the interior. This would agree with the observation made in the discussion of corner loading for the system--i.e., that there was reason to believe that the corners of the overlay slab were warped down.

It has been emphasized in this paper that not enough is yet known about the relation between the initial state of the pavement system (condition of warping) and the stress or deflection due to loads to be able to predict accurately the magnitudes of either. It is hoped that subsequent work will show that the pavement earth system behaves linearly at a certain stage defined arbitrarily as offering a degree of consistent support. The stress in the system when this stage is reached is important in predicting system performance.

SUMMARY AND CONCLUSIONS

The load-stress relation for a pavement slab is not a straight line. In order to understand the behavior of the slab, it is necessary to consider the history of warping through which it passes. A slab may be warped up, unwarped, or warped down. Depending on the state of warping of the slab, the early slope of the load-stress relation indicates (a) free bending, (b) support from the underlying layer increasing from zero to full, or (c) full support. The successive slopes follow in the same order.

In the context of the overlay systems, the upper layer is affected by warping whereas the underlying slab remains relatively unaffected. The stress in the system is dependent on the type and extent of warping of the two layers in the system.

Stresses in both layers of the system decrease with the increase in the radius of the contact plate. However, over the range of contact areas used, the stress reduction in the underlying slab is smaller than the stress reduction in the overlay. This is attributed to the load-spreading effect of the thickness of the overlay.

ACKNOWLEDGMENT

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Management System for Pavement Maintenance and Rehabilitation Based on Analytic Methods of Pavement Evaluation

PER ULLIDTZ

A management system for pavement maintenance and rehabilitation developed in Denmark is described. The system uses nondestructive testing with a falling weight deflectometer and elastic layer theory to evaluate the structural condition of existing pavements. The functional condition is evaluated in terms of root mean square values of vertical acceleration, which can be directly related to road user costs. For a given budget, the optimum maintenance strategy is determined by using integer programming. The outputs from the system are (a) an inventory of the structural and functional condition of the existing road network, (b) lists of maintenance and rehabilitation measures to be carried out to ensure the maximum reduction in user costs in view of annual budget constraints over a 3- to 5-year period, (c) prediction of the changes to the future functional and structural condition of the road network caused by alterations in the available yearly budget, and (d) the future budget needed to minimize the combined costs to the highway agency and road users.

The short-term goal of a pavement maintenance and rehabilitation management system is to assist the highway agency in answering the question, Which maintenance and rehabilitation (M&R) measures should be carried out, given a certain budget? The more long-term goal is to aid in answering the question, What will be the future standard of the road network, depending on the available budget? For society as a whole, the most important question is, Which maintenance strategy will minimize the combined costs to the highway agency and the road users?

This paper describes a pavement maintenance and rehabilitation management system developed in Denmark, the DMS, which is capable of providing answers to the above questions on both project and network levels. The system is based on analytic methods of pavement evaluation and design as stipulated in Sections 7.40.01 and 7.30.01 of the Danish Standards for Pavement Construction and Maintenance by the Danish Ministry of Transport (1).

The procedure consists of four steps:

1. Inventory--The functional and structural condition of the existing pavements is evaluated by using objective methods wherever possible;
2. Benefit/cost analysis--The functional and structural effects of each possible maintenance or rehabilitation alternative are determined and the

benefits and costs are calculated;

3. Optimization--The combination of M&R measures resulting in the highest benefit at a cost within the maintenance budget is determined; and
4. Analysis of consequences--The consequences of different budget levels for the future functional and structural condition of the road network and future user costs are analyzed.

The total pavement maintenance management system is complex and consists of a large number of submodels. The intention of this paper is to give a general review of the methodology and of the different capacities of the system. It would be impossible to include anything but a rudimentary description of the submodels in one paper. Therefore, details of the submodels and discussions of the assumptions on which they are based are given in the references. Sometimes, however, it is useful to reflect on the system in its entirety. That is the intention of this paper.

INVENTORY

A prerequisite for a pavement maintenance management system is that the present condition of the existing road network be known. In evaluating pavements it is of utmost importance to distinguish between their functional condition (ride quality) and structural condition (bearing capacity). Unfortunately, these are often confused in pavement maintenance management systems.

