A Rational Approach for the Evaluation of Pavement Pay Factors

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Synopsis

Most of Italian road superstructures are of semi-rigid and flexible type. Despite their widespread use, hot mix asphalt construction specifications and quality control / quality assurance testing plans, when employed, are still based on an empirical approach. Bituminous mixes not complying with specification are rejected or accepted with a price reduction (penalty) that is not based on the real performance and therefore it does not allow a rigorous life cycle cost analysis. In this paper a new methodology for the evaluation of pavement pay factor evaluation is presented. The methodology is based on a performance related approach. The core of the methodology is represented by a mechanistic empirical pavement design procedure that is employed in order to estimate pavement performance both in the "as design" and in "as built" condition. The pavement design procedure allows to evaluate pavement fatigue life and maximum rut depth as a function of bituminous mix properties, pavement layout, on site prevailing traffic and climatic conditions.

Because of variability of bituminous mix properties due to, on one hand, the acceptance ranges reported in hot mix asphalt specifications and, on the other hand, in-situ mix production and laying operating conditions, a constrained Monte Carlo simulation, by means of an *Latin Hypercube* Algorithm, has been carried out in order to evaluate pavement performance.

Following this stage, a criterion based on a *Life Cycle Cost Analysis* (*LCCA*) concept has been employed in order to evaluate the *Payment Adjustment Factor* (*PF*) to be applied to the Contractor as a function of the pavement performance in the as-built scenario as compared with that pertaining the as-design scenario.

Basing on a typical pavement specification framework adopted in Italy, a case study has been examined and a regression model has been developed on data generated in the Monte Carlo simulation, in order to derive a Pay Factor prediction expression as a function of the *normal deviates* of relevant asphalt concrete properties affecting pavement performance.

Preliminary results seem to indicate that this approach may be useful both in the design stage, in order to take into account the pavement performance reliability, and in the construction stage, as a reference for the contractor to allow the production and the laying of high quality bituminous mixtures.

A Rational Approach for the Evaluation of Pavement Pay Factors

Hot-mix asphalt (HMA) is extensively used throughout Italy and the world as a reliable and cost-effective pavement surfacing for roads, parking lots, and airfields, however its performance can be greatly affected by many materials and construction (M&C) factors, as well as traffic and environmental variables.
In the past, design and construction procedures of HMA, tended to be more empirical and heuristic than scientific, in that they relied primarily upon the experience and engineering judgment of the mix designers and road agencies. During the last two decades, important advances in HMA technology have occurred in the areas of materials (particularly binders) and mix design (e.g. studies on mix design in the Strategic Highway Research Program - SHRP), whereas less attention was devoted to construction quality specifications (CS). At the same time It is generally acknowledged that quality of the construction process is a major factor in determining how well a pavement will perform under traffic loading and when subjected to environmental influences. To improve the construction process, quality control/quality assurance (QC/QA) procedures and pay incentives, taking pavement performance into consideration, have to be instituted. Contractor pay incentives serve at least two objectives: they encourage the contractor to construct pavements with significantly improved performance in comparison to those meeting minimum specification requirements; and they provide a rational alternative for dealing with marginally inadequate/adequate construction.
We can distinguish between four different levels of construction quality control procedures/specification, that take pavement performance into consideration [CHAMBERLAIN, 1995]:

- Acceptance Quality Characteristics (AQCs);
- Direct Measures of Performance (DMP);
- Performance Based Specification (PBS);
- Performance Related Specification (PRS).

In AQCs procedure, that is largely applied, the materials and construction factors, used to control quality (e.g. binder content or relative compaction), is primarily tied to performance through intuition, engineering judgment, or both: These conventional QA acceptance procedures use engineering judgment also to establish individual AQC pay adjustments (and weighting factors for each) for determining the overall price adjustment for the lot.
On the other side, are DMP in which specifications describe how the finished product should perform over time (e.g. IRI < 3 after 20 years, area cracked < 10 % after 20 years , rut depth < 10 mm after 15 years). These type of specification have not been used in Italy so far, because quality and pay factor could be established after a great time to construction; therefore they could take the form of warranty or guarantee in which contractor agrees to build and maintain the pavement for a specified period of time, rather than construction specification.
In the performance-based specification (PBS) quality characteristics are directly tied to performance through empirical, or mechanistic, prediction model that accounts for the effect of deviations of the as-constructed QC level from the as-designed QC level. The difference in predicted performance between the as-designed and as-constructed pavement is then used as a basis for a contractor pay adjustment (PA).
Performance related specification (PRS), as PBS, require prediction model to evaluate the effect of deviations of quality characteristics level from its target, but the quality characteristics are less directly tied to performance. As matter of fact in PRS the effect of an overall specification, containing multiple quality characteristics, is evaluated, and the prediction models are used to develop a secondary prediction relationship, that establish the link between multiple quality characteristics (vector of QCs) and performance. PRS have two major advantages over conventional and PB specifications: they are able to identify desirable levels of AQC that provide a desired pavement performance and they provide a rational basis on which pay adjustments can be determined (basing on Life Cycle Cost Analysis).
The objective of this paper is to demonstrate a rational and feasible method for define PSR and quantitatively establishing penalties/bonuses for asphalt concrete construction with the initial emphasis placed on new asphalt concrete pavement construction. The approach taken herein for the development of pay factors take into consideration HMA quality control adopted in Italy so far, in an attempt to bridge the gap between currently used specifications and fully implementable PRS. Furthermore attention is focuses primarily on the economic impacts to the highway agency while user costs are not included.

DESCRIPTION OF THE PROCEDURE FOR THE EVALUATION OF PAY FACTOR

The *Pay Factor* (*PF*) can be defined as a reduction or amplification coefficient that has to be applied to the pavement lot bid price in order to correctly remunerate the pavement's contractor according to the quality of

the pavement constructed. The PF approach is undoubtedly an evolution in the pavement specifications as it guaranties both agency and contractor in the roadwork process. Pavements not perfectly fulfilling end-results specifications can be still accepted by means of a sensible decrease of lot bid price whereas pavements performing better than required can be awarded with a larger price.
The key aspect related to this approach is the evaluation of the quality level of pavement. According to this problem two main criteria can be employed:

- statistics based pay factors,
- performance related/based pay factors.

According to the former approach, usually adopted within a *Quality Control/Quality Assurance* (*QA/QC*) framework [USACE, 2000], for a defined asphalt mix property, statistical parameters are used in order to evaluate the pay factor. A typical example is represented by the procedure proposed by Afferton et al. reported in [ELMORE et al, 1998] according to which is possible to defined a *Quality Index* (*QI*) through the following expression:

$$QI = (X-L)/S \qquad (1)$$

Where X is the sample mean, S is the sample standard deviation and L is the specification limit. The payment is determined base on magnitude of *QI*. This approach is effective for a one-sided case (i.e. single limit specifications, such as for the thickness of pavement) whereas for a double sided specification a more general approach should be used. Other examples of statistics based pay factors are those employing the *Percent Defective* (*PD*) or the *Mean Absolute Deviation* (*MAD*) concepts. In the first case, an equation that can be effectively used when high percentage (> 80 %) of non-defective materials are expected, is:

$$PF = 1.02 - 0.002 \cdot PD \qquad (2)$$

However, it can be observed that statistics based criteria for the evaluation of payment factor are not explicitly related to pavement performance, unless a huge amount of data on past performance, from which *Operating Characteristics Curves* can be derived, are available. In addition, it has to be highlighted that the influence of multiple asphalt mix properties on the definition of payment can not be easily taken into account.
As far as the performance related/based criterion is concerned, a prerequisite of the method is the ability to predict the pavement performance as a function of material properties characterising the road superstructure in the as-designed and in the as-build scenario. Following this assumptions, several approaches can be identified:

- Distress indicators related pay factors
- *Life Cycle Cost Analysis* (*LCCA*) related pay factors.

According to the former approach, the pay factor is evaluated by comparing the individual predicted distress indicator, e.g. percent cracked area or rut depth, of the as-build pavement with that of the as-designed pavement as [LIN et al., 2001]:

$$\text{PF} = \text{Distress Index}_{\text{as-designed}} / \text{Distress Index}_{\text{as-build}} \qquad (3)$$

When the evolution of several distress indicator can be evaluated at the same time, a generalized Pay Factor can be assessed through the following expression:

$$PF = w_1PF_1+w_2PF_2+\ldots\ldots w_nPF_n \qquad (4)$$

where PF is the overall payment adjustment factor for the contractor, w_i is the weight of the i-th distress indicator and PF_i is the payment factor based on the i-th distress indicator. Major flaws associated to this method are related to the subjective assignment of the weight for each distress indicator and to the mutual interaction between the distress indicators themselves that may yield an overestimation or an underestimation of the overall pay factor. Therefore in [LIN et al., 2001] an interesting approach making use of *Principal Component Analysis* (PCA) in order to discriminate between independent distress indicator is proposed.
However, it has to be underlined that the distress indicator approach previously described, quantifies a pavement adjustment factor that is exclusively linked to a worse or a better pavement performance but not related to the additional positive (or negative) costs borne by the Agency as a consequence of a worse (or better) performing pavement within a specific analysis period.
Therefore several authors have proposed to assess the pay factor by means of a LCCA methodology. The core of this methodology is represented by the prediction of life-cycle cost of the as-designed and as-

constructed pavement. The difference between these two costs represents the lot bid price reduction or increase to be applied to the contractor as a consequence of quality level of the pavement constructed.
The major benefit of this approach is that it provides a rational, defensible process through which an adjustment can be made to a contractor's payment based on the effect that construction quality have on the estimated life and cost of maintain the pavement in the future.
In this paper a LCCA based pay factor assessment method is proposed. Details on this methodology are reported in the followings.

