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Performance-Based Pay Factors for Asphalt Concrete Construction: Comparison with a Currently Used Experience-Based Approach

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Work Conducted Under "Development of New Asphalt Concrete QC/QA Pay Factor Tables" as part of Partnered Pavement Research Center Strategic Plan Element No. 3.1.5

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Abstract: Document summarizes a procedure to establish pay factors for asphalt concrete pavement construction using performance models for fatigue and rutting based on the analysis of accelerated pavement tests from the Caltrans Heavy Vehicle Simulator (HVS) and the WesTrack accelerated pavement performance test program. Results of the performance-based approach are compared with pay factors determined by the current Caltrans procedure using percent defective and experience-based weighting factors.

Keywords:
pay factor, performance models, rutting performance model, fatigue performance model, percent within limits (PWL), percent defective

Proposals for implementation:

- Based on the results presented in the report, it is recommended that Caltrans take the necessary steps to implement the performance-based approach using the pay factor methodology described herein. A Pay Factor Calculator using some of the spreadsheet features of Microsoft® *Excel* is available, which makes use of the six pay factor tables included in the report.
- A suggested approach for implementation is to select a series of QC/QA construction projects and determine pay factors by both the current procedure and the proposed performance-based approach. The results from both procedures could then be evaluated by the Joint Caltrans/Industry Task Group to determine the efficacy of implementing the performance-based approach at the completion of this evaluation.

If the above recommendation is followed a thickness measurement would be required in addition to the conventional mix parameters.

Related documents:

- J. A. Deacon, C. L. Monismith, and J. T. Harvey. "Pay Factors for Asphalt-Concrete Construction: Effect of Construction Quality on Agency Costs". TM-UCB-CAL/APT-97-1. Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley, April 1997, 47 pp.
- J.A. Deacon, C.L. Monismith, J.T. Harvey, and L. Popescu. "Pay Factors for Asphalt Concrete Construction: Effect of Construction Quality on Agency Costs". TM-UCB-PR-2001-1. Pavement Research Center, Institute for Transportation Studies, University of California, Berkeley, February 2001, 97 pp.

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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PROJECT OBJECTIVES

This report addresses Strategic Plan Elements (SPE) 3.1.5 and 4.13.

ACKNOWLEDGEMENTS

The research that serves as the basis for this report has been supported by the California Department of Transportation (Caltrans), the Federal Highway Administration, and the National Cooperative Research Program of the Transportation Research Board (WesTrack, rutting performance model).

The authors are grateful to: Dr. J. A. Deacon for his significant contributions to the proposed approach for pay factor determinations; Mr. Paul Benson of Materials Engineering and Testing Services (METS) for the data for the Caltrans-determined pay factors contained in Table B1; and representatives of the pavement construction industry in California for the data in Table 8. Mr. David Spinner of the UC Pavement Research Center prepared the manuscript in final form and his efforts are gratefully acknowledged.

EXECUTIVE SUMMARY

The report briefly summarizes a procedure to establish pay factors for asphalt concrete pavement construction using performance models for fatigue and rutting. These models are based on a combination of mechanistic-empirical pavement analyses, SHRP-developed laboratory test data on hot-mix asphalt (HMA) to provide measures of the effects of mix variables on fatigue and rutting behavior, and accelerated performance tests under full-scale traffic loading. The approach should be applicable to any type of HMA. For mixes with aggregate gradations different than the conventional dense-graded materials used in this study, additional laboratory testing should be performed.

The performance models make use of means and variances rather than the percent within limits (PWL) approach currently used by many agencies* for asphalt concrete construction parameters. For rutting, the influence of asphalt content, air-void content, and aggregate gradation are considered. For fatigue, air-void content, asphalt content, and asphalt concrete thickness are included. Using a preselected target (design) value and a reasonable standard deviation (excluding test variance) for a specific mix property or pavement parameter, the relative performance (RP) of the as-constructed mix can be determined based on its measured mean property and standard deviation. In this instance RP is defined as the ratio of off-target traffic (ESALs) to target or design traffic (ESALs).

Costs are established using a cost model considering only agency cost consequences (road user costs are not included) of delaying or accelerating the time to the next rehabilitation. Pay factors are combined for a specific distress mode, making use of a multiplicative procedure, which Monte Carlo simulations have demonstrated is a simple yet reasonable method. The shortest RP for the combined RPs for mix and pavement characteristics considered for a specific distress mode permits determination of the pay factor from the cost model.

With this approach it is likely that both incentives and disincentives may be understated because only the first rehabilitation cycle is considered. Nevertheless, understated incentives/disincentives measured in terms of bonuses/penalties are likely to be more appropriate than overstated ones for initial use of this methodology. The methodology provides for a full bonus for superior construction and a full penalty for inferior construction. Based on current

* Caltrans uses "percent defective."

practice, the potential bonus to be awarded usually does not exceed some prescribed level established by the transportation agency. The current upper limit for Caltrans is a bonus of 5 percent. The performance-based analysis does not provide a basis for setting such an upper limit since improved materials quality and construction does, in fact, improve pavement life and reduce life-cycle costs.

The argument is made that this performance model approach, based on the use of target values and standard deviations, is a sounder approach to establishing pay factors than the current procedure using percent defective is based on relative weighting of the mix parameters considered to affect performance.

The approach emphasizes the importance of adhering to the target value for a specific pavement characteristic (mix property and layer thickness) and maintaining uniformity (low standard deviation) to achieve or exceed the desired performance level.

Combined pay factors for rutting and fatigue based on the cost model shown in Figure 8 are based on: target lives of 10 and 20 years, a 2 percent annual traffic growth rate, a 5 percent discount rate, a 2.5 percent inflation rate, and rehabilitation costs equal to 0.5 times the initial construction cost for rutting and fatigue. Other parameters, e.g., changed target lives and rehabilitation costs, will result in different values for the combined pay factors. Moreover these pay factors have been developed for asphalt concrete pavements on granular base and subbase over the subgrade.

Until further research becomes available, the approach for rutting would appear applicable for asphalt concrete overlays on portland cement concrete (PCC) pavements. Rutting resulting from shear deformations in asphalt concrete is usually limited to the upper 75–100 mm and overlays on PCC pavement usually have thicknesses of at least these values. On the other hand, cracking in overlay pavements (both cracked asphalt concrete and PCC) is likely to be reflection cracking rather than the classical fatigue cracking which can occur in conventional asphalt concrete pavements. Reference (1) provides some evidence that this is the case for asphalt concrete overlays on cracked asphalt concrete pavements. It is probable that the factors that affect fatigue cracking will also affect reflection cracking. The relative effects of these factors may not be exactly the same as for fatigue; nevertheless they can serve as a starting point.

Results from the process used by Caltrans for obtaining a combined pay factor, using weighting factors for selected mix parameters, are compared with the multiplicative procedure. The comparison suggests that weighting factors for specific mix parameters are dependent on the mode of distress; for example, the effect of asphalt content is different for fatigue and rutting.

The available evidence suggests that the effects of the mix variables using PWL (or percent defective) are based solely on experience. It is possible that the performance-based approach could be used to establish PWL; however, the authors are not aware of any such examples of this approach. In the Caltrans methodology, for example, both rutting and fatigue effects are lumped together. A major advantage of the performance-based approach is that it emphasizes the mix and pavement structure characteristics that most affect performance. As an example, the rutting model emphasizes the importance of asphalt content, degree of compaction, and aggregate gradation as defined by the P_{200} fraction, while the fatigue model emphasizes degree of compaction, pavement thickness, and asphalt content. While the contractor might consider increasing the binder content somewhat for improved degree of compaction for fatigue, this increase of the asphalt content above the design target is precluded because of rutting considerations. Moreover, as illustrated in Table 13, for rutting, the relative weighting of the pay factors are different than those for fatigue. For example, an asphalt content difference relative to the target value is more critical for rutting than fatigue, particularly on the high side. Similarly, a compaction difference (as measured by V_{air}) above the target value has a more significant effect on fatigue performance than on rutting propensity. These comparisons necessarily have to be based on reasonable differences relative to target values. For example, if the mix is compacted very poorly, at a V_{air} in the 12 percent range, considerable rutting could occur prematurely due to the volume change in the mix.

The examples presented in Table 11 and Table 12 also illustrate the advantage of the performance-based approach. For example, in Table 11, while the percent defective procedure illustrated relative uniform mix production, the performance-based approach suggested otherwise. Similarly the data in Table 12 indicate that the contractor required a number of days to achieve a mix of high quality using the performance-based approach, whereas the percent defective approach suggested a uniform mix during the entire period of production.

In general, the performance-based approach emphasizes the importance of uniformity in both materials production and placement with reasonable controls placed on inherent variability. Moreover, it emphasizes the importance of adhering to design target values and, very importantly, reflects only the materials and construction variance by eliminating the influence of test variance.

To change from the experience-based percent defective approach to the use of performance-based equations like those used herein (based on mechanistic-empirical analyses and Monte Carlo simulations) is now feasible with the introduction of mechanistic-empirical (M-E) design, e.g., CAL-ME This design methodology includes performance equations for asphalt concrete pavement (e.g., fatigue and rutting). These equations include HMA variables such as those included herein.

Field performance data are required to make this change; linking of a database containing the initial design, materials, and construction data to the pavement management system containing the field performance data will be required. An excellent example of this tie between materials and construction and field performance data has been demonstrated by the Maryland DOT in a Federal Highway Administration-supported study completed in 2003. Also, there are studies underway that are sponsored by the National Cooperative Highway Research Program (e.g., NCHRP Project 1-40B) to specifically accomplish this objective associated with the implementation of the New Design Guide.

Based on the results presented herein, it is recommended that Caltrans take the necessary steps to implement the performance-based approach to the pay factor methodology described in this report. A "Pay Factor Calculator" using some of the spreadsheet features of Microsoft® *Excel* is available and is included in Appendix C, which makes use of the six pay factor tables included in Appendix A. One approach that might be followed is to select a series of quality control/quality assurance (QC/QA) construction projects and determine pay factors by both the current procedure and the proposed performance-based approach. The results from both procedures could then be evaluated by the Joint Caltrans/Industry Task Group at an appropriate time following construction to determine the efficacy of implementing the performance-based approach.

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1.0 INTRODUCTION

The quality of a pavement upon completion of construction is a major factor in determining how well it will perform under traffic loading and environmental influences. To improve the construction process, quality control/quality assurance (QC/QA) procedures and pay incentives/disincentives (pay factors) have been instituted in the U.S. in recent years. This document briefly describes a rational and feasible method for quantitatively establishing such pay factors for asphalt concrete construction with the initial emphasis placed on new hot-mix asphalt (HMA) pavements.

