making technologies from industrialized countries, this has sometimes distorted the evolution toward road-building methods that are appropriate to the local environment.

3. The effects of climate and of the nature of available road-making materials on road-building methods are now generally understood; however, this knowledge still needs to be refined and there is the opportunity for countries of the Third World to define the way in which their road-building technologies should be evolving and to make a conscious effort to promote this evolution.

REFERENCES

1. R. Robinson, H. Hide, J.W. Hodges, J. Rolt, and S.W. Abaynayaka. A Road Transport Investment Model for Developing Countries. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, Lab. Rept. 674, 1975.
2. C.G. Harral, P. Fossberg, and T. Watanatada; World Bank. Evaluating the Economic Priority of Highway Maintenance. Pan African Conference on Highway Maintenance and Rehabilitation, Ghana, 1977.
3. J. de Weille. Quantification of Road User Savings. World Bank, Washington, DC, Occasional Paper 2, 1966.
4. H. Hide, S.W. Abaynayaka, I. Sayer, and R.J. Wyall. The Kenya Road Transport Study; Research on Vehicle Operating Costs. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, Lab. Rept. 672, 1975.
5. A Guide to the Structural Design of Bitumen-Surfaced Roads in Tropical and Sub-tropical Countries. 3rd ed. Transport and Road Research Laboratory; Her Majesty's Stationery Office, London, 1977.
6. F.A. Hansen. Bituminous Surface Treatments on Rural Highways. Proc., New Zealand Society of Civil Engineers, Vol. 21, 1934-1935.
7. A Basic Asphalt Emulsion Manual. Asphalt Institute, College Park, MD, Manual Series No. 1, MS 19, March 1979.
8. A Guide to Surface Dressing in Tropical and Sub-tropical Countries. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, Overseas Road Note 3, (in press).
9. G.P. Jackson. Surface Dressing. Shell International Petroleum Company Ltd., London, 1963.
10. Principles and Practice of Bituminous Surfacing: Vol. 1., Sprayed Work. National Association of Australian State Road Authorities, Sydney, 1965.
11. C. Richardson. The Modern Asphalt Pavement. 2nd ed. Wiley, London and New York, 1908.
12. C.P. Marais. Gapgraded Asphalt Surfacings--The South African Scene. Second Conference on Asphalt Pavements for Southern Africa, Durban, South Africa, 1974.
13. Rolled Asphalt (Hot Process) for Roads and Other Paved Areas. British Standards Institution, British Standard 594, 1973.

Publication of this paper sponsored by Committee on Low-Volume Roads and Committee on Theory of Pavement Systems.

Improved Pavement Management System for Low-Volume Roads

B. FRANK McCULLOUGH, DAVID R. LUHR, AND ADRIAN PELZNER

The economic consequences of pavement design and maintenance for low-volume roads need to be evaluated. Because many low-volume road networks have large mileages compared with high-volume road networks, the capital investment in a low-volume network can be high. Low-volume roads are more economically sensitive, on a percentage basis, to pavement design changes; therefore, the use of a pavement management system in the planning, design, construction, maintenance, and management of low-volume road pavement structures is important. An improved version of the computer program, Pavement Design and Management System (PDMS), was developed that greatly increases the capabilities of the system and also improves the rational basis for predicting pavement performance. A structural analysis of American Association of State Highway Officials road test pavement sections was conducted by using a nonlinear elastic layer procedure to characterize the pavement materials for four seasonal periods. A regression analysis was performed to develop a performance-prediction equation. The dependent variable used was the change in present serviceability index (PSI) divided by the change in vehicle applications for each seasonal period. The performance variable is used to predict the PSI-traffic curve for the pavement structure, thereby allowing the evaluation of the performance area under this curve. Because each vehicle type is considered separately, there is no need to consider axle equivalency factors. This is an important advantage because American Association of State Highway and Transportation Officials equivalency factors are found to have serious limitations.

The term pavement management system was first used in the late 1960s and early 1970s to describe a systems engineering approach to the problem of economical design, construction, and maintenance of roads. Since that time many developments have been made in the area of pavement management systems for both rigid and flexible pavements (1).

Interest in pavement management has increased substantially in recent years as transportation agencies look for new methods and tools to use in the efficient management of transportation networks. Pavement management can be a tremendous asset to the engineer faced with budget restrictions, material shortages, and important energy considerations, and at the same time it can meet increasing demands from heavier axle loads and traffic volumes.

NEED FOR LOW-VOLUME-ROAD PAVEMENT MANAGEMENT

The implementation of pavement management is associated with high-cost, high-volume roadways. The use of a pavement management system for low-cost, low-volume roads may have the appearance of applying too much sophistication to a low-cost situation. However, the term low cost may sometimes be a misnomer when applied to low-volume roads. This is because, in many transportation networks, low-volume roads constitute the majority of the network mileage.

