Standardization of Pavement Management Systems in Brazil and Other Developing Countries

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The deteriorating condition of paved road networks and the limited resources available for rehabilitating these roads in developing countries underscore the need for more rational approaches to select priority links on a road network. As a result, some developing countries have established pavement management systems (PMSs) to better manage their road infrastructure assets. A main objective of a PMS is to use reliable information and decision criteria in an organized framework to produce a cost-effective pavement program. Pavement management was developed in the United States and Canada and has been widely applied in North America, but there is a tremendous benefit to be gained by applying pavement management technology in developing countries. This has been proven in Brazil, a typical middle-income developing country, and can be applied to great benefit in other developing countries. The PMS implemented in Brazil is described, the special limitations and standardization requirements for the proper use of pavement management in a developing country are discussed. Such PMS must often be done at a technology level below that in the United States. Recommendations are presented for developing countries and for upgrading such technology.

The deteriorating condition of paved road networks and the limited resources available for rehabilitating these roads underscore the need for more rational approaches to select priority links on a road network. As a result, developing and developed countries have been establishing pavement management systems (PMSs) to better manage their road infrastructure assets.

A PMS consists of a comprehensive, coordinated set of activities associated with the planning, design, construction, maintenance, evaluation, and research of pavements. Its main objective is to use reliable information and decision criteria in an organized framework to produce a cost-effective pavement program. PMS activities are directed toward achieving the best value possible for the available funds in providing and operating pavements (1).

A PMS must be able to be updated; to consider alternative strategies; to identify the optimum alternative; to base decisions on quantified attributes, criteria, and constraints; and to use feedback information about the consequences of decisions.

Considering the needs of the network as a whole, a PMS can analyze alternative funding programs, making it possible

C. Queiroz, Western Africa Department, The World Bank, 1818 H Street N.W., Washington, D.C. 20433. W. R. Hudson, Department of Civil Engineering, University of Texas, Austin, Tex. 78712. R. Haas, Department of Civil Engineering, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1.

to identify the program that will yield the greatest benefit over the selected analysis period. At the project level, detailed consideration is given to alternative design, construction, maintenance, and rehabilitation activities for a particular section or project within the network so that an optimum strategy can be identified (2).

Pavement management was developed in the United States and Canada and has been widely applied in North America, but there is a tremendous benefit to be gained by applying the technology in developing countries. This has been proved in Brazil, a typical middle-income developing country, and can be applied to great benefit in other developing countries.

This paper summarizes the PMS implemented in Brazil for the federal network and discusses the special limitations and requirements for the proper use of pavement management in developing countries. Such PMS must often be done at a technology level somewhat below that in large cities and states in the United States. Recommendations for standardization are presented for developing countries and for upgrading such technology. A brief description of PMS-related studies in Brazil is also presented.

STEPS FOR IMPLEMENTING PMS

Experience suggests that major factors in the successful implementation and improvement of PMS are staging, preimplementation planning, and strong top-management support; the establishment of a PMS steering committee has been useful in many cases (3). An important step is that of convincing top management of the value of a PMS. Teach them what a PMS can do and what is required to develop such a system. To this end, a formal 1-week seminar by Hudson and Haas was organized in Brazil in 1983; it included the participation of senior highway managers on the first day. A follow-up seminar was given by Hudson, Haas, and Queiroz at the University of Sao Paulo in 1985. Informal meetings, formal seminars, progress reports, and conference papers are important means of communication between technical staff and managers and across divisions that cooperate in PMS implementation. For Brazil, these activities were also crucial to the dissemination of PMS techniques to state highway authorities.

Figure 1 shows the main stages in developing and implementing a PMS, which were generally followed in Brazil.

Special constraints for implementing PMSs in developing countries include limited trained local human and material resources in several countries, and Brazil is no exception.

