Title

Pay Factors for Asphalt-Concrete Construction: Effect of Construction Quality on Agency Costs

Authors
Deacon, John A.
Monismith, Carl L.
Harvey, John T.

Publication Date
1997-04-01

Technical Memorandum
TM-UCB-CAL/APT-97-1

PAY FACTORS FOR ASPHALT-CONCRETE CONSTRUCTION: EFFECT OF CONSTRUCTION QUALITY ON AGENCY COSTS

Prepared for

CALIFORNIA DEPARTMENT OF TRANSPORTATION

by

John A. Deacon, Carl L. Monismith, and John T. Harvey

April 1997

Pavement Research Center
Institute of Transportation Studies
University of California, Berkeley

The quality of the construction process is one of the most significant factors determining how well a pavement will eventually perform under traffic loading. Construction specifications provide one means by which highway agencies seek to assure adequate performance. For a variety of reasons, however, construction specifications sometimes fall short in assuring the best possible performance for each paving dollar. As a result, highway agencies supplement construction specifications with other techniques including detailed quality control/quality assurance (QC/QA) processes and, more recently, pay incentives for contractors based on construction quality. It is the objective of this work to demonstrate a rational and feasible method for quantitatively establishing penalties/bonuses for the asphalt-concrete construction phase of new flexible pavement construction.

CONCEPT

Contractor pay incentives serve two important objectives: 1) they encourage the paving contractor to construct pavements having decidedly superior performance in comparison to those simply meeting minimum specification requirements while, at the same time, maintaining costs at reasonable levels and 2) they provide a rational alternative for dealing with marginally inadequate/adequate construction. Many factors must be considered in the establishment of pay schedules that not only realize these objectives but are also agreeable to both contractor and highway agency alike.

The approach taken herein focuses principally on economic impacts to the highway agency. It assumes that an appropriate penalty for inferior construction should be the added cost to the highway agency. It also assumes that the bonus for superior construction should be no greater than the added savings to the highway agency. Smaller maximum bonuses are likely to be necessary to insure budgetary integrity and, coupled with the penalties, may provide sufficient incentive to the contractor for improving construction quality.

For new construction, these agency costs/savings are associated primarily with subsequent pavement rehabilitation. Inferior construction hastens future rehabilitation and may increase the cost of rehabilitation as well. As a result, inferior construction increases the present worth of future rehabilitation costs. Superior construction, on the other hand, reduces the present worth of these costs largely by deferring the future rehabilitation. The difference in present worths of rehabilitation costs, as constructed versus as specified and as expected, provides a rational basis for setting the level of penalty/bonus for inferior/superior construction quality.

MODELS

Computation of the differential present worth of future rehabilitation requires two different models, a performance model for determining the effect of construction quality on anticipated pavement performance and a cost model for translating these effects into rehabilitation dollars. The performance model used herein is based on a mix analysis and design system originally developed as a part of SHRP (Deacon et al., 1994b), extended to efficiently treat in-situ temperatures (Deacon et al., 1994a), calibrated to the Caltrans flexible-pavement design system

(Harvey et al., 1995), extended to incorporate construction variability (Harvey et al., 1996), and most recently used in interpreting results of the first California heavy vehicle simulator (HVS) testing of the CAL/APT program (Harvey et al., 1997). As applied herein, it is limited to fatigue distress and specifically considers the means and variances of the following asphalt-concrete construction quantities; asphalt content, air-void content, and asphalt-concrete thickness. In estimating damaging strains under traffic loading, it treats the pavement as a multilayer, elastic system. The performance model computes the distribution of pavement fatigue life, expressed as ESALs, using Monte Carlo simulation techniques.

The cost model used herein is a quite simple one which considers only the time to the next rehabilitation activity. It understates agency costs by ignoring possible effects of construction quality on future rehabilitation costs: it also ignores future rehabilitation activity beyond the first cycle. It requires an exogenous estimate of future rehabilitation cost (in current-year dollars) and considers annual inflation of rehabilitation costs, traffic growth, expected years of new-pavement life, and a discount rate representing the time value of money. This cost model differs from one presented to Caltrans in the summer of 1996 which used the AASHTO performance equations and considered 1) not only the time of first rehabilitation but also the overlay thickness and 2) the timing of second and subsequent rehabilitation activity.

Performance Model

The process embedded within the performance model is outlined schematically in Figure 1. Central to this process is the random selection of air-void content, asphalt content, and asphalt-concrete thickness for each simulation. Although not shown in Figure 1 because it is only incidental to the current application, a random selection is also made of the foundation modulus, a modulus representing the composite effects of base, subbase, and subgrade layers in an "equivalent" two-layer elastic system.

These random selections assume normally distributed random variables with known or assumed means and variances. Of particular significance are the variances that might be expected under normal construction operations. Estimates of these variances were obtained from a combination of literature review, moduli backcalculations of FWD measurements, and unpublished data recently collected as a part of the WesTrack project[1]. Summary results are presented in Table 1. These totals include not only materials and construction components but also components resulting from testing and sampling. The latter components must be removed from the variance estimates in order to isolate materials and construction effects: Table 2 summarizes the necessary data.

---

[1]WesTrack refers to a Federal Highway Administration Project, "Accelerated Field Test of Performance-Related Specifications for Hot-Mix Asphalt Construction," which incorporates an experimental road test facility in Nevada.

Finally, Table 3 summarizes the quantities used herein to represent reasonable estimates of materials/construction variability associated with conventional construction practice. The equations for estimating the standard deviation of asphalt-concrete thickness were developed herein as an approximate way to handle multilift construction. Among the assumptions made in their development was that the coefficient of variation of thickness in single-lift construction is about 14 percent.

The multilayer elastic program, ELSYM5, is used to simulate the stress and strain states within the simulated pavement structures. Loading consists of a dual-tire assembly of 9,000 pounds (total) having a center-to-center spacing of 12 inches and a contact pressure of 100 psi. The critically stressed location for fatigue is assumed to be at the bottom boundary of the asphalt-concrete layer.

For the analysis reported herein, mix properties were developed from earlier testing of a mix considered representative of those in use in California (Harvey et al., 1995). Constituents of this mix included an AR-4000 California Valley asphalt cement and a Watsonville granite. The aggregate gradation passed between the middle limits of Caltrans 3/4 medium and coarse gradations. Stiffness and fatigue-life calibrations for this mix are as follows:

$$S = \exp(15.259 - 0.07577\ AV - 0.17233\ AC)$$

$$N = \exp(-22.0012 - 0.164566\ AV + 0.575199\ AC - 3.71763\ \ln\ \varepsilon)$$

and
in which S is the stiffness of the asphalt concrete in psi, AV is the air-void content in percent, AC is the asphalt content in percent (by weight of aggregate), N is the laboratory fatigue life, and ε is the maximum tensile strain in the asphalt concrete.

Each of the Monte Carlo simulations produces an independent estimate of the laboratory fatigue life, N. The corresponding simulated in-situ life, ESALs, is computed by applying a shift factor, SF, and a temperature conversion factor, TCF, as follows:

$$ESALs = \frac{N \bullet SF}{TCF}$$

The shift factor is an empirically derived factor that accounts for differences between the laboratory and the in-situ pavement in the rate at which fatigue damage accumulates with each load application. For computations reported herein, the shift factor was calibrated to the Caltrans design model following procedures used earlier (Harvey et al., 1995). Thickness replaced strain as the independent variable, however, and engineering judgement was used to develop reasonable estimates for the thickness and thinnest pavement sections. The shift factor is computed as follows:

$$SF = 30.48 + 6.44(t - 12) \qquad for\ t > 12$$

$$SF = 0.3771\ t^2 - 2.6109\,t + 7.5121 \qquad for\ 3.6\ \_\ t\ \_12$$

and

$$SF = 3 \qquad for\ \ t < 3.6$$

in which t is the asphalt-concrete thickness in inches. The temperature conversion factor, TCF, is given by:

$$TCF = 1.754\ \ln\ t - 1.256 \qquad for\ \ t\ \_\ 4$$

and

$$TCF = 1.175 \qquad for\ \ t < 4$$

For the analyses reported herein, the 10th-percentile fatigue life was used as the basic performance estimate. This life corresponds to about 10-percent fatigue cracking in the wheel paths. As verified by sensitivity analysis, incremental agency costs due to off-target construction (of either inferior or superior quality) are not significantly affected by the chosen performance percentile (at least within a reasonable range of the 1st to the 20th percentile).

Cost Model

The performance model yields the 10th-percentile in-situ fatigue lives, ESALs, for both expected or on-target construction quality as well as off-target construction quality. The relative performance, RP, the performance input to the cost model, is computed as follows:

$$RP = \frac{off\text{-}targetESALs}{on\text{-}targetESALs}$$

The first step in the cost model is to determine the off-target pavement life in years, OTY, that results from the simulated performance differential. Assuming that traffic grows geometrically, the off-target pavement life is computed as follows:

$$OTY = \frac{\ln(1 + RP\ [(1 + g)^{TY} - 1])}{\ln(1 + g)}$$

in which g is the annual rate of traffic growth expressed as a decimal and TY is the number of years of pavement life resulting from on-target construction activity.

The cost model assesses the present worth of moving the first rehabilitation cycle from its on-target position, TY, to its off-target position, OTY. The net present worth, expressed as a percentage of the rehabilitation costs (in current-year dollars) is computed as follows:

$$\Delta\, PW = 100\left(\frac{1+d}{1+r}\right)^{TY}\left(\frac{1+r}{1+d}\right)^{OTY} - 100$$

in which Δ PW is the percentage change in the present worth of the cost of the first rehabilitation cycle, r is the annual rate of construction-cost inflation expressed as a decimal, and d is the annual discount rate expressed as a decimal. Applying this percentage to the expected rehabilitation cost yields the agency cost increment due to off-target construction.

RELATIVE COMPACTION - AN EXAMPLE

The new pavement considered in this example is a four-layer system consisting of an asphalt-concrete surface, an aggregate base, an aggregate subbase, and a subgrade with an R-value of 20. It was designed using Caltrans procedures to accommodate a traffic index of 11. Elastic parameters for this structure, identified as 11AB20, are summarized in Table 4. Performance simulations illustrating the effects of air-void content, asphalt content, and asphalt-concrete thickness are depicted in Figures 2-4, respectively. For simplicity, this example is limited to illustrating the effects of air-void content or, its equivalent, relative compaction, on agency costs.

Construction is assumed to be controlled by a relative compaction specification (Caltrans Test 375). For the example calculations reported herein, the minimum acceptable relative compaction has been set at 95 percent (maximum permissible air-void content of 9.75 percent)[2]. Because relative compaction is considered to be a random variable, some violation of the minimum relative compaction specification during construction is expected. Figure 5 illustrates how the tolerable level of failure affects the acceptability of various combinations of the average and the standard deviation of air-void content. As the tolerable failure level increases, larger and more variable air-void contents are judged to be acceptable. For the example herein and for later computations as well, the tolerable failure level has been set at 1 percent. The relatively small, 1-percent failure percentage provides a reasonable, probabilistic interpretation to what historically has been viewed as a largely deterministic specification.

$$v = 100 - \%\ relative\ compaction \bullet \left(1 - \frac{v_{max}}{100}\right)$$

[2]The 9.75% air-void content assumes that the air-void content at maximum density is 5 percent. The percent air-void content, v, is related to the percent relative compaction and the percent air-void content at maximum density, v_{max}, as follows:

The influence of as-constructed air voids on pavement performance is shown in Figure 6. The best performance is associated with small averages and small standard deviations of air-void content, in other words, a consistently well compacted asphalt-concrete layer. Details of the performance model used to produce Figure 6 are also summarized in Table 4.

The highway agency can reasonably expect typical construction variability (a standard deviation of air-void content of about 1.2 percent). It can also reasonably expect construction operations to be in compliance with the specifications, in this case, a 1-percent failure tolerance of the 95-percent relative compaction specification. The expected pavement performance in this case, corresponding to an average air-void content of 7 percent, is about 16,500,000 ESALs (Figure 7). This is a reasonable target against which to measure both inferior (less than 16,500,000 ESALs) and superior (more than 16,500,000 ESALs) construction.

Contractor penalties can reasonably be extracted when the relative compaction specification is not met and when performance is inferior. This penalty zone is highlighted in the upper right of Figure 8. Contractor bonuses can reasonably be awarded when the relative-density specification is met and when performance is superior. This bonus zone is highlighted in the lower left of Figure 8. For other cases, no pay adjustment seems to be appropriate. Although the left, wedge-shaped zone of Figure 8 represents conditions having better-than-expected performance, a bonus should not be awarded because construction fails to meet specification requirements. The right, wedge-shaped zone of Figure 8 represents complying conditions, but performance fails to meet expectations and, hence, construction does not justify a contractor bonus. The presence of these two wedge-shaped zones, due in part to the probabilistic nature of both specification compliance and pavement performance, may explain traditional problems in trying to link relative-compaction specifications with performance.

The cost model is based on a comparison between the as-constructed pavement performance and the expected performance (16,500,000 ESALs). Model details are presented in Table 4, and results are summarized in Figure 9. Results are, of course, sensitive to the model parameters, and the discount rate and inflation rate are particularly significant.

EFFECTS OF CONSTRUCTION QUALITY ON SIMULATED FATIGUE PERFORMANCE AND AGENCY REHABILITATION COSTS

One of the primary purposes of the above example is to demonstrate a feasible approach to identifying an appropriate construction target for a minimum relative compaction specification. When the minimum requirement is 95 percent and the air-void content at maximum laboratory density is 5 percent, an air-void target of 7 percent is considered to be a reasonable expectation under current construction norms (a standard deviation in air-void content of 1.2 percent). Other reasonable targets for normal construction activity include a mean asphalt content equivalent to the job-mix formula with a standard deviation of 0.19 percent (Table 3) and a mean asphalt-concrete thickness equivalent to the design thickness with a standard deviation as determined by the equation of Table 3.

With these targets in mind, a set of simulations was performed to quantify the effects of construction quality (air voids/relative compaction, asphalt content, and asphalt-concrete thickness) on both simulated in-situ fatigue performance as well as agency rehabilitation costs. Four pavement sections, typical of California construction over a range of traffic indexes (7 through 13), were evaluated including that used in the above example (Table 5). Construction expectations for these sections are summarized in Table 6. Other aspects of the simulations are identical to those employed in the above example and summarized in Table 4. Each investigation employed either 100,000 simulations (air voids/relative compaction and asphalt-concrete thickness) or 200,000 simulations (asphalt content). Detailed results are included in Appendix A (air-void/relative compaction effects), Appendix B (asphalt-content effects), and Appendix C (asphalt-concrete thickness effects).

