PERFORMANCE-BASED PAYMENT ADJUSTMENT FACTOR FOR CONCRETE PAVEMENT

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INTRODUCTION

Increasing popularity and success of adjustable payment plans in road construction, has led to the investigation of a performance-based pay factor for concrete pavement. Plans and specifications for pavement construction are based on a pavement design. The designer of a pavement prescribes desired qualities for the materials and construction factors to ensure an adequate pavement is constructed. During construction, the contractor strives to achieve the designed levels of material and construction factors, but inevitably the factors vary. Subsequently, the performance as predicted for the designed pavement will be different from the performance achieved during the life of the pavement. This disparity in performance is at least in part due to the deviation of materials and construction factors from the intended levels as designed, and is presented as the basis for payment adjustment to the contractor.

A RATIONAL METHODOLOGY

Payment adjustment plans should assess the economic effect of varying materials and construction variables and resulting deviation of achieved performance from the intended performance. The intended (as-designed) as well as provided (as-constructed) performance of the pavement can be predicted using performance modeling and these predictions can be used to base payment adjustment on at the completion of the initial construction.

A rational methodology for adjustment plans should correct the contractor's bid price according to the influence that quality deviations have on the total life cycle cost of the pavement. The difference in cost is, of course, between the cost of the pavement as was designed or intended and the cost of the pavement as was constructed. The life cycle cost should ideally include initial construction, maintenance and rehabilitation cost as well as salvage value. Maintenance and rehabilitation cost should incorporate both construction cost and user cost as result of construction, i.e. due to delays and accidents. The analysis period should cover the time until reconstruction is expected under current traffic growth projections. Analysis periods for the as-designed and as-constructed cases will not necessarily be equal, however, cases remain comparable by annualizing cost over the analysis period assuming that the life cycle pattern and thus the associated costs are repeated into the future. Figure 1 shows one possible combination of costs and rehabilitation strategies to illustrate this complete analysis.

The payment adjustment is found by calculating the difference in initial construction cost required to equalize the annualized life cycle cost for the as-designed and as-constructed cases. The flexibility of the life cycle cost analysis comes to the fore when more than one performance model or criteria is used to predict future rehabilitation needs. The multiple maintenance and rehabilitation requirements can all be channeled into the cost-time model and evaluated in a single monetary analysis.

It is clear that detailed performance prediction capabilities are required for the complete life cycle cost analysis. The evaluator has to predict what rehabilitation will be required and how long each rehabilitation will last. Furthermore, information is required linking serviceability or pavement condition levels and maintenance costs as well as user costs associated with road rehabilitation. Due to the complexity of the problem, many proposed life cycle cost analyses have not included some of the costs, excluding either or both maintenance and user costs *(1)*. Other proposals have ignored rehabilitation costs, but included maintenance costs, while focusing only on the time period up to the first rehabilitation *(2)*. It is proposed that either all the costs be included in the full analysis period, as has been explained previously, or that only the initial cost and the maintenance cost for the first performance period be analyzed. If only the initial performance period is included, it is inherently assumed that rehabilitation strategies for both the as-designed and as-constructed cases are similar and the effect thereof thus negligible. The adjustment is therefore a function of the following factors only: the expected life of as-constructed and as-designed cases until the first rehabilitation is required, the annual maintenance cost and the real discount rate. The proposed simplification is attractive because the performance of the rehabilitation contractor does not have to be taken into account.

A further simplification to the payment adjustment plan is to ignore the effect of the maintenance cost. The only factors that will therefore be included in the payment adjustment procedure, are the performance periods and the real discount rate. Equation 1 can be used to calculate the simple adjustment based on predicted design life and real discount rate. It is acknowledged that ignoring maintenance cost is a further step away from the ideal, but is shown for practical applications where maintenance predictions may be difficult at the time of construction.

$$A_c = A_d$$

where

$$A = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right]$$

therefore

$$P_c\left[\frac{i(1+i)^{lc}}{(1+i)^{lc} - 1}\right] = P_d\left[\frac{i(1+i)^{ld}}{(1+i)^{ld} - 1}\right]$$

$$\text{and } P_c = PF * P_d \qquad (1)$$

therefore

$$PF = \frac{(1+i)^{ld-lc}[(1+i)^{lc} - 1]}{(1+i)^{ld} - 1}$$

where:

Subscripts ‘c’ and ‘d’ designate as-constructed and as-designed values

A	=	Annualized cost
P	=	Present value (payment to the contractor or initial construction cost)
n	=	Generic design life in years
i	=	Real discount rate per year
lc	=	Predicted design life of the pavement as-constructed in years
ld	=	Predicted design life of the pavement as designed in years
PF	=	Payment adjustment factor

A final step in the simplification process is to consider only the predicted performance in terms of years or traffic carried and ignoring the effect of time value of money. This strategy is used in the development of the proposed payment adjustment but can be modified to include the time value of money as will be shown in an application example.