In Texas, the Interstate highway system is composed of approximately 4800 km (3000 miles) of roadway. In comparison, the low-volume farm-to-market system contains approximately 66 000 km (41 000 miles) of roadway. Even though the cost per mile of constructing an Interstate highway is 10 times the cost per mile for farm-to-market construction, the difference in mileage results in the Interstate system having only 75 percent of the capital investment of the farm-to-market system.

The roadway system of the U.S. Forest Service has very small traffic volumes and much lower construction costs per mile than the Texas farm-to-market system. However, the size of this system [420 000 km (260 000 miles)] makes the total capital investment very large. Even though 95 percent of these road miles have no bituminous surfacing, approximately $475 million will be spent in 1982 on maintenance, rehabilitation, and new construction for this system.

Also note that small differences in pavement structure design will have a larger effect on the economics of low-volume than high-volume roads. For example, an increase in the surfacing thickness of 1 in for a low-volume road may result in a 30 percent increase in the construction cost per mile. However, the same increase in the surfacing thickness of an Interstate highway may increase the construction cost by only 5 percent because the cost per mile for the Interstate is much higher. When the increased cost per mile for the low-volume road is multiplied by the large mileage in a low-volume network, the increased cost of the small difference in pavement structure is very large.

It is, therefore, obvious that decisions made regarding pavement design and maintenance for low-volume roads are economically very important. Considering the high cost involved with the number of miles in a typical low-volume road network, the use of a pavement management system as a tool in the planning, design, construction, maintenance, and management of the roadway structure should not be overlooked.

Previous Development

The road system of the U.S. Forest Service is made up entirely of low-volume roads that are often in very rugged terrain, are subjected to severe environmental conditions, and vary regionally from the low swamplands of Florida to the mountains of Alaska. Because of the complexities involved in the efficient design, maintenance, and management of pavement structures in such an extensive roadway system, the U.S. Forest Service initiated, with the University of Texas, a cooperative study in 1972 to develop a pavement management system that would be applicable to Forest Service roads. The result of this cooperative effort was the computer program Pavement Design and Management System (PDMS), which was implemented on a trial basis in the Forest Service in 1977 and on a permanent basis in 1979 (2-4).

This pavement management system calculates and optimizes pavement design and rehabilitation strategies on a project level after being given information about available construction materials, material characteristics, expected traffic volumes and loads, various costs, and required pavement performance. Pavement management is accomplished by effectively considering all costs associated with the pavement structure over the entire length of the analysis period. This includes initial construction and subsequent costs related to road maintenance, rehabilitation, and vehicle operation. In this way, the designer is able to make the most efficient use of available resources, in addition to having a tool for future planning purposes.

As a result of the implementation of this pavement management system, it was determined that the system could be revised and improved significantly through a new research and development effort. An initial investigation found that a mechanistic approach to pavement design and prediction of pavement performance would be the best way to revise the system (5). As a result of this initial investigation, plans and objectives were developed that would result in a new and improved version of PDMS.

Summary of Objectives

The objective of the research and development effort to improve PDMS was to enhance the capabilities of the pavement management system and also to improve the fundamental approach of certain performance models within the system. Specifically, the primary objectives were the following:

1. Develop a design algorithm based on a rational characterization of the pavement structure and pavement response,
2. Develop the capability to consider the seasonal characteristics of pavement materials as well as seasonal changes in traffic volume,
3. Develop the capability to consider the stress-sensitive characteristics of unbound materials in the pavement structure,
4. Develop the capability to rationally evaluate the effects of heavy loads or new axle configurations, and
5. Improve the capability to consider the effect of pavement performance on vehicle operating and user costs.

STRUCTURAL ANALYSIS

In designing a pavement structure for a low-volume road, remember that its structural behavior is no different from that of a pavement structure for a high-volume road. That is, the laws of physics that govern the structural characteristics of pavement materials do not change. Subtle differences may exist, but within the realm of a pavement management system all flexible pavements can be structurally analyzed in the same way. For this reason it was decided to structurally analyze the pavement sections at the American Association of State Highway Officials (AASHO) road test, even though the level of traffic at the road test was very high (6).

An earlier analysis of AASHO road test pavement sections indicated that a simple linear-elastic evaluation of the pavement sections by using layer theory worked fairly well in correlating pavement performance with compressive subgrade strain (5). Considering this, and also that the AASHO road test data provide some of the best information available on pavement performance, it was decided to conduct a more detailed structural analysis of the AASHO road test sections by using a non-linear-elastic methodology.

In the non-linear-elastic analysis of the pavement structures, the stress-sensitive nature of the resilient moduli for the unbound pavement materials (granular base and subbase, fine-grained subgrade) were characterized. This stress-sensitive characterization, as well as modulus values for the asphalt layer, was developed by Finn and others (7) for four different seasonal conditions at the AASHO road test. In this way, it was possible to study the seasonal differences in pavement behavior. The structural analysis of the pavement sections was carried out by using a modified version of the elastic-layer program bitumen structures analysis in roads (BISAR); the original BISAR program was developed by Shell Research (8). The development of the modified BISAR program, as well as the details of the structural analysis methodology, is discussed elsewhere (9).