The functional condition of a pavement is related to road user costs (and comfort) and depends on the shape of the pavement surface. The structural condition is of no immediate interest to the road user but it is extremely important to the highway agency because the future functional condition depends on the present structural condition.

Functional Condition

As long as the pavement surface is smooth, pavement-related road user costs will be kept at a minimum. Increasing longitudinal roughness will lead to increasing user costs, first in terms of increased vehicle maintenance costs and later also in terms of increased travel times.

In the Highway Design and Maintenance Standards Model (HDM) developed by the World Bank (2), resource consumption consists of the following components: fuel consumption, oil consumption, tire wear, maintenance parts, maintenance labor, crew, depreciation, interest charges, overhead, passenger delays, and cargo holding. On highways in most industralized countries, speed is determined by road geometry and speed limits rather than by pavement roughness. When this is the case, the costs of maintenance parts and maintenance labor are completely dominant. In the HDM model, both of these costs are functions of the longitudinal roughness of the pavement.

With the DMS, longitudinal roughness is measured as the root mean square (RMS) value of the vertical acceleration of a passenger automobile. This method is used because the International Standards Organization (3) has found that the effect of vibrations on the human body is a function of the RMS of the imposed accelerations. The accelerations are measured with a servoaccelerometer suspended so as to simulate the vibrations in a human body on a car seat.

For each 50 m, the present serviceability rating (PSR) corresponding to a standard velocity (V) is determined from the following relation:

$$\mathrm{PSR} = 5.0 - 1.9\ \mathrm{lgt}\,[1 + K \times (\mathrm{RMS}/V)^2] \qquad (1)$$

where the factor K is dependent on the suspension properties of the vehicle used for the measurements. This value is also plotted (on the pavement condition form shown later in this paper) to make the location of uniform subsections easier. The PSR is also used in the structural design.

The RMS of the acceleration is approximately proportional to roughness (R), measured in meters per kilometer with a bump integrator. The relations between resource consumption and pavement roughness developed by Hide and others (4) and used in the HDM model can therefore easily be used with functional condition measured in terms of RMS of acceleration.

Structural Condition

The structural condition of a pavement will depend on the stiffness of each of the layers, including the subgrade. Apart from the thickness of a layer, stiffness is determined by the Young's modulus (E-value) of the material. There are many methods for determining E-values but, because most pavement materials are nonlinar elastic (stress-dependent), inhomogenous, and often anisotropic, it is important that the (apparent) E-value be determined under conditions that resemble as closely as possible the in situ condition under a heavy wheel load. A close approximation is obtained with the device shown in Figure 1, the falling weight deflectometer (FWD) (5-7).

The FWD tests can be carried out nondestructively because the modulus of each layer can be calculated from the deflection basin by using elastic layer theory, provided the layer thicknesses are known (8,9). This means that the tests can be carried out quickly and cheaply and (very important) that the stresses in the pavement closely resemble the stresses under a heavy wheel load. The stress condition is especially important for the unbound materials (10).

With the FWD shown in Figure 1, the test results, in terms of contact stress and deflections at seven distances from the load center, are stored on magnetic tape by the HP-85 microcomputer that controls the FWD. The structural evaluation of the pavement system can then be carried out with the Evaluation of Layer Moduli and Overlay Design (ELMOD) program on the same HP-85 microcomputer.

From the layer thicknesses and the deflection basin, the ELMOD program first calculates the modulus of each layer in two-, three-, or four-layered pavement systems by using the method of equivalent thicknesses (MET), a simplified version of elastic layer theory. It has been shown that the program produces essentially the same results as the programs developed by Chevron and Shell (BISTRO) (9),

Figure 1. Falling weight deflectometer.

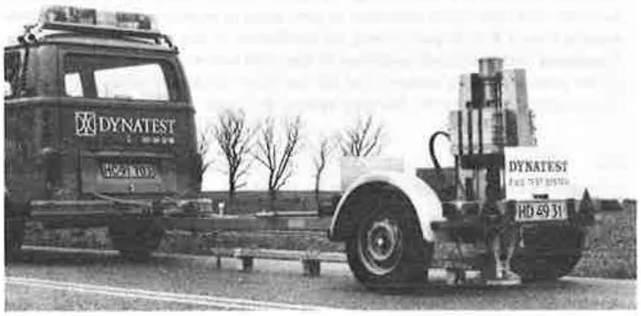


Figure 2. Variations of modulus of unbound materials with season.

