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Life-cycle cost analysis system for pavement management at project level: sensitivity analysis to the discount rate

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The Portuguese manual of pavement structures, despite the fact it uses a design period of 20 years for flexible pavements, states the importance of making a life-cycle cost analysis (LCCA) for a period of no less than 40 years. This paper presents a sensitivity analysis to the discount rate that was carried out on the application of a new LCCA system, called OPTIPAV, developed and programmed to help pavement designers to choose the best pavement structure for a road or highway. The OPTIPAV system uses the serviceability concept adopted by the American Association of State Highway and Transportation Officials (AASHTO) for use in the design of flexible pavements. The results obtained by the application of the new LCCA system clearly indicate that, for any combination between traffic and pavement foundation, the optimum pavement structure always remains the same or decreases in terms of structural capacity with the increase of the discount rate value.

Keywords: roads and highways; pavement design; life-cycle cost analysis; optimisation models; mathematical modelling; genetic algorithms

1. Background

Life cycle cost analysis (LCCA) has received increasing attention as a tool to assist transportation agencies in order to be able to make more economical investment decisions. When analysing long-term public investments, we must compare costs and benefits that occur in different time periods. As time has a money value, a dollar spent in the future is worth less than the present dollar (Jawad and Ozbay 2006). Therefore, the LCCA process uses an economic technique known as 'discounting' to convert different costs and benefits occurred at different times at a common point in time (FHWA 2002). This technique applies a financial variable called discount rate (r) to represent the time value of the money.

The discount rate used in a LCCA application can have quite a large impact on the analysis and in the conclusions that can be reached. Therefore, it is important to apply the correct discount rate for each particular decision problem. However, the question of which discount rate to actually use in a given situation does not have a simple answer.

The choice of the discount rate is one of the most debatable topics in public project evaluation and has been analysed by many researchers, but there still is uncertainty about which discount rate is most appropriate to evaluate public projects. Therefore, several authors have written about theories and practices in the choice of the social discount rate (e.g. Kula 1985, 1987, Pearce and Ulph 1995, 1999, Evans and Sezer 2002, 2004, 2005, Young 2002, Evans 2004, 2006, Spackman 2004, Rambaud and Torrecillas 2006, Spackman 2006, Jenkins and Kuo 2007, Azar 2007, Zhuang *et al.* 2007, Lally 2008, Percoco 2008, Harrison 2010). Despite the lack of consensus between authors, four alternatives of theoretical basis approaches have been considered for the choice of a social discount rate: social rate of time preference (SRTP); marginal social opportunity cost of capital (SOC); weight average (WA) and shadow price of capital (SPC).

Since there is no consensus about which approach is the most appropriate for the choice of the discount rate used for the evaluation of public projects, many governments and agencies, across countries and within countries, over time, have specified the discount rate to be employed in their public projects. Table 1 presents the social discount rate values adopted in several countries. The analysis of this table permits us to conclude that the tendency is to adopt low social discount rate values. For example, the European Commission recommends 5.5% for cohesion countries and for convergence regions elsewhere with high growth outlook, and 3.5% for competitive regions.

The lack of consensus has encouraged many authors to continue with their research studies in order to help increasing the quality of government and agency decisions. Evans (2004) estimated a discount rate for France based on the SRTP approach. At the time, the official social discount rate was 8.0%. The author showed

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Table 1. Social discount rate values.

Country/region	Values	Theoretical basis approach	Refs
USA	10% (until 1992); 7% (after 1992)	SOC/SRTP	Zhuang *et al.* (2007), OMB (1992)
Canada	10% (until 2007); 8% (after 2007)	SOC	TBCS (2007), Zhuang *et al.* (2007), Spackman (2006)
Australia	8% (until 2010); 7% (after 2010)	SOC	AG (2010), Zhuang *et al.* (2007), IA (2008)
New Zealand	10% (until 2008); 8.0% (after 2008)	SOC	NZT (2008), Zhuang *et al.* (2007)
European Commission	5.5% – countries and convergence regions, 3.5% – competitiveness regions	SRTP	EC (2008)
UK	6% (until 2003); 3.5% (after 2003)	SRTP	Zhuang *et al.* (2007), HMT (2003)
Germany	4% (until 2004); 3.0% (after 2004)	Based on federal refinancing rate	Zhuang *et al.* (2007), Spackman (2006)
France	8% (until 2005); 4.0% (after 2005)	SRTP	Zhuang *et al.* (2007), Spackman (2006), GCP (2005)
Italy	5%	SRTP	Zhuang *et al.* (2007)
Spain	6%	SRTP	Zhuang *et al.* (2007)
Portugal	4.0% (after 2003)	Based on government refinancing rate	MF (2003)
Norway	7% (until 1998); 3.5% (after 1998)	Government borrowing rate	Zhuang *et al.* (2007), Spackman (2006), Odeck (2005)
China	8%	WA	Zhuang *et al.* (2007)
India	12%	SOC	Zhuang *et al.* (2007)

Note: SRTP, social rate of time preference; SOC, marginal social opportunity cost of capital; WA, weight average; SPC, shadow price of capital.

that a 3.8% discount rate would be more appropriate. Evans and Sezer (2004), based on a consistent time preference, estimated a discount rate for six of the leading world economies: Australia, France, Germany, Japan, the UK and USA. The results show that the tight range of discount rates obtained for these six major countries (3.5–5.0%) clearly contrasts with the differences between official discount rates at the time. One year later, based on an identical approach, the same authors presented estimated discount rates to be used by the 15 member states of the European Union (EU) for evaluation of public projects (Evans and Sezer 2005). The results show that the estimated discount rates are in the range of 3.0–5.5%. Evans (2006) presented a new estimate of social discount rates for the 15 member states of the EU. In this case, a social discount rate of 3.0% was considered to be appropriate for the old EU member states, whereas a social discount rate of 5.0% was considered adequate for the cohesion countries. Azar (2007) presented an appropriated market-based estimate of the USA real social discount rate equal to 5.66%, with a range between 5.62% and 5.71% for a 95.0% confidence interval. However, Lally (2008) presented arguments against the conclusions of this study. Percoco (2008) estimated a time preference-based social discount rate for Italy, finding that a 3.7–3.8% rate would be appropriate. Consequently, he recommended a discount rate of 1.2–1.3% lower than the official discount rate (5.0%).

Over the years, highway agencies, influenced by trends suggested by some authors or by government imposition, have changed the discount rate applied in the evaluation of their public projects. Walls and Smith (1998), on life-cycle costs analysis in pavement design, specified that the discount rate needs to be consistent with the opportunity cost for the public at large and should reflect the historical trends over long periods of time. Ozbay *et al.* (2004) carried out a study to examine how LCCA was practiced by State Highway Agencies (SHA) in the USA. The results showed that in 1984 the discount rate ranged between 0.0% and 10.0% with a mean of 4.3%, whereas in 2001 the applied discount rate ranged between 3.0% and 5.0% with a mean of 3.9%. The next step of the study conducted by Ozbay *et al.* (2004) was carried out by Rangaraju *et al.* (2008). The results showed that in 2005, 19 SHA used discrete values ranging between 3.0% and 5.3%, 4 SHA used the discount rate defined by the USA Office of Management and Budget and another 4 used a variable discount rate value depending on available current data. Thoft-Christensen (2009), considering LCCA of bridges, stated that discount rates ranging from 2.0% to 3.0% are more reasonable than an unrealistically high discount rate, e.g. 6.0% commonly used in many countries.

Walls and Smith (1998) stated that all LCCA should be subject to a sensitivity analysis in order to determine the impact of the variability of the major LCCA input assumptions, projections and estimates on overall LCCA results. Christensen *et al.* (2005) affirmed that through this process, decision-makers can identify the inputs of the model which have most influence on model results and/or determine break-even points that alter the ranking of considered alternatives. According to Hall *et al.* (2003), the inputs of the model which most influence the relative cost-effectiveness of different alternatives are as follows: the project life, the predicted traffic over the project life, the initial investment, the discount rate, the timing of follow-up maintenance and rehabilitation (M&R) activities, and the quantities associated with initial and follow-up M&R activities. Thus, it is fundamental to do a sensitivity analysis in order to determine the impact of the variability of the major input parameters in LCCA results.

This paper presents a sensitivity analysis to the discount rate which was carried out on the application of a new LCCA system, called OPTIPAV, developed and programmed to help pavement designers to choose the best pavement structure for a road or highway (Santos and Ferreira 2011). The paper is divided into four sections. The first section consists of a brief description of the state-of-art in terms of discount rates that have been applied over the years in the assessment of public investment projects. The second section contains a detailed description of the OPTIPAV system. The third section presents the results obtained by the sensitivity analysis to the discount rate considered in the application of the OPTIPAV system to the pavement structures of the Portuguese Manual. The final section consists of a synthesis of the conclusions reached so far and a statement of prospects for future research.

