

**Use of Life Cycle Cost  
Analysis to Determine the  
Cost-Effectiveness of Concrete  
Pavement Design Features**

**by**

**Lawrence W. Cole**

**American Concrete Pavement Association**

**5420 Old Orchard Road**

**Suite A-100**

**Skokie, Illinois 60077**

**Telephone: (847) 966-2272**

**Fax: (847) 966-9970**

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## **Use of Life Cycle Cost Analysis to Determine the Cost-Effectiveness of Concrete Pavement Design Features**

### **SELECTING CONCRETE PAVEMENT DESIGN FEATURES - COST VS. PERFORMANCE**

The design and construction of portland cement concrete pavement for highways involves the selection, specification and construction of a number of concrete pavement features. Among these features are foundation support, concrete slab thickness, concrete strength, joint spacing, depth and method of joint construction, subsurface drainage provisions, lateral edge support, transverse joint load transfer provisions, and joint sealant material with related construction details and requirements.

There are a variety of options available for each of these features. For instance, bases under concrete highways are typically constructed of dense graded granular material, cement-treated granular material, lean concrete, open graded (drainable) granular material, cement-stabilized drainable material or asphalt-stabilized material, both dense and open graded. Choices for paved shoulders include asphalt, partial-depth concrete, full-depth concrete and widened-lane concrete pavement with asphalt shoulders. Gravel shoulders are also used when standards allow.

The large number of design features results in hundreds of various combinations of concrete pavement design possibilities. State highway agencies select the best combination of features based on experience, preference, perceived performance, perceived constructability and estimated cost.

The two criteria of performance and cost are usually interrelated. Features which improve performance often increase construction cost. The relationship between performance and cost varies from feature to feature. Some features cost relatively little to construct, but significantly increase pavement performance. Other features may significantly increase construction costs, but do little to improve performance.

Specifying agencies must balance these two criteria when selecting concrete pavement design features. Specifying a feature which adds to construction cost without a suitable increase in performance is a misuse of funds. In some cases, choosing a feature or features which considerably increase construction cost can make concrete completing unfeasible for the paving project. The pavement with such high-cost design features simply cannot be built for the available money. Unfortunately, other less costly concrete designs may not be considered, even if such designs could provide acceptable performance over the facility's service life.

Likewise, selecting design features that don't provide adequate performance is also undesired. Less-than-adequate performance leads to early repairs, rehabilitation or reconstruction. Such procedures are costly and can cost more than the savings achieved from the lower construction costs. Additionally, the roadway users are inconvenienced sooner and more often. Safety concerns, both for the motoring public and contractor's or agency's workforce, are increased.

The concrete pavement designer's challenge is to select the features which give the proper balance of performance and cost for the desired level of service over the facility's life (Figure 1a). The designer must choose features which provide more performance benefit than they cost. Adding a feature or changing a feature that increases the construction cost must be accompanied by a suitable increase in pavement performance. When adding or changing design features, the balance should tip to the performance side (Figure 1b).

### **COMPARING THE PERFORMANCE AND COSTS OF DESIGN FEATURES**

Choosing features that add more to pavement performance than they cost is a difficult proposition. It requires an understanding of both the performance and cost aspects of a very large number of design features and combinations of features. It also requires a systematic procedure to compare the dissimilar criteria of pavement performance and cost.

### **Impact of Design Features on Pavement Performance**

Changing a concrete pavement design feature is expected to have an effect on the pavement's performance. The effects of various features on concrete pavement performance have been studied extensively, beginning as early as 1920. Some of the earliest test roads (1,2) included varying such design features as slab thickness, transverse joint spacing, reinforcement, (presence and amount), base type and other features and observing performance variations under known traffic loads. Numerous other studies have been done over the last seventy years as many experimental projects built to evaluate concrete pavement have included efforts to investigate the effects of design features on performance. More recent investigations have been done on a larger scale (3,4).

