JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT
ISSN 1392-3730/eISSN 1822-3605
2015 Volume 21(1): 119–130
doi:10.3846/13923730.2013.802713

VARIABILITY OF HMA CHARACTERISTICS AND ITS INFLUENCE ON PAY ADJUSTMENT

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Received 03 Mar 2012; accepted 16 Aug 2012

Abstract. The goal of this paper is to formalize and validate a model in order to determine a pay adjustment on the basis of mechanical and functional performance of transportation infrastructures. A model to determine the pay adjustment based on life expectancy of a pavement and the variability of its main properties was formulated. Five different paths and points of view are used in order to obtain information on model suitability and robustness. An algorithm has been proposed to estimate a pay adjustment (PA, negative or positive), based on life cycle cost analysis, when both structural and non-structural deficiencies/surplus in characteristics are detected. The five different methodologies, used for deriving PA, demonstrate the validity of the model in which the PA depends on both position and dispersion measures. It has been demonstrated that the model can help in analysing a project and construction management under a common framework. Analyses and validation demonstrate that the proposed model can efficiently overcome typical problems in PA determination and in contract administration, where decisions based upon objective and sound criteria are needed. Both practitioners and researchers are expected to benefit from the outcomes of this study.

Keywords: financial engineering, pay adjustment, transportation infrastructure, externality, boundary conditions, pavement.

Introduction (PA – variability)

Material properties and other characteristics of a constructed pavement will generally vary somewhat from those specified in contract because construction operations and materials are influenced by many factors (Table 1).

Each property and characteristic of a flexible pavement can affect its performance such as the derivation of a pay adjustment when the as-designed performance differs from the as-constructed performance (Mladenovic *et al.* 2003; Seebaly, Bazi 2005; Praticò 2007; Praticò, Moro 2007; D'Apuzzo, Nicolosi 2010).

The modulus and thickness of hot mix asphalt layers (usually wearing, binder and base courses) greatly affect the expected life of a pavement.

Critical analysis responses, such as pavement surface deflection and horizontal tensile strain at the bottom of the HMA layer, depend on pavement layers (Khazanovich *et al.* 2006).

High standard deviations can be detected both in terms of moduli (values as high as 3 GPa can be detected for HMAs, or as high as 0.01 GPa for unbound materials, see Table 1) and thickness (standard deviation can raise up to 70–110 mm for HMAs or unbound materials).

In the same way, surface and functional properties of wearing courses present an appreciable variance and relevance for both rigid and flexible pavements (Boscaino, Praticò 2001; Boscaino *et al.* 2009; Praticò *et al*. 2009; Gedafa *et al.* 2012).

All these facts affect construction statistics and in particular location measures (such as averages) and dispersion measures (such as standard deviation) of many quality characteristics (such as thickness or air void content). Quality characteristics (such as air void content) and quality measures (such as average, defect percentage) are generally used by highway agencies for the acceptance of pavement construction.

For these reasons, many highway agencies incorporate quality-related pay adjustments, in the form of incentives/disincentives, in construction contracts of flexible and rigid pavements to account for the loss or gain of money by the agency.

A recurring problem is that many of the approaches used by highway agencies dealing with construction variance and assessing pay adjustment have been empirically developed without a relationship to a logic well-grounded performance. These approaches use procedures and conceptual frameworks which are

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Table 1. Variability data

Variable	Unit of measure	Standard Deviation	Coeff. of Variation (%)	Reference
Hot mix asphalt (HMA) modulus	GPa	0.04–0.97	0.2–14.8	Carvalho (2006)
		1.44	86.21	Haider (2009)
		0.37	10–0	Kim, Buch (2003)
		0.26–0.40	29–37	Kenis, Wang (2000)
		0.06–0.27	8–33	Mohammad *et al*. (2004)
		0.1–3.19	6.6–73	Stubstad *et al*. (2002)
		0.69	15.48	Retherford, McDonald (2010)
		–	9.7–51.3	Arafah (1997)
		0.14	0.1–164.5	Aguiar-Moya, Prozzi (2011)
		–	1.2–2.2	
Base course modulus	GPa	–	5–60	Kim, Buch (2003)
		0.051 – 0.055	23–25	Kenis, Wang (2000)
		0.001 – 0.081	2–56	Stubstad *et al.* (2002)
Modulus of unbound granular base	GPa	0.014	5–60	Kim, Buch (2003)
		0.008 – 0.011	9–10	Kenis, Wang (2000)
		0.006	0.8–89.6	Aguiar-Moya, Prozzi (2011)
Thickness of HMA layer	mm	12.2	15.5	Darter *et al.* (1973)
		10.4	–	Sherman (1971)
		6.6 – 12.45	3.2–12.4	Stubstad *et al.* (2002)
		6.33 – 6.81	7–8	Kenis, Wang (2000)
		54.88	3–37	Kim, Buch (2003)
		12.20	15.48	Retherford, McDonald (2010)
		–	7.8–25.6	Attoh-Okine, Kim (1994)
		8.38 – 18.29	11.7–16	Aguiar-Moya, Prozzi (2011)
		0.87 – 110.23	0.62–83.19	Selezneva *et al.* (2002)
		3.07 – 9.65	4.85–19.18	Hughes *et al.* (1997)
Thickness of HMA wearing course	mm	8.55 - 31.50	10.27–35.74	Haider (2009)
		6.8 – 36.8	24.56–30.41	Whiteley *et al.* (2005)
		8.38–18.29	3.2–18.4	Aguiar-Moya, Prozzi (2011)
		0.52–107.46	0.69–93.24	Selezneva *et al.* (2002)
Thickness of unbound granular base	mm	20.07	–	Sherman (1971)
		22.80–70.94	11.12–28.04	Haider (2009)
		8.58–9.50	4–5	Kenis, Wang (2000)
		31.75	10	Retherford, McDonald (2010)
		20.06	10	Darter *et al.* (1973)
		36.58	6–17.2	Aguiar-Moya, Prozzi (2011)
		3.20–55.76	1.90–37.44	Selezneva *et al.* (2002)
Air void content	%	0.2–2.1	2–26.4	Mohammad et al. (2004)
		0.36	0.9–39	Aguiar-Moya, Prozzi (2011)
		0.49–1.11	–	Katicha *et al.* (2011)
		0.39–0.90	8.91–29.03	Hughes *et al.* (2007)
		0.63–1.09	10.67–26.05	Hughes *et al*. (1997)
Asphalt binder content	%	0.32	0.9–39.2	Aguiar-Moya, Prozzi (2011)
		0.25–0.45	–	Katicha *et al.* (2011)
		0.07–0.25	1.18–26.7	Hughes *et al*. (2007)
		0.17–0.27	3.73–6.44	Hughes *et al*. (1997)