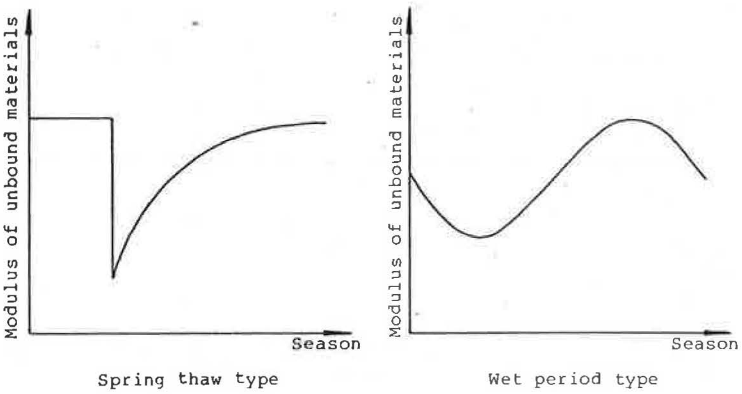
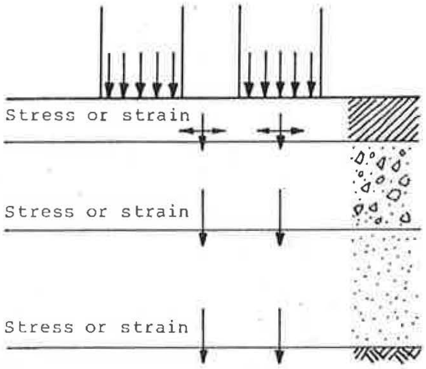


Figure 3. Locations of critical stresses and strains.



and the results compare at least as well as those of these other programs with measured values of stresses, strains, and deflections.

It is important that deflections be measured accurately, especially at distances far from the loading center. These deflections are used to determine the modulus of the subgrade and must therefore be accurate because the subgrade generally contributes two-thirds to four-fifths of the total center deflection. A small error in the determination of the subgrade modulus could lead to large errors in the moduli of the other pavement layers.

For the same reason, the nonlinearity of the subgrade must also be considered. This is essential in order to obtain a correct determination of the moduli of the pavement layers because of the effect of the subgrade on deflections (8). This can be done easily with MET.

When the modulus of each layer during the condition of testing has been evaluated (and printed in a table if desired), the program will adjust each modulus to the climatic condition of each season in the design procedure. As many as 12 seasons can be specified. For bituminous-bound materials, the moduli are adjusted with respect to temperature and, for the unbound materials (including the subgrade), they are specified as a function of the time of year in relation to the spring thaw or a wet period. Two different types of seasonal variation of unbound materials can be selected. Figure 2 shows an exponential variation typical of regions with frost and a sinusoidal variation more appropriate for regions with wet and dry periods. If desired, the modulus of each layer in each season can be printed out in a table.

To carry out the overlay design, the number of equivalent axle passages in the design period must be known as well as the load and tire configuration of the standard wheel. A single axle, an equivalent single axle, a dual wheel, or two dual wheels in tandem may be used. Figure 3 shows the possible locations of the critical stresses and strains under a dual wheel. To determine user costs, the annual daily traffic (ADT) must also be known.

By using the same method to first calculate the moduli from the response (in terms of deflections) and then the response (in terms of stresses and strains) from the moduli, discrepancies between the mathematical model and real life are offset to some extent.

Bituminous materials are assumed to crack if the horizontal strain (ϵ) at the bottom of the material exceeds the value determined from

$$\epsilon = A \times N^B \tag{2}$$

where N is the number of strain repetitions and A and B are constants that may be specified by the user.

