INVESTIGATION OF FLEXIBLE PAVEMENT RESPONSE
TO TRUCK SPEED AND FWD LOAD THROUGH
INSTRUMENTED PAVEMENTS

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Abstract. Falling weight deflectometer (FWD) and truck tests have been conducted on the Minnesota Road Research project (Mn/ROAD) in an effort to (1) study truck speed effects on flexible pavements, (2) compare pavement response under FWD and truck loads; and (3) investigate the effects of wheel path offset on the pavement response. Three flexible pavement sections were used for this study. The truck tests were performed at various speeds ranging from 10 to 103 km/h.

The results showed that on a smooth pavement (IRI=0.97 m/km) strains in the bottom of the pavement continuously reduced with the truck speed. While on a relatively (relative to the smooth pavement) rough pavement (IRI=1.74 m/km), strains in the bottom of the pavement decreased as the speed of the truck increased to a speed about 65 km/h, but the strains increased when the speed was further increased from 65 km/h to 103 km/h. The effects of the pavement surface roughness were also investigated and the influence of truck suspension type was discussed.

Keywords. Mn/ROAD project, truck speed, International Roughness Index (IRI), FWD.

INTRODUCTION

One of the primary concerns in pavement engineering is to evaluate pavement performance under traffic loads. Knowledge of how a pavement responds to real traffic is essential for advancing pavement design. Currently, pavement design practice in the United States is based on technology developed during the 1930s through early 1960s. The design methods are based on empirical performance data and material characterizations which are a function of the available traffic and other conditions which existed 30 to 60 years ago. However, heavy trucks, considered to be the major consumer of the pavement life, have increased in traffic frequency, speed, size and weight since then. Therefore, assessing the pavement behavior under current truck traffic becomes an important factor in moving from empirical to mechanistic/empirical pavement design.

A moving vehicle passing over a highway pavement imposes loads on the pavement. These loads are a combination of vehicle static weight and dynamic force induced by the pavement surface irregularities. At the same time, the material behavior of asphalt concrete is time-dependent, meaning that the deformation of asphalt concrete pavement depends on the duration of given load acting on the pavement. In general, the longer the duration, the larger the deformation for a given load. Dynamic loads generated by moving vehicles have been studied by many researchers. In the early 70s, Whittemore et al. (1970) developed a system to measure the dynamic loads and pointed out that tire stiffness, enveloping properties, and weight of the unsprung mass have a major influence on the magnitude of pavement loads based on the computational results. The experiments performed by Sweatman (1983) and Woodroofe et. al (1986) demonstrated that suspension type, vehicle speed, and pavement roughness have significant effects on dynamic response.

Recently, the study of pavement response under dynamic loads induced by moving vehicles has become a topic of great interest for pavement researchers. Gorge (1984) used instrumentation
installed on a vehicle to measure the vehicle dynamic loads. Instead of instrumenting a vehicle, Sebaaly and Tabatabaei (1993) utilized Weight-in-motion systems to measure dynamic loads. In their studies, pavement strains under the moving vehicle were also measured using strain gages embedded in the pavements. The results showed that the asphalt concrete (AC) pavement strains decreased as the vehicle speed increased and suggested that pavement design model should consider the dynamic feature of traffic loads and the viscoelastic properties of AC material. Furthermore, Papagiannakis et. al (1988) and Chatti et. al (1995) conducted both field experiments and theoretical studies on asphalt concrete pavement response under moving vehicles. Both found that truck speed, tire pressure and suspension type all have a large influence on the response of dynamic wheel loads. The studies indicated that the strains in the pavement decreased as the truck speed increased. The study from Papagiannakis et. al (1988) showed that the air suspension caused less damage to the pavements than the rubber suspension. However, Chatti et. al (1995) pointed out that while general experience has been that air suspensions produce lower dynamic effects than walking beam suspension, their observations indicated that the strains induced by walking-beam suspension axle were slightly smaller than those from the air suspension axle. In addition, the characteristics of AC material under dynamic load were examined by Sousa et. al (1987, 1988). The results illustrated the dependency of some material properties on frequency, temperature, and mode of loading. The truck speed in the field experiments performed by the above researchers was limited to 80 km/h.