2. Life-cycle cost analysis system

2.1 *Introduction*

The LCCA system called OPTIPAV, proposed by Santos and Ferreira (2011), consists of the components shown in Figure 1: the objective of the analysis, the road pavement data and models, the constraints that the system must guarantee and the results. The OPTIPAV system was implemented using Microsoft Visual Studio programming language (David *et al.* 2006, Randolph and Gardner 2008) adapting and introducing new functionalities to an existing genetic algorithm program called GENETIPAV-D (Ferreira 2001, Ferreira *et al.* 2002, 2009a) previously developed to solve deterministic optimisation models. The results of the application of the OPTIPAV system consist of the optimal pavement structure, the predicted annual pavement quality, the construction costs, the M&R plan and costs, the user costs and the pavement residual value at the end of the project analysis period. The objective of the analysis, the road pavement data and models, and the constraints that the system must guarantee are described in the following section.

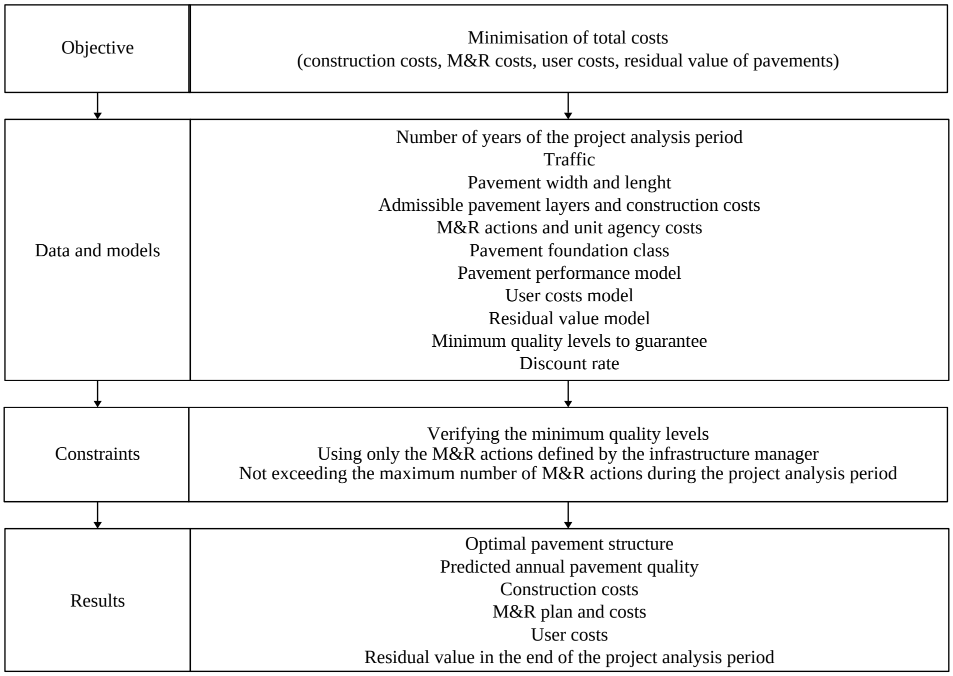


Figure 1. OPTIPAV components.

2.2 *Optimisation model formulation*

The optimisation model introduced above can be formulated as follows:

$$\text{Min } \mathrm{CC}_{s0} + \sum_{t=1}^{T}\sum_{r=1}^{R}\frac{1}{(1+d)^t}\times \mathrm{MC}_{rst}\times X_{rst} + \sum_{t=1}^{T}\frac{1}{(1+d)^t}\times \mathrm{UC}_{st} - \frac{1}{(1+d)^{T+1}}\times \mathrm{RV}_{s,T+1} \quad (1)$$

$$Z_{st} = \Phi(Z_{s0}, X_{1s1}, \ldots, X_{1st}, \ldots, X_{Rs1}, \ldots, X_{Rst}), \quad s = 1, \ldots, S;\ t = 1, \ldots, T \quad (2)$$

$$Z_{st}\begin{Bmatrix}\le\\ \ge\end{Bmatrix}\bar{Z}, \quad s = 1, \ldots, S;\ t = 1, \ldots, T \quad (3)$$

$$X_{rst} \in \Omega(Z_{st}), \quad r = 1, \ldots, R;\ s = 1, \ldots, S;\ t = 1, \ldots, T \quad (4)$$

$$\sum_{r=1}^{R} X_{rst} = 1, \quad s = 1, \ldots, S;\ t = 1, \ldots, T \quad (5)$$

$$\mathrm{CC}_{s0} = \Psi c(M_{sl}, \mathrm{Th}_{sl}), \quad s = 1, \ldots, S \quad (6)$$

$$\mathrm{MC}_{rst} = \Psi a(Z_{st}, X_{rst}), \quad r = 1, \ldots, R;\ s = 1, \ldots, S;\ t = 1, \ldots, T \quad (7)$$

$$\mathrm{UC}_{st} = \Psi u(Z_{st}), \quad s = 1, \ldots, S;\ t = 1, \ldots, T \quad (8)$$

$$\mathrm{RV}_{s,T+1} = \Theta(\mathrm{CC}_{s0}, Z_{s,T+1}), \quad s = 1, \ldots, S \quad (9)$$

$$\sum_{r=2}^{R}\sum_{t=1}^{T} X_{rst} \le N\max_s, \quad \forall s = 1, \ldots, S, \quad (10)$$

where R is the number of alternative M&R operations; S is the number of pavement structures generated for analysis; T is the number of years of the project analysis period; CC_{s0} is the construction cost of a pavement structure s in year 0 in function of the material and thickness of each layer; MC_{rst} is the maintenance cost for applying operation r to pavement structure s in year t; UC_{st} is the user cost for pavement structure s in year t; $\mathrm{RV}_{s,T+1}$ is the residual value for a pavement structure in year $T+1$; X_{rst} is equal to 1 if operation r is applied to pavement structure s in year t, otherwise it is equal to zero; d is the discount rate; Z_{st} are the condition variables for pavement structure s in year t; $\bar{Z}$ are the warning levels for the condition variables of pavement structures; M_{sl} is the material of layer l of pavement structure s; Th_{sl} is the thickness of layer l of pavement structure s; $N\max_s$ is the maximum number of M&R operations that may occur in pavement structure s

over the project analysis period; Φ are the pavement condition functions; Θ are the residual value functions; Ψc are the construction cost functions;Ψa are the agency cost functions for M&R; Ψu are the user cost functions and Ω are the feasible operations sets.

Equation (1), the objective-function of this quite complex, highly nonlinear discrete optimisation model, expresses the minimisation of total discounted costs over the project analysis period, while keeping a pavement structure above specified quality standards. Total costs include construction costs, M&R costs, user costs and the residual value of a pavement structure, i.e. its value at the end of the project analysis period.

Constraints (2) correspond to the pavement condition functions, expressing pavement condition in each year as a set of functions of the initial pavement state and the M&R operations previously applied to the pavement. These functions can describe the pavement condition with regard to variables such as cracking, rutting, longitudinal roughness, surface disintegration (potholing and ravelling) and overall quality of pavements.

$$\mathrm{PSI}_t = \mathrm{PSI}_0 - (4.2 - 1.5) \times 10^{\left[\left(\log_{10}(W_{80_t}) - Z_R \times S_0 - 9.36 \times \log_{10}(\mathrm{SN}_t + 1) + 0.2 - 2.32 \times \log_{10}(M_R) + 8.07\right) \times \left(0.4 + (1094/(\mathrm{SN}_t + 1)^{5.19})\right)\right]} \quad (12)$$

In Portugal, the Pavement Management System (PMS) of the Portuguese Road Administration (Picado-Santos and Ferreira 2008, Ferreira *et al.* 2011), and other municipal PMS (Ferreira *et al.* 2009a, 2009b), uses the pavement performance model of the flexible pavement design method developed by the American Association of State Highway and Transportation Officials (AASHTO 1993) to predict the future quality of pavements. Thus, the first application of the LCCA system (Santos and Ferreira 2011) has also considered the AASHTO flexible pavement design method. The basic design equation used for flexible pavements is Equation (11). This pavement design method considers the structural coefficients (SN) presented in Table 2, the initial and terminal present serviceability index (PSI) values presented in Table 3 and the statistic design values (Z_R and S_0) presented in Table 4. Equation (11) can be transformed into Equation (12) to be directly used in the prediction of the PSI value in each year of the design period. The PSI value ranges between 0.0 and approximately 4.5 (the value for a pavement immediately after construction). Equation (13) is used to calculate the SN value for each pavement structure. Equation (14) is used to compute the number of 80 kN equivalent single axle load (ESAL) applications until any year of the project analysis period.

$$\log_{10}(W_{80}) = Z_R \cdot S_0 + 9.36 \cdot \log_{10}(\mathrm{SN}+1) - 0.2 + \frac{\log_{10}[(\Delta\mathrm{PSI})/(4.2-1.5)]}{0.40 + (1094/(\mathrm{SN}+1)^{5.19})} + 2.32 \cdot \log_{10}(M_R) - 8.07 \quad (11)$$

$$\mathrm{SN} = \sum_{l=1}^{L} H_l \times C_l^e \times C_l^d \quad (13)$$

$$W_{80_t} = 365 \times AADT_h \times \frac{(1+g_h)^{Y_t} - 1}{g_h} \times \alpha \quad (14)$$

where W_{80} is the number of 80 kN ESAL applications

Table 2. Structural coefficients.