The rate of functional deterioration (decrease in PSR) is assumed to depend on the maximum vertical stress or strain in each of the unbound materials. The stress or strain that will cause a decrease in PSR of 2 (e.g., from 4.5 to 2.5) is found from a relation of the following type:

$$\sigma \text{ or } \epsilon = A \times N^B \times (E/E_o)^C \tag{3}$$

where

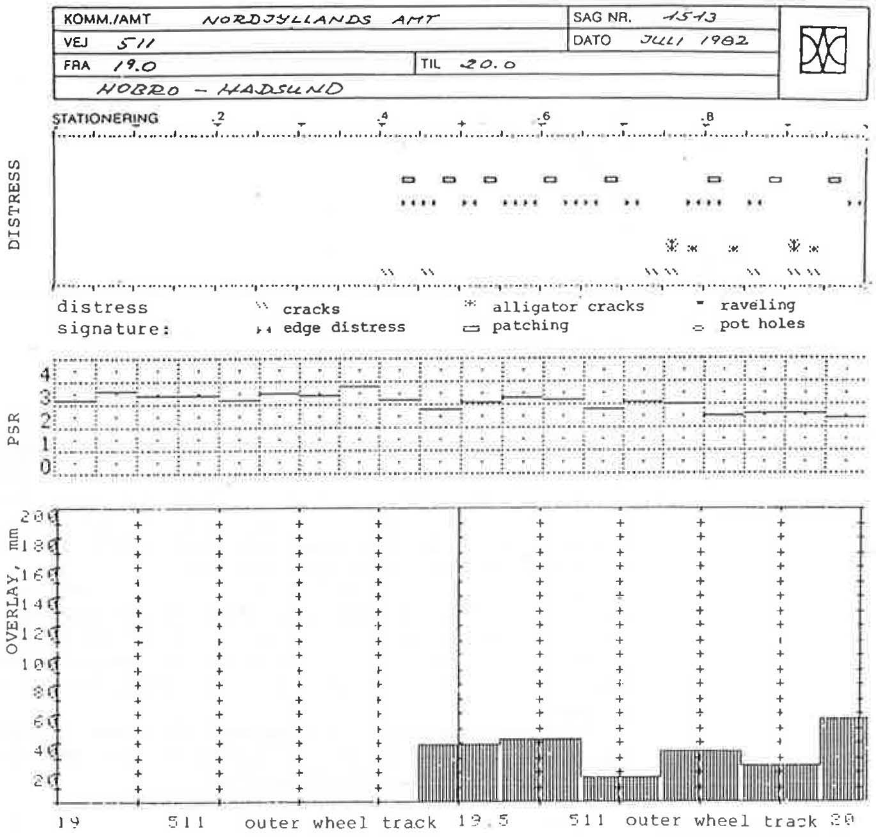
N = number of stress or strain repetitions,
E = modulus of the material,
E_O = a reference modulus, and
A, B, C = constants.

Different values of C can be used for moduli above and below E_O.

For portland cement concrete or materials stabilized by cement, lime, or fly ash, the critical value may be either horizontal stress or horizontal strain at the bottom of the layer, expressed as a function of modulus of elasticity, modulus of rupture, and number of load repetitions. The coefficients and powers of the relations may be specified by the user of the program so that the program can be calibrated to local conditions.

For a known traffic loading, the ELMOD program uses Miner's law to sum the damage for each season and to calculate the remaining life expectancy (which may be printed in a table that also gives the layer number of the critical material and the failure mode). The needed overlay thickness of a specified material and for a specified design period is also calculated. The needed overlay thickness can

Figure 4. Pavement condition form.



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be printed in a table and can also be plotted kilometer by kilometer (or mile by mile).

The overlay design produced by using the ELMOD program can be used independently of the pavement management system. In connection with the DMS, it is only a preliminary design, the main purpose of which is to help in dividing the roads into uniform subsections with respect to the structural condition. The plot of the needed overlay thicknesses is therefore mounted, kilometer by kilometer, in a pavement condition form (see Figure 4) below the plot of the PSR values showing the functional condition.

A plot of the surface condition is also included in the pavement condition form. To be able to predict the future functional condition of a pavement, the current condition of the wearing course material must be known. Unfortunately, this evaluation can only be done subjectively and must be done by an experienced asphalt engineer or a trained technician. To support this evaluation and to aid in the selection of uniform subsections, the distress pattern is recorded. The data for uniform subsections are stored in a data base that is used by the program in evaluation of the benefit/cost ratio and in optimization.

