


Consideration of Seasonal Pavement Damage for Timber Haul Roads

HANNES H. RICHTER AND FREDERICK T. HSIA

Timber haul roads are subjected to severe use conditions that make them highly susceptible to seasonal impacts. They are located in areas of extreme terrain and environmental conditions, are constructed with minimal investment in the pavement section, and support extensive traffic from heavily loaded timber trucks. This multiyear study was undertaken to evaluate relative, traffic-induced damage to roads used at different times of the year and to provide rationally based road management alternatives. The field evaluation of the pavement section was performed by using periodic surface deflection measurements that were obtained with a Benkelman Beam, and included pavement temperature measurements at the test locations. The laboratory material characterization included the determination of resilient modulus relationships for cored asphalt concrete samples and for aggregate and subgrade materials. The assessment of laboratory and field data was performed by using computerized mechanistic analysis techniques, in which the pavement structure was considered a linear elastic multilayered system and the layered materials were characterized by their resilient modulus and dynamic strain ratios. The evaluation criterion was the fatigue life of the asphalt concrete as correlated with limiting elastic strains. Relative damage ratios were established for different seasons and were found to be significant and predictable for the roads under study.

INTRODUCTION

Wide-ranging seasonal changes in climate subject low-volume roads worldwide to severe use conditions. An understanding of the roadway's response to such seasonal changes and the long-term effect on the pavement structure is critical to the development of rationally based management programs. In consideration of these points, an analysis of seasonal use impacts of paved timber haul roads was undertaken by evaluating several roads in the Sierra Nevada Mountains of California. The assessment of seasonal effects was focused on the spring thaw period, when subgrade soils are saturated and temperature shifts can be extreme. A comparison was then made with periods of strength recovery during the summer and fall when the subgrade dries.

Surface deflections and pavement temperatures were measured at representative locations on four different roadways over a 4-year period in order to characterize seasonal responses to climatic changes (1, 2). Asphalt concrete, aggregate base, and subgrade samples were obtained from two roads that were selected for detailed study and were tested in the laboratory to determine their relevant engineering properties.
A computer-aided analysis of the pavement systems to evaluate relative damage levels for different periods during the year was performed with a mechanistic model using an elastic layered theory. Deflection data were also compared with existing general criteria from the literature. Various pavement management alternatives are presented that address the seasonal changes in load carrying capacities.

**ANALYTICAL DEVELOPMENT**

**General**

Pavement structures are highly complex, multilayered systems that are critically affected by changes in stress, temperature, and moisture environments. Pavements can be reasonably modeled, however, by the mechanistic analysis approach. This approach assumes that the pavement structure is a semi-infinite, linear elastic layered system in which materials are generally homogeneous and isotropic and can be characterized by the resilient modulus and dynamic strain ratios. A loaded pavement system, in which the strains that were found to be critical to pavement structures are depicted, is shown in Figure 1. In this system \( H \), \( E \), and \( v \) are the layer thickness, resilient modulus, and resilient strain ratio (Poisson's ratio in elastic theory), respectively. When a typical, 18-kip equivalent axle load was applied to the pavement system, stresses and strains were introduced to every point in the semi-infinite half-space.

The tensile strain at the bottom fiber of the asphalt concrete layer, \( \varepsilon_t \), was related to the fatigue life of the asphalt concrete, \( N_f \) at various temperature ranges or resilient moduli as shown in Figure 2 (3). The compressive strain on the top of the subgrade, \( \varepsilon_v \), was found to have an approximate correlation with performance, particularly in terms of riding quality and rut depth. A typical behavior function between allowable compressive strain and number of 18-kip axle load applications, \( N_v \), is illustrated by empirical correlation with the AASHO Road Test results in Figure 3 (4).

The mechanical and geometrical properties of the layered system, together with the surface deflection data, were correlated to the tensile and compressive strains. A computer was used to display the correlation in a four-variable graphic form, as shown in Figures 4 and 5. Surface deflection data could be converted to fatigue life or rutting life through a process shown in Figures 2 through 5. The convenience of bypassing the resilient modulus of the subgrade if the deflection and resilient moduli of the asphalt concrete and the aggregate base are known is shown in Figures 4 and 5.