AASHTO BASED PAYMENT ADJUSTMENT PROCEDURE

The AASHTO rigid pavement thickness design equation *(3)* is an ideal performance model for the development of performance-based payment adjustment factors. Confidence in the model is illustrated by nation and world wide use for slab thickness design *(4)*. Furthermore, it is one of the few, performance models that incorporates variance of input and output factors in performance prediction. Consequently, the design equation includes variance in the form of the overall standard deviation and incorporates the concept of reliability in the design. Inclusion of variance in the performance-based payment adjustment is logical since a low variance in material and construction parameters will lead to reduced overall variance in performance. Lower overall variance leads to fewer sections of pavement failing early, an increase in performance life and reduced total cost. Applying the AASHTO equation to calculate the predicted performance, therefore captures both the effect of the input factors' mean and variance on the overall performance.

Materials and Construction Variables Selection

The AASHTO thickness design equation contains ten materials and construction factors that are input to predict performance. The payment adjustment should, however, only be based on the factors that are controllable during construction which amounts to eight factors. A sensitivity analysis was performed and the factors that are controllable by the contractor, are ranked according to performance sensitivity in Table 1. Overall standard deviation, concrete thickness and concrete strength are the three most sensitive input variables. Since thickness and strength are controlled in most specifications and influence the predicted performance most, these factors were selected to be included in the proposed payment adjustment. Present serviceability index was also selected to be included in the payment adjustment despite only ranking sixth, due to most agencies' inclusion of ride quality in incentive/disincentive specifications.

Equation Development

The proposed payment adjustment procedure is based on the relation shown in Equation 2. The method uses the ratio of the predicted initial performance period of the as-designed and as-constructed pavement, to modify the bid price. The initial performance period is defined as the number of esals from the initial level of PSI to the terminal level. For the future, the same concept will be applied to other types of predicted distress (i.e. punchouts).

$$\text{Payment adjustment} = \frac{\text{As-constructed predicted performance}}{\text{As-designed predicted performance}} * \text{Bid price} \qquad (2)$$

The procedure is an additional reduction of the simple life cycle cost analysis proposed in Equation 1. The AASHTO rigid pavement thickness design equation, as shown in Equation 3, is used to calculate the predicted performance. Hence, the performance is expressed in terms of load repetitions to failure instead of time to failure, in years. Life cycle cost analyses require performance periods to be expressed in terms of time. For an analysis as shown in Figure 1 or Equation 1, performance models' predictions, if in terms of load repetitions, will have to be converted to time by a traffic model. However, by defining performance in Equation 2 as the load repetitions to failure, the requirement for a traffic model is eliminated.

$$\log_{10} W_{18} = ZS_o + 7.35\log_{10}(D+1) - 0.06 + \frac{\log_{10}\left(\frac{p_o - p_t}{4.5 - 1.5}\right)}{1 + \frac{1.624 * 10^6}{(D+1)^{8.46}}}$$

$$+ (4.22 - 0.32p_t) * \log_{10}\left[\frac{S_c' C_d (D^{0.75} - 1.132)}{215.63 * J\left(D^{0.75} - \frac{18.42}{\left(\frac{E_c}{k}\right)^{0.25}}\right)}\right] \qquad (3)$$

where:

W_{18} = Predicted load repetitions (in terms of 80,000 N (18,000 lb) equivalent single axle loads) until the serviceability reaches the terminal value p_t

Z = Normal standard deviate for the reliability sought

S_o^2 = Overall variance in the prediction equation

$$= \sum_{j=1}^{m} S_j^2 + \sum_{i=1}^{n} \left(\frac{\partial W_{18}}{\partial x_i} \right)^2 S_{x_i}^2$$

$\sum_{j=1}^{m} S_j^2$ = All other factors that contribute to the overall variance of the thickness design equation *(5)*.