BENEFIT/COST EVALUATION

The benefit of a maintenance or rehabilitation measure is determined as the reduction in user costs. As stated earlier, maintenance parts and maintenance labor costs completely dominate when the World Bank (HDM) relations for Danish conditions are used.

The HDM relations are valid for a range of roughness somewhat higher than that usually found on highways in industrialized countries. It is therefore necessary to extrapolate from these relations. The extrapolation is done by assuming that the effect on vehicles is proportional to the mean square of the accelerations [corresponding to the effect on human bodies (11)] and by using the HDM values corresponding to minimum and maximum roughness within the valid ranges. This extrapolation leads to the following relation:

$$\Delta UC = (0.344 \times 10^{-3} \times P_V + 0.105 \times P_{LH}) \times (R_1^2 - R_2^2) \qquad (4)$$

where

ΔUC = reduction in user costs per 1,000 vehicles,
PV = average price of a vehicle,
PLH = average price of one labor hour, and
R1 and R2 = roughness before and after maintenance, respectively (m/km).

The reduction in user costs caused by a maintenance or rehabilitation measure is calculated for each year within the analysis period considered (10 to 20 years) and discounted to the year when the measure is carried out. The discount rate is the effective interest rate, which is equal to the current interest rate less the rate of inflation. To predict the future functional condition of the pavement, Equation 3 is used with the assumption that a linear relation exists between the number of load applications and the decrease in PSR. Computer simulation of the AASHO Road Test has shown this to be a reasonable assumption (11).

The reduction in user costs calculated by this method will be a conservative estimate of the total actual reduction. The calculation of user costs could be considerably refined but, with the present uncertainty in the prediction of future functional condition as well as future traffic, such a refinement would probably not be justified.

On the project level (i.e., for each subsection), the reduction in user costs of each technically feasible maintenance or rehabilitation measure is determined. As many as 50 measures are considered, including improved drainage, repaving, and reconstruction if desired. The costs of the measure as well as the costs of side effects, such as having to raise curb and gutter or repaint road markings, are calculated.

The optimum solution for each subsection is taken to be the solution that results in the highest benefit/cost ratio--i.e., the solution that gives the highest rate of return on the investment. In most cases, however, the maintenance budget of a highway agency will not allow all of the optimum solutions to be carried out. For example, in 1981 in Roskilde County in Denmark, the costs of the optimum solution were about $3 million (U.S.) but the available budget was only $1.2 million. The optimization to be carried out will of necessity be constrained by the available budget.

OPTIMIZATION

For each subsection, the solutions are first ranked according to decreasing benefit/cost ratios and uneconomical solutions are discarded. The optimization is then carried out by using 0-1 integer programming with a solution procedure developed from the procedure suggested by Mahoney, Ahmed, and Lytton (12). The procedure is heuristic but, with the reduced number of solutions per subsection, it is almost certain to find the optimum solution, or at least a near-optimum solution.

The optimum solution--i.e., that combination of maintenance measures that will result in the maximum benefit attainable with the available budget--is then printed, project by project, and the program that calculates the weighted mean values of the functional condition after maintenance (PSR), the remaining life expectancies, and the benefit/cost ratios on the network level.

The program then assumes that all of the suggested M&R measures are carried out and updates the data base by calculating the functional and structural condition of each subsection for the following year. A new optimization is then carried out by using the budget of that year and so on. Under normal conditions, the maintenance planning is carried out for 3 to 5 years into the future.

CALCULATION OF CONSEQUENCES

Repeating the optimization with different budget levels makes it possible to calculate the consequences for the maintenance standard with respect to changes in the budget. Figure 5 shows an example from an analysis of 83.4 km (40 percent) of the county road network of Roskilde County in Denmark in 1981. The figure shows the development of the functional condition and the remaining life for a 3-year period with two different budgets, where budget 2 is 20 percent higher than budget 1. By repeating the optimization, it is also possible to determine the budgets needed for the next 3 to 5 years to ensure a maintenance standard that will result in the lowest combined costs to society.