PERFORMANCE MODEL DEVELOPMENT

The structural analysis of AASHO road test pavement sections was completed by analyzing all the combinations of pavement structures and axle loads that exist at the road test by using the modified BISAR program. Several stress-strain parameters were calculated for each pavement section and are discussed in the following sections on performance variable, independent variables, and regression analysis.

Performance Variable

Once the pavement behavior of the AASHO road test sections had been mechanistically characterized by the structural analysis, the development of a performance model required the correlation of the mechanistic pavement parameters with a measure of pavement performance. In selecting the pavement performance parameter to be used, it was decided that the use of a macroperformance variable, such as present serviceability index (PSI), would be better than the use of microperformance variables (e.g., rut depth, cracking, and raveling). There were two major reasons for this decision: (a) the microperformance variables are not mutually exclusive but are highly interrelated and difficult to predict and (b) the PSI, which is primarily a roughness index, represents the performance parameter that most affects the road user.

In order to achieve the objectives mentioned at the beginning of the paper, a performance variable needed to be selected that would change with seasonal conditions. The performance variable selected was, therefore, the rate of PSI deterioration with traffic, or

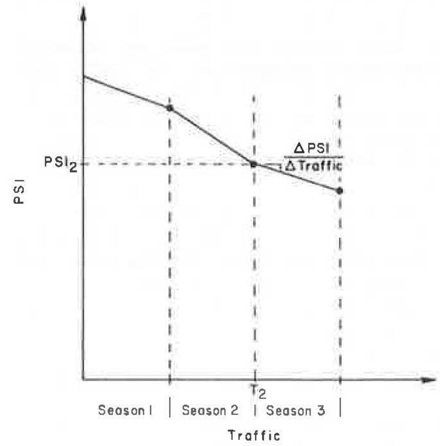
$$\text{Performance variable} = \Delta PSI/\Delta TRAFFIC \quad (1)$$

where ΔPSI is the change in PSI during a given season and ΔTRAFFIC is the change in vehicle applications during the same season. Note that, in this analysis, no seasonal weighting function was used to transform the traffic data. However, seasonal weighting of traffic data was used in the development of the American Association of State Highway and Transportation Officials (AASHTO) performance equation (6).

This performance variable concept is illustrated in Figure 1, which shows the PSI versus traffic curve divided into straight-line segments for each season. The performance variable is predicted for each season, thereby proceeding along the performance curve in a step-by-step manner until the PSI reaches some terminal, or failure, level. This type of performance prediction variable has important advantages:

1. Pavement performance is predicted for different seasons, which allows the consideration of seasonal pavement behavior or seasonal traffic conditions;
2. The performance variable is affected by the pavement performance history; for example, in Figure 1 the PSI at the end of season 2 (PSI_2) and the cumulative traffic at the end of season 2 (T_2) are used as independent variables to predict the performance variable for season 3; and
3. This procedure predicts the PSI-traffic performance curve, and the area under this curve can be used as an indicator of pavement performance that can be compared with performance areas of other pavement structures or used in analyzing other important pavement factors, such as vehicle user costs.

Figure 1. Illustration of performance variable.



Independent Variables

The independent variables used in the performance prediction model fall into three categories: vehicle type, pavement history, and pavement mechanics.

Vehicle Types

Vehicle type variables describe the vehicle being considered and include number of tires on the load axle, tire pressure, load per tire (steering and load axles), and number of load axles per vehicle. In this way, the entire vehicle is considered as one unit instead of being divided into axle applications.

Pavement History

As mentioned during the discussion of Figure 1, the values of PSI and cumulative traffic at any given time are used in the model to predict the performance variable for the next seasonal period. This causes a different rate of deterioration for a new pavement than for a pavement that has been in service for a period of time.

Pavement Mechanics

Pavement mechanics variables reflect the change in pavement performance due to seasonal conditions, pavement structures, and axle loads. The variables include tensile strain at the bottom of the asphalt layer, subgrade compressive strain, subgrade shear strain, and subgrade strain energy. Pavement deflection was specifically not included because of difficulties in predicting pavement deflection when the depth to rigid foundation (depth of roadbed) is not known (10).

Regression Analysis

During the regression analysis it was found that the best prediction equation occurred when the dependent variable was transformed by using a square-root function. A statistical summary of the prediction equations developed is given in Table 1. Several equations were developed that can be used separately for different pavement conditions and axle types. The general equations given below can be used in all

Table 1. Statistical summary of performance equations.