The approach to pay factor determination makes use of performance models for asphalt concrete* developed from results of the CAL/APT program [California Accelerated Pavement Testing Program, a pavement research program supported by the California Department of Transportation (Caltrans) at the University of California Berkeley] (1) and from WesTrack [a Federal Highway Administration (FHWA) and National Cooperative Highway Research Program (NCHRP) project entitled "Accelerated Field Test of Performance-Related Specifications for Hot-Mix Asphalt Construction," which incorporated an experimental road test facility near Carson City, Nevada] (2). The performance model for fatigue resulted from the CAL/APT program; the model for rutting was developed from results of mix performance in the WesTrack experiment. For the fatigue mode of distress, the system considers the means and variances of asphalt content, air-void content, and asphalt thickness. For the rutting distress, the means and variances of asphalt content, air-void content, and aggregate gradation are included. In estimating fatigue damage under traffic loading, the pavement is treated as a multilayer elastic system. The performance models permit computation of pavement life, expressed in Equivalent Standard Axle Loads (ESALs), using Monte Carlo simulation techniques.

Costs are established using a cost model, which considers only agency cost consequences of delaying or accelerating the time to the next surfacing or rehabilitation activity. This model understates agency costs by ignoring the possible effects of construction quality on future rehabilitation costs. It ignores future rehabilitation activity beyond the first cycle and requires an

* In September 2007, the term "asphalt concrete" was changed to "hot-mix asphalt" (HMA). Asphalt concrete will be retained in this report since the draft was completed prior to the 2007 date.

exogenous estimate of future rehabilitation costs, traffic growth, expected years of new pavement life, and a discount rate representing the time value of money.

Determination of an appropriate pay factor is based on determining the relative performance (RP). For the as-constructed mix this is defined as the ratio of off-target ESALs resulting from the mix and pavement characteristics considered in the performance models to the target ESALs. The RP governing the Contractor's pay factor is that associated with the shortest life determined for the two distress modes. With the shortest RP, the pay factor, reflecting the combined effects of the as-constructed mix and structural parameters, is then determined from the cost model.

Pay factors determined by this approach are compared with those determined from an experience-based approach used by the California Department of Transportation (Caltrans) since 1997 for Quality Control/Quality Assurance (QC/QA) projects constructed in the period January 1997 to June 2000. Comparisons are included for approximately 80 QC/QA projects.

At this time, the Caltrans Pavement Condition Survey includes both rutting and fatigue cracking data for a limited number of the approximately 80 projects noted above. Comparisons of the actual and computed pay factors are included for these projects as well as the actual performance data.

Two paving contractors supplied their information for some of the projects included among the 80 QC/QA projects noted above. Comparisons of the Caltrans and the performance-based pay factors are also presented.

Some agencies base pay factors on daily tonnage while others reimburse the Contractor at the end of the project based on the overall average of parameters used to determine these factors. A comparison of the results using both approaches is included.

2.0 APPROACH

The approach adopted for the development of pay factors focuses primarily on the economic impacts to the highway agency. The assumption is made that an appropriate disincentive (penalty) for inferior construction should be the added cost to the agency and that the incentive (bonus) for superior construction should be no greater than the added savings to the agency.[†] The bonuses coupled with the penalties may provide sufficient incentive to the contractor to improve construction quality.

For new construction, for example, these agency costs/savings are associated primarily with subsequent pavement rehabilitation. Inferior construction hastens the need for 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 worth 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.

To compute the differential present worth of future rehabilitation requires two different types of models: (1) a performance-based model or models for determining the effect of construction quality on expected pavement performance, and (2) a cost model for translating these effects into rehabilitation dollars.

Two performance models are utilized: one for rutting and one for fatigue cracking. For most construction situations, both performance models will be utilized to develop appropriate pay factors. For these circumstances, the pay factors resulting from the use of the performance models are based on the distress mode yielding the most beneficial consequence to the agency.

The performance model used for rutting is based on mix performance data developed at WesTrack (2). It is based on regression analysis, although multilayer elastic analysis of representative pavement structures was used in its development.

The model used for fatigue is based on the mix analysis and design system originally developed as a part of the Strategic Highway Research Program (SHRP) (3), extended to

[†] Subsequently the terms *bonus* and *penalty* are used for *incentive* and *disincentive*, respectively.

efficiently treat in-situ temperatures (4), calibrated to the current Caltrans flexible pavement design system (5), extended to incorporate construction variability, and used in interpreting the results of HVS tests on flexible pavements, both new and overlaid, constructed at the Richmond Field Station according to Caltrans Standards (1). In estimating damaging strains under traffic for fatigue cracking, the pavement is treated as a multilayer elastic system.

Using a preselected target (design) value and a reasonable standard deviation (excluding test variance) for a specific mix property or pavement parameter, the relative performance (RP) of the as-constructed mix can be determined based on its measured mean and standard deviation.

Monte Carlo simulations were used to quantify the effects of construction quality on simulated in-situ performance.

The cost model considers only the time to the next rehabilitation activity, i.e., it ignores future rehabilitation measures beyond the first cycle. It requires an estimate of future rehabilitation cost; it considers annual inflation of rehabilitation costs, traffic growth, expected years of the constructed life of the asphalt concrete, and a discount rate representing the time value of money.

The approach emphasizes the importance of adhering to the target value for a specific pavement characteristic (mix property and layer thickness) and maintaining uniformity (low standard deviation) to achieve or exceed the desired performance level. In addition, pay factors are combined for a specific distress mode, making use of a multiplicative procedure, which Monte Carlo simulations have demonstrated is a simple yet reasonable method. The results from the process used by Caltrans for obtaining a combined pay factor, using weighting factors for selected mix parameters, are compared with the results from the *multiplicative* procedure. As will be shown, the weighting factors for specific mix parameters are dependent on the mode of distress.

3.0 SELECTION OF MIX VARIABLES

For rutting, the variables considered are air-void content (V_{air}), asphalt content (PW_{asp}), and aggregate gradation expressed in terms of the percent passing the No. 200 (0.075 mm) sieve (P_{200}), and the fraction passing the No. 8 (2.38 mm) sieve and retained on the No. 200 (0.075 mm) sieve (fa). As will be seen subsequently, the factor fa is not included in the pay factor determinations since its influence for the range in parameters investigated was relatively small.

The parameters selected for aggregate gradation were, in part, based on current control parameters (P_{200}) and in part on controlling sieves in the Superpave mix design method (the No. 8 × No. 200 fraction). Thickness of the asphalt concrete was not included since the mix components and degree of compaction are the controlling factors for asphalt mix rutting (stability).

For fatigue, the variables include air-void content, V_{air}, asphalt content, PW_{asp}, and asphalt concrete thickness, t_{AC}. Aggregate grading effects have not been included in the performance models since the WesTrack experiment as well as the other studies discussed in Reference (2) suggest that these effects are comparatively small relative to the parameters V_{air}, PW_{asp}, and t_{AC}.

3.1 Variability Considerations

The performance models make use of means and variances for asphalt concrete construction parameters.

Random selection of the variables has assumed 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 evaluation, backcalculation of moduli from falling weight deflectometer (FWD) measurements, and data collected as a part of the WesTrack project (2). A summary of these results is presented in Table 1.

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 (*8*)
		0.1–0.4%	Individual WesTrack sections (*8*)
		0.31%	WesTrack composite (*8*)
		0.3%	Table 3 (*9*)
Air-Void Content	Standard Deviation	0.9–1.9%	Table 12.55 (*8*)
		0.4–1.5%	Individual WesTrack sections (*8*)
		1.5%	WesTrack composite (*8*)
		1.94%	Table 3 (*9*)
Thickness	Coefficient of Variation	12.5–15%	Table 12.58 (*8*)
	Standard Deviation	0–0.5 cm	Individual WesTrack sections (*8*)
		0.58 cm	WesTrack composite (*8*)
		0.99 cm	Table 3 (*9*)
Foundation Modulus	Coefficient of Variation	11.3–14.7%	HVS test sections at UCB (*1*)
		17.3–44.7%	Segment of highway in KY*
		3.6–17.7%	Individual WesTrack sections (*8*)
		14.2–28.5%	WesTrack composite (*8*)

*Unpublished data, Kentucky DOT

The totals in Table 1 include not only materials and construction components, but also components resulting from testing and sampling. To consider only materials and construction effects, the testing and sampling components were removed from the variance estimates using information contained in Table 2.

Table 3 summarizes the results of this analysis (7). The equations for estimating the standard deviation of asphalt concrete thickness were developed as an approximate way to handle multi-lift construction. Among the assumptions made in their development was that the coefficient of variation of thickness in single-lift construction is about 14 percent.

Table 2: Material/Construction Component of Total Construction Variance

Property	Materials/ Construction Component (%)	Source
Asphalt Content	40 61	Figure 7 (*10*) Table 3 (*9*)
Air-Void Content	60 90	Table 8 (inferred) (*10*) Table 3 (*9*)
Thickness	95	Table 3 (*9*)
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%
Asphalt Concrete Thickness, *t*	$0.200 \cdot t^{0.69} (cm)$	80	$0.173 \cdot t^{0.69} (cm)$
Foundation Modulus	30% (coefficient of variation)	70	25%

4.0 PERMANENT DEFORMATION

The performance model used for permanent deformation is a regression equation based on performance data obtained from the WesTrack experiment (1). This model includes the effects of air-void content, asphalt content, and aggregate gradation. The equation is based on analysis of both the field performance of 23 test sections which exhibited rutting (but no observed fatigue cracking) and the results of simple shear tests on laboratory-prepared mixes containing gradings representative of the coarse and fine gradations at WesTrack. Three gradations were used for each of the mixes: the target values and two variations of these gradations.

Reference (1) describes the procedure used to combine the field and laboratory measured performance data. Briefly stated, this procedure is based on combining mechanistic-empirical analyses with regressions. Simulations utilized five asphalt contents (4.5–6.5 percent), five air-void contents (4.5–8.5 percent), five values for P_{200} (4.5–6.5 percent), and five values for the fa parameter (20–36 percent). Caveats pertaining to the use of this experiment are also contained in Reference (1).

Figure 1 illustrates the effects of asphalt content on ESALs to a rut depth of 15 mm (0.6 in.). While other rut depths could be used for these computations, the 15-mm rut depth was considered reasonable since it is in the range where remedial action is required. Results shown in this figure certainly pass the test of engineering reasonableness.

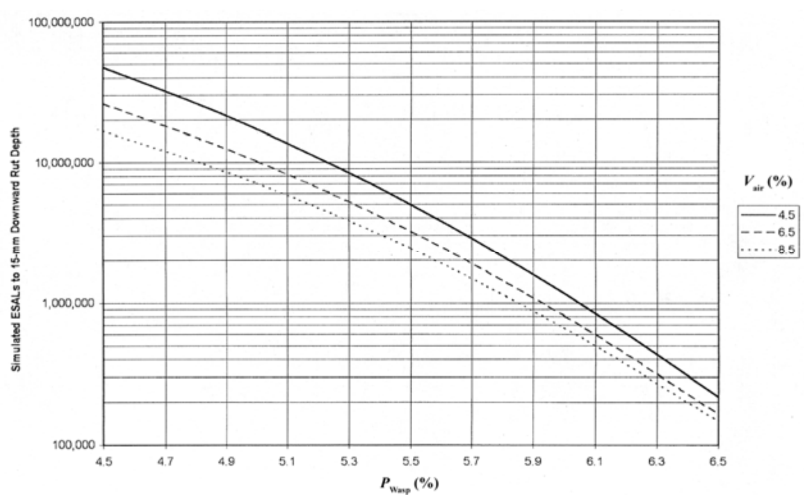

Figure 1: Effect of mix variables on simulated ESALs to 15-mm (0.6 in.) rut depth for a range in asphalt contents; P_{200} = 6%, fine aggregate = 28%

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5.0 FATIGUE CRACKING

The performance model used for fatigue is based on the procedure described in Reference (4) utilizing fatigue test data representative of mixes containing dense-graded aggregates meeting State of California specifications (14).