Life Cycle Cost Analysis

The framework for the evaluation of the life-cycle cost comprises five main components (see **Figure 1**) :

- Initialisation;
- Prediction of pavement performance;
- Determination of maintenance treatment;
- Estimation of future cost
- Computation of the life-cycle cost.

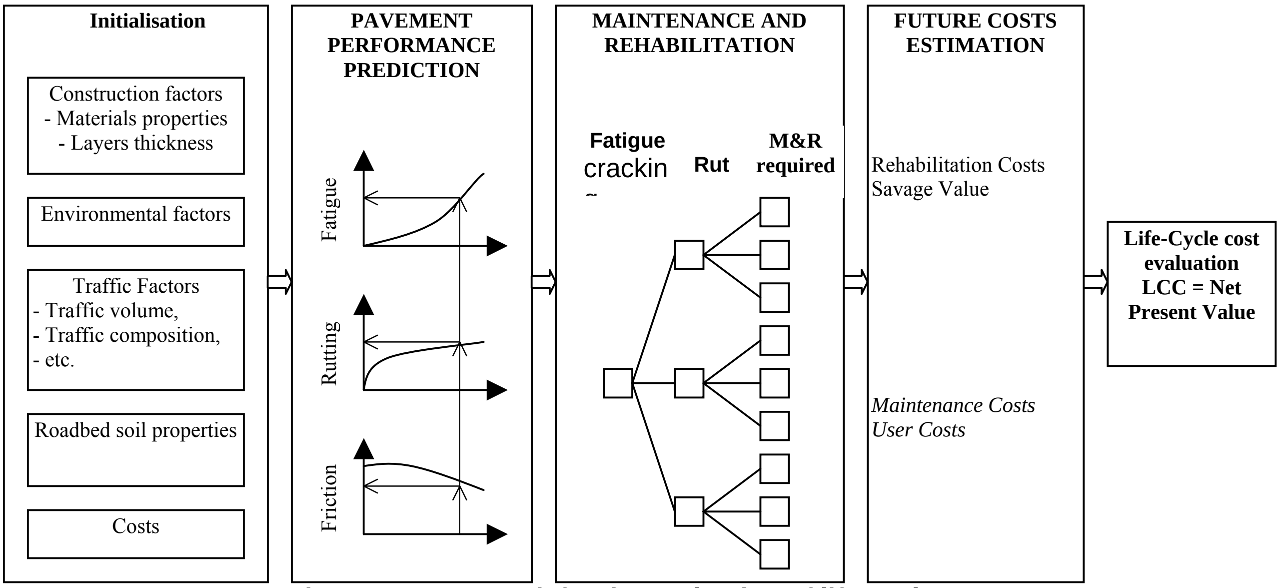

Figure 1: Framework for the evaluation of life-cycle cost

In the initialisation stage all factors that influence pavement performance during the analysis period are inputs into the model. Some inputs are related to construction quality, such as: layers thickness, asphalt mixture properties (i.e. asphalt content, air void and aggregate gradation). Others inputs are related to the project: Resurfacing, Rehabilitation and Reconstruction (RRR) policies, environmental factors, traffic, roadbed soil characteristics and maintenance intervention costs.
The input parameters, related to construction quality, are chosen according to pavement specifications actually adopted by Italian Highway Agencies.
Following the evolution of the pavement distress indicators, provided by the pavement performance prediction model, a specific RRR policy is selected according to a maintenance treatment decision tree. It is therefore possible to evaluate the most likely sequence of the maintenance interventions the pavement will undergo, within a defined analysis period, both in the as-design and as-constructed scenarios.
The life cycle cost associated to each of the two scenarios can be calculated as the sum of the overall cost related to the specific RRR policy (conveniently discounted) and the residual value of the pavement following that RRR policy. Price reduction to be applied to the Contractor can be evaluated as a difference between the Life cycle cost evaluated in the as-constructed and that assessed in the as-designed scenario.

Pavement performance prediction

The prediction of pavement performance, as determined by the occurrence of fatigue cracking and rutting, is a key element in the evaluation of LCC. In order to adequately take into account for the joint effects of construction quality and project factors (i.e. traffic and climate), in the framework developed, empirical-mechanistic deterioration models, based on the primary response of the pavement structure, has been used for evaluating the occurrence of the above mentioned distresses. Furthermore deterioration model that take into account asphalt material characteristics are sorted out.
In these section the process used to evaluate degradation progress is briefly illustrated (see figure 2).

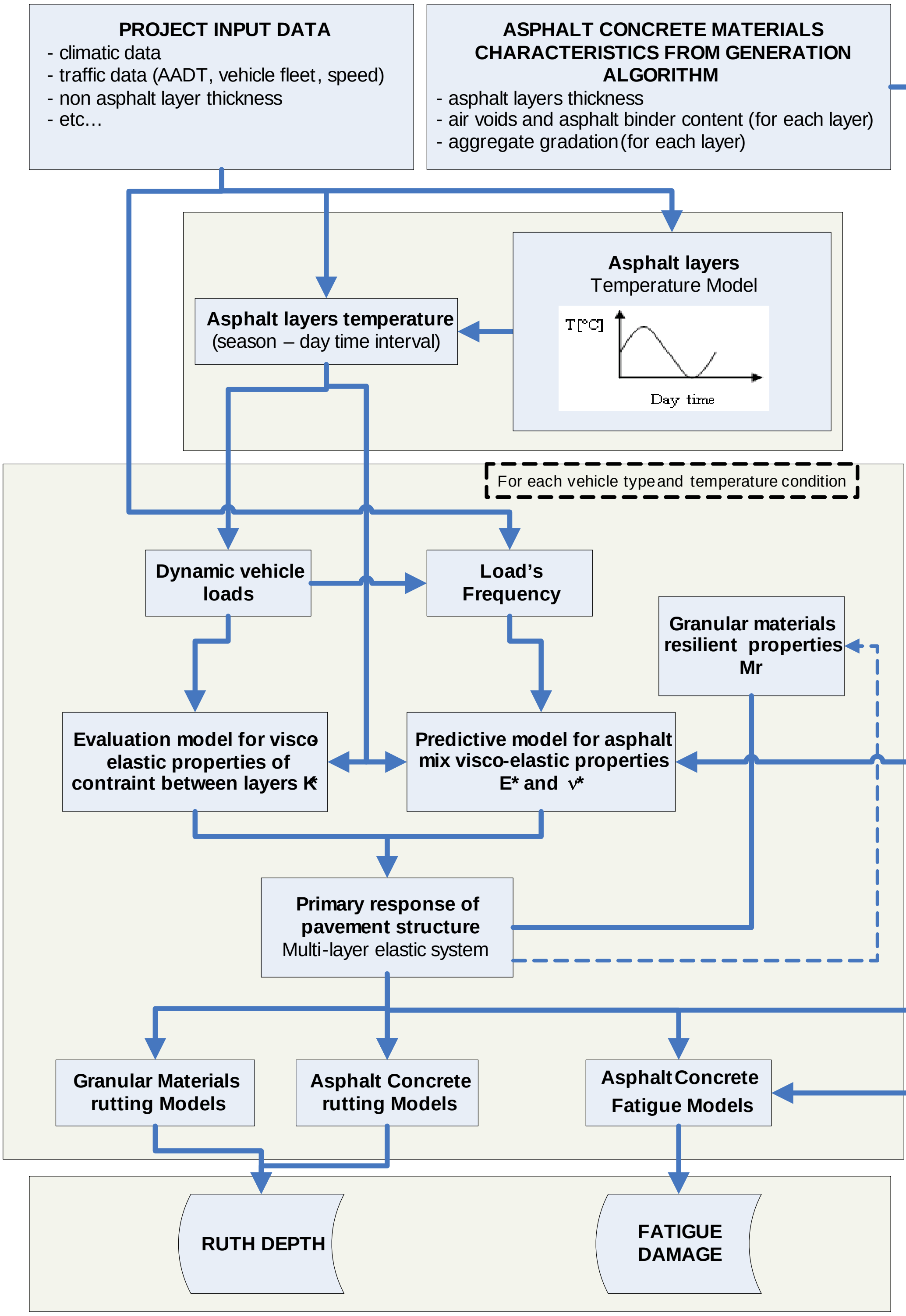

Figure 2: Framework for the evaluation of pavement performance

Climatic Factors. Climate greatly affects the performance of flexible pavement in several way; in the framework developed only temperature and ageing of the asphalt layers are considered. The temperatures in the asphalt layers of the pavement are evaluated, during the standard day of each season, or month, by the following model [BARBER, 1957]:

$$T_{pav}(z,t) = T_m + R + (A_g/2 + 3 \times R) \times F \times \exp(-C \times z) \times \sin[0.262 \times t - C \times z - \mathrm{arctg}(C/(H+C))] \qquad (5)$$

where:

$T_{pav}(z,t)$ is 24 hour periodic temperature of the road pavement in [°C] at time t (from 1 to 24) and at depth z [m],

Tm , Ag , I and v are defined in Table 1,

$R = 2/3 \times (b \times I) / (24 \times h_c)$ [°C],

$H = h_c/K$ [1/m],

h_c=4.882× (1.3+0.4332×$v^{3/4}$) [kcal/hour m^2 °C],
C=[(0.131×s×w) / K]$^{1/2}$ [hour$^{0.5}$/m],
F=H / [(H+C)^2 + C^2]$^{1/2}$,
b is the absorptivity of surface to solar radiation (e.g. 0.6 ÷ 0.95),
K is the conductivity [kcal/m hour °C] (e.g. 1.04 ÷ 1.96),
s is the specific heat [kcal/kg °C] (e.g. 0.193 ÷ 0.22),
w is the density [kg/ m^2].