Material	Description	C_n^e/cm
AC-S	Asphalt concrete – surface layer	0.17323
DAC-Bi	Dense asphalt concrete – binder layer	0.17323
AC-Bi	Asphalt concrete – binder layer	0.13386
AC-B	Asphalt concrete – base layer	0.13386
G-B	Granular material – base layer	0.05512
GC-B	Granular material treated with hydraulic cement – base layer	0.09055
G-SB	Granular material – sub-base layer	0.04331

Table 3. Initial and terminal PSI values.

Road class	PSI_0	PSI_t
Highways	4.2–4.5	2.5–3.0
National roads	4.2–4.5	2.0
Municipal roads	4.2–4.5	1.5

Table 4. Statistic design values.

Confidence level (%)	Z_R	S_0
50	− 0.000	0.40–0.50
60	− 0.253	
70	− 0.524	
75	− 0.674	
80	− 0.841	
85	− 1.037	
90	− 1.282	
91	− 1.340	
92	− 1.405	
93	− 1.476	
94	− 1.555	
95	− 1.645	
96	− 1.751	
97	− 1.881	
98	− 2.054	
99	− 2.327	
99.9	− 3.090	
99.99	− 3.750	

estimated for a selected design period and design lane, Z_R is the standard normal deviate, S_0 is the combined standard error of the traffic prediction and performance prediction, ΔPSI is the difference between the initial or present serviceability index (PSI_0) and the terminal serviceability index (PSI_t), SN is the structural number indicative of the total required pavement thickness, M_R is the sub-grade resilient modulus (pounds per square inch), C_l^e is the layer (structural) coefficient of layer l, C_l^d is the drainage coefficient of layer l, H_l is the thickness of layer l, PSI_t is the present serviceability index in year t, PSI_0 is the present serviceability index of a pavement immediately after construction (year 0), W_{80_t} is the number of 80 kN ESAL applications in year t (million ESAL/lane), SN_t is the structural number of a pavement structure in year t, $AADT_h$ is the annual average daily heavy traffic in the year of construction or the last rehabilitation, in one direction and per lane, g_h is the annual average growth rate of heavy traffic, Y_t is the time since the construction of the pavement or its last rehabilitation (years) and α is the average heavy-traffic damage factor or simply truck factor.

Constraints (3) are the warning level constraints which define the maximum (or in relation to the PSI, the minimum) level for the pavement condition variables. The warning level adopted in this study considering the AASHTO pavement design method was a PSI value of 2.0 which corresponds to the PSI terminal value for national roads (Table 3). A corrective M&R operation appropriate for the rehabilitation of a pavement structure must be carried out when the PSI value is lower than 2.0.

Constraints (4) represent the feasible operation sets, i.e. the M&R operations that can be applied to maintain or rehabilitate the pavement structure in relation to its quality condition. In this application of the OPTIPAV system, two M&R operations were considered (Table 5). M&R operation 1, which corresponds to 'do nothing', is applied to a pavement structure if the PSI value is above the warning level; that is if the PSI value is greater than 2.0. M&R operation 2 is the operation that must be applied to a pavement structure when the warning level is reached; that is this operation is applied to rehabilitate the pavement structure. The M&R operation costs, in the same way as the construction costs, were obtained from the PMS of the Portuguese road administration and correspond to the 85th percentile.

Constraints (5) indicate that only one M&R operation should be carried out per pavement structure in each year. Constraints (6) represent the construction costs, which are computed in relation to the material and thickness of each pavement layer. Constraints (7) represent the M&R costs, which are computed in relation to the pavement condition and the M&R operation applied to the pavement in a given year. Constraints (8) represent the user cost functions. They express the costs for road users as a function of the pavement condition in a given year. Equation (15) was adopted for calculating the user costs because it is already used in some Portuguese PMS for calculating this type of costs (Ferreira *et al.* 2009b).

$$UC_t = 0.39904 - 0.03871 \times PSI_t + 0.00709 \times PSI_t^2 - 0.00042 \times PSI_t^3, \tag{15}$$

where UC_t are the user costs in year t (€/km/vehicle) and PSI_t is the present serviceability index in year t.

Constraints (9) represent the residual value functions. They express the value of the pavement structure at the end of the project analysis period as a function of the construction cost and the pavement condition at that time. Equation (16) is used for calculating the residual value of pavements structures, which is also used in Portuguese PMS for the same purpose (Jorge and Ferreira 2012). Constraints (10) were included in the model to avoid frequent M&R operations on the same pavement structure.

$$RV_{T+1} = CC_0 \times \frac{PSI_{T+1} - 1.5}{4.5 - 1.5}, \tag{16}$$

where RV_{T+1} is the residual value for a pavement structure in year $T+1$; CC_0 is the construction cost of a pavement structure in year 0 depending on the material and thickness of each layer and PSI_{T+1} is the present serviceability index in year $T+1$.

Table 5. M&R operations.

M&R operation	Description	Cost	M&R actions involved	Cost
1	Do nothing	€0.00/m^2	No actions	€0.00/m^2
2	Structural rehabilitation	€21.29/m^2	Wearing layer (5 cm)	€6.69/m^2
			Tack coat	€0.41/m^2
			Base layer (10 cm)	€8.63/m^2
			Tack coat	€0.41/m^2
			Membrane anti-reflection of cracks	€1.88/m^2
			Tack coat	€0.41/m^2
			Surface levelling (2 cm)	€2.45/m^2
			Tack coat	€0.41/m^2

Table 6. Input parameters considered in the application of the OPTIPAV system.

Input parameters	Value
Project analysis period	40 years
Discount rate (%)	3
Pavement foundation	F3 ($E = 100$ MPa)
Traffic class	
T5	
$AADT_h$	300
g_h (%)	3
α	3
ESAL (20 years)	0.88×10^7
T1	
$AADT_h$	2000
g_h (%)	5
α	5.5
ESAL (20 years)	13.28×10^7

3. Sensitivity analysis to the discount rate

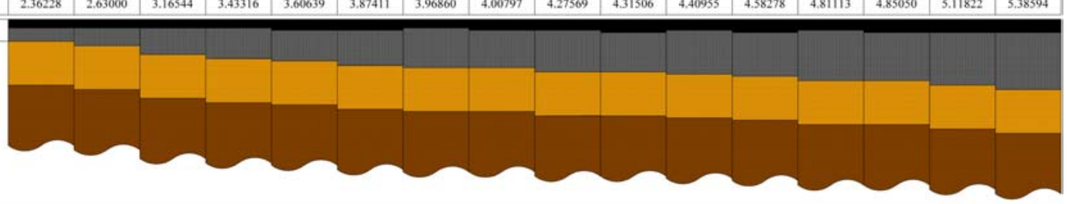
3.1 *Introduction*

Santos and Ferreira (2011) applied the OPTIPAV system in order to compare different pavement structures defined by the Portuguese manual (JAE 1995) in terms of global costs for the final choice of the pavement structure for a national road or highway. Thus, the aim of that analysis was to select the pavement structure that minimises *Net Present Value* of total costs, calculated by adding the construction costs, the annual maintenance costs, the annual user costs and deducting the residual value of pavements at the end of the project analysis period, while always keeping the pavement PSI value above the warning level of 2.0. This economic analysis was carried out using a discount rate equal to 3%. The flexible pavement structures considered by the Portuguese manual (16 in the total) were initially designed using the Shell pavement design method (Shell 1978), with verification by using the University of Nottingham (Brunton *et al.* 1987) and Asphalt Institute (AI 2001) pavement design methods. These pavement structures are recommended for different combinations between traffic and pavement foundation. The traffic class varies between T1 and T6 and is defined by the number of 80 kN ESAL applications for a design life or design period calculated in relation to the annual average daily heavy-traffic ($AADT_h$), the annual average growth rate of heavy-traffic (g_h) and the average heavy-traffic damage factor or simply, truck factor (α). The pavement foundation class is defined by the *California Bearing Ratio* (CBR) value and the design stiffness modulus (E).

In Santos and Ferreira (2011), the input parameters were used as shown in Table 6 and Figure 2. Table 6 presents the economic and traffic inputs parameters whereas Figure 2 shows the characteristics of the 16 pavement structures (type of material, thickness, stiffness modulus, Poisson's ratio, CBR, etc.) recommended by the Portuguese manual of pavement structures. These characteristics were considered in the pavement design process using the Shell and the other two pavement design methods (University of Nottingham and Asphalt Institute) to define the Portuguese manual of pavement structures. Table 7 presents the rehabilitation operations to be applied in the 16 pavement structures during the entire project analysis period considering two traffic classes (T5 and T1) and a pavement foundation F3.