Modeling vehicle dynamic response as well as pavement response under dynamic loading are also an important task in the development of a mechanistic-based pavement design method. Newland (1993) described how a moving vehicle responds to a random surface irregularities using a simple quarter-car model. The pavement surface profile was viewed as a random variable. More complicated truck models were examined by Todd and Kulakowski (1989) and they concluded that large complicated simulations should not be necessary for most studies concerning the vertical dynamics of heavy trucks. Recently, Hardy and Cebon (1993, 1994) applied a linear theory and a quarter-car model to predict a continuous pavement response to moving dynamic loads through the use of convolution integrals. The pavement structure was modeled as an elastic beam resting on a damped elastic foundation. An extensive theoretical study on the subject was performed by Gillespie et. al (1993). Their computation results suggested that fatigue damage of flexible pavements may decrease with increased speed on a smooth road, but increase with speed on a rough road.

In this study, FWD and truck tests were conducted on three instrumented flexible pavements at the MnROAD project. The three pavements have different surface roughness as measured with IRI index using Pavetech. The transverse and longitudinal strains under the bottom of the pavements were selected to monitor the pavement response under FWD and truck loads. The truck speed was increased up to an interstate speed 103 km/h. FWD tests were used to verify pavement model and the pavement response under the FWD and the truck loads were compared. The influences of the pavement surface roughness on the moving truck and pavement response were also investigated. Additionally, the effect of truck suspension type on pavement behavior was discussed. Furthermore, wheel path offset effect on the bottom strain of the pavement was examined both experimentally and analytically.

**EXPERIMENTAL SETUP**

**Minnesota Road Research project.** The Minnesota Road Research project is located about 65 km northwest of Minneapolis/St. Paul in Otsego, Minnesota on and adjacent to Interstate 94. It consists of a mainline transition roadway to carry live Interstate traffic, and a low volume closed loop road used for controlled truck research. A total of more than 4500 electronic sensors are embedded in forty 150m-long pavement sections with each section having a unique design. Among the forty sections, twenty-two are asphalt concrete pavements.

Seventeen types of sensors including strain gages, linear variable differential transformers (LVDT) and thermocouples are embedded throughout the pavement and subgrade layers to measure variables such as pavement strain and deflection due to truck loads and environmental
conditions such as temperatures and moisture contents. Fig. 1 shows a typical sensor layout on a flexible pavement section. The strain gages are placed horizontally on the bottom of the pavement in both longitudinal and transverse directions. There are three strain gages in each direction: one gage is under the wheel path, one is outside toward to the shoulder (TE3) and another is inside the wheel path toward to the centerline (TE1). This sensor layout system provides an unique tool to study the spatial variations of strain at the bottom of pavements. Also, there are at least three thermocouples located at different depths within the pavement in each section to measure the pavement temperatures.

Additionally, a system manufactured by International Road Dynamics, Inc. (IRD system) is embedded on one of the pavement sections to measure the lateral position of individual truck wheel path. The IRD system (Fig. 2) consists of an inductive loop and Dynax Axle sensors. The lateral position of each wheel path is determined based on the wheel locations on the sensors when the truck passes over the sensors. The position is automatically recorded by a computer-controlled data acquisition system.

**Truck and pavement description.** The truck used for this study is a 5 axle tractor-trailer combination. The weights have been carefully calibrated and placed on the truck so that the total weight of the truck is about 354 kN. The axle loads are distributed as follows:

- steering axle: 53.40 kN
- front axle of tractor tandem: 75.21 kN
- back axle of tractor tandem: 73.87 kN
- front axle of trailer tandem: 69.42 kN
- back axle of trailer tandem: 81.88 kN

The tractor has an air suspension, while the trailer has a four-spring tandem (short rockers) suspension.

Three flexible pavement sections were selected for this study. Cell 22 at Mn/ROAD, which is referred as section A in this paper, contains a 200 mm asphalt concrete pavement with a 460 mm thick crushed rock base. The base material is classified as A-1-a in the AASHTO classification. Section B (cell 26) and C (cell 25) are full depth asphalt pavements with thickness of 150 mm and 130 mm, respectively. The asphalt concrete pavements of all three sections have the same asphalt cement, AC120/150, and aggregate gradation. However, the subgrade soils on section B and C are classified as silt-clay (A-6) and granular material (A-1-b), respectively. Schematic representations of the three sections are shown on Fig. 3.

