LOAD TRANSFER RESTORATION WITH DIAMOND GRINDING ON RIGID PAVEMENTS: SHORT-TERM AND LONG-TERM EFFECTIVENESS

By

Sharlan R. Montgomery (Corresponding Author)  
Purdue University  
550 Stadium Mall Drive  
West Lafayette, IN 47907  
(509) 737-7069  
montgo33@purdue.edu

Samuel Labi  
Purdue University  
550 Stadium Mall Drive  
West Lafayette, IN 47907  
(765) 494-5926  
labi@purdue.edu

and

John E. Haddock  
Purdue University  
550 Stadium Mall Drive  
West Lafayette, IN 47907  
(765) 496-3996  
jhaddock@purdue.edu

Revision Submission Date: October 25, 2016  
Total number of words in abstract, text, and references: 5,186  
Number of figures and tables: 7 = 1,750  
Total equivalent word count: 6,936
ABSTRACT
The objectives of this research were to develop nonlinear regression models describing the initial effect and the effect over time of load transfer restoration and diamond grinding (LTR/DG) treatments on pavement serviceability. This research used field data previously collected by Washington State Department of Transportation on pavement sections receiving LTR/DG treatments between 1993-2006. Expanded and simplified models were developed to describe the initial performance change associated with LTR/DG treatment. Considering the simplified model requires knowledge of fewer variables and describes the performance change with less variation, it is recommended for application. Charts were provided to estimate the expected performance change associated with LTR/DG. To achieve the greatest change, LTR/DG treatments should be performed on pavement younger than 30 years. A model was developed to describe the performance loss over time occurring after LTR/DG treatment. The regression model shows a slight increase in pavement condition for the first year or two following treatment, which was a common trend among individual pavement sections. Charts were provided to estimate the expected performance loss associated with LTR/DG. The simplified performance change model can be combined with the performance loss model to estimate the extended service life a LTR/DG treatment provides a particular pavement section. Additional performance change and performance loss models are recommended for LTR/DG treatments in other states and for longer post-treatment periods.
INTRODUCTION

Jointed concrete pavements are present in 43 states in the United States (1, 2) and constitute a significant portion of the interstate highway infrastructure system (3). Load transfer across joints and transverse cracks, characteristic of jointed concrete pavements, is essential to adequate pavement performance and condition (4, 5, 6, 7, 8). Under low trafficking, aggregate interlock can provide sufficient load transfer across joints and cracks. However, under high trafficking, joints and cracks can separate substantially causing a loss of load transfer and, consequently, a loss of support (4, 6). This failure mechanism leads to such distresses as faulting, pumping, cracking, and spalling (4, 6, 8, 9, 10).

Load transfer restoration (LTR), sometimes called dowel bar retrofit (DBR), is the practice of installing mechanical devices in the wheel paths spanning the joints or cracks to restore load transfer (2, 6, 8, 9) and has been utilized in the United States since the early 1980s (6, 8). According to a survey published by the NCHRP in 2014 (11) diamond grinding and dowel bar retrofits are the most commonly used concrete-surface pavement preservation treatments. Figure 1 shows that 44 of the 57 responding state highway and provincial transportation agencies in the United States, Puerto Rico, and Canada indicated that diamond grinding (DG) was a predominant concrete-surface pavement preservation treatment, while 34 agencies indicated that DBR was a predominant concrete-surface pavement preservation treatment. DBR treatment is commonly performed with DG (2, 4, 9, 12), which combination has proven effective in reducing faulting and cracking, and restoring ride quality and serviceability (2, 8, 9, 13, 14).

FIGURE 1 Use of concrete-surfaced preservation and rehabilitation pavement types (II).

Considering the predominance of these treatments in concrete maintenance and rehabilitation, it is fitting that research has been focused on documenting and evaluating common, and best, practices including various types of LTR devices (2, 3, 5, 6, 10, 13, 14, 15) as well as modeling and predicting the load transfer abilities of jointed concrete pavements after LTR treatment (4, 5, 6, 15). These studies have contributed knowledge and understanding of how best to perform LTR and DG treatments as well as documented and modeled how load transfer is restored through these treatments. However, while LTR/DG treatments are estimated
Montgomery, Labi, and Haddock

to extend pavement life by 10-15 years (9, 16) little research has been performed to describe, model (6), or predict the effect of LTR/DG treatments on pavement serviceability and service life. The condition, or quality, of a pavement section is generally described by means of a present serviceability rating, which is based on both pavement distress and roughness. LTR treatments are generally considered to improve the ride quality of faulted concrete pavements, specifically in connection with DG, but the effect of these treatments with respect to pavement serviceability has not been previously studied or modeled quantitatively. How much serviceability does a LTR/DG treatment add to a pavement section and what factors influence that initial performance change? How does the serviceability change over time following a LTR/DG treatment and what factors influence that performance loss? Based on these questions, the objectives of this research were to develop nonlinear regression models describing