different from the ones used in project management and pavement design.

The real effect of standard deviation of material properties and other characteristics on agency costs and therefore pay adjustment is still unclear.

For the above issues in this paper a model to determine the pay adjustment based on life expectancy of a pavement and the variability of its main properties was formulated. Five different paths and points of view are used in order to obtain information on model suitability and robustness.

This paper is organized as follows. Section 1 deals with the methodology set out to derive and demonstrate the model, Section 1.1 refers to the overall methodology, Section 1.2 the new algorithm to derive PA based on E, Section 1.3 to 1.7 five different paths/methods to estimate PA based on material quality. Section 2 describes and analyses the results obtained. The final section deals with conclusions and points out future research directions.

1. Methodology

Figure 1 summarizes the methodology. The 5th path refers to the model set out herein.

1.1. Framework of the methodology

Air void content (AV) was considered as the main quality characteristic.

In the first case (1st path), the expected life of the pavement (E) is derived using the mechanistic empirical

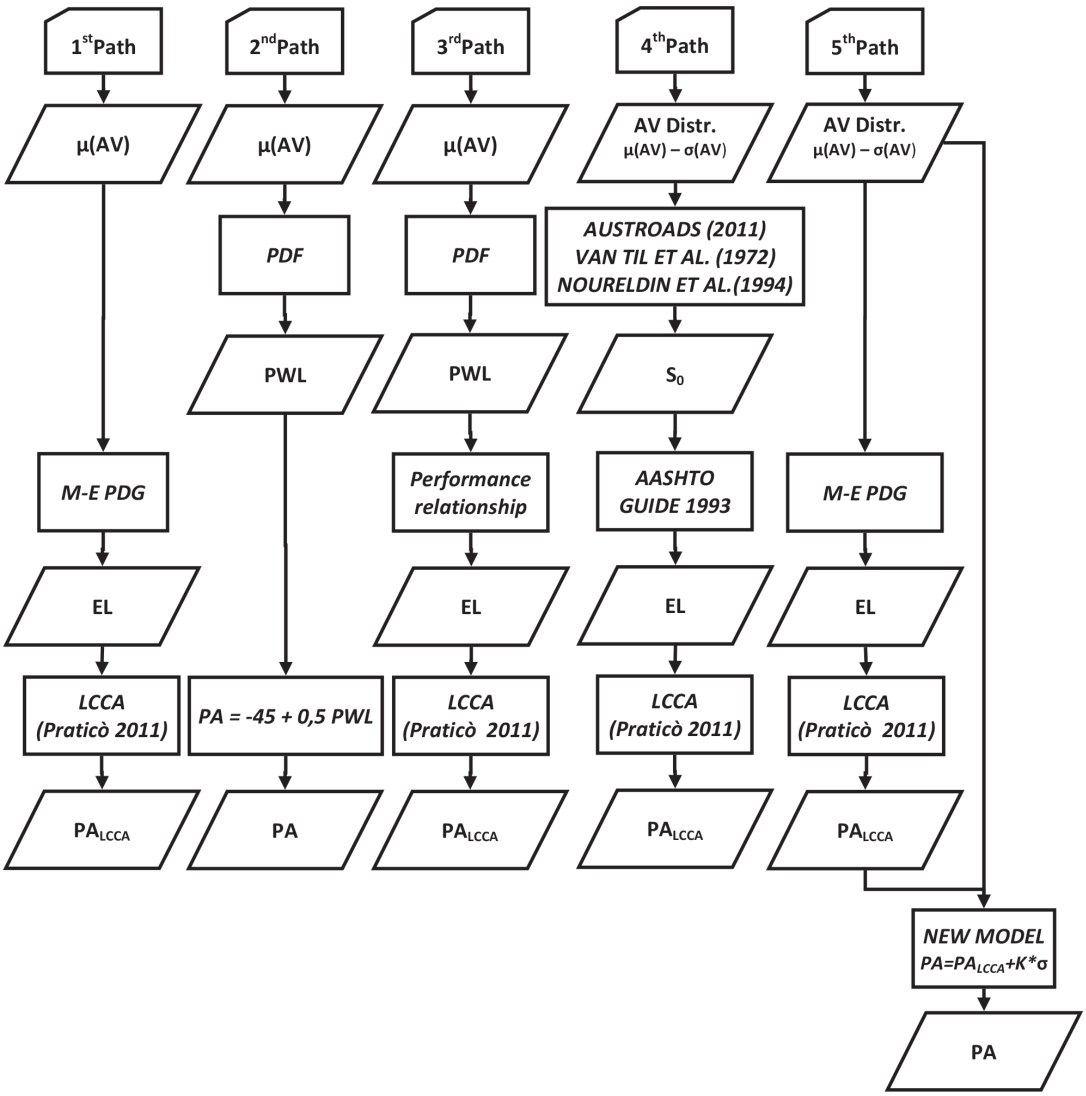


Fig. 1. Synapsis of the paper

pavement design guide (M-E PDG), and the pay adjustment (PA_{LCCA}) is derived based on a life cycle cost analysis (LCCA).

In the second case, a given probability density function (PDF) for the AV is assumed (average μ(AV), standard deviation σ(AV)), and the percentage within limits (PWL) is derived as a quality measure.

The PA is derived from the PWL based on a continuous payment schedule (PA = –45 + 0.5 PWL).

In the third case, once the PWL has been derived from the AV measure (based, as above, on a given PDF), the expected life of the pavement (E) is derived from the PWL through a performance relationship. Subsequently, the PA is inferred from E, based on LCCA.

In the fourth path a given AV distribution is supposed. Different standard deviations and averages are considered in more detail. As a consequence, based on literature (Austroroads 2011), for each couple (σ(AV), μ(AV)) the corresponding distributions of moduli and structural layer coefficients are derived. For each distribution of moduli there is a corresponding value of the overall variance S_0 (AASHTO Guide 93). This fact allows the life expectancy of the pavement to be derived, under given hypotheses, through the AASHTO Guide 93 method (AASHTO 1993). Finally, the pay adjustment (PA) is derived by comparing the expected life of the as-constructed life vs. the expected life of the as-designed pavement. The fourth procedure focuses on AASHTO Guide, 1993 and its consequences in terms of material variance. In this paper only agency costs are considered.

In the fifth path, the probability density function of AV generates, through the M-EPDG (NCHRP 2004; Manika *et al.* 2012), different values of E. These values are interpreted through a linear model of PA as a function of the standard deviation of the process.

1.2. New PA LCCA-based model