Equation	R^2	Standard Error	Coefficient of Variation	No. of Terms in Equation	No. of Data Observations
Full-depth asphalt[a]	0.931	0.0028	0.30	6	33
All other asphalt pavements[a]	0.565	0.0031	0.69	10	1469
Two and three layer					
Single axle, single tire	0.712	0.0017	0.78	4	165
Single axle, dual tire	0.510	0.0033	0.73	6	677
Tandem axle, dual tire	0.637	0.0029	0.58	10	627

[a]General equation.

cases and are primarily for considering conditions excluded in the other equations (i.e., different axle configurations).

For full-depth asphalt,

$$\begin{aligned}\Delta PSI/\Delta TRAFFIC = {} & 1.751(C) + 5.772 \times 10^{-4}(I) + 1.264 \times 10^{1}(D \cdot G) \\ & - 8.946 \times 10^{1}(J \cdot H)^2 + 1.715 \times 10^{4}(H)^3 \\ & + 1.677 \times 10^{-3}\{\log_{10}[(5.0 - L)/(M + 1)]\} \\ & + 8.449 \times 10^{-3}\end{aligned} \quad (2)$$

For all other asphalt pavements,

$$\begin{aligned}\Delta PSI/\Delta TRAFFIC = {} & 1.054 \times 10^{-4} + 0.9763\{-4.168 \times 10^{-4}(K) - 9.951(B) \\ & + 2.941 \times 10^{-1}(A \cdot C) - 6.919 \times 10^{-1}(D \cdot E) \\ & + 2.922(J \cdot F) - 3.630 \times 10^{-6}(\sqrt{M}) \\ & - 1.985 \times 10^{1}(J \cdot H)^2 + 6.037 \times 10^{-3}[(5.0 \\ & - L)/(M + 1)] + 3.785 \times 10^{-4}(J)^2 + 9.849 \\ & \times 10^{1}(I \cdot G)^2 + 4.050 \times 10^{-3}\}\end{aligned} \quad (3)$$

where

A = steering axle load per tire (kips);
B = steering axle asphalt strain;
C = steering axle subgrade strain energy;
D = load axle load per tire (kips);
E = load axle asphalt strain;
F = load axle subgrade strain;
G = load axle subgrade shear strain;
H = load axle subgrade strain energy;
I = 1 for single axle, single tire, 2 for single axle, dual tires, and 4 for tandem axle, dual tires;
J = number of load axles per vehicle;
K = asphalt layer thickness;
L = existing PSI; and
M = existing cumulative traffic.

A separate general equation was developed that does not contain any asphalt strain terms. This general equation is used to predict the performance variable for aggregate-surfaced roads and will be calibrated or replaced in the future when adequate performance data are obtained for aggregate-surfaced roads.

In the meantime, two other performance models are used when designing aggregate-surfaced roads. One model involves the accumulation of rutting caused by cumulative traffic and was developed by the Waterways Experiment Station (11). The second model concerns the reduction of the pavement structure through surface aggregate loss. This term is either input directly by the user as a function of traffic or is calculated by a regression equation (4). The PDMS program considers the aggregate-surfaced road to have failed when any of these three models fails.

In almost all equations for bituminous pavements, the subgrade stress-strain variables contributed more to the accuracy of the equation than did the asphalt tensile strain. This trend was also found in the preliminary performance equation developed during this project (5). The reason for this trend is that the subgrade parameters give a better indication of the response of the entire pavement structure, whereas the asphalt parameter tends to be dominated by conditions in the asphalt layer. In a small analysis of simple correlation coefficients, it was even found that subgrade parameters correlated better with the percentage of cracking in the asphalt than did asphalt tensile strain (12).

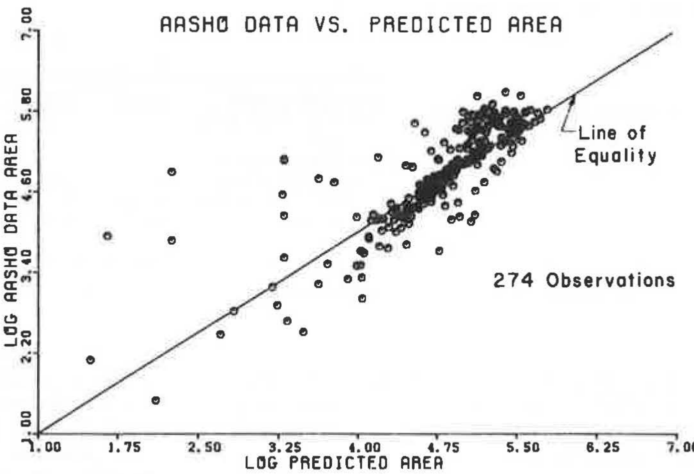
Perhaps the best way to examine the accuracy of the prediction equations is to compute the performance area under the predicted PSI-traffic curves and compare it with the performance area under the actual PSI-traffic curves from AASHO road test data. This was done for those sections that reached a PSI of 3.0 or below and the results are plotted in Figure 2. The coefficient of determination (R^2) for this set of 274 observations was 0.65, with a root-mean-square error of 0.43 ($10^{0.43} = 2.69$). An important statistic to compare with the root-mean-square error of the predicted area under the performance curve is the root-mean-square error for the replicate data sections. These replicate data give an indication of the repeatability of the measurements made at the road test. In the case of the areas under the performance curves, 24 replicate sections had a root-mean-square error of 0.22 ($10^{0.22} = 1.66$). The root-mean-square error of 0.43 for the predicted areas appears very reasonable when compared with the replicate value.

