ESTABLISHMENT OF A SKID RESISTANCE AND MACROTEXTURE MAINTENANCE PROGRAM IN DIFFERENT ROAD ENVIRONMENTS, BASED ON A COST-BENEFIT ANALYSIS

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ABSTRACT

Many countries have in their Pavement Management Systems, maintenance programs for functional properties of road pavements – skid resistance and macrotexture. However, most of them do not differentiate environments with distinct traffic, geometry and weather characteristics. The main purpose of this paper is to present the methodology and the main results of PhD research at Technical University of Lisbon (IST). This study deals with the problematic of establishing different threshold values, monitoring schedules and rehabilitation techniques in dissimilar road environments. This target will lead to an increment of traffic safety without, necessarily, increasing costs.

The first stage of this work consisted of applying different traffic characteristics, road geometry and weather conditions to road environments, using a cluster analysis. After that, the expected value of road crashes in different road scenarios was modelled with a Poisson Regression using also pavement condition as covariate. These results were fundamental to establish threshold values for the International Friction Index (IFI). Using equations that relate the evolution of skid resistance with traffic accumulated, it was possible to predict the remaining time until reach the threshold values established in the previous task of this study for each traffic condition.

Complementing these results with a Cost-Benefit Analysis, the final output of this research work was a skid resistance and macrotexture maintenance program that offers the best moment of action as well as the rehabilitation technique most economically advantageous for each road environment under specific traffic conditions, to ensure a durable and a safe pavement surface.

Keywords: skid resistance, macrotexture, road safety, pavement management, cost-benefit analysis

INTRODUCTION

A significant rise in traffic has been registered in the last few decades therefore, driving is now a task that involves more risks to the road user. However, in whole world, particularly in developed countries, Authorities have been doing great efforts to reduce road accidents, in acting in their three main causes – human behaviour, road environment and vehicles. While the road user must respect the rules, the road engineer has the responsibility to design safe roads, intervening in particular on road geometry, traffic signals and pavement design.

Nowadays, surface properties of road pavements are more relevant due to significant investment in new materials and technologies. Many countries have skid resistance and macrotexture guidelines to ensure safe levels on their roads (Highways Agency, 2004; Transit NZ, 2002) that result of research carried out on the relationship between surface properties and accident risk. In literature, there are several references to observational studies for the influence of pavement into road accidents (Gothié, 1993; Larson, 2005; Murad, 2006), the results of which indicate some trends, though they are not fully defined. For that reason, research is still needed concerning pavement surface properties and their relationship to traffic safety.

In Portugal, the traffic safety performance indicators used to assess functional road pavement quality, are skid resistance and macrotexture. The quality requirements for existing roads are generally related to maintenance programs. EP, the Portuguese Road Administration, has a new Pavement Management System, in which skid resistance and macrotexture are not considered directly in the Quality Index, but rather function as a trigger-parameter, due to their relationship to traffic safety. Low values of skid resistance and macrotexture are sufficient to prompt an investigation and an intervention, when necessary. EP recommends the use of the International Friction Index (IFI); at the moment, however, there are no reference values for this parameter (EP, 2006). This study may be a real contribution to fill this gap.

The recognition of the importance of surface pavement properties in road accidents comprehension is also expressed in the National Road Safety Plan (PNPR, 2003) through the objective V.2, transcribed below:

"(...) V.2 - Performance indicators in road safety
    (...) b) related with infrastructure
        - Coefficient of friction for dry and wet pavements (necessary to define acceptable coefficients by type of road) (...) ".

The heavy investments involved in road maintenance require more robust studies with more frequent monitoring of road conditions and more reliable accident data.

OBJECTIVES AND METHODOLOGY

The principal objective of the PhD thesis on which this paper is based is to contribute towards defining a maintenance programme for the surface characteristics of asphalt pavements in order to improve the quality of the Portuguese Road Network, thus reducing the probability and severity of road accidents. To reach this goal, the methodology adopted was structured around smaller targets, essentially based on safety and technical-economic criteria (Figure 1)..

