Life Cycle Cost Analysis of Dowel Bar Retrofit

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ABSTRACT

The California Department of Transportation (Caltrans) has used dowel bar retrofit (DBR) on several projects. Caltrans has experienced both success and problems with this pavement preservation method. The primary question at the end is: if DBR performs as expected, is it the most cost-efficient solution? This presents the results of a Life Cycle Cost Analysis (LCCA) project comparing DBR with grinding and asphalt overlay. The performance assumptions were based on observed performance in the field and under heavy-vehicle simulator loading. Costs were collected from industry and Caltrans construction cost records. The analysis assumed the typical Caltrans practice of using nighttime closures to minimize road user delay. The analysis was performed using Caltrans LCCA procedures based on use of the Federal Highway Administration's (FHWA's) software RealCost. This study used a 40-year analysis period. It fits the planning horizon for the activities considered and meets the recommendations of the FHWA. Sensitivity analysis was performed considering these variables:

Initial remaining life: This takes into account the structural condition of the pavement that is a candidate for DBR. The analysis considered 10, 20, and 30 years of expected fatigue life remaining.

Grinding life: This captures scenarios for the interval between grinding in the absence of DBR. The analysis considered 10, 12, 15, 17, and 20 years.

User cost variables: These include traffic growth, closure details (time of day/week, number of lanes affected) and traffic distribution (rural versus urban, percentage of trucks). For this analysis, all closures were considered to be on weeknights from 10:00 p.m. to 6:00 a.m. and to affect only one lane of traffic. The chosen annual growth rate was 1.5 percent.

DBR performance: To account for the uncertain maintenance cost of DBR (due to failed backfill material), analyses in this study were run using a failure rate of 0 percent, 3 percent, and 6 percent per year. Results were also produced for the cases of plus/minus 10 percent from the expected DBR initial cost.

Discount rate: A discount rate of 4 percent for LCCA was used, as typically is done by Caltrans.

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The comparison was based on a 5-mi (8-km) rural stretch of highway with an initial annual average daily traffic load of 38,500 vehicles, 24 percent of which were trucks, loosely based on a DBR site on Route 99 in Kern County. The final results of the LCCA are relatively unaffected by the details of the case study. The analysis considers the possibility of additional fatigue life from DBR. Although the *Mechanistic-Empirical Pavement Design Guide* does not show increased transverse fatigue life from DBR, RadiCal predicts increased longitudinal fatigue life. Longitudinal cracking is common in dry western environments.

INTRODUCTION

The use of dowels in California concrete pavements began in 1999. Before that year nearly all portland cement concrete (PCC) pavements were undoweled jointed plain concrete pavements (JPCP). Previous testing confirmed that new construction using doweled pavements provides load transfer at the transverse joints between slabs that is superior to that of undoweled pavements, including when cemented bases are used (Reference *1* and others cited within it). To improve the load transfer between slabs for existing undoweled JPCP, a technique called dowel bar retrofit (DBR) can be used to install dowels on existing pavements. DBR can increase the faulting life of the pavement and eliminate the need for future grinding to restore ride quality. DBR may also increase fatigue cracking life. However, widespread use of DBR has been halted because of its large initial construction cost and the marginal performance history of the backfill material on several California pavement sections.

The work presented in this paper was performed as part of a project originally proposed in 2000 by the Caltrans Headquarters Division of Design. Other Caltrans divisions participating in oversight of the project included Headquarters METS Office of Rigid Pavement Materials and Structural Concrete, as well as Caltrans Districts 1 and 7.

This research is intended to provide Caltrans with information needed for decisions regarding selection of DBR and its design and construction, in order (1) to help determine where DBR may be a cost-effective strategy for rehabilitating rigid pavement and (2) to help obtain best performance where DBR is selected as the preferred rehabilitation strategy.

Scope

This paper assesses the cost-effectiveness of DBR compared to traditional capital maintenance (CapM) and rehabilitation techniques for concrete pavements. A life-cycle cost analysis (LCCA) tool used by Caltrans is employed for this assessment. With data from industry, Caltrans, and academic sources, costs are estimated for both Caltrans and users, under varying conditions. User costs are calculated using the Federal Highway Administration (FHWA) software package called RealCost and the Caltrans *Life-Cycle Cost Analysis Procedures Manual*, which was developed by Caltrans and the University of California Pavement Research Center (UCPRC).

Objectives of LCCA Modeling

This paper completes three main objectives. Each will help determine the overall cost-effectiveness of DBR.

- Determine the agency's life-cycle costs for DBR and its alternatives.

- Determine the users' life-cycle costs for DBR and its alternatives.
- Estimate the extension of fatigue life needed for DBR to become the preferable alternative, based on economic value.

The first two objectives are straightforward. The third objective is more complex, as it stems from the unclear relationship between DBR and fatigue life. It is thought that dowels may increase the fatigue life of concrete pavement by restraining slab curling caused by vertical temperature gradients, and by reducing stresses in the slab caused by dynamic interaction of truck suspensions with faulting at the joints caused by poor load transfer. However, these potential effects are not captured in available mechanistic-empirical models, and the range of potential fatigue life extension is therefore unknown. Because this information is unavailable, the third objective is to estimate the percentage of fatigue life that must be added by DBR for it to become a cost-effective CapM solution.

Potential Impact

It is important to estimate the number of lane-miles of California pavements suitable for DBR. If only a handful of sections are candidates for this technique, then further research into the cost-effectiveness of DBR is unwarranted. To estimate the number of lane-miles, candidate projects must be filtered out from the total lane-miles of concrete pavement in the State highway system. A basic criterion for candidate pavement sections is that they consist of undoweled JPCP with no overlay. Candidate sections must also have a minimal amount of cracking, as discussed later in this paper, with regard to the remaining fatigue life of the slabs. Using data from the Caltrans Pavement Condition Survey and the Office of Construction Engineering, it was estimated there are some 8,700 lane-mi (14,001 lane-km) of pavement that can be considered for DBR. The derivation of this value is shown later in the paper.

VARIABLES

This section presents a broad overview of the variables that can affect the LCCA results. While a complete list of variables is much longer than appears in this section, the following variables will significantly influence the results or are important to describe in detail. Also included are some assumptions used in the analyses.

Initial Remaining Fatigue Life

The remaining fatigue life of the PCC pavement plays a pivotal role in determining the cost-effectiveness of DBR treatment. While a DBR joint is designed to last indefinitely, it is useful only until the PCC pavement fails. When this happens, the investment of DBR is lost. It is assumed that a doweled pavement structure offers no benefit to subsequent overlays, as new undoweled cracks will be the weakest elements. This is especially true for the crack, seat and overlay (CSOL) strategy assumed in this study. For this reason, pavement sections with long remaining fatigue lives will reap greater benefits from DBR.

LCCA was completed for pavements with 10, 20, and 30 years of expected fatigue life remaining (before DBR). Because doweled JPCP became a standard design in California in the early 2000s, and most undoweled concrete pavements were constructed between 1955 and 1980, undoweled JPCP sections with over 30 years of remaining fatigue life are rare in the State highway system.