**Experimental procedures.** Routine truck tests have been performed on the low volume loop since fall 1993. The truck travels around the loop at an average speed of 65 km/h. The pavement responses are monitored through frequent collection of the sensor response data in selected test sections. The lateral location of the truck is obtained using a moist sand strip; the lateral distance from the center of the tire imprint to a reference mark (normally corresponds to the location of TE2) on the pavement is recorded for each passage of the truck. Since this measurement only gives the lateral position of the last axle to pass over the sand strip, a special study was conducted to address the issue of wheel path skew between axles using the IRD system. This will be discussed shortly.

For the purpose of this study, two sets of special truck tests were conducted on these pavement sections. The first set was performed on sections A and B on September 22 and 25, 1995, respectively. At the same time, a series of FWD tests were also conducted over the strain gages on section A immediately prior to the truck tests. Three different load levels were applied during the FWD tests with three drops on each level. The load levels ranged from 29 to 70 kN. The purpose of the FWD tests was to compare the strain response under FWD and truck loads. The truck passed over the strain gage sensors at speeds of 24 and 56 km/h on section A, and 10, 65 and 97 km/h on section B.

The second set test was done on section B and C on April 16, 1996. The speeds of the truck were about 40; 72 and 103 km/h. In the both sets of the tests, the truck passed over the sensors at least three times on each speed. The wheel path offsets were taken relatively to the transverse strain gage TE2 under the wheel path (Fig. 1) and measured from the imprints of the truck tire on a sand strip. It has been realized that the individual wheel could have different wheel paths. However, a study using the
Fig. 1 Typical strain gage and thermocouple layout for a flexible pavement section (not in scale).

Fig. 2 Layout of Lateral Positioning Sensor Array.
Section A
(150 m)

200 mm AC
(AC 120/150)

460 mm
Crushed rock base
(A-1-a)

Section B
(150 m)

150 mm AC
(AC 120/150)

Subgrade soil
(A-6)

Section C
(150 m)

120 mm AC
(AC 120/150)

Subgrade soil
(A-1-b)

- Thermocouple

Fig. 3 Schematic representation of tested three sections.

Fig. 4 Strong contaminated signal and filtered signal.
IRD system showed that the maximum difference of the lateral positions between the steering wheel and the back wheel of the trailer axle was about only 60 mm; which means that the truck can be assumed to travel in a straightway over the sensor area. The sand strip measurement can be reasonably taken to represent the overall wheel path offset of the truck.

When the truck passed over the sensor area, all the sensors were triggered manually and simultaneously. The sensor response data with a sampling rate of 2000 Hz were recorded using a high speed data acquisition system. The data were automatically transferred from the data acquisition system into a PC-computer in a binary format for the later analysis.

**EXPERIMENTAL RESULTS**

When the truck passes over a sensor, the signal from a sensor response is a time-history trace (Fig. 4) which normally contains five peaks or valleys. Each peak or valley corresponds to the passage of each axle. Depending on the magnitude of wheel path offset, the measured strains in the pavements can be tension (positive) or compression (negative). Typically, an engineer is concerned with the maximum or minimum response underneath a truck tire or falling-weight deflectometer plate. In order to extract the information from the sensor time-histories an effective method was developed to first minimize noise effects then detect the peaks or valleys from the signals (Dai and Van Deusen, 1996).

**Noise minimization and peak detection.** During construction of the facility every effort was maintained to minimize noise effects on the sensor systems, including shielded cables and twisted-pair conductors. However, since the sensors are exposed to a noisy environment, such as power line interference and other noise sources, the signals from the various sensors sometimes are corrupted. Interpretation of data from such affected signals can lead to inaccurate or even false results. Thus, it is necessary to treat noise effects on the measurements during the analysis procedures.

A computer program based on statistical and signal process theory was developed to automatically detect peaks and valleys from sensor response signals obtained during live heavy truck and falling-weight deflectometer testing (Dai and Van Deusen, 1996). Statistical methods are applied to characterize the nature of the signal and to make the detection of maximum or minimum values more efficient. Noise effects are treated by applying filtering techniques including Fast Fourier Transform and time domain filtering. Fig. 4 shows strong contaminated original signal and filtered signal.

