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A Segment-linked Optimization Model for Deterministic Pavement Management Systems

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This paper presents a segment-linked optimization model to be used within deterministic pavement management systems. The model is aimed at determining the least-cost maintenance and rehabilitation strategy to be implemented in a road network, taking into account the applicable technical and budgetary constraints. The evolution of pavements with regard to cracking, rutting, surface disintegration, and longitudinal roughness is estimated with deterministic performance models. The overall quality of pavements is assessed through a modified version of the Present Serviceability Index (PSI). The method developed to solve the model is based on genetic algorithm principles. The application of the model is illustrated for a case study involving the road network of Coimbra, the third-largest Portuguese city. The results obtained for this case study indicate that the model is a valuable addition to the road engineer's toolbox.

Keywords: Pavement management systems; Deterministic pavement performance models; Pavement maintenance and rehabilitation; Optimization models; Genetic algorithms

INTRODUCTION

During the 1980s, and particularly after the (first) North American Pavement Management Conference, held in Toronto, Canada, in 1985, pavement management systems (PMS) were recognized to be a major tool to aid the road engineer. Since then, they have been extensively utilized by national, state, regional, and municipal road administrations in many countries of the world to define maintenance and rehabilitation (M and R) strategies for the pavements of the road networks under their jurisdiction.

Two of the main components of a PMS are: (1) the models used to predict pavement performance; and (2) the approach used to select the M and R strategy (taking into account the expected evolution of pavement performance).

The pavement performance models employed within a PMS may be deterministic or probabilistic (Ferreira et al., 1999). Deterministic models use regression equations to describe the evolution of pavement condition over time, whereas probabilistic models use Markov chains for the same purpose.

At first sight, probabilistic models may look preferable because they take into account the uncertainty inherent in pavement degradation processes. However, unlike (modern) deterministic models, they do not rely on solid theoretical foundations (i.e. probabilistic models are purely empirical). Moreover, deterministic models may (and generally do) describe pavement performance in detailed, quantitative terms, with reference to the different types of distresses (cracking, rutting, etc.) that characterize pavement condition. This is practically impossible when probabilistic models are used, pavement condition being, in this case, always assessed through qualitative, aggregate measures (such as good, fair, and poor, or 1, 2, . . ., 9). These reasons possibly explain why road administrations often prefer deterministic PMS (i.e. PMS based on deterministic pavement performance models) to probabilistic PMS.

The approach used to select the M and R strategy within a deterministic PMS typically relies on the analysis of a limited number of alternatives. Examples of PMS that follow this approach are the HDM-III and the HDM-4 PMS (Watanatada et al., 1987; ISOHDM, 1995a,b), possibly the PMS is more widely used in the world, and the Nevada PMS (Sebaaly et al., 1996). The main weakness of this approach is that it does not guarantee the selection of the best possible M and R strategy. If the alternatives considered are poor, it cannot lead to a good strategy. This can only be avoided if the approach followed to select the M and R strategy is based on optimization techniques. Probabilistic PMS, such as the Arizona

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PMS (Golabi et al., 1982; Wang and Zaniewski, 1996), follow this kind of approach. But, as stated before, they are unable to describe pavement performance in detailed, quantitative terms.

This paper presents a segment-linked optimization model for deterministic PMS developed within an R and D project recently completed at the University of Coimbra (Portugal). The model is aimed at determining the least-cost M and R strategy to be implemented in a road network, taking into account the applicable technical and budgetary constraints. The designation of segment-linked is applied to the model because M and R operations are directly assigned to road segments and not to road categories, as the models normally used within probabilistic PMS do. This ultimately signifies that, unlike these models, the model presented here automatically prioritizes M and R operations (across road segments). The model fits into a line of research initiated by Tien Fwa at the University of Singapore (Chan et al., 1994; Fwa et al., 1994), evolving from work on routine maintenance programming developed earlier at the University of Purdue (Fwa and Sinha, 1986; Fwa et al., 1988).

OPTIMIZATION MODEL

As stated before, the objective of the model is to determine the least-cost M and R strategy to be implemented in a road network. This is defined as the strategy that minimizes the total discounted costs involved in the M and R operations carried out in the segments of a given road network over a given planning time-span, while keeping pavements above given quality standards. Road segments are the decision-making units to which M and R operations apply (i.e. M and R operations do not apply to parts of a segment). In principle, road segments can be of any size. However, if they are too long, it will be difficult to describe pavement condition accurately (assuming that longer segments will be less homogeneous). Conversely, if they are too short, it is probable that the M and R operations obtained through solving the model will make pavement condition vary excessively across the road network.

Model Formulation

The optimization model introduced above can be formulated as follows:

$$\mathrm{Min}\sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{t=1}^{T}\frac{1}{(1+d)^{t}}(Ca_{rst}+Cu_{rst}) - \sum_{s=1}^{S}\frac{1}{(1+d)^{T+1}}V_{s,T+1} \qquad (1)$$

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

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

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

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

$$Ca_{rst}=\Psi a(Z_{st},X_{rst}),\quad r=1,\ldots,R;\ \ s=1,\ldots,S;\ \ t=1,\ldots,T \qquad (6)$$

$$Cu_{rst}=\Psi u(Z_{st},X_{rst}),\quad r=1,\ldots,R;\ \ s=1,\ldots,S;\ \ t=1,\ldots,T \qquad (7)$$

$$V_{s,T+1}=\Theta(Z_{s,T+1}),\quad s=1,\ldots,S \qquad (8)$$

$$\sum_{r=1}^{R}\sum_{s=1}^{S}C_{rst}X_{rst}\le B_t,\quad t=1,\ldots,T \qquad (9)$$

where R is the number of alternative M and R operations, S is the number of road segments, T is the number of years in the planning time-span, d is the discount rate, Ca_{rst} is the agency cost for applying operation r to segment s in year t, Cu_{rst} is the user cost of applying operation r to segment s in year t, $V_{s,T+1}$ is the terminal value for the pavement of segment s, Z_{st} are the pavement condition variables for segment s in year t, Φ are the pavement condition functions, X_{rst} is equal to one if operation r is applied to segment s in year t, and is equal to zero otherwise, $\bar{Z}$ are the warning levels for the pavement condition variables, Ω are the feasible operations sets, Ψa are the agency cost functions, Ψu are the user cost functions, Θ are the terminal value functions, and B_t is the budget for year t.