1. The initial effect of LTR/DG treatments on pavement serviceability
2. The effect of LTR/DG treatments over time on pavement serviceability

A better understanding of the effect and performance of this treatment will allow it to be used more effectively and have greater acceptance in practical application and prioritization of treatments (4, 10).

This research used field data, previously collected by the Washington State Department of Transportation (WSDOT), from pavement sections receiving LTR/DG treatments between 1993-2006. This dataset was then used in the development of nonlinear regression models of both the initial effect of LTR/DG treatments and the effect of LTR/DG treatments over time on pavement serviceability.

BACKGROUND
Faulting Mechanism of Concrete Pavements
Faulting, shown in Figure 2, describes a difference in slab elevation that occurs at transverse joints or cracks in concrete pavements (14, 17). This distress occurs due to two mechanisms. The first is the movement of base material from the leave slab to the approach slab. The downward depression of the first, or approach, slab under loading followed by the rebound of the approach slab in combination with the depression of the second, or leave, slab causes the base material beneath the leave slab to migrate into the void created by the rebound of the approach slab, forming a faulted joint (17).

The second is the movement of base material from the leave slab to the pavement surface. The depression of the approach slab under loading when water is present in the base material followed by the depression of the leave slab causes pumping of base material beneath the leave slab to the pavement surface, forming a faulted joint and unsupported void beneath the leave slab (17). These faulting mechanisms can only occur if the base material is erodible, the load transfer between the slabs is poor, moisture is present, and there is significant truck traffic (2, 17).

Faulting is a major factor that affects the ride quality of concrete pavements (4) and consequently the serviceability. To the traveling public, average fault heights of 0.125 in. are noticeable while fault heights of 0.1875 in. to 0.25 in. (4.763 to 6.35 mm) are objectionable (18). While general thresholds have not been accepted (6), custom thresholds have been established triggering treatments such as LTR, panel replacement, and reconstruction. For example, the California Department of Transportation recommends a LTR when the deflection load transfer is less than 60%, when the differential deflection is greater than 10 mils, or when the international roughness index (IRI) is between 150-200 in./mi (2.37 to 3.16 m/km) (9).
Load Transfer Restoration Treatment with Diamond Grinding

LTR/DG treatment involves sawing rectangular slots in the wheel paths across transverse cracks and joints, placing steel dowels in the slots at mid-slab height, filling the slots with grout, and DG the faulted concrete. While this treatment has been effective in restoring both ride quality and load transfer, it is not recommended for pavements with insignificant structural capacity (9). Figure 3 shows the dowel bars and slots spanning an existing joint, a diamond ground concrete surface, and a finished LTR section with three dowels in each wheel path.

(a)

FIGURE 3 Load transfer restoration with diamond grinding process: (a) Dowel bars and slots (13) (b) Diamond ground surface (12) and (c) Finished load transfer restoration section (12).
Correlation Models of Present Serviceability with Roughness

In 1994, two correlation models, the Al-Omari and Darter model \((20)\) and the Gulen et al model \((21)\), were published relating the international roughness index (IRI) with the present serviceability index (PSI). The IRI is an objective method of describing the collective roughness of a pavement section, and is expressed in units of inches per mile. The PSI is unit-less, ranges from 0 to 5, and describes the condition of a pavement section by incorporating visual distresses, such as cracking and patching, with roughness.
Al-Omari and Darter Correlation Method

This model was developed using data from the NCHRP project 1-23 data base, which represents five states, and was combined with data from one additional state. Linear and nonlinear models were explored with the best model being exponential. Equation 1 was published as the best fit for portland cement concrete (PCC) pavements. This model forces pavements with an IRI of 0 in./mi to be equal to a PSI of 5.

\[
PSI = 5.0e^{-0.0043*IRI}
\]  

(1)

where:
PSI: present serviceability index
IRI: international roughness index (in./mi)

