MEASURED AND THEORETICAL COMPARISONS OF TRAFFIC LOADS AND PAVEMENT RESPONSE DISTRIBUTIONS

Bruce A. Chadbourn, David E. Newcomb, and David H. Timm
University of Minnesota
122 Civil Engineering Bldg.
500 Pillsbury Dr. SE
Minneapolis, MN 55455

Abstract. The correlations between traffic load distributions and tensile strains in flexible pavements are discussed in this paper, and these relationships are compared against theoretical strains computed from layered elastic theory. Six flexible pavement test sections at the Minnesota Road Research Project (MnROAD) were selected for the analysis presented in this paper. Wheel-weight data from the weigh-in-motion station at the MnROAD site were taken for a number of time periods during 1995. Weight data distributions were then matched to temperature-corrected transverse strains measured at the bottom of the asphalt concrete in the test sections. Finally, a layered elastic analysis was performed, the results of which were compared to actual measurements under traffic. It was found that the measured strains and the strains computed from the analytical model matched well when the loads were modeled as dual wheels with constant tire pressure and a varying load magnitude.

Keywords. Pavement Design, Pavement Analysis, Traffic Data, Weigh-in-Motion Data, Pavement Performance

INTRODUCTION

Background. Mechanistic-empirical pavement design procedures are becoming increasingly popular. Central to such methods is the computation of pavement responses, such as stress and strain under loading, and the relationship between these responses and the structural integrity of the pavement structure. Layered elastic analysis is one of the more accepted mechanical models used in simulating flexible pavement behavior. Although there are several underlying assumptions in the model, it is used primarily because of its simplicity.

Field validation of the use of layered elastic theory has been accomplished previously at the Minnesota Road Research Project (MnROAD) (Van Deusen and Newcomb, 1994). Researchers have found close correlations between measured and computed strains in asphalt pavements when failing weight deflectometer measurements have been made. This helped to establish confidence in layered elastic theory to represent the response of a pavement to vehicle loading.

Mechanical models are useful in their ability to quantify the effects of changes in loading conditions and material properties in terms of stress, strain or displacement. Finn, et al. (1977) and other researchers have developed equations for predicting the number of repetitions to failure for fatigue and permanent deformation in flexible pavements using a phenomenological approach. These describe pavement performance for a particular set of conditions, i.e., material properties and load, and generally take the form:

\[ N_f = k_1 e^{k_2} \]

where

- \( N_f \) = number of repetitions to failure,
- \( e \) = strain at a critical point in the pavement structure,
- \( k_1 \) and \( k_2 \) = regression constants.

Since this applies only for one set of conditions, a means must be used for accumulating damage in different conditions. Miner's hypothesis is a method in which the ratios of actual loadings to the number of repetitions to failure for a given set of condition are summed:

\[ D = \sum \sum \frac{n_{ij}}{N_{ij}} \]

where

- \( D \) = total damage,
- \( n_{ij} \) = actual number of load repetitions at loading condition \( i \) and material condition \( j \),
- \( N_{ij} \) = number of repetitions to failure at loading condition \( i \) and material condition \( j \).
Given the above two relationships, the importance of understanding the distribution of traffic and the resulting distribution of strain is evident in defining the range of loading conditions to which a pavement may be subjected during its life.

Objective. The objective of this research can be divided into two parts. First, a method of correlating wheel load distributions from actual traffic to measured flexible pavement response (strain) distributions is needed. Such a correlation can then be used to validate a theoretical pavement response model. This was accomplished by Newcomb et al. (1997) and is expanded upon in this paper. The second part of the objective involves using layered elastic theory to simulate the pavement response over a range of measured wheel loads, and comparing the results to the measured response. Ultimately, the authors hope this research will lead to the development of a mechanistic-empirical design procedure by which the performance of a given pavement can be predicted with greater certainty.