Field investigations of in-service pavement performance will undoubtedly continue as pavement engineers desire more and better information on the effects of design features on pavement performance. Some of the most significant information will come from the Federal Highway Administration's Long-Term Pavement Performance Program (LTPP). One of the six specific objectives of LTPP is:

“Determine the effects of specific design features to improve pavement performance.” (5)

The Long-Term Pavement Performance Program Specific Pavement Study on structural factors for rigid pavements (SPS-2) promises to be extremely beneficial in determining the effect of various design features on pavement performance. In total, 192 sections at sixteen sites in four climatic regions are planned. Concrete pavement design features variations include:

- Base (dense graded granular, lean concrete, asphalt-stabilized open graded)
- Slab thickness (200 mm and 275 mm)
- Concrete flexural strength (two levels)
- Lane width (3.65 m and 4.27 m) (12 ft and 14 ft)

Additional supplemental sections, as determined by the specifying agency sponsoring each SPS-2 section, will increase the design features evaluated in this undertaking.

In addition to information from observations of in-service pavements, performance models have been developed which allow comparisons of the effect of pavement design features on pavement performance. Many of these models are based on performance observations of in-service pavements. The most prominent of these is the AASHTO model for predicting drop in pavement serviceability (6). Others (7,8) are primarily founded on mechanistically-based analyses, usually calibrated to field performance in some manner. Most such models allow for changes in concrete pavement design features, thus allowing for performance comparisons to be made. Despite the large amount of study that this topic has been given, knowledge on the impact of various concrete pavement design features on pavement performance will continue to be sought and more study will be done.

#### **Impact of Design Features on Pavement Costs**

While significant research has been conducted for many years on the effects of concrete pavement design features on pavement performance, much less effort has been made to determine how design features impact construction costs (9,10,11).

One study (12) presents the impacts of concrete pavement design features on pavement construction costs. The study was made in terms of relative costs, not specific dollar values. This offers several advantages to users of the information. Concrete pavement construction costs vary across the United States, depending on labor and material costs, contractor equipment and capabilities, project size, availability of work, potential weather delays and many other factors. Likewise, general economic inflation and recession pressures can effect costs from year to year. Relative costs diminish the effect of these factors. These relative costs were intended for general comparisons of one concrete pavement feature to another for the general information of pavement designers and specifiers and were not intended for any other use.

To determine the relative cost of rigid pavement features, fourteen U.S. concrete paving contractors completed a series of feature cost survey forms. The forms included graphical and

descriptive representations of concrete pavement cross-sections and were grouped according to the feature being studied.

Each form began with the “reference section.” The reference section was described and assigned a relative cost value of 100. A specific concrete pavement feature was then changed, and the contractors were asked to determine the relative cost of the modified section. The same reference section was used to study all features. The reference section is shown in Figure 2.

The contractors were asked to give relative costs in terms of total project costs. The total project costs included all materials, equipment and labor necessary for subgrade preparation, base, concrete pavement, drainage system, shoulders and joint construction as shown on pavement cross-sectional diagrams on the survey form. In all cases, the individual completing the survey form was an owner, senior manager or chief estimator with the firm.

Since it would not be feasible to investigate the relative cost impacts of all design features, it was necessary to select specific features for study. Variations in the following design features were studied:

- Slab thickness
- Foundation
- Shoulders
- Transverse joint spacing
- Transverse joint load transfer
- Transverse joint sealant

A summary of these relative cost impacts of various design features is presented in Table 1.

### **Making Comparisons of Pavements with Different Design Features**

Changing a concrete pavement design feature will change both construction costs and expected performance. The designer’s challenge is to select features which add more performance benefit than cost. For such comparisons to be meaningful, it is essential to use a rational method of comparison.

One challenge is the dissimilar criteria used to measure performance and cost. Cost is measured in terms of dollars. Performance on the other hand, is more difficult to quantify in a single unit of measurement.

One method of measuring performance is the number of vehicle loads that a pavement can carry before it deteriorates to some minimum level of serviceability. This measurement method is used in the AASHTO rigid pavement design model (6). The number of traffic loads, expressed as 80 kN (18,000 lb.) equivalent single axle loads (ESAL's), carried until the pavement deteriorates to a minimum acceptable level of pavement condition, expressed in terms of pavement serviceability index (PSI), is calculated. Pavement rehabilitation is required when the minimum acceptable value, called the terminal pavement serviceability index, is reached. The difference between the pavements initial PSI and terminal PSI is the serviceability loss,  $\Delta$ PSI, where:

$$\Delta\text{PSI} = \text{PSI}_{\text{Initial}} - \text{PSI}_{\text{Terminal}}$$

The  $\Delta$ PSI can be used to compare the impacts of design features on pavement performance. For instance, the AASHTO model may show that changing from a dense-graded aggregate base to a lean concrete base, with no other design changes, will increase the number of ESALs required for the same  $\Delta$ PSI by 35%.

