PREDICTING SKID-RESISTANCE PROGRESSION THROUGH MATHEMATICAL MODEL

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ABSTRACT

The assessment of the evolution of skid resistance and texture of surface pavement plays a key role in the planning of interventions within a modern Pavement Management System. However, the study of the problem appears to be extremely complex since different factors (e.g. material related, environmental, traffic related, etc) affecting the skid resistance and macro-texture progression can be detected. Therefore, empirical models derived from experimental measures have been developed in the past. Actually, following skid resistance and macro-texture measurements carried out within a 5-6 year long period on a specific road section, regression curves are usually derived as a function of cumulated traffic. The main drawback of this approach is related to its effectiveness being strictly dependent on the context in which the expression has been derived and to the extended monitoring period required.

In this paper, a different methodology for the development of skid resistance and macro-texture empirical deterioration model has been proposed. Basing on this approach, with a few day long period, skid resistance and macro-texture measurements have to be carried out on several road sections in which similar bituminous mixes of different age have been laid. If a suitable equivalency criterion for damage induced by commercial vehicles is used, it becomes possible to describe the deterioration state of a specific bituminous mix as a function of cumulated damage induced by the traffic and of mix properties.
Keywords: maintenance, skid resistance, deterioration models.

1. INTRODUCTION

The evaluation of evolution of friction / texture level developed at tyre-pavement interface represents a key aspect in a modern Pavement Management System (PMS). The prediction of texture and skid resistance progression has to be implemented in a spatial and temporal allocation system of interventions that is optimised with respect to budget constraints in order to achieve a generalized reduction of cost born by road users, highway administration and the overall community.

A friction or texture progression model can be conceptually described by the following expression:

$$F = F(E, T) \qquad \text{(Eq. 1)}$$

Where F represents a Friction or Texture descriptor/indicator, E is related to environmental factors and T describes traffic-related factors.

Environmental factors such as temperature variations may be responsible for altering the soundness of aggregates due to freeze-thaw cycles. In addition ageing of bitumen cement may occur due to oxidation and photochemical degradation (MONTEPARA et alii. 1996). Bitumen hardening can lead to bituminous mixes characterised by worse mechanical performance as surface stress induced by traffic actions are concerned. However, it has to be said that aggregates employed in wearing course are usually subjected to more severe pre-qualification laboratory tests according to conventional pavement specifications whereas bitumen undergoes to a gradual hardening that progresses throughout its whole service life, and therefore the environmental-related contribution to the texture or friction decay appears usually poor if compared with that induced by traffic.

Traffic actions play a major role in the friction and texture progression. In detail, as far as the macro-texture scale is concerned, a dramatic decrease of macro-texture occurs in the early life of wearing course as a consequence of traffic-induced post-compaction phenomena that are more pronounced in the wheel path areas. As a results of mix densification due to repeated loads, in-situ mix air voids undergo to a decrease (WITCZAK et alii, 2001) that, in turn, may affects surface macro-texture (PROWELL et alii, 2005). Pavement surface defects such as cracking and ravelling may also contribute to the change of macro-texture.

As far as the micro-texture is concerned, polishing caused by traffic loads is responsible for the loss of micro-texture. On a phenomenological point of view, the interaction between the tyre and the road surface can be described as a tribological system where different wear mechanisms may occur (LUPKER et alii, 2002):

- *adhesive wear* that is the removal of material caused by high transient adhesion;
- *abrasive wear* caused by cutting-rupture action of sharp angular asperities on the sliding counterface or as third bodies;
- *erosive wear*, i.e. the cutting-rupture action of particles in a liquid stream
- *corrosive wear*, induced by chemical agents reacting with surface materials;
- *fatigue wear*, caused by rapid or gradual material property changes generating cracks and subsequently a loss of material.

With reference to the road surface polishing phenomenon, abrasive, erosive and fatigue wear are likely to affect, in a different complex manner and under various tyre-road operating conditions, the micro-texture decay, and, therefore, consolidated relationships linking the wear mechanisms with road surface polishing have not been developed yet.