This section deals with the formalization of a new model based on LCCA and on the consideration of the standard deviation of processes and materials. From a practical standpoint the new model can be divided into two parts: the first part (Praticò 2011) is based on LCCA and takes advantage from previous algorithms (Weed 2001; Praticò 2007; Praticò *et al.* 2011). The second part deals with a practical methodology which considers the relevance and the role of variance.

As for the first part of the model, all the previous LCCA-based models, under given hypotheses, can be simplified as in Eqn (1), where PA_{old} is the pay adjustment (the subscript is herein added), R is the ratio between (1 + i) and (1 + r), where i is the inflation rate (typically 0.04) and r is the interest rate (typically 0.08). D (for example, 20 years) is the expected life of the as-designed pavement (AD), E (for example 15 years) is the expected life of the as-constructed pavement (AC), O is the time between two successive rehabilitations or resurfacings (typically 10 years). Furthermore, let C_0 (€ or €/m^2) be the cost of the pavement at the time 0 and C the cost of rehabilitation at the given year. Then C_0 and C can be identical:

$$PA_{old} = C \cdot \left(R^D - R^E\right) \cdot \left(1 - R^O\right)^{-1}. \quad (1)$$

The as-designed pavement will need a rehabilitation after D years, after 2D years, etc. As a consequence the present value, PV, of the total expenditures in T years (where T is the period of analysis, for example 50 years), will be as in Eqn (2), where $n \cdot D \leq T$, and S is the salvage value:

$$PV_{ADT} = C_0 + C \cdot \sum_{i=1}^{n} R^{i \cdot D} - S \cdot R^T. \quad (2)$$

If T tends to infinite, then Eqns (3)–(5) can be derived:

$$\lim_{n\to\infty} \sum_{i=1}^{n} R^{i \cdot D} = R^D \cdot \left(1 - R^D\right)^{-1}; \ \lim S = 0. \quad (3), (4)$$

$$PV_{AD} = \lim_{n\to\infty} PV_{ADT} = C_0 + C \cdot R^D \cdot \left(1 - R^D\right)^{-1}. \quad (5)$$

The present value of AC and the pay adjustment (PA) result:

$$PV_{AC} = C_0 + C \cdot R^E \cdot \left(1 - R^D\right)^{-1}; \quad (6)$$

$$PA = PV_{AD} - PV_{AC} = C \cdot \left(R^D - R^E\right) \cdot \left(1 - R^D\right)^{-1}. \quad (7)$$

Note that if E tends to D, then PA tends to 0, while if E tends to 0, then PA tends to –C and the penalty (in absolute value) equals the cost. As for the resurfacings of AD, they are scheduled at O, D + O, 2D + O, ... In contrast, for the AC pavement, they are usually performed at O, E + O, E + D + O, E +2D + O, etc. The results are (where F = 1 when E > O, while F = 0 if E ≤ O and O < D):

$$PV_{AD\_RES} = C_{RES} \cdot R^O \cdot \left[1 + R^D \cdot \left(1 - R^D\right)^{-1}\right]; \quad (8)$$

$$PV_{AC\_RES} = C_{RES} \cdot R^O \cdot \left[F + R^E \cdot \left(1 - R^D\right)^{-1}\right]; \quad (9)$$

$$PA_{RES} = C_{RES} \cdot R^O \cdot \left[11 - F + \left(R^D - R^E\right) \cdot \left(1 - R^D\right)^{-1}\right]; \quad (10)$$

$$PA + PA_{RES} = C \cdot \left(R^D - R^E\right) \cdot \left(1 - R^D\right)^{-1} + C_{RES} \cdot R^O \left[1 - F + \left(R^D - R^E\right) \cdot \left(1 - R^D\right)^{-1}\right]. \quad (11)$$

Note that the above equations do not consider the standard deviation of the process/materials. The PA of Eqn (7) will be herein stated as PA_{LCCA}.