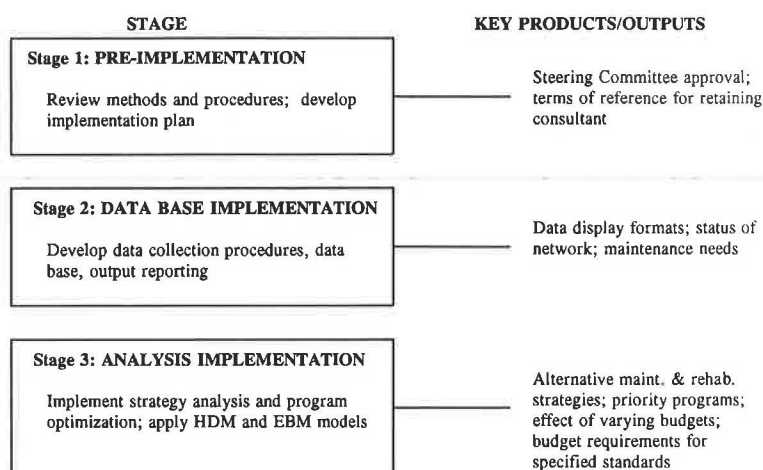| STAGE	KEY PRODUCTS/OUTPUTS
Stage 1: PRE-IMPLEMENTATION Review methods and procedures; develop implementation plan	Steering Committee approval; terms of reference for retaining consultant
Stage 2: DATA BASE IMPLEMENTATION Develop data collection procedures, data base, output reporting	Data display formats; status of network; maintenance needs
Stage 3: ANALYSIS IMPLEMENTATION Implement strategy analysis and program optimization; apply HDM and EBM models	Alternative maint. & rehab. strategies; priority programs; effect of varying budgets; budget requirements for specified standards

FIGURE 1   Major stages in development and implementation of PMS.

Adopting less-sophisticated methods and equipment for data collection can minimize the material needs. As the amount of modern equipment used to evaluate pavements has grown, so has the concern to choose the most-appropriate devices. An illustrative case is the measurement of pavement deflection, for which the traditional Benkelman beam is of particular interest; not only does it achieve adequate productivity at generally lower costs, but its use can lead to a high degree of accuracy in applying road investment analysis models such as HDM (4). Operation of Benkelman beams is labor-intensive, and the instruments are robust.

As for the human resource limitations, foreign consultants were used part time during the first 3 years of PMS implementation (about 1983–86). Consultants have also been useful in PMS improvement and can help to maintain a strong interest by agency managers through periodic visits and seminars. The consultants should work closely with committed local counterparts to insure PMS sustainability.

PMS STRUCTURE

The detailed structure of a PMS depends on the organization of the particular agency within which it is implemented. For Brazil it was considered important to include the following subsystems (5):

● *Information subsystem*, which includes data on road length, pavement type, roughness, distress, structural adequacy, traffic, and costs. A simple and realistic procedure for periodically collecting data on the road network that takes advantage of sampling techniques was designed to best fit the needs and capability of the federal roads agency;

● *Maintenance strategy subsystem*, which should be able to simulate total life-cycle conditions and costs for multiple road maintenance (and eventually design) alternatives for road links making up the network. This subsystem should also assist in determining current and future needs (i.e., those sections in the network that have reached or will reach their minimum acceptable or "trigger" level, depending on the criteria specified);

● *Optimization subsystem*, which is necessary whenever the needs exceed the available funds (a common situation in developing countries); and

● *Report subsystem*, which should be able to provide information on the current status of the paved road network, priority programs of rehabilitation, reconstruction and maintenance, and effects of different budget levels on these programs and on the state of the network.

For easier access, the computerized part of a PMS should operate on a personal computer workstation, which can eventually be linked to a mainframe system. A PMS should be flexible in the options provided to the user and in the graphical and tabular reporting functions ranging from detailed to summarized.

PAVEMENT EVALUATION

A systematic approach to pavement management started in Brazil in 1983 under the Brazilian National Highway Department (DNER) for application on the paved federal road network, and several states in Brazil have gradually adopted the developed methodology.

A specific pavement evaluation methodology has been developed as part of the DNER PMS (5). For evaluation, the paved road network is divided into homogeneous subsections. The following sequence of procedures is applied to define sample segments, where deflections are measured, and assessment areas, where detailed condition surveys are carried out (Figure 2):

1. Identification of homogeneous subsections within the unitary sections of the National Highways Plan (PNV). These subsections should be between 0.3 and 20 km long. The subsections are selected visually by the resident engineer, without using any equipment. The main factors considered are the type and condition of the surfacing and the homogeneity of traffic.