Multilayer elastic analysis with ELSYM5 was used to simulate the stress and strain states for a range in structural pavement sections. Loading consisted of a dual-tire assembly of 40 kN (9,000 lb) with a center-to-center spacing of 300 mm (12 in.) and a tire contact pressure of 690 kPa (100 psi). The critically stressed location for fatigue was assumed to be at the bottom boundary of the asphalt concrete layer. Mix properties for the analyses were obtained from tests on a representative State of California mix containing a dense-graded aggregate and a representative asphalt content. Details of the analyses are described in References (9, 10).

The 10th percentile fatigue life was used as the basic performance estimate. This life corresponds to about 10 percent fatigue cracking in the wheelpaths. 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) (8).

6.0 EFFECTS OF CONSTRUCTION QUALITY ON SIMULATED IN-SITU PERFORMANCE

For the performance simulations, target values and standard deviations used for the selected mix parameters are shown in Table 4. This Table also contains an expression for the standard deviation of thickness used for the sections analyzed herein.

Monte Carlo simulations were used to quantify the effects of construction quality on simulated in-situ performance. The levels and ranges used for these simulations are shown in Table 5, Monte Carlo simulations [described in References (8, 9, 10)] were performed to define relationships between ESALs to 10 percent rutting [15 mm (0.6 in.)] or more and the mix parameters shown in Table 5.

Figure 2 and Figure 3 illustrate the effects of as-constructed asphalt content and air-void content on the ESALs to 10 percent rutting [15 mm (0.6 in.) or more] for a range in standard deviations for each of the parameters.

Table 4: Construction Targets

Variable	Mean	Total Standard Deviation (Including Sampling and Testing)	Percent of Variance Attributed to Materials and Construction
Asphalt Content (%)	5.0	0.3	40
Air-Void Content (%)	7.0	1.5	60
Mineral Filler* (%)	5.5	0.9	75
Fine Aggregate (%)	30.0	3.0	85
Asphalt-Concrete Thickness (in.)	4 pavement structures	$0.15 \times$ AC thickness$^{0.69}$	75

* Mineral filler: percent passing No. 200 sieve.

Table 5: Levels and Ranges for Variable Evaluated

Variable	Mean		As-Constructed Standard Deviation	
	Levels	Range	Levels	Range
Asphalt Content	21	4.0 to 6.0	9	0.114 to 0.266
Air-Void Content	21	5.0 to 9.75	9	0.648 to 1.596
Mineral Filler*	21	3.0 to 8.0	9	0.467 to 1.09
Fine Aggregate	21	24.0 to 36.0	9	1.660 to 3.872
Thickness	21 for each of 4 pavement sections	-1.0 to 1.0	9	4.8% to 11.2%

* Mineral filler: percent passing No. 200 sieve.

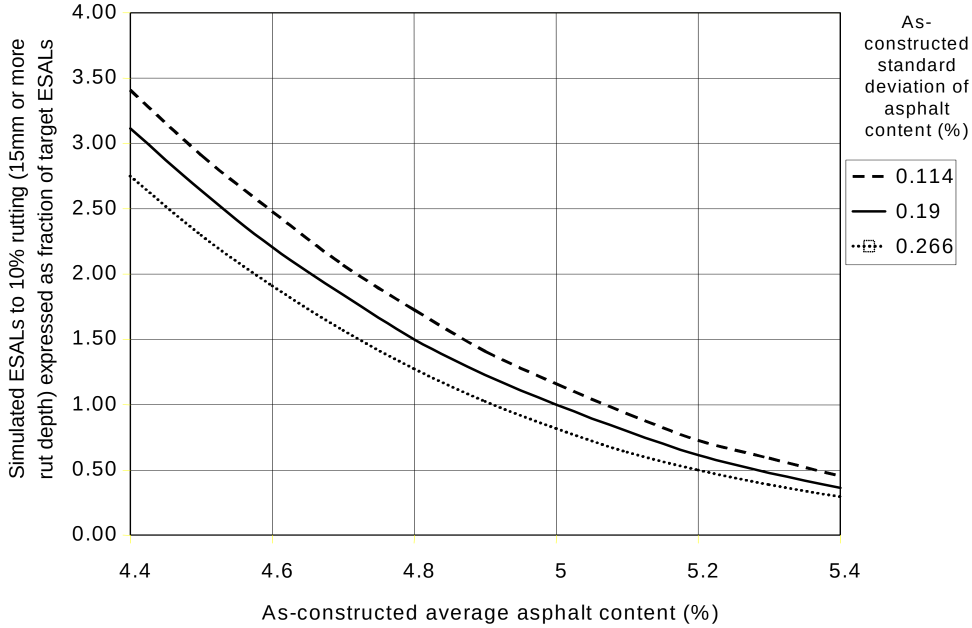

Figure 2: Influence of as-constructed asphalt content on rutting performance.

As with rutting, Monte Carlo simulations were used to quantify the effects of construction quality on fatigue. Results for a structure consisting of asphalt concrete [244 mm (10 in.) thick] resting on a granular base and subbase [366 mm (14 in.) total thickness] and a subgrade with a modulus of 84 MPa (12,000 psi) are shown in Figure 4 and Figure 5, illustrating the effects of air-void content and asphalt concrete thickness, respectively. Reference (8) contains additional results for a range of HMA thicknesses. Not so critical proves to be the effect of asphalt content on fatigue performance as seen in Figure 6.

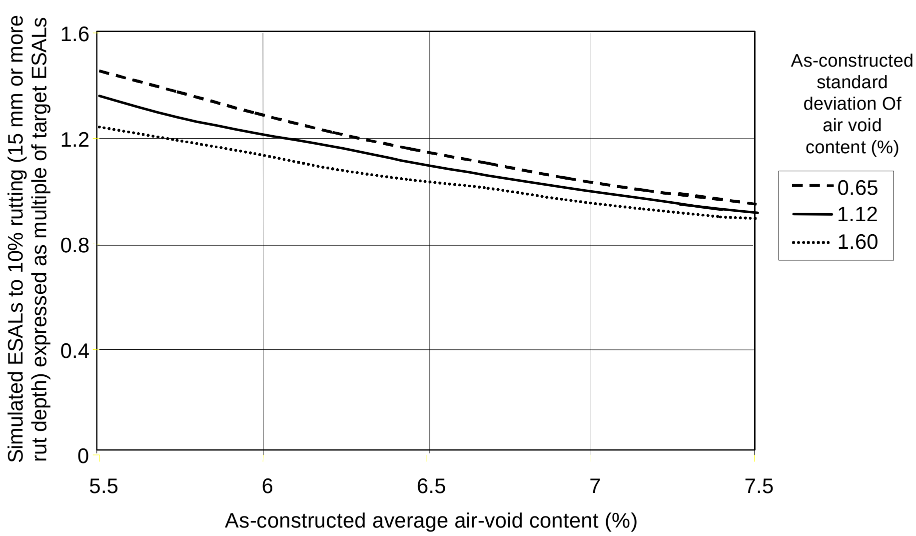

Figure 3: Influence of as-constructed air-void content on rutting performance

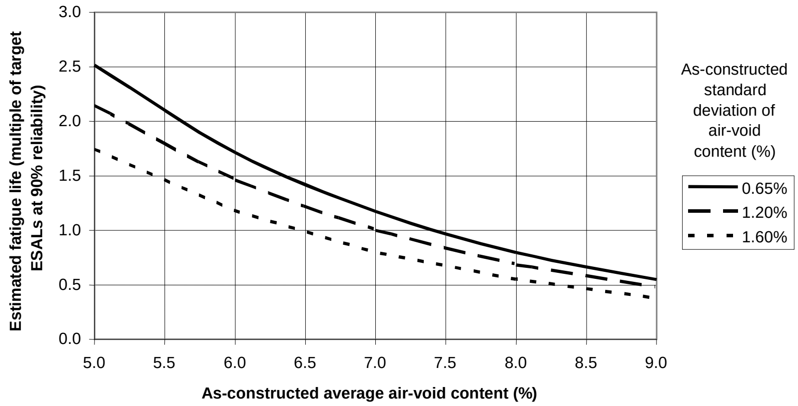

Figure 4: Effects of as-constructed air-void content on pavement fatigue performance.

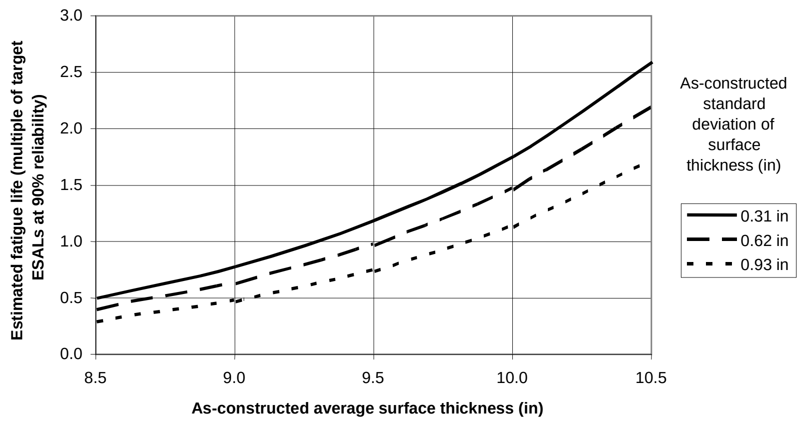

Figure 5: Effects of as-constructed asphalt concrete thickness on pavement fatigue performance.

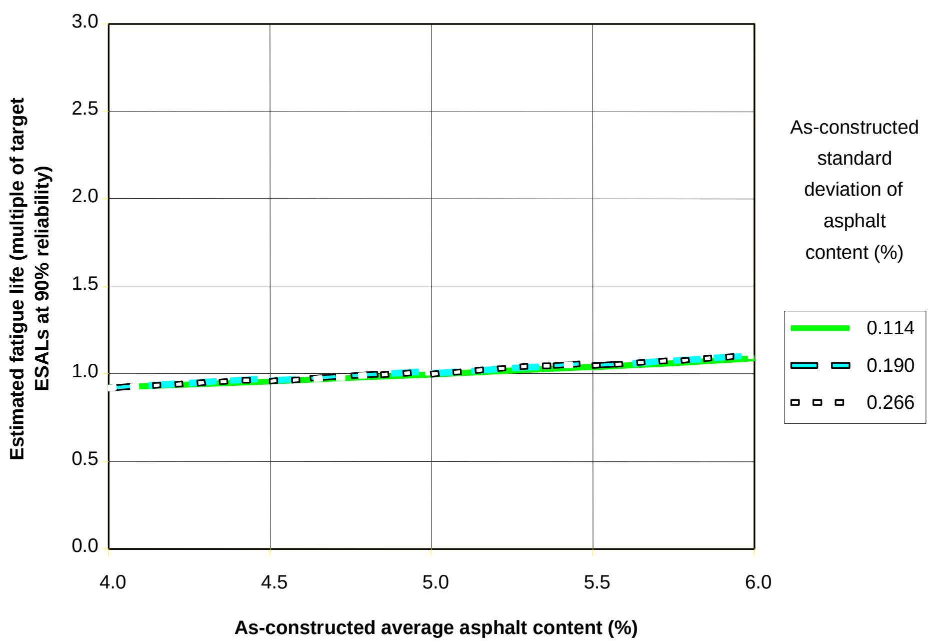

Figure 6: Effects of as-constructed asphalt content on pavement fatigue performance.