Grinding Life

Another variable is the time period between subsequent grinding treatments. The increase in load transfer efficiency provided by DBR will reduce faulting to a negligible amount. Therefore, pavement grinding will become generally unnecessary after DBR. Assessing the financial benefit from this requires knowing the number of grinding treatments that DBR will avoid over the life of the PCC. For example, if grinding without DBR is expected to last 12 years on a given pavement segment and 30 years of fatigue life are left in that pavement, then two pavement grindings (in Years 12 and 24) will be avoided by DBR.

Grinding life is sensitive to the pavement structure, traffic, the climate, and the International Roughness Index (IRI) trigger level. Because of the many variables involved, it is difficult to provide an "average" expected life for grinding. Several previous studies have attempted to provide a single value *(3, 4)*, but they included extrapolations and low confidence levels. Therefore, rather than adopt those values for this life-cycle cost analysis, the UCPRC used the Mechanistic-Empirical Pavement Design Guide (MEPDG) software to develop new estimates based on variables specific to California. The results from the initial estimates are shown in Table 1. PCC slab thicknesses of 8 in. and 9 in. (200 and 225 mm) were assumed since nearly all undoweled concrete pavements in the State were constructed with one of those design thicknesses.

Caltrans' acceptable IRI level (or "trigger" level in the Caltrans Pavement Management System) before a pavement section requires maintenance is considerably higher than that of FHWA. On California highways, an IRI of less than 213 in/mi (3.37 m/km) is acceptable, whereas national levels generally mandate only an IRI of 160 in/mi (2.53 m/km) or less. The difference between these values results in grinding life that lasts twice as long in California as in other parts of the Nation, depending on the definition of failure in terms of ride quality. This does not mean that grinding is more effective in California, but only that a higher level of roughness is allowed before the pavement is expected to require treatment.

Because grinding life is affected by traffic, PCC thickness, and climate, the LCCA uses variable grinding lives of 10, 12, 15, 17, and 20 years. This range includes the expected grinding life of 17 years, as stated in a previous report to Caltrans (*3*).

Table 1
Estimates of Grinding Lives from MEPDG

PCC Thickness (in.)	Yearly Traffic (ESALs)	Climate*	Years for PCC to Reach Faulting: 0.16 in. (IRI ~ 160 in/mi)	Years for PCC to Reach Faulting: 0.26 in. (IRI ~ 213 in/mi)
8	0.025×10^6	Central Coast	60+	60+
		Desert	60+	60+
		Low Mountain	60+	60+
	0.5×10^6	Central Coast	55	60+
		Desert	40	60+
		Low Mountain	36	60+
	2×10^6	Central Coast	14	27
		Desert	10	23
		Low Mountain	9	22
	5×10^6	Central Coast	6	11
		Desert	4	9
		Low Mountain	4	9
9	0.025×10^6	Central Coast	60+	60+
		Desert	60+	60+
		Low Mountain	60+	60+
	0.5×10^6	Central Coast	60+	60+
		Desert	60+	60+
		Low Mountain	54	60+
	2×10^6	Central Coast	20	38
		Desert	16	34
		Low Mountain	14	31
	5×10^6	Central Coast	8	15
		Desert	6	14
		Low Mountain	6	13

1 in. = 25.4 mm; 1 in/mi = 15.8 mm/km

*Note: Central Coast climate taken from weather station at San Francisco International Airport. Desert and Low Mountain climates are from Daggett and Santa Rosa, respectively.

Analysis Period

Several elements of a project influence the analysis period selected. First, the period should correspond with the planning horizon of the decision-making agency. Second, the period should allow for as many future maintenance and rehabilitation activities as reasonable. Finally, the period should be the same for all scenarios.

This study used a 40-year analysis period, which fits the above criteria and meets the FHWA's recommendations in its *Economic Analysis Primer (5)*. Changing the analysis period may have a significant impact on the results. The analysis period should meet the needs of a specific project. Because this research is aimed at estimating the overall cost-effectiveness of using DBR, an analysis period of 40 years was chosen, to represent an average situation.

User Cost Variables

A number of variables affect only the user cost calculations. Among these, traffic growth has the most significant influence on the analysis. Because the analysis period is 40 years, even a moderate yearly increase will sharply inflate traffic levels. For example, a modest growth of 2 percent per year for annual average daily traffic (AADT) will more than double the AADT over 40 years. Traffic growth significantly affects user costs when the capacity of the highway is reached during construction, thus creating a traffic queue. User costs have a tendency to increase precipitously as these queues develop. However, it is unrealistic to assume that moderate traffic growth will be sustained over the course of the analysis period without major enhancements being made to the capacity of the pavement section. In all likelihood, increased traffic demand will be curbed by adding a lane to the section, by creating an alternate route, or by a naturally occurring slower growth of traffic each year.

Two other notable variables that affect the user costs are the closure details (time of day/week, number of lanes affected) and traffic distribution (rural versus urban, percentage of trucks). For this analysis, all closures are considered to be on weeknights from 10:00 p.m. to 6:00 a.m. and to affect only one lane of traffic.

DBR Maintenance

The performance of DBR projects has achieved limited success in California. Applied Research Associates (ARA) in 2004 *(6)* and the UCPRC in 2007 surveyed the condition of selected projects and found that the grout in many of the backfilled DBR slots has failed since being installed. In the surveyed projects some 1.2 percent to 5.9 percent of their slots were found to have failed each year. While the slots can be fixed by removing the failed grout, resetting the dowel bar, and regrouting, doing so is a relatively expensive process that costs $10 to $15 per slot *(6)*. Extrapolated over a 10 lane-mi (16-km) DBR project, maintenance could run up to $25,000 per year on that section. Moreover, when a DBR slot has severely failed, it may no longer be providing the increased load transfer efficiency between PCC slabs. The damage to the pavement, though not quantified economically in this research, will (in theory) increase the life-cycle costs of the pavement section.

California's experience with DBR is unlike that of other States. DBR projects elsewhere in the United States have required little to no repairs during their life cycles *(2, 7, 8)*. The reason for the disparity between California's and other States' experiences is unclear, though contractor inexperience or inadequate grout materials are possible causes.

To account for the uncertain maintenance cost of DBR, analyses in this study were run using a failure rate of 0 percent, 3 percent, and 6 percent per year. This enables conclusions to be made about ideal, average, and worst-case scenarios, respectively. More information regarding the ARA and UCPRC condition surveys of the DBR sites, and estimation of failure rates, is given in references *(2, 9)*.

Discount Rate

Choosing an appropriate discount rate for the LCCA is crucial. Studies have shown LCCA to be highly sensitive to the chosen discount rate *(10)*. While Caltrans has commonly adopted a discount rate of 4 percent for LCCAs *(10)*, rates ranging from 3 percent to 10 percent are not uncommon for LCCA of pavement infrastructure. The 4 percent discount rate used by Caltrans is a reasonable value, but it should be noted that this rate has a significant impact on the results. For this LCCA, raising the discount rate would make DBR a less suitable alternative because the activities and user delays that retrofitting prevents are discounted to a lower net present value (NPV). Even small changes to the 4 percent discount rate could dramatically affect the LCCA results. External fiscal factors, such as any anticipated inflation differences between alternatives and the rate of return on investments, should also be considered *(5)*.