2. Measurement of roughness on homogeneous subsections. Roughness was adopted as the primary measure of
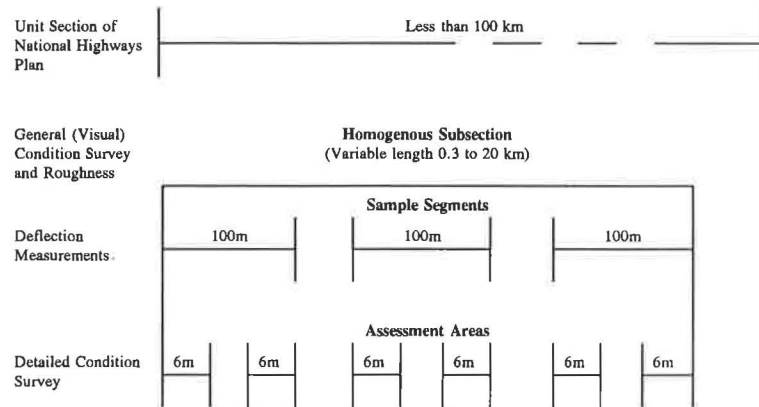
FIGURE 2 Sampling system for network survey.

pavement condition because it relates to safety, the overall economics of road transportation, and rider comfort and performance.

3. Identification in situ of sample segments considered representative of each homogeneous subsection. Three sample segments (each 100 m long) are identified at the beginning, middle, and end of each homogeneous subsection.

4. Measurement of deflection on the sample segments. Pavement deflection is an important parameter for predicting future pavement condition. The Benkelman beam has been adopted to measure deflection in external wheel tracks at 20-m intervals on alternate sides of each sample segment.

5. Survey of pavement condition. Determining the types and extent of pavement defects (such as cracking, potholes, and rutting) is of great importance for planning road maintenance and rehabilitation. Six assessment areas are marked out on each homogeneous subsection, that is, two on each of the extremes of the three 100-m sample segments. Pavement distress found in the assessment areas is duly recorded in both qualitative and quantitative terms.

In summary, under the DNER PMS, pavement evaluation includes a survey of pavement condition and deflection measurements on a sampling basis and of roughness measurements on the whole network.

Resources permitting, these measurements will continue to be taken annually and will be summarized in a format useful to senior management besides being used in economic and technical analyses.

ECONOMIC ANALYSIS OF ALTERNATIVE MAINTENANCE STRATEGIES

PMS implementation requires the use of a valid model to simulate total life-cycle performance and costs for several road maintenance and rehabilitation alternatives for each of the road links composing the network (4). For Brazil, the model of choice is the Highway Design and Maintenance Standards Model (HDM-III).

HDM is designed to make comparative cost estimates and economic evaluations of different construction and maintenance options, either for a given road project on a specific alignment or for groups of links on an entire network. A user can search for the alternative with the lowest discounted total cost. If HDM is used in conjunction with the Expenditure Budgeting Model (EBM), the set of design and maintenance options that would minimize total discounted transport costs of an entire road network under year-to-year budget constraints can be determined (4). Thus the EBM model assists the analysis team in identifying priority sections and the best maintenance alternative for each priority road section. Microcomputer versions of both HDM and EBM are now available, which makes the models more flexible for general use.

The models used to quantify the relationships between the costs of road construction and maintenance and vehicle operation in HDM resulted from data collected under a collaborative large-scale research program, most of which was carried out in Brazil under a wide range of environmental conditions (4,6). HDM relationships are thus directly applicable to Brazil and other tropical regions.

OPTIMAL REHABILITATION PROGRAM

An appropriate methodology for gathering data on the road infrastructure—along with data on the volume, composition, and weight of traffic on each homogeneous subsection—provides the basic information necessary for an economic analysis of alternative strategies to maintain and rehabilitate a road network. This analysis can be applied at the project and network levels using a program such as HDM.

The data necessary for running the HDM model refer to the structure and condition of the existing network, the various sets of maintenance, rehabilitation and reconstruction alternatives, maintenance standards, unit costs, traffic projections, and environmental parameters. Using these data, the model carries out the following series of calculations:

- Vehicle speeds and consumption of resources;
- Road deterioration and maintenance resources;
- Road construction resources;
- User, agency, and total financial and economic costs, calculated on the basis of physical quantities and unit costs; and
- Net present values, internal rates of return and first-year benefits.

Running the HDM-III is divided into the following phases (*4*):

- Data entry and generation of diagnoses;
- Simulation of traffic flows and variations in road condition year by year, taking account of deterioration, maintenance, and possible improvements; and
- Economic comparisons and analyses of alternative construction and maintenance options for selected groups of road links.

A fourth phase is executed by using the EBM model that selects the optimum combination of projects and maintenance alternatives in light of budget constraints.