The value recommended by the AASHTO design guide is 0.0913.

x_i = Performance parameters in Equation 3

S_{xi}^2 = Variance for the performance parameter x_i

D = Concrete thickness

p_o = Initial present serviceability index

p_t = Terminal present serviceability index

S_c' = Concrete flexural strength

C_d = Drainage coefficient

J = Joint load transfer coefficient

E_c = Concrete elastic modulus

k = Effective modulus of subgrade reaction

When Equation 3 is substituted into Equation 2, the resultant pay factor, expressed in simplified form, is shown in Equation 4. In order to develop a payment adjustment factor that includes only the three most sensitive input variables identified earlier as: strength, thickness and serviceability, the assumption is made that all other input factors remain constant for the as-designed and as-constructed cases. This assumption leads to the reduction of Equation 4 to the form shown in Equation 5. It can be seen that the equation includes values for the concrete elastic modulus, effective modulus of subgrade reaction and terminal serviceability index. Although these values are assumed to be equal in design and construction, their effect on the pay factor has to be investigated before they can be ignored.

$$PF = \frac{W_{18\,\text{as constructed}}(D, p_o, p_t, S_c', C_d, J, E_c, k)}{W_{18\,\text{as designed}}(D, p_o, p_t, S_c', C_d, J, E_c, k)} \qquad (4)$$

$$\log_{10} PF = Z(S_{o,d} - S_{o,c}) + 7.35\log_{10}\left(\frac{D_c+1}{D_d+1}\right) + \frac{\log_{10}\left(\frac{p_{o,c}-p_t}{3}\right)}{1+\frac{1.624 * 10^7}{(D_c+1)^{8.46}}} - \frac{\log_{10}\left(\frac{p_{o,d}-p_t}{3}\right)}{1+\frac{1.624 * 10^7}{(D_d+1)^{8.46}}}$$

$$+ (4.22 - 0.32p_t)\log_{10}\left[\frac{S'_{c,c}(D_c^{0.75} - 1.132)}{S'_{c,d}(D_d^{0.75} - 1.132)} * \frac{D_d^{0.75} - \frac{18.42}{\left(\frac{E}{k}\right)^{0.25}}}{D_c^{0.75} - \frac{18.42}{\left(\frac{E}{k}\right)^{0.25}}}\right] \qquad (5)^*$$

* Subscript ',c' denotes as-constructed value, subscript ',d' denotes as-designed value

$$PF = 10^{Z(S_{o,d} - S_{o,c})} \left(\frac{D_c}{D_d}\right)^{6.13} \left(\frac{S'_{c,c}}{S'_{c,d}}\right)^{3.42} \left(\frac{p_{o,c}}{p_{o,d}}\right)^{2.85} \qquad (6)^*$$

where:

$$S_o^2 = \left[\frac{3.192}{D+1} - \frac{2.168 * 10^7}{(D+1)^{9.46}}\right]^2 S_D^2 + \left[\frac{1.485}{S_c'}\right]^2 S_{Sc'}^2 + \left[\frac{0.6167}{(p_o - 1.5)^2}\right]^2 S_{Po}^2 + 0.1206$$

* Subscript ',c' denotes as-constructed value, subscript ',d' denotes as-designed value

A regression equation that models Equation 5 is proposed as shown in Equation 6. The equation ignores the effect of the concrete elastic modulus, modulus of subgrade reaction and terminal serviceability on the performance prediction. A comparison between Equation 5 and 6 is shown in Figure 2. A variety of possible scenarios were used to test the validity of Equation 6. All variables were allowed to vary within limits expected during construction, while Equations 5 and 6 were used to calculate payment adjustment factors. The data produced a good correlation. The factors that were left out of Equation 5 for the development of Equation 6 had negligible effect on the correlation. Equation 6 is therefore, a payment adjustment factor equivalent to Equation 5, in a somewhat more simple form that may be used in a specification.