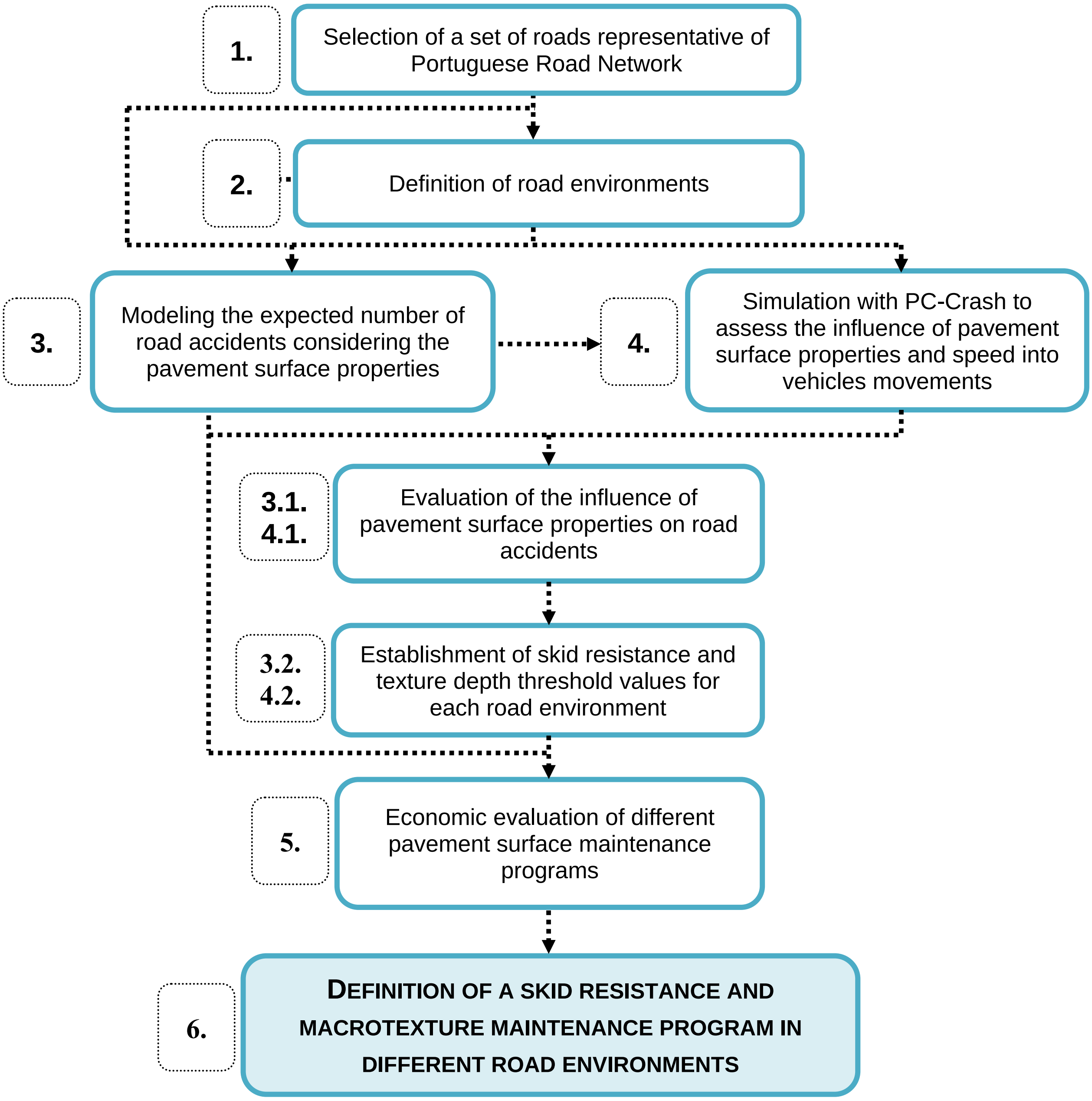

Figure 1 – Structure of the methodology adopted

This paper focuses essentially on the last two targets, however it is important to explain how the research was conducted to reach that point and which were the main results with importance for the last two objectives.

The study began with the selection of a set of roads, typically in rural environment, which sufficiently represents the primary and secondary Portuguese road network. For the selection procedure, a sequential type of non-random sampling method was chosen, as it was considered the most appropriate in light of data availability constraints.

Using cluster analysis, the selected itineraries were divided into 1 km-long segments and organised into quite homogeneous groups. The groups, denoted by type of road environment, possess different traffic characteristics, road layout and weather conditions.

Next, the expected number of accidents for each road environment was modelled by pavement condition in order to study the influence of surface pavement properties on accident risk. Generalised linear modelling was chosen as a statistical technique. From the results, and following analysis of the coefficients associated with the pavement condition variable, it was possible to establish minimum and safe skid resistance and texture depth threshold values, that were later used in the cost-benefit analysis.

The threshold values were validated using software for accident reconstruction, through the simulation of the most frequent manoeuvres in sections with typical characteristics of each road environment by varying surface properties and traffic speed.

Finally, using a cost-benefit analysis, alternative maintenance programmes were defined for each road environment under specific traffic conditions, considering different moments of action (preventive and limit) and distinct rehabilitation techniques. The more economic scenarios were proposed to define a skid resistance and macrotexture maintenance programme for asphalt pavements in different road environments. A more detailed methodology for this target is expressed in Figure 2.

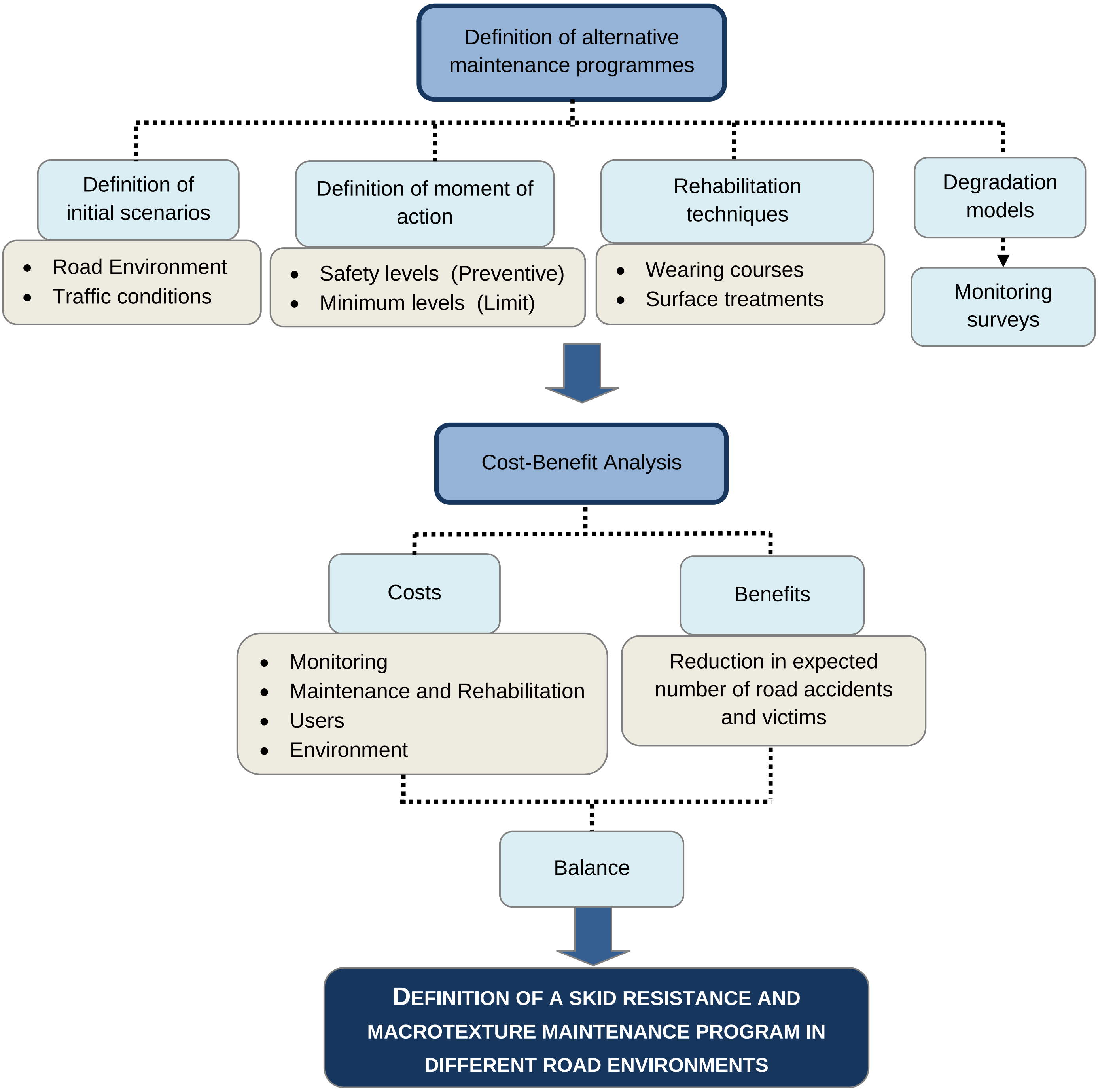

Figure 2 – Methodology for the cost-benefit analysis

DEFINITION OF SKID RESISTANCE AND MACROTEXTURE THRESHOLD VALUES BASED ON SAFETY CRITERIA

Selection of roads and collection of data

Roads were selected by applying a sequential type of non-random sampling method. Despite this method's disadvantages, it was considered the most appropriate for the prevailing conditions. The sample was chosen and adjusted according to the information available. To avoid a biased sample, roads covering different road categories (primary and secondary networks) were chosen, ensuring a varied geographical distribution and including good and bad levels of pavement conditions and road accidents. The final set comprises eight roads with a total length of 254 km (Table I).

