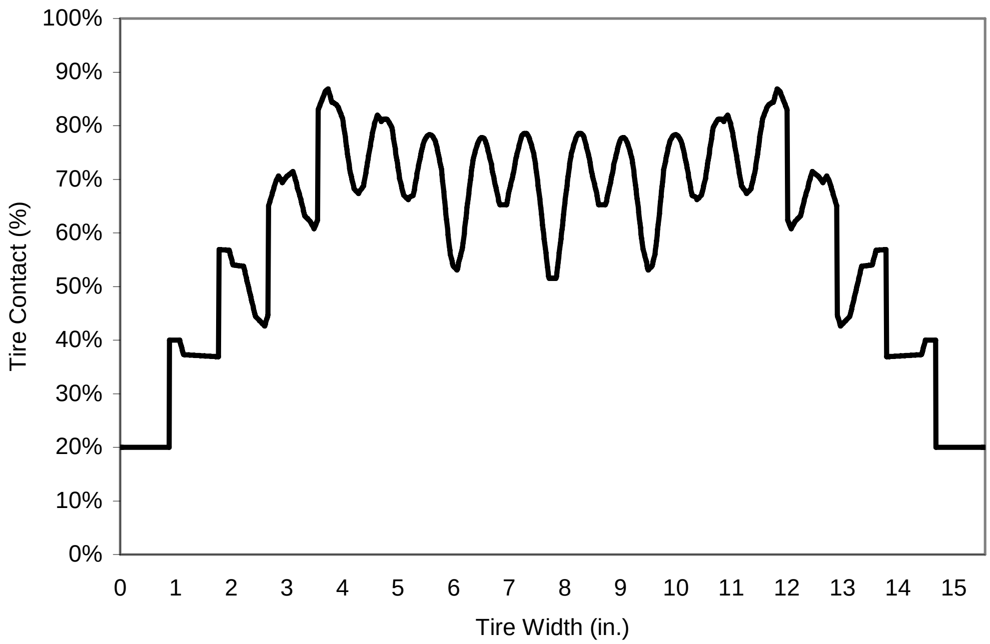


FIGURE 9 Total amount of tire-pavement contact as measured along the test width during uni-directional loading mode with a 3.56-inch wheel wander in a 0.89-inch increment.

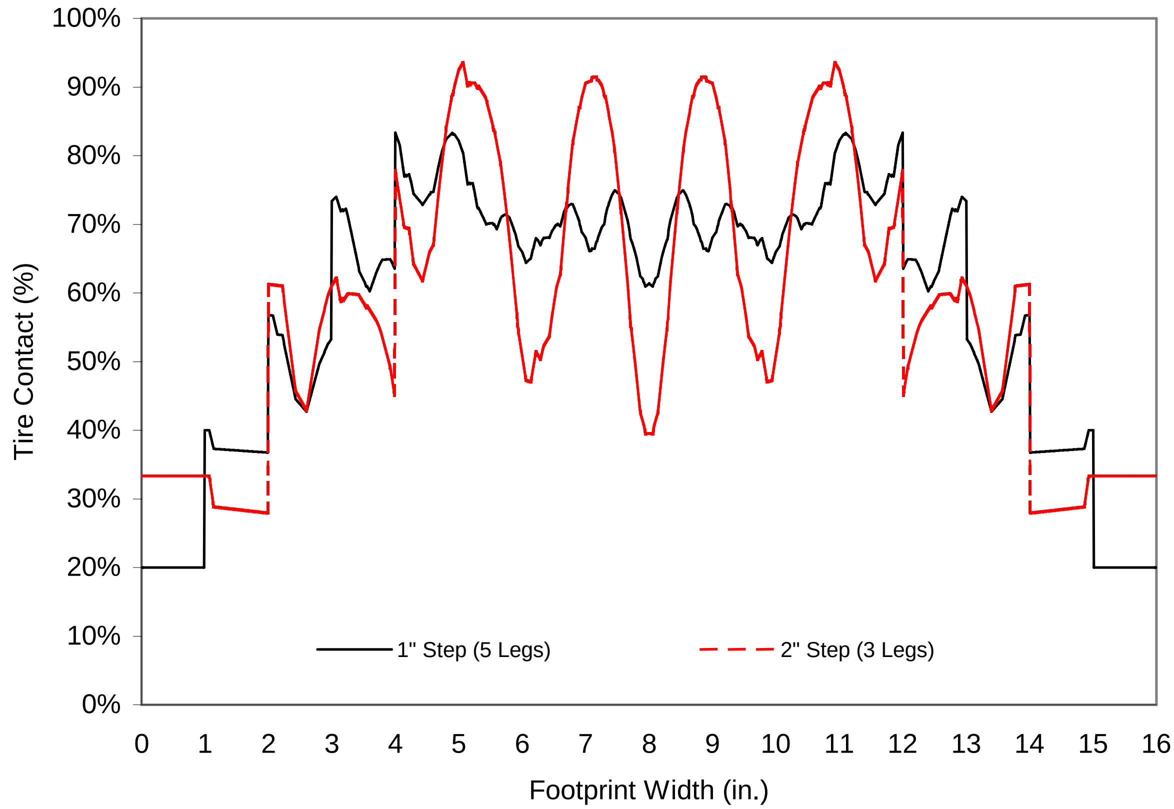


FIGURE 10 Comparative amount of tire-pavement contact as measured along the test width during uni-directional loading mode with a 4-inch wheel wander, in 1- and 2-inch increments respectively.