Therefore climate conditions are characterized through the follows data: average air temperature, "T_m", average daily variation in the air temperature "A_g ", average daily radiation "I", average wind speed, v (see **Table 6**).

Traffic loads. The performance of the pavement is affected by heavy vehicle traffic and especially by cumulative traffic, vehicle type, weight and speed. The annual average daily traffic (AADT), and the heavy vehicle traffic spectrum are considered as input data in the framework developed. Fifteen types of heavy vehicles is used to describe traffic flow, as suggested by Italian Catalogue of pavement structures [C.N.R. 1995] (see **Table 5**). The DLC (Dynamic Load Coefficient) is used for evaluating the dynamic effect, which is evaluated by a simple linear "quarter car" vehicle model, considering a surface profile generated as described in [D'APUZZO et al. 2004].
Load frequency in asphalt layer was evaluated as suggested by PELLINEN et al. (2004) but a correction was introduced to take into account the footprint area [ULLIDTZ, 1979]:

$$f = \frac{1}{2 \cdot \pi \cdot 10^{0.5\cdot(2\cdot a+h)} \cdot \frac{0.18928}{v^{0.94}}} \qquad (6)$$

where
f is the frequency of loading [Hz],
h is the depth from surface [m],
a is the radius of the contact area between the tire and the road surface [m],
v is the vehicle speed [m/sec].

Asphalt concrete visco-elastic properties. The visco-elastic properties of undamaged bituminous layers are calculated by Asphalt Institute Method [WITCZAK et al., 1996, DRAGOS et al., 1999]:

$$|E^*| = 689.5 \cdot 10^a \qquad (7)$$

where:
$\left|E^*\right|$ is the asphalt mix complex modulus [MPa],

$$a = -1.249937 + 0.029232 \cdot p_{200} - 0.001767 \cdot (p_{200})^2 - 0.002841 \cdot p_4 - 0.058097 \cdot V_a + -0.802208 \cdot \frac{V_b}{(V_b + V_a)} +$$
$$+ \frac{3.871977 - 0.0021 \cdot p_4 + 0.003958 \cdot p_{3/8} - 0.000017 \cdot (p_{3/8})^2 + 0.00547 \cdot p_{3/4}}{1 + e^{\left(-0.603313 - 0.313351 \cdot Log(f) - 0.393532 \cdot Log\left(\frac{\eta}{10^6}\right)\right)}}$$

η is the bitumen viscosity [Poise],
f is the load frequency [Hz],
V_a is the air voids in the mix by volume [%],
V_{beff} is the percent effective bitumen content by volume [%],
$p_{3/4}$ is the percent retained on ¾ in. sieve (19 mm) by total aggregate weight (cumulative) [%],
$p_{3/8}$ is the percent retained on 3/8 in. sieve (9.5 mm) by total aggregate weight (cumulative) [%],
p_4 is the percent retained on No.4 sieve (4.75 mm) by total aggregate weight (cumulative) [%],
p_{200} is the percent passing No.200 sieve (0.075 mm) by total aggregate weight [%],
The effect of temperature and aging on bituminous binder viscosity are considered through the relation:

$$\log \log(\eta) = A + VTS \cdot \log(1.8 \cdot T + 491.68) \qquad (1)$$

where η is the binder viscosity [centipoises], T is the temperature of the layers [°C], and A and VTS are parameters function of bitumen type and aging.
The Poisson coefficient is calculated by the following relationship [NCHRP 1-37A, 2004]:

$$\nu = 0.15 + \left(\frac{0.35}{1 + e^{-7.500 + 2.291 \cdot \log(|E^*|)}} \right) \quad (8)$$

Asphalt concrete fatigue behaviour. The fatigue transfer function suggested by Marchionna (1989) and used in the Italian Catalogue of road pavement is implemented in the framework developed:

$$N_f = 10^{\left(6 + 4.7619 * \left(Log\left(\frac{\Gamma * V_b}{V_b + V_v} \right) - Log\varepsilon_x \right) \right)} + 1.373 * e^{-1.098n} * h^{(-0.157 + 0.476n)} * \left[\left(\frac{E}{10} \right)^{\alpha'} * \left(\frac{\sigma}{10} \right)^{\beta'} * 10^{\mu'} \right] \quad (9)$$

where

N_f predicted fatigue life (10% fatigue cracking in the wheel path),
ε_x initial tensile strain at the bottom of asphalt layers,
σ_x initial tensile stress at the bottom of asphalt layers [MPa];
V_b volume of binder [%],
V_v air void content [%],
Γ binder correction factor (e.g. $1.25*10^{-4}$)
E mean mix stiffness dynamic (complex) modulus [MPa],
h asphalt layers thickness [cm];
n asphalt mix correction factors (e.g. 5),
α' $=\alpha(n/5)$
β' $=\beta(n/5)$
μ' $=(n/5)+0.84(1-n/5)$
α , β and μ experimentally determined coefficient.

Asphalt concrete non-resilient behaviour (permanent deformation). Some model have been proposed until now in order to evaluate permanent deformation in bituminous concrete layers, in this work the model suggested by Verstraeten is used [VERSTRAETEN et. al. 1977 and 1982], as it allows to take into account the volumetric characteristics of the mixes:

$$\varepsilon_{pAC}(N) = A \cdot \frac{(\sigma_1 - \sigma_3)}{|E^*|} \cdot \left(\frac{N}{1000 \cdot f} \right)^{b_{AC}} \quad (10)$$

where:

ε_{pAC} is permanent strain in the bituminous layer,
b_{ac} are constants (e.g. $b_{ac} = 0.25$ for standard bituminous concrete),

$$A = H \cdot (\sigma_1 - \sigma_3) / |E^*|$$

$$H = \frac{100}{0.65 * 5.5 * \left(1 - 1.02 \cdot \frac{V_b}{V_b + V_v} \right)}$$

f is the frequency of the loads,
|E*| is the complex modulus of the bituminous concrete of the layers,
σ_1 and σ_3 are the vertical and radial stress.

Unbound granular materials and soil resilient modulus. The isotropic resilient behaviour of unbound granular materials was defined by the resilient modulus "Mr" and Poisson's ratio. The model suggested by Uzan is used to evaluate the resilient modulus "Mr" [COST 337 (2000), COURAGE (1999), AMBER et al. (2002)].

$$Mr = k_1 \cdot P_a \cdot \left(\frac{\theta}{P_a} \right)^{k_2} \cdot \left(\frac{\tau}{P_a} + 1 \right)^{k_3} \quad (11)$$

where

Mr is the resilient modulus [MPa]
σ_1 is the major principal stress [kPa],
$\sigma_2 = \sigma_3$ is minor principal stress or confining pressure [kPa]

$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}$ is the octahedral shear stress,

Pa is the atmospheric pressure (100 kPa)

k_1, k_2 and k_3 are regression material constants (see [AMBER et al. 2002]).

The Poisson ratio of granular materials are taken as a constant in pavement analysis.

Unbound granular materials and soil permanent deformation. Paute model (see equation 12) is used in this work to describe permanent strain in unbound granular materials (i.e. sub-base and sub-grade layers) [COST 2000, LEKARP and DAWSON, 1998, GIDEL et. al., 2001]:

$$\varepsilon_p(N) = A \cdot \left(1 - \left(\frac{N}{100}\right)^{-B}\right) + \varepsilon_p(100) \qquad (12)$$

where

A is function of stress level, e.g. from Gidel et. al. (2001)

$l_{max} = \sqrt{p_{max}^2 + q_{max}^2}$, $p=(\sigma_1+2\sigma_3)/3$ and $q=\sigma_1-\sigma_3$

σ_1 is the max stress (vertical) in granular layer,

σ_3 is the confining stress (horizontal) in granular layer,

B, ε_{p0}, m, n and s are material constants.

Pavement response model. Data from climatic conditions, dynamic loads, material properties are implemented in a pavement primary response model for the evaluation of the stress and strain level. A layered linear elastic system has been assumed as pavement model, taking into account the interaction between the layers. The modulus "K" of the elastic constrain between layers was function of temperature and interface normal stress, according to Uzan et al. (1978) and Crispino et al. (1997).

Determination of Maintenance Treatment

Although preventive and corrective maintenance is needed in a comprehensive pavement management program, in order to compare overall cost between as designed ad as constructed pavement the emphasis should be placed on corrective maintenance. Furthermore as the effects of material properties on friction and texture deterioration are difficult to be considered, rehabilitation due to loss of adherence are considered equal in the as designed and as constructed scenarios. Therefore only rutting and cracking deteriorations are chosen for selecting rehabilitation strategy; the decision tree implemented is illustred in **Figure 3**.