Objective-function

Function (1), the objective-function of this quite complex, highly non-linear discrete optimization model, expresses the minimization of total discounted M and R costs over the planning time-span. Agency costs, user costs, and the terminal value of pavements (i.e. the value of pavements at the end of the planning time-span) are taken into account in the calculation of total costs. Costs need to be discounted to reflect the time-value of money. In order to allow a proper trade-off between light and heavy M and R operations, the minimum length of the planning time-span must be, say, eight years. Quite often, a 20-year planning time-span is considered.

Pavement Condition Functions

Constraints (2) correspond to the pavement condition functions. They express pavement condition in each segment and year as a set of functions (Φ) of the initial pavement state and the M and R strategy previously applied to the segment. The functions describe pavement condition with regard to the following five variables: cracking (including alligator cracking), surface disintegration (potholing and raveling), rutting, longitudinal roughness, and overall quality of pavements.

For the evolution of cracking, surface disintegration, and rutting over time, the following functions are used (Fwa et al., 1996):

$$C_t = 617.14 \times N_{80_t}^{Dim} \times SN_t^{-SN_t} \tag{10}$$

$$S_t = 2.29 \times (e^{2.2677 \times N_{80_t}^{Dim}} - 1) \tag{11}$$

$$R_t = 4.98 \times SN_t^{-0.5} \times Y_t^{0.166} \times (N_{80_t}^{Dim})^{0.13} \tag{12}$$

$$N_{80_t}^{Dim} = 365 \times TMDA_p \times \frac{(1+tc)^{Y_t} - 1}{tc} \times \alpha \tag{13}$$

$$SN_t = \sum_{n=1}^{N} H_n \times C_n^e \times C_n^d \tag{14}$$

where C_t is the total cracked area in year t ($m^2/100\,m^2$), $N_{80_t}^{Dim}$ is the cumulative equivalent standard axle load (ESAL) at age t (million ESAL/lane), SN is a structural number given by Eq. (14), S_t is the total surface disintegrated in year t ($m^2/100\,m^2$), R_t is the rut depth in year t (mm), Y_t is the age of pavements since the construction or the last rehabilitation (years), $TMDA_p$ is the annual average daily heavy traffic in the year of construction or the last rehabilitation, in one direction and per lane, tc is the annual growth average tax of heavy traffic, α is the average damage factor of heavy traffic, C_n^e is the structural coefficient of layer n, C_n^d is the drainage coefficient of layer n, and H_n is the thickness of layer n (mm).

The longitudinal roughness of pavements is measured through the International Roughness Index (IRI). The evolution of this index over time is calculated as follows (Watanatada et al., 1987):

$$\begin{aligned} IRI_t = {} & 980.0 \times e^{m \times Y_t} \\ & \times \left(\frac{IRI_0}{1000} + 135 \times SNCK_t^{-5} \times N_{80_t}^{Dim}\right) \\ & + 143.0 \times R_t + 6.8 \times C_t + 56.0 \times P_t \end{aligned} \tag{15}$$

$$SNCK_t = 1.0 + SNC_t - 0.00004 \times HB_t \times C_t \tag{16}$$

$$\begin{aligned} SNC_t = {} & \sum_{n=1}^{N} H_n \times C_n^e \times C_n^d + 3.51 \times \log CBR \\ & - 0.85 \times (\log CBR)^2 - 1.43 \end{aligned} \tag{17}$$

where IRI_t is the International Roughness Index in year t (mm/km), m is the environment coefficient based on climatic variables, $SNCK_t$ is the modified structural number for the pavement, reduced for the effect of cracking in the asphalt layers, P_t is the total area with patching in year t ($m^2/100\,m^2$), SNC_t is the modified structural number for the pavement that takes into account the sub-grade strength, HB_t is the thickness of the bound layers in year t (mm), CBR is the California Bearing Ratio of sub-grade.

These functions are modified versions of the functions used in the HDM-III PMS to compute the IRI, and are also used, for instance, in the pavement performance model upon which the RoSy PMS is based (PPC, 1998).

The overall quality of pavements is measured through the Present Serviceability Index (PSI). The evolution of this index over time is calculated as follows (AASHTO, 1993):

$$\begin{aligned} PSI_t = {} & 5 \times e^{-0.0002598 \times IRI_t} - 0.002139 \times R_t^2 - 0.03 \\ & \times (C_t + S_t + P_t)^{0.5} \end{aligned} \tag{18}$$

This equation is a modified version of the equation established during the American Association of State Highway Officials road test for the computation of the PSI, and is used, for instance, in the pavement performance model upon which the Nevada PMS is based (Sebaaly et al., 1996).

All the pavement condition functions referred to above involve calibration parameters, and may not perform well when outside the calibration context. If this is the case, they must be re-calibrated before being applied in a different context.