Up to now, because of the intrinsic complexity of the problem, only empirical deterioration models have been developed in order to evaluate the evolution of skid resistance and of surface macro-texture due to vehicular traffic (GIANNATTASIO et alii, 2002).

As regards the development of a friction/texture deterioration model, on an operating point of view, two main approaches have been pursued:

- texture / friction measurements are carried out on a sample of pavements in order to follow skid-resistance and macro-texture evolution (GIANNATTASIO et alii, 2002) (CAMOMILLA et alii, 1990) (NOYCE et alii, 2005);
- specifically devoted laboratory tests are developed in order to simulate traffic polishing action in a controlled environment and to correlate laboratory mix behaviour with in-service pavement performance (NITTA et alii, 1990) (DIRINGER et alii, 1990) (BOSCAINO et alii, 2005).

With reference to the former approach, data collection can be tackled by means of two main procedures: namely, diachronic and synchronic. In the former one, skid resistance, texture and traffic measurements are performed on a specific road section that is monitored till the terminal values are reached (usually within 5-7 years), whereas in the latter, provided that equivalency damage criteria are available, skid resistance and texture measurements are carried out in a very short period on several pavement sections undergoing to different traffic where similar bituminous mixes of different age have been laid.

The first approach is more time consuming but usually yields relationships characterised by lower scattering, whereas the second approach appears more fast but relationships between friction/texture values and cumulated traffic, derived from statistical regressions, usually appears more weak because of the increase of number of independent variables and the lack of information as the sample dimension is getting higher.

In this paper, following an original methodology applied in analysing friction and pavement data, a synchronic approach has been employed in order to develop an empirical friction progression model. The works starts from early studies carried out within a National Research Project (D'APUZZO et alii 2005) where friction degradation models have been developed on empirical basis for different mixes. An in-depth analysis on the bituminous mixes laid in the pavement sections examined and on traffic induced damage has been carried out in order to derive more refined friction progression models.

2. DESCRIPTION OF THE MODEL

In the proposed mathematical model, traffic and pavement related factors have been assumed as the main independent variables affecting the polishing of road aggregate. In the followings, the approach adopted in order to evaluate the traffic aggressiveness and the road aggregate polish susceptibility have been conveniently described in detail.

2.1 The energy-based damage equivalency concept

Traffic represents the main independent variable in a pavement degradation model, however it is straightforward to argue that different vehicle types may induce different damage when all the other variables involved are kept constant. Therefore it is necessary to evaluate a criterion by which damage induced by one vehicle type can be compared with that caused by another one. As regards the aggregate polishing, several equivalency criteria have been proposed but theoretical justification is still lacking. Most of authors (GIANNATTASIO et alii, 2002) (NOYCE et alii, 2005) assume that damage induced by light vehicle is negligible if compared with that produced by commercial ones, but only few ones are able to discriminate between different vehicle types (D'APUZZO et alii 2005) (COLONNA 1996) (D'APUZZO et alii 2004).

In this paper an energy-based damage equivalency criterion is proposed in order to evaluate the polishing action exerted by different types of vehicle. This criterion is based on the main assumption, recently proposed also within a European Research Project (LUPKER et alii, 2002) (DOMENICHINI et alii, 2004) (BRAGHIN et alii, 2006) according to which the energy involved in the tyre wear process can be regarded as equal to that spent to polish the road surface. In other terms, it is assumed that the damage induced by tyre on the road surface is proportional to the energy dissipated in the tyre wear progression.

As far as the tyre consumption is concerned, an energetic approach may be employed. The problem is usually tackled by splitting the phenomenon into two main phases: the evaluation of dissipated energy per unit distance travelled, on one hand, and the assessment of tyre tread wear rate as a function of unit energy applied, on the other. The former is affected by vehicle and tyre characteristics, environmental and operating conditions (such as road alignment, driver behaviour and pavement condition) whereas the latter is influenced by pavement texture, rubber composition, temperature and interface contaminants.