Sensitivity Analysis

A sensitivity analysis was performed on Equation 6. Figure 3 shows the sensitivity of the mean values of the performance variable ratios for thickness, concrete strength and initial serviceability. Performance variable ratios are the ratio of as-constructed and as-designed parameters. The mean values of the performance variable ratios were varied between a range of 0.8 and 1.2. For the initial serviceability index, a maximum ratio of 1.1 was used because a serviceability larger than five is not possible by definition. The sensitivity clearly follows the value of the exponent with thickness being the most sensitive variable followed by strength and serviceability. The reason that sensitivities vary from those presented in Table 1, is that here the variables are varied regardless of the typical variation, as experienced in construction. The ranking in Table 1 takes the combined effect of typical field variance and model sensitivity into account.

Figure 4 shows the sensitivity of the pay factor equation to the variance of the performance factors. The pay factor is most sensitive to the thickness variability followed by strength and serviceability. The cause of the variance of the pay factor due to changing variance of the performance factors is due to the reliability concept built into the AASHTO design equation. The proposed AASHTO payment adjustment, therefore, takes the quality of the performance parameter into account without calculating percent within limits values as is required by other payment adjustment methods.

Limited Adjustment

In order to be practical, the payment adjustment has to be limited to acceptable values for both contractor and agency. Clearly the pay factor can be exploited by contractors by increasing thickness and sacrificing strength to catapult the pay factor to a high level. This strategy will be feasible since the cost of increasing thickness is easily offset by the savings on decreasing strength and the increase in payment. Therefore, it is proposed that the pay factor be capped both at a high and low value. These values will first prevent the exploitation as described above. Second, the capped pay factor will ensure that the design factors remain compatible. For example, disproportionately high strength will not be compatible with steel or joint designs and might cause performance problems due to large joint and crack widths and/or high steel stresses. Third, the lower cap on the pay factor will be a warning for owner and contractor to investigate the source of the low quality. The lower cap acts as an acceptable quality limit, warning the owner when quality falls low enough to warrant closer investigation. The exact values of the caps are dependent on each agency and related industry. Currently the Texas Department of Transportation is investigating 0.7 and 1.05 as the proposed limits.

Data Simulation

A simple but efficient way to verify that a pay factor will produce acceptable results is by calculating the expected distribution by data simulation. Data simulation is the process of generating materials and construction factor data using random number generators. Random values for quality assurance data that are required to calculate the proposed pay factor was generated. Distributions for the quality assurance data were assumed to be normal with variances as reported by the AASHTO Design Guide, Appendix EE *(5)*. A data set of 2500 lots, each with five sublots or 12,500 sublots in total, was generated. Each sublot consisted of a value for thickness, strength and initial ride quality from the populations as shown in Table 2. The sublot data were used to calculate an average, standard deviation, percent within limits and a set of pay factors.

The percent within limits calculations were based on two sided limits for each variable. The specification limits were set at two standard deviations from the 'specified' mean value, except for strength, where the upper limit was set at three standard deviations and the lower limit at one standard deviation from the mean. The skewed limits for strength are due to the fact that contractors currently adjust the mean value for strength to ensure compliance to the specification. In effect the mean specified value is moved up one standard deviation.

The following pay factors were calculated:

1. AASHTO — As in Equation 6
2. AASHTO (adjusted) — Equation 6 adjusted to produce a mean value of one
3. AASHTO (capped) — Equation 6 adjusted and capped at 1.05 and 0.70
4. New Jersey (multi) (*1*) — $PF = 1.02 - 0.2(1 - PWL_{f_c})$
5. New Jersey (strength) (*1*) — $PF = 1.05 - 0.12(1 - PWL_D) - 0.10(1 - PWL_{f_c}) - 0.11(1 - PWL_{p_o})^2$

where:

PF	=	Pay factor (correction to the bid price)
PWL	=	Percent within limits (quality level)
D	=	Concrete slab thickness
f_c	=	Concrete compressive strength
p_o	=	Initial ride quality (serviceability)

Figure 5 shows the development of the AASHTO payment adjustment factor compared to the New Jersey multiple adjustment. The data used to develop the figure are from a specific Texas Project where testing necessary to apply the concepts on a trail basis was used. The mean value for the AASHTO pay factor was 0.92 and the standard deviation 0.29. An adjustment was made to the pay factor to move the distribution to have a mean value of one. The reason for the adjustment being necessary is not very clear. It was thought that the shift was due to the assumptions made when Equation 6 was developed, however, when data were checked using Equation 5, the shift remained the same.