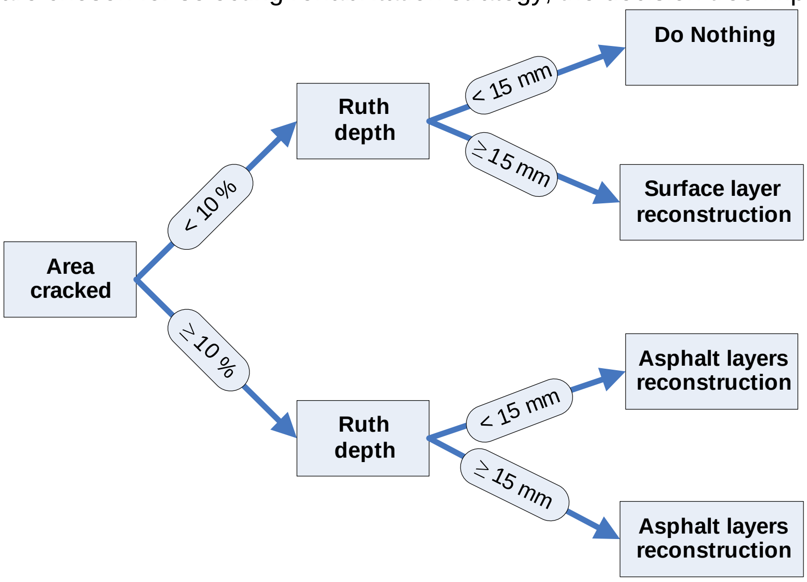

Figure 3: Maintenance treatment decision tree

Estimation of Future Cost and Computation of the Life-Cycle cost.

On a general point of view, once that the RRR policy has been identified in the as-constructed and as-designed scenario, the *Life Cycle Cost* (*LCC*) within a specific analysis period can be evaluated through the following expression:

$$LCC_{des} = C_p + \left(\sum_{ij} \frac{C_j}{(1+r)^i} \right)_{des} + \frac{R_{des}}{(1+r)^n} \quad (13)$$

$$LCC_{cons} = C_p + \left(\sum_{ij} \frac{C_j}{(1+r)^i} \right)_{cons} + \frac{R_{cons}}{(1+r)^n} \quad (14)$$

where C_p is the overall cost of the pavement superstructure sustained at the beginning of the analysis period on which the pay adjustment has to be applied, C_j is the maintenance intervention of type *j* that will be carried out at the *i*-th year of the analysis period, *R* represent the residual value of the whole road superstructure at the end of the analysis period assumed in *n* years, *r* is annual discount rate and the subscripts *des* and *cons* refer to the as-designed and as-constructed scenarios respectively.
Following these assumption the PF can be evaluated as:

$$PF = \frac{C_p - (LCC_{cons} - LCC_{des})}{C_p} = 1 - \frac{(LCC_{cons} - LCC_{des})}{C_p} \quad (15)$$

On an operating point of view, the annual discount rate, *r*, should be the average value of the analysis period. It is also suggested that the analysis period should be, almost, equal to twice the service life of the pavement in the as-design scenario.

PAY FACTOR PREDICTION RELATIONSHIP

It is important to evaluate the effect that deviation from the target quality construction specifications will have on payment or pay-adjustment. The approach used in this paper is based on the development of approximate pay-adjustment relationship that coveys to the contractor and administration the effect that deviation from target values will have on payment. The process used for generating the preliminary PAF relationship is illustrated in **Figure** 4; it takes into account the framework of the specification actually in force in Italy. It is important to emphasize that the relationship that results from this process is project-specific, that is, it is applicable only to the construction project under consideration (in term of pavement structure, traffic, clime conditions etc.).

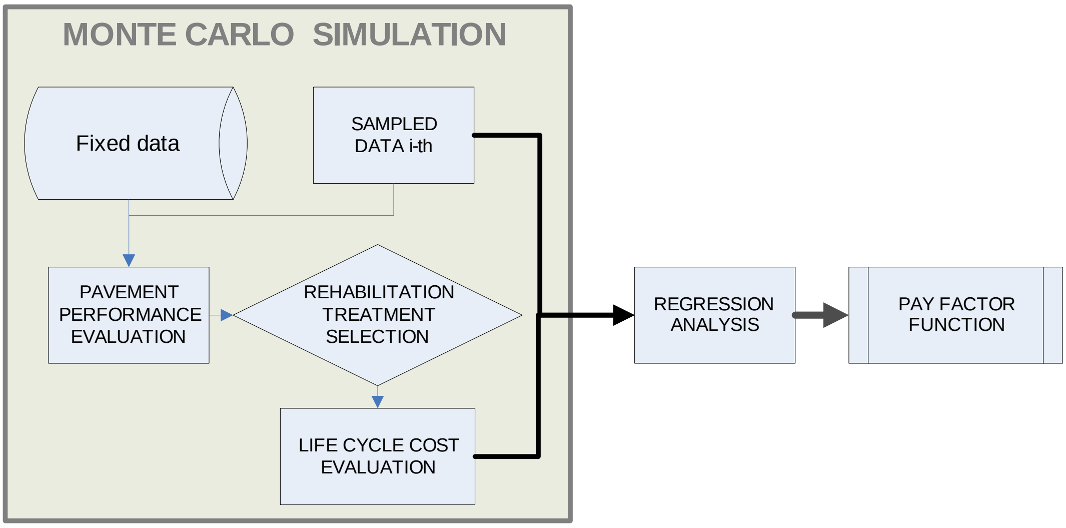

Figure 4: Process used to built the Pay-Factor Function.

Implementation of pavement specifications into the procedure

A key step in the procedure is represented by the implementation of an end-results pavement specifications for the simulation of pavement performance variability in the as-design scenario. Conventional pavement end-result specifications report threshold limits for volumetric properties and grading properties of bituminous mixtures employed in each pavement layer. For sake of simplicity, the procedure has been split according to the different type of bituminous mix properties. A typical Italian pavement specification framework has been adopted requiring Marshall mix design method [ANAS, 1998]. Although this latter procedure is going to be replaced by a more sound mix design method developed within the SHRP project (SuperPave), it still remains the main method currently adopted in pavement construction works in Italy.

Volumetric mix properties.

As far as volumetric properties are concerned, most of end results Italian pavement specifications prescribe that the bitumen content and Marshall voids of bituminous mix should fall within a defined range based on the bituminous course where they are likely to be employed. Contractor is usually entitled to submit a mix recipe according to the Marshall mix design method complying with the aforementioned specifications. Nevertheless, during the road construction, bitumen content may differ from target value employed in the mix design. Furthermore, compaction may yield to bituminous mixes with void content higher than provided by Marshall tests, therefore, minimum level of compaction (expressed as the ratio between the on site density and Marshall density) is also prescribed.

Basing on these premises, conventional pavement specifications allow a certain degree of variability in the mix volumetric properties that have to be correctly modelled. Let:

- γ_a = Specific gravity of aggregate;
- γ_b = Specific gravity of bitumen;
- γ = Specific gravity of mixture;
- V = Void content;
- V_{site} = On site void content;
- $V_{marshall}$ = Marshall void content;
- V_b = Bitumen content, by volume;
- V_a = Aggregate content, by volume;
- $B\%$ = Bitumen content with respect to aggregate weight, in percent;
- LC = Level of Compaction = $\gamma_{site} / \gamma_{marshall}$;

For a given initial bitumen content, B%*, and initial Marshall void, $V^*_{marshall}$, as derived from the Marshall mix design method, the initial bitumen and aggregate content by volume are respectively:

$$V^*_b = \frac{\left(1 - V^*_{marshall}\right)}{\left(1 + \frac{\gamma_b \cdot 100}{B\%^* \cdot \gamma_a}\right)} \qquad (16)$$

$$V^*_a = 1 - V^*_b - V^*_{marshall} \qquad (17)$$

When the bitumen content, $B\%$, differs from the target value derived by the Marshall mix design method (provided that it is always within the specifications limits), it can be assumed that the increase of bitumen content occurs at the expense of void content, leaving the initial aggregate content by volume, V^*_a, substantially invariant. Since aggregate and bitumen content by volume can be related through the following expression:

$$V_b = \frac{B\% \cdot \gamma_a}{100 \cdot \gamma_b} V_a \qquad (18)$$

Therefore, it is possible to evaluate the *new* value of Marshall void content, $V_{marshall}$ following the change in bitumen content by aggregate weight, $B\%$, by combining expression (17) and (18):

$$V_{marshall} = V_{marshall}(B\%) = 1 - V^*_a \left(1 + \frac{B\% \cdot \gamma_a}{100 \cdot \gamma_b}\right) \qquad (19)$$

If the Marshall void content is known, according to a defined Level of Compaction, LC, it becomes possible to evaluate the on-site void content of the mix, by means of the following equation:

$$V_{site} = 1 - LC + LC \cdot V_{marshall}(B\%) = 1 - LC + LC \cdot \left[1 - V^*_a \left(1 + \frac{B\% \cdot \gamma_a}{100 \cdot \gamma_b}\right)\right] \qquad (20)$$

and finally calculate the corresponding on-site bitumen content by volume, V_{bsite}:

$$V_{bsite} = \frac{(1 - V_{site})}{\left(1 + \frac{\gamma_b \cdot 100}{B\% \cdot \gamma_a}\right)} \qquad (21)$$

Therefore, in order to correctly simulate the variability in mix volumetric properties as a result of specification range, the following procedure has been followed:
starting from a target mix recipe, the initial value of aggregate content by volume, V^*_a, is evaluated;
bitumen content by aggregate weight, *B%*, and Level of Compaction, *LC* are randomly generated, according to specification limits;
on-site void content, V_{site}, is calculated by means of expression (20);
on-site bitumen content by volume, V_{bsite}, is calculated by means of expression (21).
These latter two parameters affect the mechanical behaviour of bituminous mixes according to the aforementioned prediction models.
On an operating point of view, a random Gaussian variable is suggested, in order to describe variability of bitumen content, *B%*, and Level of Compaction, *LC*, assuming a mean value centred in the specification range and a standard deviation equal to ¼ of the corresponding specification range. According to this latter hypothesis, 95.45 % of generated values will fall within the specification limits.
The simulation procedure of volumetric properties variability has been conveniently implemented for the bituminous mixture employed in each pavement course (wearing, binder and base course).