An example of applying the HDM-EBM methodology is provided here by the economic analysis of alternative programs for rehabilitating the Brazilian federal paved road network, which took into account various annual budget levels for the period from 1986 to 1988. This was the first exercise of this type carried out for the Brazilian federal network, and it is to be followed by subsequent 3-year rolling programs. An analysis period of 12 years was used. The main objective of the analysis was to identify the sections of road that if rehabilitated would result in the maximum overall net present value for each level of investment.

Most of the benefits result from the reduction in vehicle operating costs over each year of the analysis period, a consequence of the improved road condition brought about by rehabilitation or maintenance, or both. The study was relatively conservative in that it did not take account of the reduction in accidents costs caused by safer pavements.

Data for the study were obtained on about 33 000 km of the federal paved network, which resulted in about 3,400 homogeneous subsections, or 10,200 sample segments (where Benkelman beam deflections were measured) and 20,400 assessment areas (where detailed condition survey was performed, including cracking, ravelling, pothole, patching, and rutting measurements).

Running HDM to analyze 3,400 sections would be too costly and time-consuming. To make the analysis manageable, the homogeneous subsections were classified by means of a factorial matrix with 108 cells, each of which represented a set of sections with a relatively narrow range of features. The following factors and respective levels were used to define the matrix (*7*):

- Average daily traffic (four levels): less than 1,000; 1,000 to 3,000; 3,000 to 5,000; and more than 5,000 vpd;
- Benkelman deflection (three levels): less than 0.5; 0.5 to 0.8; and more than 0.8 mm;
- Percentage of pavement area cracked: less than 20, 20 to 40, and more than 40 percent; and
- Roughness, in terms of the quarter-car index (QI): less than 40, 40 to 60, and more than 60 counts/km.

Ten sets of rehabilitation and maintenance alternatives were defined for possible application to each road section (or groups of road sections in a cell of the factorial matrix) during the analysis period, as given in Table 1.

The HDM model was then run for each cell of the factorial matrix, using as input data the weighted average of pavement condition and traffic applicable to each cell. The optimum maintenance and rehabilitation alternative selected from those shown in Table 1 was then identified for each group of road sections in a cell, that is the alternative that would maximize the net present value (*7*). Ideally, it would be desirable to implement physically the optimum option for all of the road sections on the network. However, it was found that the

TABLE 1   PAVEMENT REHABILITATION OPTIONS

Option	HDM Code	Maintenance/Rehab Alternative	Minimum Useful Life (years)	Roughness, QI (counts/km)	Cracking (%)
0	12	Routine maintenance	-	-	-
1	08	Deep Patching	-	-	-
	12	Routine maintenance	-	-	-
2	09	Slurry seal	3	-	30
	12	Routine maintenance	-	-	-
3	09	Double surface dressing	5	-	30
	12	Routine maintenance	-	-	-
4	10	Overlay (4 cm AC)	5	50	-
	12	Routine maintenance	-	-	-
5	10	Overlay (8 cm AC)	5	40	-
	12	Routine maintenance	-	-	-
6	10	Overlay (8 cm AC)	5	60	-
	12	Routine maintenance	-	-	-
7	10	Overlay (12 cm AC)	5	40	-
	12	Routine maintenance	-	-	-
8	10	Overlay (12 cm AC)	5	60	-
	12	Routine maintenance	-	-	-
9	11	Reconstruction (15 crushed stone + 5 AC)	10	80	-
	12	Routine maintenance	-	-	-

funds required were well over the available or plausible budget levels.

Using as input the HDM output for each cell, as well as the most plausible budget levels, an improved version of the EBM model was run to select priority cells to be rehabilitated. The criterion adopted was that of maximizing the overall net present value. The priority sections thus identified served as the basis for a major road rehabilitation program in 1986–88. Actual rehabilitation design for each priority road section was done by the application of an optimal design method (8). The improved EBM model, developed at the Brazilian Road Research Institute, excludes any restriction with regard to number of projects or of budgetary periods yet provides the same results as EBM when run with data within EBM limitations (9).

ACCEPTABILITY INDEX TO PRIORITY RANK REHABILITATION SECTIONS

The HDM-EBM analysis of a road network, as described, may become too costly and time-consuming for large road networks. To circumvent this problem, it was deemed worthwhile to develop an acceptability index (AI) that could be computed directly from the field parameters characterizing the homogeneous subsections of a network and yet enable rehabilitation priorities to be assigned to the subsections much more rapidly and simply than by means of a detailed economic analysis (10).