**Damage Accumulation**

The linear summation technique known as Miner’s hypothesis was used to sum the compound loading damage that occurred to the pavement. The determination of pavement life was based on the accumulated damage level reaching unity for the total number of load applications. For a unit truck load, the damage level for fatigue, \( DL_f \), and the damage level for rutting, \( DL_v \), for a certain period, can be expressed as reciprocals of \( N_f \) and \( N_v \) for that period.

\[
DL_f = \frac{1}{N_f} \quad (1a)
\]

\[
DL_v = \frac{1}{N_v} \quad (1b)
\]
When these damage levels for individual periods are calculated throughout the truck operating season, the total damage levels for the whole operating season can be obtained through integration.

\[
(DL)_T = \int_{t_1}^{t_f} DL(t) dt
\]  

(Hsia and Padgett defined the relative damage levels for a certain period as damage ratios, with \( DR_f \) representing the damage ratio for fatigue, and \( DR_v \) representing the damage ratio for rutting \((3)\). Damage ratios are expressed by comparing them with either total damage levels \((DL)_T\) or selected reference damage levels \((DL)_R\).

\[
\begin{align*}
DR_f &= \frac{DL_f}{(DL)_R} \\
DR_v &= \frac{DL_v}{(DL)_R}
\end{align*}
\]  

When several representative sections are to be considered in order to evaluate the whole road, the combined effect can be expressed in matrix form as:

\[
[(DL)_T] = \sum_{j=1}^{n} [(DL)_T]_{ij} [(DR)_j]_{ij}
\]  

\[
[(DL)_R] = \sum_{j=1}^{n} [(DL)_R]_{ij} [(DR)_j]_{ij}
\]  

in which

\[
[(DL)_T], [(DL)_R] = \text{column matrices of damage ratio for fatigue and rutting at time } t \text{ for the whole road,}
\]

\[
[(DR)_j] = \text{square matrices of damage ratio for fatigue and rutting for the } j^{th} \text{ section at time } t,
\]

\[
[(i_j)] = \text{column matrix of section length, and}
\]

\[
\sum_{j=1}^{n} i_j = \text{a scaler representing the total length of sections under evaluation.}
\]

It should be noted that developments presented to this point are theoretical, and discrepancies may exist between theoretical analysis and field performance. Although relative damage levels may not be affected, a determination of total damage levels as they relate to ultimate pavement life may require that a correlation function between theoretical development and actual field performance be established.

\[
[(DL)_T]_{\text{field}} = f(x) [(DL)_T]_{\text{theoretical}}
\]

\[
[(DL)_R]_{\text{field}} = g(x) [(DL)_R]_{\text{theoretical}}
\]
The correlation functions \( f(x) \) and \( g(x) \) should be determined in the field and may be discontinuous for discriminatory categories. Until calibration can be accomplished for a given set of conditions or locality, it is suggested that a constant of 1.0 be assigned to both for simplicity, as follows:

\[
f(x) = g(x) = c = 1.0
\]

FIELD AND LABORATORY PROGRAM

Roadway Descriptions

Field tests were begun on selected representative sections of 50 mi of four paved USDA Forest Service roads in the California Sierra Nevada Mountains. Two roads were chosen for detailed evaluation of relative pavement damage during the timber haul season. Both roads were paved with 4 in of AR-4000 asphalt concrete over 5 in of aggregate base that rested on a subgrade soil, the consistency of which ranged from clayey sands to silty sands. Road A was located at an elevation of 6,000 to 7,000 ft and Road B at 3,600 to 4,800 ft. A 2-year pavement deflection study was conducted on both roads. Road condition surveys indicated no significant rutting problems on either road, although fatigue cracking was prevalent at many locations on Road A.

Deflection Measurements

Deflection measurements were taken from late April, after the snow had melted enough to allow access, through November, which was near the end of the timber haul season. Measurements were repeated at approximately 2- to 3-week intervals through June, once at the end of July, and once or twice in late fall. The Asphalt Institute Benkelman Beam rebound method was used in this study, as depicted in Figure 6 (5, 6). The deflection measurements were made at selected sections of the roads in the loaded lane and predominantly in the outside wheelpath. Test sections consisted of 10 sample points in 1,000 ft. These sections were considered to be representative of the soils and pavement structure, based on a more continuous sampling that was performed earlier. Pavement temperatures were also recorded for each section. Temperature adjustments were in accordance with the Asphalt Institute procedure (6).