Gradation mix properties.
Recalling what has been previously stated on the prediction of visco-elastic properties of asphalt concrete, particle size distribution affects the mechanical behaviour of bituminous mixes. As far as grading properties are concerned, conventional pavement specifications usually define three major grading fractions:

- Coarse aggregate fraction, that is the percent retained on 2 mm sieve by total aggregate weight (cumulative) [%];
- Fine aggregate fraction, that is the percent passing on the 2 mm sieve and retained on 0.075 mm sieve by total aggregate weight (cumulative) [%];
- Filler fraction, that is the percent passing on the 0.075 mm sieve by total aggregate weight (cumulative) [%].

Grading (target) curve proposed by Contractor within the mix recipe according to Marshall method, may undergo to partial modification provided that the aforementioned fractions will fall within defined limits reported in specifications.
This source of variability affecting asphalt concrete behaviour has been modelled according to the following procedure:

- filler and fine aggregate fractions are randomly generated within the specifications limits according to a Gaussian distribution, that is, the mean value corresponds to the target value of the Marshall mix recipe whereas the standard deviation is equal to ¼ of the corresponding specification range;
- coarse aggregate fraction is automatically derived once filler and fine aggregate fraction are defined, since the overall sum of the three major fraction must yield 100;
- within the coarse aggregate fraction, n-1 sub-fractions are randomly generated according to a triangle-shaped probability density function whose mean value corresponds to the target value in the grading curve of the mix recipe and the base length is 0.2 of the target value; the use of this distribution is mainly related to the need of generating a coherent and sound set of values;
- the *n*-th sub fraction is automatically derived once the remaining sub-fraction have been generated.

Also for grading properties the aforementioned simulation framework, has been extended to the bituminous mixture employed in each pavement course (wearing, binder and base course).
Once all the relevant sub-fractions of the particle size distribution curve have been randomly generated, together with volumetric properties, it becomes possible to evaluate visco-elastic properties of asphalt concrete, by means of aforementioned prediction models.

Input data generation
As previously stressed the parameters controlled by the specification are: layer thickness, relative compaction, binder content, fine aggregate fraction, and filler content (coarse aggregate fraction are valued from the latter ones). Therefore, in the problem considered, the *LCC* is a function of the above mentioned "X_k" independent variables ($k = 5 \times h$ where h is the number of asphalt concrete layers). In order to investigate how does *LCC* vary when the construction parameters vary, according to some assumed joint probability distribution, we apply a Monte Carlo simulation based on a constrained sampling scheme, well-known as "*Latin Hypercube sampling*" [MCKAY, CONOVER and BECKMAN, 1979]. In this sampling scheme the range of each variable is divided into m non-overlapping intervals on the basis of equal probability, and one values from each interval is selected at random with respect to probability density in the interval. The m

values thus obtained for each “X_i” variable are paired in a random manner (equally likely combinations), the pairing was done by associating a random permutation, of the first m integers, with each input variable (see **Figure** 5). To help clarify the sampling process, consider m = 5 intervals (each interval correspond to a 20% probability) , let be x_{ij} the values of i-th variable picked in the *j-th* interval, use a permutation to order the values and form a vector (e.g. let be the permutation 3, 1, 5, 2, 4 the vector for the *i-th* variable is x_{i3}, x_{i1}, x_{i5} , x_{i2}, x_{i4}). Next form an ($m \times k$) matrix of input where the column are the vector formed as previously illustrated; the *i-th* row of the matrix contains specific values of each of the k input variables to be used on the *i-th* run of the model. The process is repeated n times in order to generate $n \times m$ input vectors.
This approach yields reasonable estimates for the distribution of the dependent variable (i.e. *LCC*) even with reduced dimension sample, unlike non constrained sampling.
In the framework proposed we assume that random variables “X_k” have a normal distribution with a mean value equal to target value and a standard deviation equal to two times the allowed deviation (obtained from the specification).
As coarse aggregate grading is required in predictive model for the dynamic (complex) modulus of asphalt mixture, it is random generated based on coarse aggregate fraction (parameter directly controlled) considering a triangular distribution of the sub-fractions (e. g. 10/15, 15/20, 20/25, etc.). The sampling process and the generation of derived parameters is illustrated in figure 5.

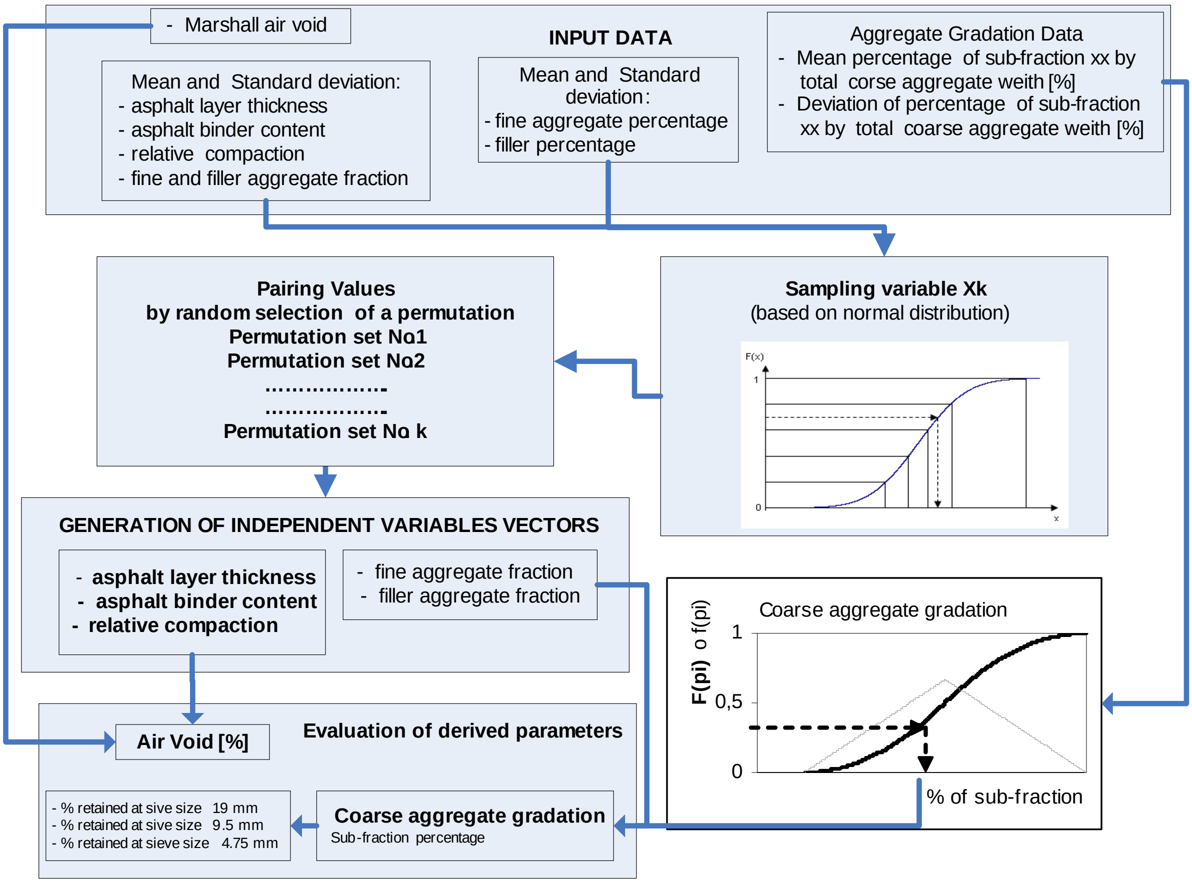

Figure 5: Sampling scheme for generating input values of the parameters.

Development of a regression model for the pay factor assessment

Once that the input parameter have been generated, previously described pavement performance prediction models are employed in order to evaluate the service life of pavement as far as several distress indicator (rutting, cracking, etc.) are concerned. Following this phase, *LCC* analysis is performed, in order to evaluate the Payment Adjustment Factor, *PF*, to be applied to in the as-constructed state.
By knowing the asphalt concrete property values underlying each pavement performance simulation, it is possible to derive a $M \times k$+1 array of data where M is the amount of simulation performed and k is the amount of asphalt concrete properties taken into account in the simulation affecting pavement performance whereas the k+1-*th* variable represents the corresponding *PF* value derived from the performance evaluation based on those specific values of asphalt concrete properties.
It is therefore possible to perform a regression on this array of data that allows to derive an expression to evaluate the *PF* as a function of values of asphalt concrete properties according to pavement specifications. As a matter of fact, it appears more convenient to express the specific bituminous mix property in a dimensionless manner by using a statistical transformation of variable. The value of the single asphalt

concrete property can be therefore expressed as a *normal deviate*, Z_i, i.e. as a deviation from the as-design (or mean) value in terms of standard deviation, by means of the following expression [EPPS et al., 2002]:

$$Z_i = (ACP_i - \mu_i) / \sigma_i \qquad (22)$$

where:
ACP_i is the value of the *i-th* asphalt concrete property;
μ_i is the as-design (mean) value of the *i-th* asphalt concrete property;
σ_i is the standard deviation of the as-designed distribution of the *i-th* asphalt concrete property.