IMPLEMENTATION

The above simulations provide the basis for establishing appropriate pay-factor schedules based on construction quality. The following considerations dictate the specific recommendations herein:

1) One pay-factor schedule should apply to all new construction, that is, job-specific pay factors are undesirable;
2) The contractor should generally be charged a penalty for inferior construction which is out-of-specification, the magnitude of which should equal the full added cost to the agency of failure to meet the construction target;
3) The contractor should generally be awarded a bonus for superior construction which is within specification, the magnitude of which should be some fraction of the full added benefit to the agency resulting from the improved pavement performance (one half has been chosen herein as an appropriate point from which to start);
4) Pay-factor schedules should incorporate average and standard-deviation categories consistent with the accuracy within which estimates are determined from field measurements;
5) Because pay-factor schedules should be as simple as possible, increments of 5 percent in the bonuses/penalties seem appropriate; and
6) The standard deviations of pay-factor schedules must reflect expected testing and sampling errors as well as materials/construction variabilities.

Recommended contractor pay-factor schedules, based on these guidelines, are presented in Table 7 for relative compaction, Table 8 for asphalt content, and Table 9 for asphalt-concrete thickness. In developing these recommendations, average agency costs for the four pavement sections that were evaluated herein are assumed to be reasonably representative of typical new construction in California.

For practical application a pay-factor schedule must be developed for various combinations of off-target conditions, not just relative compaction, asphalt content, and asphalt-concrete thickness individually. Development of such a schedule began by identifying 10 conditions, five for air voids and five for thickness, which individually resulted in a "constant" pay factor of about -20 percent. The combination effects from the simulations are shown in Table 10. Interestingly the combination pay factor is about -36 percent, when both air-void content and thickness are off-target with individual pay factors of -20 percent each. This suggests the possibility that the combination pay factor as a decimal fraction, cpf, might be expressed as follows:

$$cpf = (1 + pf_{av})(1 + pf_t) - 1$$

in which the individual pay factors are expressed as decimal fractions instead of percents.

To further investigate this possibility, the simulations of Table 11 were performed. Again the focus was on air voids/relative compaction and thickness because these are the dominant parameters of interest. This time, however, the as-constructed conditions were selected to yield large ranges in individual pay factors including bonuses (instead of -20 percent). Next calculations for comparable conditions using the above equation yielded results summarized in Table 12. Although there is one notable difference at one extreme (96.1 percent versus 69.1 percent), results of the combined simulations (Table 11) and the computations (Table 12) are in remarkable agreement. As a result the above equation seems suitable for determining pay factors for combined conditions. An extension to include asphalt content yields the following recommendation for computing combined contractor pay factors:

$$cpf = (1 + pf_{av})(1 + pf_{ac})(1 + pf_t) - 1$$

Rational pay factors resulting from the above analysis and expressed as percentages are summarized in Table 13. An exogenous estimate of the current-year cost of the first pavement rehabilitation cycle is necessary to translate these percentages to dollar amounts. While other considerations may also influence the selection of an implementable pay-factor scale, the Table 13 quantities should serve as a useful point of departure.

PROS AND CONS AND FURTHER QUESTIONS

The approach illustrated here is simpler than the approach demonstrated during the summer of 1996 and doesn't require use of the AASHTO performance equations. As a result, it seems to be considerably less vulnerable to criticism. Although additional laboratory testing would be required, it is applicable to virtually any type of bituminous mix[3]. A downside is that both

[3]The basic approach advocated herein is thought to be applicable to rigid, Portland cement concrete pavements as well as flexible pavements. However, it has not yet been applied to rigid pavements, and further development, testing, and calibration work would first be necessary.

penalties and bonuses are likely understated because only the first rehabilitation cycle is considered, and the thickness (and, hence, the cost) of the first overlay is assumed to be independent of the quality of the initial construction. At the same time, understated penalties/bonuses are likely to be more appropriate than overstated ones for pilot or demonstration use.

The development of appropriate pay-factor schedules must probably be viewed as an incremental process evolving over an extended time frame. Among the future refinements that can be anticipated are the following:

1) Incorporation of aggregate gradation as a significant construction quantity affecting pavement performance in fatigue;
2) Incorporation of ride quality as a significant product of the construction process;
3) Consideration of permanent deformation and thermal cracking in addition to fatigue;
4) More accurate estimates of agency costs as new performance models become available (California Maintenance Program, 1996);
5) Inclusion, if desired, of maintenance and user costs;
6) Extension to include rehabilitation activity ; and
7) Extension to include Portland cement concrete pavements.

Quickly moving from concept to practice is possible although more information is needed about a host of factors including 1) the identity of parameters of interest to Caltrans, 2) the current Caltrans construction specifications for these parameters and the types and extent of construction-related measurements, 3) the schemes envisioned by Caltrans for applying pay factors based on these specifications (possibly together with other construction-quality considerations), 4) the interplay between QC/QA (as it affects construction practice) and pay factors, 5) the appropriateness of parameters of the cost and performance models, 6) the appropriateness of the proposed pay-factor display (that is, the formats of Tables 7-9 and Table 13), 7) etc.

There are even more basic questions: does the interest focus on new pavements and/or overlays and can initial consideration be limited to asphalt-concrete applications? In addition help is ultimately needed from Caltrans personnel to validate the variances that have been assumed to be representative of current construction practice. Additionally, past construction projects should be reviewed to evaluate their distribution relative to any pay-factor schedule that is ultimately proposed. Finally, some consideration seems necessary about how best the CAL/APT program can support the Caltrans initiative for demonstrating a new or modified pay factor approach for asphalt-concrete construction and what Caltrans' timeline is for such a demonstration.

REFERENCES

Benson, P. (1995), "Comparison of End-Result and Method Specifications for Managing Quality," A Paper Presented at the 74th Annual Meeting of the Transportation Research Board, Washington, D.C.

Caltrans Maintenance Program (1996), "California State of the Pavement Report, 1995," California Department of Transportation, Pavement Management Information Branch.

Deacon, J.A., J.S. Coplantz, A.A. Tayebali, and C.L. Monismith (1994a), "Temperature Considerations in Asphalt-Aggregate Mixture Analysis and Design," Research Record 1454, Transportation Research Board, Washington, D.C. pp. 97-112.

Deacon, J.A., A.A. Tayebali, J.S. Coplantz, F.N. Finn, and C.L. Monismith (1994b), "Fatigue Response of Asphalt-Aggregate Mixtures: Part III, Mix Design and Analysis," Report SHRP-A-404, University of California (Berkeley), Institute of Transportation Studies, Asphalt Research Program.

Epps, J. (1996), "Accelerated Field Test of Performance-Related Specifications for Hot-Mix Asphalt Construction - Task G, Interim Report," Chapter 12, Submitted by the Nevada Automotive Test Center et al. to the Federal Highway Administration.

Granley, E. (1969), "Part 4 - Variations of Bituminous Construction," *Public Roads*, Vol. 35, No. 9.

Harvey, J.T., J.A. Deacon, A.A. Tayebali, R.B. Leahy, and C.L. Monismith (1996), "A Reliability-Based Mix Design and Analysis System for Mitigating Fatigue Distress," A Paper Submitted for Consideration by the Eighth International Conference on Asphalt Pavements, August 10-14, 1997, Seattle, Washington.

Harvey, J.T., J.A. Deacon, B.W. Tsai, and C.L. Monismith (1995), "Fatigue Performance of Asphalt Concrete Mixes and Its Relationship to Asphalt Concrete Pavement Performance in California," University of California (Berkeley), Institute of Transportation Studies, Asphalt Research Program, CAL/APT Program.

Harvey, J.T., L. du Plessis, F. Long, J.A. Deacon, I. Guada, D. Hung, and C. Scheffy (1997), "CAL/APT Program: Test Results from Accelerated Pavement Test on Pavement Structure Containing Asphalt Treated Permeable Base (ATPB)-Section 500 RF," Draft Report, University of California (Berkeley), Institute of Transportation Studies, Asphalt Research Program.

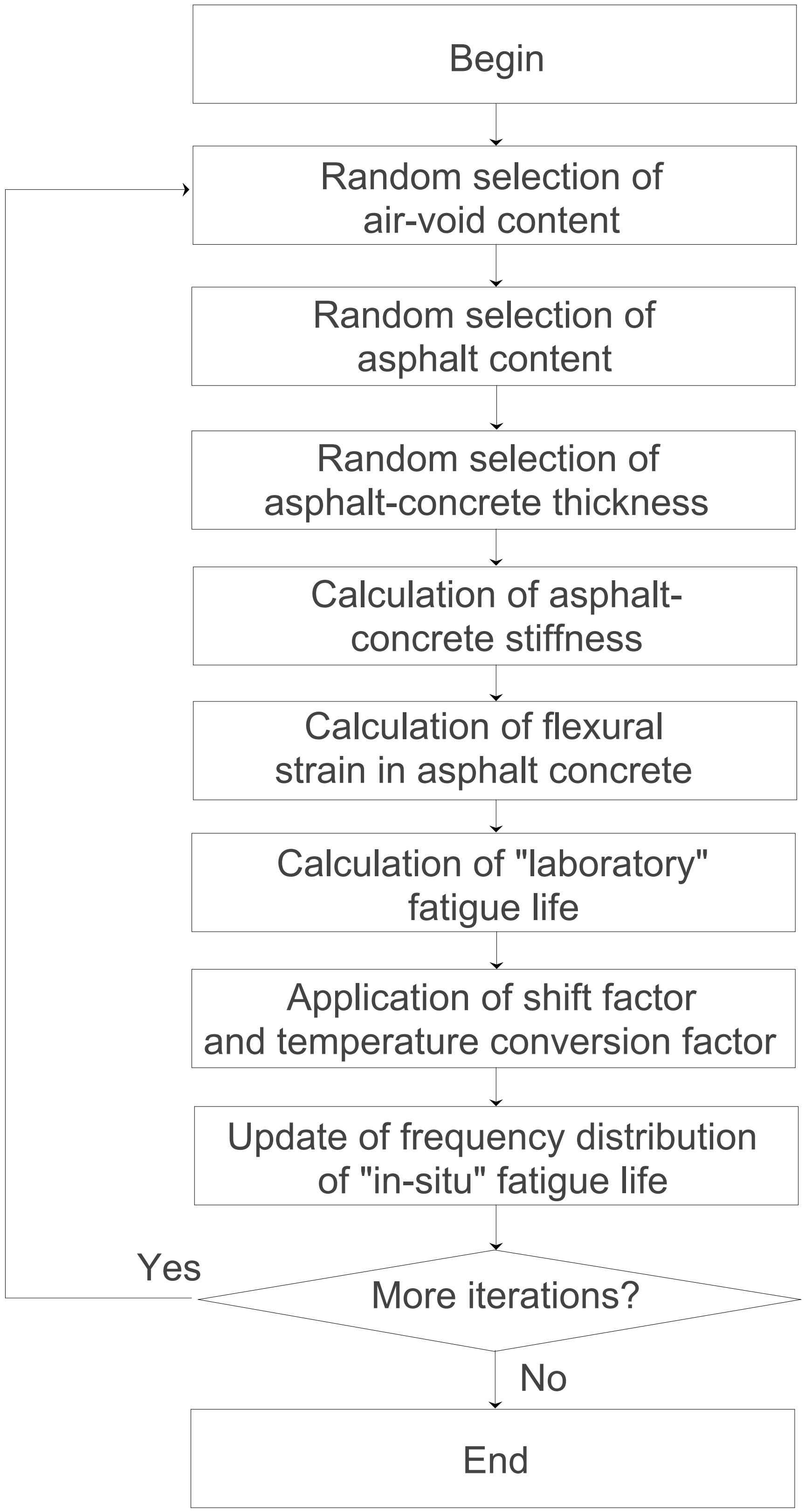

Figure 1. Outline of the pavement performance model simulation.

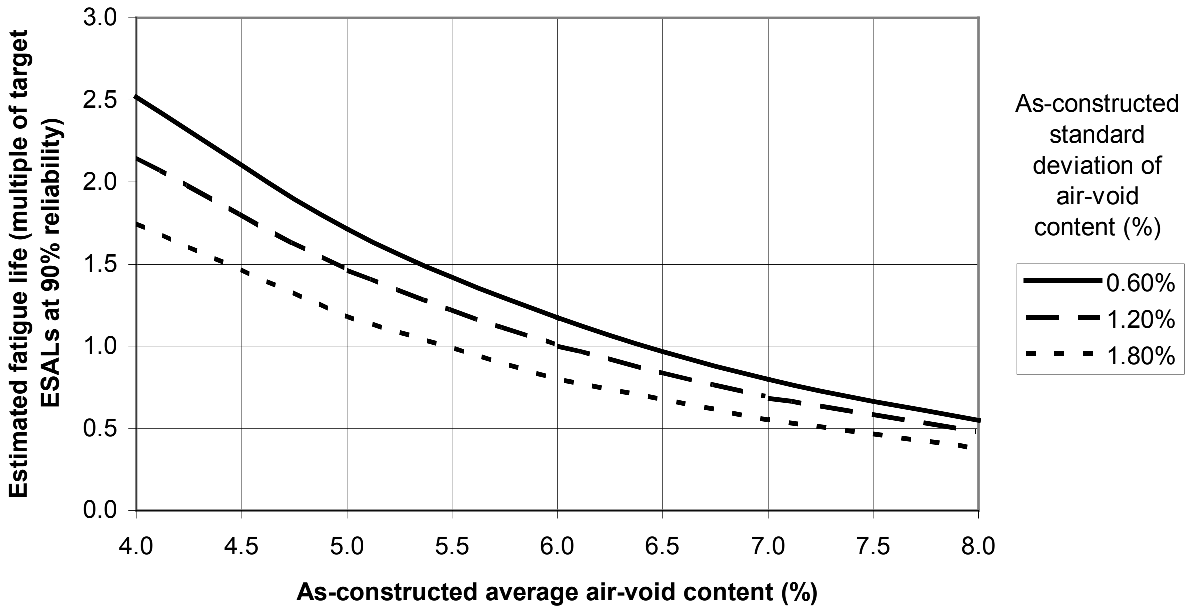

Figure 2. Effects of as-constructed air-void content on pavement fatigue performance.