PAVEMENT MANAGEMENT SYSTEM FRAMEWORK

The PDMS program evaluates and optimizes pavement structure design and rehabilitation strategies on the basis of total overall cost for the life of the desired analysis period. This total overall cost includes the initial construction cost, cost of routine maintenance, rehabilitation costs, user vehicle and delay costs, and salvage value, all considered on a net-present-value basis.

The program inputs indicate what pavement materials are available and at what cost, the traffic loads that the pavement structure will be required to carry, constraints with respect to pavement thickness and initial construction funds, performance requirements, and user costs. PDMS evaluates candidate pavement structures to determine if they satisfy the designer's constraints. The candidate structures are first analyzed structurally to calculate the stress-strain parameters used in the prediction equations. This is accomplished by using regression equations that model the modified BISAR program, rather than the entire modified BISAR program, so that computation time is not excessive. The performance prediction equations are then used to predict the change in PSI due to each vehicle type for each season. Since each vehicle type is considered separately, there is no need to use axle equivalency factors. The total change in PSI due to all vehicle types in the traffic stream is accumu-

Figure 2. Measured versus predicted performance areas from AASHO road test sections.

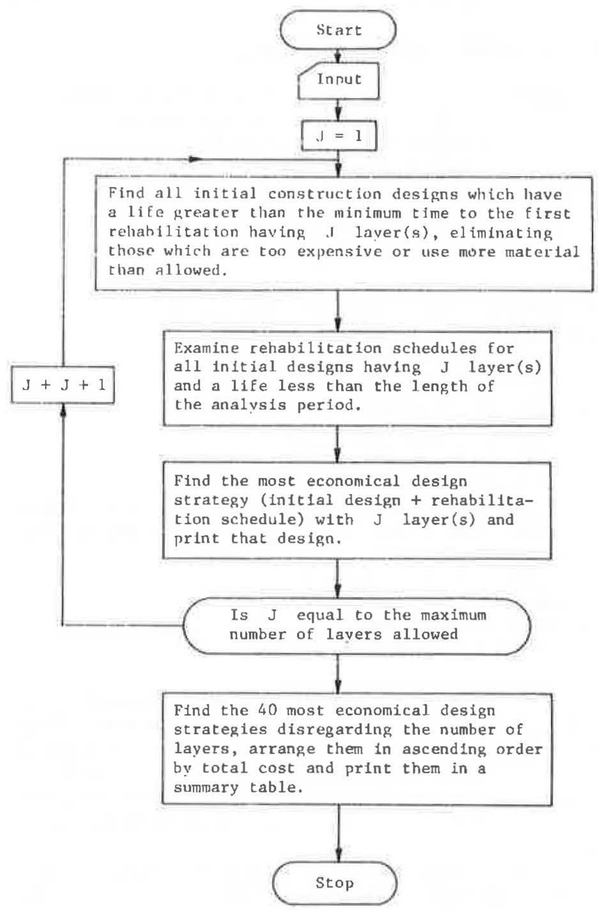


lated for each year, proceeding until the terminal, or failure, level of PSI is reached. This process of repeatedly adding the change in PSI caused by each vehicle type eliminates the need to use Miner's rule in determining the cumulative pavement damage.

When the terminal serviceability level is reached the program will consider a range of overlay thicknesses, by using the procedure above, until the pavement again deteriorates to the terminal PSI level or the end of the analysis period is reached (Figure 3). The program, therefore, has the capability of considering hundreds of different pavement design and rehabilitation strategies, including the use of different pavement materials and variations in the layer thicknesses and number of layers in the structure. This procedure allows the comparison of a thick (and expensive) initial construction that requires little maintenance with a thin initial construction that requires frequent rehabilitation (stage construction).

All pavement designs and rehabilitation strategies that satisfy the designer's constraints are sorted according to total overall cost, and the 40 designs that have the lowest cost are printed. In addition, the cost/area ratio (calculated by dividing total cost by the performance area under the PSI-traffic curve) is calculated for each design. This parameter assists the designer in evaluating the 40 lowest-cost designs, because the expenditure of an additional amount of money may decrease the cost/area ratio significantly. The designer may then decide that the optimum pavement design and rehabilitation strategy is not the one that has the absolute minimum cost but rather the one that has the minimum cost/area ratio.