Warning Level Constraints

Constraints (3) are the warning level constraints. They define the maximum (or, in respect to the PSI, the minimum) level for the pavement condition variables. The warning levels adopted in this study are shown in Table I. For example, the table shows that an M and R operation appropriate to eliminate cracking must be performed on a road segment when the area affected by cracking exceeds 10% of the segment's area. The warning levels indicated on the table reflect the current pavement engineering practice in Portugal.

Feasible Operation Sets

Constraints (4) represent (comprehensively) the feasible operation sets, i.e. the M and R operations that can be

TABLE I Warning levels by distress type

Distress type	Warning level
Cracking and alligator cracking	Area = 10.0%
Surface disintegration	Area = 10.0%
Rutting	Mean rut depth = 20 mm
Longitudinal roughness	IRI = 3500 mm/km
Present serviceability index	PSI = 2.5

TABLE II Types of M and R action

M and R action	Description
1	Do nothing
2	Crack sealing
3	Rut leveling
4	Patching
5	Longitudinal roughness leveling
6	Membrane anti-reflection of cracks
7	Asphalt concrete layer (5 cm)
8	Two asphalt concrete layers (5 + 5 cm)
9	Two asphalt concrete layers (5 + 8 cm)

TABLE III Types of M and R operation

M and R operation	M and R actions involved
1	1
2	2
3	4
4	2 + 4
5	6 + 7
6	3 + 6 + 7
7	5 + 6 + 7
8	3 + 5 + 6 + 7
9	6 + 8
10	3 + 6 + 8
11	5 + 6 + 8
12	3 + 5 + 6 + 8
13	6 + 9
14	3 + 6 + 9
15	5 + 6 + 9
16	3 + 5 + 6 + 9

performed in each segment and year. These operations depend on the pavement condition characterizing the segment. For instance, the application of an M and R operation can be adequate for a segment presenting only cracking problems, but may be inadequate if it also suffers from surface disintegration problems.

In this study, 16 different M and R operations were considered, corresponding to nine M and R actions applied individually or in combination. The types of M and R action and operation considered are presented in Tables II and III.

The M and R operation 1 corresponds to "do nothing". The next eight M and R operations are the simplest operations that can be applied when some warning level or levels for pavement condition are reached. As shown in Table IV, the operations to apply depend on the warning levels reached. Operation 2 applies to cracking problems. Operation 3 applies to surface disintegration problems. Operation 4 applies to simultaneous cracking and surface disintegration problems. Operation 5 applies to pavement serviceability problems (i.e. when the warning level for the PSI is reached). Operation 6 applies to simultaneous rutting and pavement serviceability problems. Operation 7 applies to simultaneous longitudinal roughness and pavement serviceability problems. Finally, operation 8 applies to simultaneous rutting, longitudinal roughness, and pavement serviceability problems.

The remaining eight M and R operations (i.e. operations 9 to 16) are obtained from operations 5 to 8 through replacing M and R action 7 (asphalt concrete layer with 5 cm) with M and R actions 8 (asphalt concrete layer with 5 + 5 cm) or 9 (asphalt concrete layer with 5 + 8 cm). These actions perform the same basic role of M and R action 7 but they have a longer efficiency period. The efficiency of an M and R action is defined as the time between its application to the pavement and the moment when the pavement reaches the warning level for the PSI.

When deciding which M and R operations should be applied to a given segment in a given year, it is possible to select either the simplest operation needed to cope with the distresses affecting its pavement, or more complex operations. Indeed, selecting a more complex operation may be more efficient (less costly) in the medium or long-term. The alternatives to the simplest M and R operations considered in this study are depicted in Table V.

The analysis of Table V makes clear that the application of M and R operations may be corrective or preventive. An M and R operation is corrective for some particular pavement distress if it is performed when the warning level corresponding to that distress is reached, and it is preventive if it is performed before the warning level is reached. For instance, if no warning levels are attained in a given segment and year, it would be possible to select operation 1 (do nothing) for application to the segment. That is, no corrective operation would be needed. However, it may be efficient to perform some preventive operation in that year, in order to avoid having to perform the appropriate corrective operation later, at larger (discounted) costs. In the case of operation 1, all other 15 operations are possible alternatives.

Annual Operations Constraints

Constraints (5) state that only one M and R operation per segment should be performed in each year. These constraints may be omitted from the model. The need for applying several M and R operations to a given segment during the same year only occurs in exceptional circumstances (for instance, when land sliding or flooding affects the pavement after the M and R operation is applied). The model is not designed to deal with circumstances of this kind.

Agency Cost Functions

Constraints (6) represent the agency cost functions. They express the costs for the road agency involved in the application of a given M and R operation to a segment in a given year as a function (Ψa) of the pavement condition in that segment and year. These costs are obtained through the multiplication of the unit agency costs for the M and R actions involved in the M and R operation by the pavement areas or volumes to which the M and R actions apply.

TABLE IV Application of the simplest M and R operations

M and R operation	M and R action	Cracked area (%)	Mean rut depth (mm)	Disintegration (%)	IRI (mm/km)	PSI
1	1	<10	<20	<10	<3500	>2.5
2	2	≥ 10	<20	<10	<3500	>2.5
3	4	<10	<20	≥ 10	<3500	>2.5
4	$2+4$	≥ 10	<20	≥ 10	<3500	>2.5
5	$6+7$	Any value	<20	Any value	<3500	≤ 2.5
6	$3+6+7$	Any value	≥ 20	Any value	<3500	Any value
7	$5+6+7$	Any value	<20	Any value	≥ 3500	≤ 2.5
8	$3+5+6+7$	Any value	≥ 20	Any value	≥ 3500	≤ 2.5

User Cost Functions

Constraints (7) represent the user cost functions. They express the costs for road users associated to the application of a given M and R operation to a segment in a given year as a function (Ψu) of the pavement condition in that segment and year. User costs consist of several components: vehicle costs, travel time costs, accident costs, and so forth. Information on the relationship between user costs and M and R operations is growing, but is still scarce. For this reason, instead of being explicitly considered, they are often handled through surrogate constraints.