One must be careful, however, not to directly compare increases in load-carrying capacity to construction cost. Noting from Table 1 that the addition of a lean concrete base might increase construction cost by 22%, one might incorrectly compare this to the increase in load-carrying capacity of 35% to conclude that the addition of the lean concrete base is economically warranted. However, this may not be a correct conclusion. Construction costs, in terms of dollars, and pavement performance, in terms of ESAL capacity or other performance measurement, cannot be directly compared because the units of measurement are different. Likewise, changes in dollars and ESALs brought about by changes in other design features cannot be directly compared because the units of measurement are completely dissimilar.

## **LIFE CYCLE COST ANALYSIS TO DETERMINE THE COST-EFFECTIVENESS OF DESIGN**

### **FEATURES**

Life cycle cost analysis (LCCA) can be used to compare pavement design alternatives. LCCA can be defined as:

“A cost-centered engineering economic analysis whose objective is to systematically determine the costs attributable to each of one or more alternative courses of action over a specified period of time.” (13)

LCCA is well suited for the evaluation of alternative concrete pavement designs with different design features because it systematically accounts for both the monetary costs and benefits that the feature provides over the life of the pavement. For instance, by comparing life cycle costs of two pavement designs, one design with a specific feature and the other without the feature, the designer can determine which pavement design has the lower life cycle cost. The design with the lower life cycle cost would be considered more cost-effective. The most cost effective pavement design is that with the lowest life cycle costs.

### **Factors to Consider in LCCA**

The *AASHTO Guide for Design of Pavement Structures* (6) suggests that two categories of costs be considered in the economic evaluation of alternative pavement strategies - agency costs are user costs. Agency costs include:

- Initial construction costs
- Future construction or rehabilitation costs
- Maintenance costs recurring throughout the design period
- Salvage or residual value at the end of the design period (a negative cost)
- Engineering and administrative costs
- Traffic control costs

User costs included:

- Travel time

- Vehicle operation
- Accidents
- Discomfort
- Time delay and extra vehicle operating costs during resurfacing or major maintenance

These factors should be considered when making a LCCA of alternative concrete pavement designs with different design features.

### **Using Existing LCCA Models to Determine the Cost-Effectiveness of Design Features**

By comparing alternative designs with LCCA, it is possible to determine if a design feature is cost-effective. Existing LCCA models can be used. These models have been developed by state highway agencies and are based on observations of pavement performance tempered by engineering judgment. They are most commonly used for pavement type decisions, but can also be used for evaluating the cost-effectiveness of concrete pavement design features.

#### *Example #1 - Cost-Effective Analysis of Asphalt-Stabilized Drainable Bases Using Wisconsin DOT LCCA Model*

For example, the State of Wisconsin Department of Transportation (DOT) has developed a LCCA model (14) for concrete pavements which can be used to compare the cost-effectiveness of subsurface drainage for concrete pavements. A LCCA time-line for the options is shown in Figure 3.

For purposes of this illustration, the following assumptions about relative costs will be used:

- Initial construction without drainage - Cost = 100
- Initial construction with asphalt-stabilized drainable base - Cost = 123
- First repair and grinding - Cost = 20
- Subsequent repairs and overlay - Cost = 25

The relative costs applied to the LCCA time-line are also shown in Figure 3. Figure 3 uses average values for service lives of construction and rehabilitation options from the Wisconsin DOT LCCA model. The relative net present worth value calculated at a real discount rate of 5% (as used by the State of Wisconsin DOT in LCCA) can be determined.

- Relative net present worth of undrained design = 114
- Relative net present worth of drained design = 132

By comparing the relative life cycle costs it is apparent asphalt-stabilized drainable base is not cost-effective using Wisconsin DOT's LCCA model. In this example, a comparison between the relative net present worth of the undrained pavement design to the relative initial cost of the drained pavement design is also informative:

- Relative net present worth of the undrained design including all expected rehabilitation costs over the next 50 years = 114
- Relative initial cost of design that includes asphalt-stabilized open graded base = 123

The LCCA shows that the relative initial cost of concrete pavement with asphalt-stabilized open graded base is greater than the relative net present worth of undrained concrete pavements accounting for all expected rehabilitation for 50 years using Wisconsin DOT's LCCA model. This indicates that even if concrete pavement with asphalt-stabilized open graded base were to need no rehabilitation for 50 years, the design would not be cost-effective compared to a similar pavement section construction on dense graded aggregate base.