7.0 COST MODEL

The performance models yield the 10th percentile in-situ expected pavement lives for ruts [15 mm (0.6 in.) depth] and fatigue cracking (10 percent in wheelpaths) 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:

$$RP = \frac{off\text{ - }target\ ESALs}{on\text{ - }target\ ESALs} \qquad \textbf{(1)}$$

The cost model requires that a determination of the off-target pavement life in years (OTY) be obtained from the simulated performance differential. Equation (2) is used to compute the OTY parameter assuming that the traffic grows geometrically:

$$OTY = \frac{\ln\left(1 + RP\left[(1+g)^{TY} - 1\right]\right)}{\ln(1+g)} \qquad \textbf{(2)}$$

In this expression:

1. g is the annual rate of traffic growth expressed as a decimal;
2. 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 target position, TY, to its off-target position, OTY. Development of an expression for the net present worth, expressed as a percentage of the rehabilitation costs (in current-year dollars) is described in Reference (10).

The difference between the present worth of the TY and OTY (DPW) is expressed as follows:

$$\Delta PW = C\left(\frac{(1+r)^{OTY}}{(1+d)^{OTY} - 1} - \frac{(1+r)^{TY}}{(1+d)^{TY} - 1}\right)\left(\frac{(1+d)^{OTY} - 1}{(1+d)^{OTY}}\right) \qquad \textbf{(3)}$$

In this expression:

1. C is the resurfacing /rehabilitation cost in current-year dollars;
2. TY is the target pavement life;
3. r is the annual rate of growth in resurfacing/rehabilitation cost, that is, the construction cost index;
4. d is the annual discount rate.

When OTY exceeds the target life, the service life for comparison purposes may be set at either the target life or the longer OTY. It should be noted that if the longer period is chosen, it is beneficial to the contractor’s interests.

8.0 PAY FACTORS

With the above information, it is then possible to determine as constructed pay factors for asphalt concrete. The following assumptions are reflected in the approach discussed herein: (1) the contractor should generally be charged a penalty for inferior construction that is out of specification and the magnitude of this penalty should equal the full added cost to the agency for failure to meet the construction target; (2) the contractor should generally be rewarded for superior construction that is within specification; (3) schedules should incorporate average and standard-deviation categories consistent with the accuracy within which estimates are determined from field measurements; and (4) the standard deviations shown in the schedules must reflect expected testing and sampling errors as well as materials/construction variables.

For the pay factors developed in this section, bonuses for superior construction and penalties for inferior construction reflect full agency cost increments. In addition, the examples reflect the following:

1. The sole construction quality effect is the date of first resurfacing/rehabilitation.
2. Relative performance (RP) is determined independently for the rutting and fatigue modes of distress.
3. Relative performance for rutting reflects the effects of: (1) asphalt content, PW_{asp}; (2) air-void content, V_{air}; and (3) Percent Passing No. 200 sieve, P_{200}. The fine aggregate, fa, factor has not been included since it has, for the range of the parameters evaluated, a minor influence on relative performance and therefore on the pay factor.
4. Relative performance for fatigue is based on: (1) asphalt content, PW_{asp}; (2) air-void content, V_{air}; and (3) the thickness of the asphalt concrete layer, t_{AC}.

The combined RP for rutting is determined from the following expression:

$$\text{combined } \mathrm{RP}_{\mathrm{rut}} = RP_{PW_{asp}} \cdot RP_{V_{air}} \cdot RP_{P_{200}} \qquad \textbf{(4)}$$

Similarly for fatigue, the combined RP is:

$$\text{combined } \mathrm{RP}_{\mathrm{fat}} = RP_{PW_{asp}} \cdot RP_{V_{air}} \cdot RP_{t_{AC}} \qquad \textbf{(5)}$$

Figure 7 illustrates, for rutting, that this multiplicative approach provides the same results as Monte Carlo simulations considering random combinations of the RP for the rutting variables.

Reference (8) illustrates that such an approach is also applicable for fatigue. Thus this methodology provides a sound, yet simpler procedure for combining pay factors for each distress mode.

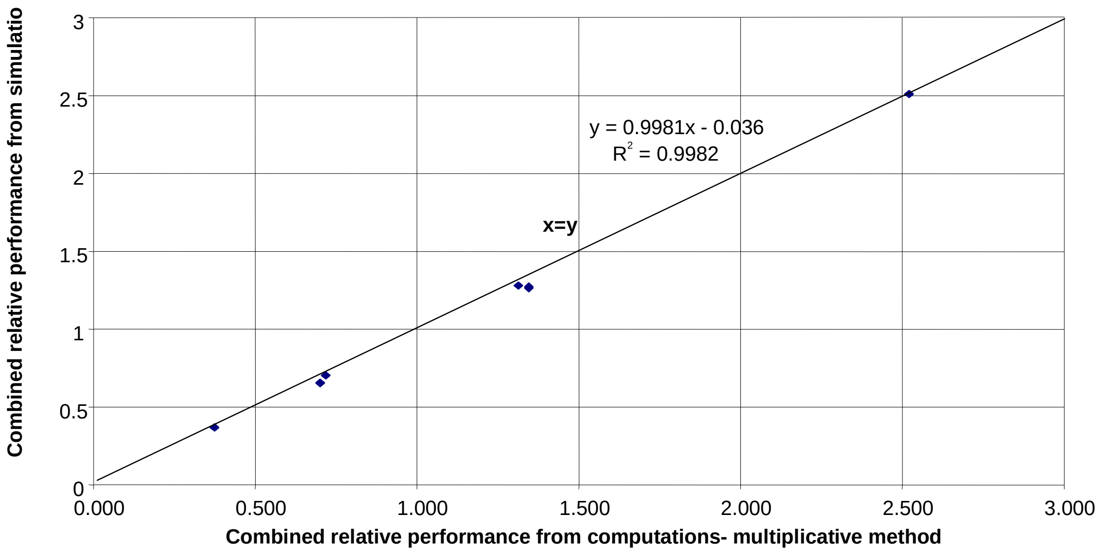

Figure 7: Comparison of the Combined Relative Performance for Rutting using the Multiplicative Procedure versus Combined Relative Performance from Monte Carlo simulations.

1. The relative performance which governs the contractor's pay factor is that associated with the shortest life determined from the two distress modes.
2. As stated earlier: (1) rutting life corresponds to ESALs to 10-percent of rutting with downward depths of 15 mm (0.6 in.) or more based on WesTrack performance; and (2) fatigue to ESALs to 10-percent cracking based on Caltrans experience as described earlier.

Reference (10) includes tables for the relative performance factors for rutting based on PW_{asp}, V_{air}, and P_{200} and for those for fatigue based on PW_{asp}, V_{air}, t_{AC}. Table 6 and Table 7 are examples for both rutting and fatigue.

Table 6: Relative Performance for Rutting as a Function of Asphalt Content.

Difference Between As-Measured Average Asphalt Content and Design Asphalt Content (%)	As-Measured Standard Deviation of Asphalt Content (%)		
	Low Variability (Below 0.255)	Average Variability (0.255 to 0.345)	High Variability (Above 0.345)
-1.1 to –0.91	5.816	5.552	5.233
-0.90 to –0.71	4.528	4.265	3.957
-0.70 to –0.51	3.381	3.151	2.870
-0.50 to –0.31	2.439	2.236	2.011
-0.30 to –0.11	1.688	1.526	1.349
-0.1 to 0.09	1.127	0.997	0.868
0.10 to 0.29	0.720	0.629	0.534
0.30 to 0.49	0.439	0.375	0.314
0.50 to 0.69	0.255	0.212	0.173
0.70 to 0.89	0.138	0.112	0.087
0.90 to 1.09	0.067	0.051	0.039

Table 7: Relative Performance for Fatigue as a Function of Air-Void Content

Difference Between As-Measured Average Air-Void Content and Design Air-Void Content (%)	As-Measured Standard Deviation of Air-Void Content (%)		
	Low variability (Below 1.32)	Average Variability (1.32 to 1.78)	High Variability (Above 1.78)
-2.24 to –1.76	2.275	2.093	1.899
-1.75 to –1.30	1.981	1.763	1.595
-1.29 to –0.82	1.624	1.482	1.339
-0.81 to –0.35	1.367	1.284	1.125
-0.34 to 0.13	1.151	1.048	0.945
0.14 to 0.60	0.968	0.882	0.796
0.61 to 1.08	0.816	0.743	0.671
1.09 to 1.55	0.732	0.628	0.568
1.56 to 2.03	0.581	0.532	0.483
2.04 to 2.5	0.493	0.454	0.415
2.51 to 2.99	0.422	0.391	0.361

With this information, pay factors can then be established for combined relative performance for rutting and fatigue. For the computations shown herein, expected pavement lives (target years, TY), in Equation (3) of 10 and 20 years have been assumed and the following cost parameters have been utilized:

1. A 2 percent annual rate of inflation in resurfacing/rehabilitation cost (*r*);
2. A 2.5 percent annual rate of traffic growth (g);

3. A 5 percent discount rate (d); rutting failure results in resurfacing which costs 20 percent or 50 percent of the cost of new pavement construction in current-year dollars;

4. Fatigue failure results in rehabilitation which costs 50 percent of the cost of new pavement construction in current-year dollars. Figure 8 shows the pay factors for both rutting and fatigue for rehabilitation cost equal to 50 percent of the initial construction cost.

While the RP for asphalt content for rutting is high for asphalt contents below the target value, for fatigue, durability, and compaction considerations would preclude this from occurring.

A "Pay Factor Calculator" using some of the spreadsheet features of Microsoft® *Excel* is available in Appendix C Reference (13). This program makes use of the six pay factor tables included in Appendix A.