Terminal Value Functions

Constraints (8) represent the terminal value functions. They express the value of the pavement of a segment at the end of the planning time-span as a function of pavement condition at that time. When the planning time-span is large (say, 20 years or more), the corresponding term in the objective-function becomes relatively unimportant, and is often omitted from it.

Annual Budget Constraints

Constraints (9) are the annual budget constraints. They specify the maximum amount of money to be spent in M and R operations during each year. These constraints may also be omitted from model, or may apply only to the initial years of the planning time-span (budgetary constraints regarding the final part of a 20-year planning time-span would hardly be credible). In both cases, the model, once solved, automatically determines the optimum budget for the years to which no budget constraints are specified.

Other Possible Constraints

In addition to the constraints presented above, many other constraints may be included in the model to reflect the conditions within which M and R operations are to be carried out. This includes constraints working as surrogates to user costs. For instance, constraints designed to avoid frequent M and R operations on the same segment, because this would cause excessive annoyance both to people who live close to the segment and to people who travel very often through it. These constraints can be formulated as follows:

$$\sum_{r=2}^{R}\sum_{t=1}^{T} X_{rst} \leq Nmax_s, \quad \forall s = 1, \ldots, S \tag{19}$$

where $Nmax_s$ is the maximum number of M and R operations that may occur in segment s over the planning time-span.

TABLE V Alternatives to M and R operations

	Alternative M and R operations															
M and R operation	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
2	–	×	–	×	×	×	×	×	×	×	×	×	×	×	×	×
3	–	–	×	×	×	×	×	×	×	×	×	×	×	×	×	×
4	–	–	–	×	×	×	×	×	×	×	×	×	×	×	×	×
5	–	–	–	–	×	×	×	×	×	×	×	×	×	×	×	×
6	–	–	–	–	–	×	–	×	–	×	–	×	–	×	–	×
7	–	–	–	–	–	–	×	×	–	–	×	×	–	–	×	×
8	–	–	–	–	–	–	–	×	–	–	–	×	–	–	–	×
9	–	–	–	–	×	×	×	×	×	×	×	×	×	×	×	×
10	–	–	–	–	–	×	–	×	–	×	–	×	–	×	–	×
11	–	–	–	–	–	–	×	×	–	–	×	×	–	–	×	×
12	–	–	–	–	–	–	–	×	–	–	–	×	–	–	–	×
13	–	–	–	–	×	×	×	×	×	×	×	×	×	×	×	×
14	–	–	–	–	–	×	–	×	–	×	–	×	–	×	–	×
15	–	–	–	–	–	–	×	×	–	–	×	×	–	–	×	×
16	–	–	–	–	–	–	–	×	–	–	–	×	–	–	–	×

MODEL SOLVING

The model presented in the previous section is extremely complex, being impossible to solve with exact optimization methods (except, for small, academic instances, through complete enumeration). Indeed, it can only be solved through heuristic methods.

In this study, a genetic algorithm, called GENETIPAV-D, was developed to solve the model. Since they were proposed by Holland (1975), genetic algorithms have been successfully used in many occasions to deal with complex engineering optimization problems. Like any other heuristic methods, genetic algorithms do not guarantee global optimum solutions. However, if properly designed, they will often provide either optimum or near-optimum solutions to the model. In general terms, a genetic algorithm is built as follows (Fig. 1). The first step involves the creation of an initial population of chromosomes, or, within an optimization framework, solutions. Each chromosome (solution) consists of a given number of genes, or, within an optimization framework, attributes (the possible values taken by the instrumental decision variables, i.e. in this case, variables X). The population evolves over time through reinsertion, crossover, and mutation of solutions. Reinsertion is the transfer of the best solutions of the existing population to the next generation. Crossover is the interchange of some attribute or attributes between two existing solutions. Mutation is the transformation of some attribute or attributes of an existing solution. Selection of solutions takes place in such a way that only the best solutions from successive generations survive, thus avoiding the occurrence of overpopulation. Through this process, the quality of solutions will progressively tend to improve, leading eventually to a population consisting only of optimum or near-optimum solutions. In-depth presentations of genetic-algorithm principles can be found in Mitchell (1996) or Michalewicz (1999).