**AC strain response to FWD loads.** Routine and inventory FWD tests as well as periodic tests for specific sensors have been conducted since fall 1993. EVERCALC 4.1 was used for the backcalculation analyses. The pavement temperature at the time of each FWD test was estimated using the BELL procedure (Stubstad et al., 1994). It should be noted that the authors are aware of the existing BELL procedure that is currently being revised. The results presented in this paper will be adjusted if needed when the new procedure becomes available.

Past research has shown that backcalculated pavement parameters can predict well the measured pavement strain during FWD tests (Lenngren, 1991). A study that was recently completed (Van Deusen, 1996) also showed that good predictions can be obtained for a range of pavement structural thickness. Fig. 5 gives the typical relationship between AC modulus and pavement temperature. An example of the comparison between measured and calculated strains on one section is shown in Fig. 6. Similar relations have been observed for other AC sections at Mn/ROAD that have thickness greater than 100 mm.

To further investigate AC pavement behavior under external loads, special FWD tests over the strain gages embedded on the bottom of the AC layers were performed on section A and B. As discussed above, the FWD tests on section A were conducted immediately prior to the truck tests. The average pavement temperature on the section at the time of the tests was about 70°C. The typical peak strain response is shown in Fig. 7a. Also, the peak strain response from section B is given in Fig. 7b. However, the average pavement temperature of about 40°C was observed at the time of the tests on section B. Both figures show that the peak strains on the bottom of the pavements are linearly related
Fig. 5 Relationship of asphalt concrete modulus with Bells temperature.

\[ y = 21779e^{-0.1047x} \]
\[ R^2 = 0.8544 \]

Fig. 6 Comparison of backcalculated strain with measured strain from FWD test.
Fig. 7 Typical pavement strain response to FWD load at different temperatures.
to the FWD loads and the lines pass through the origins, which means that the peak strains respond linearly and elastically to external loads and could be estimated using the linear elasticity up to an average pavement temperature of 40°C.

**Strain response to truck speeds.** Two sets of truck tests were conducted. In the first set, the tests were performed on section A on September 22, 1995 and on section B on September 25, 1995. To explain and further study a observed phenomenon from the first set of tests, the second set of truck tests were performed on section B and C on April 16, 1996. The experimental results from these two sets of the tests are summarized below.

In the first set of tests, the truck tests were conducted on section A immediately after the FWD tests in the same morning. All the experiments including FWD and truck tests were finished within one hour (9:00am-10:00am). The change of pavement average temperature varied from 70°C to 90°C in the hour. The truck passed over the strain gages three times at each speed of 24 km/h and 56 km/h. Chatti et al. (1995) showed that about 100 mm offset from a given sensor location is acceptable for studying the speed effects, so, only the tests with offset less than 100 mm or with the similar offsets from different tests were used for the study. Fig. 8 shows the longitudinal and transverse strain responses to truck speed. Also, the strains were compared with the strain measurements from the FWD tests. There were five peak strains for each pass of the truck. Each peak corresponded to an individual axle of the truck. It can be seen that the strains decreased as the truck speed increased. The strains generated by a FWD test under about 40 kN seemed to match with the strains from truck loads, which means that the peak strains produced by the truck loads can be reasonably represented by the strains generated by the FWD load under 40 kN.

The speed of the truck in the above tests was limited up to 56 km/h which is below the normal truck speed traveling on an interstate highway. To investigate the pavement behavior as the truck speed increases to an interstate speed, another truck test was conducted on section B. The truck traveled over section B at speeds of 10, 65 and 97 km/h with at least three passes at each speed. Again, only the tests which had wheel path offsets less than 100 mm were selected for the study. Strain responses to the truck speeds are shown in Fig. 9. As the speed increased from 10 km/h to 65 km/h, the strains decreased. However, when the speed further increased from 65 km/h to 97 km/h, the strains showed an increase. This increase may be due to the roughness of the pavement and dynamic loads generated by the moving truck. It is well known that higher speed reduces loading time on the pavement, therefore the pavement strain tends to decrease due to the nature of the material’s viscosity. Meanwhile, the higher speed produces higher dynamic loads, especially on a rough road. The higher dynamic load in turn increases the pavement strain. So, the strain response to truck speed depends on which mechanism dominates.