Laboratory Testing

Repetitive loading devices were used to test the resilient modulus \( E \), dynamic strain ratio \( v \), and fatigue properties of soil, untreated aggregate base, and asphalt concrete. Dynamic strain ratios, based on a literature survey (Poisson's ratio in the elastic range), can be assigned the following values:

<table>
<thead>
<tr>
<th>Material</th>
<th>( v )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt concrete</td>
<td>0.35</td>
</tr>
<tr>
<td>Aggregate base</td>
<td>0.40</td>
</tr>
<tr>
<td>Subgrade</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Subgrade and Aggregate Base

Subgrade soil and aggregate base samples were compacted to 90 and 95 percent of the AASHTO T-180 maximum density, respectively, in accordance with original construction specifications, and as verified by in situ density testing. The sample was then tested in the triaxial cell at different confining stresses and cyclic deviator stresses, which were varied to accommodate the possible stress conditions. After the dry test was performed to define the upper-bound resilient modulus, back pressure was applied to saturate the sample as much as possible. The sample was then retested at this high degree of saturation to approximate the lower-bound resilient modulus.

Asphalt Concrete

The resilient modulus of asphalt concrete can be determined by stress-controlled, diametral repetitive loading devices (7).
Fatigue tests can be conducted either at varied modulus (loading) values or at different temperatures. The former is apparently easier to perform in the laboratory, whereas the latter provides a more direct approach to the evaluation procedure, and therefore minimizes unintentionally introduced errors.

Because the effects of temperature on the resilient modulus of the asphalt concrete were considered critical, cored samples were tested in diametral, resilient modulus devices at various temperatures. An example of the test results is shown in Figure 7.

DISCUSSION OF ANALYSIS AND RESULTS

Results

The sophisticated nature of the procedures and the interrelated characteristics of the variables necessitated a computer-aided analysis to execute the calculations and plot results. A modified version of the CHEV 5L computer program was used.

The results of typical computer calculations of damage ratios are presented in graphic form in Figures 8 and 9. The bases selected for comparison were October 4 for Road A and October 5 for Road B. Damage levels on these dates were not the lowest levels possible during the hauling season, but they were selected because the subgrade condition was fairly dry in the early part of October, and a reasonable amount of timber hauling could still have been expected before the season ended.

An examination of the $D_R$ values in Tables 1 and 2 for various sections indicates that some of the values are abnormally high and that the most critical period for rutting is delayed almost to the end of June for Road B, which does not coincide with the critical period for fatigue. The most promising method to estimate rut depth using the plasticity theory was the Prandtl-Reuss equation with a von Mises yield criterion. Because the application of this equation is complicated, and minor amounts

![Figure 7](https://example.com/figure7.png)  
**FIGURE 7** Resilient modulus versus temperature curves.

![Figure 8](https://example.com/figure8.png)  
**FIGURE 8** Damage ratios for different sections of Road A.
of rutting are generally not considered to seriously distress low-speed, timber haul roads, it was decided that only $DR_f$ would be taken into consideration (8).

The combined effect of all sections on $DR_p$, defined as $(DR_p)$, in Equation 4a, is shown in Figure 10. This figure was used to evaluate the relative potential damage of the whole road at different periods of the timber haul season. It should be noted that the peak periods of June 11 and May 19 for each road were established based on available field data. Had a day-to-day measurement been conducted during the critical period, peaks could have been relocated and would be expected to be somewhat higher than the ones shown. However, daily measurements were prohibitively costly and the peaks that were obtained in these figures should not have been much less than the actual peaks.

Straight lines were drawn between sample points until more data could be obtained to justify statistical smoothing techniques. It should be noted that although values may vary from year to year depending on climatic conditions, the pattern remains consistent.