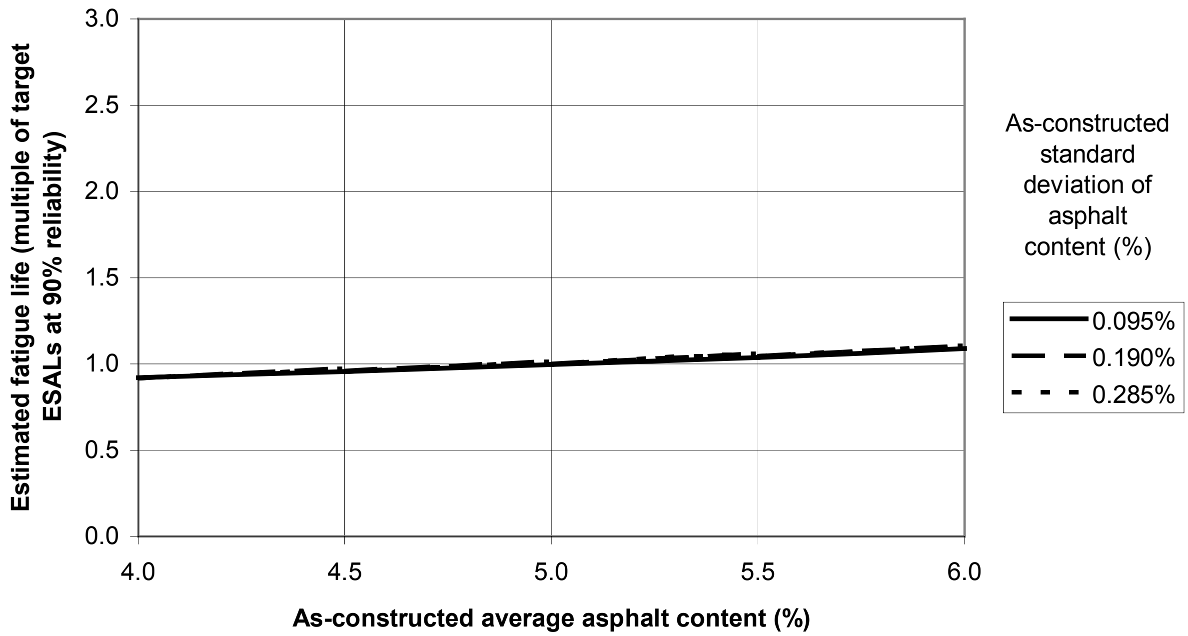

Figure 3. Effects of as-constructed asphalt content on pavement fatigue performance.

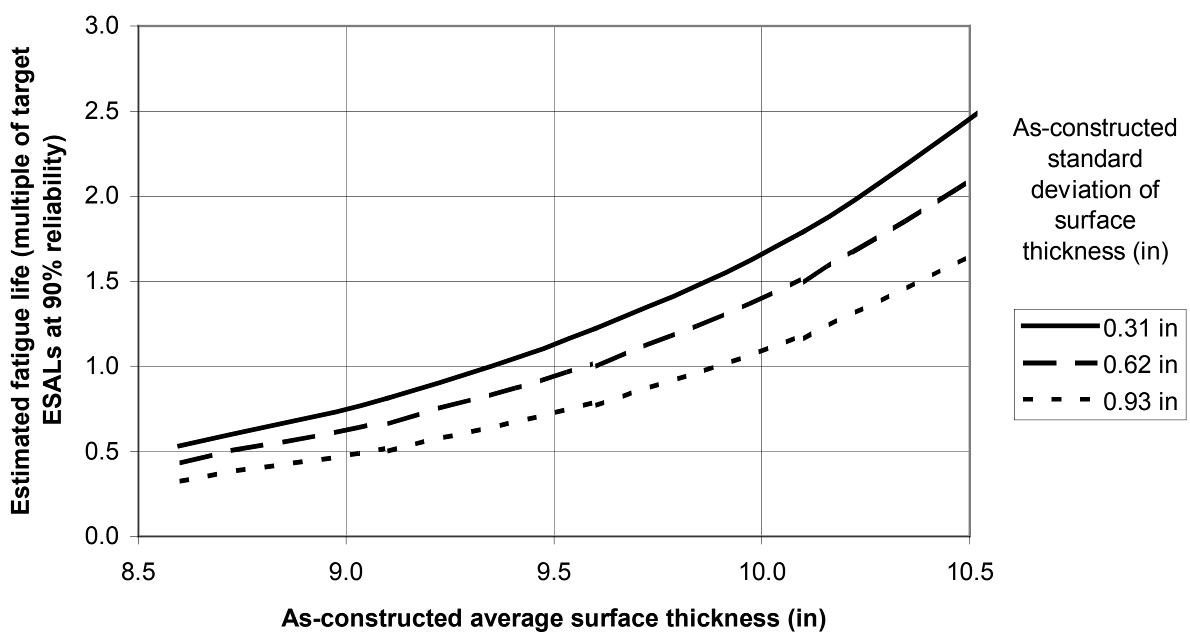

Figure 4. Effects of as-constructed surface thickness on pavement fatigue performance.

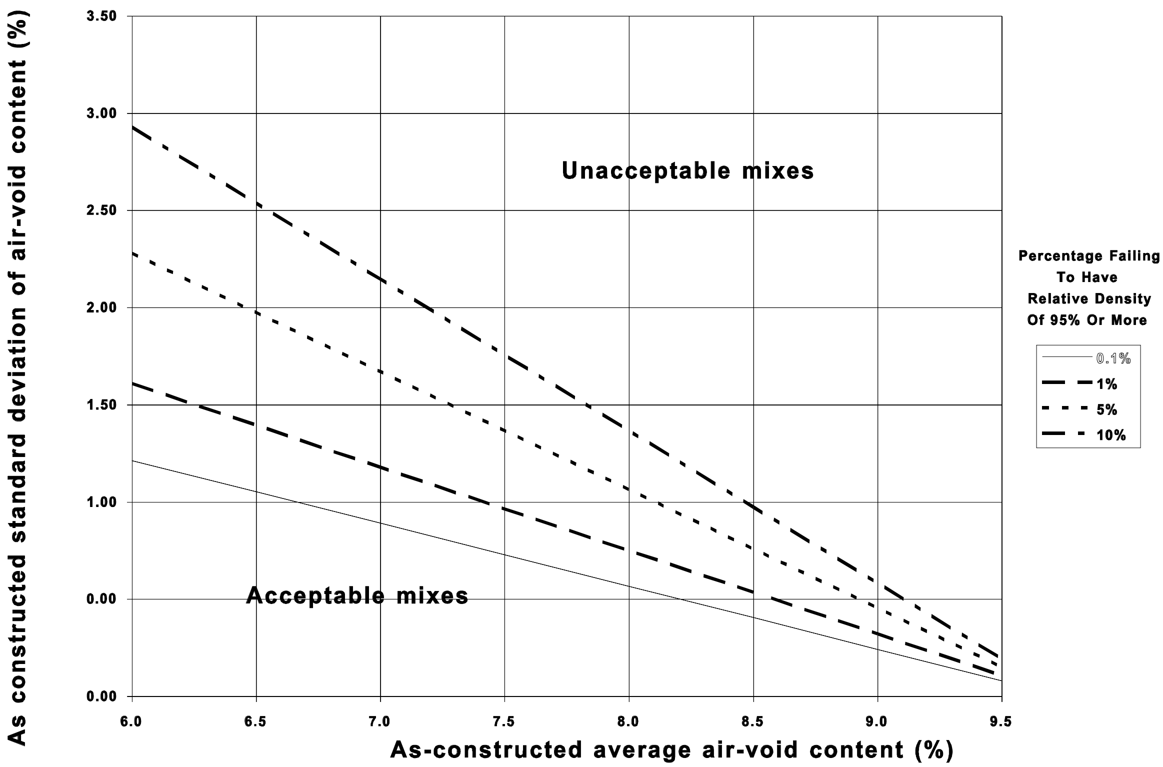

Figure 5. Effect of specification failure level on acceptability of mix compaction.

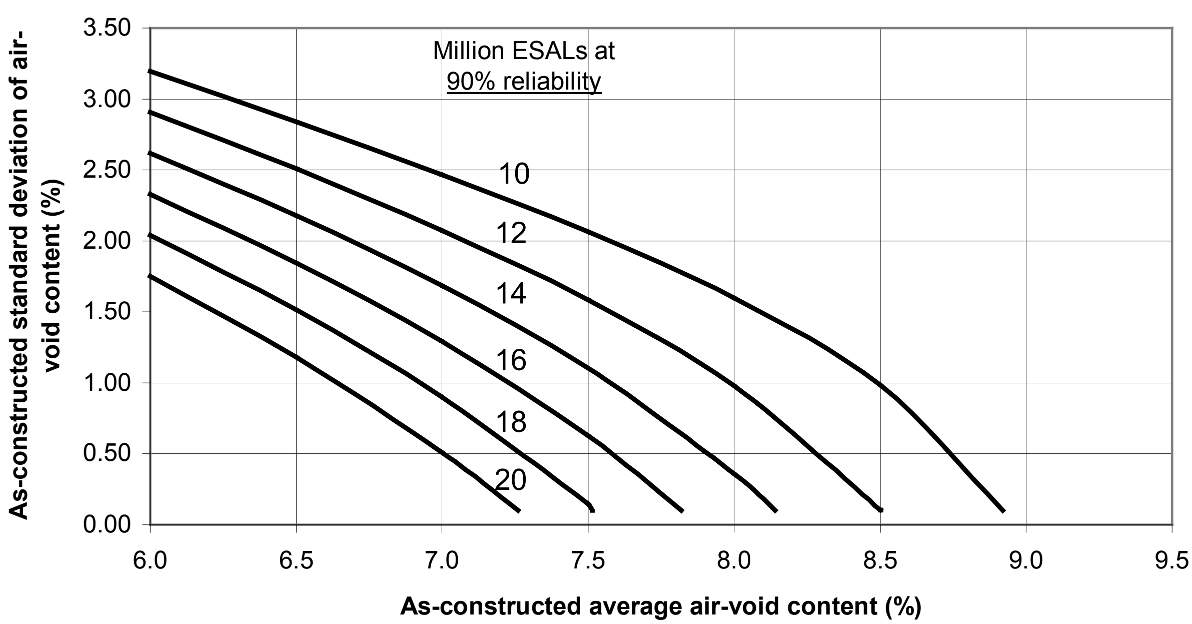

Figure 6. Influence of air voids on pavement performance.