Gulen et. Al Correlation Method

This model relied on 10 randomly selected raters to evaluate 20 random sections; 9 were flexible pavements and 11 were rigid pavements. The PSI ratings, determined by the randomly selected raters, were related statistically to the measured IRI values for each of the 20 pavement sections. Linear and nonlinear models were explored with the recommended model being exponential as shown in Equation 2. This model, theoretically, allows pavements with low IRI values (less than approximately 65 in./mi) to have corresponding PSI values greater than 5.

\[
PSI = 9.0e^{-0.008784*IRI}
\]  

(2)

where:
PSI: present serviceability index
IRI: international roughness index (in./mi)

EXPERIMENTAL METHODOLOGY

In 1993, WSDOT began a large-scale LTR project in eastern Washington, which included LTR with DG (2). Thirty-two test sections, which represent over 300 miles of pavement, received LTR/DG treatments during a period of 14 years, from 1993 to 2006. IRI data were collected before and after the treatment until the end of the study period. Additionally, the pavement age at the time of treatment, the PCC pavement thickness, the base type (untreated, asphalt treated, or cement treated), the base thickness, and the subgrade type (fine or coarse) were determined and recorded for each pavement section.

For this research, the IRI data were converted to PSI ratings using the Al-Omari and Darter method (20) previously presented. This method was selected because it relates specifically to PCC pavements rather than grouping all pavement types into a single model. For each pavement section, the deterioration curves were evaluated and the PSI rating relating to the pavement condition before the LTR/DG treatment was performed was identified. The initial effect of the treatment, or performance change, was calculated as the difference between the PSI rating before the treatment and the PSI rating for the year directly following treatment. Since each pavement section did not receive the LTR/DG treatment at the beginning of the study period and some received additional treatments, the data were reduced to include only PSI ratings that described the pre-treatment condition and the post-treatment condition up until an
additional treatment was performed. The effect of the LTR/DG treatment over time was quantified by calculating the loss in PSI for each year of data available following treatment. This was done by subtracting the PSI rating for a given year from the PSI rating for the previous year. With this convention, a positive value indicates a loss of serviceability. For example, a change in serviceability of 0.25 PSI would mean that the pavement serviceability was reduced by 0.25 PSI during the year of interest.

A correlation analysis was performed to investigate the correlation between the pavement age at the time of treatment, the PSI before treatment, the base type, and the base thickness. Because of the low variability of the PCC thickness and the subgrade type across the test sections, these variables were omitted from the regression analyses.

To describe how much serviceability a LTR/DG treatment provides a pavement section, the initial effect, or performance change, was modeled using non-linear regression techniques. Additionally, to describe how the serviceability changes over time after treatment, the effect of LTR/DG treatments on pavement serviceability over time, or the performance loss, was also modeled using non-linear regression techniques. The variables included in the analyses were the pavement age at the time of the treatment, the PSI rating before treatment, the base type, and the base thickness. Base type values of 1, 2, and 3, represent untreated base, asphalt treated base, and cement treated base respectively. The following sections discuss additional methodology for both models.

**Initial Effect of LTR/DG Treatments**

To model the initial performance change (ΔPSI) that occurred as a result of LTR/DG treatments, the twenty-five WSDOT test sections that included a roughness measurement before treatment were included in the nonlinear regression analysis.

Basic statistics were calculated for the dataset including sample size, minimum, maximum, range, average, standard deviation, and coefficient of variation. The calculated ΔPSI values were divided into ranges and normalized frequencies to determine if the data were normally distributed.

Nonlinear regression analyses were performed to describe the relationship between the dependent variable, ΔPSI, and the independent variables. Several model types were explored including exponential, sigmoidal, and various power models. Considering the knowledge and availability of each variable is sometimes impractical, simplified models were also explored relating ΔPSI to only two independent variables: the PSI rating before treatment and the pavement age at the time of treatment.

**Effect of LTR/DG Treatments over Time**

To model the post-treatment performance change (PSI_{loss}) that occurred after LTR/DG treatments, the same twenty-five WSDOT test sections that included a roughness measurement before treatment were included in the nonlinear regression analysis.

Cooks distance, which estimates the relative influence of a data point, was calculated for the dataset and 5 of the 86 data points were removed as outliers considering the residuals were greater than 4/n. Basic statistics were then calculated for the dataset including sample size, minimum, maximum, range, average, standard deviation, and coefficient of variation.
Nonlinear regression analyses were performed to describe the relationship between the dependent variable, PSIloss, and the independent variables. Several model types were explored including exponential, sigmoidal, and various power models.