Scope. Six flexible pavement test sections at the Minnesota Road Research Project (MnROAD) were selected for the analysis presented in this paper. Wheel-weight data from the weigh-in-motion station at the MnROAD site were taken for the first week of August, 1995. Weight data distributions were then matched to temperature-corrected transverse strain measured at the bottom of the asphalt concrete in the test sections. Finally, a layered elastic analysis was performed using laboratory-determined material properties and some simplifying assumptions concerning traffic load and wheel configurations. The results of the theoretical analysis were then compared to actual measurements under traffic.

EXPERIMENTAL FACILITIES

Description of MnROAD. MnROAD is located on I-94 approximately 60 km northwest of Minneapolis. The two westbound lanes of the interstate highway serve as the location for the mainline experiment with a low-volume road portion running parallel. The high-volume portion, which provided the data for this paper, contains test sections designed for an expected 10 years of service on the east end and 5 years of service on the west end. The 10-year segment has approximately 1830 m of flexible pavements and 710 m of rigid pavements. The 5-year part of the main experiment has 730 m of asphalt surface pavements and 915 m of rigid pavements. The pavements were designed according to the current empirical Granular Equivalency Method employed by the Minnesota Department of Transportation (MnDOT).

The natural subgrade in this area is primarily a loam with an American Association of State Highway and Transportation Officials (AASHTO) classification of A-6. There are minor variations of silt and clay present. MnROAD is located on one of the highest truck volume routes in the state. The design average daily traffic for this portion of I-94 is 24,200 vehicles with 3,200 of these classified as heavy commercial vehicles. For the 5-year sections, this means that about 3.2 million equivalent single axle loads (ESAL) will be experienced by the flexible pavements, and the 10-year flexible pavements can expect 7.2 million ESAL.

Selected Test Sections. Six flexible pavement sections at MnROAD were selected for this study: test sections 1, 4, 15, 17, 21, and 22. The cross-sections and material properties of which are listed in Table 1. Test section 1 is a conventional, layered pavement, which was designed for a five-year life and which consists of 145 mm of asphalt concrete, prepared with a 120/150 penetration asphalt binder, over 840 mm of a MnDOT Class 4 granular base material. Test sections 4 and 15 are full-depth pavements structurally designed for a five-year and a ten-year life, respectively. Test section 4 has a total pavement thickness of 220 mm of asphalt concrete, and contains a binder having a penetration grade of 120/150. Test section 15 is comprised of 275 mm of asphalt concrete, with a comparably stiff AC-20 viscosity grade asphalt. The pavement cross-section in test section 17 is 200 mm of asphalt concrete over 710 mm of a relatively poor MnROAD Class 3 granular base course. The asphalt cement used in test section 17 is an AC-20 viscosity grade. Test sections 21 and 22 are conventional asphalt concrete (200 mm) over granular base sections, in which the asphalt concrete has a 120/150 penetration grade binder. The MnDOT Class 5 granular base course in test section 21 is a partially-crushed, dense-graded pit material, 585 mm in thickness. The base material used in test section 22 is a 100-percent crushed dense-graded granite (Mn/DOT Class 6), which is 455 mm in thickness.

Material Properties.

Asphalt Concrete. The asphalt resilient modulus was determined from laboratory indirect tensile tests using field-mixed, laboratory-compactcd mixtures (Newcomb and Stroup-Gardiner, 1996). The mixtures were tested at a range of temperatures from -18°C to 40°C in order to determine the relationship between modulus and temperature. The asphalt modulus values in Table 1 were measured at 25°C which was the assumed baseline temperature for the asphalt strains in this study. Each mixture either had an AC 20 viscosity grade or 120/150 penetration grade asphalt binder. Those made with the AC-20 binder had a modulus on the order of 4000 MPa, while those with the 120/150 binder had modulus values of about 2600 MPa. Poisson's ratio for the asphalt layer was assumed to be 0.35.

Base Materials. The three-layer pavements had a granular base layer made up of either Class 3, 4, 5, or 6 material. Mn/DOT classifies base materials so that a stiffer material (e.g. higher modulus) will also have a higher class number. Class 5 material is the typical base for Mn/DOT pavements. Each base material was laboratory tested for resilient modulus with varying moisture contents and bulk stresses. Laboratory data obtained from the MnROAD database was used to define the modulus distribution for each test section, as shown in Table 1, at an optimum moisture content and a bulk stress of 300 kPa. Class 4 material, found in test section 1, had the lowest modulus value as measured (105 MPa), which contradicts the Mn/DOT classification system. The highest modulus measured (165 MPa) was for a Class 6 material, found in test section 22. Poisson's ratio for the base layer was assumed to be 0.40.