Table I – Information about each road

Road	Province	Road Category	Length (km)	CAT	AAE	Number accidents	(Fatal. + Serious Inj.)/100accid
A	Lisboa	Secondary	19	34	0,584	121	36
B	C. Branco	Secondary	21	58	0,729	70	79
C	Beja	Principal	43	72	0,650	89	35
D	Évora	Secondary	15	61	0,586	90	46
E	Faro	Secondary	39	40	0,576	718	22
F	C. Branco	Principal	25	68	0,622	101	27
G	Vila Real	Principal	52	67	0,700	140	37
H	Bragança	Principal	40	69	0,675	65	108
TOTAL			254			1394	

The pavement surface characteristics were obtained from a pavement condition survey performed in 1999 by the Portuguese Road Administration and University of Minho. Skid resistance (CAT) and macrotexture (AAE) were measured at 60 km/h using, respectively, a SCRIM and a laser texturemeter device.

Accident data was collected from the Directorate-General for Traffic and just include accidents with victims that occurred between 1997 and 2002.

It is almost impossible to analyse the influence of pavement on road accidents without considering other explanatory variables. In addition to skid resistance, macrotexture and road accidents, information about traffic, road geometry and weather conditions was also collected. This information was obtained from the Portuguese Road Administration and the Hydro Resources Information System.

Definition of road environments – a cluster analysis

Some road environments require higher levels of skid resistance. To isolate different road environments with distinct traffic characteristics, road layouts and weather conditions, a cluster analysis was undertaken using STATISTICA 6.0 software. The variables used in the cluster analysis were carefully chosen to closely reflect reality and to appropriately characterise the road environments (RE). These variables include the percentage of heavy traffic (%H_TRAF), average speed (AV_SP), 85th percentile speed (SP_85), percentage of a segment's stretch in intersections (%EXT_I), percentage of a segment's stretch in urban zones (%EXT_UZ), curved stretch (EXT_C), class of curvature (CL_C), class of longitudinal gradient (CL_G) and annual precipitation (A_PREC).

The final result was a set of seven distinct road environments, a solution which presented better statistically significant results. Table II summarises information about each cluster, necessary to classify each road environment.

Table II: Means of variables for each cluster

Variables	Cluster 1 (RE1)	Cluster 2 (RE2)	Cluster 3 (RE3)	Cluster 4 (RE4)	Cluster 5 (RE5)	Cluster 6 (RE6)	Cluster 7 (RE7)	Mean	Standard Deviation
%H_TRAF	26%	4%	8%	7%	10%	9%	9%	10%	6%
AV_SP (km/h)	81	81	84	83	89	94	85	86	5
SP_85 (km/h)	90	90	94	92	91	101	93	94	4
%EXT_I	7,9%	29,2%	2,1%	3,8%	10,4%	7,3%	50,3%	11,7%	19,4%
%EXT_UZ	23%	87%	1%	1%	0%	0%	0%	7%	24%
EXT_C (m)	320	220	41	466	486	471	270	321	264
CL_C	2,3	1,8	0,1	2,2	3,0	2,3	1,7	1,8	1,5
CL_G	0,3	0,0	0,1	0,3	0,8	0,6	0,2	0,4	0,4
A_PREC (mm)	1058	735	591	693	1669	490	722	881	461
Number of elements	19	15	63	38	55	39	25		

From Table 2, one may conclude the following:

- RE1 differs from the others with its very high percentage of heavy traffic and a significant proportion of urban crossings;
- RE2 is characterised by an extremely high percentage of urban crossings, a low percentage of heavy traffic and segments with no longitudinal gradient;
- RE3 segments are mostly straight, with low annual average precipitation;
- RE4 is characterised by segments with 50% of their stretch curved;
- RE5 is characterised by very high precipitation and segments with 50% of their stretch curved, a longitudinal gradient and a small radius of curvature;
- RE6 is characterised mainly by very low precipitation and speeds above the acceptable speed, and by segments with 50% of their stretch curved with a longitudinal gradient;
- RE7 is characterised by a heavy presence of intersections in rural areas.

For further research, it is important to note that With cluster analysis, one starts with the assumption that the characteristics of each element in each cluster are homogenous. However, while this may naturally occur in some variables, it is not true for all of them. In the final seven groups, some features clearly differentiate the cluster, while others are less important and present some variation (though lower within a group than between groups).

Modelling the expected value of road accidents using GLZ

Modelling the expected number of road accidents (Naccid/km) was achieved by using generalised linear models in order to assess the influence of pavement surface properties on road accidents. The International Friction Index (IFI) was chosen to represent the pavement surface. For SCRIM and texturemeter, the formula that relates the IFI with skid resistance (CAT) and macrotexture (AAE) measurements is presented in Equations 1 and 2.

$$\mathrm{IFI} = -0{,}0141 + 0{,}875 \times \mathrm{CAT} \times \mathrm{e}^{\left(\frac{-39{,}5}{\mathrm{S_p}}\right)} \tag{1}$$

$$\mathrm{S_p} = 17{,}63 + 93 \times \mathrm{AAE} \tag{2}$$

Where Sp is the speed constant.

Equation 3 represents the general model, where β_i is the regression coefficient associated with each variable. Traffic volume was introduced in the model as an “offset variable” to represent exposure to risk. To do this, a variable representative of the total traffic accumulated during the period of analysis, $\mathrm{TRAF_{ACUM}}$, was created

$$\begin{aligned}\mathrm{N_{accid}/km} = {} & \mathrm{TRAF_{ACUM_i}} \\ & \times \exp\big(\beta_0 + \beta_1 \times \mathrm{IFI_i} + \beta_2 \times \%\mathrm{H_{TRAF_i}} + \beta_3 \\ & \times \mathrm{AV\_SP_i} + \beta_4 \times \mathrm{SP\_85_i} + \beta_5 \times \%\mathrm{EXT\_UZ_i} + \beta_6 \\ & \times \%\mathrm{EXT\_I_i} + \beta_7 \times \mathrm{EXT\_C_i} + \beta_8 \times \mathrm{CL\_C_i} + \beta_9 \\ & \times \mathrm{CL\_G_i} + \beta_{10} \times \mathrm{A\_PREC_i}\big)\end{aligned} \tag{3}$$

The influence of surface characteristics on accident occurrence was evaluated by analysing the coefficients associated with the explanatory variable IFI and measuring the impact that a change in IFI produces in the expected number of accidents.