According to Moore, as reported by BENNETT et alii (2001), the dissipated frictional energy in the rolling, braking or yawing condition can be evaluated through the following expression:

$$Ed = \mu_{l,s} \cdot N \cdot \lambda_{l,s} \qquad \text{(Eq. 2)}$$

where:
Ed is the frictional dissipated energy per unit length travelled in J/m
$\mu_{l,s}$ is the longitudinal or the side friction coefficient, dimensionless;
N is the normal tyre force, in N;
$\lambda_{l,s}$ is the tyre longitudinal or side slip, dimensionless.

If tyre longitudinal or side slip is small, λ can be expressed as:

$$\lambda_{l,s} = k_{l,s} \cdot \frac{F_{l.s}^{n}}{N^{\frac{n+1}{2}}} \qquad \text{(Eq. 3)}$$

where:
$k_{l,s}$ is the dimensionless longitudinal or side slip coefficient and it is a function of tyre geometrical and mechanical properties;
$F_{l,s}$ is the longitudinal or side tyre friction force in N;
n is a experimentally derived constant that for most of tyre-road conditions can be assumed equal to 1.

Substituting Eq. 3 in Eq. 2 we obtain:

$$Ed_{l.s} = \mu_{l,s} \cdot N \cdot k_{l,s} \cdot \frac{F_{l,s}}{N} = k_{l,s} \cdot \frac{F_{l,s}^{2}}{N} \qquad \text{(Eq. 4)}$$

As already stated, *Ed* is the frictional dissipated energy per unit length travelled by a tyre, however we are interested in evaluating the frictional energy transferred to the road surface due to the tyre moving on it. If a tyre has moved forward of a length *x*, a frictional energy *Ed·x* has therefore been transmitted to a surface area that, disregarding the contribution of terminal lobes, can be assumed as rectangular. Dimensions of the area swept by the tyre are therefore $B \times x$, where *B* is the width of tyre footprint.

Basing on these premises, the frictional energy per unit surface area, namely the surface energy, is *Ed*/*B* and the total damage *D*, in terms of road aggregate wear, exerted by a tyre can be regarded as:

$$D_{l,s} \propto \frac{Ed_{l,s}}{B} A \qquad \text{(Eq. 5)}$$

where *A* is the tyre footprint area.

It has to be underlined that longitudinal and side friction forces in Eq. 4 are affected by specific vehicle motion conditions, i.e. in critical points such as sharp bends, steep grades and close to at-level junctions, friction demand is likely to be high. However, for most of roadway alignment, tangential tyre forces sustaining vehicle motion may undergo to random fluctuations depending on specific driver behaviour, therefore, on average, they can be assumed as steady. Since the total friction force can be expressed in the following form:

$$F_{tot} = \sqrt{F_l^2 + F_s^2} = \sqrt{(\mu_l^2 + \mu_s^2)N^2} = \mu_{tot} \cdot N \qquad \text{(Eq. 6)}$$

where μ_{tot} is the total demand friction coefficient that, as already stated, can be considered as constant . Substituting Eq. 4 and Eq. 6 in Eq. 5 and hypothesizing, for sake of simplicity, a circular tyre contact area, one can obtain:

$$D_{tot} \propto \frac{Ed_{tot}}{B} A = \frac{k_{tot} \cdot \mu_{tot}^2 \cdot N}{2 \cdot r} \pi \cdot r^2 = \frac{k_{tot} \cdot \mu_{tot}^2 \cdot N}{2} \pi \cdot r \qquad \text{(Eq. 7)}$$

where r is the radius of the circular tyre footprint area and k_{tot} is the dimensionless total slip coefficient defined as vectorial sum of longitudinal and side slip coefficient and, as previously stated, it is a function of tyre geometrical and mechanical properties. Once the damage induced by a tyre has been defined, it is trivial to derive a damage equivalency factor, in order to evaluate the relative aggressiveness of different vehicle types in a traffic stream. Assuming the damage exerted by a light vehicle tyre as a reference, the relative damage induced by an i-type heavy vehicle is:

$$DR_i = \frac{\sum_{j=1}^{nw_i} k_{i,j} \cdot \mu^2 \cdot N_{i,j} \cdot r_{i,j}}{\sum_{j=1}^{4} k_{lv,j} \cdot \mu^2 \cdot N_{lv,j} \cdot r_{lv,j}} \qquad \text{(Eq. 8)}$$