The main purpose of calculating AI is to classify the various sections of a road network in terms of rehabilitation priorities. The higher the value of AI, the greater the acceptability of the section and, therefore, the smaller the need for rehabilitation. The AI to be investigated would be allowed to range from 0 to 100. A section with an AI of 0 would have no acceptability and would therefore be assigned maximum priority, whereas a section with an AI of 100 would receive zero priority. The AI cannot replace the economic analysis, but it is helpful as a means to first screen the road network and select a subset of road sections in most need of rehabilitation. The HDM-EBM analysis would then be carried out on this subset and be of a much more manageable size.

The AI calculation algorithm was developed at the Brazilian Road Research Institute (11). Two sets of data are necessary for calculating the AI. The first concerns the road section itself, and the second is based on the averages and standard deviations for certain features of the road network. The values relating to the individual road section are as follows:

- Roughness, in terms of the quarter-car index in counts per kilometer (QI);
- Percentage of paved area affected by cracks rated as Class 2 or worse, plus patching and potholes (CR);
- Average Benkelman beam deflection in 0.01 mm (BD);
- Average daily volume of cars and light trucks in vehicles per day (CA);
- Average daily volume of buses in vehicles per day (BU);
- Average daily volume of trucks (medium, heavy, and semitrailers) in vehicles per day (TR);
- Annual rainfall in millimeters per year (RA); and
- Indicator denoting topographic relief, that is, 1 = flatland, 2 = hilly, 3 = mountainous (RE).

The values relating to the road network are expressed as the averages and standard deviations of these eight variables. As an example, a set of values for these parameters, calculated from the 1985 survey of the Brazilian federal paved road network, is given in Table 2 (10). Calculating AI for a road section requires the following steps:

1. Calculation of the reduced value—$R(x)$—of each of the parameters above:

$$R(x) = (x - \text{average})/\text{deviation}$$

where

$$
\begin{aligned}
R(x) &= \text{reduced value,} \\
x &= \text{parameter value for the section,} \\
\text{average} &= \text{average of parameter } (x) \text{ for the network, and} \\
\text{deviation} &= \text{standard deviation of parameter } (x) \text{ for the network.}
\end{aligned}
$$

2. Calculation of the standardized value—$S(x)$—of each of the parameters above: $S(x)$ is obtained as the area under the normal curve corresponding to $R(x)$. For example, if $R(QI) = 2.86$, then $S(QI) = 0.9979$. If the standardized value is negative, its absolute value should be used.

3. AI can then be computed by

$$AI = 100 - 0.03993 \times (FQI \times FTR \times FST)^{2.278}$$

TABLE 2 SUMMARY CHARACTERISTICS OF BRAZILIAN FEDERAL PAVED ROADS

Item No.	Variable	Average	Std. Deviation
1	Roughness, QI (counts/km)	49.94	13.86
2	Cracking (%)	18.44	26.34
3	Deflection (mm)	57.38	37.99
4	Average daily traffic: cars	1,641.06	3,973.21
5	Average daily traffic: buses	279.08	1,003.48
6	Average daily traffic: trucks	1,391.29	2,271.21
7	Rainfall (mm/yr)	1,299.45	548.08
8	Relief	1.90	0.59

where

$$FQI = [10 \times S(QI)]^{0.0633};$$
$$FTR = [10 \times S(CA)]^{0.141} + [10 \times S(BU)]^{0.164}$$
$$+ [10 \times S(TR)]^{0.514}; \text{ and}$$
$$FST = [10 \times S(CR)]^{0.038} + [10 \times S(BD)]^{0.083}$$
$$+ [10 \times S(RA)]^{0.024} n + [10 \times S(RE)]^{0.014}.$$

It is pertinent to note that the equation given to compute the acceptability index was developed through regression analysis with the results of the HDM-EBM analysis of the federal paved network (11). The objective was to obtain an AI that would approximate the priorities given by the economic analysis. The criterion chosen was that the AI should be correlated with the unit net present value (NPV/km) resulting from the optimum rehabilitation alternative of a road section (10). In fact, a comparison between priorities assigned by the HDM-EBM analysis and those computed by the AI showed very good agreement.