To further study this phenomenon, a second set of tests was performed on section B and C on April 16, 1996. The surface profiles of the two sections were measured using Pavetech van and the International Roughness Indexes (IRI) were calculated (Fig. 10). IRI on section B was 1.74 m/km, while IRI on section C was 0.97 m/km. This indicates that section B was much rough than section C. These sections are adjacent to each other on a straight road. Therefore, the tests can be performed on both sections at the same time without affecting the truck speed. The truck speeds were about 40, 65 and 103 km/h. Fig. 11a and Fig. 11b give the transverse strain responses in relation to speed on both sections. Also, Fig. 11c shows the longitudinal strain on section B. The transverse strain continuously decreased as the speed increased in section C, while the both transverse and longitudinal strains in section B again reduced as the speed increased to 65 km/h, then the strain increased when the speed further increased from 65 to 103 km/h. This may further illustrate that the pavement response depends on the pavement roughness and the vehicle speed based on the existing pavement conditions.

**Suspension type effects.** Suspension effects on the pavement strains can be distinguished by studying the strains generated by each axle. Recall that the truck has an air suspension on the tractor and a spring suspension on the trailer. It was realized that the offsets also has effects on the strains. So, to minimize the offset effects, only the tests with offset less than 25 mm were used for the study.
Fig. 8 Speed effects on the strains in the bottom of section A and strain comparison from FWD and truck tests (a) Longitudinal strain (b) Transverse strain; different symbols represent different truck passes; a dot is the strain due to passage of an axle.
Fig. 9 Speed effects on the strains in the bottom of section B; different symbols represent different truck passes.
Fig. 10 Surface profiles of section B and C; section B shows a higher IRI than section C. Also sensor locations are indicated.
(a) Transverse strain in section C

(b) Transverse strain in section B

(c) Longitudinal strain in section B

Fig. 11 Speed effects on the strains in the bottom of the pavements.
Furthermore, since the axles have different loads, the strain generated by each axle was also normalized to a standard 40 kN axle load for the purpose of comparison. Fig. 12 shows the transverse strains produced by each truck axle for the three different speeds on section B. It seems that the steering axle generated the least strain. When the speed was low (10 km/h), the strains produced by the tractor and trailer were, on average, not much different. However, the tractor with the air suspension caused higher strains than the trailer with the spring suspension when the speed increased to 65 km/h. But, when the speed further increased to 97 km/h, the trailer produced higher pavement strain than the tractor. This feature may be due to the effects of pavement roughness, tractor and trailer interaction, suspension characteristic and different offset between the tractor and the trailer.

Offset effects on strain. As mentioned above, the offset was measured relatively to the strain gage (TE2) under the wheel path. There are three transverse (TE1, TE2 and TE3) and longitudinal strain (LE1, LE2 and LE3) gages embedded in the bottom of the pavements (Fig. 1). So, the wheel path offset relative to the other gages can be evaluated. Figs. 13a, 13b, and 13c show the strain distributions produced by the steering axle with relation to the offset from routine truck tests on a day of May, 1996. Also, the strain distributions generated by the tractor and trailer tandem axles are illustrated in Figs. 14a, 14b and 14c, where the symmetrical twin peaks from the dual tires can be seen. The compressive strains on TE1 occurred when the offset of the steering axle was larger than about 220 mm. Furthermore, the compressive strains on TE1 from the tandem axle groups are also evident when the offset was larger than about 320 mm.

Additionally, the analytical calculations were performed to assess the offset effect on the strain by using the software WESLEA based on the linear elasticity. The ground penetrating radar study (Maser, 1995) showed that a 10 mm standard error of the pavement thickness exists. As mentioned above, the layer moduli were backcalculated from FWD deflection basin. Also the relationship of AC modulus with BELLS temperature was developed for each section (for example: Fig. 5). Considering the variations of the pavement thickness and modulus, the calculations were conducted under the following four cases (table 1):