where:
nw_i is the number of wheel pertaining the i-type heavy vehicle;
k_{ij} is the dimensionless total slip coefficient of the j-th vehicle wheel of the i-type heavy vehicle;
N_{ij} is the normal load transmitted by the j-th vehicle wheel of the i-type heavy vehicle, in N (CNR, 1994);
r_{ij} is the radius of tyre footprint of the j-th vehicle wheel of the i-type heavy vehicle in m;
k_{lvj} is the dimensionless total tyre slip coefficient of the j-th vehicle wheel of the standard light vehicle;
N_{lvj} is the normal load transmitted by the j-th vehicle wheel of the standard light vehicle, in N;
r_{lvj} is the radius of tyre footprint of the j-th vehicle wheel of the standard light vehicle, in m.

Assuming that the slip coefficient value is the same for all tyres mounted on a specific vehicle type and that vertical tyre loads can be roughly estimated by dividing the total vehicle weight by the number of tyres, whereas footprint radius can be evaluated once the tyre pressure is known, Eq. 8 can be further simplified:

$$DR_i = \frac{k_i \cdot W_i \sqrt{\dfrac{W_i}{nw_i \cdot \pi \cdot p_i}}}{k_{lv} \cdot W_{lv} \sqrt{\dfrac{W_{lv}}{4 \cdot \pi \cdot p_{lv}}}} \qquad \text{(Eq. 9)}$$

where:
W_i is the total weight of the i-type heavy vehicle, in N;

p_i is the tyre pressure of the wheel for the i-type heavy vehicle, in Pa;
W_{lv} is the total weight of the standard light vehicle, in N;
p_{lv} is the tyre pressure of the wheel for the standard light vehicle, in Pa.

It is interested to notice that, differently from what has been derived in pavement fatigue behaviour, the damage seems to be related to the vertical load according to a 1.5 power law. This may support the point that the contribution of light vehicle traffic is not negligible in the evaluation of friction decay progression.

It is also worth to observe that damage equivalence factors proposed in early studies (D'APUZZO et alii, 2005) were based only on total tyre contact area and therefore heavy vehicle contribution on aggregate polishing was further underestimated.

Assuming that a standard light vehicle passage induces a unit damage on the pavement surface, once that heavy vehicle traffic composition is known, it becomes easy to evaluate the cumulated damage expressed in terms of equivalent number of standard light vehicle passes after *i* years, neq_i:

$$neq_i = AADT_0 \cdot i \cdot 365 \cdot \left[(1 - FHV) + FHV \cdot DR'\right] \qquad \text{(Eq. 10)}$$

where:
$AADT_0$ is the Annual Average Daily Traffic at year 0, in vehicles/day;
i is the number of years in service;
FHV is the fraction of heavy vehicle on the total traffic flow, dimensionless;
DR' is the weighted average of the damage equivalency factor for the heavy vehicle flow that can be evaluated if the heavy vehicle traffic spectrum is known.

2.2 The aggregate related factor

In the previous section, traffic-related factors have been defined by introducing an energy-based damage equivalency factor. However, for a unit energy input to the road surface, rate of wear is mainly affected by the quality of aggregates employed in the wearing course. Is therefore necessary to consider an additional independent variable that takes into account polish performance of aggregates.

Aggregate mineralogical composition is universally acknowledged as the main discriminating factor in evaluating the polishing resistance. Soft rocks such as limestone undergo to a higher micro-texture decay because of traffic polishing actions whereas hard rocks such as igneous ones, are able to retain their micro-texture for a longer period. However aggregate hardness is not the only factor affecting polishing properties. As a matter of fact, several authors (CRISMAN et alii, 2002) (HOSKING 1992) (LEDÉE et alii, 2005) have shown that differential hardness behaviour may be beneficial for micro-texture retention, especially when harder grains are included in a softer matrix.