As for the second part of the model (see also the 5th path below), the probability density functions describing the main quality characteristics (AV, thickness, asphalt binder content, etc.) determine the probability density function of the expected lives.

By splitting the pavement, under investigation, in N parts, it follows that:

$$PA = \sum_{i=1}^{N} PA_i = \sum_{i=1}^{N} C_i \cdot PA_i^*, \quad (12)$$

where: PA_i and PA^*_i (pay adjustments) and E_i (expected life) refer to the *i*th part of the pavement. It is supposed that (equal sections or parts under consideration).
It follows that:

$$\frac{PA}{C_i} = \frac{PA \cdot N}{C} = \sum_{i=1}^{N} PA_i^*, \quad (13)$$

and

$$\frac{PA}{C} = PA^* = \frac{\sum_{i=1}^{N} PA_i^*}{N}, \quad (14)$$

If σ_E indicates the standard deviation of *E*, then:

$$\lim_{\sigma_E \to 0} \frac{PA}{c} = \frac{\sum_{i=1}^{N} PA_i^*}{N} = PA^*_{LCCA}, \quad (15)$$

where PA^*_{LCCA} is derived through Eqn (7) (where PA^*_{LCCA} stands for the ratio between PA in Eqn (7) and C). On the other hand, if σ_E results only from σ_{AV}, that is, all defects arise from the air void content, and variations in the air void content affect the expected life, it can be easily seen that:

$$\forall \sigma_{AV} > 0 \qquad PA^* < PA^*_{LCCA}, \quad (16)$$

and

$$PA^* = PA^*_{LCCA} + F(\sigma_{AV}), \quad (17)$$

where F stands for function. A generalized algorithm can then be proposed:

$$PA^* = PA^*_{LCCA} + F^*(\sigma_{AV}, \sigma_{TH}, ...), \quad (18)$$

where F* is a function and σ_{AV}, σ_{TH} are the standard deviations of the quality characteristics that can affect the expected life of the as-constructed pavement.

These fundamental Eqns (17) and (18) are intrinsically related to the nonlinearity of the E *vs.* AV relationship. Apart from the relationship between E and AV, the equations are consistent with: 1) the need for homogeneous production; 2) an increase in the life cycle cost to increase the number of work zones (agency costs, etc.). Furthermore, the hypothesized normal distribution suggests that if the μ_{AV} ranges from 4 to 8 and σ_{AV} ranges from 0 to 3 then:

$$PA^* = PA^*_{LCCA} - k\sigma_{AV}, \quad (19)$$

where *k* ranges from 2.3 to 4.7 and only accounts for an increase in the absolute value of the PA due to the peculiar assumptions under investigation (the normality of AV, the derivation of E through the M-EPDG).

1.3. First path

In the first path, a multi-layered pavement has been considered for analysis. For each layer (friction course), thickness, material type, traffic (Russo, Musolino 2012), and annual climate statistics must be specified, as shown in Table 2.

The M-E PDG provides a conceptual and operational framework in order to design road pavements. The M-E PDG is used to derive an expected life (EL) corresponding to failure criteria (i.e. longitudinal cracking) for a given AV.

The following failure criteria must be considered (NCHRP 2004):

– Longitudinal cracking (ft/mi), defined as pavement cracking predominantly parallel to the direction of traffic;
– Alligator cracking (%), defined as interconnected or interlaced cracks forming a pattern that resembles an alligator's hide. Also, map cracking;
– AC rutting (in), defined as asphalt concrete longitudinal depression or wearing away of the pavement in wheel paths under load;
– IRI, international roughness index (in/mi; baseline: 0.1mi, see Múčka, Granlund 2012), defined as a pavement roughness index computed from a longitudinal profile measurement using a quarter-car simulation at a speed of 50 mph (80 Km/h).

For a given AV, a minimum expected life (E) of the pavement is derived based on the minimum expected life for each criterion (*i* = 1,2…,5):

$$E = \min_{i = 1,2,.......,5} (E)_i . \quad (20)$$

Finally, the pay adjustment is derived using Eqn (7).

1.4. Second path

In the 2nd path, the first step (Fig. 1), the PDF describes the air void content, f(AV), for each average value of AV (Akkinepally, Attoh-Okine 2006; Burati, Weed 2006; Zaniewski, Hughes 2006; Wang *et al.* 2009; Katicha *et al.* 2011; Uddin *et al.* 2011). The PDF and cumulative distribution functions, PCF = f(AV) for each average may be used to estimate the defect percentage, PD = 100 – PWL, for a given specification limit (Burati *et al.* 2003).