		Flexible Pavement Design Alternatives															
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16
HMA Surface Layer	Thickness (cm)	4	4	4	4	5	5	4	5	5	6	5	6	5	6	6	6
	Stiffness Modulus (MPa)	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	Poisson´s ratio	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	Material	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
HMA Base Layer	Thickness (cm)	6	8	12	14	14	16	18	17	19	18	20	20	23	22	24	26
	Stiffness Modulus (MPa)	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	Poisson´s ratio	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	Material	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
Sub-base Layer	Thickness (cm)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	Stiffness Modulus (MPa)	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
	Poisson´s ratio	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	Material	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
Sub-grade	Thickness (cm)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
	Stiffness Modulus (MPa)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
	Poisson´s ratio	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	CBR (%)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Total HMA Layer Thickness (cm)		10	12	16	18	19	21	22	22	24	24	25	26	28	28	30	32
Structural Number		2.36228	2.63000	3.16544	3.43316	3.60639	3.87411	3.96860	4.00797	4.27569	4.31506	4.40955	4.58278	4.81113	4.85050	5.11822	5.38594

Illustration:



Key: AC - Asphalt Concrete; G - Granular Material; CBR - California Bearing Ratio; HMA - Hot Mix Asphalt

Figure 2. Characteristics of pavement structures.

Table 7. Rehabilitation operations to be applied in pavement structures for traffic class T5 and T1.

Pavement structure	Rehabilitation plan; foundation F3 ($E = 100\,\text{MPa}$); traffic class			
	T5		T1	
	Year	PSI final	Year	PSI final
P1	4	3.23	2/20	2.92
P2	10	3.54	2/23	3.09
P3	27	4.10	4/24	3.23
P4	34	4.34	6/26	3.50
P5	38	4.47	7/32	4.08
P6	–	2.51	10/34	4.19
P7	–	2.66	11/35	4.25
P8	–	2.71	11/37	4.38
P9	–	2.97	14	1.77
P10	–	2.99	15/38	4.43
P11	–	3.06	16/39	4.50
P12	–	3.17	17	2.64
P13	–	3.29	20	2.78
P14	–	3.31	20	2.99
P15	–	3.43	23	3.28
P16	–	3.54	26	3.56

3.2 *Results of the sensitivity analysis to the discount rate*

Figure 3 shows the evolution of the discount factor – $f(r, t)$ – represented by Equation (17) throughout the project analysis period considering different discount rate values. This figure shows that as the discount rate value increases, the present value of any cost or benefit decreases over time. This figure also shows that as the discount rate value increases the curvature also increases over time.

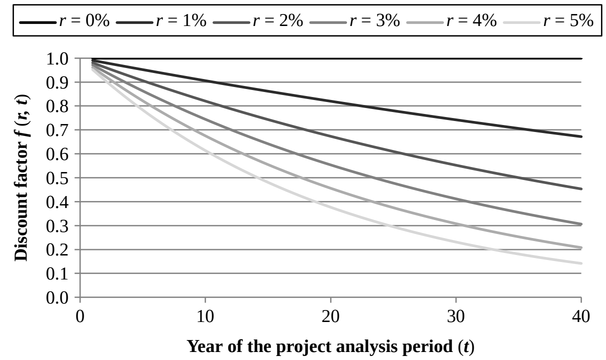


Figure 3. Evolution of the discount factor throughout the project analysis period for different discount rate values.

$$f(r,t) = \frac{1}{(1+r)^t}, \tag{17}$$

where $f(r, t)$ is the discount factor, r is the discount rate value and t is any year of the project analysis period.

In this sensitivity analysis, the discount rate value varied between 0% and 5%, incremented by 1%, while keeping all the other input values. Using this methodology, the decision-maker can understand the variability in the ranking of pavement structures, associated with the choice of the discount rate value.

Figure 4 shows the construction costs of each pavement structure. These costs are independent of the discount rate value because they occur in the first year of the project analysis period. Figure 5 presents the M&R

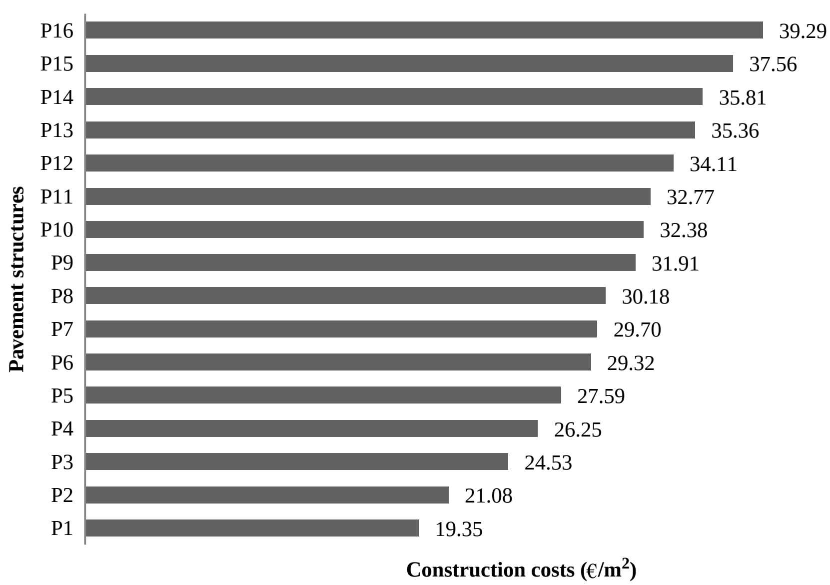


Figure 4. Construction costs of pavement structures.

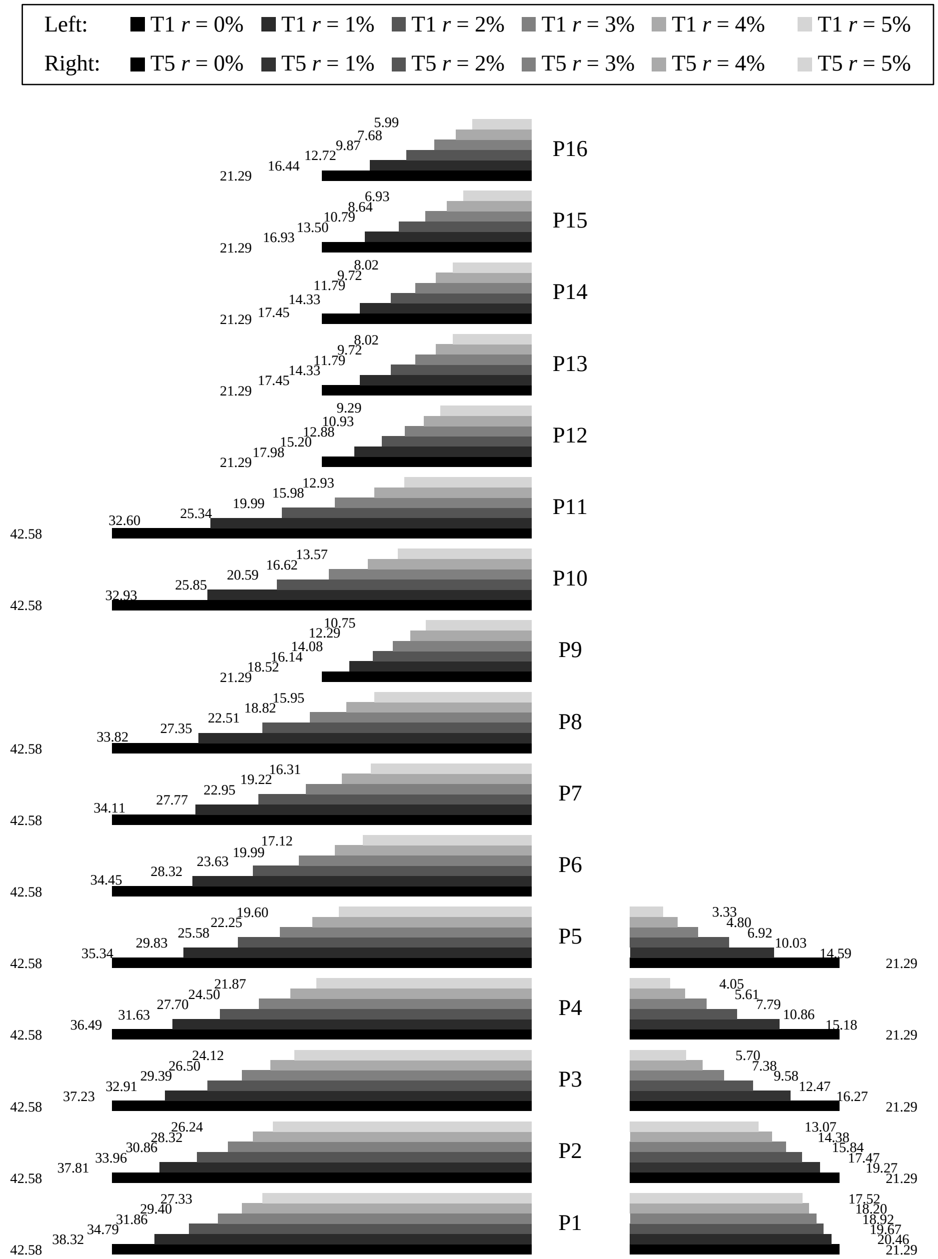


Figure 5. M&R costs throughout the project analysis period for each pavement structure computed by using different discount rates values.

costs throughout the project analysis period for each pavement structure computed by using different discount rates values. As expected, the M&R costs always decrease with the increase of the discount rate value. For traffic class T5 there are several pavement structures (P6–P16) with no M&R costs during the 40 years of the project analysis period. Figure 6 presents the user costs during the project analysis period of all pavement structures for both traffic classes T5 and T1 computed by using different discount rates value. As it can be observed, the total user costs always decrease with the increase of the discount rate value. Figure 7 presents the residual value of all pavement structures for both traffic classes T5 and T1 computed by using different discount rate values. As expected, the residual value always decreases with the increase of the discount rate value.