Once that the normal deviate values have been computed, a regression model can be seeked between the Zi and the PF, in the form:

$$PF = F(Z_1, Z_2, \dots Z_n) \qquad (23)$$

CASE STUDY

A case study has been carried out in order to test the process developed; the pavement structure selected is illustrated in **Table 1**. The *Annual Average Daily Traffic* (*AADT*) of commercial vehicle considered (trucks and buses) is 3668, the annual increase rate is 1%, and the traffic composition is summarized in Table 5. Asphalt concrete properties (mean and deviation allowed) are selected based on the Italian specification [ANAS, 1998] and are summarized in Table 1, Table 2, Table 3 and Table 4. The environmental conditions are those reported in Table 6. An analysis period of 30 years and an annual discount rate of 3.25% have been selected.

Over 6000 pavement samples (namely 6244) have been generated and calculated; input data and corresponding Pay Factor are reported for the first 20 samples in table 7 and in standardized form (normal deviates) in table 8. If a simple permutation scheme had been implemented, by assuming 3 relevant values (minimum, mean and maximum) for each asphalt concrete property, for 15 relevant properties, it would have required to carry out 3^{15} = 14’348’907 simulations.

Following this stage, for each pavement sample, life cycle cost has been conveniently evaluated.

Chi-square test performed on pavement service life data has confirmed the substantially Gaussian shape of the distribution. Within the main assumptions regarding the spread of the Gaussian distributions assumed for asphalt concrete properties, a mean value of 25.37 service life as been calculated and the 95.45 % of 6244 pavement samples generated has a service life falling in range comprised between 21.98 and 28.76 years.

Table 1. Pavement structure and thickness specifications

Layer	Nominal Thickness [mm]	Thickness deviation [mm]
Surface course (HMA)	50	0.75
Binder course (HMA)	70	0.105
Base course (HMA)	150	0.225
Subbase course (Granular)	400	-

Table 2. Volumetric properties of asphalt concrete

	Asphalt Binder content [%]		Relative Compaction [%]		Marshall Air void
Layer	Mean value	Standard Deviation	Mean value	Standard Deviation	
Surface course	5.25	0.15	0.985	0.0075	4.5
Binder course	4.75	0.15	0.985	0.0075	6.0
Base course	4.0	0.15	0.985	0.0075	6.5

Table 3. Asphalt concrete fraction aggregate specifications.

	Fine Aggregate [%]		Filler [%]	
Layer	Mean value	Standard Deviation	Mean value	Standard Deviation
Surface course	6.5	1.5	8.5	0.75
Binder course	26.392	1.5	4.014	0.75
Base course	23.646	1.5	4.252	0.75

Table 4. Asphalt concrete aggregate grading properties.

	Fraction 30/40		Fraction 25/30		Fraction 15/25		Fraction 10/15		Fraction 5/10	
Layer	Target value	Range Allowed	Target value	Range Allowed	Target value	Range Allowed	Target value	Range Allowed	Target value	Range Allowed
Surface course	0	0.2	0	0.2	0	0.2	15	0.2	30	0.2
Binder course	0	0.2	0	0.2	16.39	0.2	19.15	0.2	20.36	0.2
Base course	1.224	0.2	6.124	0.2	34.35	0.2	14.57	0.2	4.36	0.2

Table 5.Traffic data

Vehicle type	Axle type	Axles load [kN]	% on traffic strem
1) Light truck	S + S	↓10 ↓20	25.83
2) " "	S + S	↓15 ↓30	-
3) Light and medium truck	S + S	↓40 ↓80	8.4
4) " " "	S + S	↓50 ↓110	5.02
5) Heavy truck	S + T	↓40 80↓ ↓80	0.83
6) " "	S + T	↓60 100↓ ↓100	4.2
7) Truck with trailer and Articulated truck	S + S + S + S S + S + T	↓40 ↓90 ↓80 ↓80 ↓40 ↓90 80↓ ↓80	8.1
8) " "	S + S + S + S S + T + T	↓60 ↓100 ↓100 ↓100 ↓60 ↓100 100↓ ↓100	16.55
9) " "	S + T + S +S S + T + T	↓40 80↓ ↓80 80↓ ↓80 ↓40 80↓ ↓80 ↓80 ↓80	4.54
10) " "	S + T + S +S S + T + T	↓60 90↓ ↓90 ↓100 ↓100 ↓60 90↓ ↓90 100↓ ↓100	9.26
11) " "	S + S + TR	↓40 ↓100 ↓80 ↓80↓80	4.54
12) " "	S + S + TR	↓70 ↓110 ↓90 ↓90↓90	9.26
13) Dumpers	S + S + TR	↓4 0 ↓130 ↓ 130 ↓130↓130	0.06
14) Bus	S + S	↓40 ↓80	-
15) "	S + S	↓60 ↓80	-
16) "	S + S	↓50 ↓80	3.41

S=single axle, T= tandem axle, TR= tridem axle

Table 6. Climatic data [Di Mascio and Domenichini, 1995].

SEASON	Average air temperature T_m [°C]	Average daily variation in the air temperature A_g [°C]	Average daily radiation I [kCal / gg]	Average wind speed v [m/sec]
Winter	3÷5	5÷7	2718	13÷18
Spring	11÷13	8÷10	5785	12÷19
Summer	22÷24	10÷12	6507	9÷15
Autumn	13÷15	7÷9	3547	11÷17

Table 7. Input parameter for the first 20 pavement samples generated.

	Wearing course					Binder course					Base course					
ID	Thickness [cm]	Compaction Level	Bitumen Content [%]	Fine Aggregate [%]	Filler [%]	Thickness [cm]	Compaction Level	Bitumen Content [%]	Fine Aggregate [%]	Filler [%]	Thickness [cm]	Compaction Level	Bitumen Content [%]	Fine Aggregate [%]	Filler [%]	PF
1	4.962	0.986	5.422	6.161	7.559	7.008	0.982	4.688	26.782	2.473	15.591	0.98	4.016	22.572	4.593	1.077
2	4.919	0.997	5.277	7.706	8.933	7.041	1.001	4.496	26.01	4.669	14.977	0.974	4.064	23.707	4.359	1.017
3	5.03	0.979	5.164	5.195	9.433	7.111	0.985	4.807	23.349	3.436	15.181	0.988	4.217	21.045	3.75	1.019
4	5.003	0.977	4.895	8.207	8.217	6.952	0.978	4.786	26.523	4.126	14.866	0.984	3.791	25.497	3.568	0.976
5	5.081	0.99	5.355	6.017	8.33	6.836	0.991	4.948	28.447	4.316	14.648	0.996	3.914	24.088	5.054	0.910
6	4.994	0.994	5.326	8.72	9.426	7.017	0.979	4.684	26.356	5.257	14.684	0.984	4.028	25.296	5.031	0.954
7	4.905	0.968	5.224	4.778	9.021	6.951	0.987	4.564	23.736	4.025	15.081	0.992	3.798	22.639	3.499	1.005
8	4.959	0.98	5.032	7.696	8.058	7.028	0.984	4.858	25.755	4.238	14.877	0.981	4.101	21.99	4.636	0.987
9	5.079	0.987	5.406	6.239	7.543	7.105	0.991	4.885	27.055	3.795	14.999	0.969	3.901	23.335	3.768	1.013
10	5.035	0.987	5.17	5.747	8.351	6.891	0.969	4.753	27.82	3.206	15.249	0.991	4.158	24.049	4.152	1.030
11	4.966	0.972	5.253	6.665	7.534	6.963	0.99	4.947	26.287	3.698	14.584	0.985	3.966	22.602	5.34	0.891
12	5.094	0.983	5.32	5.039	9.397	6.87	1	4.654	27.523	4.106	15.2	0.992	4.098	26.116	4.476	1.024
13	4.994	0.993	5.53	7.757	8.573	7.002	0.982	4.734	23.842	4.457	14.966	0.968	4.198	21.823	3.196	0.988
14	5.025	0.984	5.065	8.173	8.76	7.135	0.985	4.533	25.675	5.294	15.182	0.982	3.701	24.654	4.023	1.095
15	4.933	0.987	5.206	5.857	8.068	7.051	0.972	4.8	28.275	2.684	14.92	0.989	3.891	23.622	4.344	0.967
16	4.915	0.975	5.31	6.851	7.659	6.945	0.99	4.523	29.004	3.83	15.09	0.981	3.979	22.248	4.257	1.012
17	4.985	0.985	4.993	3.626	8.08	6.982	0.979	5.06	25.531	3.2	14.87	0.984	4.153	22.953	3.36	0.953
18	5.026	0.989	5.242	9.631	8.572	7.039	0.977	4.773	26.106	4.269	15.329	0.991	4.074	24.337	4.573	1.092
19	5.067	1.004	5.442	5.726	8.714	6.886	0.998	4.844	24.99	3.577	14.955	0.978	3.772	23.551	4.035	0.959
20	4.954	0.983	5.16	7.334	9.74	7.116	0.985	4.71	27.604	4.737	14.714	0.994	3.944	26.509	5.702	0.996

Table 8. Input parameters, in terms of normal deviates, for the first 20 pavement samples generated.