From this analysis, it was possible to conclude that there are, basically, three environments (E_i) where the pavement properties significantly, yet distinctly, influence the occurrence of accidents:

- E_1: Rural environment with a heavy presence of urban characteristics (e.g., urban crossings and intersections) – RE1 and RE2;
- E_2: Environment characterised by a considerable predominance of intersections in a rural environment – RE7;
- E_3: Environment with curved segments, high longitudinal gradients and average speed higher than the tolerable speed – RE6.

Figure 3 represents the accident risk (Naccid/vehic.km) as a function of IFI where one can see some differences between the three environments. Clearly in E_3, when IFI falls below 30, there is a sharp increase in accident risk, reaching unacceptable levels for values below 22. In environments with urban characteristics (E_1) and intersections (E_2), where braking manoeuvres are often necessary, the permissible IFI values fall to 20 and 25, respectively, while for smaller values a strong increase in accident risk is expected.

The IFI, skid resistance (CAT) and macrotexture (AAE) threshold values for these three environments were established according to these results and by using the relationship between IFI, CAT and AAE, as expressed in Equation 1 and Equation 2. As the Highways Agency (2004) recommends, the values should not be set too low. Therefore, safety values were also set to intervene in a preventive manner. These safety values translate into an increase from the minimum values of 0.1 mm for texture depth, 10 units for coefficient of friction and 3 to 5 units for IFI (Table III).

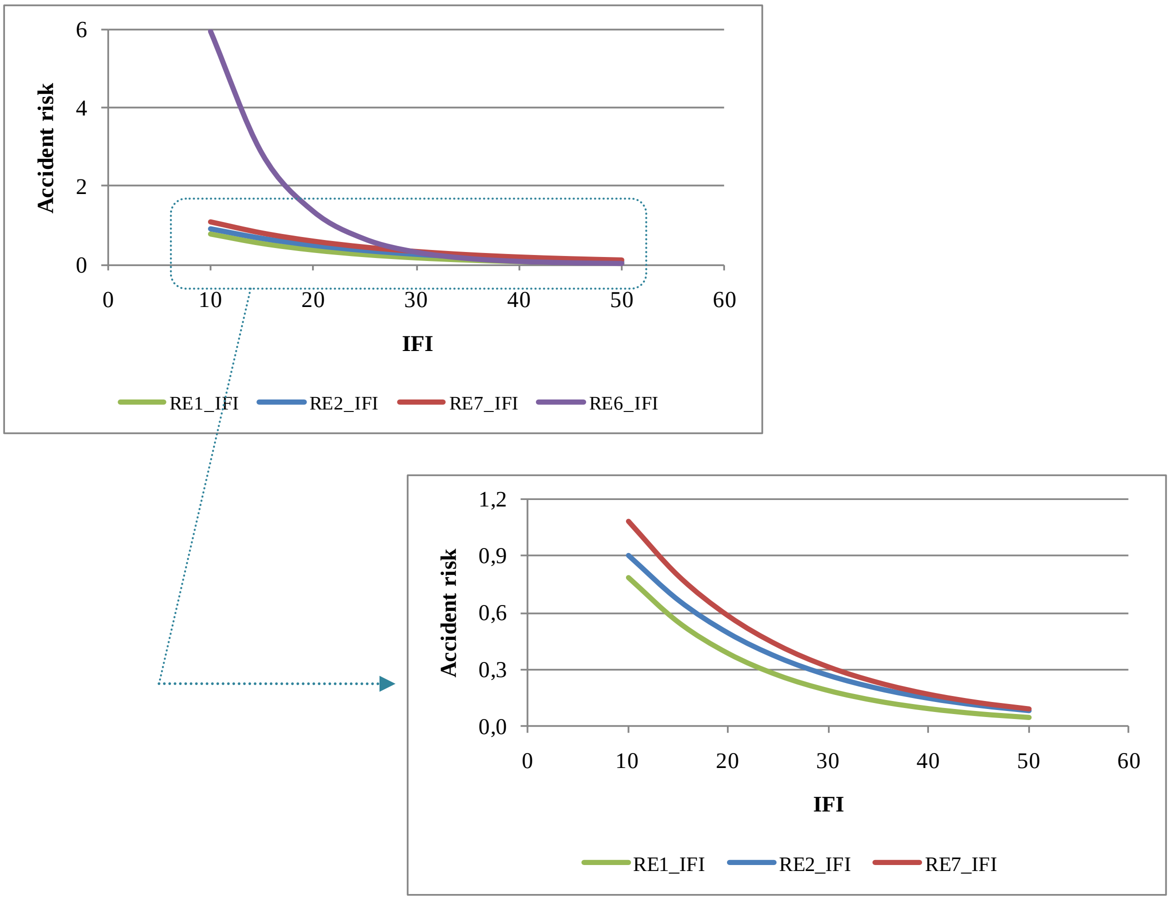

Figure 3: Accident risk and IFI

Table III: Threshold values for IFI, coefficient of friction (measured at 60km/h) and texture depth

	Minimum Values / Safety Values		
	IFI	CAT	AAE (mm)
E_1	20 / 25	40 / 50	0,4 / 0,5
E_2	25 / 28	45 / 55	0,4 / 0,5
E_3	30 / 33	50 / 60	0,5 / 0,6

A COST-BENEFIT ANALYSIS OF DIFFERENT PAVEMENT SURFACE MAINTENANCE PROGRAMMES

So far, one tried to define threshold values for skid resistance and macrotexture based on safety criteria.

In this chapter, one proposes to define maintenance programmes for surface pavement characteristics appropriate to different road environments under specific traffic conditions. To reach this objective, the pre-established limits, based on safety criteria, were subjected to an economic analysis to decide in which circumstances it is more advantageous to act: when they reach the minimum values or the safety values and which rehabilitation technique is most economically advantageous.

Definition of alternative maintenance programmes

The definition of alternative maintenance programmes to be used in the cost-benefit analysis (CBA) comprised the following five steps:

- Definition of basic scenarios
- Establishment of two different moments of intervention
- Selection of rehabilitation techniques
- Estimation of the skid resistance degradation with traffic accumulated
- Monitoring surveys schedule

Definition of basic scenarios

The basic scenarios were applied to segments with 1 km length situated in the three road environments defined previously (Table IV) and subject to three traffic conditions: low, moderate and high volume (Table V).