Figures 8 and 9 show, for each pavement structure and for both traffic classes T5 and T1, the impact caused by adopting different discount rate values on costs directly related to a highway operator or highway agency, i.e.

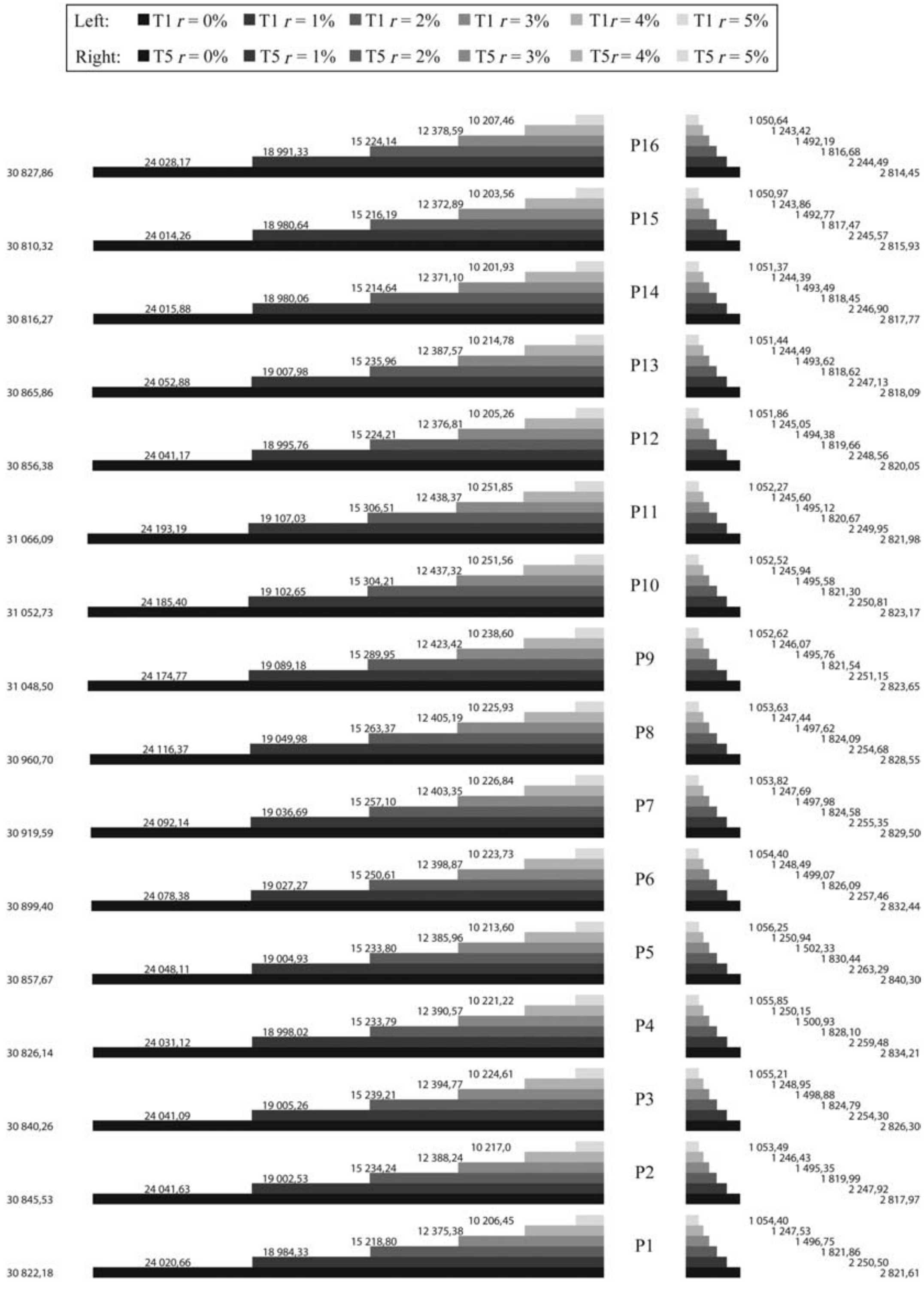


Figure 6. User costs throughout the project analysis period for each pavement structure computed by using different discount rates values.

construction costs, M&R costs and residual value of pavement structures. Analysing Figure 8, if we look at traffic class T5, we can see that the differences between agency costs using different discount rates become more pronounced with the increase in the pavement structural capacity, and this is particularly significant for lower

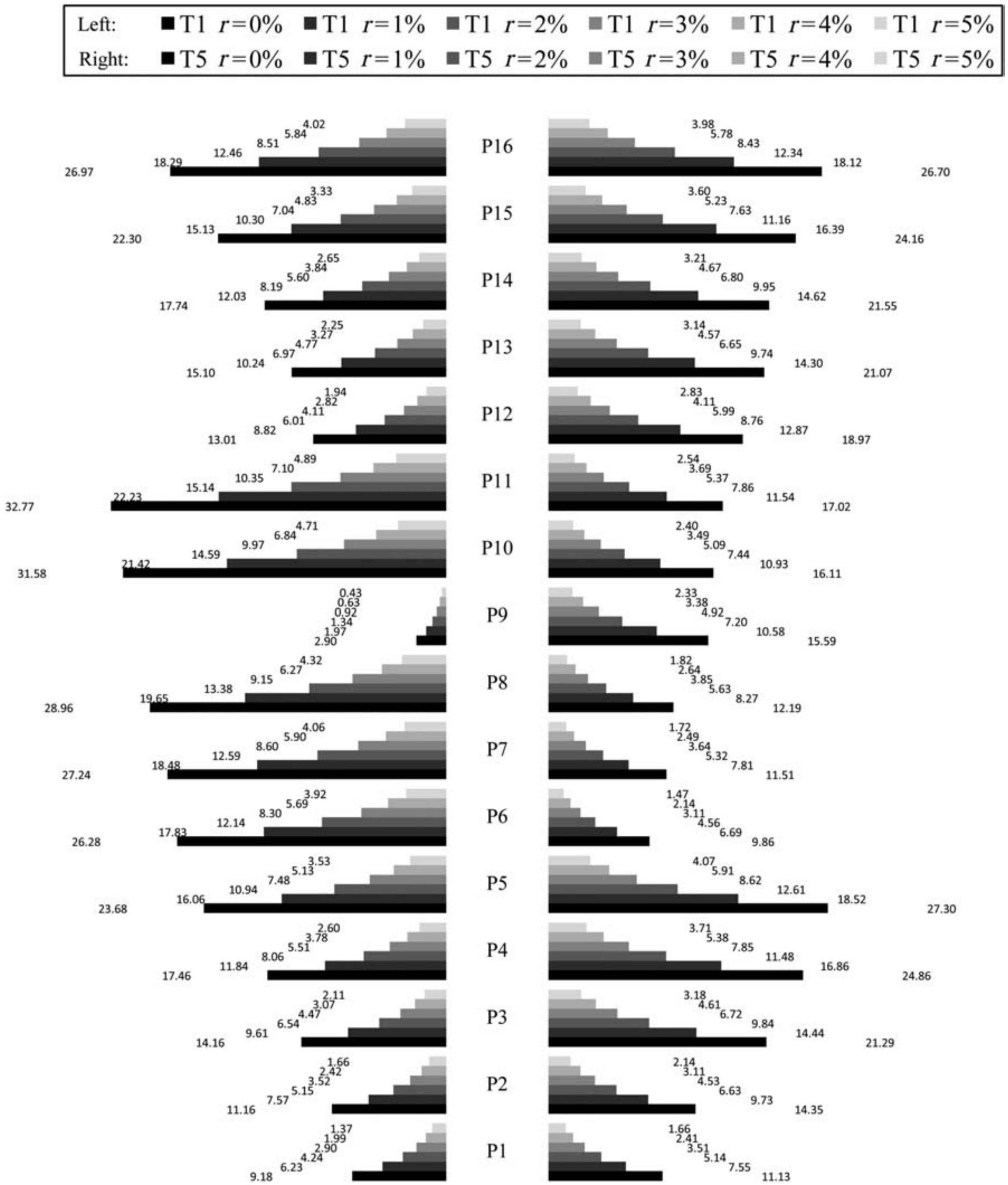


Figure 7. Residual value for each pavement structure computed by using different discount rate values.

discount rates. On the other hand, contrary to what might be expected, for traffic class T5 and for almost all the pavement structures, the agency costs increase when the discount rate value also increases. This happens because the residual value is deducted from the other components (construction costs and M&R costs) in the computation of the agency costs, and the residual value always decreases with the increase of the discount rate.