Subgrade. The bottom layer for both two-layer and three-layer pavements consisted of a soil subgrade with an R-value of 12. A uniform resilient modulus of 83 MPa was used for the analysis of each test section, as shown in Table 1. This value was obtained by

<table>
<thead>
<tr>
<th>Test Section</th>
<th>1</th>
<th>4</th>
<th>15</th>
<th>17</th>
<th>21</th>
<th>22</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Asphalt Concrete</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Binder Classification</td>
<td>120/150 Penetration</td>
<td>120/150 Penetration</td>
<td>AC 20</td>
<td>AC 20</td>
<td>120/150 Penetration</td>
<td>120/150 Penetration</td>
</tr>
<tr>
<td>Resilient Modulus (MPa)</td>
<td>2,855</td>
<td>2,770</td>
<td>3,621</td>
<td>4,425</td>
<td>2,825</td>
<td>2,349</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>Layer Thickness (mm)</td>
<td>145</td>
<td>220</td>
<td>275</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
</tbody>
</table>

| **Granular Base** | | | | | | |
| Mn/DOT Material Classification | Class 4 special | N/A | N/A | Class 3 special | Class 5 special | Class 6 special |
| Resilient Modulus (MPa) | 105 | N/A | N/A | 134 | 139 | 165 |
| Poisson's Ratio | 0.40 | N/A | N/A | 0.40 | 0.40 | 0.40 |
| Layer Thickness (mm) | 840 | N/A | N/A | 710 | 585 | 400 |

| **Subgrade Soil** | | | | | | |
| AASHTO Soil Classification | A-8 | A-8 | A-8 | A-8 | A-8 | A-8 |
| Resilient Modulus (MPa) | 83 | 83 | 83 | 83 | 83 | 83 |
| Poisson's Ratio | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 |
| Layer Thickness (mm) | semi-infinite | semi-infinite | semi-infinite | semi-infinite | semi-infinite | semi-in infinite |
Thermocouples are classified as static sensors and are embedded at various depths in the pavement structure. Readings from the thermocouples in the asphalt layer were used to make temperature corrections to the strain data.

**DATA COLLECTION AND RETRIEVAL**

**Data Collection.** The dynamic sensors continuously monitor pavement responses at a rate of 2000 samples per second. When the signal exceeds a preset threshold, the pavement response is temporarily recorded. The signals from the sensors are initially digitized and temporarily stored in roadside data acquisition equipment. From there they are transmitted to field protocol converters for further processing before being sent to the main on-site computer for storage. Periodically, the data are downloaded over a dedicated line to the computer in the Mn/DOT Materials and Research Laboratory. All data collected at MnROAD are stored on an ORACLE database for retrieval and analysis either locally or over a network system.

**Time Period.** Weigh-in-motion, transverse strain, and thermocouple data, were retrieved from the MnROAD database for the month of August, 1995, with the exception of test section 1. Strain data from this test section for the month of August was not used due to the failure of two strain sensors in late July. Data from the month of June was used for the analysis of the sensor layout and sensor triggering times. These data were used to adjust each strain reading to a single wheel load equal to the greater of the two.

**Strain gages are classified as dynamic sensors. Although there are a number of types of pavement response sensors in the flexible pavements, in this paper, transverse strain at the bottom of the asphalt layer was selected as the pavement response to traffic loads. Horizontal strain at the bottom of the asphalt layer has been related to the fatigue failure of pavements at stresses above the typical noise level. As it was not always clear if a dual peak was due to noise or a tandem axle, and tandem axle events can reasonably be treated as single loads, each dual peak was reduced to a single strain equal to the greater of the two. Correspondingly, each tandem WIM event was reduced to a single wheel load equal to the greater of the two.