*Example #2 - Cost-Effectiveness of Sealing Transverse Joints Using Wisconsin DOT LCCA Model.*

Similar LCCA can also be used to assist in judging whether a change in design features is cost-effective. Again consider the Wisconsin DOT LCCA model for undrained concrete pavements to evaluate the cost-effectiveness of transverse joint sealant. The current Wisconsin DOT standard practice is to leave transverse joints unsealed. The current LCCA model is based

on this practice. What increase in performance is necessary to make silicone joint sealing cost-effective? For purpose of illustration, the following assumptions about relative costs will be used:

- Initial construction with unsealed joints - Cost = 99  
(Unsealed transverse joints at 4.6 m (15 ft) spacing)
- Initial construction with silicone sealed joints - Cost = 104  
(Sealed transverse joints at 4.6 m (15 ft) spacing)
- First repair and grinding - Cost = 20
- Subsequent repairs and overlay - Cost = 25

In this case, the additional life until first rehabilitation required to make joint sealing cost-effective will be calculated. The time between subsequent rehabilitations will be assumed to remain unchanged. The LCCA time-lines for equivalent life cycle costs for undrained pavement using the Wisconsin DOT LCCA model is shown in Figure 4.

From Figure 4, silicone joint sealant must increase the pavements performance from 23 years to 28 years before the first rehabilitation is done in order to be cost-effective compared to unsealed transverse joints using the Wisconsin DOT life cycle cost analysis model.

It is important to recognize that these examples are for illustration purposes only. Assumptions about relative costs of rehabilitation procedures may or may not be realistic. Furthermore, the examples did not include any consideration of user costs as the Wisconsin DOT generally does not include user costs directly in LCCA for pavement type selection. The purpose of these examples was to show how existing LCCA models can be used to evaluate the cost-effectiveness of concrete pavement design features. These examples should not be considered as an endorsement or criticism of the Wisconsin DOT LCCA model or pavement design practices.

## **USING PAVEMENT PERFORMANCE PREDICTION MODELS AND LCCA TO DETERMINE THE COST-EFFECTIVENESS OF DESIGN FEATURES**

### **Using the AASHTO Rigid Pavement Design Procedure and LCCA**

The AASHTO rigid pavement design procedure (6) and life cycle cost analysis can be used to determine the cost-effectiveness of design features. Consider again the example of the use of lean concrete base the design of a concrete highway using the following conditions and assumptions in LCCA:

- 1) Design features as shown in Figure 2, except
  - Asphalt shoulder in lieu of gravel shoulders.
  - Transverse joints at 4.6 m (15 ft) spacing in lieu of 6.1 m (20 ft) spacing.
  - Transverse joints with dowels (round, epoxy coated steel, 38 mm (1½ in.) diameter), 450 mm (18 in.) long, spaced at 300 mm (12 in.) on-center) in lieu of undoweled joints.
- 2) Design alternate #1 includes a dense graded aggregate base, 150 mm (6 in.) thick. Design alternate #2 includes 100 mm (4 in.) of lean concrete base placed on 150 mm (6 in.) dense graded aggregate layer. All other design features are the same for both alternate designs.
- 3) The pavement design period is 20 years.
- 4) The traffic volume and weight remains constant from year to year (i.e. constant ESALs/year).
- 5) The relative cost of pavement rehabilitation is 30.
- 6) The time between subsequent pavement rehabilitations is 10 years.
- 7) The LCCA period is 50 years.
- 8) A real interest rate of 4% is used in LCCA.

- 9) Routine maintenance costs, salvage value and other agency costs are the same for both alternatives and are therefore not included in the comparative LCCA.
- 10) User costs are not considered.

The AASHTO rigid pavement design procedure can be used to calculate the following:

- For design alternate #1 (dense graded base), the ESAL capacity is 8,111,000.
- For design alternate #2 (lean concrete base), the ESAL capacity is 10,994,000.

Design alternate #2 has a calculated ESAL capacity that is 35% greater than design alternate #1. Assuming that alternate #1 has a 20 year design period, alternate #2 will serve 7 years longer before rehabilitation.