DATA AND METHODOLOGY

To analyze the cost-effectiveness of DBR under particular conditions, each permutation in the analysis is compared to an equivalent "base case" that does not employ the DBR strategy. The Caltrans *Life-Cycle Cost Analysis Procedures Manual* includes maintenance and rehabilitation (M&R) schedules for concrete pavements, giving base-case scenarios. These schedules can be altered to include DBR activities, resulting in customized DBR scenarios.

Activities and Schedules

The scenarios consist of the following activities:

- DBR—Insertion of dowel bars into existing undoweled JPCP.
- Grind—Diamond grinding of the PCC surface to remove faulting and other surface distresses.
- CPR-A—CPR on pavements where the total number of slabs that exhibit third-stage cracking or have been previously replaced is between 5 percent and 7 percent.
- CPR-A (NG)—Same as CPR-A, but without diamond grinding.
- CPR-B—CPR on pavements where the total number of slab that exhibit third-stage cracking or have been previously replaced is between 2 percent and 5 percent.
- CPR-B (NG)—Same as CPR-B, but without diamond grinding.
- CPR-C—CPR on pavements where the total number of slab that exhibit third-stage cracking or have been previously replaced is less than 2 percent.
- CPR-C (NG)—Same as CPR-C, but without diamond grinding.
- CSOL—Crack, seat, and overlay consisting of 0.10-ft (30-mm) hot-mix asphalt (HMA) over pavement-reinforcing fabric over 0.35-ft (107-mm) HMA.
- HMA (0.10 ft)—HMA overlay of 0.10-ft (30-mm) thickness.
- HMA (0.25 ft)—HMA overlay of 0.25-ft (76-mm) thickness.
- 2 percent DO—Digout of distressed portion equivalent to 2 percent of the section
- 5 percent DO—Digout of distressed portion equivalent to 5 percent of the section

CPR, which stands for "concrete pavement rehabilitation," consists of diamond grinding, slab replacement, spall repair, and joint seal repair.

From the above list of activities, M&R schedules were created for pavements with 10, 20, and 30 years of remaining fatigue life, for both the base case and the DBR alternative. Table 2 and Table 3 show these schedules.

Table 2
M&R Schedules for a Base Case (No DBR) and 10-Year Grinding Life

10-Year Fatigue Life		**20-Year Fatigue Life**		**30-Year Fatigue Life**	
Yr	**Activity**	**Yr**	**Activity**	**Yr**	**Activity**
0	CPR-B	0	CPR-C	0	Grind
5	CPR-A (NG)	10	CPR-B	10	CPR-C
10	CSOL	15	CPR-A (NG)	20	CPR-B
28	HMA (0.10')	20	CSOL	25	CPR-A (NG)
33	HMA (0.10') + 2% DO	38	HMA (0.10')	30	CSOL
38	HMA (0.10')	43	HMA (0.10') + 2% DO	48	HMA (0.10')
43	HMA (0.25') + 5% DO	48	HMA (0.10')	53	HMA (0.10') + 2% DO

Table 3
M&R Schedules for DBR

10-Year Fatigue Life		**20-Year Fatigue Life**		**30-Year Fatigue Life**	
Yr	**Activity**	**Yr**	**Activity**	**Yr**	**Activity**
0	DBR + CPR-B	0	DBR + CPR-C	0	DBR + Grind
5	CPR-A (NG)	10	CPR-B (NG)	10	CPR-C (NG)
10	CSOL	15	CPR-A (NG)	20	CPR-B (NG)
28	HMA (0.10')	20	CSOL	25	CPR-A (NG)
33	HMA (0.10') + 2% DO	38	HMA (0.10')	30	CSOL
38	HMA (0.10')	43	HMA (0.10') + 2% DO	48	HMA (0.10')
43	HMA (0.25') + 5% DO	48	HMA (0.10')	53	HMA (0.10') + 2% DO

To account for the sensitivity to variable grinding lives, four additional base cases were created for the scenario having 30 years of remaining fatigue life. These four cases are shown in Table 4. Each of these can be equitably compared to the "30-Year Fatigue Life" scenario in Table 3. The 30-year scenario was chosen because of the hypothesis that pavements with longer fatigue lives hold more promise for cost-effective DBR implementation.

Pavement grinding could be viewed as potentially decreasing the service life of a PCC pavement by reducing slab thickness. Although grinding reduces the thickness minimally, the MEPDG model was used to investigate to what extent a decrease in PCC thickness could reduce the pavement's fatigue life. For example, if a grinding activity removes 0.25 in. (6 mm) of material from an 8-in. (203-mm) PCC slab (a 3 percent material loss), the loss of fatigue life is roughly 10 percent to 30 percent. These results were obtained using the MEPDG software to predict cracking for slabs of different thicknesses.

Table 4
M&R Schedules for Base Case (No DBR) and 30-Year Remaining Fatigue Life

12-Year Grinding Life		15-Year Grinding Life		17-Year Grinding Life		20-Year Grinding Life	
Yr	**Activity**	**Yr**	**Activity**	**Yr**	**Activity**	**Yr**	**Activity**
0	Grind	0	Grind	0	Grind	0	Grind
10	CPR-C (NG)	10	CPR-C (NG)	10	CPR-C (NG)	10	CPR-C (NG)
12	Grind	15	Grind	17	Grind	20	CPR-B
20	CPR-B (NG)	20	CPR-B (NG)	20	CPR-B (NG)	25	CPR-A (NG)
24	Grind	25	CPR-A (NG)	25	CPR-A (NG)	30	CSOL
25	CPR-A (NG)	30	CSOL	30	CSOL	48	HMA (0.10')
30	CSOL	48	HMA (0.10')	48	HMA (0.10')	53	HMA (0.10') + 2% DO

In practice, it is believed that the first grinding does not reduce thickness by more than 0.10 to 0.15 in. (about 2 to 3 mm) when taken as average over the entire slab. To test this, three levels of fatigue life loss rates (10 percent, 20 percent, and 30 percent) resulting from grinding are analyzed using grinding lives of 10, 15, and 20 years. These scenarios appear in Table 5, Table 6, and Table 7. All the scenarios are based on a PCC pavement with 30 years of remaining fatigue life. It is assumed that the initial grind (Year 0) does not decrease the fatigue life and therefore that only subsequent grindings affect the pavement's structural integrity. This is a reasonable assumption, because the comparison DBR case (30 years of fatigue life remaining—see Table 3) does not model the loss of fatigue life from grinding that is performed at the time of the DBR. Thus, neglecting the life lost from the initial grind at Year 0 creates an equitable comparison framework for the ensuing analyses.