In order to take into account aggregate performance in the polishing process, it is necessary to quantify the proportion of the different mineralogical varieties contributing to the overall surface mix performance. To that purpose an Aggregate Exposure Factor has been defined according to the following hypotheses:

— the surface fraction of a specific mix component (bitumen, aggregate or void) may be regarded as equal to its volumetric fraction;

- aggregates as small as 2 mm may contribute to the micro-texture level of the overall mix;
- two main mineralogical varieties have been considered in the mix composition according to the conventional mix specifications and on-site availability: igneous rock, namely “basalt”, and sedimentary rock, namely “limestone”.

Once that volumetric and grading properties, on one hand and mineralogical composition, on the other, are known, it is possible to evaluate a *Basalt Exposure Factor*, *BEF*, that is the ratio between the basalt volumetric fraction and the total aggregate volumetric fraction for grain size > 2 mm, by means of the following expression:

$$BEF = Vag \cdot \frac{Volume\_basalt}{Volume\_aggregate} = Vag \cdot \frac{\sum_{i=1}^{nf} \frac{Fb_i \cdot F_i}{\gamma_{ba}}}{\sum_{i=1}^{nf} \frac{Fb_i \cdot F_i}{\gamma_{ba}} + \frac{Fl_i \cdot F_i}{\gamma_{li}}} \qquad \text{(Eq. 11)}$$

where:
Vag is the dimensionless aggregate volume fraction of the mix;
nf is the number of aggregate grading fractions (percentage by weight of aggregate passing a specific sieve and retained at following lower diameter sieve, divided by 100) in the grading curve starting from the 2 mm sieve to the maximum grain size;
F_i is the dimensionless value of the i-th aggregate grading fraction i.e. the percentage by weight of the i-th fraction on the total aggregate divided by 100;
Fb_i is the fraction of basalt aggregate i.e. the percentage by weight of basalt aggregate on total aggregate for the i-th aggregate grading fraction, divided by 100;
Fl_i is the fraction of limestone aggregate i.e. the percentage by weight of limestone aggregate on total aggregate for the i-th aggregate grading fraction, divided by 100;
γ_{ba} is the basalt specific gravity in Kg/m^3;
γ_{li} is the limestone specific gravity in Kg/m^3.

2.3 The friction degradation model

Once that traffic and aggregate related independent variables have been defined, the following analytical expression has been proposed in order to interpreter the experimental data:

$$FR(neq, BEF) = (a \cdot BEF + b) \cdot e^{\frac{-neq}{c \cdot BEF}} + d \cdot BEF + e \qquad \text{(Eq. 12)}$$

where *a*, *b*, *c*, *d* and *e* are the experimentally derived model coefficients.

Experimental measures and analysis of collected data in order to calibrate the prediction model are reported in the followings.

3. DESCRIPTION OF EXPERIMENTAL CAMPAIGN AND ANALYSIS OF RESULTS

Side Friction Coefficient (SFC) and macro-texture (TXT) measurement have been carried out by means of a SCRIM (Side Coefficient Routine Investigation Machine) device along two main rural roads (namely S.S. 7quater and S.S. 7bis/dir) located in the ANAS road network in the district of Naples within one day in March 2003 (D'APUZZO et alii, 2005). The two roads have been chosen because of the high number of wearing courses of different age stressed by different traffic flows and spectra. Only conventional bituminous mixes designed according the ANAS specifications have been examined. The overall road stretch investigated is about 136 Km long and road is often characterised by a two-way single carriageway layout although there are some section where roadway has a two carriageway layout. In this case, measurements have been performed on both passing and normal lanes according to the Italian Standards (CNR, 1992).

Together with friction measurements, extensive data have been collected on:

- age of the surfaces;
- volumetric and grading properties of mixes laid on the road sections examined;
- mineralogical composition of mixes;
- traffic flows and spectra.

Data have been conveniently combined in order to derive for each pavement section the corresponding *neq* and *BEF* values. Following this phase, friction data and pavement and traffic data have been regressed in order to derive the model coefficients previously introduced. In the following table relevant statistics of the model proposed have been reported. A graphical representation of model is also depicted in the next figure (see Fig. 1).