RESULTS
The correlation analysis indicated that most of the variables exhibited no sign of interdependence as evidenced by very low correlation values. However, one pair of variables, base type and base thickness, exhibited a relatively strong dependent relationship as evidenced by a correlation value of -0.66. Considering this relationship, the best fit models for the performance jump associated with LTR/DG treatments and for the performance loss occurring after LTR/DG treatments included dependent relationships between the base type and thickness. These models are provided and discussed in the following sections.

Initial Effect of LTR/DG Treatments
For the twenty-five test sections included in the model, the calculated ΔPSI values ranged from a minimum of 0.2 to a maximum of 2.04 with an average of 1.10. The standard deviation and coefficient of variation for the dataset were 0.50 and 0.45, respectively. After plotting and evaluating the frequency of the ΔPSI data, it was determined that data were relatively normally distributed, with the exception of one data point. Considering the unknown maintenance history of the variously aged pavement sections, and the nonlinear regression analysis of each of independent variable with respect to the performance change, the PSI rating prior to the LTR/DG treatment (PSIpre) was identified as the dominant component in the regression.

The best fit expanded initial effect model is provided in Equation 3. The corresponding R² value for this model was 0.463. Although the intercept for this mode is large compared to the normal range of PSI (0-5), the model provides appropriate ΔPSI data values

\[ \Delta PSI = 596.185 - 593.751 \times 1.001^{PSI_{pre}} - (5.128 \times 10^{-13})^{AGE^{7.229}} - 0.026^{BASE \times t_b} \]  

where:
- \( \Delta PSI \): performance change in PSI due to LTR/DG treatment (PSI)
- \( PSI_{pre} \): PSI of the pavement prior to LTR/DG treatment (PSI)
- \( AGE \): pavement age at time of LTR/DG treatment (years)
- \( BASE \): base type, (untreated base = 1, asphalt treated base = 2, cement treated base = 3)
- \( t_b \): base thickness, (in.)

The best fit simplified model is provided in Equation 4. The corresponding R² value for this model was 0.545.

\[ \Delta PSI = 0.946 + \frac{0.82}{-1.643 + e^{PSI_{pre}}} - 4.05 \times 10^{-19} \times AGE^{11.125} \]  

where:
- \( \Delta PSI \): performance change in PSI due to LTR/DG treatment (PSI)
- \( PSI_{pre} \): PSI of the pavement prior to LTR/DG treatment (PSI)
- \( AGE \): pavement age at time of LTR/DG treatment (years)
Since the simplified model provides less variation than the expanded model, base type and base thickness have less influence on the performance change associated with LTR/DG treatments. Considering the simplified model requires knowledge of and accessibility to fewer variables and describes the performance change associated with LTR/DG treatment with less variation, the simplified model is recommended for application. Since the models were developed using data from pavement sections ranging in age from 17 to 44 years and in PSI rating prior to treatment from 0.76 to 2.53 PSI, the models are only applicable to pavements in these age and PSI_pret ranges, respectively.

Figure 4 shows a chart for the simplified model, which is recommended for application over the expanded model. This chart can be used to estimate the expected performance change associated with LTR/DG treatments. For example, for a 30-year old concrete pavement with a PSI rating of 2.0 and a 7-in. thick untreated base, the anticipated initial performance change from a LTR/DG treatment would be 1.08 PSI, as obtained from Figure 4. Figure 4 may be used whether or not the base thickness and type are known.

As can be seen in Figure 4, the initial performance change obtained from the treatment is relatively constant until the pavement is about 30 years old at which point the performance change begins to rapidly decrease. Therefore, to achieve the greatest initial performance change, LTR/DG treatments should be performed on pavement younger than 30 years. Additionally, the vertical spacing between the PSI_pret values, 1.0, 1.5, 2.0, and 2.5 is not equal, or skewed. This means that as the pavement deteriorates, the rate of change in ΔPSI that can be added to a pavement by a LTR/DG treatment changes. This change occurs near a PSI_pret value of 1.5. Therefore, pavements with a PSI less than 1.5 before treatment have a greater ΔPSI than pavements with a PSI greater than 1.5 before treatment. The worse a pavement gets, the greater the initial performance change will be.