Table 5
M&R Schedules for Loss of Fatigue Life With 10-Year Grinding Life

10% Fatigue Life Lost From Grinding		20% Fatigue Life Lost From Grinding		30% Fatigue Life Lost From Grinding	
Yr	**Activity**	**Yr**	**Activity**	**Yr**	**Activity**
0	Grind	0	Grind	0	Grind
10	CPR-C	10	CPR-C	10	CPR-C
19	CPR-B (NG)	18	CPR-B (NG)	17	CPR-B (NG)
20	Grind	20	Grind	20	Grind
23	CPR-A (NG)	22	CPR-A (NG)	21	CPR-A (NG)
27	CSOL	25	CSOL	23	CSOL
45	HMA (0.10')	43	HMA (0.10')	41	HMA (0.10')

Table 6
M&R Schedules for Loss of Fatigue Life With 15-Year Grinding Life

10% Fatigue Life Lost From Grinding		20% Fatigue Life Lost From Grinding		30% Fatigue Life Lost From Grinding	
Yr	**Activity**	**Yr**	**Activity**	**Yr**	**Activity**
0	Grind	0	Grind	0	Grind
10	CPR-C (NG)	10	CPR-C (NG)	10	CPR-C (NG)
15	Grind	15	Grind	15	Grind
20	CPR-B (NG)	19	CPR-B (NG)	19	CPR-B (NG)
25	CPR-A (NG)	23	CPR-A (NG)	22	CPR-A (NG)
29	CSOL	27	CSOL	25	CSOL
47	HMA (0.10')	45	HMA (0.10')	43	HMA (0.10')

Table 7
M&R Schedules for Loss of Fatigue Life With 20-Year Grinding Life

10% Fatigue Life Lost From Grinding		20% Fatigue Life Lost From Grinding		30% Fatigue Life Lost From Grinding	
Yr	**Activity**	**Yr**	**Activity**	**Yr**	**Activity**
0	Grind	0	Grind	0	Grind
10	CPR-C (NG)	10	CPR-C (NG)	10	CPR-C (NG)
20	CPR-B	20	CPR-B	20	CPR-B
25	CPR-A (NG)	24	CPR-A (NG)	24	CPR-A (NG)
29	CSOL	28	CSOL	27	CSOL
47	HMA (0.10')	46	HMA (0.10')	45	HMA (0.10')
52	HMA (0.10') + 2% DO	51	HMA (0.10') + 2% DO	50	HMA (0.10') + 2% DO

To avoid removing too much of the structural capacity of the PCC slabs, the maximum number of grinds that can be performed is sometimes capped. In these cases, the pavement can fail by faulting rather than by cracking. To test this scenario, the M&R schedules presented in Table 5 were modified because of the maximum of two grinds (Years 0 and 10). Consequently, the CSOL activity is bumped up to Year 20 to compensate for the inability to perform another PCC grind. This makes faulting the critical distress mechanism. Table 8 shows the modified M&R schedules, which are capped at two grinds over the PCC service life.

Table 8
M&R Schedules for Loss of Fatigue Life With 10-Year Grinding Life and Maximum of Two Grinds

10% Fatigue Life Lost From Grinding		20% Fatigue Life Lost From Grinding		30% Fatigue Life Lost From Grinding	
Yr	**Activity**	**Yr**	**Activity**	**Yr**	**Activity**
0	Grind	0	Grind	0	Grind
10	CPR-C	10	CPR-C	10	CPR-C
19	CPR-B (NG)	18	CPR-B (NG)	17	CPR-B (NG)
20	CSOL	20	CSOL	20	CSOL
38	HMA (0.10')	38	HMA (0.10')	38	HMA (0.10')
43	HMA (0.10') + 2% DO	43	HMA (0.10') + 2% DO	43	HMA (0.10') + 2% DO
48	HMA (0.10')	48	HMA (0.10')	48	HMA (0.10')

Cost and Productivity Data

The basic data needed to perform an LCCA are the agency's initial and maintenance costs and the construction productivity rates (for the user delay costs). Many of the values adopted for this LCCA are taken from the Caltrans *Life-Cycle Cost Analysis Procedures Manual (9)*. Other sources include the Caltrans Office of Construction Engineering *(11)*, the *2005 State of the Pavement Report (12)*, and contacts at the International Grooving and Grinding Association (IGGA) *(8, 13)*. Historic construction cost records available on the Caltrans Intranet were also surveyed to validate certain costs. Table 9 shows the costs and productivities for the activities used in the analyses. Productivity is estimated assuming a 10-hour night shift. The initial and maintenance costs listed for DBR are for eight dowels per joint (four dowels per wheelpath) with an annual slot failure rate of 3 percent.

Table 9
Cost and Productivity Information

Activity	Initial Cost ($1,000/ln-mi)	Maintenance ($1,000/yr/ln-mi)	Productivity* (ln-mi/shift)	Source
DBR	120.0	0.84†	0.21	Roberts (*8*); Perez (*11*); Caltrans Intranet
Grind	46.3	n/a	7.00	Holloway (*13*); Perez (*11*); Caltrans Intranet
CPR-A	148.0	2.10	2.00	Caltrans (*9*)
CPR-A (NG)	101.7	2.10	2.33	Caltrans (*9*)
CPR-B	106.0	4.14	2.80	Caltrans (*9*)
CPR-B (NG)	59.7	4.14	3.50	Caltrans (*9*)
CPR-C	89.0	4.14	7.00	Caltrans (*9*)
CPR-C (NG)	42.7	4.14	14.00	Caltrans (*9*)
CSOL	279.0	1.32	0.52	Caltrans (*9*)
HMA (0.10')	99.0	0.63	1.87	Caltrans (*9*)
HMA (0.25')	299.0	0.63	0.66	Caltrans (*9*)
2% DO	1.0	n/a	n/a	Caltrans (*12*)
5% DO	2.5	n/a	n/a	Caltrans (*12*)

*Assumes a 10-hr night shift. †Assumes a slot failure rate of 3%.

Extension of Fatigue Life

The results for this analysis are presented in terms of the fatigue life extension needed in order for DBR to become cost-effective. For instance, a value of 33.3 percent fatigue life extension needed indicates that on a pavement with an estimated 20 years of remaining fatigue, DBR would need to extend that life to 26.7 years to be cost-competitive with the base case. This includes delaying each rigid pavement maintenance activity by the same percentage. Once the pavement is cracked, seated, and overlaid, the fatigue life extension benefits from DBR are nullified, making the duration between maintenance activities after CSOL identical for both the base case and the DBR case.

Figure 1 shows the cash flow diagram for an example base case, assuming a 20-year fatigue life remaining and a 10-year grind life. Figure 2 and Figure 3 show the cash flow diagrams for the equivalent DBR cases with 0 percent and 33.3 percent extension of fatigue life, respectively. The costs are for an assumed 20 lane-mi (32 lane-km) project, assuming a 5-mi (8-km) rural stretch of highway with two lanes in each direction (a total of 20 lane-mi [32 lane-km]). The section carries an annual average daily traffic (AADT) load of 38,500 vehicles, with an annual growth rate of 1.5 percent. Trucks account for 24 percent of the total AADT. The section is loosely based on a Route 99 DBR site in Kern County constructed in June 2000 that runs from post mile 54 to post mile 71.