**Table 2. WIM and Transverse Strain Statistics, August 1995**

<table>
<thead>
<tr>
<th>Test Section</th>
<th>Time Period</th>
<th>Count</th>
<th>Mean</th>
<th>C.V.</th>
</tr>
</thead>
<tbody>
<tr>
<td>WIM* (kN)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 hour</td>
<td>145</td>
<td>41</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>1 day</td>
<td>3,087</td>
<td>34</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>1 week</td>
<td>15,688</td>
<td>34</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>1 month</td>
<td>63,384</td>
<td>34</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>1' (μ)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 hour</td>
<td>128</td>
<td>27</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>1 day</td>
<td>1,741</td>
<td>27</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>1 week</td>
<td>10,273</td>
<td>25</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>1 month</td>
<td>26,574</td>
<td>25</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

**Temperature Corrections.** The transverse strain response is very sensitive to the temperature of the asphalt layer. As shown in Figure 1, the mean transverse strain values varied from hour to hour, reaching a peak in mid-afternoon. Temperature was undoubtedly responsible for some of this variation, but there was also the possibility that the mean wheel load values changed during the day. Although the actual traffic volume varied according to the temperature range, the mean value for wheel loads over 25 kN remained nearly constant. Transverse strain correction factors were calculated based on representative asphalt layer temperatures (spatial averages of readings from thermocouples embedded in the pavement). Strains were temperature-corrected to 25°C by collecting temperature and strain data from several days throughout 1995 to achieve a wide temperature range. The hourly average strain values for each test section were then plotted against the corresponding hourly average pavement temperatures. Regression equations from these plots were used to adjust each strain reading to a 25°C level based upon the average asphalt layer temperature at the time of the reading. The results of temperature correction are demonstrated in Figure 1. On some days, thermocouple data was not available for

![Figure 1. Hourly Mean Wheel Load, Measured Strain, and Temperature-Corrected Strain Values for Test Section 17, August 1, 1995](image-url)

In order to compare the wheel load distributions to strain readings collected over a period of time during which the pavement temperature varied, further sorting was required. In order to examine trends in wheel load, strain, and temperature levels, data from each day was grouped by hour, and average values were plotted. Figure 1 shows the hourly average heavy wheel loads (over 25 kN) and the hourly mean strain values in test section 21 for August 1, 1995.
every hour. In such cases, the correction factor was calculated such that the corrected mean strain equaled the corrected mean strain from the previous hour. The regression equations used in this study differ from the equation used by Newcomb et al. (1997) which was calculated using strain and temperature data from FWD testing conducted at MnROAD.

**DISTRIBUTIONS OF TRAFFIC AND RESPONSE DATA**

Temporal Distribution. Table 2 shows the mean wheel loads and pavement strains and corresponding coefficients of variation (C.V.) for each of the six test sections. The first observation is that the mean wheel load and the C.V. for the wheel loads are constant beyond time periods of one day for those wheel loads greater than 25 kN. The C.V. of the wheel loads in the range examined was 20 percent, which is considerably lower than the C.V. for the strain measurements which was about 25 to 30 percent for time periods greater than one day. At first thought, it might be expected that the WIM scale and the strain gauges would show approximately the same amount of dispersion. However, the WIM measurement is not especially sensitive to lateral placement of the loads since the scale covers the entire wheelpath, and the strain gauge is located at essentially one point in the pavement, so that lateral placement of the load is very critical to the value. It is important to note that the C.V. for strain measurements is fairly consistent from one section to another, which is useful when considering the distribution of strains in pavement design, as would be the case when reliability is incorporated into the design process.

The measured strains in test sections 1 and 4 show slightly less variability than those in the other test sections. Because test section 1 has the thinnest asphalt layer, the strains were concentrated in a smaller area of the pavement at the bottom of the asphalt layer. This would result in a higher mean strain with a lower coefficient of variation. The relatively low coefficient of variation for strains in test section 4 may be explained by the presence of rutting. A survey in September of 1993 showed this test section had rutting on the order of 6 mm compared to 3.5 to 4.5 mm for the other test sections included in this study (Palming, 1995).