![Figure 4 LTR/DG treatment initial effect as a function of pre-treatment condition and age.](image-url)
Effect of LTR/DG Treatments over Time

The calculated performance loss for each year following a LTR/DG treatment for the twenty-five test sections are plotted in Figure 5, which also shows the average performance loss for each year. Table 1 lists the basic statistics for the dataset. The maximum time after a LTR/DG treatment up until an additional treatment was performed was determined to be 6 years. In Figure 5 and Table 1, years 1-6 represent the amount of PSI lost during years 1-6, respectively, since the retrofit was performed. A positive performance loss indicates a decrease in PSI while a negative performance loss indicates an increase in PSI, as per the convention used. An increase in PSI for the first year or two, as exhibited by the average performance loss trend line, was a common trend among individual pavement sections. This effect may be attributed to the change in texture of the diamond grinding during this period. The roughness measurements were collected by WSDOT using laser sensors, which equipment has issues producing artificially high values on diamond ground textures. As the diamond ground texture wore away during the first year or two after treatment, the artificially high roughness was removed.

FIGURE 5 Performance loss per year since treatment.

TABLE 1 Basic Statistics for the Performance Loss Model

<table>
<thead>
<tr>
<th>Statistic</th>
<th>PSI Loss Per Year</th>
<th>Age After Treatment (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.00</td>
<td>-0.42</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.00</td>
<td>0.67</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-0.07</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>-</td>
<td>0.24</td>
</tr>
<tr>
<td>Coefficient of Variation</td>
<td>-</td>
<td>-3.42</td>
</tr>
</tbody>
</table>
The best fit performance loss model is provided in Equation 5. The corresponding $R^2$ value for this model was 0.328. Since the model was developed using data from pavement sections ranging in time since treatment from 1-6 years, in age from 17 to 44 years, and in PSI rating prior to treatment from 0.76 to 2.53 PSI, the model is only applicable to pavements in these time, age, and PSI$_{pre}$ ranges, respectively.

$$PSI_{loss} = -0.215 + \frac{0.009}{(0.04 + 167.3 \times TIME^{10.571})} + \frac{4245.3}{(-470493.6 + 28656.3 \times AGE)} + 0.01e^{PSI_{pre}} + 0.005 \times BASE \times t_b$$ (5)

where:
- $PSI_{loss}$: performance loss after the LTR/DG treatment (PSI/year)
- $TIME$: time since LTR/DG treatment (years)
- $AGE$: pavement age at time of LTR/DG treatment (years)
- $PSI_{pre}$: PSI of the pavement prior to LTR/DG treatment (PSI)
- $BASE$: base type, (untreated base = 1, asphalt treated base = 2, cement treated base = 3)
- $t_b$: base thickness, (in.)

Figure 6 shows charts for the performance loss model. The charts provided are for an untreated base, which was the most common base type with a thickness of 7-in., which was the median base thickness observed in the dataset. Figure 6a, 6b, and 6c show the performance loss models associated with 20 year-old, 30 year-old, and 40 year-old pavement, respectively, which lie within the applicable age range of the model. These charts can be used to estimate the expected performance loss per year for the six years following LTR/DG treatments. For example, for a 30-year old concrete pavement with a PSI rating of 2.0 and a 7-in. thick untreated base, the anticipated performance loss directly following a LTR/DG treatment would be -0.10, -0.04, 0.12, 0.13, 0.13, and 0.13 PSI for years 1-6, respectively, as obtained from Figure 6b.

Consistent with the trend observed by the average performance loss trend line in Figure 5, the regression model shows a slight increase in pavement condition for the first year or two following LTR/DG treatment after which the pavement begins to deteriorate, losing serviceability, and finally follows a relatively linear deterioration rate.

Combining the initial performance change model with the performance loss model, the extended service life added to a concrete pavement section by performing a LTR/DG treatment can be estimated. For example, for a 30-year old concrete pavement with a PSI rating of 2.0 and a 7-in. thick untreated base, the anticipated initial performance change was 1.08 PSI using the recommended simplified model. Using the deterioration rates for years 1-6 from Figure 6b, and assuming the pavement continues to deteriorate after year 6 following the linear deterioration rate exhibited for the last three years of the model, it would take 11 years total for the pavement to deteriorate to a PSI rating equivalent to its PSI rating prior to the LTR/DG treatment. Thus, for this example, the LTR/DG treatment extends the pavement life by approximately 11 years. This extended service life falls within the range estimated by previous researchers (9, 16). This method for estimating the extended service life of LTR/DG treated pavements will be helpful for jurisdictions considering treatment.
FIGURE 6  Performance loss per year for (a) 20 year-old, (b) 30 year-old, and (c) 40 year-old pavements with a 7-in. thick untreated base.
CONCLUSION AND RECOMMENDATIONS

Load transfer across joints and transverse cracks, characteristic of jointed concrete pavements, is essential to adequate pavement performance and condition. Under high trafficking, joints and cracks can separate substantially causing a loss of load transfer and, consequently, a loss of support. This failure leads to faulting, pumping, cracking, and spalling. LTR is commonly performed with DG, which combination has proven effective in reducing faulting and cracking, and restoring ride quality and serviceability.