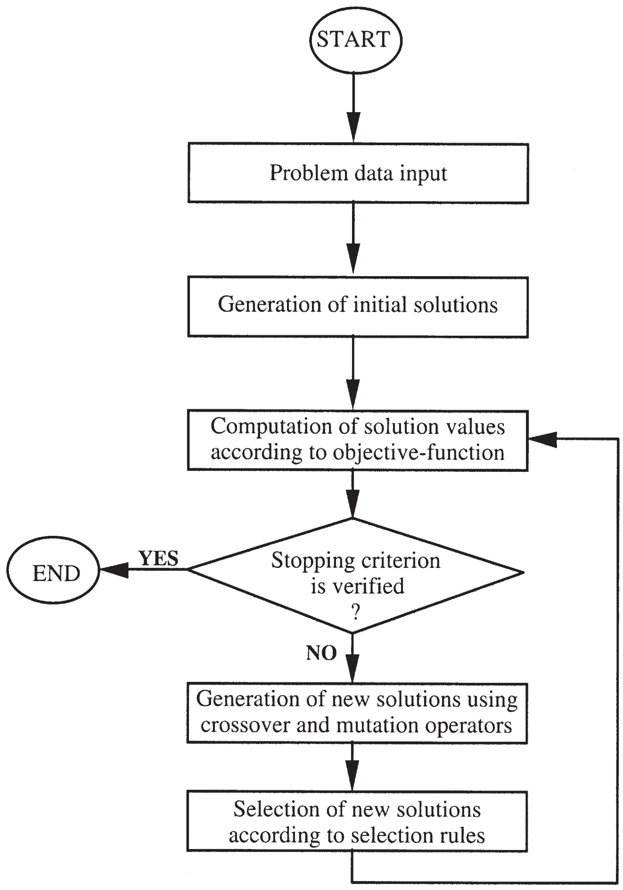

FIGURE 1 Flowchart of a genetic algorithm.

Detailed information on the implementation of GENETIPAV-D, and particularly on the selection and calibration of the genetic parameters, can be found in Ferreira (2001). The implementation was made along the lines set in Chan et al. (1994).

Through solving the model, GENETIPAV-D determines a least-cost (or close-to-least-cost) M and R strategy for the pavements of a road network, consisting of both corrective and preventive M and R operations. In addition to this, GENETIPAV-D can be used to compare this strategy to a least-cost corrective-only M and R strategy or to any user-defined M and R strategy (for the whole network or a part of it).

COMPUTER PROGRAM

The algorithm GENETIPAV-D is available for application through SIGPAV, a Visual BASIC program developed at the University of Coimbra to run under Windows 95/98/ME (Ferreira, 1998; Ferreira et al., 2001).

The SIGPAV consists of three basic modules: a Road Network Database, a Quality Evaluation Tool, and a Decision-Aid Tool. The Road Network Database is used to store information on road geometry, traffic, pavement condition, pavement history, M and R costs, and so forth. All data stored in the database is associated to a geo-referenced network model created with ArcInfo (ESRI, 2000a). The Quality Evaluation Tool exploits the information stored in the Road Network Database, and particularly the information on pavement condition, to calculate indicators for the overall quality of pavements. One of the indicators calculated within the Quality Evaluation Tool is the PSI. The Decision-Aid Tool determines the optimum (or near-optimum) M and R strategy for each road segment, and produces the corresponding geo-referenced information. The user can choose to work with probabilistic or deterministic segment-linked optimization models (i.e. segment-linked optimization models based, respectively, on probabilistic and deterministic performance models). Both models are solved with genetic algorithms: GENETIPAV-P solves the probabilistic model (Ferreira et al. 2002), and GENETIPAV-D solves the deterministic model.

All geo-referenced information stored in the Road Network Database, or obtained through the Quality Evaluation Tool or the Decision-Aid Tool, can be visualized

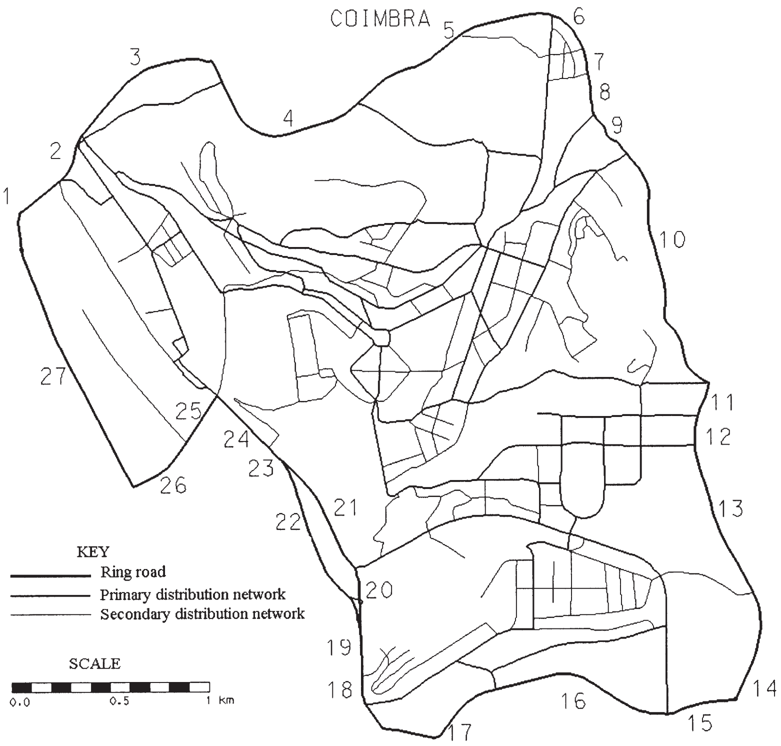

FIGURE 2 Coimbra's main road network.

on a map. This is possible because the SIGPAV is linked to ArcView GIS (ESRI, 2000b) for visualizing information and performing searches, queries, and several other mapping operations.

TEST PROBLEMS

The performance of GENETIPAV-D was first tested on two problems defined for the road network of Coimbra, the third-largest Portuguese city, with approximately 100,000 inhabitants. The city's main road network, displayed in Fig. 2, has a total length of 75 km, and the corresponding network model has 254 segments. The ring road comprises 14 km and 27 segments. The primary distribution network has 32 km and 119 segments. The secondary distribution network comprises 29 km and 108 segments.

The two problems defined for the road network of Coimbra consisted of the definition of long-term (20-year) M and R strategies for the city's ring road (27 segments) and for the city's main road network (254 segments).