The following observations can be made from an examination of Figures 8, 9, and 10:
TABLE 2  DAMAGE RATIOS FOR ROAD B

<table>
<thead>
<tr>
<th>Damage Ratio for Fatigue, DRf</th>
<th>Damage Ratio for Rutting, DRv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date (month/day)</td>
<td>Date (month/day)</td>
</tr>
<tr>
<td>Section</td>
<td>4/19</td>
</tr>
<tr>
<td>1</td>
<td>1.2</td>
</tr>
<tr>
<td>2</td>
<td>1.1</td>
</tr>
<tr>
<td>4</td>
<td>2.4</td>
</tr>
<tr>
<td>6</td>
<td>1.7</td>
</tr>
<tr>
<td>10</td>
<td>2.4</td>
</tr>
<tr>
<td>12</td>
<td>3.1</td>
</tr>
<tr>
<td>14</td>
<td>1.5</td>
</tr>
<tr>
<td>17</td>
<td>1.2</td>
</tr>
<tr>
<td>18</td>
<td>1.6</td>
</tr>
<tr>
<td>20</td>
<td>0.8</td>
</tr>
<tr>
<td>22</td>
<td>2.9</td>
</tr>
</tbody>
</table>

1. Damage ratios for each section of the road have a wider range in the critical period than in the summer or fall, which are dry seasons in the Sierra Nevada Mountains.
2. Ranges in the damage ratios for each section of the road during the peak period are more dramatic for Road B than for Road A. This may indicate that Road A experiences more severe environmental conditions or is more distressed than Road B, or both.
3. Average damage ratios for the critical period for Road B are lower than those for Road A.
4. The critical period of Road A is delayed when compared to Road B. This delay is believed to be the result of a difference in elevations, because Road A is located at a higher elevation and the thaw comes later in the year.

Economic Impacts

The potential economic effects of these damage ratios can be demonstrated with the following example. If 10 percent of the yearly traffic travels the road during the critical period, at 10 times the damage, the effect is 100 percent of the traffic during the spring, or a total net traffic of 190 percent. This effective doubling of the traffic could therefore halve the pavement life and dramatically increase its life-cycle costs.

Comparison With Deflection Criteria

Certain surface deflection data obtained in this study were compared with existing empirical criteria for tolerable deflection values, such as those developed by Kruse and Skok or presented by the Asphalt Institute (4, 5). Tentative application of these criteria to the roads in this study led to conclusions similar to those of the original studies in regard to the timing of allowable spring use. However, use of these criteria is limited and inappropriate for use by general management. Empirical criteria do not provide a means of assessing the long-term effects on the pavement structure and they cannot be confidently extrapolated to differing pavement, environmental, and traffic conditions.

Further Analysis

It is generally accepted that the worst road conditions usually occur in the spring thaw period when the subgrade is wet and provides weak support, and the asphalt concrete is cold, brittle, and consequently very susceptible to fatigue damage. It is important to point out that this conclusion should not be generalized and deflections alone may be insufficient to determine damage levels. Because of the variation in properties and geometries of layered systems, as well as the degree of severity of environmental influences, it is possible that the worst conditions may occur in the hot summer months when the stiffness of the asphalt concrete layer is low (8). Locally gathered deflection data must be combined with a mechanistic analysis to rationally assess relative damage for a specific area.

An investigation of the remaining life of the pavement was excluded in this study because of the lack of traffic data and past maintenance history. If these two categories of data are available, they should be incorporated into the management program. The deflection directly underneath the tires should
also be used in the analysis. A future extension of the research should include the curvature of the deflection bowl, which is a better representation of the flexibility characteristics of the asphalt pavement.

CONCLUSIONS AND RECOMMENDATIONS

Analyses of seasonal pavement deflections with mechanistic techniques were successfully performed to assess relative pavement damage at different periods during the year. The establishment of limiting criteria for low-volume roads must be considered part of a pavement management program and should include evaluation of economic and sociopolitical issues. Actions could include one or several alternatives that involve higher user costs, higher maintenance and replacement costs, or a combination of the two. The following alternatives encompass a broad range of potentially sensitive issues and should be carefully assessed for possible application on a local level.

Higher User Costs

1. Limit traffic during the critical period.
2. Reduce the loads carried by each truck during the critical period.
3. Increase the maintenance deposit to be used during the critical period.
4. Close roads to heavy trucks during critical periods.

Higher Maintenance and Replacement Costs

1. Do not impose seasonal use limitations.
2. Strengthen the pavement structural section with an overlay to accommodate the worst season.
3. Use an overlay to accommodate average conditions and accept the limitations of pavement life.

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REFERENCES