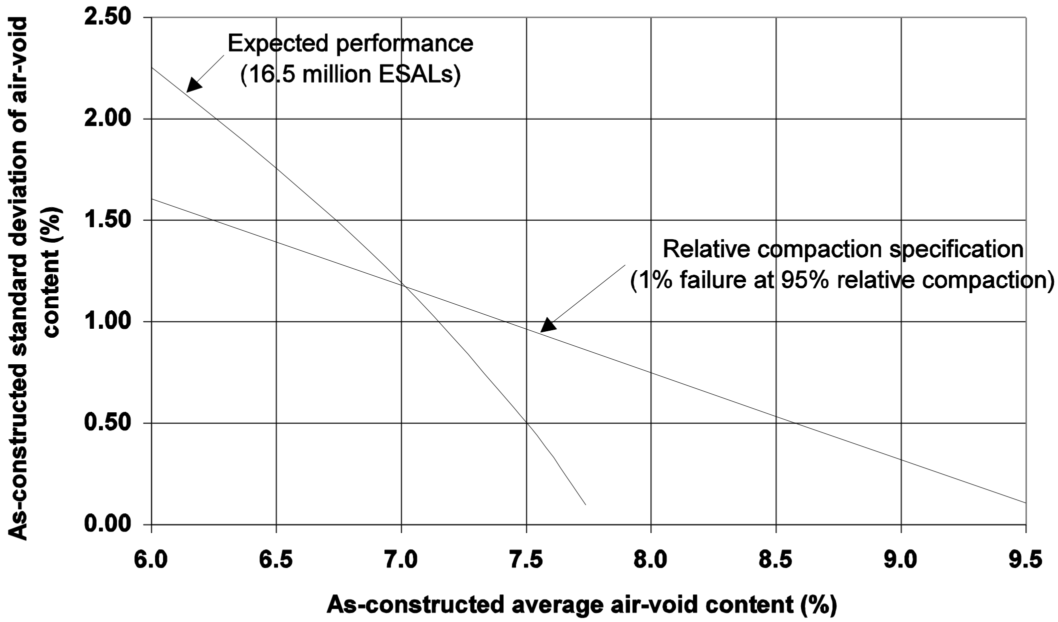

Figure 7 Expected pavement performance

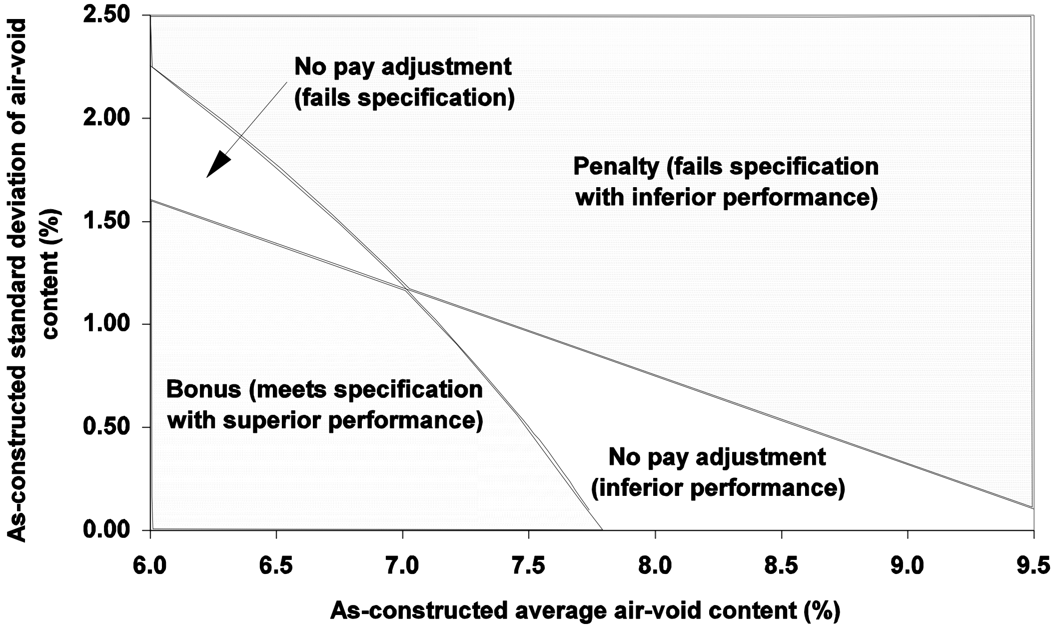

Figure 8 Influence of air voids on contractor pay adjustments

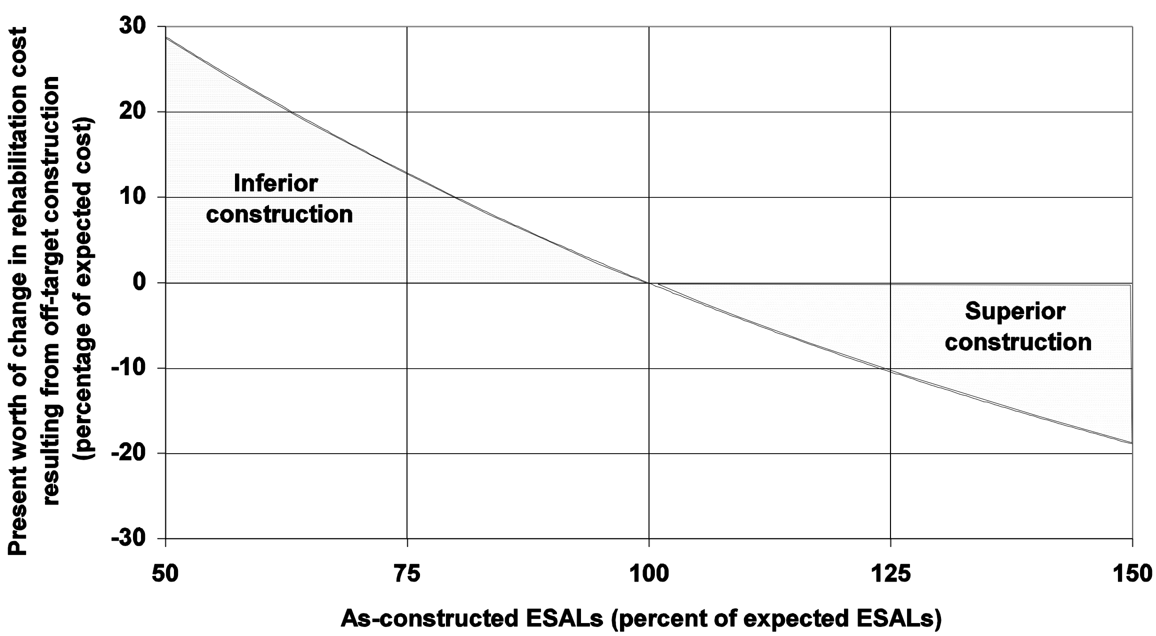

Figure 9 Influence of pavement performance on pay factors

Table 1 Construction variation of mix and structural characteristics

Property	Measure of variation	Value or range	Source
Asphalt content	Standard deviation	0.15-0.44%	Table 12.46 (Epps, 1996)
	Standard deviation	0.1-0.4%	Individual WesTrack sections
	Standard deviation	0.31%	WesTrack composite
	Standard deviation	0.3%	Table 3 (Benson, 1995)
Air-void content	Standard deviation	0.9-1.9%	Table 12.55 (Epps, 1996)
	Standard deviation	0.4-1.5%	Individual WesTrack sections
	Standard deviation	1.5%	WesTrack composite
	Standard deviation	1.94%	Table 3 (Benson, 1995)
Thickness	Coefficient of variation	12.5-15%	Table 12.58 (Epps, 1996)
	Standard deviation	0-0.5 cm	Individual WesTrack sections
	Standard deviation	0.58 cm	WesTrack composite
	Standard deviation	0.99 cm	Table 3 (Benson, 1995)
Foundation modulus	Coefficient of variation	11.3-14.7%	HVS test sections at UCB
	Coefficient of variation	17.3-44.7%	Segment of AA highway in KY
	Coefficient of variation	3.6-17.7%	Individual WesTrack sections
	Coefficient of variation	14.2-28.5%	WesTrack composite

Table 2 Materials/construction component of total construction variance

Property	Materials/construction component (%)	Source
Asphalt content	40	Figure 7 (Granley, 1969)
	61	Table 3 (Benson, 1995)
Air-void content	60	Table 8 (inferred) (Granley, 1969)
	90	Table 3 (Benson, 1995)
Thickness	95	Table 3 (Benson, 1995)
Foundation modulus	70	Assumed

Table 3 Variation of mix and structural characteristics for Monte Carlo simulations

Property	Total standard deviation	Percentage of variance due to materials/construction	Materials/construction component of standard deviation
Asphalt content	0.30%	40	0.19%
Air-void content	1.6%	60	1.2%
Surface thickness	$0.200 \bullet T^{0.69}$ *cm*	80	$0.173 \bullet T^{0.69}$ *cm*
Foundation modulus	30% (coefficient of variation)	70	25%

Table 4 Summary of parameters in example

Context	New pavement construction
Performance model	90-percent reliability California coastal temperatures Average asphalt content, 5% Standard deviation of asphalt content, 0.19% Standard deviation of thickness, 0.6 in Coefficient of variation of foundation modulus, 25%
Cost model	2% annual rate of inflation in rehabilitation cost 2.5% annual rate of traffic growth 5% discount rate 20-year expected pavement life
Construction specification	95% relative compaction 1% tolerable failure 5% air-void content at maximum density and 9.75% at 95% relative compaction
Performance expectation	16,500,000 ESALs
Pavement structure	9.6-in asphalt concrete (E = varies, v = 0.40) 6-in aggregate base (E = 25,000 psi, v = 0.45) 8.4-in aggregate subbase (E = 20,000 psi, v = 0.45) Subgrade (E = 12,200 psi, v = 0.50)

Table 5 Pavement structures

Designation	Layer	Target thickness (in)	Modulus (psi)	Poisson's ratio
	Surface	3.6	Variable	0.40
	Base	7.2	30,000	0.45
	Subbase	6.0	20,000	0.45
7AB20	Subgrade	-	12,200	0.50
	Surface	6.6	Variable	0.40
	Base	6.6	30,000	0.45
	Subbase	7.8	20,000	0.45
9AB20	Subgrade	-	12,200	0.50
	Surface	9.6	Variable	0.40
	Base	6.0	25,000	0.45
	Subbase	8.4	20,000	0.45
11AB20	Subgrade	-	12,200	0.50
	Surface	10.2	Variable	0.40
	Base	7.8	25,000	0.45
	Subbase	12.6	20,000	0.45
13AB20	Subgrade	-	12,200	0.50

Table 6 Construction expectations

Designation	Property	Target mean	Target standard deviation
All	Air-void content (%)	7.0	1.20
All	Asphalt content (%)	5.0	0.19
7AB20		3.6	0.314
9AB20		6.6	0.476
11AB20		9.6	0.620
13AB20	Asphalt-concrete thickness (in)	10.2	0.640

Table 7 Recommended contractor pay factors for relative compaction
(Percentage of future rehabilitation cost in current-year dollars)

As-measured average relative compaction (%)	As-measured standard deviation of relative compaction (%)		
	< 1.2	1.2 to 1.9	> 1.9
98.9 to 99.0	15	10	0
98.7 to 98.8	10	10	0
98.5 to 98.6	10	5	0
98.3 to 98.4	10	5	0
98.1 to 98.2	5	5	-5
97.9 to 98.0	5	0	-5
97.7 to 97.8	5	0	-10
97.5 to 97.6	0	-5	-10
97.3 to 97.4	0	-5	-15
97.1 to 97.2	0	-10	-20
96.9 to 97.0	0	-15	-20
96.7 to 96.8	0	-15	-25
96.5 to 96.6	0	-20	-25
96.3 to 96.4	0	-20	-30
96.1 to 96.2	-20	-25	-30
95.9 to 96.0	-20	-25	-35

Note: Bonuses are positive and penalties are negative

Table 8 Recommended contractor pay factors for asphalt content
(Percentage of future rehabilitation cost in current-year dollars)

Difference between as-measured average asphalt content and design asphalt content (%)	As-measured standard deviation of asphalt content (%)		
	< 0.2	0.2 to 0.4	> 0.4
-1.0 to -0.9	-5	-5	-5
-0.8 to -0.7	-5	-5	-5
-0.6 to -0.5	-5	-5	-5
-0.4 to -0.3	0	0	0
-0.2 to -0.1	0	0	0
0.0 to 0.1	0	0	0
0.2 to 0.3	0	0	0
0.4 to 0.5	0	0	0
0.6 to 0.7	0	0	0
0.8 to 0.9	5	0	0
1.0 to 1.1	5	5	5

Note: Bonuses are positive and penalties are negative

Table 9 Recommended contractor pay factors for asphalt-concrete thickness (Percentage of future rehabilitation cost in current-year dollars)

Difference between as-measured average asphalt-concrete thickness and design thickness (in)	As-measured coefficient of variation of asphalt-concrete thickness (%)		
	< 6	6 to 10	> 10
-1.0 to -0.9	-30	-35	-40
-0.8 to -0.7	-20	-30	-35
-0.6 to -0.5	-15	-20	-30
-0.4 to -0.3	-10	-15	-25
-0.2 to -0.1	0	-10	-15
0.0 to 0.1	5	0	-10
0.2 to 0.3	10	5	-5
0.4 to 0.5	10	5	0
0.6 to 0.7	15	10	5
0.8 to 0.8	20	15	10
1.0 to 1.1	25	20	15

Note: Bonuses are positive and penalties are negative

Table 10 Pay factors for combination conditions (from simulations)
(Conditions set to yield individual pay factors of about -20%)

		Average air-void content (%)				
Surface thickness (in)		7.000	7.755	8.040	8.325	8.610
Average	Standard deviation	Standard deviation of air-void content (%)				
		1.200	1.696	1.378	1.028	0.637
9.6	0.620	0.0	-20.3	-19.6	-19.7	-20.3
8.8	0.353	-21.0	-37.8	-37.2	-36.5	-36.0
9.0	0.587	-20.7	-36.9	-36.5	-36.6	-36.8
9.2	0.791	-20.7	-36.2	-36.3	-36.7	-37.4
9.4	0.975	-20.6	-35.2	-36.2	-36.9	-38.2

Table 11 Pay factors for combination conditions (from simulations)
(Conditions set to yield varying individual pay factors)

			Average air-void content (%)				
			5.95	7.09	7.00	7.09	8.80
			Standard deviation of air-void content (%)				
Surface thickness (in)			0.570	0.570	1.200	1.710	1.520
			Individual pay factor				
Average	Standard deviation	Individual pay factor	0.262	0.060	0.000	-0.097	-0.320
10.5	0.60	0.340	96.1	41.6	33.9	23.5	-2.8
9.9	0.60	0.123	39.3	18.2	12.2	2.5	-22.8
9.6	0.62	0.000	26.2	6.3	0.0	-9.5	-32.0
9.3	0.70	-0.134	11.3	-8.6	-13.7	-22.5	-41.1
8.5	0.80	-0.408	-24.0	-38.5	-41.0	-45.3	-56.5

Table 12 Pay factors for combination conditions (from calculations)
(Conditions set to yield varying individual pay factors)

			Average air-void content (%)				
			5.95	7.09	7.00	7.09	8.80
			Standard deviation of air-void content (%)				
Surface thickness (in)			0.570	0.570	1.200	1.710	1.520
			Individual pay factor				
Average	Standard deviation	Individual pay factor	0.262	0.060	0.000	-0.097	-0.320
10.5	0.60	0.340	69.1	42.0	34.0	21.0	-8.9
9.9	0.60	0.123	41.7	19.0	12.3	1.4	-23.6
9.6	0.62	0.000	26.2	6.0	0.0	-9.7	-32.0
9.3	0.70	-0.134	9.3	-8.2	-13.4	-21.8	-41.1
8.5	0.80	-0.408	-25.3	-37.2	-40.8	-46.5	-59.7

Table 13 Recommended combined contractor pay factors
(Percentage of future rehabilitation cost in current-year dollars)

Contractor pay factor for asphalt content (%)	Contractor pay factor for asphalt-concrete thickness (%)	Contractor pay factor for relative compaction (%)										
		15	10	5	0	-5	-10	-15	-20	-25	-30	-35
5	25	51	44	38	31	25	18	12	5	-2	-8	-15
5	20	45	39	32	26	20	13	7	1	-5	-12	-18
5	15	39	33	27	21	15	9	3	-3	-9	-15	-22
5	10	33	27	21	16	10	4	-2	-8	-13	-19	-25
5	5	27	21	16	10	5	-1	-6	-12	-17	-23	-28
5	0	21	16	10	5	0	-5	-11	-16	-21	-27	-32
5	-5	15	10	5	0	-5	-10	-15	-20	-25	-30	-35
5	-10	9	4	-1	-5	-10	-15	-20	-24	-29	-34	-39
5	-15	3	-2	-6	-11	-15	-20	-24	-29	-33	-38	-42
5	-20	-3	-8	-12	-16	-20	-24	-29	-33	-37	-41	-45
5	-25	-9	-13	-17	-21	-25	-29	-33	-37	-41	-45	-49
5	-30	-15	-19	-23	-27	-30	-34	-38	-41	-45	-49	-52
5	-35	-22	-25	-28	-32	-35	-39	-42	-45	-49	-52	-56
5	-40	-28	-31	-34	-37	-40	-43	-46	-50	-53	-56	-59
0	25	44	38	31	25	19	13	6	0	-6	-13	-19
0	20	38	32	26	20	14	8	2	-4	-10	-16	-22
0	15	32	27	21	15	9	3	-2	-8	-14	-20	-25
0	10	27	21	16	10	4	-1	-6	-12	-18	-23	-29
0	5	21	16	10	5	0	-5	-11	-16	-21	-27	-32
0	0	15	10	5	0	-5	-10	-15	-20	-25	-30	-35
0	-5	9	4	0	-5	-10	-15	-19	-24	-29	-34	-38
0	-10	3	-1	-5	-10	-15	-19	-24	-28	-33	-37	-42
0	-15	-2	-6	-11	-15	-19	-24	-28	-32	-36	-41	-45
0	-20	-8	-12	-16	-20	-24	-28	-32	-36	-40	-44	-48
0	-25	-14	-18	-21	-25	-29	-33	-36	-40	-44	-48	-51
0	-30	-20	-23	-27	-30	-34	-37	-41	-44	-48	-51	-55
0	-35	-25	-29	-32	-35	-38	-42	-45	-48	-51	-55	-58
0	-40	-31	-34	-37	-40	-43	-46	-49	-52	-55	-58	-61
-5	25	37	31	25	19	13	7	1	-5	-11	-17	-23
-5	20	31	25	20	14	8	3	-3	-9	-15	-20	-26
-5	15	26	20	15	9	4	-2	-7	-13	-18	-24	-29
-5	10	20	15	10	4	-1	-6	-11	-16	-22	-27	-32
-5	5	15	10	5	0	-5	-10	-15	-20	-25	-30	-35
-5	0	9	4	0	-5	-10	-15	-19	-24	-29	-34	-38
-5	-5	4	-1	-5	-10	-14	-19	-23	-28	-32	-37	-41
-5	-10	-2	-6	-10	-15	-19	-23	-27	-32	-36	-40	-44
-5	-15	-7	-11	-15	-19	-23	-27	-31	-35	-39	-43	-48
-5	-20	-13	-16	-20	-24	-28	-32	-35	-39	-43	-47	-51
-5	-25	-18	-22	-25	-29	-32	-36	-39	-43	-47	-50	-54
-5	-30	-24	-27	-30	-34	-37	-40	-43	-47	-50	-53	-57
-5	-35	-29	-32	-35	-38	-41	-44	-48	-51	-54	-57	-60
-5	-40	-34	-37	-40	-43	-46	-49	-52	-54	-57	-60	-63