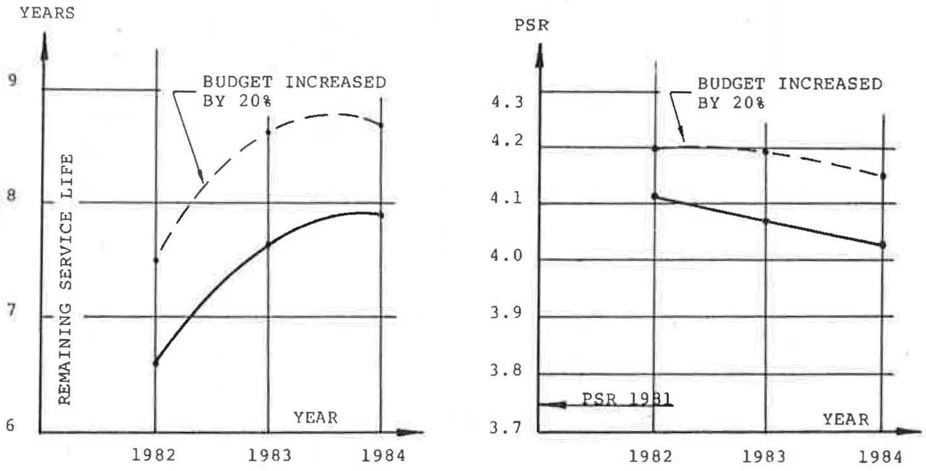
PRACTICAL APPLICATIONS

The DMS was used to evaluate approximately 180 km of the county road network in two Danish counties (Roskilde and North Jutland) during the summer of 1981. For Roskilde County it was possible to compare the results of optimizations for a 3-year period with a maintenance plan that had previously been worked out by a group of experienced highway engineers. This plan was based on measurements made with the bump integrator and with a traveling deflectometer but without detailed knowledge of the structural condition subsequently obtained through FWD tests.

For 85 percent of the subsections the optimization resulted in small changes to the original plan, either in overlay thickness or in scheduling of the maintenance measures. For the remaining 15 percent, however, the optimization resulted in major changes. In most of these cases (9 out of 10), it turned out that the subsection needed a thicker overlay than was planned due to inadequate bearing capacity, which could not be remedied by a normal wearing course.

Of the evaluated road network, 22 percent in Roskilde County and 83 percent in North Jutland County needed major rehabilitation. The two figures cannot be directly compared because they represent different percentages of each county network (40 percent in Roskilde and 12 percent in North Jutland). In the summer of 1982, the system was extended to cover the total road network in Roskilde County (204 km) and about 250 km of the network in North Jutland. The system was also adopted by other Danish highway agencies.

Figure 5. Consequences of different budget levels.



The optimizations for Roskilde County were done for a 5-year period--i.e., 1983 to 1987 inclusive. In addition to the planned budget level, the consequences of increasing or decreasing the future budget by 10 percent were determined. Figure 6 shows the future functional condition of the road network in terms of PSR. A slight decrease in PSR is to be expected with all three budget levels.

Figure 7 shows the remaining life expectancy. The predictions made for 1986 and 1987 are uncertain because it has not been possible to quantify the likely degradation of the structural condition with time. The normal life expectancy of wearing courses in Denmark is assumed to be 10 to 12 years. A reasonable level of life expectancy for the network should therefore by 5 to 6 years. With the planned budget, the remaining life expectancy is seen to be a little on the low side.

To determine the budget level that would result in the highest benefit/cost ratio, two more optimizations were carried out for budget increases of 30 and 50 percent over the planned budget. Figure 8 shows the benefit/cost ratio as a function of the total budget for the 5-year period, discounted to 1983. The present worth (1983) of the planned budget is $5 million and the optimum budget is seen to be $6 million. The high rate of return in this case is due to the high level of traffic in Roskilde County.

Figure 6. Future functional condition of road network for three budget levels.