Once PD (or PWL) is estimated, the following continuous payment schedule can be defined:

$$PA^* = 5 - 0.5 \cdot PD, \quad (21)$$

where PA* indicates PA/C (%). Note that Eqn (21) implies that:

$$PA^* = 5\text{-}0.5 \cdot PD = 5 - 05 \cdot (100 - PWL) = \\ 5 - 50 + 0.5 \cdot PWL = -45 + 0.5\,PWL. \quad (22)$$

Table 2. Layer parameters and boundary conditions used to implement the M-E PDG

Structural inputs						
Layers 1 and 2 – Asphalt concrete			Layer 3 – Granular base		Layer 4 – Subgrade	
Material type:	AC	AC	UM	A-1-a	UM	A-1-b
TH	1.2 in. (30.5 mm)	1.8 in. (45.7 mm)	TH	11.8 in. (300 mm)	TH	infinite
Asphalt Mix (AM)			Strength Properties		Strength Properties	
C%R (3/4)	0	0	PR	0.35	PR	0.35
C%R (3/8)	5	35	K_0	0.5	K_0	0.5
C%R (#4)	61	55	MOD	30000 psi (207 MPa)	MOD	26500 psi (183 MPa)
%P (#200)	10	6				
Asphalt Binder (AB)						
Pen	60–70	85–100				
General Properties (GP)						
TR	*70 °F (21 °C)*					
B%	11					
UW	148 pcf (23.2 kN/m^3)					
PR	0.35					
Traffic inputs						
Initial two-way AADTT: 1450; Number of lanes in the design direction: 2; Percentage of trucks in the design direction: 50%; Percentage of trucks in the design lane: 95%; Operational speed: 60 mph (96.5 km/h).						
Annual climate statistics						
mean annual air temperature: 62.12 *°F* (16.7 °C); mean annual rainfall: 14.17 in. (360 mm); freezing index: 0.17 ºF-days; average annual number of freeze/thaw cycles: 0.						
Performance criteria failure mechanism limit						
AC surface down cracking: 2000 ft/mi (380 m/km); AC bottom up cracking: 25%; AC permanent deformation: 0.25 in. (6.4 mm); total permanent deformation: 0.75 in (19 mm); terminal IRI: 172 in/mi (2.7 mm/m).						

Notes: 1 in. = 25.4 mm; °C = (°F-32)·5/9; 1 psi ≅ 0.0068 MPa; 1 pcf ≅ 0.157 kN/m^3; 3/4 in. ≅ 19 mm; 3/8 in. ≅ 9.5 mm; #4 → 4.75 mm; #200 → 0.075 mm.
Symbols: AC = asphalt concrete; UM = unbound material; TH = thickness; C%R(3/4) = cumulative % retained in the given ¾ sieve; %P (#200) = % passing #200 sieve; Pen = penetration grade (0.1 mm); TR = reference temperature; B% = effective binder content (volume, %); UW = total unit weight; PR = Poisson's ratio; K_0 = Coefficient of lateral pressure; MOD = modulus.

It follows that:

$$PF = 100 + PA^* = 100-45 + 0.5PWL = 55 + 0.5PWL, \quad (23)$$

where PF is the pay factor. This result yields the acceptance quality level (AQL), which is the minimum PWL for which PA = 0 is 90%.

1.5. Third path

In the third logical path, a PWL (percentage within limits) is derived for each AV (under the abovementioned probability distribution hypotheses). Additionally, for each PWL, a PD (defect percentage) is derived. In this case, the performance relationship $E(PD_i)$ can be described by a polynomial performance model (Burati *et al.* 2003), i.e. expected life as function of defect percentage:

$$E = 22.9 - 0.163 \cdot PD_{AV} - 0.135\,PD_{TH} + 0.000961 \cdot PD_{TH}, \quad (24)$$

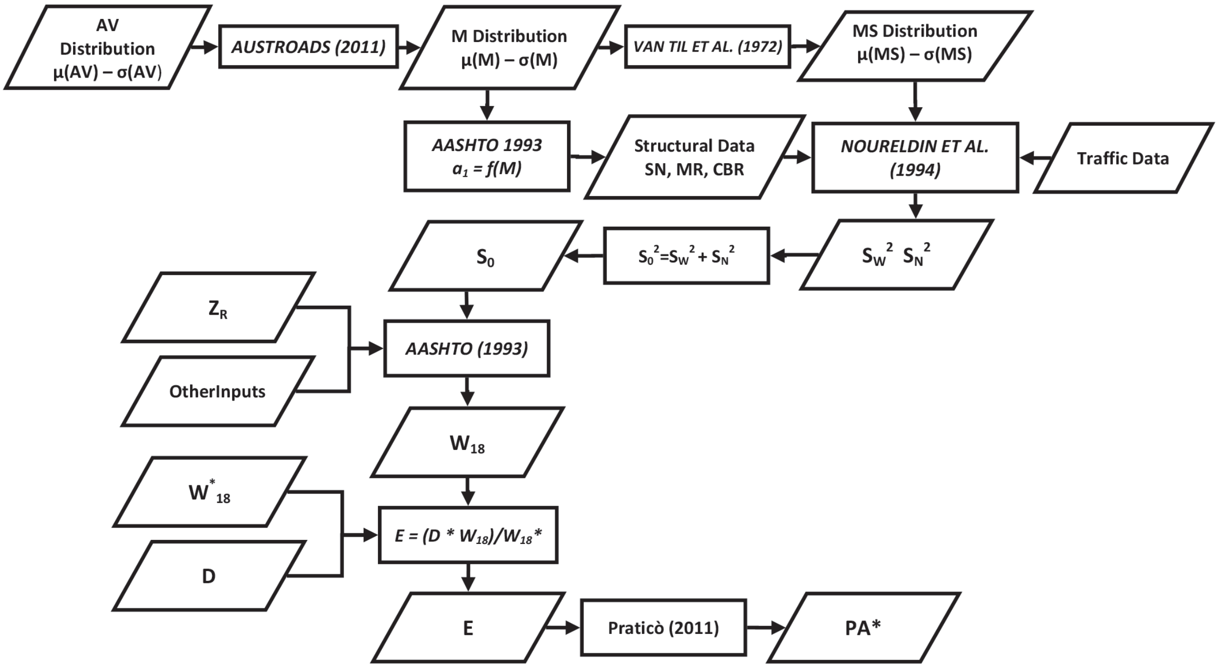
where PD_{AV} and PD_{TH} respectively stand for the air void and thickness defect percentage. It is noted that the thickness defect percentage is assumed to be 10%, as in (Burati *et al.* 2003). Equation (24) yields an expected life of E = 20 years for $PD_{AV} = PD_{TH} = 10$, and E = 5 years for $PD_{AV} = 75$ and $PD_{TH} = 90$. Finally, the pay adjustment is estimated.