Note: Bonuses are positive and penalties are negative

APPENDIX A

Effect of As-Constructed Air Voids on

Simulated Fatigue Performance

and

Effect of As-Constructed Relative Compaction on

Future Agency Rehabilitation Costs

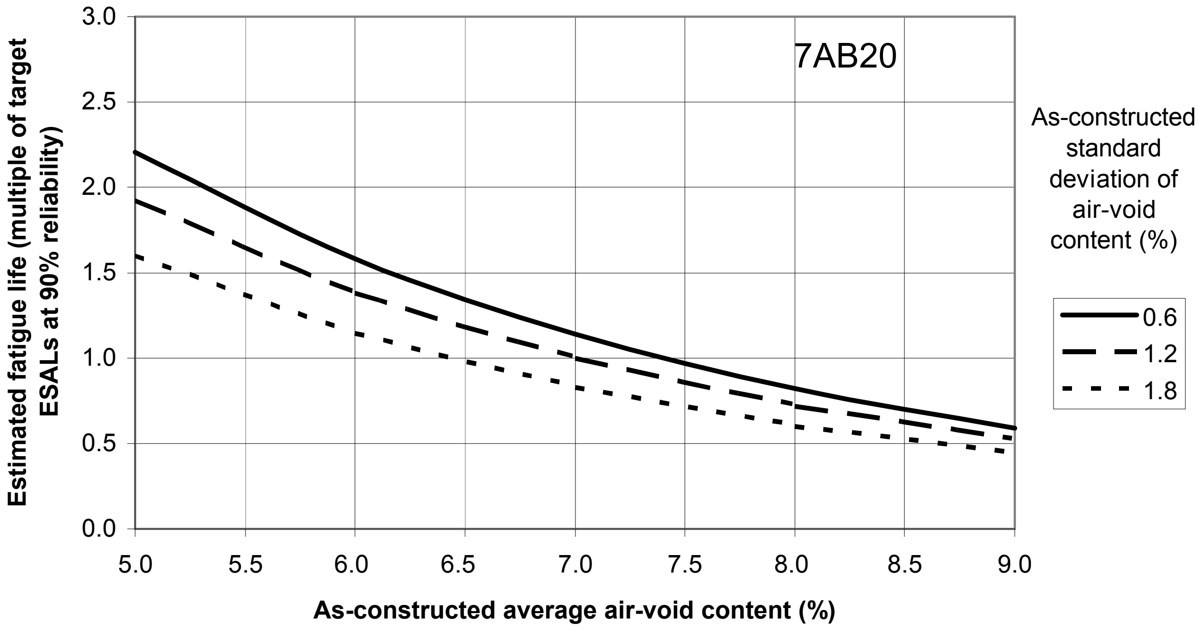

Figure A-1. Effect of As-Constructed Air Voids on Fatigue Performance (7AB20)

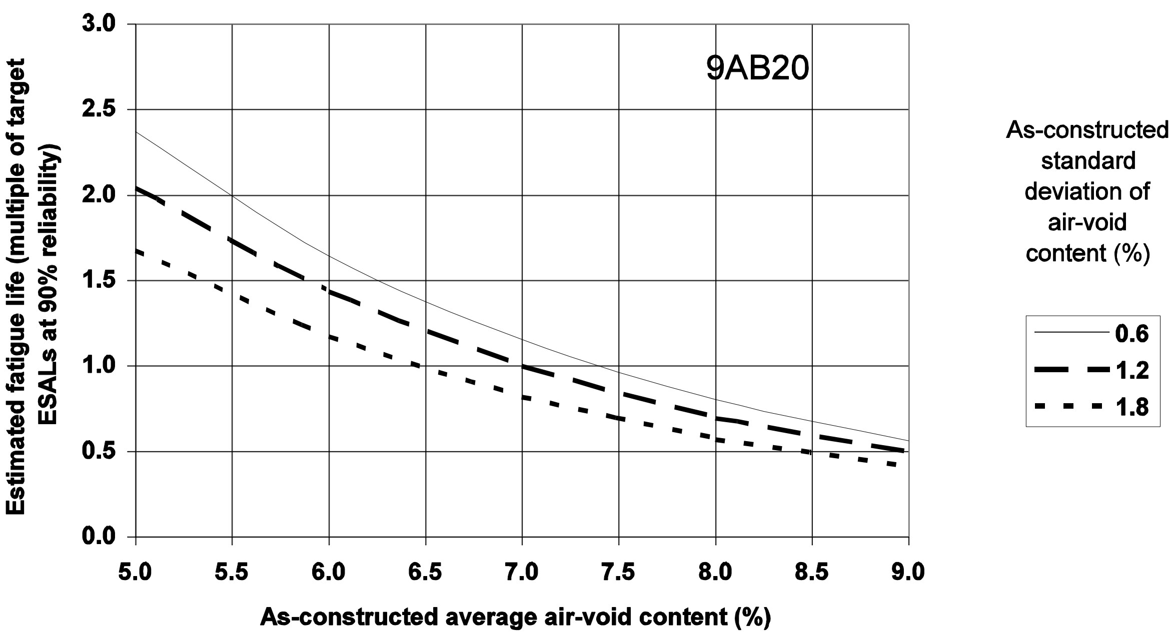

Figure A-2. Effect of As-Constructed Air Voids on Fatigue Performance (9AB20)

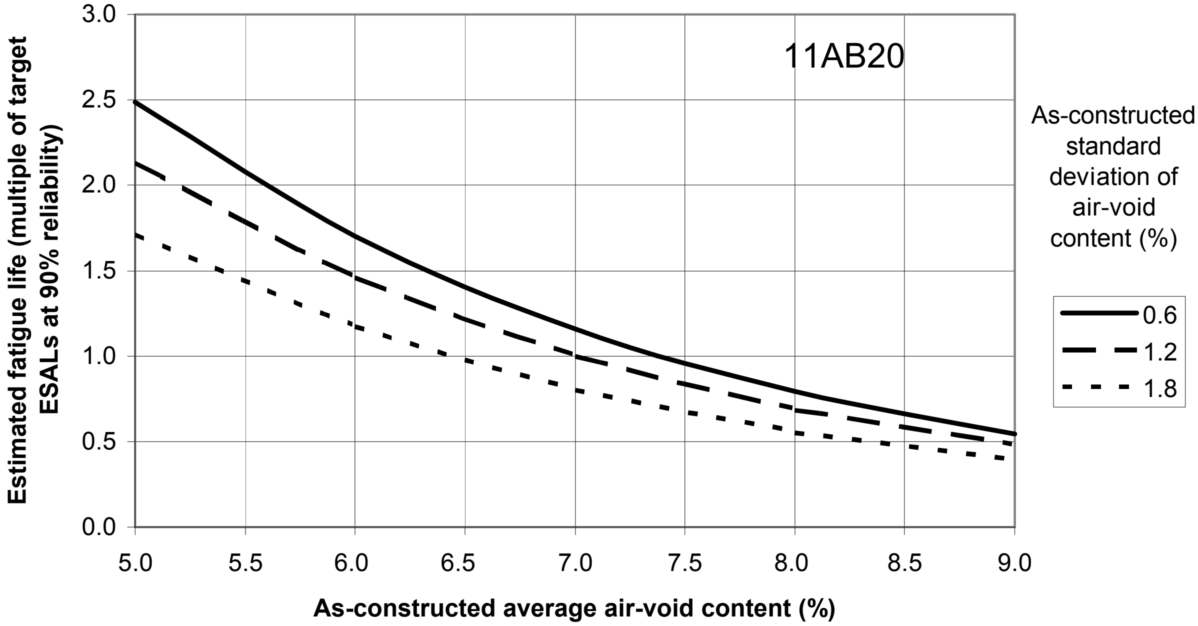

Figure A-3. Effect of As-Constructed Air Voids on Fatigue Performance (11AB20)

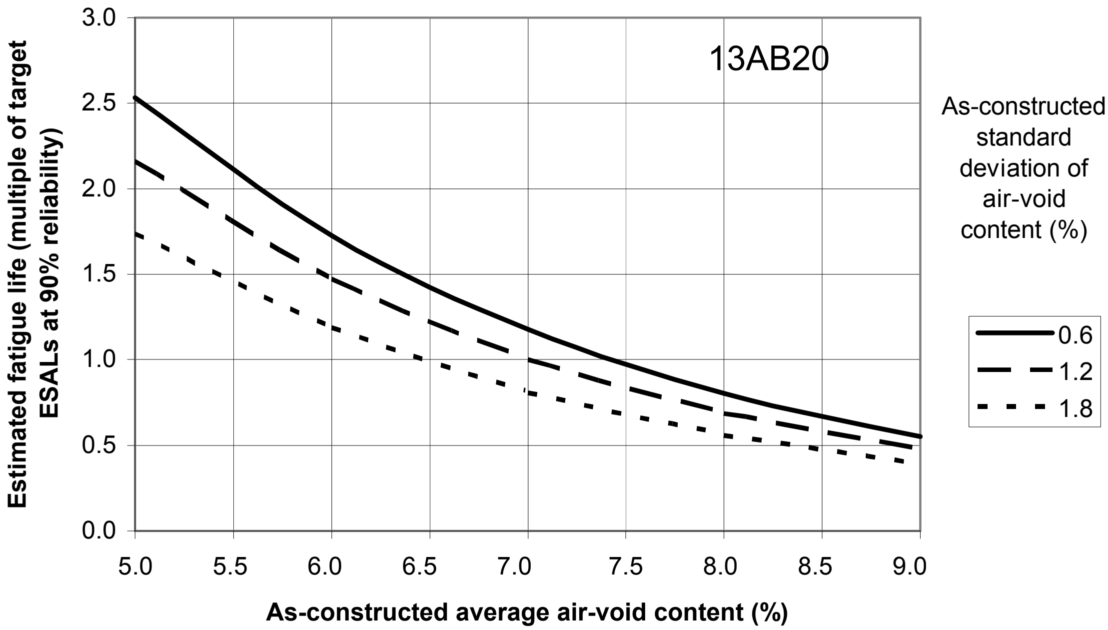

Figure A-4. Effect of As-Constructed Air Voids on Fatigue Performance (13AB20)

Table A-1. Effect of Off-Target Relative Compaction on Future Agency Rehabilitation Cost for 7AB20
(Percent Change)

As-constructed average relative compaction (%)	As-constructed standard deviation of relative compaction (%)						
	0.6	0.8	1.0	1.2	1.4	1.6	1.8
99.0	-22.9	-20.9	-18.8	-16.5	-14.2	-11.7	-9.0
98.9	-21.5	-19.4	-17.3	-15.1	-12.7	-10.2	-7.6
98.8	-20.0	-18.0	-15.9	-13.6	-11.2	-8.7	-6.1
98.7	-18.6	-16.6	-14.4	-12.2	-9.8	-7.3	-4.6
98.6	-17.1	-15.1	-13.0	-10.7	-8.3	-5.8	-3.2
98.5	-15.7	-13.6	-11.5	-9.2	-6.9	-4.4	-1.7
98.4	-14.2	-12.2	-10.0	-7.8	-5.4	-2.9	-0.3
98.3	-12.8	-10.7	-8.6	-6.3	-3.9	-1.5	1.2
98.2	-11.3	-9.3	-7.1	-4.9	-2.5	0.0	2.6
98.1	-9.9	-7.8	-5.7	-3.4	-1.0	1.4	4.0
98.0	-8.4	-6.4	-4.2	-2.0	0.4	2.8	5.4
97.9	-6.9	-4.9	-2.8	-0.5	1.8	4.2	6.8
97.8	-5.5	-3.4	-1.3	0.9	3.2	5.6	8.2
97.7	-4.0	-2.0	0.1	2.3	4.6	7.0	9.5
97.6	-2.6	-0.6	1.5	3.7	6.0	8.4	10.9
97.5	-1.2	0.9	3.0	5.1	7.4	9.7	12.2
97.4	0.3	2.3	4.4	6.5	8.8	11.1	13.5
97.3	1.7	3.7	5.8	7.9	10.1	12.4	14.8
97.2	3.1	5.1	7.1	9.3	11.4	13.7	16.1
97.1	4.5	6.5	8.5	10.6	12.8	15.0	17.3
97.0	5.9	7.9	9.9	11.9	14.1	16.3	18.6
96.9	7.3	9.2	11.2	13.3	15.4	17.5	19.8
96.8	8.7	10.6	12.5	14.6	16.6	18.8	21.0
96.7	10.0	11.9	13.9	15.9	17.9	20.0	22.2
96.6	11.4	13.3	15.2	17.1	19.2	21.2	23.4
96.5	12.7	14.6	16.5	18.4	20.4	22.4	24.5
96.4	14.1	15.9	17.8	19.7	21.6	23.6	25.7
96.3	15.4	17.2	19.0	20.9	22.8	24.8	26.8
96.2	16.7	18.5	20.3	22.1	24.0	26.0	27.9
96.1	18.0	19.8	21.5	23.4	25.2	27.1	29.1
96.0	19.3	21.1	22.8	24.6	26.4	28.3	30.2

Table A-2. Effect of Off-Target Relative Compaction on Future Agency Rehabilitation Cost for 9AB20 (Percent Change)

As-constructed average relative compaction (%)	As-constructed standard deviation of relative compaction (%)						
	0.6	0.8	1.0	1.2	1.4	1.6	1.8
99.0	-24.6	-22.5	-20.3	-18.0	-15.5	-12.9	-10.1
98.9	-23.0	-20.9	-18.7	-16.4	-13.9	-11.3	-8.5
98.8	-21.4	-19.3	-17.1	-14.8	-12.3	-9.7	-6.9
98.7	-19.9	-17.8	-15.5	-13.2	-10.7	-8.1	-5.3
98.6	-18.3	-16.2	-14.0	-11.6	-9.1	-6.5	-3.7
98.5	-16.7	-14.6	-12.4	-10.0	-7.5	-4.9	-2.1
98.4	-15.1	-13.0	-10.8	-8.4	-5.9	-3.3	-0.5
98.3	-13.5	-11.4	-9.2	-6.8	-4.3	-1.7	1.0
98.2	-12.0	-9.8	-7.6	-5.2	-2.7	-0.1	2.6
98.1	-10.4	-8.2	-6.0	-3.6	-1.1	1.5	4.2
98.0	-8.8	-6.6	-4.4	-2.0	0.5	3.0	5.8
97.9	-7.2	-5.0	-2.8	-0.4	2.0	4.6	7.3
97.8	-5.6	-3.5	-1.2	1.1	3.6	6.2	8.8
97.7	-4.0	-1.9	0.4	2.7	5.2	7.7	10.4
97.6	-2.5	-0.3	1.9	4.3	6.7	9.2	11.9
97.5	-0.9	1.2	3.5	5.8	8.2	10.7	13.4
97.4	0.6	2.8	5.0	7.3	9.7	12.2	14.8
97.3	2.2	4.3	6.5	8.8	11.2	13.7	16.3
97.2	3.7	5.8	8.0	10.3	12.7	15.1	17.7
97.1	5.2	7.3	9.5	11.8	14.1	16.5	19.1
97.0	6.7	8.8	11.0	13.2	15.5	17.9	20.4
96.9	8.2	10.3	12.4	14.7	17.0	19.3	21.8
96.8	9.7	11.8	13.9	16.1	18.3	20.7	23.1
96.7	11.2	13.2	15.3	17.5	19.7	22.0	24.4
96.6	12.6	14.6	16.7	18.8	21.0	23.3	25.6
96.5	14.1	16.0	18.1	20.2	22.3	24.6	26.8
96.4	15.5	17.5	19.5	21.5	23.6	25.8	28.1
96.3	16.9	18.8	20.8	22.8	24.9	27.0	29.2
96.2	18.3	20.2	22.2	24.1	26.2	28.2	30.4
96.1	19.7	21.6	23.5	25.4	27.4	29.4	31.5
96.0	21.2	23.0	24.8	26.7	28.6	30.6	32.6