Figure 6 compares the capped AASHTO factor to the New Jersey payment adjustment factors. The AASHTO adjustment is sensitive to the performance parameter qualities with more than 15 percent of the cases below the lower cap and 40 percent above the upper cap. The New Jersey adjustment factors are more risk averse and show smooth distributions with low probability of large payment adjustments. The New Jersey models seem to dampen the effect of performance models, distributing the pay factor evenly between set upper and lower limits.

Limited Comparison of the Proposed Payment Adjustment to a Life Cycle Cost Method

The data used in the data simulation exercise were used to compare Equation 1 (using the AASHTO design equation to predict life) to the proposed AASHTO based payment adjustment from Equation 6. The comparison investigates the effect of ignoring the life cycle cost analysis procedure in its simplest form. The performance prediction variables were assumed to be as shown in Table 3 for the design case. Thickness, strength and initial serviceability were varied for the constructed case as was done in the data simulation example. In order to complete the life cycle cost analysis, the AASHTO performance prediction, which is in terms of ESALs, needed to be converted to time. A traffic model was arbitrarily selected for the purpose of this example. Traffic was assumed to be 200,000 ESALs in year one, increasing annually by four percent, leading to a cumulative traffic volume of 11.2 million ESALs in year 30. All AASHTO load repetition predictions were rounded off to the nearest year. The design case produced a predicted life of 14 years. The model predicted lives of 8 to 20 years for the as-constructed cases which is considered reasonable. Figure 7 compares the AASHTO payment adjustment distribution to the life cycle cost payment adjustment distribution for two discount rates. The stepwise distribution for the life cycle cost factors are a result of rounding off the predicted life to the nearest year. It is clear that including discount rate in the adjustment dampens the severity of the pay factor. As the discount rate increases, the dampening effect increases since the benefit of an extended life or cost of a shortened life becomes less sensitive. The inclusion of a life cycle cost analysis is considered an improvement of the adjustment factor calculation procedure.

CONCLUSION

The paper provides a fundamental and fair method by which to adjust payment to the contractor. The method is based on expected performance of the pavement rather than arbitrarily selected scales. The performance equation used in the payment adjustment procedure, the AASHTO thickness deign equation, is widely used and accepted, and captures the effect of the distribution of relevant input factors on the quality of pavement provided.

The concepts of this paper were applied on a shadow specification basis to four concrete paving projects in Texas. Although the incentives/disincentives were not fully implemented, the value of the approach was demonstrated since the material variability is tied to actual performance rather than arbitrary limits.
The payment adjustment factor as shown in Equation 6 provides a reasonable estimate of the value of the as-constructed pavement. Inclusion of the effect of the time value of money as shown in Equation 1 or of a full scale life cycle cost analysis as shown in Figure 1 is , however, desired if reliable performance and rehabilitation prediction models are available.

TABLE 1 Controllable Variables for the AASHTO Model Ranked According to Sensitivity

TABLE 2 Assumed Normal Distribution Properties for Performance Factor Data

TABLE 3 Performance Prediction Variables for the Design Case

TABLE 1 Controllable Variables for the AASHTO Model Ranked According to Sensitivity

Rank	Variable
1	Overall standard deviation
2	Concrete flexural strength
3	Concrete thickness
4	Joint load transfer coefficient
5	Drainage condition
6	Initial present serviceability index
7	Modulus of subgrade support
8	Concrete elastic modulus

TABLE 2 Assumed Normal Distribution Properties for Performance Factor Data

Quality Assurance Variable	Mean	Standard Deviation	CV (%)
Thickness (mm)	250	10	4
Tensile strength (kPa)	3450	345	10
Initial serviceability (PSI)	4.2	0.28	7

1inch=25.4mm
1psi=6.98kPa

TABLE 3 Performance Prediction Variables for the Design Case

Performance variable	Design value
Thickness	250 mm
Tensile strength	3450 kPa
Initial serviceability	4.2 PSI
Reliability	95 %
Terminal serviceability	2.5 PSI
Concrete elastic modulus	34,500 MPa
Modulus of subgrade support	81.5 MPa/m
Load transfer coefficient	2.8
Drainage coefficient	1.0
Overall standard deviation	0.39