Salvage Value, shown in Figure 1 and all subsequent cash-flow diagrams, is calculated for any activities that have design lives that extend past the end of the analysis period. Salvage Value is calculated by taking the cost of the activity and multiplying it by the design life years after the end of the analysis period, and dividing by the design life. This assumes straight-line depreciation of the value of the activity and zero residual value at the end of its design life.

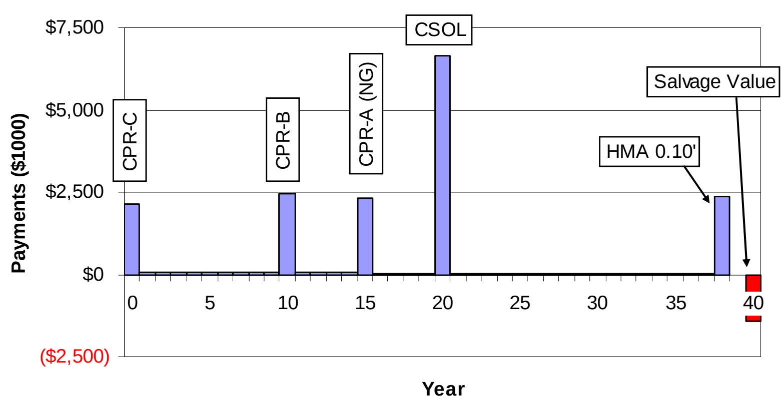

Figure 1. Example base case: 20-year fatigue life remaining and 10-year grind life.

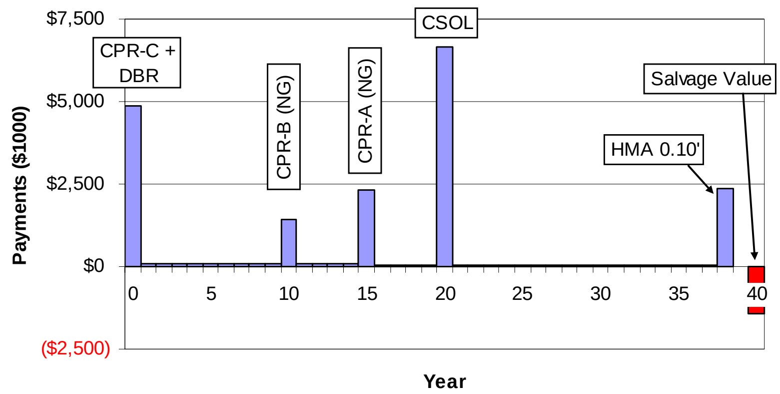

Figure 2. Example DBR case: 20-year fatigue life remaining.

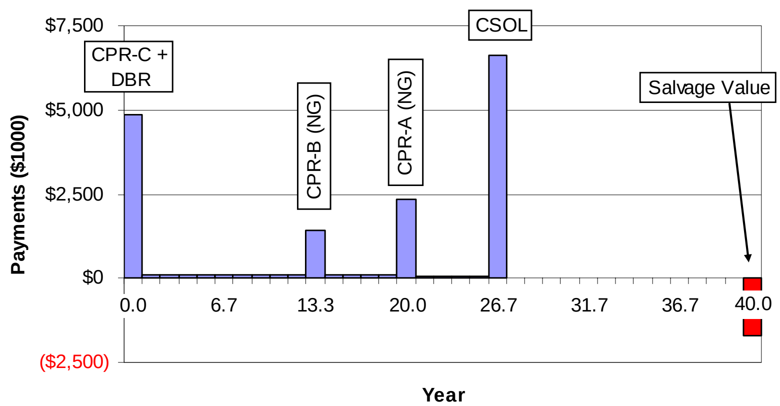

Figure 3. Example DBR case: 20-year initial fatigue life remaining with 33.3 percent extension.

It seems reasonable to expect that a well-constructed DBR could potentially extend fatigue life up to a maximum 50 percent. Although this is a great simplification, it is based on concrete pavement fatigue equations such as those in reference 14, which show that linear reductions in tensile stress in the concrete slab increase its fatigue life exponentially.

However, the current MEPDG models for fatigue cracking do not show any sensitivity to dowels, primarily due to the manner in which the finite element analyses used in the software to calculate tensile stresses were developed. The MEPDG can therefore be considered inadequate to evaluate the effect of DBR on concrete fatigue life. A comprehensive recalculation of the effects of DBR on tensile stresses is outside the scope of this project, however to illustrate the potential effects of DBR on tensile stresses causing fatigue cracking, a simple example was analyzed using a 3-D finite element program for concrete pavements called *EverFE (15)*.

The case consisted of three slabs in a lane, 3.6 m (12 ft) wide and 4.6 m (15 ft) long. The two-layer system had PCC slabs 225 mm (9 in.) thick, a subgrade k-value of 0.06 MPa/mm (221 lbf/in^2/in.), a PCC flexural strength of 4.5 MPa (650 lbf/in^2), and typical stiffnesses for the PCC and dowels. The pavement was modeled as three slabs in a row in the direction of traffic.

Two loading cases which illustrate the expected extremes of the effect of dowels on stresses causing cracking were analyzed:

1. A dual-single axle of 80 kN (18,000 lbs) at the mid-point of the center slab near the longitudinal edge of the slab (Figure 4), and no temperature difference between the top and bottom of the slab. This case would occur several hours after sunrise or several hours after sunset. It was assumed that the average slab temperature was low and therefore that there was no aggregate interlock between slabs.

2. A dual-tandem axle of 140 kN (31,500 lbs) with one axle on the center slab and the other on the preceding slab, combined with a steering single axle of 55 kN (12,375 lbs) near the transverse joint of the center slab. Both axles are near the longitudinal edge of the slab as shown in Figure 4. A temperature difference was assumed in the slab of –15°C (–27°F) between the top and bottom (cooler on top), which would occur in the Central Valley on a summer night.

These results were used with the fatigue equation cited above, and the percentage change in fatigue life was calculated for the cases with neither DBR nor aggregate interlock (common on cool nights) and with DBR (four dowels per wheelpath, typical spacing). The results are shown in Table 10.