Table A-3. Effect of Off-Target Relative Compaction on Future Agency Rehabilitation Cost for 11AB20 (Percent Change)

As-constructed average relative compaction (%)	As-constructed standard deviation of relative compaction (%)						
	0.6	0.8	1.0	1.2	1.4	1.6	1.8
99.0	-26.2	-24.0	-21.6	-19.0	-16.3	-13.4	-10.3
98.9	-24.6	-22.3	-19.9	-17.3	-14.6	-11.7	-8.6
98.8	-22.9	-20.6	-18.2	-15.7	-12.9	-10.0	-6.9
98.7	-21.2	-19.0	-16.5	-14.0	-11.2	-8.3	-5.2
98.6	-19.6	-17.3	-14.9	-12.3	-9.5	-6.6	-3.5
98.5	-17.9	-15.6	-13.2	-10.6	-7.8	-4.9	-1.9
98.4	-16.2	-13.9	-11.5	-8.9	-6.1	-3.2	-0.2
98.3	-14.5	-12.2	-9.8	-7.2	-4.4	-1.6	1.5
98.2	-12.8	-10.5	-8.1	-5.5	-2.8	0.1	3.2
98.1	-11.1	-8.8	-6.4	-3.8	-1.1	1.8	4.8
98.0	-9.4	-7.1	-4.7	-2.1	0.6	3.5	6.5
97.9	-7.7	-5.4	-3.0	-0.4	2.3	5.1	8.1
97.8	-6.0	-3.7	-1.3	1.3	3.9	6.7	9.7
97.7	-4.3	-2.0	0.4	2.9	5.6	8.4	11.3
97.6	-2.7	-0.4	2.1	4.6	7.2	9.9	12.8
97.5	-1.0	1.3	3.7	6.2	8.8	11.5	14.3
97.4	0.7	3.0	5.3	7.8	10.4	13.1	15.9
97.3	2.3	4.6	6.9	9.4	11.9	14.6	17.3
97.2	4.0	6.2	8.5	11.0	13.5	16.1	18.8
97.1	5.6	7.8	10.1	12.5	15.0	17.5	20.2
97.0	7.2	9.4	11.7	14.0	16.5	19.0	21.6
96.9	8.8	11.0	13.2	15.5	17.9	20.4	23.0
96.8	10.4	12.5	14.7	17.0	19.4	21.8	24.3
96.7	11.9	14.0	16.2	18.4	20.8	23.2	25.6
96.6	13.4	15.5	17.7	19.9	22.1	24.5	26.9
96.5	14.9	17.0	19.1	21.3	23.5	25.8	28.2
96.4	16.4	18.4	20.5	22.6	24.8	27.1	29.4
96.3	17.9	19.9	21.9	24.0	26.1	28.3	30.6
96.2	19.3	21.3	23.3	25.3	27.4	29.6	31.8
96.1	20.8	22.7	24.6	26.6	28.7	30.8	32.9
96.0	22.2	24.1	26.0	27.9	29.9	32.0	34.0

Table A-4. Effect of Off-Target Relative Compaction on Future Agency Rehabilitation Cost for 13AB20 (Percent Change)

As-constructed average relative compaction (%)	As-constructed standard deviation of relative compaction (%)						
	0.6	0.8	1.0	1.2	1.4	1.6	1.8
99.0	-27.0	-24.7	-22.2	-19.7	-17.0	-14.1	-11.0
98.9	-25.3	-23.0	-20.6	-18.0	-15.3	-12.4	-9.2
98.8	-23.6	-21.3	-18.9	-16.3	-13.6	-10.7	-7.5
98.7	-21.9	-19.6	-17.2	-14.6	-11.9	-9.0	-5.8
98.6	-20.2	-17.9	-15.5	-12.9	-10.2	-7.2	-4.1
98.5	-18.5	-16.2	-13.8	-11.2	-8.5	-5.5	-2.4
98.4	-16.9	-14.5	-12.1	-9.5	-6.7	-3.8	-0.7
98.3	-15.2	-12.8	-10.4	-7.8	-5.0	-2.1	1.0
98.2	-13.5	-11.1	-8.7	-6.1	-3.3	-0.4	2.7
98.1	-11.8	-9.4	-7.0	-4.4	-1.6	1.3	4.3
98.0	-10.1	-7.7	-5.3	-2.7	0.1	2.9	6.0
97.9	-8.4	-6.0	-3.6	-1.0	1.7	4.6	7.6
97.8	-6.7	-4.3	-1.9	0.7	3.4	6.2	9.2
97.7	-5.0	-2.6	-0.2	2.4	5.0	7.9	10.8
97.6	-3.3	-1.0	1.5	4.0	6.7	9.5	12.4
97.5	-1.6	0.7	3.1	5.6	8.3	11.0	13.9
97.4	0.0	2.3	4.7	7.3	9.9	12.6	15.4
97.3	1.7	4.0	6.4	8.8	11.4	14.1	16.9
97.2	3.3	5.6	8.0	10.4	13.0	15.6	18.4
97.1	5.0	7.2	9.5	12.0	14.5	17.1	19.8
97.0	6.6	8.8	11.1	13.5	16.0	18.6	21.2
96.9	8.2	10.4	12.7	15.0	17.5	20.0	22.6
96.8	9.7	11.9	14.2	16.5	18.9	21.4	24.0
96.7	11.3	13.4	15.7	18.0	20.3	22.8	25.3
96.6	12.8	15.0	17.2	19.4	21.7	24.1	26.6
96.5	14.4	16.5	18.6	20.8	23.1	25.5	27.9
96.4	15.9	17.9	20.1	22.2	24.5	26.8	29.2
96.3	17.4	19.4	21.5	23.6	25.8	28.1	30.4
96.2	18.9	20.9	22.9	25.0	27.1	29.3	31.6
96.1	20.3	22.3	24.3	26.3	28.4	30.6	32.8
96.0	21.8	23.7	25.7	27.7	29.7	31.8	34.0

APPENDIX B

Effect of As-Constructed Asphalt Contents on

Simulated Fatigue Performance

and

Future Agency Rehabilitation Costs

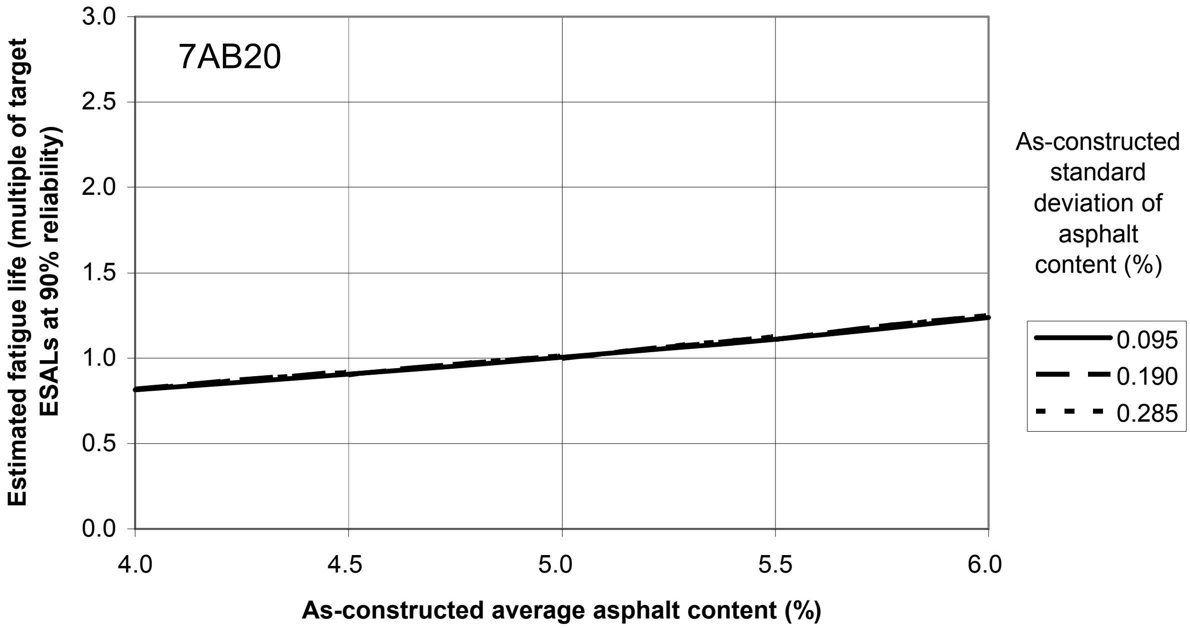

Figure B-1. Effect of As-Constructed Asphalt Contents on Fatigue Performance (7AB20)

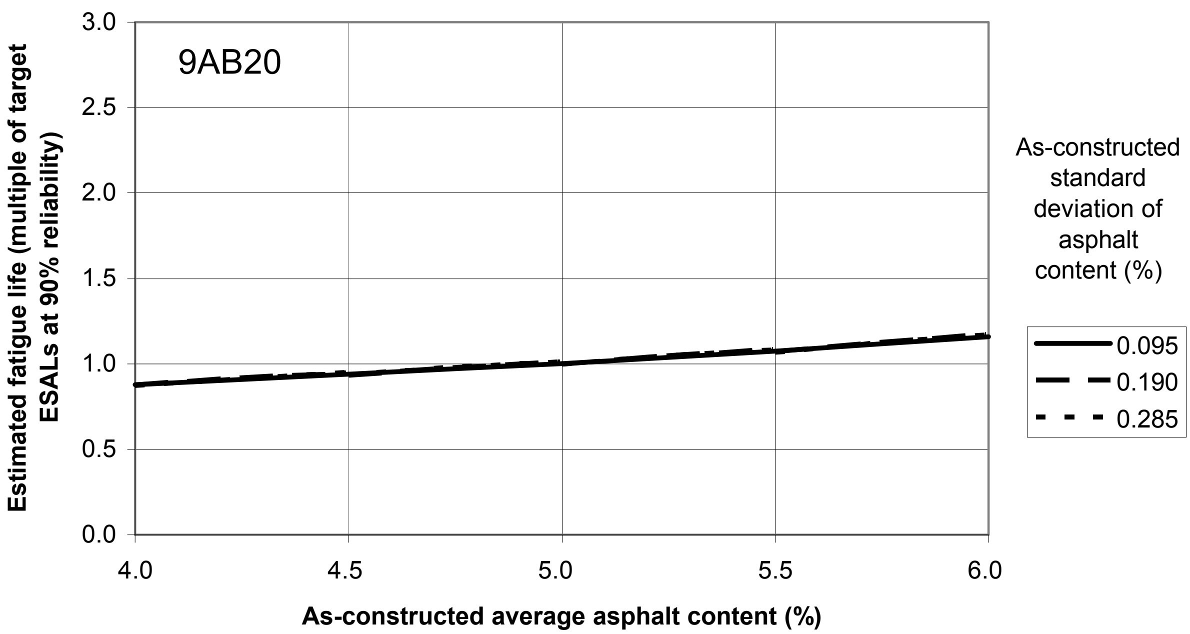

Figure B-2. Effect of As-Constructed Asphalt Contents on Fatigue Performance (9AB20)

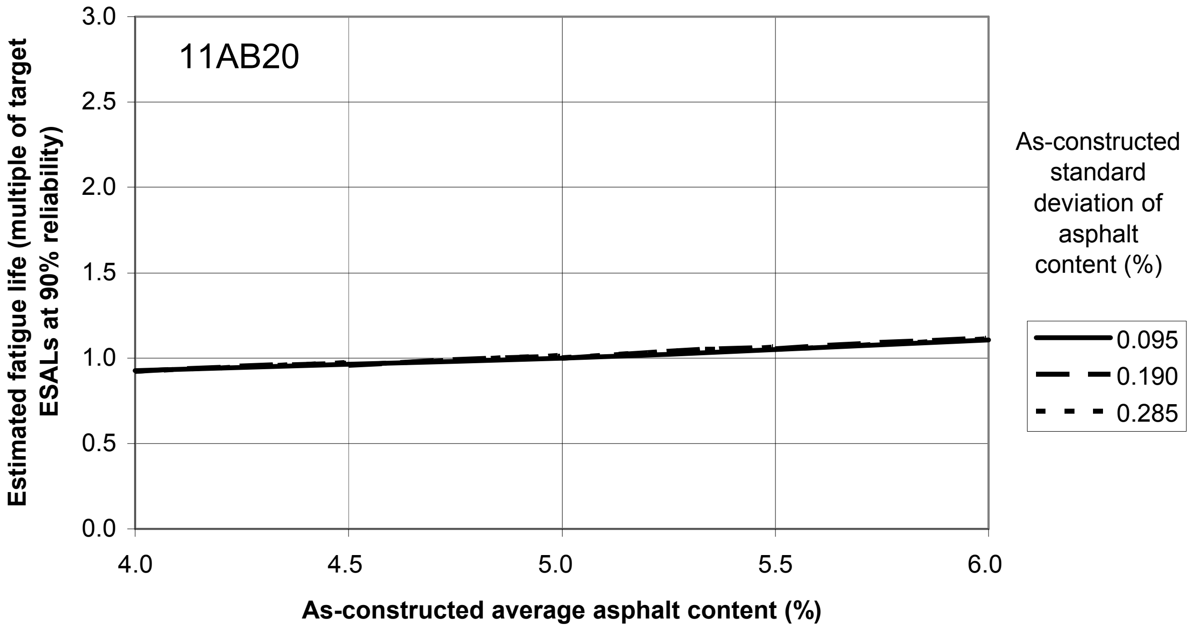

Figure B-3. Effect of As-Constructed Asphalt Contents on Fatigue Performance (11AB20)