For traffic class T5, Figures 8 and 9 also show that pavement structures P2 and P3 present a maximum agency costs value for a discount rate equal to 3%. In addition, it may still be observed that the discount rate has an impact on the ranking of the alternative pavement structures. This is proved by the interception of the curves when the discount rate is higher than 1% (the first break-even point). Considering traffic class T1, Figures 8 and 9 show that the

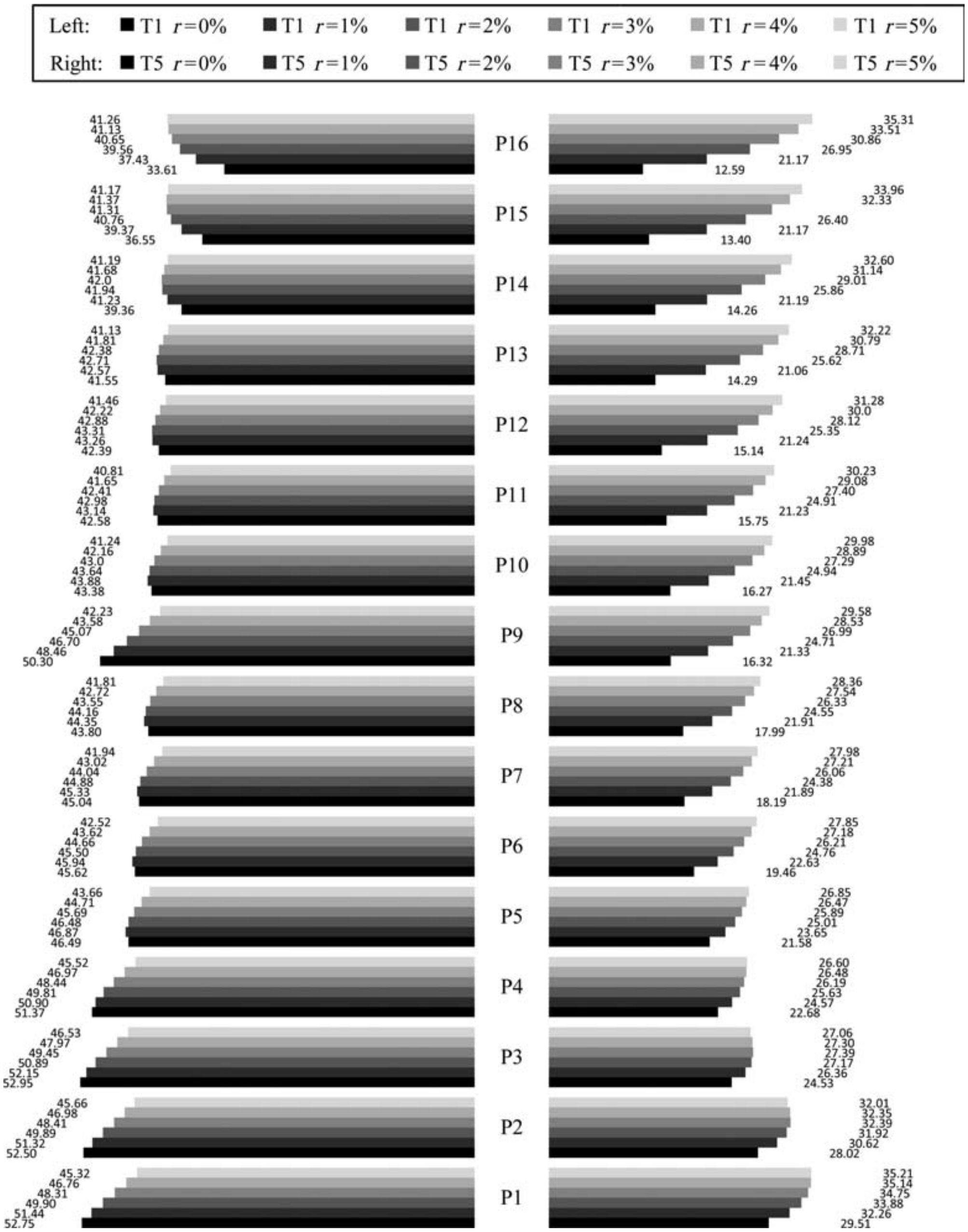


Figure 8. Highway operator cost for each pavement structure computed by using different discount rate values.

adopted discount rate value has different effects on the agency costs of each pavement structure and that impact tends to change with pavement structural capacity. Figure 9 shows that pavement structures with a lower structural capacity (e.g. P1–P4) present agency costs that always decrease with the increase of the discount rate value. On the other hand, pavement structures with a higher structural capacity (e.g. P16) present agency costs that always increase with the increase of the discount rate value. Figures 8 and 9 also show that almost all pavement structures with intermediate structural capacity present a maximum agency costs value for a specific discount rate value that increases with the structural capacity of the pavement structure. For traffic class T1, just as for traffic class T5, the discount rate also has an impact on the ranking of the alternative pavement structures. Nevertheless, this impact is less pronounced for traffic class T1 than for traffic class T5 and it occurs at higher discount rate values.

Figures 10 and 11 present the total costs (sum of the construction costs, the M&R costs and the user costs, and deducting the residual value of the pavement structure) for

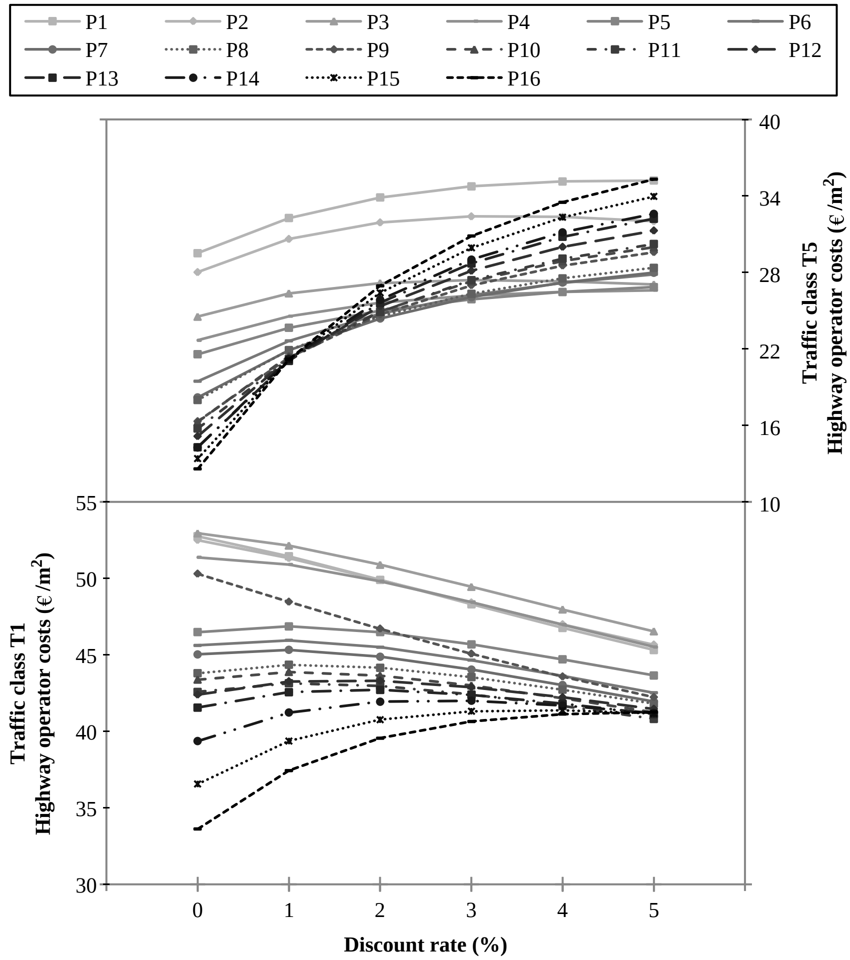


Figure 9. Sensitivity analysis of highway operator costs to the discount rate.

each pavement structure computed by using different discount rates values. As expected, the total costs always decrease with the increase of the discount rate value. These figures also show that for each pavement structure, by increasing the discount rate value, the variation of the total costs decreases. Moreover, that difference is higher when the pavement structures are subject to traffic class T1.