Unit net present value (NPV/km) and the acceptability index are well correlated (coefficient of determination of 0.96) by Coelho (11):

$$NPV/km = 1564/(AI^2 + 1) + 164 \exp(-0.098\ AI)$$

The AI is a simple ranking approach that estimates the relative rehabilitation need (and economic return) of road sections making up a network. It is a method that can be applied for large road networks when the number of sections is high and the HDM-EBM optimization method may not be practical. The AI not only has a direct connection with the optimization technique but also can be linked with the utility concept. In a road facility management system, utility is the level of overall effectiveness that can be achieved by undertaking a project (12). A road section with an AI of 0 has the highest priority to be rehabilitated, and therefore the utility value of rehabilitating this section should be maximum, that is, equal to 100. Conversely, if a section's AI is 100, this section is totally acceptable and does not require any rehabilitation; the utility value of rehabilitating it should be minimum, that is, zero. Therefore, the acceptability index and the utility value (UV) can be linked by

$$UV = 100 - AI$$

ROUGHNESS SCALE

Roughness plays an important role in pavement management because it is the most important measure of road condition influencing vehicle operating costs and because it affects the safety, comfort, and speed of travel. Roughness was expressed in this paper in terms of QI in counts per kilometer (13). However, roughness measurements are now generally expressed in terms of the international roughness index (IRI) (14). IRI is mathematically defined from relatively true profile to simulate the vertical motions induced in a moving quarter-car (i.e., one wheel, suspension, and sprung mass).

The basic concepts of QI and IRI come from simulation of vertical motion on a road profile. QI was the roughness standardized in the Brazil/UNDP study (6), which provided most of the data originating the HDM model. The relationship between QI (in counts per kilometer) and IRI (in meters per kilometer) scales is (15)

$$QI = 13\ IRI$$

Roughness measurements for the Brazilian PMS are obtained using a vehicle instrumented to produce a numeric proportional to the vehicle response to the road traversed. Two such systems, which are called response-type road roughness measuring systems (RTRRMSs), have been used in Brazil: Maysmeters and Linear Displacement Integrator (6,16). The roughness numeric obtained from a RTRRMS for a road section depends on the test speed, type and condition of host vehicle, and other factors. Therefore, any RTRRMS must be periodically calibrated to produce QI or IRI.

All RTRRMSs used in Brazil are calibrated by correlation, which is performed on control road sections. The QI (or IRI) for each control section is obtained by a rod-and-level survey (17). The RTRRMS to be calibrated measures 10 or more of their control sections, and the results are used with QI to determine a regression equation that is used to convert RTRRMS measurements into QI. As a result of this calibration, roughness measurements under the Brazilian PMS are stable over time and can be compared with careful measurements taken in any other region of the country or the world.

RECOMMENDATIONS FOR OTHER DEVELOPING COUNTRIES

Although developed for Brazil, the pavement management technology described herein can be applied directly, or with slight adjustments, to other developing countries with large road networks. For countries with smaller road networks (up to about 50 links or homogeneous subsections), it is recommended that the HDM-EBM optimization analysis be applied directly to the road links composing the network, without the need for grouping links into cells of a factorial matrix. Future improvements to the HDM-EBM software should make it feasible to apply the optimization technique directly to larger networks.

The periodic computation and display of acceptability indexes (or utility values) for a road network provides a simple means for senior management, and eventually the public user, to monitor performance of the networks they manage or use. It is recommended that an acceptability index similar to the one shown here be computed and used in developing countries in the future.

CONCLUSIONS

The successful development, implementation, improvement, and sustainability of a PMS in Brazil appeared to result from careful preimplementation planning, strong support by senior management, a sound data base, use of adequate models, and a commitment by those responsible for its operation. External resources, in terms of specific financing and consultant expertise, have played a key role in all phases of PMS development and implementation.

This paper described the main stages and activities in the development of a PMS for use in Brazil, including condition surveys, roughness measurements, a data base for pavement-related information, an analysis scheme (including the use of HDM and EBM models and an acceptability index), and implementation procedures.

The acceptability index presented is a simple ranking approach that provides the relative rehabilitation need (and economic return) of road sections comprising a network. It is a method that can be applied for large road networks for which the number of sections is high and the HDM-EBM optimization method may not be practical. The AI not only has a direct connection with the optimization technique used but also can be linked with utility concepts.

Although developed for Brazil, the pavement management technology described in this paper can be applied directly, or with slight adjustments, to other developing countries. Certainly the concepts are applicable everywhere.

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