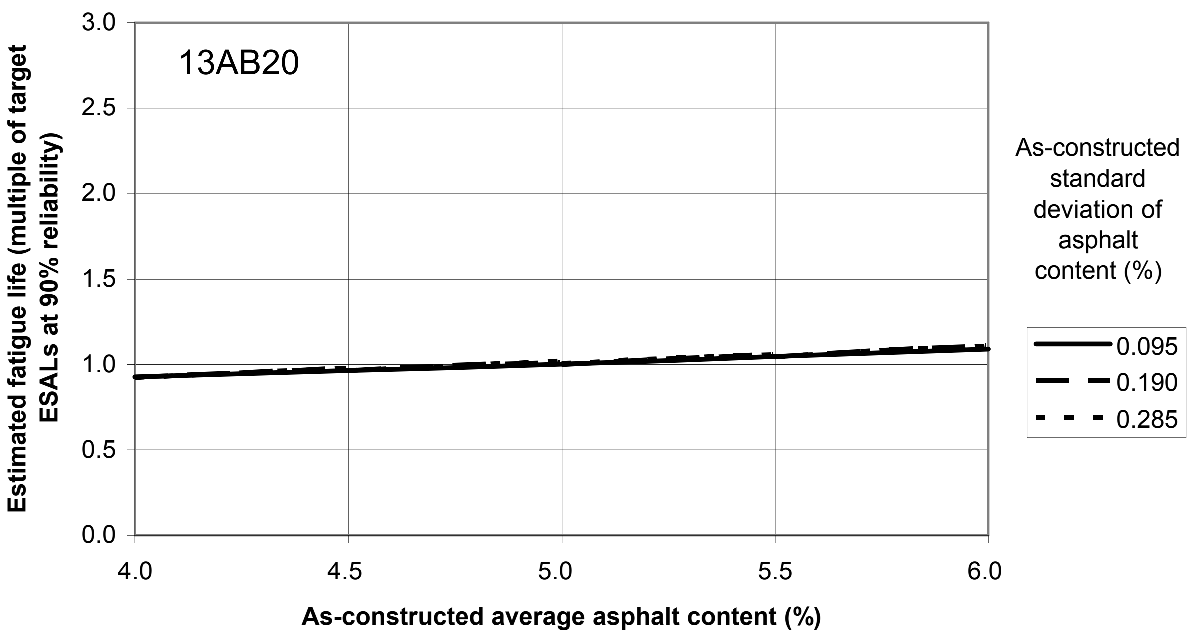

Figure B-4. Effect of As-Constructed Asphalt Contents on Fatigue Performance (13AB20)

Table B-1. Effect of Off-Target Asphalt Content on Future Agency Rehabilitation Cost for 7AB20 (Percent Change)

As-constructed average asphalt content (%)	As-constructed standard deviation of asphalt content (multiple of 0.19%)								
	0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40
4.0	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2
4.1	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
4.2	7.3	7.3	7.4	7.4	7.4	7.4	7.4	7.4	7.4
4.3	6.4	6.4	6.4	6.5	6.5	6.5	6.5	6.5	6.5
4.4	5.5	5.5	5.5	5.5	5.6	5.6	5.6	5.6	5.6
4.5	4.6	4.6	4.6	4.6	4.6	4.7	4.7	4.7	4.7
4.6	3.6	3.7	3.7	3.7	3.7	3.7	3.8	3.8	3.8
4.7	2.7	2.7	2.7	2.8	2.8	2.8	2.8	2.9	2.9
4.8	1.8	1.8	1.8	1.8	1.9	1.9	1.9	1.9	2.0
4.9	0.8	0.9	0.9	0.9	0.9	1.0	1.0	1.0	1.0
5.0	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	0.1	0.1
5.1	-1.1	-1.0	-1.0	-1.0	-1.0	-0.9	-0.9	-0.9	-0.9
5.2	-2.0	-2.0	-2.0	-1.9	-1.9	-1.9	-1.9	-1.9	-1.8
5.3	-3.0	-2.9	-2.9	-2.9	-2.9	-2.9	-2.8	-2.8	-2.8
5.4	-3.9	-3.9	-3.9	-3.9	-3.9	-3.8	-3.8	-3.8	-3.8
5.5	-4.9	-4.9	-4.9	-4.9	-4.8	-4.8	-4.8	-4.8	-4.8
5.6	-5.9	-5.9	-5.8	-5.8	-5.8	-5.8	-5.8	-5.8	-5.8
5.7	-6.9	-6.8	-6.8	-6.8	-6.8	-6.8	-6.8	-6.8	-6.8
5.8	-7.8	-7.8	-7.8	-7.8	-7.8	-7.8	-7.8	-7.8	-7.8
5.9	-8.8	-8.8	-8.8	-8.8	-8.8	-8.8	-8.8	-8.8	-8.8
6.0	-9.8	-9.8	-9.8	-9.8	-9.8	-9.8	-9.8	-9.8	-9.8

Table B-2. Effect of Off-Target Asphalt Content on Future Agency Rehabilitation Cost for 9AB20 (Percent Change)

As-constructed average asphalt content (%)	As-constructed standard deviation of asphalt content (multiple of 0.19%)								
	0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40
4.0	5.9	5.9	6.0	6.0	6.0	6.0	6.0	6.0	6.1
4.1	5.3	5.3	5.3	5.4	5.4	5.4	5.4	5.4	5.4
4.2	4.7	4.7	4.7	4.8	4.8	4.8	4.8	4.8	4.8
4.3	4.1	4.1	4.1	4.2	4.2	4.2	4.2	4.2	4.2
4.4	3.5	3.5	3.6	3.6	3.6	3.6	3.6	3.6	3.7
4.5	2.9	2.9	3.0	3.0	3.0	3.0	3.0	3.0	3.1
4.6	2.3	2.3	2.4	2.4	2.4	2.4	2.4	2.4	2.5
4.7	1.7	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.9
4.8	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.3
4.9	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.7
5.0	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0
5.1	-0.7	-0.7	-0.7	-0.7	-0.6	-0.6	-0.6	-0.6	-0.6
5.2	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.2	-1.2	-1.2
5.3	-2.0	-2.0	-1.9	-1.9	-1.9	-1.9	-1.9	-1.9	-1.8
5.4	-2.6	-2.6	-2.6	-2.6	-2.6	-2.5	-2.5	-2.5	-2.5
5.5	-3.3	-3.3	-3.3	-3.2	-3.2	-3.2	-3.2	-3.2	-3.2
5.6	-4.0	-4.0	-3.9	-3.9	-3.9	-3.9	-3.9	-3.9	-3.8
5.7	-4.7	-4.6	-4.6	-4.6	-4.6	-4.6	-4.6	-4.5	-4.5
5.8	-5.4	-5.3	-5.3	-5.3	-5.3	-5.3	-5.3	-5.3	-5.2
5.9	-6.1	-6.1	-6.1	-6.0	-6.0	-6.0	-6.0	-6.0	-6.0
6.0	-6.8	-6.8	-6.8	-6.8	-6.8	-6.7	-6.7	-6.7	-6.7

Table B-3. Effect of Off-Target Asphalt Content on Future Agency Rehabilitation Cost for 11AB20 (Percent Change)

As-constructed average asphalt content (%)	As-constructed standard deviation of asphalt content (multiple of 0.19%)								
	0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40
4.0	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
4.1	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
4.2	3.0	3.0	3.0	3.0	3.1	3.1	3.1	3.1	3.1
4.3	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.8
4.4	2.3	2.3	2.3	2.3	2.3	2.4	2.4	2.4	2.4
4.5	1.9	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0
4.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
4.7	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
4.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
4.9	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5.1	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4
5.2	-0.9	-0.9	-0.9	-0.9	-0.9	-0.9	-0.9	-0.9	-0.9
5.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3
5.4	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.8	-1.8
5.5	-2.2	-2.2	-2.2	-2.2	-2.2	-2.2	-2.2	-2.2	-2.2
5.6	-2.7	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6
5.7	-3.1	-3.1	-3.1	-3.1	-3.1	-3.1	-3.1	-3.1	-3.1
5.8	-3.6	-3.6	-3.6	-3.6	-3.5	-3.5	-3.5	-3.5	-3.5
5.9	-4.1	-4.1	-4.1	-4.0	-4.0	-4.0	-4.0	-3.9	-3.9
6.0	-4.6	-4.6	-4.5	-4.5	-4.5	-4.4	-4.4	-4.4	-4.3

Table B-4. Effect of Off-Target Asphalt Content on Future Agency Rehabilitatio Cost for 13AB20 (Percent Change)

As-constructed average asphalt content (%)	As-constructed standard deviation of asphalt content (multiple of 0.19%)								
	0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40
4.0	3.6	3.6	3.6	3.7	3.7	3.7	3.7	3.8	3.8
4.1	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.4
4.2	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
4.3	2.6	2.6	2.6	2.6	2.6	2.6	2.5	2.5	2.5
4.4	2.3	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.1
4.5	1.9	1.9	1.9	1.9	1.8	1.8	1.8	1.8	1.8
4.6	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.4
4.7	1.2	1.2	1.1	1.1	1.1	1.1	1.1	1.0	1.0
4.8	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7
4.9	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3
5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1
5.1	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4
5.2	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8
5.3	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.1
5.4	-1.6	-1.6	-1.6	-1.6	-1.5	-1.5	-1.5	-1.5	-1.5
5.5	-2.0	-2.0	-2.0	-1.9	-1.9	-1.9	-1.9	-1.9	-1.9
5.6	-2.4	-2.4	-2.4	-2.3	-2.3	-2.3	-2.3	-2.3	-2.3
5.7	-2.8	-2.8	-2.8	-2.7	-2.7	-2.7	-2.7	-2.7	-2.7
5.8	-3.2	-3.2	-3.2	-3.2	-3.2	-3.1	-3.1	-3.1	-3.1
5.9	-3.6	-3.6	-3.6	-3.6	-3.6	-3.6	-3.6	-3.6	-3.6
6.0	-4.0	-4.0	-4.0	-4.0	-4.0	-4.0	-4.0	-4.0	-4.0

APPENDIX C

Effect of As-Constructed Asphalt-Concrete Thickness on

Simulated Fatigue Performance

and

Future Agency Rehabilitation Costs

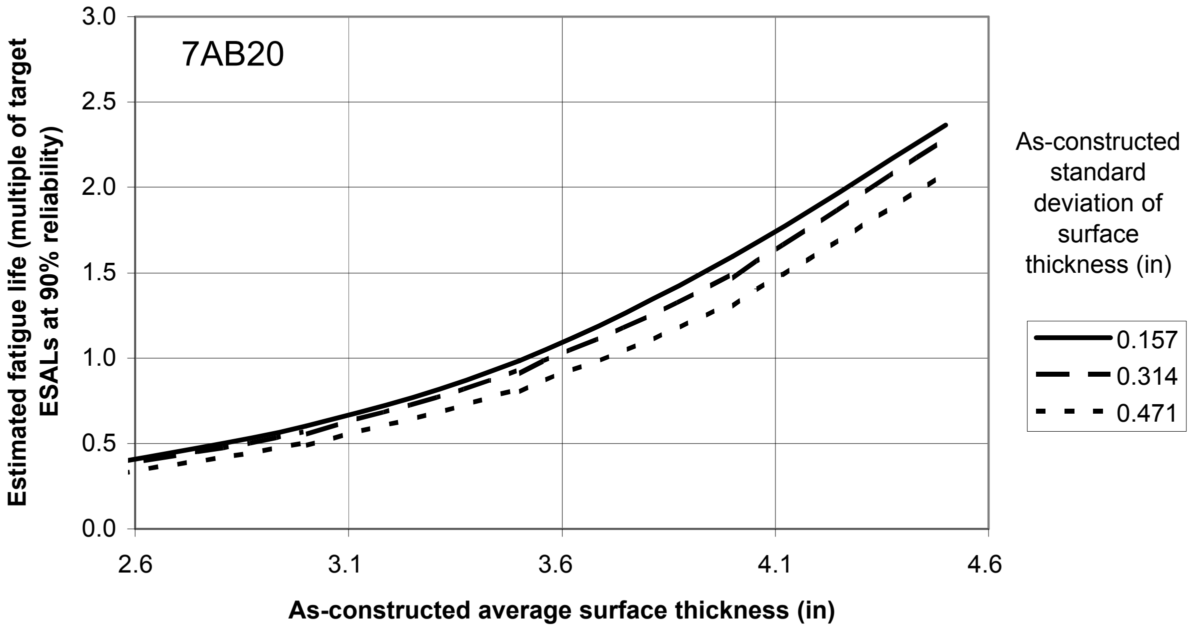

Figure C-1. Effect of As-Constructed Surface Thickness on Fatigue Performance (7AB20)

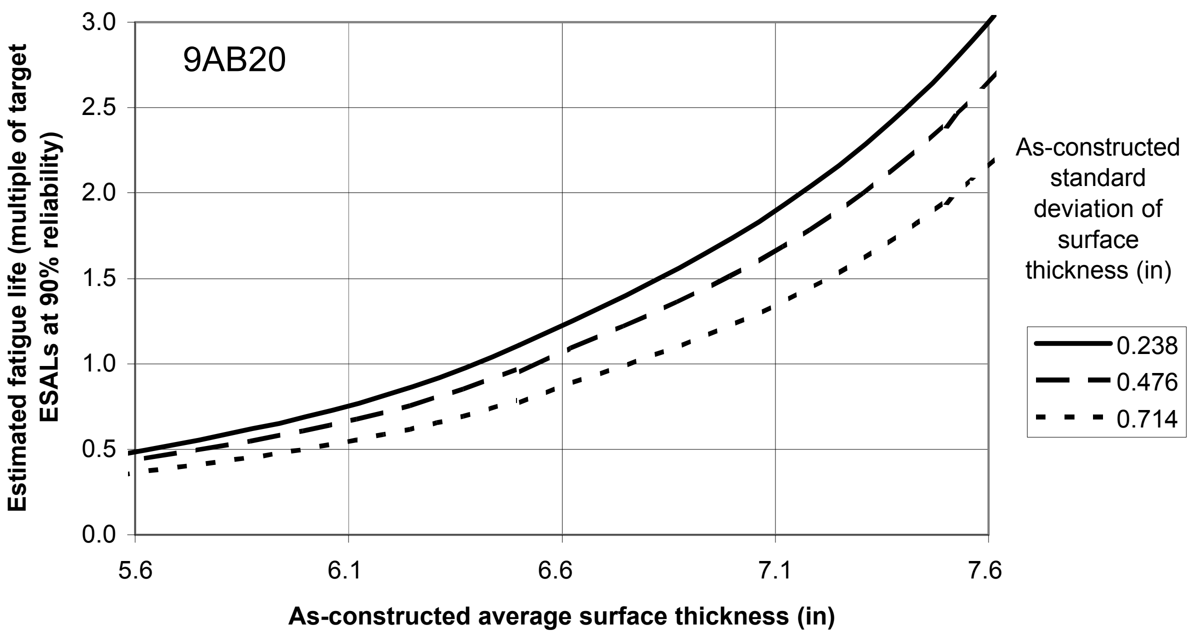

Figure C-2. Effect of As-Constructed Surface Thickness on Fatigue Performance (9AB20)