1.6. Fourth path

In the fourth path (Fig. 2), based on AV distribution, the distribution of the layer modulus is derived (Austroads 2011). Based on mechanical properties and their statistics, it is possible to estimate the variance in pavement performance prediction (S_N^2) and the overall standard deviation (S_0) (Noureldin *et al.* 1994). For each AV distribution, an estimate of the expected life, is derived according to the AASHTO Guide 1993 and, finally, an estimate of the pay adjustment.

It is noted that AV variability generates modulus variability and this latter causes the variability of Marshall Stability, which is the input of Noureldin Model (Noureldin *et al.* 1994). The factor S_0 in the AASHTO 1993 Algorithm (AASHTO 1993) is consequently modified.

Under these assumptions the expected life (E) associated to each couple (μ(AV), σ(AV)) is derived and the pay adjustment is estimated by using Eqn (7).



Notes:
AV = Air Voids (%), M = Modulus (psi), MS = Marshall Stability (lb), a_1 = Structural Layer Coefficient,
SN = Structural Number, MR = Subgrade Resilient Modulus (psi) , CBR = California Bearing Ratio (%),
S^2_W = Variance in Traffic prediction, S^2_N = Variance in Pavement Performance prediction, S^2_0 = Overall Variance,
S_0 = Overall Std. Deviation, Z_R = Std. Normal Deviate,W_{18} = predicted number of 18.000 lb ESALs,
D = Design Life (Years), W^*_{18} = number of 18.000 lb ESALs corresponding to D, E = Expected Life (Years),
PA = Pay Adjustment/cost (%).*

Fig. 2. Fourth path used to derive PA – flowchart

1.7. Fifth path (new model)

In the 5th path, it was assumed that the probability density functions describing the main quality characteristics (AV, thickness, asphalt binder content, etc.) determine the PDF of the expected lives.

It is assumed that σ_{EL} results only from σ_{AV}, that is, that all defects arise from the air void content, and variations in the air void content affect the expected life.

So the values of pay adjustment derived through the 1st path (PA^*_{LCCA}) are corrected by Eqn (19) (in which $k = 2.3$) in order to account variability in air void content.

This path refers to the application of the model set out in Section 1.2.

2. Results

Tables 3 to 10 and Figure 3 summarize results.

1st path

Based on the conceptual framework described above, the air void content (AV_m, where AV_m stands for μ(AV)) is assumed to vary from 5% to 11%, as described in Table 3 (a value of 11–12% is usually referred to as acceptance limit, Seebaly and Bazi (2005)).

Table 3 also lists the expected lives E_i (months) obtained through the application of the MEPDG reported for each failure criterion for a given AV_m.

The expected life of the as-designed pavement, D, is assumed to correspond to AV = 5%, whereas E, the expected life of the as-constructed pavement, is derived from Table 3 as a function of the air void content.

Table 3. Minimum expected life for different failure criteria

	E_i (months)					E minimum (months)
AV (%)	Longitudinal	Alligator	Rutting AC	Total Rutting	IRI	Min. E
5	395	549	240	288	638	240
8	178	222	189	212	445	178
11	91	94	129	202	249	91

Table 4 summarizes the main inputs used and the pay adjustments obtained (see Eqns (1) and (7)).

Note that in this case, PA/C ranges from –53% (11 vs. 5%) to 0% (process completely under control in terms of the mean). Despite this appreciable difference, in both cases (AV = 5% and AV = 11%), half the population has values greater than the average of an unknown quantity, depending on the standard deviation. On the other hand, regardless of the distribution, for a given AV_m (for example 8%), high σ implies that a considerable part of the pavement is characterized by AV < AV_m, and a considerable part of the pavement has AV > AV_m. Higher values of σ would require rehabilitation across areas in which high and low values coexist. This conclusion reflects the fact that σ_{AV} contains essential information not included in AV_m.