For both problems, three different M and R policies were considered:

Policy I: corrective-only policy involving the simplest M and R operations (i.e. operations 1–8)

Policy II: optimization approach (corrective–preventive) involving all possible M and R operations (i.e. operations 1–16), with no limit on the number of operations to be performed in each road segment over the planning time-span

Policy III: optimization approach (corrective–preventive) involving all possible M and R operations, but with a limit of five on the number of operations to be performed in each road segment over the planning time-span.

The objective to be achieved through these policies was to minimize agency costs while keeping pavements above given quality standards. Some user costs are indirectly taken into account for policy III, through the consideration of a limit for the number of operations to be performed in each road segment. The terminal value of pavements was not taken into account because of the length of the planning time-span.

All problem data was taken from the SIGPAV. In particular, the M and R action costs considered in this study are presented in Table VI. For economy of space, other data are not included here.

PROBLEM RESULTS

The results obtained for the ring road problem (27 segments) in the absence of budgetary constraints are summarized in Figs. 3 and 4. Figure 3 presents the agency (discounted) M and R costs corresponding to policies I, II and III. It shows that, as expected, policy II

TABLE VI M and R action costs

M and R action	Cost
Do nothing	0.00€/m2
Crack sealing	1.50€/m2
Rut levelling	91.78€/m3
Patching	91.78€/m3
Longitudinal roughness levelling	91.78€/m3
Membrane anti-reflection of cracks	2.50€/m2
Asphalt concrete layer (5 cm)	5.94€/m2
Two asphalt concrete layers (5 + 5 cm)	10.25€/m2
Two asphalt concrete layers (5 + 8 cm)	12.83€/m2

(corrective–preventive) is the least-cost policy, allowing savings of approximately 21% with regard to policy I (corrective-only). Indeed, the M and R costs for policy I are 1747.6 × 10^3€, against 1444.8 × 10^3€ for policy II. It also shows that policy III, which assumes a limit on the number of M and R operations to be performed in each road segment, would lead to M and R costs of 1855.6 × 10^3€, that is, an increase of approximately 28% in respect to policy II. However, it must be said that this increase in M and R costs may be offset by the smaller frequency of traffic disturbances (i.e. smaller user costs) that characterize policy III. Figure 4 describes the accumulated distribution of M and R costs over the 20-year planning time-span. It shows that policy I leads to smaller M and R costs in the short-run, but is less efficient than policy II in the long-term. Under policy II, the concentration of M and R outlays in planning year 9 and other relatively early stages of the planning time-span would indeed allow a substantial reduction of the M and R effort in subsequent years, as compared to the M and R effort involved in the implementation of policy I. Under policy III, M and R outlays would be concentrated in planning year 4.

In addition to these summary results, GENETIPAV-D provides extensive information on the M and R strategy to be implemented for each road segment. This information is exemplified in Figs. 5 and 6 and Table VII. Figure 5 displays the operations to be performed across Coimbra's road network on the first year of the planning time-span if M and R policy II is adopted. Table VII identifies the M and R operations to be performed in segment 1 over the planning time-span. Figure 6 describes the evolution of pavement condition in the same segment, as a consequence of the M and R operations applied there.

The analysis of Table VII and Fig. 6 clarifies the implications of adopting M and R policies I, II, or III in segment 1. For example, if policy I was adopted, the first heavy intervention on the segment would only occur in planning year 12 (because the warning level for the PSI would be reached this year), and would consist of M and R operation 5. Before that year, starting at year 4, and after that year, M and R operation 2 would have to be applied every year (with the exception of year 6). If policy II was adopted, the first heavy intervention would be heavier (M and R operation 9 instead of 5), and would be applied earlier (planning year 9 instead of 12). Following the preventive application of M and R operation 9, no intervention on the segment would be needed in the next five years. The M and R costs involved in the application of policy II in the segment would be 21.9 × 10^3, much smaller than the 26.3 × 10^3€ corresponding to the application of policy I. If policy III was adopted, the M and R strategy for the segment would be the same as for policy II until year 6, but would be completely different from that year on. The first heavy intervention would be one of the heaviest available (M and R operation 13), and its application would delay the need for any other intervention until year 17. The M and R costs for the segment would be

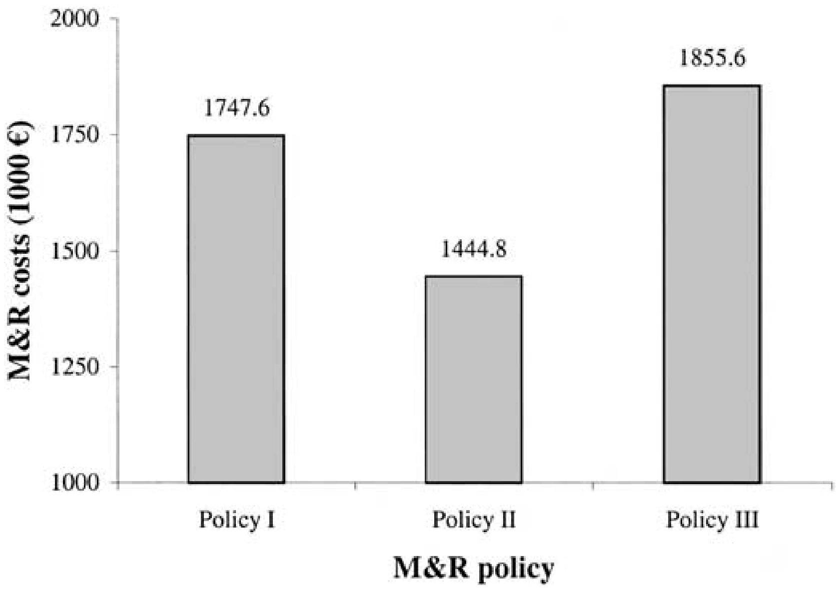

FIGURE 3 Total M and R costs under policies I, II, and III for the ring road problem.