ID	Wearing course					Binder course					Base course					PF
	Thickness Z_1	Compaction Level Z_2	Bitumen Content Z_3	Fine Aggregate Z_4	Filler Z_5	Thickness Z_6	Compaction Level Z_7	Bitumen Content Z_8	Fine Aggregate Z_9	Filler Z_{10}	Thickness Z_{11}	Compaction Level Z_{12}	Bitumen Content Z_{13}	Fine Aggregate Z_{14}	Filler Z_{15}	
1	-0.507	0.133	1.147	-0.226	-1.255	0.076	-0.400	-0.413	0.260	-2.055	2.627	-0.667	0.107	-0.716	0.455	1.077
2	-1.080	1.600	0.180	0.804	0.577	0.390	2.133	-1.693	-0.255	0.873	-0.102	-1.467	0.427	0.040	0.143	1.017
3	0.400	-0.800	-0.573	-0.870	1.244	1.057	0.000	0.380	-2.029	-0.771	0.804	0.400	1.447	-1.734	-0.669	1.019
4	0.040	-1.067	-2.367	1.138	-0.377	-0.457	-0.933	0.240	0.087	0.149	-0.596	-0.133	-1.393	1.234	-0.912	0.976
5	1.080	0.667	0.700	-0.322	-0.227	-1.562	0.800	1.320	1.370	0.403	-1.564	1.467	-0.573	0.294	1.069	0.910
6	-0.080	1.200	0.507	1.480	1.235	0.162	-0.800	-0.440	-0.024	1.657	-1.404	-0.133	0.187	1.100	1.039	0.954
7	-1.267	-2.267	-0.173	-1.148	0.695	-0.467	0.267	-1.240	-1.771	0.015	0.360	0.933	-1.347	-0.672	-1.004	1.005
8	-0.547	-0.667	-1.453	0.797	-0.589	0.267	-0.133	0.720	-0.425	0.299	-0.547	-0.533	0.673	-1.104	0.512	0.987
9	1.053	0.267	1.040	-0.174	-1.276	1.000	0.800	0.900	0.442	-0.292	-0.004	-2.133	-0.660	-0.208	-0.645	1.013
10	0.467	0.267	-0.533	-0.502	-0.199	-1.038	-2.133	0.020	0.952	-1.077	1.107	0.800	1.053	0.268	-0.133	1.030
11	-0.453	-1.733	0.020	0.110	-1.288	-0.352	0.667	1.313	-0.070	-0.421	-1.849	0.000	-0.227	-0.696	1.451	0.891
12	1.253	-0.267	0.467	-0.974	1.196	-1.238	2.000	-0.640	0.754	0.123	0.889	0.933	0.653	1.646	0.299	1.024
13	-0.080	1.067	1.867	0.838	0.097	0.019	-0.400	-0.107	-1.700	0.591	-0.151	-2.267	1.320	-1.216	-1.408	0.988
14	0.333	-0.133	-1.233	1.115	0.347	1.286	0.000	-1.447	-0.478	1.707	0.809	-0.400	-1.993	0.672	-0.305	1.095
15	-0.893	0.267	-0.293	-0.429	-0.576	0.486	-1.733	0.333	1.255	-1.773	-0.356	0.533	-0.727	-0.016	0.123	0.967
16	-1.133	-1.333	0.400	0.234	-1.121	-0.524	0.667	-1.513	1.741	-0.245	0.400	-0.533	-0.140	-0.932	0.007	1.012
17	-0.200	0.000	-1.713	-1.916	-0.560	-0.171	-0.800	2.067	-0.574	-1.085	-0.578	-0.133	1.020	-0.462	-1.189	0.953
18	0.347	0.533	-0.053	2.087	0.096	0.371	-1.067	0.153	-0.191	0.340	1.462	0.800	0.493	0.460	0.428	1.092
19	0.893	2.533	1.280	-0.516	0.285	-1.086	1.733	0.627	-0.935	-0.583	-0.200	-0.933	-1.520	-0.064	-0.289	0.959
20	-0.613	-0.267	-0.600	0.556	1.653	1.105	0.000	-0.267	0.808	0.964	-1.271	1.200	-0.373	1.908	1.933	0.996

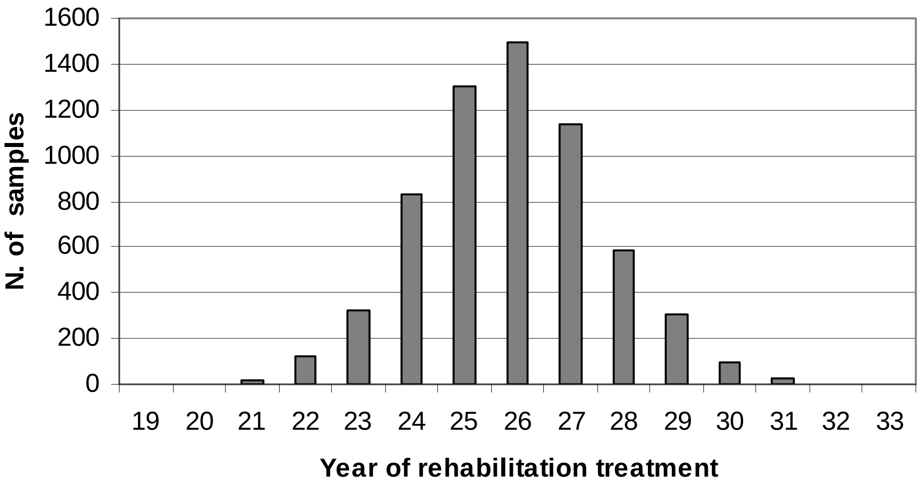

Figure 6. Histogram of year of first rehabilitation treatment.

PF prediction model

Following the pavement performance prediction stage, it has been observed that, for each pavement sample generated, fatigue cracking threshold has been reached prior than rutting threshold. Therefore according to the maintenance treatment decision tree previously depicted (Figure 3) a maintenance policy has been undertaken with reference to a single distress indicator (fatigue cracking), i.e. it has been hypothesized that no other RRR interventions are going to be carry out within the analysis period apart from the total reconstruction of the bituminous layers once that the end of the service life has been reached according to the fatigue cracking criterion.

Furthermore, by assuming that the residual value of the pavement can be considered proportional to the residual service life according to that specific distress indicator, a simplified expression for the evaluation of payment adjustment factor can be derived in the followings.

As a matter of fact, let:

n = predicted service life of pavement in the as-design scenario, expressed in years;
n^* = predicted service life of pavement in the as-constructed scenario, expressed in years;
N_{des} = Heavy vehicle cumulated traffic withstood by the pavement in the in the as-design scenario, in number of vehicle passes;
N_{cos} = Heavy vehicle cumulated traffic withstood by the pavement in the in the as-constructed scenario, in number of vehicle passes;
$N(T)$ = Heavy vehicle cumulated traffic in the analysis period, in number of vehicle passes;
AHVCT = Annual Heavy Vehicle Cumulated Traffic, in number of vehicle passes;
$Cpav$ = Bituminous layer overall construction cost (demolition and transport-to-waste costs included) assumed to be invariant in the analysis period, expressed in currency/m^2;
T = analysis period, in years;
g = annual traffic growth rate
r = annual discount rate.

The life cycle cost, *Cp*, the Highway Agency will undergo throughout the analysis period, *T*, in the as-design scenario is:

$$Cp = Cpav + \sum_{i=1}^{h} \frac{Cpav}{(1+r)^{n_i}} - Rp_T \qquad (24)$$

where:
h is the integer part of the $N(T)/N_{des}$ ratio (i.e. the number of reconstruction interventions within the analysis period), n_i is the year when the *i-th* intervention will have to be carried out, in the as-designed scenario, that can be evaluated as:

$$n_i = \frac{\log\left(\frac{i \cdot N_{des} \cdot g}{AHVT} + 1\right)}{\log(1+g)} \quad \text{for } i = 1,2,\ldots.h$$

whereas Rp_T is the discounted residual value of the pavement at the end of the analysis period, *T*, that can be evaluated through the following expression:

$$Rp_T = Cpav\left[1 + h - \frac{N(T)}{N_{des}}\right]\frac{1}{(1+r)^T} \qquad (25)$$

The life cycle cost, *Ce*, the Highway Agency will undergo throughout the analysis period, *T*, in the as-constructed scenario (assuming that the bituminous layers will comply with pavement specifications in the subsequent reconstructions and therefore pavement performance will respect the as-design prediction) is:

$$Ce = Cpav + \frac{Cpav}{(1+r)^{n^*}} + \sum_{i=1}^{k} \frac{Cpav}{(1+r)^{n_j}} - Rr_T \qquad (26)$$

where k is the integer part of the $[(N(T)-N_{cos})/N_{des}]$ ratio (i.e. the number of reconstruction intervention within the analysis period in the as-constructed scenario), n_j is the year when the *j-th* intervention will have to be carried out, in the as-constructed scenario, that can be evaluated as:

$$n_j = \frac{\log\left(\frac{N_{cons} + j \cdot N_{des}}{AHVT} g + 1\right)}{\log(1+g)} \quad \text{for } j = 1,2,\ldots.k$$

whereas Rr_T is the discounted residual value of the pavement at the end of the analysis period, *T*, that can be evaluated through the following expression:

$$Rr_T = Cpav\left[1 + k + \frac{N_{cons} - N(T)}{N_{des}}\right]\frac{1}{(1+r)^T} \qquad (27)$$

Following the lower service life of as-constructed pavement, the higher maintenance cost, *P*, the highway agency will undergo within the analysis period, i.e. the variation of Life Cycle Costs between the two scenarios, as far as the pavement structural serviceability is concerned, is:

$$P = Ce - Cp \quad (28)$$

Therefore, the PF can be evaluated by means of the following expression:

$$PF = \frac{Cpav - (Ce - Cp)}{Cpav} = 1 - \frac{(Ce - Cp)}{Cpav} \quad (29)$$

In the following figure (Figure 7) a graphical description of the LCCA concept in the performance based Pay Factor assessment assuming a service life in the as-designed scenario equal to the analysis period is conveniently depicted.