From Table 1 the relative cost of design alternate #1 can be determined to be 112, while the relative cost of design alternate #2 can be determined to be 134. Design alternate #2 costs 20% more than design alternate #1.

Again, at first glance, design alternate #2 (with lean concrete base) might appear cost-effective when compared to design alternate #1 (with dense graded aggregate base) as the additional cost of 20% is significantly less than the increase in ESAL capacity of 35%. Life cycle cost analysis may show this conclusion to be incorrect.

The LCCA time-line for the alternate designs is shown in Figure 5. The addition of lean concrete base extends pavement design performance period from 20 years to 27 years, with subsequent pavement rehabilitation at 10 year periods for the LCCA period of 50 years.

The relative net present worth relative costs are:

- Design alternate #1 - 136
- Design alternate #2 - 149

This LCCA shows that the lean concrete pavement design feature is not cost-effective compare to dense graded aggregate base.

As with the previous examples using the Wisconsin DOT LCCA model, this example is meant to illustrate the use of LCCA to determine the cost-effectiveness of design features. It should not be used to conclude that lean concrete base is not cost-effective as the conditions and assumption used in these AASHTO rigid pavement design calculations and subsequent LCCA analysis must be substantiated before any such conclusion is valid.

Rather, the example shows how pavement design procedures coupled with relative costs and LCCA can be used to determine the cost-effectiveness of design features. It also shows that direct comparisons of increased performance (increased ESAL capacity) to increased construction costs is not a valid method of determining the cost-effectiveness of design features.

#### **USER COSTS IN LCCA TO DETERMINE COST-EFFECTIVENESS OF PAVEMENT DESIGN FEATURES**

In the examples shown in this study, user costs were not included in the relative cost of any rehabilitation procedures in LCCA. This is because user costs are not considered by most state highway agencies in the U.S. when performing life cycle cost analysis for pavement type selection. A recent compilation (15) by William A. Hyman of a 1993 survey of State Departments of Transportation indicates that 14 of the 38 responding DOTs include user costs in LCCA, but the report does not indicate if user costs are specifically used in LCCA of pavement design alternatives. Of these 14, however, 13 DOTs indicated they include delay costs as a user cost leading Hyman to conclude:

“Thus, it appears that the principal justification for including user costs in LCCA is to account for congestion delay costs.” (15)

User delay costs can considerably impact LCCA and should be considered when using LCCA for pavement type determination and for determining the cost-effectiveness of pavement design features. It is essential, however, that the user delay costs be applied consistently if they

are to be used. If LCCA for pavement type selection does not include user delay cost, then this factor should likewise be ignored when determining the most cost-effective concrete pavement design. If user delay costs are used in LCCA for pavement type selection, they should be included in selecting the most cost-effective design features.

Inclusion of user delay cost in LCCA for determining the cost-effectiveness of design features can be shown by revisiting the Wisconsin DOT LCCA model for drained and undrained pavements using relative costs and the following assumptions and estimates:

- Project length 8 km (5 miles) of four-lane divided highway.
- One lane closed for rehabilitation.
- Duration of lane closure - 30 days per lane, 120 days total.
- Speed reduction 105 km/hour (65 miles/hour) to 64 km/hour (40 miles/hour).
- Restricted flow length 8 km (5 miles).
- Restricted flow for 7.5 minutes (8 km at 64 km/hour) (5 miles at 40 miles/hour).
- Overall increased travel time - 2.9 minutes.
- Value of time lost (cars) - \$.25/minute.
- Value of time lost (trucks) - \$1.00/minute.
- Average daily traffic (cars) - 25,000.
- Average daily traffic (trucks) - 5,000.
- Delay cost (cars) -  $120 \times 2.9 \times .25 \times 25,000 = \$2,175,000$ .
- Delay cost (trucks) -  $120 \times 2.9 \times 1.00 \times 5,000 = \$1,740,000$ .
- Total delay cost - \$3,915,000.
- Relative cost of user delays for rehabilitation - .59.

When rehabilitation costs are adjusted to include an additional relative cost of 59 for each rehabilitation operations on the LCCA time line shown in Figure 3, the relative net present worth LCCA shows:

- Relative net present worth of undrained design - 151.
- Relative net present worth of drained design -156.