1inch=25.4mm
1psi=6.98kPa
1pci=0.275MPa/m

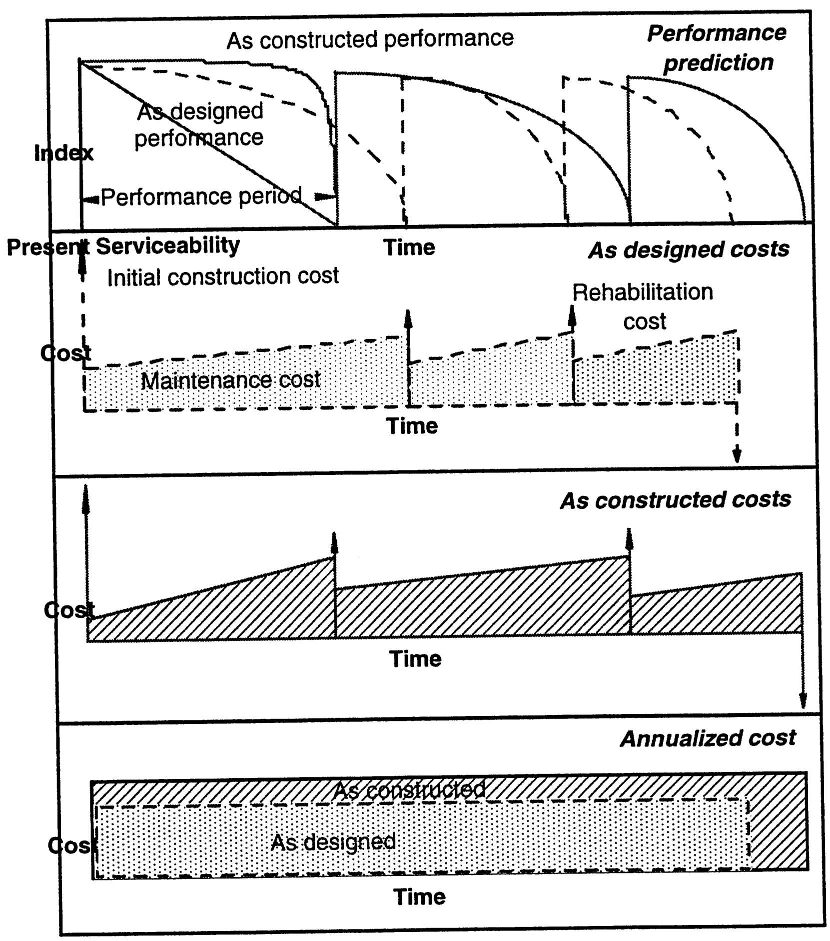
As constructed performance
Performance prediction
As designed performance
Index
Performance period
Present Serviceability
Time
As designed costs
Initial construction cost
Rehabilitation cost
Cost
Maintenance cost
Time
As constructed costs
Cost
Time
Annualized cost
As constructed
Cost
As designed
Time