Table 4. Pay adjustment (1st path)

AV (%)	INT	INF	R	D (Years)	E (Years)	PA^*_{OLD} (Eqn (1))	PA* (Eqn (7))
5	0.08	0.04	0.962963	20	20.00	**0.00%**	**0.00%**
8	0.08	0.04	0.962963	20	14.81	**–32.00%**	**–19.02%**
11	0.08	0.04	0.962963	20	7.56	**–89.23%**	**–53.04%**

Table 5. Pay adjustment (2nd path)

	PD (%)			PA (%)		
AV (%)	σ_{AV} = 0.5	σ_{AV} = 2.4	σ_{AV} = 3	σ_{AV} = 0.5	σ_{AV} = 2.4	σ_{AV} = 3
5	0	10	16	**5.00**	**0.00**	**–2.93**
8	50	50	50	**–20.00**	**–20.00**	**–20.00**
11	100	90	84	**–45.00**	**–40.00**	**–37.07**

2nd path

In the second path, a Gaussian probability density function is assumed for each average value (5, 8, 11%) and for three different values of standard deviation (σ = 0.5, 2.4, 3%). This range has been chosen based on a survey of literature data (Hughes 1996; Katicha *et al.* 2010).

Based on Eqns (21)–(22), PA is derived as in Table 5.

3rd path

In the third case, for each AV and σ_{AV}, a PWL is derived, again based on a Gaussian PDF. From PWLs, PDs, are derived (Table 6).

Table 6 summarizes the values of E corresponding to each AV and σ_{AV}. The values of E are used to estimate PA using the algorithms described above (Weed 2001; Praticò 2007, 2011). Table 7 summarizes the obtained results. Larger differences in the as-designed AV (5%) and the as-constructed AV (11%) produce higher PDs and, therefore, lower pay factors. Note that the empirical nature of the method can lead to criticism that illogical or inconsistent results may be obtained (for example, if nonconformities refer to other quality characteristics, or if the design life is not 20 years).

The standard deviation strongly affects the results of the second and third path due to the dependence of PWL (or PD) on σ (standard deviation) for a given quality characteristic. This interaction can also affect the potential assumption of violation normality. Based on these assertions, the following observations may be made:

- the LCCA-based method (1st path) is partly inconsistent because it does not depend on the dispersion (variability) of the quality characteristics;
- the PD-based methods (2nd and 3rd paths) are intrinsically empirical due to a lack of well-grounded links between PA and the expected life.

Table 6. Expected life (3rd Path)

	PD (%)			PD_{TH} (%)	E (years)		
AV (%)	σ_{AV} = 0.5	σ_{AV} = 2.4	σ_{AV} = 3		σ_{AV} = 0.5	σ_{AV} = 2.4	σ_{AV} = 3
5	0	10	16	10	21.55	20.02	19.12
8	50	50	50	10	13.88	13.88	13.88
11	100	90	84	10	6.21	7.74	8.64

Consequently, an excess of variability in the layer quality characteristics would not provide variable pay adjustment in the first class of methods because the averages of the main quality characteristics are unchanged. Similarly, pavement with a higher expected life can correspond to a lower pay factor in the second class of methods. In summary, both classes of methods lead to questionable conclusions.

4th path

For each AV distribution (1st and 2nd columns in Table 8) an estimate of the expected life is derived (penultimate column in Table 8) according to the AASHTO Guide (1993) and, finally, an estimate of the pay adjustment.

The above table shows how the factor S_0 and the expected life (E) of the pavement vary in function in a standard deviation of the air void content (AV). Higher sigmas yield lower expected lives and consequently higher values of the pay adjustment, especially when high values of the air void content are considered.

5th path

The results obtained for the fifth path (i.e. the proposed method) are reported in Table 9.

Eqn (1), Eqn (7) and Eqn (19) show the same trend but only Eqn (19) permits the synergetic consideration of location and dispersion indicators of expected life. Furthermore, being based on expected life and LCCA, they allow for consideration of innovative and/or premium pavements and surfaces (Chen *et al.* 2011; Hoyos *et al.* 2011; Romanoschi *et al.* 2004, Praticò *et al.* 2010).

2.1. Comparison

To compare the models, a wide range of AV values (4~11) was considered. The standard deviation has been varied over the range 0.5–3.

Figure 3 illustrates the dependence of PA* (pay adjustment/cost) on AV_m for the five selected algorithms.

Finally, Table 10 summarizes the dependence of PA* on method and data (mean and standard deviation, k = 2.3).

The first path (and its related fifth path, the proposed model) fit the remaining models for AV lower than approximately 6%. In contrast, the 1st and 3rd paths yielded similar behaviour for AV values higher than

Table 7. Pay adjustment (3rd Path)

AV (%)	D (Years)	E (Years) σ_{AV}			O (Years)	PA^*_{OLD} (%) (Eqn (1)) σ_{AV}			PA* (%) (Eqn (7)) σ_{AV}		
		0.5	**2.4**	**3**		**0.5**	**2.4**	**3**	**0.5**	**2.4**	**3**
5	20	21.55	20.02	19.12	10	**8.50**	**0.09**	**–5.07**	**5.04**	**0.05**	**–3.01**
8	20	13.88	13.88	13.88	10	**–38.85**	**–38.85**	**–38.85**	**–23.05**	**–23.05**	**–23.05**
11	20	6.21	7.74	8.64	10	**–102.9**	**–87.94**	**–80.01**	**–60.57**	**–52.17**	**–47.47**

Table 8. Pay adjustment (4th Path)