**Table 1: Cases of the analytical calculation on wheel path offset effect on the pavement strains**

<table>
<thead>
<tr>
<th>Case</th>
<th>Thickness</th>
<th>Value (mm)</th>
<th>AC Modulus</th>
<th>Value (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Design thickness - SDT</td>
<td>122</td>
<td>Average E - SDM</td>
<td>6220</td>
</tr>
<tr>
<td>2</td>
<td>Design thickness + SDT</td>
<td>137</td>
<td>Average E - SDM</td>
<td>9110</td>
</tr>
<tr>
<td>3</td>
<td>Design thickness - SDT</td>
<td>147</td>
<td>Average E + SDM</td>
<td>4152</td>
</tr>
<tr>
<td>4</td>
<td>Design thickness + SDT</td>
<td>163</td>
<td>Average E + SDM</td>
<td>6731</td>
</tr>
</tbody>
</table>

where SDT is one standard deviation of the pavement thickness, Average E and SDM are the AC modulus at the average temperature and one standard deviation of the AC modulus on that day, respectively. The following dual tire loading configuration was used to simulate the dual wheels of the tractor and trailer axle groups:

![Fig. 15 Dual tire loading configuration for offset effects on strain.](image)

The calculated results are also given in Figs. 13a, 13b, 13c and 14a, 14b, 14c. Comparing the measurements and the analytical results, the measurements of the longitudinal strain were very well within the range between case 1 and case 4 of the analytical solutions. However, for the transverse strain, the measurements of the strain (TE1) on the inside wheel path toward the centerline seemed to match reasonably with the analytical solutions, while a slightly
Fig. 12 Suspension effects on pavement performance for different vehicle speeds.
Fig. 13 Strain distributions generated by the steering axle on section B and C; analytical solutions are also indicated.
Fig. 14 Strain distributions generated by the tandem axle groups on section B and C; analytical solutions are also indicated.
underestimation of the analytical solutions to the strains (TE3) on the outside wheel path toward to the shoulder was observed.

SUMMARY AND CONCLUSIONS

Flexible pavement responses to FWD load and truck speed were examined using instrumented pavements on the Mn/ROAD project. Three pavements which have different surface profiles and designs were selected for the study. The field experiments involved in various truck speeds up to an interstate speed of about 103 km/h. The study shows that the linear elasticity assumption seems to be acceptable to calculate the peak strains in the bottom of a flexible pavement at the average pavement temperature up to 40°C for at least 150 mm thick pavement. Also, the analytical solution to the strain in the bottom of the pavements based on the linear elasticity matched well with the field measurements under FWD load.

It has been observed that the strain in the bottom of the pavement continuously reduced as the truck speed increased on the smooth pavement (IRI=0.97 m/km). However, on the relatively rough pavement (IRI=1.74 m/km), the strain decreased as the speed increased up to about 65 km/h, then the strain increased when the speed further increased from 65 to 103 km/h. The results may indicate that truck speed effect on the AC pavement used in this study depends on pavement roughness and truck speed. Normally, the higher the vehicle speed, the less the duration of load acting on the AC pavement, which causes the strain in the bottom of pavement to decrease. However, on the other hand, the high vehicle speed on a rough road can produce high dynamic loads which may cause the strain to increase.

The effect of truck suspension type on asphalt pavement response seems to depend on the truck speed. At low speed, air suspension caused a higher pavement strain than spring suspension, while spring suspension generated a higher pavement strain than air suspension at a relatively high truck speed. Further research on this subject is required. The research should consider the speed and pavement profile to study truck suspension effects on AC pavement performance. Also, more tests need to be conducted to investigate the reliability of truck speed and suspension effects on AC pavement response.

Results from the field experiments illustrate that the transverse strain in the bottom of a pavement from a moving truck could be under tension or compression depending on the magnitude of wheel path offset. The strain measurements showed the symmetrical twin peaks generated by the dual wheels of the truck. Using the linear elasticity, the truck wheel path offset effect on the strains in the bottom of the pavements was investigated. The measured longitudinal strain showed a good agreement with the analytical solution. The measured transverse strain on the inside wheel path toward to the centerline matched reasonably with the theoretical solution, but the strain on the outside wheel path toward to the shoulder was slightly higher than the theoretical solution.

A planned research will be conducted on Mn/ROAD to further investigate the influence of vehicle configuration, such as tire pressure, vehicle type, and vehicle speed, on pavement performance. The research will also consider seasonal effects.

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