Figure 1

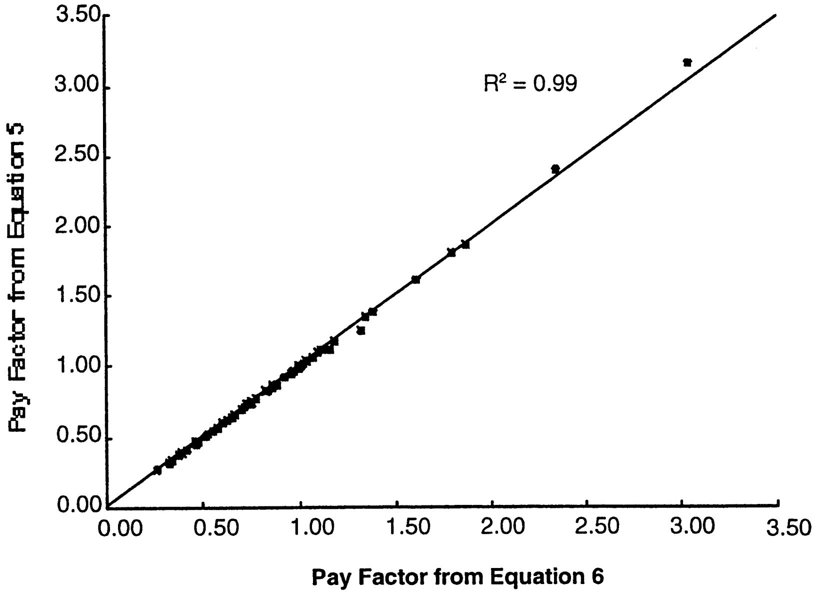

Figure 2

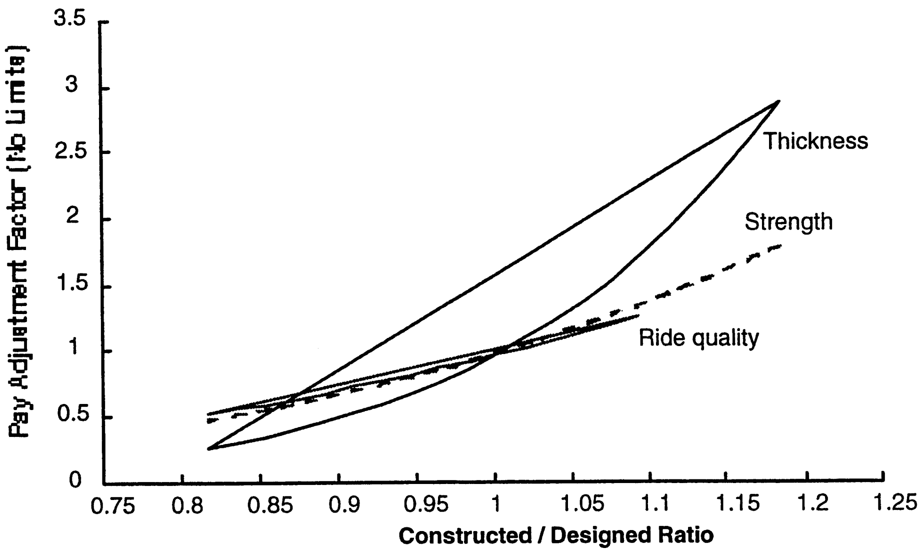

Figure 3

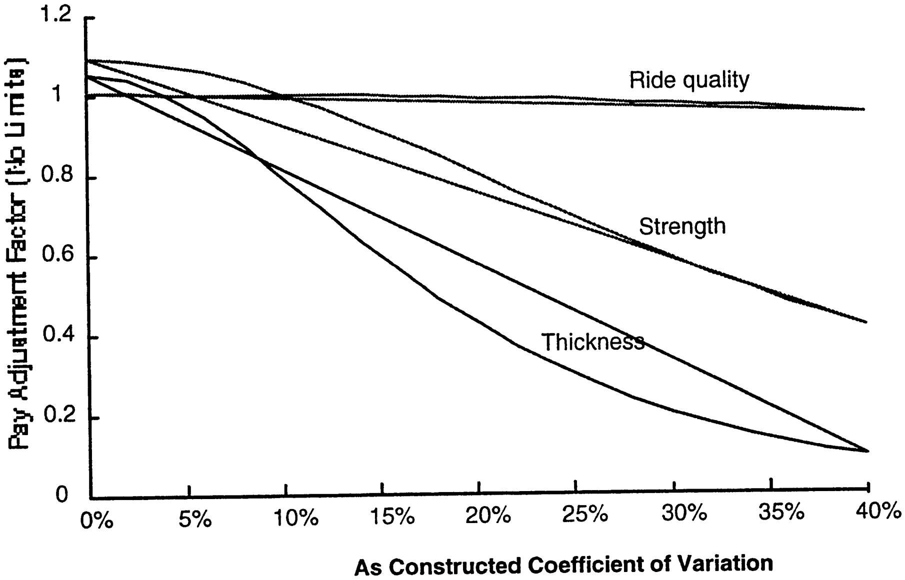

Figure 4

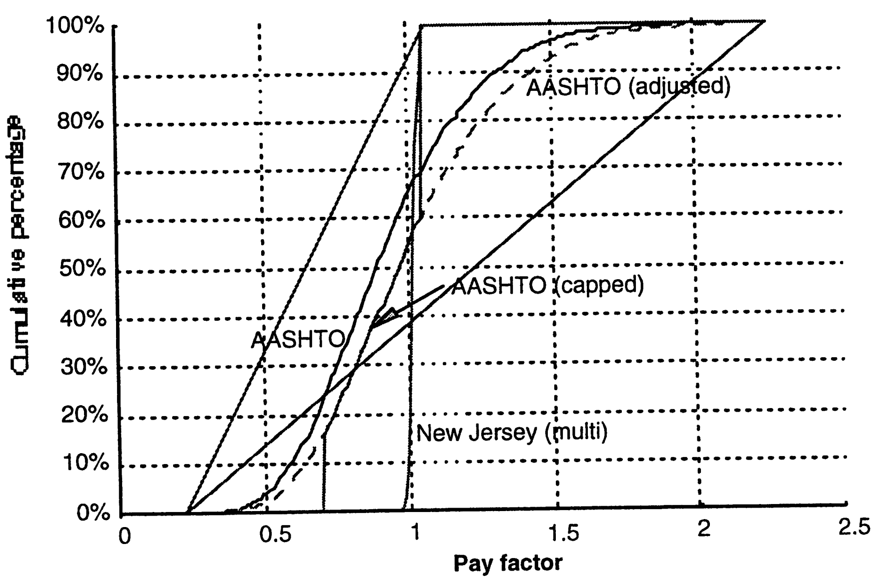