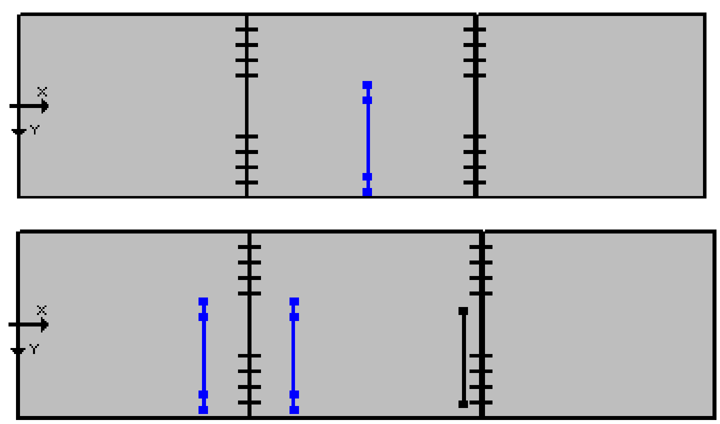

Figure 4. Load Locations for calculations shown in Table 10 (dual/single at mid-slab edge above; steering single on center slab and dual/tandem on two slabs below).

Table 10
Tensile Stresses in PCC and Estimated Change in Fatigue Life for Example Load Cases

	Maximum Tensile Stress in Slabs in MPa		**Fatigue Life**	**Fatigue Life**	**% Change in Fatigue Life With DBR**	
	1 Axle Mid-Slab	**2 Axles on Slab**	**1 Axle Mid-Slab**	**2 Axles on Slab**	**1 Axle Mid-Slab**	**2 Axles on Slab**
DBR	1.51	2.36	5.0E+11	2.4E+08	9%	626%
No DBR	1.52	2.58	4.6E+11	3.3E+07		

1 MPa = 145 lbf/in^2

The results displayed in Table 10 show that for some load situations the dowels have little effect on estimated fatigue life, such as the case with one axle on the slab in Table 10, which shows that dowels have little effect on mid-slab loading near the edge. The results for the case with two axles on the slab and a nighttime temperature gradient indicate that tensile stresses can be reduced by dowels. It is interesting to note that the case with two axles on the slab resulted in maximum tensile stresses at the midslab, which would contribute to classical transverse fatigue cracking in the slab.

The purpose of these very simple and limited scope fatigue life extension calculations is to provide an indication as to whether it is even possible for DBR to extend the fatigue life of existing PCC pavements. If DBR cannot extend fatigue life, then it is not economically viable compared to the base case of grinding only because, as will be seen in Results, the high initial cost of DBR is not overcome by elimination of later grinding in terms of life-cycle cost if faulting is the only mode of failure considered.

RESULTS

The LCCA was performed using the agency and user cost algorithms developed in the FHWA RealCost software package *(16)*. The data input to the program included the variables and scenarios presented above in previous sections. The rest of the data were taken from recommendations in the *Life-Cycle Cost Analysis Procedures Manual (9)*.

It is important to note that the final results of the LCCA are relatively unaffected by the case study's details. The traffic distribution (rural versus urban) affects only the user costs in the model, and that effect is minimal. While AADT and truck traffic would seem to have a significant impact on the results, their influence must be accounted for when estimating the remaining fatigue life of the pavement. The RealCost software uses only the direct input of AADT and truck traffic in calculating user costs, which are only road user delay costs associated with construction work zone traffic closures. As discussed below, the user costs are quite small when compared to the agency costs because of the use of nighttime traffic closures.

Variable Initial Remaining Fatigue Lives

Aside from the initial (before DBR) remaining fatigue lives of 10, 20, and 30 years, results have also been produced at plus/minus 10 percent from the expected DBR initial cost ($120,000/lane-mi) and at yearly slot failure rates of 0 percent, 3 percent, and 6 percent. These permutations were analyzed to check the sensitivity of the results to uncertain initial cost and the varying performance history of DBR in California. The results are shown in Table 11. Recall the assumptions in this analysis and their significance as discussed above, that is, a discount rate fixed at 4 percent and an analysis period of 40 years.

Table 11
LCCA Results for 10, 20, and 30-Year Remaining Fatigue Lives
(Assumes a 10-Year Grinding Life)

Initial Cost of DBR	DBR Maintenance (Failed Slots/Yr)	Percent Fatigue Life Extension Needed From DBR to Equal Life Cycle Cost of Base Case: 10-Yr Remaining Fatigue Life	20-Yr Remaining Fatigue Life	30-Yr Remaining Fatigue Life
Base Case Net Present Value →		**$11.21M**	**$9.40M**	**$6.65M**
$0.108M	0%	71%	35%	20%
	3%	74%	38%	24%
	6%	78%	42%	28%
$0.120M	0%	80%	41%	25%
	3%	84%	44%	29%
	6%	87%	48%	33%
$0.132M	0%	90%	47%	30%
	3%	93%	51%	34%
	6%	96%	54%	39%

Note: Dollar values are in millions of dollars per lane mile.

The percentages in Table 11 show that pavements with 30 years of initial remaining fatigue life hold the most promise for the cost-effective implementation of DBR, because they require the least amount of fatigue life extension from the DBR to have the same life cycle cost as the base case (grinding without DBR). It must be kept in mind, for reference, that a 50 percent extension in fatigue life for a pavement with 20 years of remaining life at the time of the DBR means that the eventual crack, seat, and overlay treatment must be deferred to Year 30. Depending on specific aspects of a given project, this may or may not be reasonable.

Variable Grinding Lives

Table 12 provides a closer examination of the 30-year remaining fatigue life scenario by varying the grinding life in the base case (grinding without DBR) between 10, 12, 15, 17, and 20 years. Since additional grinding is not needed after the initial grinding that is part of the DBR treatment, the variation in years between subsequent grindings affects only the base-case scenarios.

Table 12 shows that the grinding life in the base case (no DBR) is not as important as the number of times grinding has to be performed during the remaining fatigue life. This is exemplified by the significant jump in fatigue life extension needed between the 12-year and 15-year grinding cases. When a grinding activity lasts for only 12 years, it needs to be performed three times (Years 0, 12, and 24) over a 30-year span; when it lasts for 15 years, grinding needs to be performed only twice (Years 0 and 15) before a major rehabilitation occurs. The change in fatigue life extension needed between other grinding lives (for example, 10 years and 12 years, or 15 years and 17 years) ranges between 1 percent and 3 percent, whereas the change between the 12- and 15-year grinding lives is between 8 percent and 16 percent.

Table 12
LCCA Results for Variable Grinding Lives
(Assumes a 30-Year Remaining Fatigue Life)

		Fatigue Life Extension Needed from DBR				
Initial Cost of DBR	**DBR Maintenance (Failed Slots/Yr)**	**10-Yr Grinding**	**12-Yr Grinding**	**15-Yr Grinding**	**17-Yr Grinding**	**20-Yr Grinding**
Base Case Net Present Value →		**$6.65M**	**$6.56M**	**$6.05M**	**$6.01M**	**$5.90M**
$0.108M	0%	20%	22%	30%	31%	33%
	3%	24%	25%	34%	36%	38%
	6%	28%	29%	40%	41%	44%
$0.120M	0%	25%	26%	36%	37%	40%
	3%	29%	30%	42%	43%	46%
	6%	33%	34%	47%	49%	52%
$0.132M	0%	30%	31%	43%	45%	48%
	3%	34%	35%	49%	51%	54%
	6%	39%	41%	55%	57%	60%

Note: Dollar values are in millions of dollars per lane-mile.