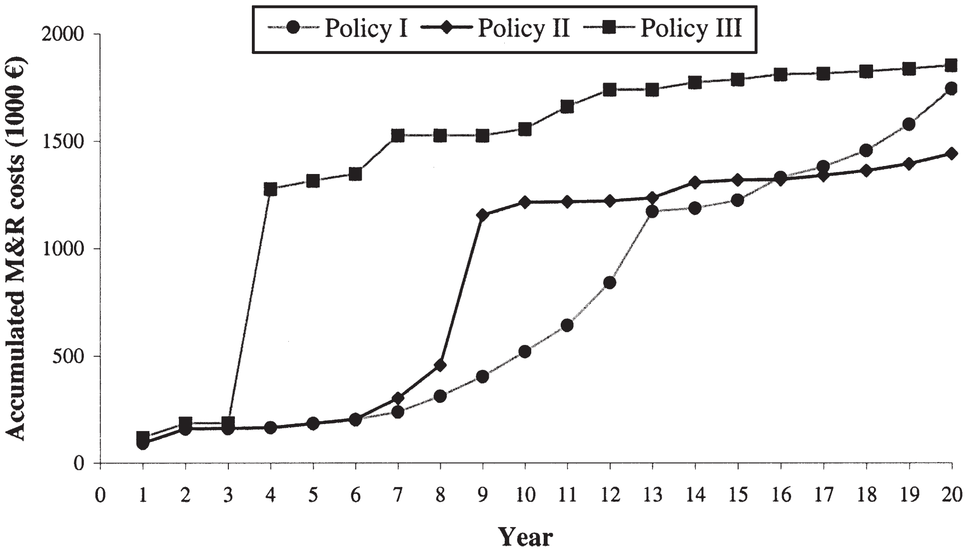

FIGURE 4 Accumulated M and R costs under policies I, II, and III for the ring road problem.

26.0×10^3€, a little less than those corresponding to the adoption of policy I.

The results obtained for the main road network problem (254 segments) are summarized in Fig. 7. They are qualitatively similar to the results obtained for the ring road problem. That is, the costs involved in the application of policy II (6064.3×10^3€) are clearly smaller than the costs involved in the application of policy I (7708.0×10^3€) and of policy III (7981.2×10^3€). But, quantitatively, the cost differences increased. The costs corresponding to policy I and to policy III are, respectively, 27 and 32% larger than the costs

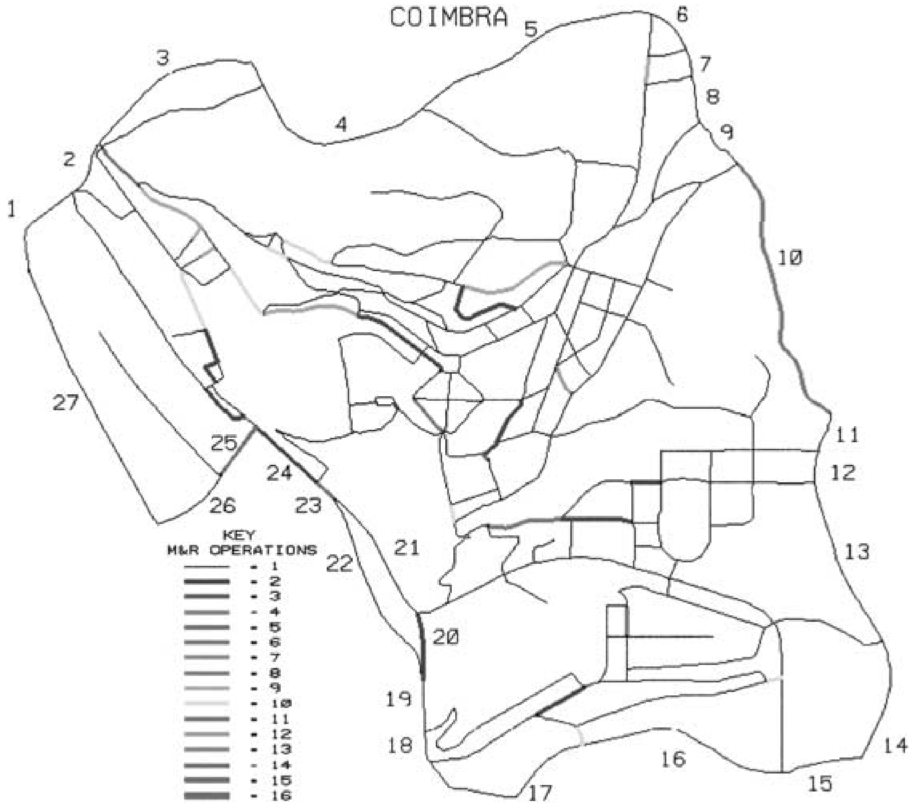

FIGURE 5 First-year M and R operations under policy II.