Although the relative net present worth of drained designs are closer when user delay costs are included, the use of an asphalt-stabilized open graded drainage layer is not cost effective using the Wisconsin DOT LCCA model based on the conditions and assumptions used in this example.

However, when the example using the AASHTO rigid pavement design procedure to predict pavement performance and LCCA to evaluate the cost-effectiveness of lean concrete base is recalculated using user delay costs, a different conclusion can be reached than when delay costs were not considered. If LCCA time-line in Figure 5 were changed to reflect a change in relative rehabilitation costs from 30 to 89 (59 added for user delay cost), the discounted net relative net present worth costs are:

- Alternate design with dense graded aggregate base - 199.
- Alternate design with lean concrete base - 186.

The alternate design with lean concrete base is cost-effective when user delay costs are included. When user delay costs were not included, the lean concrete base design feature was not cost-effective.

As with previous examples, these LCCA including user delay costs are for illustrative purposes only. Conclusions on the cost-effectiveness of any design feature in this study are only for illustration and are based on the assumed relative costs of rehabilitation operations (including user delay costs), and time periods between rehabilitation operations, which may or may not be valid.

## **CONCLUSIONS**

Concrete pavement design involves the selection of a number of design features. The pavement designer's challenge is to select the combination of features which provide the most cost-effective pavement design that balances two pavement qualities - performance and cost. The most cost-effective pavement design is that with the lowest life cycle costs.

Life cycle cost analysis (LCCA) can be a useful tool for evaluating the cost-effectiveness of concrete pavement design features because it provides a systematic method of comparing the dissimilar criteria of performance and cost over the useful life of the pavement. LCCA for evaluating the cost-effectiveness of design features can be done using existing LCCA models or can incorporate models that determine pavement performance or distress.

Relative costs are useful in such LCCA. Relative construction costs for a number of design features have been determined from a survey of U.S. concrete paving contractors.

Finally, inclusion user costs in LCCA can have a significant impact on the determination of the cost-effectiveness of design features. Although most State DOTs do not include user costs in LCCA for pavement type determination, some State DOTs include user delay cost in such LCCA. The consideration of user delay costs must be consistent. If user delay costs are used to determine the cost-effectiveness of specific concrete pavement design features, they should be included when making LCCA to determine which type of pavement (concrete or asphalt) to use on a project-by-project basis.

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Table 1 - Changes in Relative Cost of Reference Section as shown in Figure 2 (from Reference 12)

Change From	Change To	Change in Relative Cost	
		Average Response	Range of Responses
Slab thickness of 250 mm (10 in.) with 75 mm (3 in.) deep transverse joints at 6.1 (20 ft) spacing	Slab thickness of 150 mm (6 in.) with 45 mm (1 1/4 in.) deep transverse joints at 3.7 m (12 ft) spacing.	81	70 - 93
	Slab thickness of 200 mm (8 in.) with 57 mm (2 1/4 in.) deep transverse joints at 4.6 m (15 ft) spacing.	91	86-104
	Slab thickness of 300 mm (12 in.) with 90 mm (3 1/2 in.) deep transverse joints at 6.1 m (20 ft) spacing.	114	104-135
Undoweled transverse joint spacing of 6.1 m (20 ft) with joints sawed 75 mm (3 in.) deep, filled with hot-pour asphaltic joint sealant	Undoweled transverse joint spacing of 4.6 m (15 ft) with joints sawed 75 mm (3 in.) deep, filled with hot-pour asphaltic sealant material.	101	95-107
	Undoweled transverse joints spacing of 4.6 m (15 ft) with joints sawed 75 mm (3 in.) deep with a widened sealant reservoir 25 mm (1 in.) deep with backer rod and silicone sealant material.	104	101-107
Dense graded aggregate base, 150 mm (6 in.) thick on subgrade prepared by scarifying and recompacting at optimum moisture content to a depth of 150 mm (6 in.)	No base material. Concrete placed directly on subgrade scarified to a depth of 150 mm (6 in.) and recompacted at optimum moisture content.	84	78-95

Table 1 - (continued)