Figure 3. Simplified flowchart of PDMS.



SIGNIFICANCE OF PDMS IMPROVEMENTS

Stress Sensitivity

One reason that PDMS considers the stress sensitivity of unbound pavement materials is for the rational economic comparison of materials. The condition may occur where two materials, for example an expensive high-quality granular material (with high stiffness) and an inexpensive low-quality granular material (with low stiffness), would be compared as possible construction materials for a pavement structure. By assuming constant stiffness of the materials, the expensive material would always provide a stronger pavement structure, assuming that each material is of equal thickness. However, considering the situation of a very weak subgrade and heavy wheel loads, the high tensile strains in the granular layer would have the effect of reducing the stiffness of the granular layer. This could reduce the effectiveness of the expensive material until it was only slightly stiffer than the inexpensive material. Therefore, for economic comparisons, it is important that PDMS characterize the stress-sensitive nature of pavement materials. This is especially true when the use of a subbase material to build-up the structure from a weak subgrade is being evaluated. This fact, along with the relatively good correlation obtained between predicted and measured performance areas under the PSI-traffic curve

Figure 4. Measured and AASHTO 80-kN equivalence factors for single axle loads.

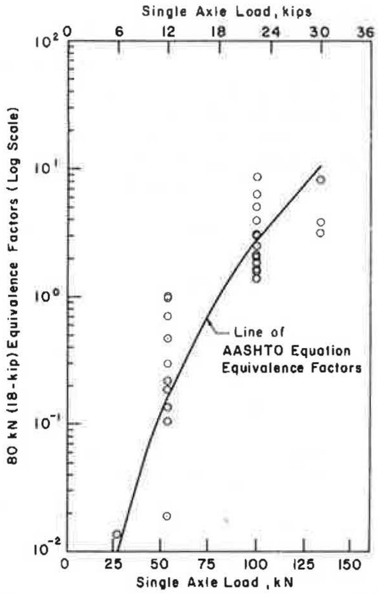
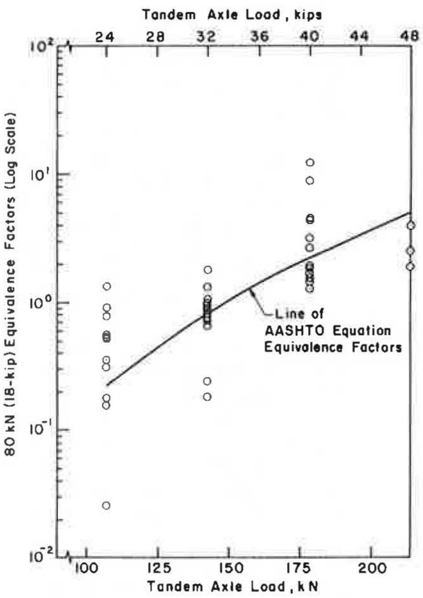


Figure 5. Measured and AASHTO 80-kN equivalence factors for tandem axle loads.



(Figure 2), helps to show the benefit of characterizing the stress-sensitive nature of unbound pavement materials.

Axle Equivalence Factors

An earlier development of an AASHO road test algorithm indicated that axle equivalence factors may also be affected by stress sensitivity in the pavement structure, because different equivalence factors were computed for different pavement structures (5). Axle equivalence factors developed by the AASHTO performance equation and tabulated in the AASHTO Interim Guide indicate that equivalence factor values seldom change by more than 10 percent from a thin pavement structure to a thick structure. Stated more simply, the AASHTO equivalence factor values are nearly constant for a given axle load (13).

The accuracy of axle equivalence factors may be evaluated by analyzing the identical pavement structures that carried different loads at the AASHO road test. For example, eight different test sections were built with identical 7.5-cm (3-in) asphalt, 7.5-cm base, and 10-cm (4-in) subbase pavement structures. Each of these test sections carried one type of axle load; they included loads of 9-kN (2-kips), 53-kN (12-kips), 80-kN (18-kips), 100-kN (22.4-kips) single axle and 27-kN (6-kips), 107-kN (24-kips), 142-kN (32-kips), 178-kN (40-kips) tandem axle.

Since an 80-kN (18-kip) equivalence factor is computed by

$$e_x = W_{t80}/W_{tx} \tag{4}$$

where

e_x = 80-kN equivalence factor for axle load x,
W_{t80} = applications of 80 kN necessary to reach a given PSI level, and
W_{tx} = applications of axle load x necessary to reach a given PSI level,

actual equivalence factors from the AASHO road test data can be computed for those identical pavement sections with different axle loads. To examine specifically the 80-kN equivalence factor, those identical sections at the road test that had 80-kN loads in addition to at least one other load were found. With these data, it was possible to calculate 80-kN equivalence factors for 28 single-axle cases and 49 tandem-axle cases. The results are shown for single axles in Figure 4 and for tandem axles in Figure 5. On both figures, because a logarithmic scale is used, a single solid line represents the AASHTO equivalence factors. From these figures it can be seen that the equivalence factors from the AASHTO performance equation do not satisfactorily explain the variation in equivalence factors from the road test data, especially when it is considered that the equivalence factors are plotted on a logarithmic scale. Because of the error involved in using equivalence factors, that PDMS considers vehicle types separately and does not use equivalence factors is important.