Spatial Distribution. As mentioned earlier, wheel wander was a concern in collecting transverse strain data. Lateral placement data was collected from April 24 through June 7, 1996 for wheel loads greater than 25 kN. The lateral placement data in the MnROAD database represents the position of the right edge of the right tire. In order to observe the position of the wheel centers, it was assumed that the majority of the heavy loads were due to dual tires. These positions were determined by shifting the right edge position 275 mm to the left (assuming a 550 mm dual wheel width). A histogram of the lateral position data with a superimposed normal distribution curve is shown in Figure 2. Data from the right side of the distribution is missing due to tires extending over the right edge of the sensor.

**Correlations between traffic and response.** Drawing correlations between wheel loads and pavement response requires paired data at different wheel load values. An attempt was made to match WIM and transverse strain data for a pairwise comparison. This was not possible due to the distances between the WIM station and the test sections, varying vehicle speeds, and insufficient accuracy in the time readings. Therefore, histograms were constructed and the distributions were compared.

Histograms. As a result of differences in instrumentation sensitivity, the WIM recorded significantly more events than the strain sensors in a given period of time. This suggests that transverse strains caused by wheel loads below a certain threshold are negligible. In light of this, the threshold wheel load was determined for each test section and WIM events below this level were excluded so that the WIM sample size matched that of the test section (Fig. 3). This threshold value ranged from 22 kN (test section 13) to 31 kN (test section 1), with the thresholds for the remaining test sections falling closer to 25 kN.

Percentile Matching. Since one-to-one matching was not possible, a comparison of statistical parameters was considered. A comparison of mean values may provide some insight into the relationship between wheel load and pavement response, but this allows a comparison at only one value of the wheel load, and given the nature of the WIM distribution, the mean may not be the best representation of wheel loads.

**Figure 2. Lateral Placement of Truck Tires (Center of Load) at MnROAD**

Buiter et al. (1989) used a statistical analysis of wheel wander and Miner's hypothesis to characterize the damage expected in full-depth asphalt pavements in the Netherlands. They concluded that the most important factor determining the wander (standard deviation) of vehicles is lane width. The lane width of the pavements considered in this study is 3.66 m. The wander of 0.24 m matches the wander measured in the Netherlands for lanes ranging in width from 2.88 to 3.12 m. The wander for the widest class of lanes measured in the Netherlands (3.38 to 3.62 m) was 0.29 m (Buiter et al., 1989).

The positions of the transverse strain sensors are also indicated in Figure 2. Based on the lateral placement distribution and the position of the strain sensors, one would expect most of the strain readings to occur on the center sensors, with the remainder equally divided between the left and right sensors. This is confirmed in Table 3, with the exception of test section 17, whose center strain sensor is inoperable. The reason for the large proportion of strain readings on the right sensor in test section 17 is not known.
2. The coefficient of variation in heavy wheel loads is approximately 20 percent, which again remained constant for time periods greater than one day. It would appear that this value can be used in a probabilistic approach to characterizing traffic.

3. The coefficient of variation in the transverse strain at the bottom of the asphalt layer ranges from 25 to 30 percent. The variability is reduced for asphalt layer thicknesses of 150 mm or less and in pavements where rutting on the order of 6 mm is present.

4. There is a good correlation between measured and simulated strains. This is true for a range of pavements having asphalt layer thicknesses from 150 to 300 mm (high volume pavement design).

5. Differences between measured and simulated strains can be explained by possible nonlinear material behavior or wheel wander not accounted for in the simulation of strains.

6. Wheel wander can be assumed to account for the increase in variability in strain data relative to wheel load data.

ACKNOWLEDGMENTS

Funding for this research was provided by the Minnesota Department of Transportation. The authors extend special thanks to the Mn/DOT Office of Minnesota Road Research for their excellent technical assistance in providing much of the data used herein.

REFERENCES


DeCabooter, P. H., "Wisconsin Truck Tire Pressure Study," Report FHWA/RI-88/1, Wisconsin Department of Transportation, Division of Highways and Transportation Services, Madison, WI, January 1988.