AV (%)	σ_{AV}	S_W^2	S_N^2	S_0^2	S_0	Z_R (95%)	$S_0 * Z_R$	W_{18}	W_{18}^*	E (years)	PA^*_{old} (%) (Eqn (1))	PA* (%) (Eqn (7))
5	**0.71**	0.03	0.0721	0.1021	0.3196	–1.645	–0.526	433,624	418,123	20.74	**4.13**	**2.45**
	1.15		0.0784	0.1084	0.3292		–0.542	418,123		20.00	**0.00**	**0.00**
	2.00		0.0975	0.1275	0.3571		–0.587	376,236		18.00	**–11.75**	**–6.97**
	3.00		0.1318	0.1618	0.4023		–0.662	317,016		15.16	**–29.96**	**–17.77**
8	**0.71**	0.03	0.0699	0.0999	0.3161	–1.645	–0.520	312,676	418,123	14.96	**–31.37**	**–18.61**
	1.15		0.0736	0.1036	0.3219		–0.530	305,819		14.63	**–33.63**	**–19.95**
	2.00		0.0852	0.1152	0.3394		–0.558	286,181		13.69	**–40.24**	**–23.87**
	3.00		0.1073	0.1373	0.3706		–0.610	254,370		12.17	**–51.46**	**–30.52**
11	**0.71**	0.03	0.0701	0.1001	0.3164	–1.645	–0.520	181,827	418,123	8.70	**–79.58**	**–47.21**
	1.15		0.0741	0.1041	0.3227		–0.531	177,504		8.49	**–81.38**	**–48.27**
	2.00		0.0877	0.1177	0.3431		–0.564	164,296		7.86	**–86.95**	**–51.58**
	3.00		0.2253	0.2553	0.5053		–0.831	88,886		4.25	**–121.44**	**–72.03**

Symbols: see Figure 2

Table 9. Pay adjustment (5th Path)

AV (%)	PA^*_{old} (%) (Eqn (1))	PA^*_{LCCA} (%) (Eqn (7))	k	PA* (%) New Model (Eqn (19)) ($PA^* = PA^*_{LCCA} - k \cdot \sigma_{AV}$) $\sigma_{AV} = 0.5$	$\sigma_{AV} = 3$
5	0.00%	0.00%	2.3	**–1.15**	**–6.90**
8	–32.00%	–19.02%		**–20.17**	**–25.92**
11	–89.23%	–53.04%		**–54.19**	**–59.94**

Note: Eqn (19) contains Eqn (7)

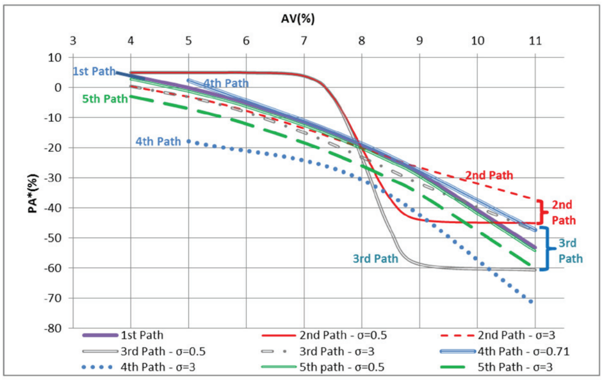


Fig. 3. PA* as a function of AV (1st to 5th path)

Table 10. PA*, synthesis

Path	AV (%)	σ(AV)	E (years)	PA^*_{old} (Eqn (1))	PA* (Eqn (7))
1st	4~11	–	7.5~21	–89~6.8	–53~4
2nd [PA= f(PWL)]	4~11	0.5–3	–	–45~5	–
3rd	4~11	0.5–3	6~21.5	–102~8.5	–60~5
4th	5–8–11	0.7–3	4~20.7	–121~4	–72~2.5
5th (New Model, Eqn (19))	4~11	0.5–3	–	–96~5.7	–60~3

approximately 8%. By referring to values that might be expected in practice, it is noted that the convergence of the different models for medium-to-high AV (~7–9%) and medium-to-high σ (~1–2), where there is evidence of recurring issues for road agencies (Vazquez *et al.* 2009).

Main findings

Pavement design, construction, quality assurance and control often follow different conceptual frameworks. This paper presents the formalization and validation of a model to determine a pay adjustment on the basis of mechanical and functional performance of transportation infrastructures. A model to determine a pay adjustment based on the expected life of the pavement and the variability of its main properties was formulated.

The dependence of pay adjustment on the acceptance procedures and pavement quality was analyzed. Under the hypotheses described above, the LCCA-based 3rd approach and the purely empirical 2nd approach yield similar results for small values of AV and small σ. In contrast, they diverge for high values of AV and high σ. The LCCA-based 1st approach correlates well with the LCCA-based 3rd approach only for high AV and low σ. These results agree with those derived from the 2nd path but for only low AV and low σ.

The weak points of the LCCA-based and PD-based models are analysed and discussed, and a new model is proposed. The new model features the advantages of the LCCA-based model without neglecting the relevance of process variability (in terms of standard deviation).

In the model set out, compensatory characteristics and variability issues are synergistically addressed under the framework of life cycle cost analysis.

Although more research is needed, analyses prove that the new model is able to provide a solution which is well grounded in logic, even in cases where characteristics such as air void content, thickness, drainability or friction are defective and a premature failure is expected. In the new algorithm, the penalty-to-cost ratio doesn't assume values lower than –1, which agrees with common logic.

The model developed here may be applied toward a variety of applications and may link design processes with construction performance and solutions. The use of algorithms for predicting the expected life of a pavement may be easily implemented as part of the model proposed here.

The main application of this model is in the field of quality assurance for porous asphalt concretes and sustainable infrastructures, the price of which can be consistently higher than that, such traditional dense-graded friction courses. Future developments of the model may well emerge in the field of life expectancy estimates for functional performance.

Acknowledgment

The authors would like to acknowledge Dr Richard Weed for the insightful suggestions.

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