Table 1 Regression statistics for the proposed model

Parameter	Value	Standard Error	t-ratio	Prob(t)*
a	-61.7267909	19.69142238	-3.134704528	0.00242
b	57.29436885	11.95341658	4.793137468	0.00001
c	89404037.99	15179643.23	5.889732495	0.0
d	27.5191113	4.042041285	6.808221234	0.0
e	30.38012371	1.892982382	16.04881483	0.0
Summary of main model statistics				
Number of observation = 84				
Sum of Residuals = -1.03329611533809E-09				
Average Residual = -1.23011442302153E-11				
Residual Sum of Squares (Absolute) = 961.188840083904				
Residual Sum of Squares (Relative) = 961.188840083904				
Standard Error of the Estimate = 3.48811515618883				
Coefficient of Multiple Determination (R^2) = 0.7976258158				
* Probability of rejecting the null hypothesis a, b ..e $\neq 0$				

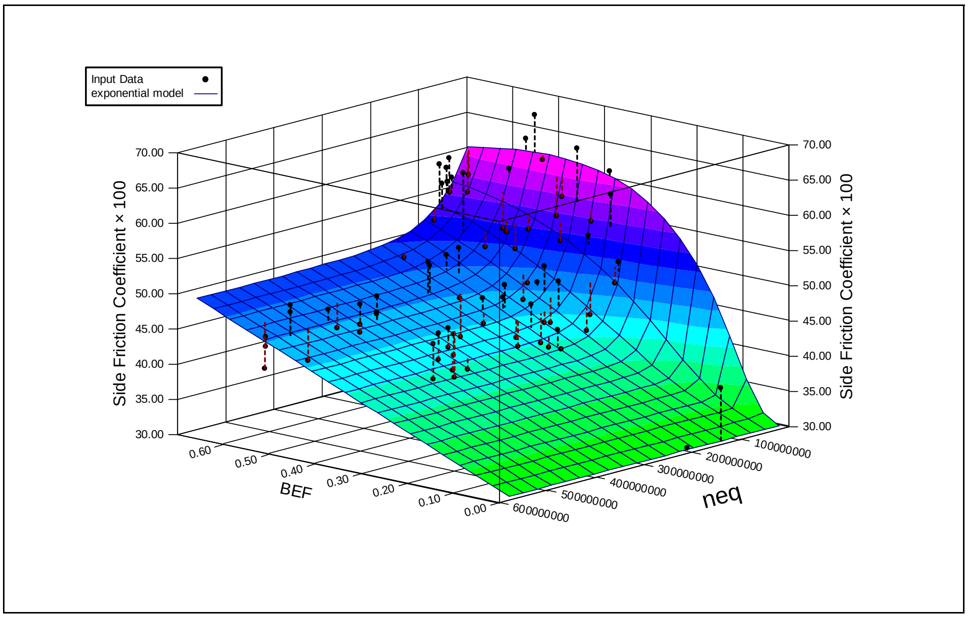

Figure 1 Graphical comparison between experimental data and model predictions

As it can be easily observed, the prediction capability of the model appears to be fairly good with a Correlation Coefficient of 0.80; furthermore coefficient values seem consistent with the model hypotheses.

It is also worth to notice that if the cumulated damage is to be calculated according to the approach proposed in early studies (the damage is proportional to the total tyre contact area), a lower Correlation Coefficient of 0.77 is obtained, thus providing an additional evidence in favour of the energy-based damage concept proposed.

4. CONCLUSIONS

A new Side Friction Coefficient progression model has been proposed. The mathematical prediction model has been developed by means of a synchronic approach following a friction measurements campaign lasting only one day. The model is dependent on cumulated traffic damage and on mix properties, and can be effectively employed if SFC progression of typical ANAS wearing courses is to be estimated.

Preliminary results seem to indicate that prediction potential is fairly good especially if it is compared with that pertaining progression models making use of different damage equivalency criteria, thus confirming the validity of the theoretical framework developed.

Further studies are needed in order to refine the evaluation of energy-based damage concept and to take into account seasonal effect.

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