Seasonal Variation

Pavement performance is affected by seasonal changes that occur in the pavement structure. Seasonal conditions change from one region to another, therefore, it is necessary to characterize the seasonal influence on performance. PDMS does not consider non-load-associated environmental distress (i.e., temperature cracking) in a direct manner; however, the environmental effects on load-associated distress are considered in the way pavement performance is modeled separately for each season.

The U.S. Forest Service and some other transportation agencies in northern climates that manage low-volume roads have the authority to impose roadway axle load limits during certain times of the year when the pavement structure is in a very weak condition. This situation usually occurs in the springtime, when melting in the upper layers of the pavement structure causes water to accumulate above the still frozen lower layers. The PDMS program has the capability to evaluate the economic trade-off of increasing road restrictions or paying higher pavement costs.

User Cost

The improved prediction of the PSI-traffic curve enables PDMS to increase considerably the analysis of vehicle user cost. Little is known about the relation between user cost and pavement performance. However, substantial research and development work is currently being done in this area (14,15). The improved framework of PDMS allows the designer to define user cost as a function of PSI for each vehicle. Since the PSI level is predicted for every season, the user cost can be computed and included in the total overall cost. This procedure is an optional feature of PDMS because the designer may not have accurate user data or simply may not wish to consider user cost. If user cost data are not available and the designer would still like an indication of the level of pavement performance, the performance area under the PSI-traffic curve can be used as an indicator of which pavement design and rehabilitation strategy provides the highest level of service (and, therefore, the lowest overall user costs).

Extrapolation of Performance Models

Because of constantly changing conditions, pavement materials, axle loads, and axle configurations, any model of pavement performance developed will almost certainly be subject to use outside the data range from which it was developed. In addition, moving the performance model from one region or country for use in a different environment will result in the same type of extrapolation. This is a serious problem for strictly empirical performance models such as the AASHTO performance equation, which relies on subjective parameters such as the material strength coefficient, soil support value, and regional factor to extrapolate beyond the data at the AASHO road test. However important these parameters are when used in the AASHTO equation, no quantitative methods are available to determine their values.

Perhaps the most-important improvement of PDMS comes from the mechanistic basis of the new performance model. Parameters similar to the material strength coefficient or soil-support value are not necessary because the pavement and roadbed materials are characterized by using the resilient modulus. No regional factor terms are necessary because the pavement performance is directly a function of the seasonal characteristics of the material. This greatly improves the ability to use this pavement management system in a wide range of circumstances, including aggregate-surfaced roads. However, a comprehensive data base of pavement performance information is necessary to calibrate or revise the performance models in PDMS, particularly for the aggregate-surfaced roads. The U.S. Forest Service appreciates this and, in the near future, plans to develop a data base system for its road network (16).

CONCLUSIONS

This paper presents the results of a research and development effort to improve PDMS. Based on the information presented, the following conclusions are made:

1. A pavement management system is an important tool in evaluation of the significant economic effects of low-volume road design;
2. The mechanistic approach used in developing the performance model provides a good foundation for the inevitable extrapolation outside the range of original data; however, it is no substitute for a comprehensive data base;
3. The performance variable is used to predict the PSI-traffic curve, thereby allowing the evaluation of the performance area under this curve;
4. Pavement deterioration is calculated by adding the change in PSI due to each vehicle type instead of using Miner's rule to estimate cumulative damage;
5. The consideration of the stress sensitivity of unbound pavement materials is important in a pavement-management system;
6. The AASHTO equation equivalence factors have definite limitations, and that equivalence factors are not used is an advantage of PDMS;
7. Seasonal variation of pavement and traffic conditions is important and is characterized in PDMS; and
8. PDMS has the capability to consider user cost, which will be important in the future when more data are available, and is capable of considering user preferences through the cost/area ratio.

ACKNOWLEDGMENT

The research and development work discussed in this paper was conducted under a cooperative agreement between the University of Texas at Austin and the U.S. Forest Service, U.S. Department of Agriculture. The purpose of the project is to review and improve the flexible pavement design chapter of the Forest Service Transportation Engineering Handbook.