Figure 5

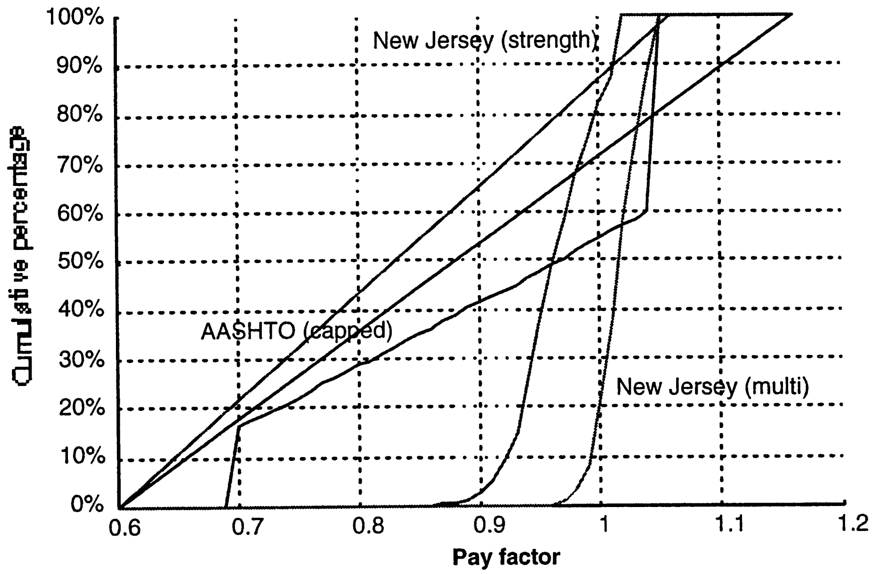

Figure 6

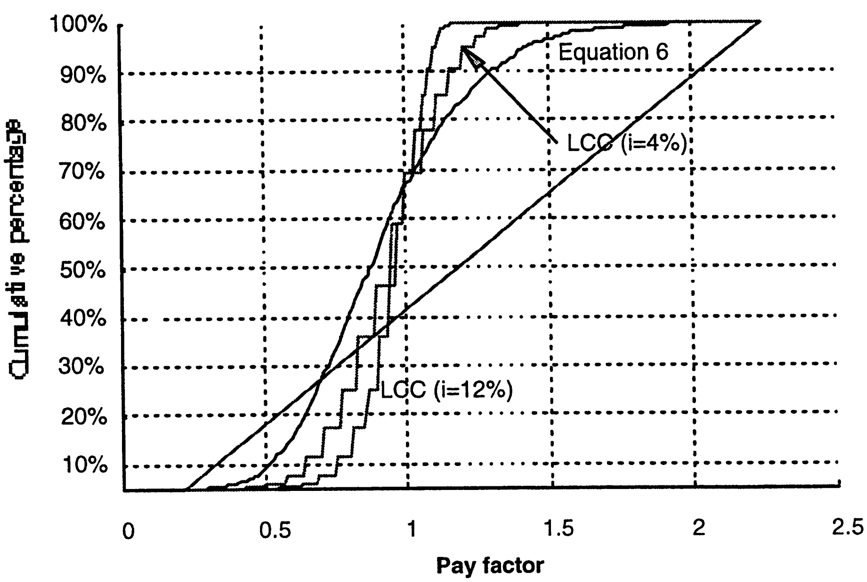

Figure 7

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