Table 8 presents the pavement structures recommended by the Portuguese manual and also the optimum pavement structures defined by using the OPTIPAV system considering total costs and considering only agency costs computed by using different discount rate values. Figure 12 presents the difference in percentage of total costs between the optimum and the remaining pavement structures using different discount rate values. The optimum pavement structure corresponds to the pavement structure with lower total costs, i.e. the pavement structure defined by the intersection point of the curves with the horizontal axis. This figure shows that the optimum pavement structure changes with the discount rate value. For traffic class T5, by increasing the discount rate value, the optimum pavement structure has less or at best the same structural capacity. The optimum pavement structures are P16, P16, P16, P13, P9 and P7 for discount rate values 0%, 1%, 2%, 3%, 4% and 5%, respectively (Table 8 and Figure 12). For traffic class T1, as the discount rate value increases, the optimum pavement structure also has less or at best the same structural capacity. The optimum pavement structures are P15, P15, P15, P14, P14 and P14 for discount rate values 0%, 1%, 2%, 3%, 4% and 5%, respectively (Table 8 and Figure 12).

Analysing Table 8, we can see that the optimum pavement structures tend to be structurally weaker with the increase of the discount rate value for almost all combinations between traffic class and pavement foundation. Two factors contribute to this: (1) the difference between M&R costs, user costs and the residual value of different pavement structures decreases with the increase of the discount rate value; (2) the pavement structures with less structural capacity have smaller

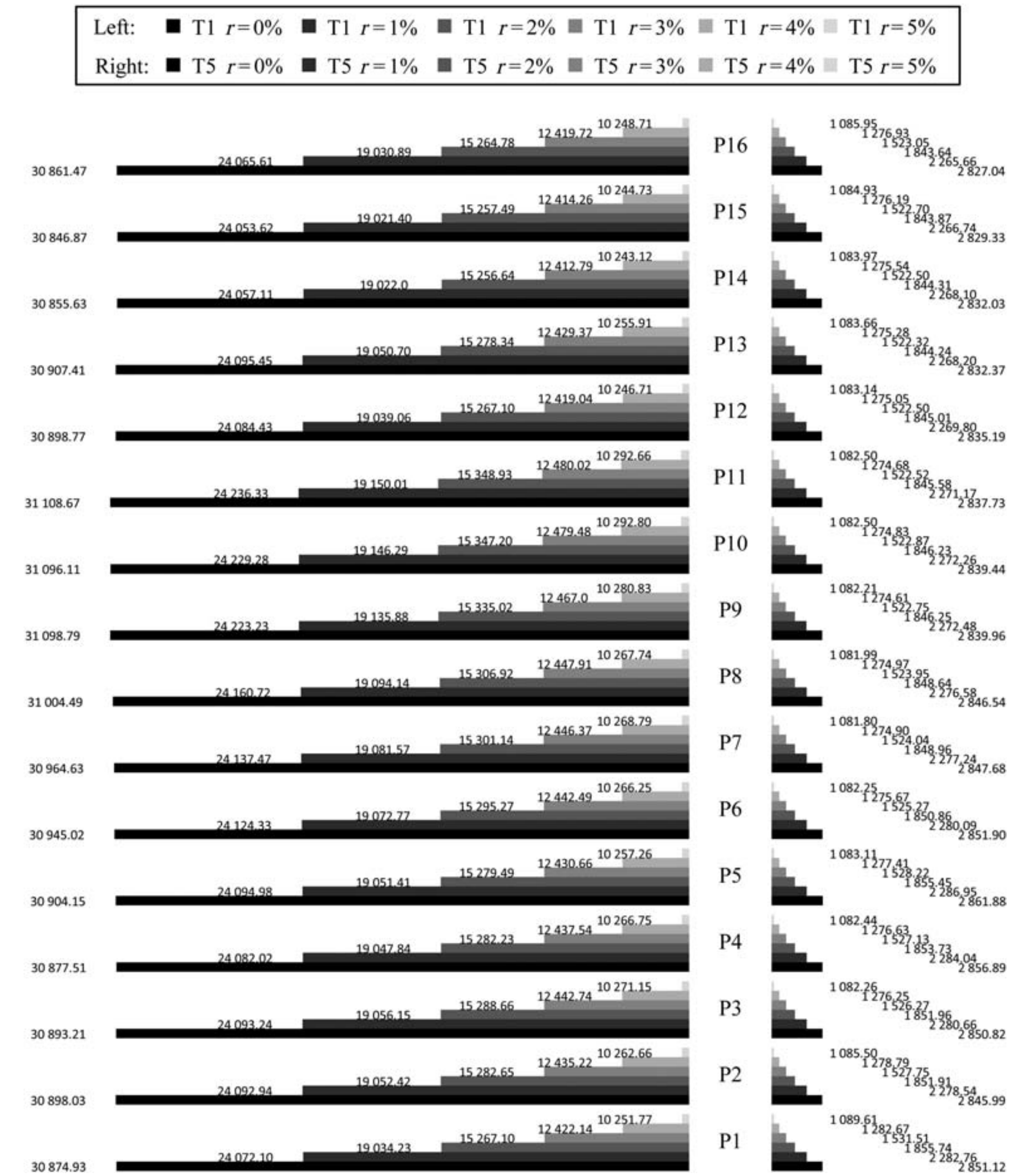


Figure 10. Total costs for each pavement structure computed by using different discount rate values.

construction costs which are independent of the discount rate value. Therefore, the total costs tend to be lower for weaker pavement structures, despite the fact that these pavement structures may have higher M&R costs because the M&R operations may occur earlier (Table 7).

In addition, the influence of the discount rate on the selection of different pavement structures increases with the structural capacity of the pavement foundation and this is more pronounced when the user costs are not included in the analysis. For example, if we take the pavement foundation F1 and the minimisation of agency costs, we can see that the optimum pavement structure is always P16 for all discount rate values and traffic classes T1–T5 (Table 8). On the other hand, considering the pavement foundation F4 and the minimisation of agency costs, the optimum pavement structures are very different for all discount rate values and traffic classes T1–T5. In these cases, the optimum pavement structure remains the same or decreases in terms of structural capacity with the increase of the discount rate value.

4. Conclusions

The results of a sensitivity analysis to the discount rate presented in this paper demonstrate the importance of a

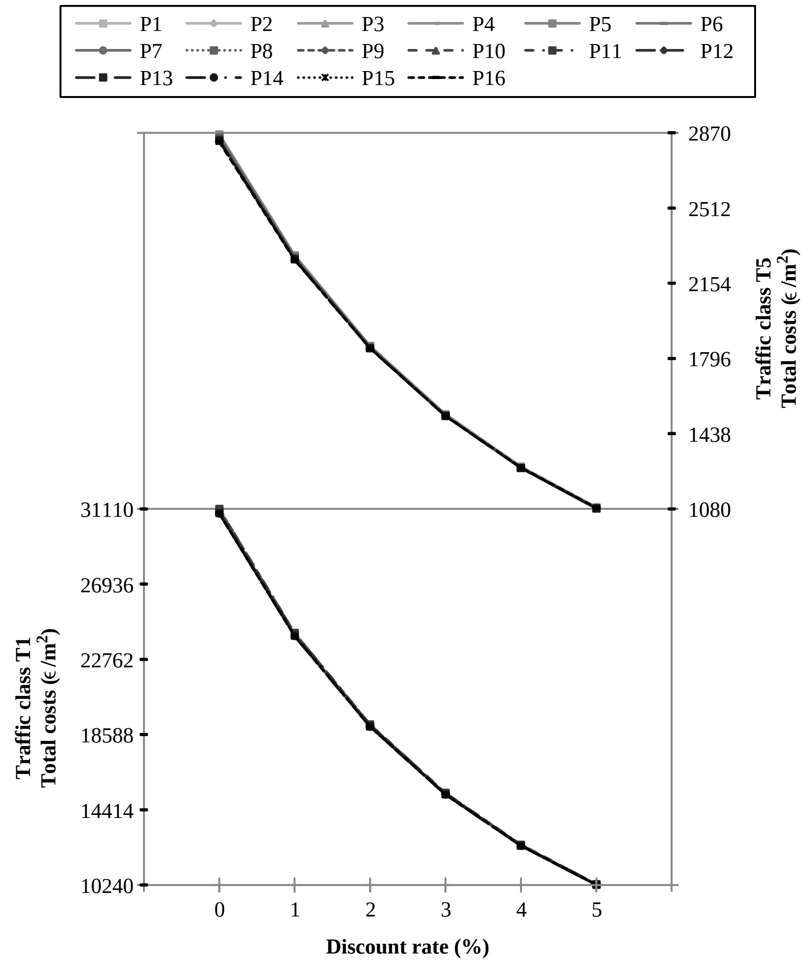


Figure 11. Sensitivity analysis of total costs to the discount rate.

right choice of the discount rate value in a LCCA application, in order to avoid a bad allocation of private/public funds to highway projects, particularly now that Portugal and other European countries are facing an economic crisis. A good decision in the selection of this key parameter, specifically in the application of a LCCA to pavement management at project-level, is advantageous not only for the highway agencies, which can apply the available budget better on construction and M&R operations, but also for the users, who will benefit from roads with better levels of quality, comfort and safety.