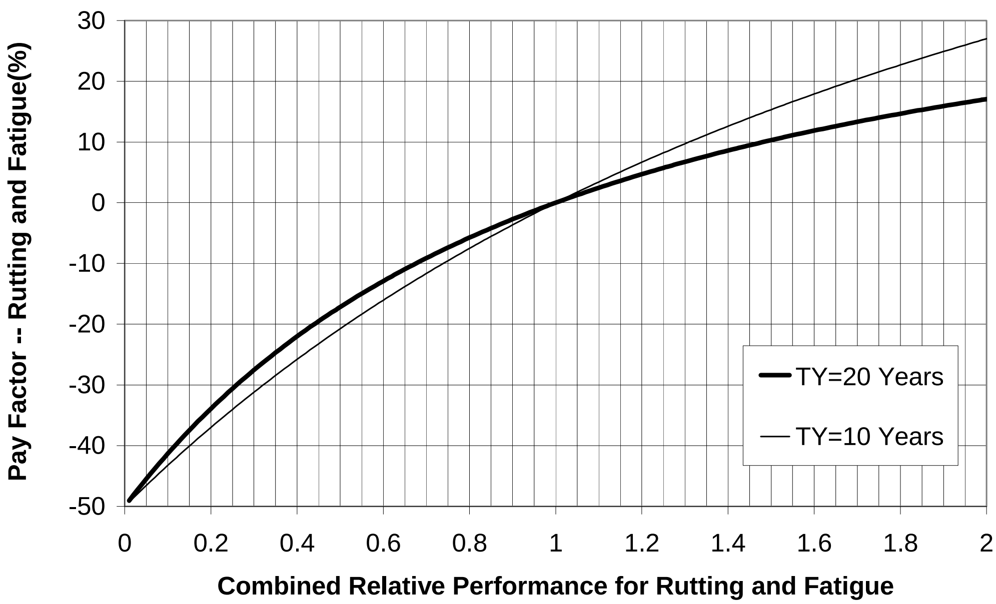

Figure 8: Pay Factors for Rutting and Fatigue as a function of Combined Relative Performance.

9.0 COMPARISON OF PAY FACTORS USING THE PERFORMANCE-BASED APPROACH AND THE EXPERIENCE-BASED PROCEDURE

The State of California Department of Transportation (Caltrans) introduced the use of pay factors in 1997 with the inception of a Quality Control/Quality Assurance Program for projects requiring 10,000 or more tons of asphalt concrete (11). Determination of the pay factors is based on asphalt content, degree of compaction, and aggregate gradation. Weighting factors are assigned to these parameters as follows:

1. 0.3 of the PW_{asp} for asphalt content;
2. 0.4 of the percent of the theoretical maximum density, γ_{tm}, for degree of compaction;
3. 0.30 for aggregate gradation, of which approximately 23 percent (a value of 0.07) is assigned to the P_{200}.

Data were supplied by Caltrans for approximately eighty QC/QA projects constructed during the period 1997–2000. The data from the projects, asphalt content and degree of compaction, are included in Appendix B. Pay factors have been determined for these projects according to the Caltrans method and are shown in Figure 9. The data shown in this figure are summarized in Table B1; also shown in this table are pay factors for the same two parameters according to the performance-based approach described in the preceding section (for these computations, RP for thickness and aggregate gradation have been assumed to be 1.0). Pay factors for the performance-based approach are based on the parameters used to compute Tables A1 through A6; i.e., d = 5 percent, r = 2 percent, g = 2.5 percent.

From data presented in Table B1 it can be seen that the pay factors for fatigue are generally larger. Relative to this point, it must be emphasized that Caltrans has set an upper limit for the pay factor at 5 percent. Performance-based pay factors illustrated herein have not included this limit, primarily to emphasize the potential future savings which could be achieved.

Data in Table B1 were further grouped in two sets. One set included all pay factors for which rutting was the predicted mode of failure (Figure 10) and the second set included pay factors for which the predicted mode of failure was fatigue (Figure 11). Comparison between performance-based pay factors for which rutting was the predicted mode of failure and the experience-based pay factors with few exceptions, were in the range +/-5%. Data in Figure 11 emphasize what was stated earlier, namely the fact that the performance-based pay factors are in general higher than the experience-based ones. This emphasizes the potential savings to the Agency resulting from good compaction and being on target in terms of thickness since repairing fatigue damage is a more expensive activity than rut-depth correction.

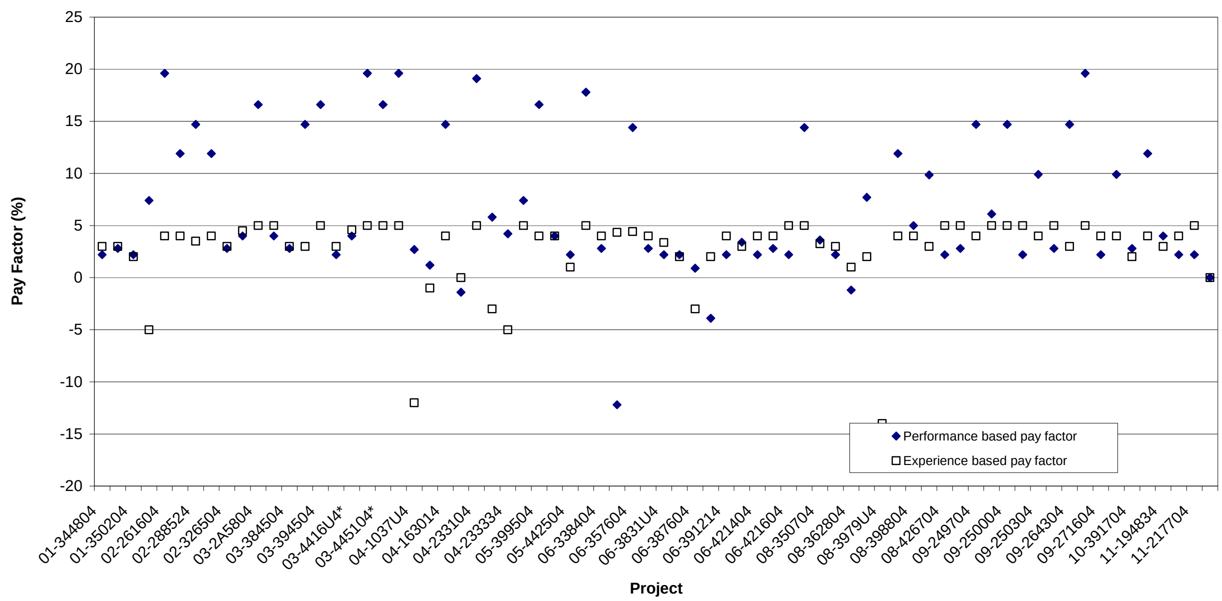

Figure 9. Comparison of performance-based and experience-based pay factors for a set of QC/QA projects.

Two contractors supplied information for projects listed in Table 8. The pay factors calculated in Table B1, only considered variations from the target for asphalt content and air-void content. The P_{200} and thickness were assumed to be on target (relative performances of 1 for both parameters). However, the performance-based pay factors in Table 8 reflect the effect of the P_{200}; as for Table B1 thicknesses were assumed to be on target. For comparison, both performance-based pay factors (with and without the P_{200} effect) were included in Table 8. Caltrans pay factors still reflect only the effect of air-void content and asphalt content except for a few projects marked with an asterisk (*) for which detailed QC/QA data—including individual pay factor values for P_{200}, asphalt content and air-void content—were available. This information allowed the recalculation of the pay factor that the contractor might had been given based only on the three parameters mentioned above. The majority of projects in Table 8, although QC/QA test data were made available by Caltrans, did not include the values of the individual pay factors, hence it was not possible to calculate pay factors that represent the experience-based approach.

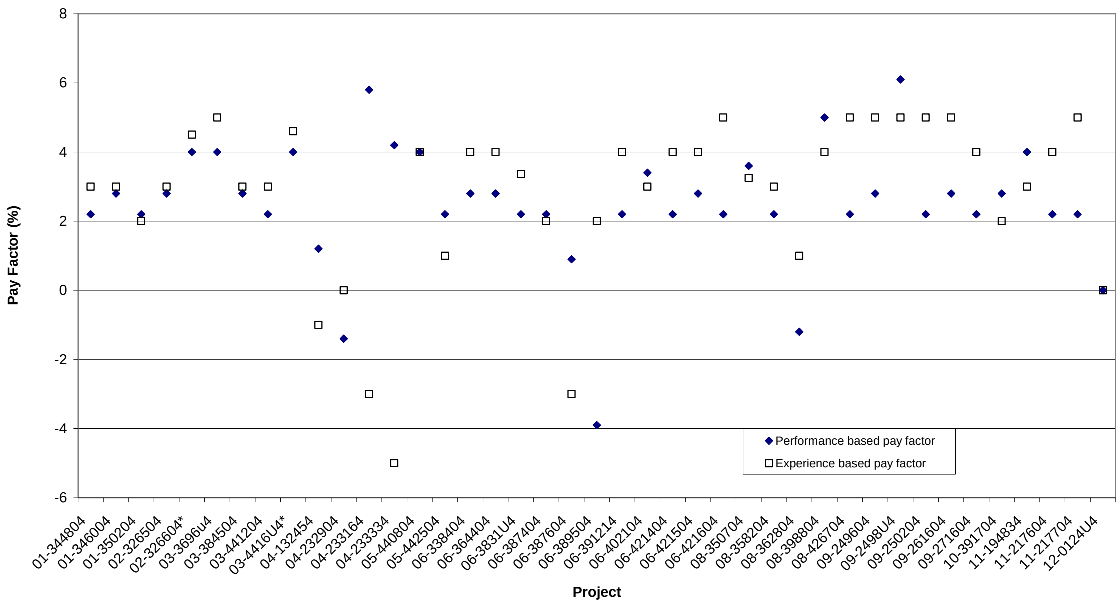

Figure 10. Variation of pay factor values when rutting is the predicted distress.

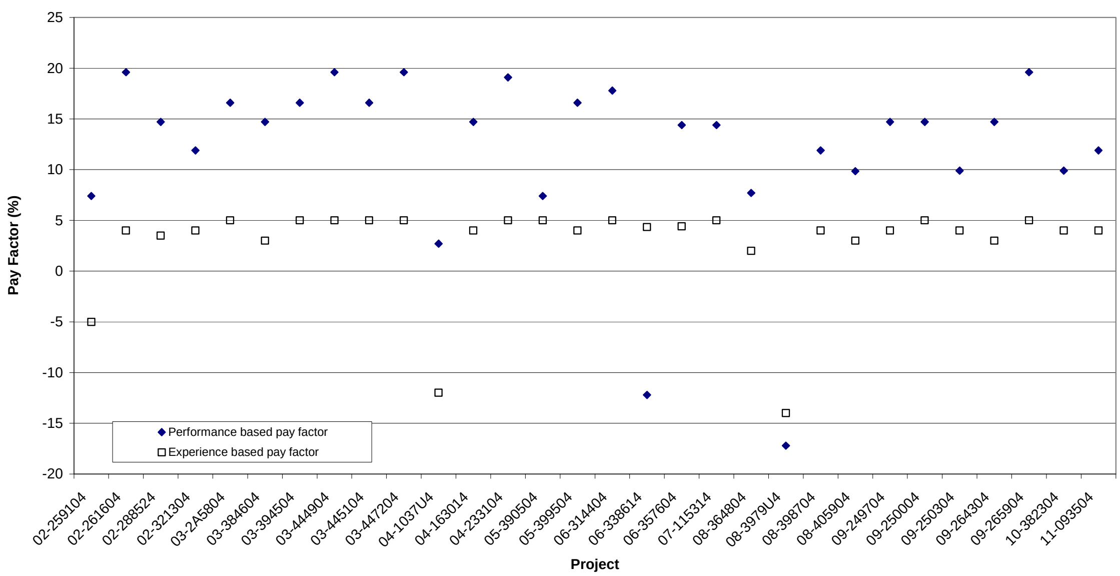

Figure 11. Variation of pay factor values when fatigue is the predicted distress.