The pavement, in first year, is a traditional asphalt concrete pavement with initial skid resistance equal to 65.

Table IV: Road environments

Road Environments	Description
E_1	Rural environment with a heavy presence of urban characteristics
E_2	Environment characterised by a considerable predominance of intersections in a rural environment
E_3	Environment with curved segments, high longitudinal gradients and average speed higher than the tolerable speed

Table V: Traffic categories

Traffic category	AADT (veh/day)	Values assumed for CBA (veh/day)
T_1	Low: ≤ 8000	4000
T_2	Moderate: Between 8000 and 20000	12000
T_3	High: ≥ 20000	30000

Moment of intervention

The two moments established for intervention (to improve skid resistance and macrotexture) correspond to two perspectives: one preventive and one limit:

- **M_1**: Preventive – to act when pavement skid resistance and macrotexture reach safety values. These are slightly above the minimum limits and, consequently, it requires more frequent interventions but with a greater reducing in skid accident risk.
- **M_2**: Limit – to act only when pavement skid resistance and macrotexture reach minimum values, below which there is a higher risk of accident.

Table VI shows the values of skid resistance (CAT), macrotexture (AAE) and International Friction Index (IFI) for each moment of intervention and road environment. Those values represent the ones that were established in previous target. The intervention, in any perspective, should be done whenever one of them is below the limit set.

Table VI: Threshold values for skid resistance and macrotexture in each road environment

Road Environment	Parameter	Perspective Preventive (**M_1**)	Perspective Limit (**M_2**)
E_1	CAT	50	40
	AAE (mm)	0,50	0,40
	IFI	25	20
E_2	CAT	55	45
	AAE (mm)	0,50	0,40
	IFI	28	25
E_3	CAT	60	50
	AAE (mm)	0,60	0,50
	IFI	33	30

Selection of rehabilitation techniques for pavement surface properties

For the cost-benefit analysis, one chose the techniques that are most used in the Portuguese Road Network (Table VII).

Solutions from R_1 to R_5 consider milling before the application of the new layer. Solution R_6 can only be applied in small extensions (no more than 250m) and in zones with low traffic. For that reason, R_6 was only tested on road environments E_1 and E_2 (in approaching to intersections or urban crossings) with traffic T_1. The other solutions are possible to apply in either scenario.

In every solutions, one considers that the pavement is in good structural condition.

Table VII specifies indicative values for CAT and AAE reached after the rehabilitation with each technique. One considers that a traditional asphalt pavement is the solution with lower initial skid resistance values. The friction asphalt concrete mixtures achieves the highest skid resistance values and open-graded asphalt mixtures present less tire-pavement contact points, due to their higher porosity and consequently skid resistance values are slightly smaller but even higher than traditional asphalt concrete. Skid resistance and macrotexture for anti-skidding surface and shot-blasting were determined in researchs realized by the Technical University of Lisbon (Menezes et al., 2009) and by the National Laboratory for Civil Engineering (Antunes et al., 2008).

Table VII: Rehabilitation techniques. Values for CAT and AAE after the application of each technique

Rehabilitation solution		Abbreviation	CAT_{after} (approximate)	AAE_{after} (mm) (minimum)
R_1	Milling and replacement with traditional asphalt concrete	AC14 surf (BB)	65	0,80
R_2	Milling and replacement with friction asphalt concrete	AC14 surf (BBr)	75	1,00
R_3	Milling and replacement with thin friction asphalt concrete layers	AC10 surf (mBBr)	75	1,00
R_4	Milling and replacement with open asphalt rubber mixture	MBA-BMB	70	1,15
R_5	Milling and replacement with porous asphalt concrete	PA12,5	70	1,25
R_6	Application of anti-skidding surfacing	RAD	70	1,00
R_7	Shot-Blasting	Gr	80	1,00

Skid resistance degradation

The prediction of skid resistance and macrotexture degradation is fundamental to road managers plan monitoring surveys.

Given the significant differences between the models available in the literature (Do et al., 2009, Baptista & Matos, 2008, LNEC, 2005), that are used to predict skid resistance deterioration, and their low adaptability to this reality, one chose to simulate the evolution of functional properties by assigning an annual degradation rate, according to traffic category and technique of rehabilitation (Equation 4).

It was considered, moreover, that the degradation rate of skid resistance would not be the same over the years, but it has an annual reduction (t_{deg_a}). This consideration allowed simulating the stabilization of the skid resistance over the years (Equation 5).

$$CAT_{n+1} = CAT_n \times (1 - t_{deg_n}) \tag{4}$$

$$t_{deg_n} = t_{deg_1} \times (1 - t_{deg_a})^{n-1} \tag{5}$$

where, CAT_{n+1} – Skid resistance in year $n+1$
CAT_n – Skid resistance in year n
t_{deg_n} – Annual degradation rate of the skid resistance in year n
t_{deg_a} – Annual degradation rate reduction
$n = 1, \ldots, 20.$

The choice of the initial degradation rate and the annual degradation rate reducing, represented in Table VIII, took into account that the average lifetime of rehabilitation treatments can vary between 3 to 5 years for micro wearing courses and between 7 to 10 years for macro and reinforcement layers (Chelliah et al., 2003).

The skid resistance degradation rate depends on the aggregate properties and weather conditions so, it was decided to established a range of values instead of a fixed value. In anti-skidding surfacing it was used an initial degradation rate of 7%.

During the analysis, when friction coefficient reaches the values defined in the two perspectives (M_1 and M_2), the pavement is improved and its skid resistance rises to the values given in Table VII.

One excluded from the cost-benefit analysis, all the scenarios that would require more than five interventions in the period of analysis, which is not considered a reasonable policy.

Table VIII: Skid resistance degradation rates

Traffic Category	Initial annual degradation rate t_{deg_1}(%)		Annual degradation rate reduction t_{deg_a}(%)
	Possible values	Adopted values	
T_1	2 to 5	4	10
T_2	6 to 8	7	
T_3	9 to 10	9	

Monitoring survey schedule

Monitoring surveys were scheduled according to the average lifetime of the wearing course (or surface treatment). In cases where lifetime is expected to be between 4 and 8 years, one recommends two campaigns and when it is greater than 3 years, it is recommended three campaigns. The spacing between two surveys varies according to the expected lifetime of the wearing course (or treatment).