The outcomes obtained with the sensitivity analysis to the discount rate value, when applying the OPTIPAV system to a case study, permit us to draw the following conclusions:

(1) The construction costs are independent of the discount rate value.
(2) The M&R costs, the user costs and the residual value of pavements always decrease with the increase of the discount rate value.
(3) The agency costs (the sum of the construction costs and the M&R costs, deducting the residual value of pavements) do not have uniform behaviour. Usually for a pavement structure with high structural capacity for the traffic that uses it, the agency costs increase with the increase of the discount rate value. For a pavement structure with low structural capacity for the traffic that uses it, the agency costs decrease with the increase of the discount rate value.
(4) The total costs (the sum of the construction costs, the M&R costs and the user costs, deducting the residual value of pavements) always decrease with the increase of the discount rate value.
(5) For any combination between traffic and pavement foundation, the optimum pavement structure remains the same or decreases in terms of structural capacity with the increase of the discount rate value.

In the near future, in terms of sensitivity analysis, our research will follow with the consideration of other input

Table 8. Optimum pavement structures defined by OPTIPAV system by using different discount rates values.

Traffic class	$AADT_h$	g_h (%)	α	ESAL (20 years)	Pavement foundation	Pavement (manual)	Pavement (OPTIPAV)											
							Minimisation of the total costs						Minimisation of the agency costs					
							$r = 0\%$	$r = 1\%$	$r = 2\%$	$r = 3\%$	$r = 4\%$	$r = 5\%$	$r = 0\%$	$r = 1\%$	$r = 2\%$	$r = 3\%$	$r = 4\%$	$r = 5\%$
T6	150	3	2	0.29×10^7	F1	NAF	P16	P16	P14	P14	P11	P11	P16	P16	P16	P16	P15	P13
T5	300	3	3	0.88×10^7	F1	NAF	P16	P16	P16	P16	P16	P16	P16	P16	P16	P16	P16	P16
T4	500	4	4	2.17×10^7	F1	NAF	P6	P6	P6	P6	P6	P6	P16	P16	P16	P16	P16	P16
T3	800	4	4.5	3.91×10^7	F1	NAF	P15	P15	P15	P15	P14	P14	P16	P16	P16	P16	P16	P16
T2	1200	5	5	7.24×10^7	F1	NAF	P16	P16	P16	P16	P16	P16	P16	P16	P16	P16	P16	P16
T1	2000	5	5.5	13.28×10^7	F1	NAF	P9	P9	P9	P9	P9	P9	P16	P16	P16	P16	P16	P16
T6	150	3	2	0.29×10^7	F2	P3	P16	P16	P16	P13	P4	P4	P16	P16	P8	P7	P7	P6
T5	300	3	3	0.88×10^7	F2	P7	P7	P7	P7	P7	P7	P7	P15	P15	P15	P15	P13	P11
T4	500	4	4	2.17×10^7	F2	P11	P13	P13	P13	P13	P13	P13	P16	P16	P16	P16	P16	P13
T3	800	4	4.5	3.91×10^7	F2	P13	P16	P16	P16	P16	P16	P16	P16	P16	P16	P16	P16	P16
T2	1200	5	5	7.24×107	F2	P15	P7	P7	P7	P7	P7	P7	P15	P15	P15	P15	P15	P15
T1	2000	5	5.5	13.28×10^7	F2	P16	P14	P14	P14	P14	P14	P14	P16	P16	P16	P16	P16	P16
T6	150	3	2	0.29×10^7	F3	P2	P16	P4	P3	P3	P3	P3	P16	P3	P3	P3	P3	P3
T5	300	3	3	0.88×10^7	F3	P4	P16	P16	P16	P13	P9	P7	P16	P13	P7	P5	P5	P4
T4	500	4	4	2.17×10^7	F3	P6	P16	P16	P16	P16	P3	P3	P16	P12	P12	P11	P7	P7
T3	800	4	4.5	3.91×10^7	F3	P9	P6	P6	P6	P6	P6	P6	P15	P15	P15	P15	P13	P7
T2	1200	5	5	7.24×10^7	F3	P12	P11	P11	P11	P11	P11	P11	P16	P16	P16	P16	P13	P13
T1	2000	5	5.5	13.28×10^7	F3	P14	P15	P15	P15	P14	P14	P14	P16	P16	P16	P16	P16	P11
T6	150	3	2	0.29×10^7	F4	P1	P2	P2	P2	P1	P1	P1	P2	P2	P2	P1	P1	P1
T5	300	3	3	0.88×10^7	F4	P3	P16	P5	P4	P3	P3	P3	P16	P4	P3	P3	P3	P3
T4	500	4	4	2.17×10^7	F4	P5	P16	P16	P16	P16	P13	P13	P16	P16	P7	P5	P5	P4
T3	800	4	4.5	3.91×10^7	F4	P8	P16	P16	P16	P16	P16	P16	P16	P16	P10	P10	P7	P6
T2	1200	5	5	7.24×10^7	F4	P10	P7	P7	P7	P7	P7	P7	P14	P13	P13	P13	P9	P7
T1	2000	5	5.5	13.28×10^7	F4	P12	P9	P9	P9	P9	P9	P9	P16	P16	P16	P16	P13	P11

Notes: NAF, not an adequate foundation for a flexible pavement with an asphalt base layer according to the Portuguese Manual; F1, foundation 1 ($E = 30$ MPa, $\nu = 0.35$); F2, foundation 2 ($E = 60$ MPa, $\nu = 0.35$); F3, foundation 3 ($E = 100$ MPa, $\nu = 0.35$); F4, foundation 4 ($E = 150$ MPa, $\nu = 0.35$).

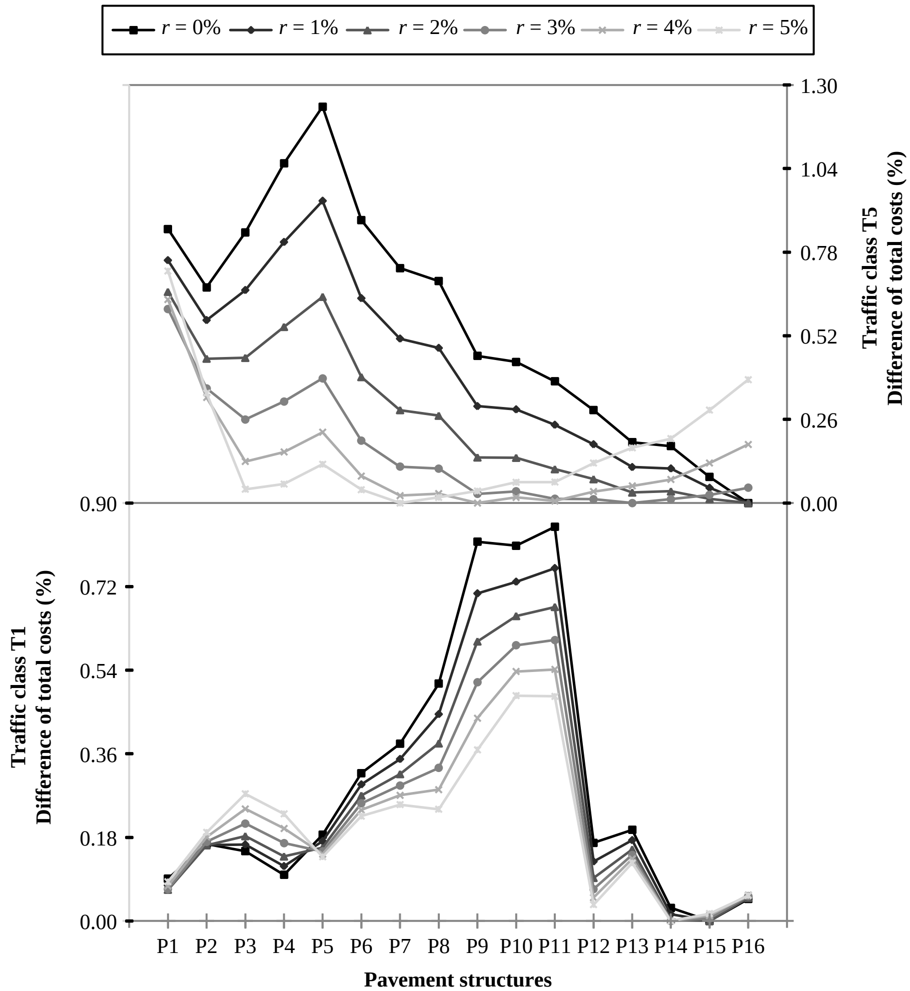


Figure 12. Difference in percentage of total costs between the optimum and the remaining pavement structures.

parameters, such as the project analysis period or the CBR value of the pavement foundation.

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Note

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