Variable Fatigue Life Lost Due to Grinding

Using data from the MEPDG model, a 0.25-in (6-mm) grind will result in a 10 percent to 30 percent loss in fatigue life for PCC pavement. Applying DBR will aid fatigue life in two ways: (1) reducing deflections and stresses in the slab because of the presence of dowels at the joints, and (2) precluding the need to remove a fraction of the structural material (slab thickness) in future grindings.

Table 13 shows the results for a PCC pavement with an estimated 30-year remaining fatigue life. Because the percentage of life lost will vary between grinding activities, results are for fatigue life-lost increments of 10 percent, 20 percent, and 30 percent. The results are relative to the DBR case, with 30 years of initial remaining fatigue life at a cost of $120,000 per lane-mile and a 3 percent slot failure rate per year.

Table 13 also includes a case where the grinding has been capped at a maximum of two grinds over its service life. To model this scenario, CSOL is performed at Year 20. This is the year when a third grinding would normally occur but is not allowed due to the two-grind limit.

Table 13
LCCA Results Modeling Fatigue Life Lost from Grinding (Assumes a 30-Year Remaining Fatigue Life)

	Fatigue Life Extension Needed From DBR			
Percent Fatigue Life Lost From Grinding	**10-Yr Grinding**	**15-Yr Grinding**	**20-Yr Grinding**	**10-Yr Grinding, Maximum Two Grinds**
10%	21%	38%	42%	23%
20%	15%	30%	37%	22%
30%	9%	24%	33%	22%

As expected, modeling the fatigue life lost due to grinding will result in smaller percentages of fatigue life extension needed from DBR for DBR to be cost-effective compared to grinding without DBR. An intriguing note is that it is more cost-effective to cap the maximum number of grindings than to continue maintaining the PCC pavement for the rest of its service life. This is because multiple grindings may remove significant material from the surface. This makes future CapM activities (such as CPR) ineffective, due to the reduced life that can be expected from those future activities. For instance, if CPR-A is performed after 0.50 in (12.5 mm) of PCC has been removed, its expected life has been decreased from 5 years to between 2 and 4 years. The shortened life of this CPR activity due to thinning of the slab supports a plan to overlay the section before the pavement's fatigue life is exhausted.

CANDIDATE LANE-MILES IN THE CALTRANS NETWORK

DBR can be applied only to pavements that meet the following three basic conditions: (1) the surface layer is PCC, (2) the PCC is undoweled JPCP, and (3) the PCC has a minimal amount of cracking (discussed below). Identifying the number of lane-miles that meet all these criteria will produce an estimate of the potential benefit that can be obtained from the addition of dowel bars.

The Caltrans Pavement Condition Survey (PCS) database contains records of the surface type and distress level of all pavements in the State's highway network. The lane-miles of PCC and their respective cracking levels can be extracted from this database. The database has to be filtered to keep only those cases where the pavement surface type is PCC and the slabs exhibit low levels of cracking. Requiring a low cracking level ensures that the pavement has enough remaining fatigue life to warrant investing resources to dowel the pavement's joints. If a section has high cracking levels, it is not practical to install dowels because it will likely be reconstructed shortly after their installation. For the purpose of mining the PCS database for candidate lane-miles for this project, the thresholds for first- and third-stage cracking were set at 10 percent and 5 percent, respectively. Pavement sections that exceeded either of those cracking levels were not considered as potential candidates for DBR.

First-stage cracks are transverse, longitudinal, or diagonal cracks that do not intersect but that divide the slab into two or more large pieces. Third-stage cracks are interconnected cracks that divide the slab into three or more large pieces. Some transverse cracks can be retrofitted with dowels at the same time as transverse joints (*17, 18*), as long as the transverse cracking is not too extensive. Extensive longitudinal cracks and corner cracks make it very difficult to execute DBR. First-stage cracking in the PCS database can be either transverse or longitudinal cracking.

According to the PCS, the total lane-miles of PCC that have less than 10 percent first-stage cracking and 5 percent third-stage cracking is roughly 10,200 lane-mi (16,415 lane-km). This estimate has been filtered from an original total pool of 12,800 lane-mi (20,600 lane-km) of PCC pavement across the State as of the 2006 survey.

The 10,200 lane-mi (16,415 lane-km) include the three different types of PCC pavements used in California: undoweled JPCP, doweled JPCP, and CRCP. Undoweled JPCP is the only concrete pavement that can be considered for DBR. Therefore, the lane-miles of CRCP and doweled pavements must be subtracted from the 10,200 lane-mi (16,415 lane-km) of PCC pavements identified in the condition survey database. CRCP is extremely rare in California. The only known occurrence of this on the State highway network is a short test section on westbound I-80 in Fairfield. Another section near Tracy was overlaid with asphalt some years ago, but because there is such a small amount its length is negligible when compared to the total lane-miles of PCC pavement across the State.

California began using dowel bars in new construction in 1999. It became mandatory in 2004. According to the Caltrans Office of Construction Engineering, approximately 1,500 to 2,000 lane-mi (2,414 to 3,219 lane-km) of new PCC, full-depth pavement have been constructed since 1999. Unfortunately, since there is no comprehensive pavement structure inventory information in the current Caltrans database system, the only method of determining how many of those lane-miles contain doweled joints is to examine them on a case-by-case basis, which is too labor-intensive for this project. According to the Office of Construction Engineering, it is safe to assume that most PCC construction projects from 1999 to 2004 have dowels. For that reason, the value on the high end of the range is adopted: 2,000 lane-mi (3,219 lane-km) of doweled pavements.

The result of the above analysis is that there are approximately 8,200 lane-mi (13,197 lane-km) of pavement that are possible candidates for DBR. A further refinement to this value would be to stratify it by traffic levels because pavements with higher levels of truck traffic would benefit more from a doweled structure. This, however, is not easily accomplished using the available databases, therefore stratifying was only done in terms of truck and nontruck lanes. According to the PCS, 37 percent of the PCC lanes are truck lanes. Therefore, roughly 3,000 lane-mi (4,828 lane-km) of PCC are in truck lanes and currently do not contain dowels. These sections are likely to be good candidates for DBR. Because this represents roughly 25 percent of the total PCC pavement in the State, DBR could have a significant impact as a maintenance strategy, provided those lane-miles have sufficient remaining fatigue life to make DBR potentially economically competitive.

The construction dates of existing PCC pavements in the State are not available in any Caltrans databases at this time, and estimation of remaining fatigue life of PCC lane-miles across the network based on past truck traffic is outside the scope of this project. This analysis should be performed on a project-by-project basis if DBR is to be evaluated for LCCA versus grinding alone.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The question that this study has tried to answer is whether DBR is an economically competitive option for rehabilitation of concrete pavements. Although a single, simple answer cannot be given, some important conclusions are drawn from the work presented here.