Cost-Benefit Analysis

In this chapter, the social return of the measures proposed in each alternative maintenance programme is calculated, through the analysis of the balance between the consequent benefits and the costs of investment.

Costs

Table IX shows the unit costs of each rehabilitation solution, that correspond to the national average of 2007 works (Antunes et al., 2009). As the base year is 2009, the unit costs from 2007 were updated with the inflation rates provided by Bank of Portugal.

The costs of monitoring surveys were also identified (Table X). It was assumed that the monitoring campaigns always encompassed measurements of skid resistance and macrotexture.

Table IX: Unit costs of each rehabilitation technique per km (prices of 2009)

	Thickness (m)	Width (m)	Average Cost (€/km)
AC14 surf (BB)	0,05	3,5+3,5	42.350,00
AC14 surf (BBr)	0,05	3,5+3,5	34.580,00
AC10 surf	0,03	3,5+3,5	29.750,00
MBA-BMB	0,04	3,5+3,5	35.700,00
PA12,5	0,04	3,5+3,5	25.900,00
RAD	0,004	3,5+3,5	175.000,00
Gr	-	3,5+3,5	14.000,00
Milling	0,05	3,5+3,5	18.340,00

Table X: Unit costs of skid resistance and macrotexture monitoring surveys (prices of 2009)

Property	Device	Cost (€/km)
Skid resistance	Grip-Tester	40,00
Macrotexture	Laser device	35,00

Benefits

To calculate the economic benefits of proposed interventions, one considers the reduction in the expected number of accidents caused by rising the skid resistance and/or the macrotexture. The benefit corresponds to the total value saved by the reduction in the number of fatalities, serious injuries and slight injuries. Equation 6 represents that "gain" and Table XI resumes the unit costs:

$$B_{accid} = C_F \times N_F + C_{SI} \times N_{SI} + C_{LI} \times N_{LI} \tag{6}$$

where, B_{accid} – Reduction in the cost of accidents

C_F – Cost of a fatality
C_{SI} – Cost of a serious injury
C_{LI} – Cost of a light injury
N_F – Reduction in the number of fatalities
N_{SI} – Reduction in the number of serious injuries
N_{LI} – Reduction in the number of light injuries

Table XI: Costs per fatality, serious injury and light injury (Bickel et al., 2006)

	(€, 2002)	(€, 2009)
C_F	803.000	966.648
C_{SI}	107.400	129.288
C_{LI}	7.400	8.907

Residual value

In this particular case, the residual value of the pavement represents its functional potential at the end of the period of analysis, considering the last functional rehabilitation. The estimated residual value (RV), based only on it functional capacity, was calculated using Equation 7:

$$RV = C_f \times \frac{(A-P)}{D} \tag{7}$$

where, C_f – Cost of the last functional rehabilitation

A – Year of the next functional intervention (year of the last intervention plus the expected lifetime of the rehabilitation technique)
P – Period of analysis (20 years)
D – Expected lifetime of rehabilitation technique

In scenarios where the lifetime is more than 20 years, the residual value corresponds to 10% of the cost of the last intervention. In situations where there was no intervention during the analysis period, the cost of intervention is zero and therefore, it the residual value is zero.

Balance

The balance, also called the Net Present Value (NPV) is calculated by Equation 8.

$$NPV = \sum_{n=1}^{T} \left(\frac{B-C}{(1+d)^{n-1}}\right) + RV \times \left(\frac{1}{(1+d)^T}\right) \tag{8}$$

where, B – Benefits in year n

C – Costs in year n
d – Discount rate
T – Period of analysis
RV – Residual value

Looking at Table XII to XIV, it is obvious the prevalence of the costs of rehabilitation in the total cost of each scenario. Although not negligible, the cost of monitoring has order of magnitude much less than the cost of intervention. The residual value of the pavement has order of magnitude between 5% and 35% of the total cost. It is greater, the later the intervention is made.

All of the scenarios present BCR (benefit-cost ratio) greater than the unit, which means that all of them have a positive social return.

Table XII: Present costs, present benefits, NPV and BCR of all the scenarios in E_1

Scenario	Present monitoring costs (€/km)	Present rehabilitation costs (€/km)	Present total costs (€/km)	Present benefits (€/km)	Present residual value (€/km)	NPV (€/km)	BCR
E1T1M1R1	254,67	40.999,99	41.254,66	131.237,92	5.036,02	95.019,28	3,2
E1T1M1R2	174,34	35.750,86	35.925,19	191.040,99	2.415,20	157.531,00	5,3
E1T1M1R3	174,34	32.487,88	32.662,22	191.040,99	2.194,76	160.573,54	5,8
E1T1M1R4	214,38	36.507,49	36.721,87	174.602,43	12.331,58	150.212,13	4,8
E1T1M1R5	214,38	29.886,96	30.101,34	189.488,59	10.095,28	169.482,53	6,3
E1T1M1R6	295,02	52.914,42	53.209,44	264.683,89	9.983,46	221.457,92	5,0
E1T1M1R7	174,34	9.457,90	9.632,23	204.227,53	638,94	195.234,24	21,2
E1T2M1R1	360,17	124.581,75	124.941,91	1.227.959,38	5.539,62	1.108.557,09	9,8
E1T2M1R2	267,23	75.278,76	75.545,99	1.332.877,68	6.038,00	1.263.369,69	17,6
E1T2M1R3	267,23	68.408,08	68.675,31	1.332.877,68	5.486,91	1.269.689,29	19,4
E1T2M1R4	316,32	107.262,98	107.579,30	1.471.498,03	16.442,10	1.380.360,82	13,7
E1T2M1R5	316,32	87.811,15	88.127,47	1.596.954,23	13.460,37	1.522.287,13	18,1
E1T2M1R7	268,77	18.981,69	19.250,46	1.238.522,85	4.646,85	1.223.919,24	64,3
E1T2M2R1	249,63	39.423,07	39.672,70	672.934,14	9.232,71	642.494,15	17,0
E1T2M2R2	172,39	34.375,82	34.548,21	831.074,59	2.415,20	798.941,58	24,1
E1T2M2R3	172,39	31.238,35	31.410,73	831.074,59	2.194,76	801.858,62	26,5
E1T2M2R4	210,89	35.103,35	35.314,24	787.605,21	12.331,58	764.622,55	22,3
E1T2M2R5	210,89	28.737,46	28.948,35	826.969,48	10.095,28	808.116,41	28,6
E1T2M2R7	172,39	9.094,13	9.266,52	865.944,44	638,94	857.316,87	93,4
E1T3M1R1	465,42	166.533,34	166.998,75	4.124.597,34	6.924,53	3.964.523,12	24,7
E1T3M1R2	361,80	109.241,51	109.603,31	4.544.117,01	12.076,00	4.446.589,70	41,5
E1T3M1R3	361,80	99.271,06	99.632,86	4.544.117,01	10.973,82	4.455.457,98	45,6
E1T3M1R4	407,40	141.017,84	141.425,23	4.683.929,85	24.663,15	4.567.167,77	33,1
E1T3M1R5	407,40	115.444,65	115.852,05	5.083.269,85	20.190,56	4.987.608,36	43,9
E1T3M1R7	315,64	27.972,19	28.287,82	4.394.696,14	5.476,64	4.371.884,96	155,4
E1T3M2R1	252,72	81.166,37	81.419,09	3.697.586,96	7.913,75	3.624.081,61	45,4
E1T3M2R2	251,05	66.337,65	66.588,70	3.664.800,74	21.956,36	3.620.168,39	55,0
E1T3M2R3	251,05	60.283,02	60.534,08	3.664.800,74	19.952,41	3.624.219,07	60,5
E1T3M2R4	295,02	69.918,36	70.213,38	3.883.643,40	16.442,10	3.829.872,12	55,3
E1T3M2R5	295,02	57.238,86	57.533,88	4.077.746,69	13.460,37	4.033.673,18	70,9
E1T3M2R7	209,02	10.638,85	10.847,87	3.401.255,83	1.277,88	3.391.685,85	313,5