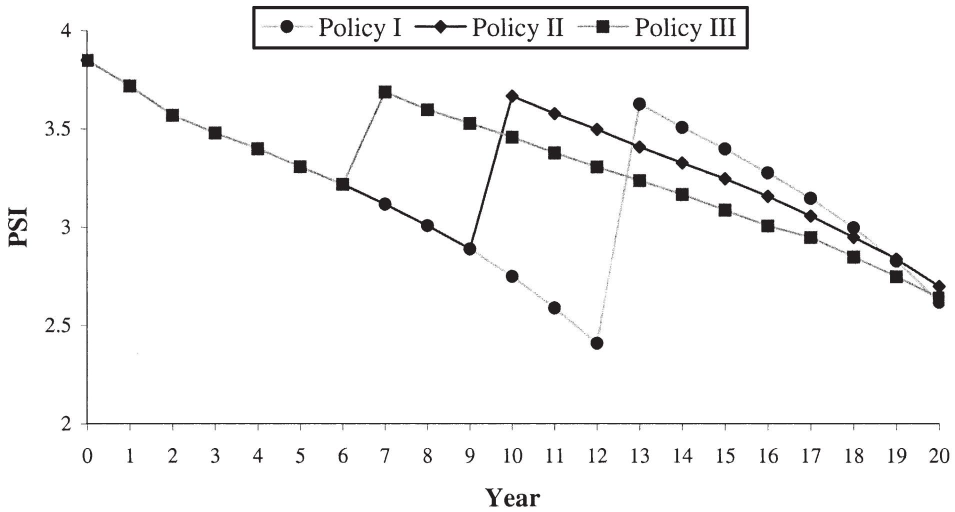

FIGURE 6 Evolution of pavement condition in segment 1 under policies I, II, and III for the ring road problem.

corresponding to policy II (the equivalent figures for the ring road problem were 21 and 28%).

The time required to determine the policy II results on a 450 MHz PC was approximately 12 min for the ring road problem and 221 min for the main road network problem. This computing effort must be considered extremely reasonable, given the complexity of the model and, in the case of the main road network, the size of the network.

CONCLUSION

The segment-linked optimization model for deterministic PMS presented in this paper is aimed at determining the least-cost M and R strategy to be implemented in a road network, taking into account the applicable technical and budgetary constraints.

The model fits into a line of research initiated by Tien Fwa at the University of Singapore in the early 90s. The contribution of the paper to this line of research is four fold. First, a formulation of the model in conventional optimization syntax is now available. Such a formulation is important because it clarifies the assumptions upon which the model is built and the information required to run it. Second, the benefits that may be derived from applying the model, and the genetic algorithm developed to solve it (GENETIPAV-D), were demonstrated on two test problems. This was accomplished through comparing the costs of the corrective–preventive M and R policy implicit to the model with the costs of a corrective-only M and R policy. Third, it was shown that the model is capable of handling quite large problems within reasonable computing effort. One of the test problems involved a 254-segment real-world network, and was solved in less than 4 h. The test problems addressed in previous papers involved 20-segment academic networks. Fourth, the model is available for application through a user-friendly, GIS-based computer program (SIGPAV). In the absence of this kind of tool, the practical relevance of the model would be considerably smaller.

In the near future, our research in the pavement management field will primarily be carried out within the framework of a four-year contract signed approximately two years ago between the Municipality of Lisbon and the University of Coimbra for the development of Lisbon's PMS (Picado-Santos et al., 2000). This will surely motivate improvements in the SIGPAV's interface, adjustments to the model (including, possibly, the re-calibration of pavement condition functions), and improvements in GENETIPAV-D, and requires the corresponding research effort. Additionally, we will try to upgrade the SIGPAV from a pavement management system into a road asset management system, thus following the path that the Fifth International Conference on Managing Pavements, recently held in Seattle, USA, clearly established (Haas, 2001).

TABLE VII M and R strategies for segment 1 under policies I, II, and III for the ring road problem

	Year																			
Policy	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
I	1	1	1	1	2	1	2	2	2	2	2	2	5	1	2	2	2	2	2	2
II	1	1	1	1	2	1	2	2	2	9	1	1	1	1	1	2	2	2	2	2
III	1	1	1	1	2	1	13	1	1	1	1	1	1	1	1	1	4	1	2	2

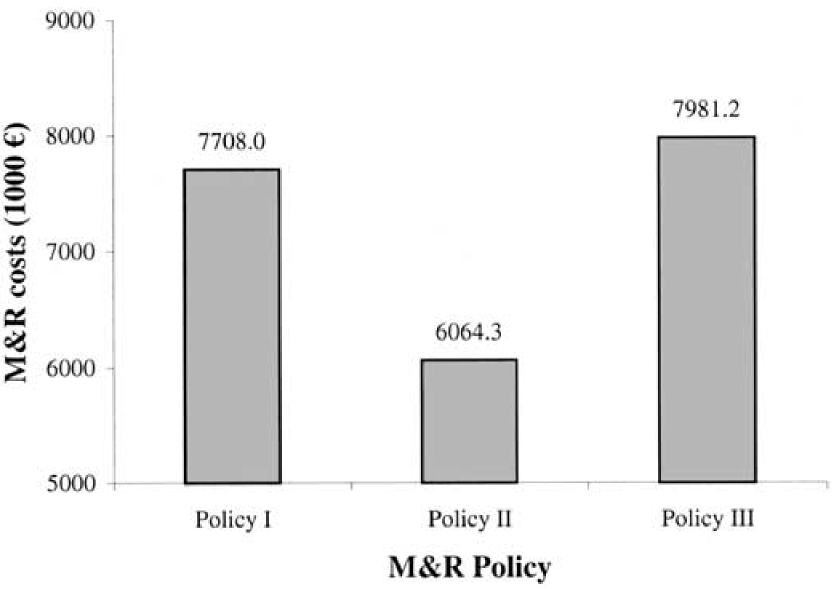

FIGURE 7 Total M and R costs under policies I, II, and III for the main road network problem.

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