Table 8: Contractor Data

Project No.	Contractor	Project Length (km)	AC stdev	AC difference (Asbuilt - Target)	AV stdev	AV difference (Asbuilt-Target)	P200 stdev	P200 difference (Asbuilt-Target)	Critical Distress	Pay Factor	Caltrans Pay Factor	Old Pay Factor (AC and AV only)
08-344704*	A	1.3	0.230	0.150	1.250	-2.081	0.800	0.180	Rutting	4.7	2.75	4
08-350704*	A	5.5	0.250	0.060	1.390	-2.500	0.680	-0.670	Rutting	1.7	3.25	3.6
08-397804	A	27.0	0.220	-0.100	0.581	-0.607	0.861	0.300	Fatigue	7.7	2	7.7
08-3979U4	A	6.4	0.264	0.024	0.820	2.261	0.928	0.532	Rutting	-17.2	-14	-17.2
08-405904	A	11.1	0.127	-0.010	0.584	-0.762	0.686	-0.551	Fatigue	9.85	3	9.85
11-194834	A	8.9	0.187	0.053	1.301	-1.993	0.709	0.385	Rutting	5.7	3	4
12-0124U4	A	2.9	0.184	0.200	1.420	-1.580	0.699	-0.700	Rutting	-1.9	0	0
02-326504	B	5.0	0.233	0.091	0.795	-1.493	0.483	-0.106	Rutting	2.4	3	2.8
03-2A5804	B	7.2	0.213	-0.030	0.607	-1.442	0.801	-1.273	Rutting	3.4	5	16.6
03-3696u4	B	1.9	0.146	0.060	0.530	-2.223	0.765	0.000	Rutting	4	5	4
03-394504	B	2.6	0.195	-0.022	0.573	-1.424	0.374	0.106	Fatigue	16.6	5	16.6
03-441204	B	2.4	0.211	0.052	0.519	-0.741	0.563	0.095	Rutting	3.3	3	2.2
03-4416U4*	B	N/A	0.176	0.064	0.642	-2.021	0.296	-0.022	Rutting	3.6	4.6	4
03-445104*	B	17.4	0.184	-0.008	0.530	-1.600	0.359	-0.284	Rutting	6.5	5	16.6
03-447204*	B	15.3	0.167	-0.042	0.866	-2.350	0.461	0.321	Fatigue	19.6	5	19.6
05-390504	B	5.1	0.096	-0.148	0.238	-0.612	0.309	-0.384	Fatigue	7.4	5	7.4
05-442504	B	6.8	0.204	0.089	0.406	-0.565	0.411	-0.995	Rutting	-0.56	1	2.2
06-314404	B	2.1	0.170	-0.136	0.688	-1.748	0.957	0.400	Fatigue	17.8	5	17.8
06-389504	B	10.0	0.260	0.130	0.510	1.170	0.765	0.000	Rutting	-3.9	2	-3.9
06-391214	B	11.9	0.142	0.154	0.480	-0.817	0.765	0.000	Rutting	2.2	4	2.2
06-402104	B	9.0	0.250	0.100	0.860	-1.720	0.765	0.000	Rutting	3.4	3	3.4
07-115314	B	7.2	0.165	-0.147	0.454	-1.382	0.417	0.379	Fatigue	14.38	5	14.38
08-426704	B	12.1	0.100	0.016	0.416	-1.366	0.503	0.444	Rutting	3.96	5	2.2
09-249604	B	4.5	0.154	0.024	0.552	-1.487	0.724	0.203	Rutting	3.8	5	2.8
09-250004	B	23.7	0.162	-0.017	0.149	-1.386	0.774	0.800	Fatigue	14.66	5	14.66
09-250204	B	28.0	0.089	0.022	0.212	-1.335	0.547	0.523	Rutting	3.96	5	2.2
09-261604	B	4.8	0.132	0.127	0.251	-1.484	0.506	1.295	Rutting	5.9	5	2.8
09-264304	B	19.6	0.095	-0.025	0.860	-1.216	0.643	0.400	Fatigue	14.7	3	14.7
09-271604	B	7.1	0.089	0.083	0.511	-1.008	0.844	0.750	Rutting	4.372	4	2.2
10-328304	B	5.5	0.169	-0.085	0.360	-0.735	0.348	0.198	Fatigue	9.85	4	9.85

Unfortunately, detailed performance data were not available for all of the projects listed in Table B1. However, 17 of the listed projects did have measurements of the rutting and fatigue cracking in the wheelpaths. The cracking included both longitudinal and alligator cracking. The condition survey data was collected between 2002 and 2006 during the *Pavement Performance Evaluation Study* conducted for Caltrans by Stantec.

Table 9 contains a summary of that data. The relationship between the categories of distress and the approximate magnitudes are as follows:

	Low	**Medium**	**High**
Rutting (mm)	6.5 to 13	13 to 25.4	> 25.4
Fatigue (crack width, mm)	< 13	13 to 25.4	> 25.4

The values reported in Table 9 were presented as follows. Each selected QC/QA section consisted of several Caltrans pavement condition survey subsections. For each of the subsections, a set of values representing the percent of alligator cracking in the wheelpaths, length of longitudinal cracking in the wheelpaths, and rut depth were measured. The longitudinal cracking length in the wheelpaths was then converted to a percentage relative to the length of each condition survey subsection. The numbers reported in Table 9 are the ratios of the sum of the measured percentages for each of the abovementioned distresses—except for rutting, where the average values were used — to the total length of the Caltrans pavement condition survey subsections within a QC/QA section. These performance data represent about three to nine years of pavement service.

In general, the relationships between the pay factors and the measured field pavement performance appear reasonable. The one exception could be Project 06-402104. For this project, the rutting exceeds the 13-mm criteria.

One note needs to be made with regard to the values of the pay factors presented in Table 9; the pay factors include the effect of air-void content and asphalt content only. Not enough information was available to calculate the performance-based pay factors so that they include the effect of P_{200}. Final performance of the pavement as indicated from the pavement condition survey reflects the influence of all three mix parameters in relation to the target (design) values.

Table 9. Shadowing Study Data

EA	Direction	Wheelpath Long. Cracking (%)/ Total Length of Condition Survey Subsections			Alligator Cracking (% area)/ Total Length of Condition Survey Subsections			Rutting (%)/ Total Length of Condition Survey Subsections			Predicted Critical Distress	Pay Factor Caltrans (Based on AC and AV)	Performance-Based Pay Factor (Based on AC and AV)
		Low	Med	High	Low	Med	High	Low	Med	High			
03-411204	L2 and R2	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	Rutting	3	2.2
03-3696U4	L2 and R2	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	Rutting	5	4
05-390504	L1	1.7	0.4	0.0	0.0	3.5	0.1	100.0	0.0	0.0	Fatigue	5	7.4
05-390504	R1	5.4	4.2	0.0	0.3	4.0	0.0	100.0	0.0	0.0	Fatigue	5	7.4
06-402104	L2	0.5	0.0	0.0	0.0	0.0	0.0	29.0	71.0	0.0	Rutting	3	3.4
06-402104	R2	20.4	0.0	0.0	0.1	0.2	0.0	3.0	97.0	0.0	Rutting	3	3.4
08-398804	L2 and R4	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	Rutting	4	5
09-265904	L	5.5	0.0	0.0	0.4	0.0	0.0	96.0	0.0	0.0	Fatigue	5	19.6
09-265904	R	2.3	0.0	0.0	0.1	0.0	0.0	100.0	0.0	0.0	Fatigue	5	19.6
01-344704	R	0.0	0.0	0.0	0.0	0.0	0.0	62.0	0.0	0.0	Rutting		4.1
01-344804	L	0.0	0.0	0.0	0.0	0.0	0.0	98.0	0.0	0.0	Rutting	3	2.2
01-350204	R	3.6	0.0	0.0	0.4	0.0	0.0	67.4	0.0	0.0	Rutting	2	2.21
01-350204	L	3.0	0.2	0.0	0.0	0.0	0.0	99.5	0.5	0.0	Rutting	2	2.21
01-346004	R	1.4	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	Rutting	3	2.8
05-399504	R	0.0	0.0	0.0	0.0	0.0	0.0	95	0.0	0.0	Fatigue	4.0	16.6
05-440804	R	0.0	0.0	0.0	0.0	0.0	0.0	100	0.0	0.0	Rutting	4.0	4.0
09-250004	R	0.0	0.0	0.0	0.0	0.0	0.0	100	0.0	0.0	Fatigue	5.0	14.7
11-093504	R	0.0	0.0	0.0	0.0	0.0	0.0	100	0.0	0.0	Fatigue	4.0	11.9
11-194834	L	1.4	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	Rutting	3	4.0
11-217604	R	17.0	2.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	Rutting	4	2.2
11-217704	R	38.0	0.0	0.0	3.4	0.0	0.0	92.0	6.0	0.0	Rutting	5	2.2

10.0 PAY FACTOR DETERMINATIONS BASED ON DAILY VERSUS TOTAL PROJECT PRODUCTION

Pay factors used to make payment adjustments to contractors for asphalt concrete can be based on either of the following:

1. Results of tests on the tonnage per each day's production.
2. Results of tests on the total project tonnage.

Data contained in Appendices A, B, and C of Reference (17) provide information for these two analyses.

Calculations using these two procedures for six projects are summarized in Table 10. Day-by-day results for two of these projects are shown in Table 11 and Table 12. When using the total tonnage basis, it is important to recognize that one cannot include mixes falling below some minimum standard.

In Table 10, which is based on the performance-based pay factors results, it will be noted that there is not a consistent pattern between the average for the daily pay factors and the pay factor based on total production.

When comparing Table 11 and Table 12, which include both the performance-based and experience-based pay factors, two patterns of production are observed. In Table 11, the performance-based pay factors suggest a somewhat variable daily production whereas the data in Table 12 suggest, based on the performance-based pay factors, a gradually improving daily production to a relatively consistent pattern after the eighth day.