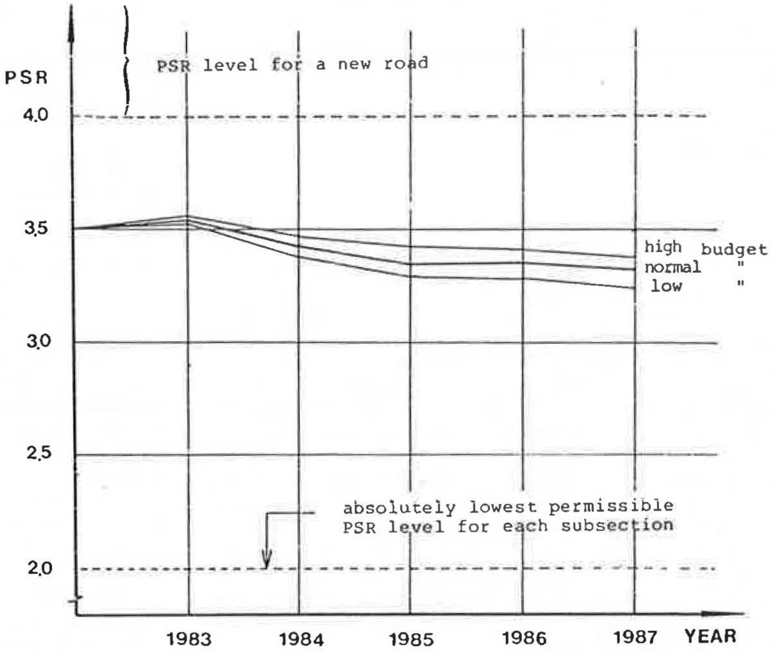


Figure 7. Remaining life expectancy for three budget levels.

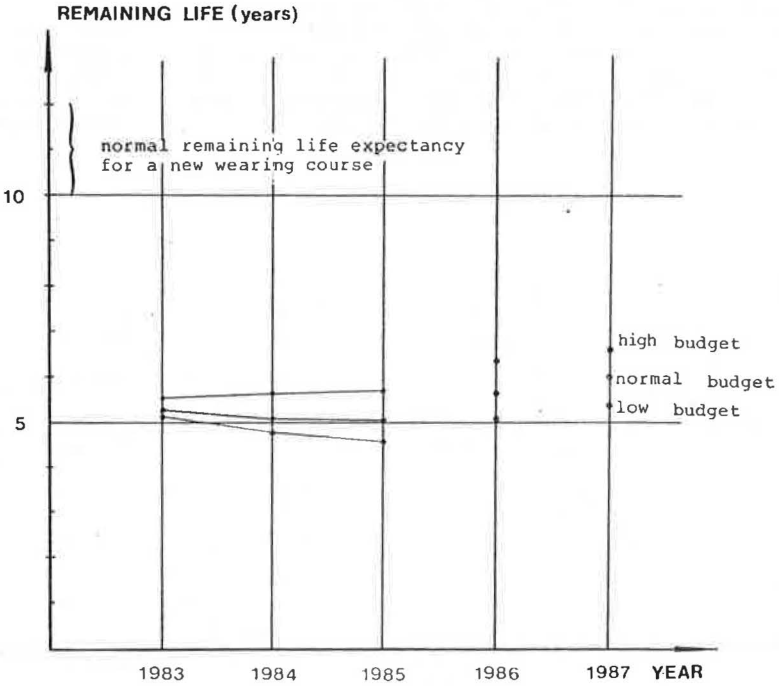
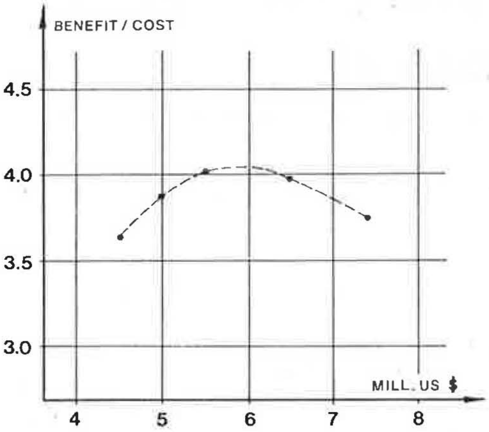


Figure 8. Benefit/cost ratio for 5-year period as a function of budget level.



CONCLUSIONS

The pavement management system described in this paper should be seen as the first attempt at incorporating analytic (mechanistic) design procedures in a system for predicting future pavement performance. The system has been implemented and will answer most of the technical and economic questions raised by highway officials responsible for maintaining a road network. There is no doubt, however, that many of the submodels will be refined in the future in light of new knowledge. The system is therefore continually monitored and updated. What is not likely to be changed is the basis of the system--namely, that the prediction of future structural and functional pavement conditions is based on the in situ measured physical properties of the pavements.

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