Change From	Change To	Change in Relative Cost Average Response	Range of Responses
	Lime-treated subgrade. No aggregate base material. Concrete placed directly on subgrade stabilized with lime to a depth of 300 mm (12 in.).	97	87-108
	Lean concrete base, 100 mm (4 in.) thick placed on 150 mm (6 in.) dense graded aggregate base layer. Subgrade preparation same as reference section.	122	96-144
	Unstabilized open graded aggregate granular layer, 100 mm (4 in.) thick placed on 150 mm (6 in.) of dense graded aggregate material. Trench edge drain under outside shoulder wrapped with geotextile and containing a 150 mm (6 in.) diameter flexible perforated pipe. Lateral rigid pipe outflows at 150 m (500 ft) spacing. Subgrade preparation same as reference section.	114	105-122
	Asphalt-stabilized open graded aggregate granular layer, 100 mm (4 in.) thick placed on 150 mm (6 in.) of dense graded aggregate material. Trench edge drain under outside shoulder wrapped with geotextile and containing a 150 mm (6 in.) diameter flexible perforated pipe. Lateral rigid pipe outflows at 150 m (500 ft) spacings. Subgrade preparation same as reference section.	123	109-132
	Cement-stabilized open graded aggregate granular layer, 100 mm (4 in.) thick placed on 150 mm (6 in.) of dense graded aggregate material. Trench edge drain under outside shoulder wrapped with geotextile and containing a 150 mm (6 in.) diameter flexible perforated pipe. Lateral rigid pipe outflows at 150 m (500 ft) spacing. Subgrade preparation same as reference section.	124	110-135
Gravel shoulders, 3.0 m (10 ft) wide outside shoulder, 1.2 m (4 ft) wide inside shoulder	Asphalt shoulders, 150 mm (6 in.) thick on 150 mm (6 in.) thick dense graded aggregate base. Same width as reference section.	111	105-125

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Partial-depth concrete shoulders, 150 mm (6 in.) thick on 150 mm (6 in.) thick dense graded aggregate base. Same width as reference section.

124

108-145

Table 1 - (continued)

Change From	Change To	Change in Relative Cost Average Response	Range of Responses
	Full-depth tied concrete shoulders on 150 mm (6 in.) thick dense graded aggregate base. Same width as reference section.	132	115-160
	Widened concrete lane. Outside traffic lane widened from 3.7 m (12 ft) to 4.1 m (14 ft) with 150 mm (6 in.) thick asphalt shoulders on 150 mm (6 in.) thick dense graded aggregate base. Asphalt shoulders are 2.4 m (8 ft) wide on outside and 1.2 m (4 ft) wide on inside.	112	104-122
Undoweled transverse joints at 6.1 m (20 ft) uniform spacing, no skew	Doweled transverse joints at 6.1 m (20 ft) spacing with round epoxy-coated steel dowel bars spaced at 300 mm (12 in.) on-center. Dowel bars are 38 mm (1½ in.) diameter, 450 mm (18 in.) long.	108	105-118
	Dowel transverse joints at 4.6 m (15 ft) spacing with round epoxy-coated steel dowel bars spaced at 300 mm (12 in.) on-center. Dowel bars are 38 mm (1½ in.) diameter, 450 mm (18 in.) long.	112	106-121
	Continuous reinforcement. No transverse joints. Continuous steel reinforcement with #6 deformed bars spaced 200 mm (8 in.) on-center longitudinally and 500 mm (36 in.) on-center transversely, placed one-half to one-third of the slab depth from the top surface of the concrete.	134	118-190
Transverse joints at 6.1 m (20 ft) spacing cut single width to a depth of 75 mm (3 in.) filled with hot pour asphaltic sealant material	No joint sealant.	98	94-99

Table 1 (continued)

Change From	Change To	Change in Relative Cost Average Response	Range of Responses
	Silicone sealant. With transverse joint spaced at 6.1 m (20 ft) spacing, joints are widened to create a 25 mm (1 in.) deep, 13 mm (1/2 in.) wide sealant reservoir. Joints are prepared and sealed with backer rod and silicone joint sealant material.	102	101-105
	Silicone sealant. With transverse joint spaced at 4.6 m (15 ft), joints are widened to create a 25 mm (1 in.) deep, 13 mm (1/2 in.) wide sealant reservoir. Joints are prepared and sealed with backer rod and silicone joint sealant material.	104	101-107
	Preformed compression sealant. With transverse joint spaced at 6.1 m (20 ft), joints are widened to create a 25 mm (1 in.) deep, 13 mm (1/2 in.) wide sealant reservoir. The joint is prepared and sealed with preformed compression sealant material.	105	102-115