Table 10: Pay Factor Values Calculated both on Tonnage for Each Day's Production and on the Total Project[§]

Project	Target Values			Pay Factor (%)		Production Days	Avg. Samples per Day
	AC (%)	AV (%)	P_{200} (%)	End Project	Avg. of Daily PF		
02-288524	4.4	8.8	4	14.7	10.4	10	6
02-326604	4.8	8.8	5	7	10.3	14	6
06-338614	4.9	8.8	4.7	16.3	15.3	18	9
06-357604	4.7	8.8	5.7	14.4	10	23	5
06-3831u4	5.3	8.8	4.2	2.5	2.9	6	4
08-344704	5.3	8.8	4.2	4.7	5.8	8	6

[§] Appendices A, B, and C References (17)

Table 11: Project A—Daily Production Data and Pay Factors[**]

Date	No. of Samples	Performance-Based Pay Factor	Experience-Based Pay Factor	Daily Production (tons)
6/29/99	5	19.4	3.36	2421
6/30/99	3	-4.1	3.36	2359
7/1/99	6	0.9	3.36	2118
7/6/99	3	1.4	3.36	2434
7/7/99	6	2.5	3.36	2089
7/8/99	3	-3	3.36	1568

[**]Appendix B, Reference (17)

Table 12: Project B—Daily Production Data and Pay Factors[**]

Date	No. of Samples	Performance-Based Pay Factor	Experience-Based Pay Factor	Daily Production (tons)
7/6/99	5	1.4	0.87	2093
7/7/99	8	7	4.47	3569
7/8/99	7	2.2	4.07	3186
7/9/99	8	6.7	3.67	3547
7/12/99	8	5.6	3.11	3482
7/13/99	4	4.9	3.41	1838
7/14/99	7	4.9	2.91	3347
7/16/99	3	18.1	2.81	2866
7/19/99	8	16.6	3.11	3507
7/20/99	7	14.7	2.91	2930
7/21/99	8	7	3.41	3590
7/22/99	3	17.8	3.71	1635
7/23/99	4	17.6	3.71	1606

[**]Appendix Reference (17)

11.0 DISCUSSION OF WEIGHTING FACTORS TO DETERMINE COMBINED PAY FACTORS

An additional argument in favor of the performance-based approach (in lieu of the current Caltrans procedure) is related to the use of fixed weighting factors in the experience-based approach to arrive at a combined pay factor. In Section 9 it was noted that Caltrans uses weighting factors of 0.3, 0.4, and 0.07 for PW_{asp}, V_{air}, and P_{200} respectively (0.3 is assigned to aggregate grading controls with 23 percent [0.07] assigned to the P_{200} fraction).

As shown in the following example, weighting factors for mix parameters differ between distress modes. Consider a mix with the following characteristics: PW_{asp} 0.5% above target, V_{air} 2.0% higher than target, P_{200} 1.0% less than target, and t_{AC} 0.2 in. less than target. According to the performance-based approach, the RPs shown in Table 13 would be obtained. The pay factor for rutting is a 35 percent reduction from Figure 8 based on a combined RP of 0.17 (0.3 x 0.75 x 0.75). For fatigue, not considering asphalt concrete thickness (currently not used by Caltrans), a reduction of 17 percent is obtained from Figure 8 based on an RP of 0.52 (1.07 x 0.49). If thickness is considered, a 20 percent reduction would result in a combined RP of 0.44 (1.07 x 0.49 x 0.84). As seen in Table 13 the RP for PW_{asp} indicates a significant reduction in rutting performance but a better than designed fatigue cracking performance. In this case the weighting factor for asphalt content would be higher for rutting than that for fatigue. On the other hand the weighting factor for V_{air} would be larger for fatigue than for rutting.

Further, relative to the above example, if the mix was placed as an overlay and rutting was the primary concern, the relative weights for PW_{asp}, V_{air}, and P_{200} from Table 13 are 0.59, 0.205, and 0.205 respectively. Considering the Caltrans weighting factors and only that associated with P_{200} fraction, the values of 0.3, 0.4, and 0.07 (0.23 x 0.3) become 0.42, 0.52, and 0.09. In this case degree of compaction would be given a considerably higher weight than that resulting from the performance-based approach (0.52 vs. 0.205).

Table 13. The Effect of Mix Parameters on Relative Performance (RP)

Performance Characteristics	Asphalt Content	Air-Void Content	P_{200} (rutting)/ t_{AC} (fatigue)
Rutting	+ 0.5% RP = 0.30	+ 2.0% RP = 0.75	– 1% RP = 0.75
Fatigue	+ 0.5% RP = 1.07	+ 2.0% RP = 0.49	– 0.2 in. RP = 0.84

12.0 SUMMARY

The performance-based approach to pay-factor determination as used herein should be applicable to any type of hot-mix asphalt. For mixes with aggregate gradings different than the conventional dense-graded materials used in this study, additional laboratory testing should be performed. It is likely, however, that both incentives and disincentives may be understated because only the first rehabilitation cycle is considered. Nevertheless, understated incentives/disincentives are likely to be more appropriate than overstated ones for initial use of this methodology.

The approach provides for a full incentive (bonus) for superior construction and a full disincentive (penalty) for inferior construction. Based on current practice, the potential incentive usually does not exceed some prescribed level. For example, the current limit for Caltrans is a bonus of 5 percent. The performance-based analysis does not provide a basis for setting such an upper limit since improved construction does, in fact, improve pavement life.

It must be emphasized that the combined pay factors for rutting and fatigue shown in Figure 8 are based on: a target life of 10 or 20 years, a 2 percent annual traffic growth rate, a 5 percent discount rate, a 2.5 percent inflation rate, and rehabilitation costs 0.5 times the initial construction cost for fatigue and rutting (Figure 8). Other parameters, e.g., changed target lives and rehabilitation costs, will result in different values for the combined pay factors.

Pay factors shown in Figure 8 have been developed for asphalt concrete on granular base and subbase over the subgrade. The approach for rutting may also be applied to asphalt concrete overlays on portland cement concrete (PCC) pavements until further research becomes available. Rutting resulting from shear deformations in the asphalt concrete is usually limited to the upper 75–100 mm; overlays on PCC pavement usually have thicknesses of at least 100 mm. On the other hand, cracking in overlay pavements (both cracked asphalt concrete and PCC) is likely to be reflection cracking rather than the classical fatigue cracking that can occur in conventional asphalt concrete pavements. Reference (1) provides some evidence that this is the case for asphalt concrete overlays on cracked asphalt concrete pavements. While it is probable that the factors which affect fatigue cracking also will affect reflection cracking, it is not readily apparent that the relative effects of these factors will be the same as for fatigue; nevertheless, however, they could serve as a starting point. (14)

It should be noted that while the rutting model is based on a regression model derived from the WesTrack performance data, it involved laboratory testing and mechanistic-empirical analysis of the pavement sections in its development. Reference (2) provides a methodology whereby a mechanistic-empirical procedure like that used for fatigue, can be developed using the results of the SHRP-developed shear test and multilayer elastic analysis.

An example of a process that could be used to eventually implement performance-based pay factors has been presented using approximately 80 projects constructed by Caltrans that include incentives and disincentives. Comparisons of actual pay factors assigned to these projects with those determined by the performance-based approach are included.

Changing from the experience-based PWL approach to the use of performance-based equations like those used herein (based on mechanistic-empirical analyses and Monte Carlo simulations) is now feasible with the introduction of the M-E pavement design procedures [e.g., *CalME* (15)]. *CalME* includes performance equations for asphalt concrete pavement performance (e.g., fatigue and rutting). These equations include HMA variables such as those included herein.

When this change is made, field performance data will be required to validate the system; based on these data some modifications to the relative performance tables may be required. Linking of databases containing the design, materials, and initial construction data to the pavement management system containing the field performance data will be required. An excellent example of this tie between materials and construction data and field performance data has been described in Reference (16).

One of the advantages of the performance-base approach is that it emphasizes the mix and pavement structure characteristics that most affect performance. As an example, the rutting model emphasizes the importance of asphalt content, degree of compaction, and aggregate gradation as defined by the P_{200} fraction while the fatigue model emphasizes degree of compaction, pavement thickness, and asphalt content. While the contractor might consider increasing the binder content somewhat for improved degree of compaction for fatigue, increase of the asphalt content above the design target precludes this because of rutting considerations.

In general, the performance-based approach emphasizes the importance of uniformity in both materials production and placement with reasonable controls placed on inherent variability.

Moreover, it emphasizes the importance of adhering to design target values. It also attempts to consider only the materials and construction variance by eliminating the influence of test variance.

APPENDICES

Appendix A: Relative Performance Tables for Rutting and Fatigue

Table A1

RELATIVE PERFORMANCE FOR RUTTING AS A FUNCTION OF ASPHALT CONTENT

Difference between as-measured average asphalt content and design asphalt content (%)	As-measured standard deviation of asphalt content (%)		
	Low variability (Below 0.255)	**Average variability (0.255 to 0.345)**	**High variability (Above 0.345)**
-1.1 to –0.91	5.816	5.552	5.233
-0.90 to –0.71	4.528	4.265	3.957
-0.70 to –0.51	3.381	3.151	2.870
-0.50 to –0.31	2.439	2.236	2.011
-0.30 to –0.11	1.688	1.526	1.349
-0.1 to 0.09	1.127	0.997	0.868
0.10 to 0.29	0.720	0.629	0.534
0.30 to 0.49	0.439	0.375	0.314
0.50 to 0.69	0.255	0.212	0.173
0.70 to 0.89	0.138	0.112	0.087
0.90 to 1.09	0.067	0.051	0.039

Table A2

RELATIVE PERFORMANCE FOR RUTTING AS A FUNCTION OF AIR-VOID CONTENT

Difference between as-measured average air-void content and design air-void content (%)	As-measured standard deviation of air-void content (%)		
	Low variability (Below 1.32)	**Average variability (1.32 to 1.78)**	**High variability (Above 1.78)**
-2.24 to –1.76	1.642	1.569	1.486
-1.75 to –1.30	1.451	1.392	1.328
-1.29 to –0.82	1.292	1.248	1.195
-0.81 to –0.35	1.162	1.126	1.091
-0.34 to 0.13	1.050	1.030	0.996
0.14 to 0.60	0.963	0.943	0.925
0.61 to 1.08	0.888	0.876	0.863
1.09 to 1.55	0.824	0.819	0.812
1.56 to 2.03	0.775	0.771	0.770
2.04 to 2.5	0.734	0.735	0.735
2.51 to 2.99	0.702	0.704	0.707

Table A3

RELATIVE PERFORMANCE FOR RUTTING AS A FUNCTION OF MINERAL FILLER AMOUNT

Difference between as-measured average mineral filler* content and design mineral filler content (%)	As-measured standard deviation of mineral filler* content (%)		
	Low variability (Below 0.765)	Average variability (0.765 to 1.035)	High variability (Above 1.035)
-2.76 to –2.26	0.494	0.477	0.458
-2.25 to –1.76	0.574	0.554	0.530
-1.75 to –1.26	0.666	0.643	0.615
-1.25 to –0.76	0.769	0.745	0.714
-0.75 to –0.26	0.890	0.861	0.827
-0.25 to 0.24	1.033	0.996	0.955
0.25 to 0.74	1.190	1.155	1.104
0.75 to 1.24	1.376	1.332	1.280
1.25 to 1.74	1.593	1.538	1.477
1.75 to 2.24	1.841	1.781	1.704
2.25 to 2.74	2.121	2.057	1.973

* Mineral filler: percent passing No. 200 sieve.