Research related to LTR treatments has focused on documenting and evaluating common, and best, practices and modeling and predicting load transfer abilities after treatment. However, while LTR/DG treatments are estimated to extend pavement life by 10-15 years, little research has been performed to describe, model, or predict the effect of LTR/DG treatments on pavement serviceability and service life. Therefore, the objectives of this research were to develop nonlinear regression models describing the initial effect of LTR/DG treatments on pavement serviceability and the effect of LTR/DG treatments over time on pavement serviceability. Using field data collected by WSDOT in connection with LTR/DG treatments performed between 1993-2006, nonlinear regression models were developed to describe the initial performance change associated with LTR/DG treatments as well as the performance loss occurring in the years following LTR/DG treatments.

The initial performance change expanded model had an $R^2$ value of 0.463 while the simplified model had an $R^2$ value of 0.545. Considering the simplified model requires knowledge of and accessibility to fewer variables and describes the performance change associated with LTR/DG treatment with less variation, the simplified model is recommended for application. Charts were provided to estimate the expected performance change associated with

---

(c) FIGURE 6 Performance loss per year for (a) 20 year-old, (b) 30 year-old, and (c) 40 year-old pavements with a 7-in. thick untreated base, continued.
LTR/DG, which is relatively constant until the pavement is about 30 years old at which point it begins to rapidly decrease. Therefore, to achieve the greatest initial performance change, LTR/DG treatments should be performed on pavement younger than 30 years.

The best fit performance loss model developed had an $R^2$ value of 0.328. The regression model shows a slight increase in pavement condition for the first year or two following treatment after which the pavement begins to deteriorate, losing serviceability, and finally follows a relatively linear deterioration rate. The increase in condition for the first year or two was a common trend among individual pavement. Charts were provided to estimate the expected performance loss associated with LTR/DG. An example was provided showing how the initial performance change model can be combined with the performance loss model to estimate the extended service life a LTR/DG treatment provides a pavement section. This method for estimating the extended service life of LTR/DG treated pavements will be helpful for jurisdictions considering treatment.

Although the data included in this research represents over 300 miles of treated pavement in Washington State, the length of the pavement sections varied significantly and only six years of post-treatment pavement condition are represented. While the models presented in this research can be used to estimate the initial performance change, the performance loss and, consequently, the extended service life provided to a pavement section by a LTR/DG treatment, additional research is recommended to build upon and verify the applicability of these models to other locations and situations. Specifically, initial performance change and performance loss models for LTR/DG treatments in other states and for longer post-treatment periods would extend and enhance this research for more widespread application and estimation of extended service life.
ACKNOWLEDGEMENTS

The authors would like to acknowledge and thank Dr. Linda Pierce for her assistance in
providing access to data and for her collaboration throughout this research project.

REFERENCES

   Department of Transportation, 2005.
2. Pierce, L. M. Evaluation of Dowel Bar Retrofit for Long-term Pavement Life in
   Washington State. Ph.D. dissertation, Department of Civil Engineering, University of
   Performance of Dowel Bar Retrofit Application, Performance, and Lessons Learned.
   Transportation Research Board. Transportation Research Board of the National
   Bar Retrofit Technique Using Statistical Modeling. Road Materials and Pavement
   Concrete Pavement Under Heavy Vehicle Simulator Loading. Transportation Research
   Record: Journal of the Transportation Research Board, No. 1823, Transportation
   American Society of Civil Engineers, 2004, pp. 29-35.
   Transportation Research Record, National Conference on Preservation, Repair, and
   Rehabilitation of Concrete Pavements, St. Louis, Missouri, 2009.
    Retrofit in Washington State. Sixth International Purdue Conference on Concrete
    Pavements. Purdue University, West Lafayette, IN, 1997.
    Practice. NCHRP Synthesis 457. Transportation Research Board of the National
    Interstate Highway Rehabilitation and Replacement. Washington State Department of