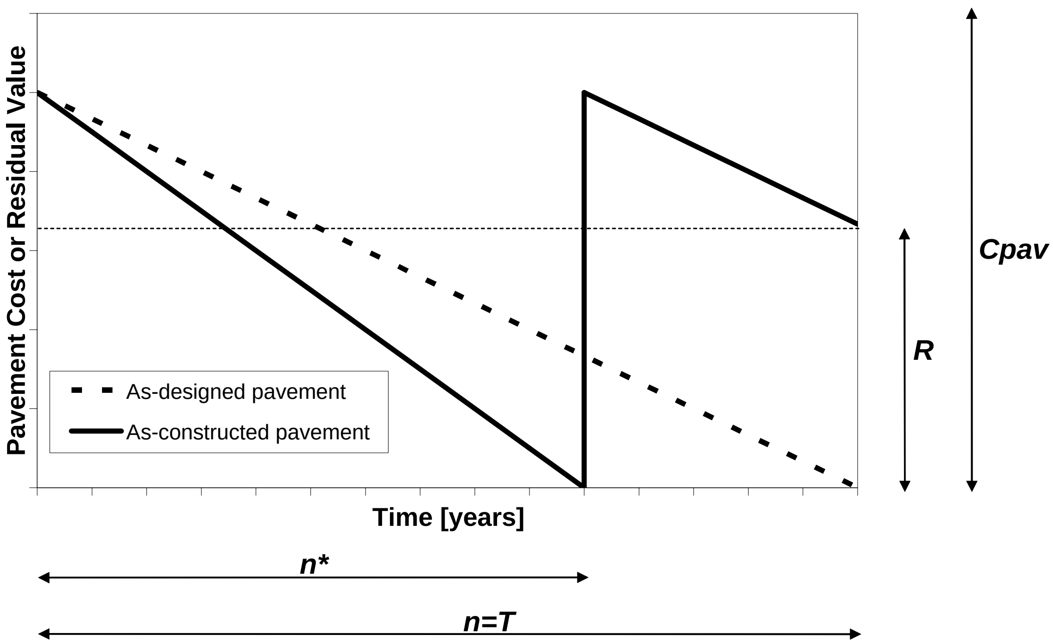

Figure 7: Graphical description of the LCCA concept in the performance based Pay Factor assessment assuming a service life in the as-designed scenario equal to the analysis period

Following the LCCA phase, for each of the generated pavement sample, PF has been evaluated. Therefore, it has been possible to derive a multiple regression allowing to express the PF as a function of the 15 normal deviates of asphalt concrete properties that have been taken into account in the analysis. The analytical form of the regression found is the following:

$$PF=a_1Z_1+a_2Z_2+a_3Z_3+a_4Z_4+a_5Z_5+a_6Z_6+a_7Z_7+a_8Z_8+a_9Z_9+a_{10}Z_{10}+a_{11}Z_{11}+a_{12}Z_{12}+a_{13}Z_{13}+a_{14}Z_{14}+a_{15}Z_{15}+1 \quad (30)$$

where:
Z_1 is the normal deviate of the thickness of the wearing course;
Z_2 is the normal deviate of the Level of Compaction (LC) of the wearing course;
Z_3 is the normal deviate of the Bitumen content, B%, of the wearing course;
Z_4 is the normal deviate of the Fine Aggregate fraction of the wearing course;
Z_5 is the normal deviate of the Filler fraction of the wearing course;
Z_6 is the normal deviate of the thickness of the binder course;
Z_7 is the normal deviate of the Level of Compaction (LC) of the binder course;
Z_8 is the normal deviate of the Bitumen content, B%, of the binder course;
Z_9 is the normal deviate of the Fine Aggregate fraction of the binder course;
Z_{10} is the normal deviate of the Filler fraction of the binder course;

Z_{11} is the normal deviate of the thickness of the base course;
Z_{12} is the normal deviate of the Level of Compaction (LC) of the base course;
Z_{13} is the normal deviate of the Bitumen content, B%, of the base course;
Z_{14} is the normal deviate of the Fine Aggregate fraction of the base course;
Z_{15} is the normal deviate of the Filler fraction of the base course.

Relevant data and statistics of the regression model developed are reported in the following table (Table 9).

Table 9. Relevant statistics of PF regression developed

Variable	Value	Standard Error	Value / Standard error	Prob(t)*
a_1	0.012478056	0.000153643	81.2146585	0
a_2	-0.000563416	0.000154546	-3.645610215	0.00027
a_3	-0.00472107	0.000152519	-30.95403665	0
a_4	0.002738694	0.00015533	17.63145494	0
a_5	0.000354539	0.000153616	2.307953167	0.02103
a_6	0.018605132	0.000151377	122.90564	0
a_7	-0.00084751	0.000153325	-5.527521819	0
a_8	-0.006726719	0.00015274	-44.04026615	0
a_9	0.002777963	0.000154287	18.00516679	0
a_{10}	0.014470111	0.000154671	93.5544215	0
a_{11}	0.043043718	0.000151923	283.3261407	0
a_{12}	-0.000330237	0.000153123	-2.15667435	0.03107
a_{13}	0.000492524	0.000154102	3.196095608	0.0014
a_{14}	3.06E-05	0.00015395	0.198695526	0.84251
a_{15}	0.00097909	0.000153515	6.377793137	0
***(Probability of the Test Hypothesis: $a_i = 0$)**				

Sum of Residuals = -1.37782845327865
Average Residual = -2.2066439033931E-04
Residual Sum of Squares (Absolute) = 0.903939688201508
Residual Sum of Squares (Relative) = 0.903939688201508
Standard Error of the Estimate = 1.20464910414687E-02
Coefficient of Multiple Determination (R^2) = 0.9482290154
Proportion of Variance Explained = 94.82290154%
Adjusted coefficient of multiple determination (Ra^2) = 0.9481126575
Durbin-Watson statistic = 2.03703872428836

Analysis of the regression developed showed that even a multinomial linear regression may yield to a acceptable estimate of Payment Adjustment Factor.

CONCLUSION

In this paper a new methodology for the evaluation of pavement pay factor evaluation has been presented. The methodology is based on a performance related approach. The core of the methodology is represented by a mechanistic empirical pavement design procedure that is employed in order to estimate pavement performance both in the "as design" and in "as built" condition. The pavement design procedure allows to evaluate pavement fatigue life and maximum rut depth as a function of bituminous mix properties, pavement layout, on site prevailing traffic and climatic conditions.
Because of variability of bituminous mix properties due to, on one hand, the acceptance ranges reported in hot mix asphalt specifications and, on the other hand, in-situ mix production and laying operating conditions, a constrained Monte Carlo simulation, by means of an *Latin Hypercube* Algorithm, has been carried out in order to evaluate pavement performance.
Following this stage, a criterion based on a *Life Cycle Cost Analysis* (*LCCA*) concept has been employed in order to evaluate the *Payment Adjustment Factor* (*PF*) to be applied to the Contractor as a function of the pavement performance in the as-built scenario as compared with that pertaining the as-design scenario.
Basing on a typical pavement specification framework adopted in Italy, a case study has been examined and a regression model has been developed on data generated in the Monte Carlo simulation, in order to derive a Pay Factor prediction expression as a function of the *normal deviates* of relevant asphalt concrete properties affecting pavement performance.

Preliminary results seems to indicate that the methodology developed may assist:

- the Highway Engineer in the design stage, allowing the explicit evaluation of variability of pavement performance as a function of a defined framework of specification ranges; as a matter of fact, by setting a specific threshold limits for relevant asphalt concrete and pavement properties within a framework specification, it becomes possible to estimate the worst pavement performance that may be expected if the Contractor will provide a mixture complying with specifications and therefore adjust and calibrate design parameters in order to obtain a defined reliability related to pavement performance;
- the Highway Agency Engineer in the operating stage, allowing the adoption of “tailored” pavement specifications that are context-sensitive, performance related and that report a clear and defensible approach for the remuneration of pavement Contractor;
- the Contractor Engineer that, by means of a pay factor prediction model specifically developed for the construction site, may design higher quality bituminous mixtures, by monitoring the relevant asphalt concrete properties in order to avoid payment reduction and to aim major reward from bituminous material provided.

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