Table XIII Present costs, present benefits, NPV and BCR of all the scenarios in E_2

Scenario	Present monitoring costs (€/km)	Present rehabilitation costs (€/km)	Present total costs (€/km)	Present benefits (€/km)	Present residual value (€/km)	NPV (€/km)	BCR
E2T1M1R1	304,15	115.829,27	116.133,43	346.900,12	23.081,77	253.848,46	3,0
E2T1M1R2	214,71	41.823,44	42.038,15	376.918,71	3.220,27	338.100,82	9,0
E2T1M1R3	214,71	38.006,23	38.220,94	376.918,71	2.926,35	341.624,12	9,9
E2T1M1R4	304,15	72.715,09	73.019,24	428.875,53	13.701,75	369.558,03	5,9
E2T1M1R5	304,15	59.528,42	59.832,57	482.814,71	11.216,98	434.199,12	8,1
E2T1M1R6	398,64	110.992,96	111.391,60	830.327,44	14.975,20	733.911,04	7,5
E2T1M1R7	165,99	11.064,40	11.230,39	414.948,88	638,94	404.357,43	36,9
E2T2M1R2	376,27	113.611,17	113.987,44	2.633.427,48	8.050,67	2.527.490,70	23,1
E2T2M1R3	376,27	103.241,90	103.618,17	2.633.427,48	7.315,88	2.537.125,19	25,4
E2T2M1R7	328,26	29.091,07	29.419,34	2.642.230,42	4.563,87	2.617.374,96	89,8
E2T2M2R1	252,72	81.166,37	81.419,09	1.734.197,43	7.913,75	1.660.692,08	21,3
E2T2M2R2	249,63	65.332,93	65.582,56	1.782.990,83	24.152,00	1.741.560,27	27,2
E2T2M2R3	249,63	59.370,00	59.619,63	1.782.990,83	21.947,65	1.745.318,84	29,9
E2T2M2R4	254,20	68.808,65	69.062,85	1.848.532,07	19.730,52	1.799.199,74	26,8
E2T2M2R5	254,20	56.330,40	56.584,60	1.983.322,54	16.152,45	1.942.890,39	35,1
E2T2M2R7	204,31	10.638,85	10.843,16	1.785.543,88	1.879,24	1.776.579,96	164,7
E2T3M1R7	365,64	39.514,22	39.879,86	9.290.811,74	3.833,65	9.254.765,53	233,0
E2T3M2R1	360,17	124.581,75	124.941,91	6.979.719,31	5.539,62	6.860.317,03	55,9
E2T3M2R2	267,23	75.278,76	75.545,99	7.060.889,28	6.038,00	6.991.381,29	93,5
E2T3M2R3	267,23	68.408,08	68.675,31	7.060.889,28	5.486,91	6.997.700,88	102,8
E2T3M2R4	306,17	103.819,84	104.126,01	7.075.948,18	24.663,15	6.996.485,32	68,0
E2T3M2R5	306,17	84.992,41	85.298,58	7.591.909,14	20.190,56	7.526.801,12	89,0
E2T3M2R7	307,77	19.280,68	19.588,45	6.829.933,16	3.833,65	6.814.178,36	348,7

Table XIV: Present costs, present benefits, NPV and BCR of all the scenarios in E_3

Scenario	Present monitoring costs (€/km)	Present rehabilitation costs (€/km)	Present total costs (€/km)	Present benefits (€/km)	Present residual value (€/km)	NPV (€/km)	BCR
E3T1M1R2	321,75	106.539,59	106.861,33	2.326.459,24	24.152,00	2.243.749,90	21,8
E3T1M1R3	321,75	96.815,74	97.137,48	2.326.459,24	21.947,65	2.251.269,41	24,0
E3T1M1R4	423,69	146.658,55	147.082,24	2.914.192,99	19.730,52	2.786.841,27	19,8
E3T1M1R5	423,69	120.062,44	120.486,13	3.183.961,68	16.152,45	3.079.627,99	26,4
E3T1M1R7	321,75	20.219,65	20.541,40	2.031.677,60	4.259,61	2.015.395,81	98,9
E3T1M2R1	254,67	40.999,99	41.254,66	1.583.449,94	5.036,02	1.547.231,30	38,4
E3T1M2R2	174,34	35.750,86	35.925,19	1.930.454,71	2.415,20	1.896.944,72	53,7
E3T1M2R3	174,34	32.487,88	32.662,22	1.930.454,71	2.194,76	1.899.987,26	59,1
E3T1M2R4	214,38	36.507,49	36.721,87	1.857.754,74	12.331,58	1.833.364,45	50,6
E3T1M2R5	214,38	29.886,96	30.101,34	1.924.313,81	10.095,28	1.904.307,75	63,9
E3T1M2R7	174,34	9.457,90	9.632,23	1.976.579,48	638,94	1.967.586,19	205,2
E3T2M1R7	365,64	39.514,22	39.879,86	11.432.297,40	3.833,65	11.396.251,19	286,7
E3T2M2R1	360,17	124.581,75	124.941,91	14.815.933,20	5.539,62	14.696.530,91	118,6
E3T2M2R2	267,23	75.278,76	75.545,99	13.468.627,70	6.038,00	13.399.119,71	178,3
E3T2M2R3	267,23	68.408,08	68.675,31	13.468.627,70	5.486,91	13.405.439,30	196,1
E3T2M2R4	316,32	107.262,98	107.579,30	15.656.611,97	16.442,10	15.565.474,77	145,5
E3T2M2R5	316,32	87.811,15	88.127,47	16.217.552,31	13.460,37	16.142.885,21	184,0
E3T2M2R7	268,77	18.981,69	19.250,46	11.986.821,10	4.646,85	11.972.217,49	622,7
E3T3M2R1	465,42	166.533,34	166.998,75	49.765.293,25	6.924,53	49.605.219,03	298,0
E3T3M2R2	361,80	109.241,51	109.603,31	45.917.957,10	12.076,00	45.820.429,79	418,9
E3T3M2R3	361,80	99.271,06	99.632,86	45.917.957,10	10.973,82	45.829.298,07	460,9
E3T3M2R4	407,40	141.017,84	141.425,23	49.836.609,15	24.663,15	49.719.847,07	352,4
E3T3M2R5	407,40	115.444,65	115.852,05	51.622.140,03	20.190,56	51.526.478,54	445,6
E3T3M2R7	315,64	27.972,19	28.287,82	42.533.277,82	5.476,64	42.510.466,64	1503,6