Conditions That Make DBR Economically Effective

The benefits of DBR will not be immediately realized, which means that the avoidance and delay of future M&R activities only occurs after significant time has passed. But the LCCA results show that DBR *can* be a cost-effective solution under certain conditions. On rigid pavements with relatively long remaining fatigue lives (~30 years), the investment in DBR is recaptured through avoiding future grindings and extending the initial fatigue life. Alternatively, on pavement sections with short remaining fatigue lives (~10 years), much of the capital investment in

DBR will probably not be fully recovered. When a PCC pavement will need to undergo a major rehabilitation in the near future, the DBR benefits will not have sufficient time to materialize.

Extension in Fatigue Life Expected From DBR

Under the currently typical California case analyzed (initial cost of $120,000 per lane-mile, 3 percent failed DBR slots per year, 10-year grinding life, 20 years remaining fatigue life—see Table 11, DBR is the best solution if it provides at least a 44 percent increase in fatigue life. That is almost gaining 9 more years as a result of the DBR. The 44 percent is for a typical case, but Table 11 shows a sensitivity analysis and that, depending on the assumptions, this value can range from 20 percent to 96 percent. Some State agencies, like those of Kansas, Washington, Oklahoma, and South Dakota, seem to believe that such fatigue life extensions are possible, and have conducted extensive rehabilitation with DBR (see Reference *2*).

If DBR is limited to pavement with 30 years of remaining fatigue life (Table 12, which is to say pavements with almost no cracking [could be less than 5 percent slabs with first-stage cracking]), then an increase in fatigue life from DBR between 20 percent and 60 percent (depending on life of the grinding-only treatment and the initial cost) would be sufficient. If the slab thickness reduction from grinding and associated fatigue life reduction is taken into account (see Table 13, which assumes 30 years of remaining fatigue life), then the results show that using a 40-year planning horizon and a 4 percent discount rate, DBR must increase the fatigue life of the pavement between 9 percent and 42 percent to be a cost-effective solution, depending on grinding life and effect of thickness reduction.

A simple, quick analysis indicated that DBR could potentially increase the fatigue cracking life of PCC slabs. A reasonable upper bound might be 50 percent, primarily based on judgment and the fact that for many cases, such as the single-axle case analyzed, DBR provides no fatigue cracking benefit, while for others, such as the two axles-on-the-slab case analyzed, DBR can reduce tensile stresses and therefore increase fatigue cracking life. Determining the actual extent of a potential fatigue cracking life increase would require a detailed study as the increase depends on the pavement structure, subgrade, climate, load locations, axle types, and other factors.

Agency Versus Users Costs

Although this analysis considered both user costs and agency costs, the latter drove the results. The user costs, while substantially higher for the DBR cases, accounted for only a very small percentage of the total costs. In this analysis, agency costs were generally two orders of magnitude larger than the accompanying user costs for a given activity. For user costs to make a significant impact in the results, long traffic queues would have to develop as a result of the construction. Queues such as these can be produced by using high traffic growth rates and/or peak-time construction closures, both of which are contrary to the assumptions used in this analysis. However, it is realistic to assume that Caltrans will take measures to mitigate the inconvenience posed to users through the Traffic Management Plan when performing the retrofit. This includes using nighttime and off-peak closure schedules whenever possible.

Sensitivity to Construction and Maintenance Costs

The only initial construction cost that had a notable effect on the results was that of the DBR. A 10 percent change in the initial cost of DBR resulted in a 5 percent to 10 percent change in the fatigue life extension needed to be life-cycle cost competitive; this can be seen by the permutations included in Table 11 and Table 12. Economies of scale (which arise when DBR is implemented as a statewide rigid pavement capital maintenance activity) or other economic efficiency gains can reduce DBR construction costs.

The initial cost of grinding and the longevity of grinding activities are much less important to the results than the number of grinds that need to be performed over the remaining fatigue life of the JPCP. When the base case requires multiple grindings, the equivalent DBR case can avoid these future activities, thus saving the costs associated with them. The resulting loss of fatigue life is exacerbated when multiple grindings are necessary over the service life of the pavement. Therefore, when faulting is the anticipated trigger distress, DBR becomes a more feasible alternative because of its ability to improve load transfer efficiency and therefore avoid future grindings.

The annual maintenance costs also play a key role. Although California has encountered varied maintenance demand on its finished DBR projects, DBR has performed much better on a nationwide scale. It is not unreasonable to expect that the maintenance demand can approach zero failed slots per year if experienced contractors are selected and if underperforming backfill materials are ruled out. Closer inspection during the construction process would also help to ensure a quality initial product, as would considering warranty contracts for DBR projects.

Recommendations

In general, DBR is best suited for JPCP sections that have a substantial fatigue life remaining and that are susceptible to faulting. Because external inputs are highly sensitive, it is impossible to claim that DBR should (or should not) be used under all circumstances.

The first recommendation is that the decision to use DBR should be made on a project-by-project basis using the tables generated in this study. However, the results are interpreted, greatly simplified, as showing that:

DBR should not be performed on pavements containing more than 5 percent cracked slabs (third-stage cracking, either with slabs presenting interconnected cracks or having previously been replaced). The 5 percent cracking limit is subjective, but it was selected to reflect shorter fatigue life remaining in the candidate pavement. Even if slabs have been replaced and the current cracking level has therefore been reduced below 5 percent, the fact that slabs had been replaced should be interpreted as an indicator that the fatigue life of the original remaining slabs is about to be exhausted.

Another greatly simplified interpretation is that *DBR should be performed on pavements exhibiting less than 2 percent cracked slabs*. This will prevent faulting and will help in delaying slab cracking.

There is a grey area between the 2 percent and 5 percent where greater reliance on engineering judgment is required as part of a special project review. The primary factor to consider is the rate of faulting development. If there is sufficient fatigue life, then DBR is more likely to be life-cycle cost-effective where the rate of faulting development is high.

Factors increasing the rate of faulting development are:

- *Erodability of the base*: DBR will be more effective if the base is susceptible to erosion, which would lead to a faster rate of faulting development.
- *Poor aggregate interlock*: Smaller aggregates and lower strength aggregates will tend to lose load transfer efficiency faster, leading to faster faulting development. Loss of aggregate interlock also occurs where slabs have had greater shrinkage or have higher coefficients of thermal expansion, leading to opening of the joint.
- *Traffic forecasting*: DBR will be more cost-effective in situations with heavier traffic.

Each of these factors contributes to load transfer efficiency, which, combined with historical measurements of faulting development (current fault height divided by cumulative truck traffic or age), will give an indication of fault development rate.

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ACKNOWLEDGMENTS AND DISCLAIMER

Prepared in cooperation with the State of California, Business Transportation and Housing Agency, Department of Transportation. Technical direction was provided by William Farnbach and Tom Pyle for the Caltrans Pavement Standards Team, under the chairmanship of Tom Hoover and Peter Vacura. The technical representative for the Division of Research and Innovation was

T. Joseph Holland. The contract manager was Michael Samadian, assisted by Alfredo Rodriguez. The authors would like to thank all those involved for support and advice on this project.