Table A4

RELATIVE PERFORMANCE FOR FATIGUE AS A FUNCTION OF AIR-VOID CONTENT

Difference between as-measured average air-void content and design air-void content (%)	As-measured standard deviation of air-void content (%)		
	Low variability (Below 1.32)	Average variability (1.32 to 1.78)	High variability (Above 1.78)
-2.24 to –1.76	2.275	2.093	1.899
-1.75 to –1.30	1.981	1.763	1.595
-1.29 to –0.82	1.624	1.482	1.339
-0.81 to –0.35	1.367	1.284	1.125
-0.34 to 0.13	1.151	1.048	0.945
0.14 to 0.60	0.968	0.882	0.796
0.61 to 1.08	0.816	0.743	0.671
1.09 to 1.55	0.732	0.628	0.568
1.56 to 2.03	0.581	0.532	0.483
2.04 to 2.5	0.493	0.454	0.415
2.51 to 2.99	0.422	0.391	0.361

Table A5
RELATIVE PERFORMANCE FOR FATIGUE AS A FUNCTION OF ASPHALT CONTENT

Difference between as-measured average asphalt content and design asphalt content (%)	As-measured standard deviation of asphalt content (%)		
	Low variability (Below 0.255)	Average variability (0.255 to 0.345)	High variability (Above 0.345)
-1.1 to –0.91	0.884	0.882	0.882
-0.90 to –0.71	0.906	0.905	0.904
-0.70 to –0.51	0.928	0.928	0.927
-0.50 to –0.31	0.951	0.951	0.951
-0.30 to –0.11	0.976	0.975	0.974
-0.1 to 0.09	1.000	1.000	1.000
0.10 to 0.29	1.027	1.027	1.027
0.30 to 0.49	1.055	1.054	1.054
0.50 to 0.69	1.084	1.084	1.082
0.70 to 0.89	1.115	1.114	1.112
0.90 to 1.09	1.146	1.146	1.144

Table A6
RELATIVE PERFORMANCE FOR FATIGUE AS A FUNCTION OF AC THICKNESS

Difference between as-measured thickness of asphalt and design thickness (in.)	As-measured standard deviation of asphalt thickness (%)		
	Low variability (Below 7.85)	Average variability (7.85 to 10.62)	High variability (Above 10.62)
-1.1 to -0.90	0.472	0.426	0.380
-0.89 to -0.70	0.554	0.499	0.444
-0.69 to -0.50	0.655	0.589	0.524
-0.49 to -0.30	0.780	0.700	0.622
-0.29 to -0.10	0.930	0.837	0.743
-0.09 to 0.09	1.110	1.000	0.889
0.10 to 0.29	1.321	1.194	1.066
0.30 to 0.49	1.564	1.421	1.272
0.50 to 0.69	1.849	1.679	1.511
0.70 to 0.89	2.211	1.993	1.790
0.90 to 1.09	2.784	2.423	2.142

Appendix B: Caltrans Project Data

Table B1: Caltrans Project Data

Project	AC std. dev.	AC diff	AV std. dev.	AV diff	Critical Distress	Performance-Based Pay Factor (%)	Caltrans Pay Factor (%)
01-344804	0.218	0.021	0.910	-1.270	Rutting	2.2	3
01-346004	0.255	0.087	0.850	-1.910	Rutting	2.8	3
01-350204	0.228	0.105	0.580	-0.874	Rutting	2.2	2
02-259104	0.157	-0.172	1.030	-0.675	Fatigue	7.4	-5
02-261604	0.153	-0.018	1.170	-2.024	Fatigue	19.6	4
02-288404	0.200	-0.037	0.610	-1.074	Rutting	11.9	4
02-288524	0.250	-0.090	0.810	-1.340	Fatigue	14.7	3.5
02-321304	0.175	-0.116	0.500	-1.131	Fatigue	11.9	4
02-326504	0.233	0.091	0.790	-1.492	Rutting	2.8	3
02-326604*	0.230	0.080	0.990	-2.546	Rutting	4	4.5
03-2A5804	0.213	-0.030	0.610	-1.444	Fatigue	16.6	5
03-3696u4	0.146	0.060	0.530	-2.223	Rutting	4	5
03-384504	0.137	0.046	0.980	-1.511	Rutting	2.8	3
03-384604	0.153	-0.120	0.920	-1.359	Fatigue	14.7	3
03-394504	0.195	-0.022	0.570	-1.425	Fatigue	16.6	5
03-441204	0.211	0.052	0.520	-0.741	Rutting	2.2	3
03-4416U4*	0.176	0.064	0.642	-2.020	Rutting	4	4.6
03-444904	0.141	-0.072	0.550	-2.014	Fatigue	19.6	5
03-445104*	0.184	-0.008	0.530	-1.600	Fatigue	16.6	5
03-447204	0.166	-0.042	0.866	-2.349	Fatigue	19.6	5
04-1037U4	0.188	-0.022	2.140	-0.494	Fatigue	2.7	-12
04-132454	0.384	0.035	1.310	-2.375	Rutting	1.2	-1
04-163014	0.149	-0.130	0.520	-1.207	Fatigue	14.7	4
04-232904	0.243	0.297	0.670	-1.843	Rutting	-1.4	0
04-233104	0.053	-0.257	0.250	-2.242	Fatigue	19.1	5
04-233164	0.340	-0.062	1.140	-1.501	Rutting	5.8	-3
04-233334	0.345	-0.082	1.340	-1.501	Rutting	4.2	-5
05-390504	0.096	-0.148	0.240	-0.608	Fatigue	7.4	5
05-399504	0.122	-0.054	0.700	-1.473	Fatigue	16.6	4
05-440804	0.165	0.043	1.110	-2.689	Rutting	4	4
05-442504	0.203	0.098	0.600	-0.675	Rutting	2.2	1
06-314404	0.170	-0.136	0.690	-1.748	Fatigue	17.8	5
06-338404	0.277	0.076	0.670	-2.518	Rutting	2.8	4
06-338614	0.100	-0.190	0.320	1.670	Fatigue	-12.2	4.34
06-357604	0.120	-0.160	0.380	-1.292	Fatigue	14.4	4.42
06-364404	0.264	0.039	0.630	-2.147	Rutting	2.8	4
06-3831U4	0.240	0.130	0.570	-1.283	Rutting	2.2	3.36
06-387404	0.211	0.018	0.640	-0.893	Rutting	2.2	2
06-387604	0.305	0.046	0.660	-0.760	Rutting	0.9	-3
06-389504	0.260	0.130	0.510	1.170	Rutting	-3.9	2
06-391214	0.142	0.154	0.480	-0.817	Rutting	2.2	4

Project	AC std. dev.	AC diff	AV std. dev.	AV diff	Critical Distress	Performance-Based Pay Factor (%)	Caltrans Pay Factor (%)
06-402104	0.250	0.100	0.860	-1.720	Rutting	3.4	3
06-421404	0.210	0.090	0.580	-1.330	Rutting	2.2	4
06-421504	0.170	0.030	0.710	-1.500	Rutting	2.8	4
06-421604	0.220	0.060	0.470	1.380	Rutting	2.2	5
07-115314	0.165	-0.147	0.450	-1.387	Fatigue	14.4	5
08-350704	0.250	0.060	1.390	-2.499	Rutting	3.6	3.25
08-358204	0.169	0.023	0.630	-0.817	Rutting	2.2	3
08-362804	0.206	0.295	1.680	-3.791	Rutting	-1.2	1
08-364804	0.169	-0.041	0.450	-0.589	Fatigue	7.7	2
08-3979U4	0.264	0.024	0.820	2.261	Fatigue	-17.2	-14
08-398704	0.170	-0.028	0.630	-1.112	Fatigue	11.9	4
08-398804	0.142	0.006	0.720	-1.615	Rutting	5	4
08-405904	0.127	-0.010	0.580	-0.760	Fatigue	9.85	3
08-426704	0.100	0.016	0.420	-1.368	Rutting	2.2	5
09-249604	0.154	0.024	0.550	-1.482	Rutting	2.8	5
09-249704	0.172	-0.128	0.770	-1.387	Fatigue	14.7	4
09-2498U4	0.168	0.005	0.950	-2.309	Rutting	6.1	5
09-250004	0.162	-0.017	0.160	-1.378	Fatigue	14.7	5
09-250204	0.089	0.022	0.210	-1.340	Rutting	2.2	5
09-250304	0.164	-0.032	0.510	-0.827	Fatigue	9.9	4
09-261604	0.132	0.127	0.250	-1.482	Rutting	2.8	5
09-264304	0.094	-0.025	0.860	-1.216	Fatigue	14.7	3
09-265904	0.142	-0.027	0.610	-1.919	Fatigue	19.6	5
09-271604	0.089	0.083	0.510	-1.007	Rutting	2.2	4
10-382304	0.169	-0.085	0.360	-0.732	Fatigue	9.9	4
10-391704	0.253	0.109	1.120	-1.615	Rutting	2.8	2
11-093504	0.132	-0.057	0.450	-1.064	Fatigue	11.9	4
11-194834	0.187	0.053	1.300	-1.995	Rutting	4	3
11-217604	0.190	0.055	0.420	-0.865	Rutting	2.2	4
11-217704	0.198	0.095	0.430	-1.112	Rutting	2.2	5
12-0124U4	0.180	0.188	1.420	-1.577	Rutting	0	0

Note: Projects marked (*) used data provided by the Contractor to estimate pay factors by the performance based method. In the computation of the Caltrans pay factors only the weightig factors for compaction degree and asphalt content were considered.

Additionally, Seventy (70) percent of the projects listed in Table B1 represent rehabilitation and new construction projects; the remaining 30 percent being resurfacing projects.

Appendix C: Computer Application—Pay Factor Determinations

The "Pay Factor Calculator" is a simple application using some of the spreadsheet features of Microsoft® *Excel*. Based on the inputs in the main screen (Figure C1), the program finds the individual relative performances of each of the pay factor parameters by looking up the appropriate value in Tables A1 to A6 stored in a separate spreadsheet, "Relative Performance." The application then calculates the combined relative performance for both rutting and fatigue and picks the lower value of the two (the case least beneficial to the Agency) to calculate the pay factor. Input parameters such as traffic growth, annual discount rate, construction index cost, cost of resurfacing, cost of rehabilitation, and design life can be changed. The results can be saved in a separate spreadsheet named "SavedScenarios" by clicking the "Save Scenario" button.

Project EA:	08-350704	Bid Item #	

Save Scenario

Construction-cost index (r)	Annual discount rate (d)	Annual rate of traffic growth (g)	*Cost of resurfacing% (C)*
1.02	**1.05**	**1.025**	**20**
Design life (years)			*Cost of rehab % (C)*
20			**50**
Std AC	Std AV	Std Mineral Filler	Std AC Thickness
0.1	0.32	0.68	7.85

	AC: difference between measured and target	AV: difference between measured and target	Mineral Filler: difference between measured and target	AC Thickness: difference between measured and target	Design Relative compaction	Avg Relative compaction	Difference measured-design converted into AV
	-0.19	-1.5865	-0.67	0	96	97.67	-1.5865
					Combined RP		
Rutting:RP	1.688	1.451	0.827		2.027	Rutting	
Fatigue:RP	0.976	1.981		1.000	1.934	Fatigue	

RESULTS

OTY	**33**
PW(%)	**16.3**

Caltrans PF 1.0186

Figure C1. Pay factor calculator.

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