The CBA results allow to conclude about the better moments to act and the most appropriate techniques for each road environment and traffic category:

In E_1:

- In sections with low traffic (T_1), in accordance with the established function of degradation, the values defined as the minimum limits are never reached in a period of 20 years. Operating in a perspective of prevention, it is necessary to rehabilitate, but where the benefits achieved by reducing the accident rate are largely superior to total cost (monitoring and rehabilitation).
- In situations of moderate and high traffic (T_2 and T_3), both moments of intervention are possible, however, the balance between benefits and costs involved, points to a more favorable economic return if action is taken in a preventive way. As the annual degradation induced by traffic is larger, the difference in NPV, in scenarios M_1 and M_2 is smaller. At a certain moment scenario M_1 is impractical, because too many

interventions will be necessary to prevent the pavement to reach values lower than those established in this context.

- Reducing the safety limits established in M_1 resulted in an immediate reduction in the cost of rehabilitation, because it is required less interventions. The benefits also decrease, because the intervention occurs only when the skid resistance reaches lower values and, therefore, the section is exposed to a higher risk of accidents. The NPV is less than the one achieved with the pre-established limits so, one considers that these are the most advantageous.
- Considering the costs assumed in the CBA, in situations of low traffic, the technique economically more advantageous is the anti-skidding surface. In case of moderate or high traffic, the rehabilitation techniques that have a higher NPV are the open-graded wearing courses (MBA-BMB and PA12,5).

In E_2:

- As in E_1, in sections with low traffic, the values defined as the minimum limits are never reached in a period of 20 years. Operating in a perspective of prevention, benefits achieved by reducing the accident rate are largely superior to total cost.
- In some scenarios with moderate to high traffic, the preventive perspective resulted in too much interventions in the period of analysis, which is almost impractical. In scenarios where it is possible to choose M_2, this is the scenario more advantageous with moderate traffic, when it is not possible, reducing safety values in 5 units can bring more benefits. With high traffic, the better solution is choosing limit values.
- Again, the technique most advantageous in situations of low traffic is the anti-skidding surface and the ones that have a higher NPV, in cases of moderate to high traffic, are MBA-BMB and PA12,5. When the sections are located outside areas with frequent precipitation, the friction mixtures are the most recommended.

In E_3:

- In sections characterized by low traffic, T_1, the preventive perspective is economically better than the limit. In both cases, the total cost is noticeably low than the benefits reached with the intervention.
- In situations of moderate and high traffic, the preventive perspective demands too much interventions in 20 years. Thus, one suggests M_1, which balance is positive.
- The techniques recommended for low traffic are the open-graded mixtures.

CONCLUSIONS

This work constitutes a further scientific attempt to establish relationships between functional characteristics of pavement and road accidents by using a set of roads selected from the Portuguese road network.

Results show that road environments where braking manoeuvres (E_1 and E_2) are more common or those with small radii of curvature and high speeds (E_3) require higher skid resistance and macrotexture levels.

The cost-benefit analysis provides the assessment of the social return consequent from the improvement of the pavement surface characteristics: suggesting the best moment to act and defining which rehabilitation technique is most economically favourable for each road environment. Table XV summarizes the conclusions of the work

Table XV: Moment of intervention and rehabilitation technique most economically favourable

Road Environment	Traffic category	Moment of intervention	Rehabilitation technique
E_1	T_1	Preventive (safety values) CAT: 50 AAE: 0,5 mm IFI: 25	- Highest VAL: Anti-skidding surface - Highest BCR: Shot-Blasting
	T_2 e T_3	Preventive (safety values) CAT: 50 AAE: 0,5 mm IFI: 25	- Highest VAL: Porous asphalt - Highest BCR: Shot-Blasting
E_2	T_1	Preventive (safety values) CAT: 55 AAE: 0,5 mm IFI: 28	- Highest VAL: Anti-skidding surface - Highest BCR: Shot-Blasting
	T_2	Preventive with reduction of 5 units in CAT CAT: 50 AAE: 0,5 mm IFI: 28	- Highest VAL: Porous asphalt - Highest BCR: Shot-Blasting
	T_3	Limit (Minimum values) CAT: 45 AAE: 0,4 mm IFI: 25	- Highest VAL: Porous asphalt - Highest BCR: Shot-Blasting
E_3	T_1	Preventive (safety values) CAT: 60 AAE: 0,6 mm IFI: 33	- Highest VAL: Open-graded mixtures - Highest BCR: Shot-Blasting
	T_2 e T_3	Limit (Minimum values) CAT: 50 AAE: 0,5 mm IFI: 30	- Highest VAL: Porous asphalt - Highest BCR: Shot-Blasting

Legend: T_1 – Low traffic – TMDA≤ 8000 veh/day
T_2 – Moderate traffic – 8000 < TMDA < 20000 veh/day
T_3 – High traffic – TMDA ≥ 20000 veh/day

The Portuguese Highways Agency recently recognised the importance of research studies to support the development of maintenance programmes for surface characteristics to be incorporated into pavement management systems. This work seeks to be useful to Road Administrations, as it may:

- Contribute with reference skid resistance and macrotexture values to be used in a pavement management system, having in consideration the different characteristics of road environments.
- Include the CBA methodology in the selection of the best moment of intervention and rehabilitation technique, considering the benefits resultants from the expected accident reduction.

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