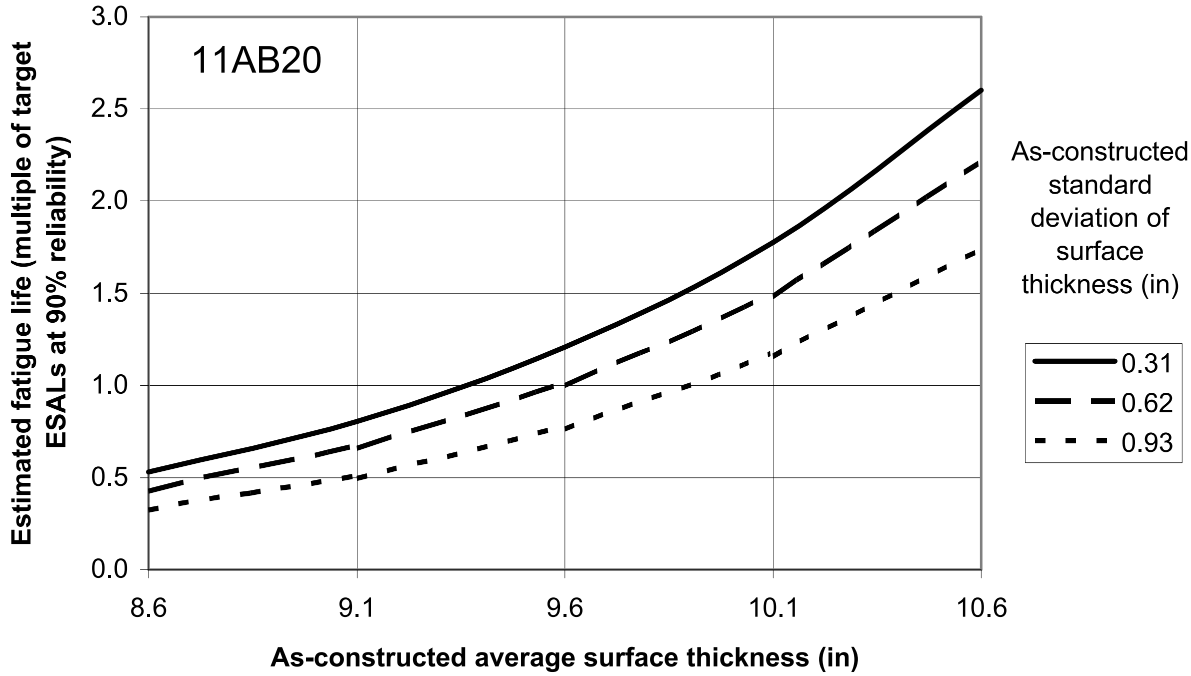

Figure C-3. Effect of As-Constructed Surface Thickness on Fatigue Performance (11AB20)

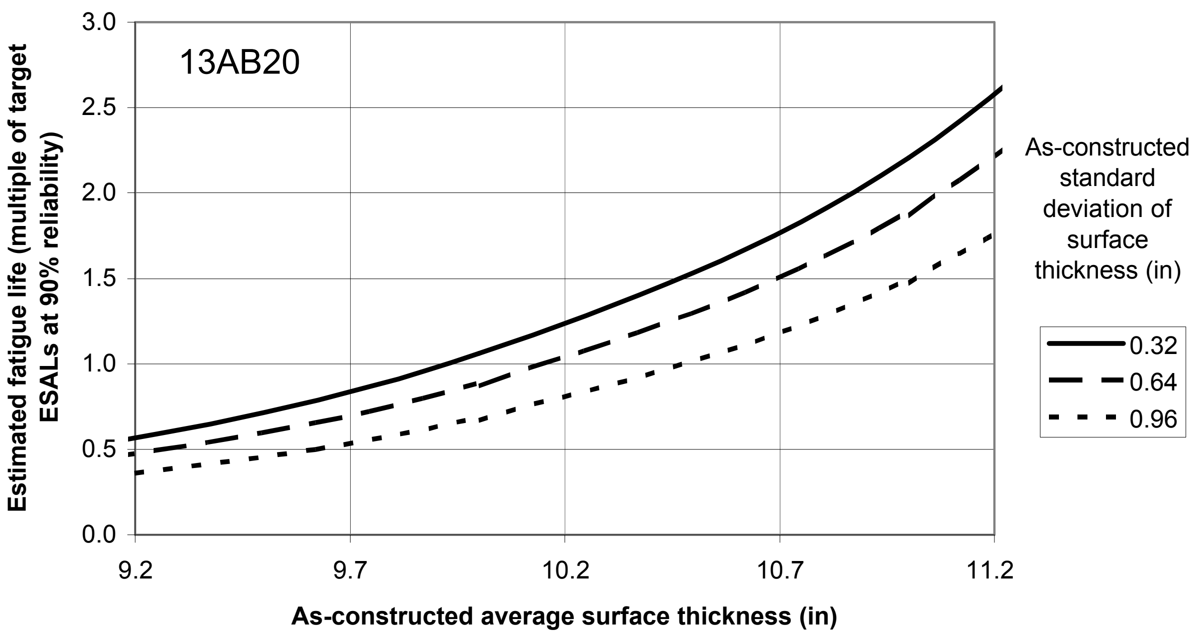

Figure C-4. Effect of As-Constructed Surface Thickness on Fatigue Performance (13AB20)

Table C-1. Effect of Off-Target Asphalt-Concrete Thickness on Future Agency Rehabilitation Cost for 7AB20 (Percent Change)

As-constructed average asphalt-concrete thickness (in)	As-constructed standard deviation of asphalt-concrete thickness (multiple of 0.314)								
	0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40
2.6	36.8	37.4	38.0	38.6	39.2	39.8	40.4	41.0	41.6
2.7	33.8	34.4	35.0	35.6	36.2	36.8	37.4	38.1	38.7
2.8	30.5	31.1	31.7	32.4	33.0	33.6	34.3	34.9	35.5
2.9	26.8	27.5	28.2	28.8	29.5	30.2	30.8	31.5	32.2
3.0	22.9	23.6	24.3	25.0	25.7	26.5	27.2	28.0	28.7
3.1	18.7	19.5	20.2	21.0	21.8	22.6	23.4	24.2	25.0
3.2	14.4	15.2	16.0	16.8	17.7	18.5	19.4	20.2	21.1
3.3	9.9	10.7	11.6	12.5	13.4	14.3	15.2	16.1	17.0
3.4	5.3	6.2	7.1	8.0	9.0	9.9	10.8	11.8	12.8
3.5	0.8	1.7	2.6	3.5	4.5	5.4	6.4	7.4	8.5
3.6	-3.8	-2.9	-1.9	-1.0	0.0	1.0	2.0	3.0	4.0
3.7	-8.2	-7.3	-6.4	-5.5	-4.5	-3.5	-2.5	-1.5	-0.4
3.8	-12.6	-11.7	-10.8	-9.9	-8.9	-7.9	-7.0	-6.0	-4.9
3.9	-16.8	-15.9	-15.0	-14.1	-13.2	-12.3	-11.3	-10.4	-9.4
4.0	-20.8	-20.0	-19.2	-18.3	-17.4	-16.5	-15.6	-14.7	-13.8
4.1	-24.8	-24.0	-23.2	-22.4	-21.5	-20.7	-19.8	-18.9	-18.0
4.2	-28.6	-27.8	-27.1	-26.3	-25.5	-24.7	-23.9	-23.1	-22.2
4.3	-32.4	-31.7	-31.0	-30.2	-29.5	-28.7	-27.9	-27.1	-26.3
4.4	-36.4	-35.6	-34.9	-34.2	-33.4	-32.7	-31.9	-31.2	-30.4
4.5	-40.6	-39.8	-39.1	-38.3	-37.6	-36.8	-36.1	-35.4	-34.6
4.6	-45.3	-44.5	-43.7	-42.9	-42.1	-41.4	-40.6	-39.9	-39.1

Table C-2. Effect of Off-Target Asphalt-Concrete Thickness on Future Agency Rehabilitation Cost for 9AB20 (Percent Change)

As-constructed average asphalt-concrete thickness (in)	As-constructed standard deviation of asphalt-concrete thickness (multiple of 0.476 in)								
	0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40
5.6	29.7	30.7	31.7	32.7	33.7	34.8	35.8	36.9	37.9
5.7	27.2	28.2	29.3	30.4	31.5	32.6	33.7	34.9	36.0
5.8	24.4	25.5	26.7	27.8	29.0	30.2	31.4	32.6	33.9
5.9	21.3	22.5	23.8	25.0	26.3	27.6	28.9	30.2	31.5
6.0	18.0	19.3	20.6	21.9	23.3	24.6	26.0	27.5	28.9
6.1	14.5	15.8	17.2	18.6	20.0	21.5	22.9	24.4	26.0
6.2	10.7	12.1	13.5	15.0	16.5	18.0	19.5	21.1	22.8
6.3	6.6	8.1	9.6	11.1	12.7	14.2	15.9	17.6	19.3
6.4	2.4	3.9	5.4	7.0	8.6	10.3	12.0	13.7	15.5
6.5	-2.0	-0.4	1.1	2.7	4.4	6.1	7.8	9.6	11.5
6.6	-6.4	-4.9	-3.3	-1.7	0.0	1.7	3.5	5.3	7.2
6.7	-10.9	-9.4	-7.8	-6.2	-4.5	-2.8	-1.0	0.9	2.8
6.8	-15.4	-13.9	-12.3	-10.7	-9.1	-7.3	-5.5	-3.7	-1.7
6.9	-19.8	-18.3	-16.8	-15.2	-13.6	-11.9	-10.1	-8.3	-6.3
7.0	-24.2	-22.7	-21.2	-19.7	-18.1	-16.4	-14.7	-12.8	-10.9
7.1	-28.6	-27.1	-25.6	-24.1	-22.5	-20.9	-19.1	-17.4	-15.5
7.2	-33.0	-31.5	-30.0	-28.5	-26.9	-25.3	-23.6	-21.8	-20.0
7.3	-37.8	-36.2	-34.5	-32.9	-31.3	-29.7	-28.0	-26.2	-24.4
7.4	-43.1	-41.2	-39.4	-37.7	-35.9	-34.2	-32.4	-30.6	-28.8
7.5	-49.5	-47.2	-45.0	-43.0	-40.9	-39.0	-37.1	-35.2	-33.3
7.6	-57.6	-54.6	-51.9	-49.3	-46.8	-44.5	-42.3	-40.1	-38.1

Table C-3. Effect of Off-Target Asphalt-Concrete Thickness on Future Agency Rehabilitation Cost for 11AB20 (Percent Change)

As-constructed average asphalt-concrete thickness (in)	As-constructed standard deviation of asphalt-concrete thickness (multiple of 0.62 in)								
	0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40
8.6	27.7	29.2	30.7	32.2	33.7	35.3	36.9	38.5	40.2
8.7	24.3	25.9	27.5	29.1	30.7	32.4	34.1	35.9	37.6
8.8	21.0	22.6	24.3	26.0	27.7	29.5	31.3	33.1	35.0
8.9	17.6	19.3	21.0	22.7	24.5	26.4	28.3	30.2	32.2
9.0	14.1	15.8	17.6	19.4	21.3	23.2	25.2	27.2	29.2
9.1	10.6	12.4	14.2	16.1	18.0	19.9	22.0	24.0	26.2
9.2	7.0	8.8	10.7	12.6	14.5	16.6	18.6	20.8	23.0
9.3	3.4	5.2	7.1	9.0	11.0	13.1	15.2	17.4	19.6
9.4	-0.3	1.6	3.4	5.4	7.4	9.5	11.6	13.8	16.1
9.5	-3.9	-2.1	-0.3	1.7	3.7	5.8	8.0	10.2	12.5
9.6	-7.6	-5.8	-4.0	-2.0	0.0	2.1	4.3	6.5	8.9
9.7	-11.3	-9.5	-7.7	-5.8	-3.8	-1.7	0.5	2.8	5.1
9.8	-15.0	-13.2	-11.4	-9.5	-7.5	-5.5	-3.3	-1.0	1.3
9.9	-18.6	-16.9	-15.1	-13.2	-11.3	-9.2	-7.1	-4.9	-2.5
10.0	-22.2	-20.5	-18.7	-16.9	-15.0	-13.0	-10.9	-8.7	-6.3
10.1	-25.8	-24.1	-22.3	-20.5	-18.6	-16.7	-14.6	-12.4	-10.1
10.2	-29.3	-27.7	-25.9	-24.1	-22.3	-20.3	-18.3	-16.1	-13.9
10.3	-33.0	-31.3	-29.5	-27.7	-25.8	-23.9	-21.9	-19.8	-17.5
10.4	-36.8	-35.0	-33.2	-31.3	-29.4	-27.5	-25.4	-23.4	-21.2
10.5	-41.0	-39.0	-37.0	-35.0	-33.0	-31.0	-29.0	-26.9	-24.7
10.6	-45.8	-43.5	-41.2	-39.0	-36.9	-34.7	-32.6	-30.4	-28.2

Table C-4. Effect of Off-Target Asphalt-Concrete Thickness on Future Agency Rehabilitation Cost for 13AB20 (Percent Change)

As-constructed average asphalt-concrete thickness (in)	As-constructed standard deviation of asphalt-concrete thickness (multiple of 0.64 in)								
	0.60	0.70	0.80	0.90	1.00	1.10	1.20	1.30	1.40
9.2	25.5	27.0	28.6	30.2	31.8	33.5	35.2	36.9	38.6
9.3	22.7	24.3	25.9	27.5	29.2	31.0	32.7	34.5	36.3
9.4	19.7	21.4	23.1	24.8	26.5	28.3	30.1	32.0	33.9
9.5	16.7	18.4	20.1	21.8	23.6	25.5	27.4	29.3	31.2
9.6	13.5	15.2	17.0	18.8	20.6	22.5	24.4	26.4	28.5
9.7	10.2	11.9	13.7	15.6	17.4	19.4	21.4	23.4	25.5
9.8	6.8	8.5	10.3	12.2	14.1	16.1	18.2	20.3	22.4
9.9	3.3	5.0	6.9	8.8	10.7	12.7	14.8	17.0	19.2
10.0	-0.3	1.5	3.3	5.2	7.2	9.3	11.4	13.5	15.8
10.1	-3.9	-2.1	-0.3	1.6	3.6	5.7	7.8	10.0	12.3
10.2	-7.5	-5.7	-3.9	-2.0	0.0	2.0	4.2	6.4	8.7
10.3	-11.1	-9.4	-7.6	-5.7	-3.7	-1.6	0.5	2.7	5.0
10.4	-14.7	-13.0	-11.2	-9.3	-7.4	-5.3	-3.2	-1.0	1.3
10.5	-18.2	-16.6	-14.8	-13.0	-11.0	-9.0	-6.9	-4.8	-2.5
10.6	-21.7	-20.1	-18.4	-16.5	-14.7	-12.7	-10.6	-8.5	-6.2
10.7	-25.2	-23.6	-21.9	-20.1	-18.2	-16.3	-14.3	-12.2	-9.9
10.8	-28.7	-27.0	-25.3	-23.6	-21.8	-19.9	-17.9	-15.8	-13.6
10.9	-32.2	-30.5	-28.8	-27.0	-25.2	-23.4	-21.4	-19.4	-17.2
11.0	-35.8	-34.0	-32.3	-30.5	-28.7	-26.8	-24.9	-22.9	-20.8
11.1	-39.7	-37.8	-35.9	-34.0	-32.2	-30.3	-28.3	-26.3	-24.2
11.2	-44.0	-41.9	-39.8	-37.8	-35.8	-33.8	-31.8	-29.8	-27.7