REFERENCES

1. R. Haas and W.R. Hudson. Pavement Management Systems. McGraw-Hill, New York, 1978.
2. T.G. McGarrah and W.R. Hudson. A Pavement Design and Management System for Forest Service Roads--Conceptual Study. Council for Advanced Transportation Studies, Univ. of Texas at Austin, Austin, Res. Rept. 12, July 1974.
3. F.L. Roberts, B.F. McCullough, H.J. Williamson, and W.R. Wallin. A Pavement Design and Management System for Forest Service Roads--Working Model. Council for Advanced Transportation Studies, Univ. of Texas at Austin, Austin, Res. Rept. 43, Feb. 1977.
4. B.F. McCullough and D.R. Luhr. A Pavement Design and Management System for Forest Service Roads--Implementation. Council for Advanced Transportation Studies, Univ. of Texas at Austin, Austin, Res. Rept. 60, Jan. 1979.
5. D.R. Luhr and B.F. McCullough. Development of a Rationally Based AASHO Road Test Algorithm. TRB, Transportation Research Record 766, 1980, pp. 10-17.
6. The AASHO Road Test: Report 5--Pavement Research. HRB, Special Rept. 61E, 1962.
7. F. Finn, C. Saraf, R. Kulkarni, K. Nair, W. Smith, and A. Abdullah. The Use of Distress Prediction Subsystems for the Design of Pavement Structures. Proc., 4th International Conference on Structural Design of Asphalt Pavements, Univ. of Michigan, Ann Arbor, Aug. 1977.
8. D.L. DeJonk, M.G.F. Pentz, and A.R. Korswagen. Computer Program BISAR, Layered Systems Under Normal and Tangential Surface Loads. Shell Research, Amsterdam, External Rept., July 1972.
9. D.R. Luhr and B.F. McCullough. Structural Analysis of AASHO Road Test Flexible Pavements for Performance Evaluation. TRB, Transportation Research Record, 1982 (in preparation).
10. B.F. McCullough and K.J. Boedecker. Use of Linear-Elastic Layered Theory for the Design of CRCP Overlays. HRB, Highway Research Record 291, 1969, pp. 1-13.
11. V.C. Barber, E.C. Odom, and R.W. Patrick. The Deterioration and Reliability of Pavements. U.S. Army Waterways Experiment Station, Vicksburg, MS, Tech. Rept. S-78-8, July 1978.
12. D.R. Luhr. Comparison of Subgrade Strain Equation with Shell Pavement Design Procedure.

Center for Transportation Research, Univ. of Texas at Austin, Austin, Forest Service Project Tech. Memorandum 44, Jan. 1981.
13. AASHTO Interim Guide for Design of Pavement Structures--1972. AASHTO, Washington, DC, 1974.
14. R.J. Wyatt, R. Harrison, B.K. Moser, and L.A.P. de Quadros. The Effect of Road Design and Maintenance on Vehicle Operating Costs--Field Research in Brazil. TRB, Transportation Research Record 702, 1979, pp. 313-320.
15. J.P. Zaniewski and others. Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors. Texas Research and Development Foundation, Austin, Final Rept. FHWA 11 9878, March 1982.
16. J. Hernandez, B.F. McCullough, and W.R. Hudson. A Data Base for the U.S. Forest Service Pavement Management System. Center for Transportation Research, Univ. of Texas at Austin, Austin, Res. Rept. 66, May 1981.

Publication of this paper sponsored by Committee on Low-Volume Roads and Committee on Theory of Pavement Systems.

Performance of Various Thicknesses of PCC Pavement

JOHN I. HELMERS AND VERNON J. MARKS

If adequately designed and high-quality material and good construction practices are used, portland cement concrete is very durable. This is demonstrated by the oldest pavement in Iowa (second oldest in the United States), which was paved in 1904. It performed well for 70 years without resurfacing. The design thickness is an important factor in both the performance and cost of pavement. The objective of this paper is to provide a 30-year performance evaluation of a pavement constructed to determine the required design thickness for low-volume secondary roadways. In 1951 Greene County and the Iowa Highway Research Board of the Iowa Department of Transportation initiated a 4-mile (6.4-km) demonstration project to evaluate thicknesses that ranged from 4.5 to 6 in (11.4-15.2 cm). The project, which consisted of 10 research sections, was formed pavement placed on a gravel roadbed with very little preparation except for redistribution of the loose aggregate. Eight sections were nonreinforced except for centerline tie bars, and no contraction joints were used. Mesh reinforcing and contraction joints spaced at 29 ft 7 in (9.02 m) intervals were used in two 4.5-in (11.4-cm) thick sections. The only air-entrained section was nonreinforced. The pavement performed well over its 30-year life of carrying a light volume of traffic and did not require major maintenance. Cracking was substantial; average slab length varied directly with thickness. The 4.5-in-thick nonair entrained, mesh-reinforced pavement with contraction joints has performed the best.

Iowa's portland cement concrete (pcc) paving began in 1904 with one-half block in the town of LeMars (second oldest pavement in the United States). This two-lift pavement was 6.5 in (16.5 cm) thick, and the top 1.5 in (3.8 cm) had a greater cement factor than the bottom 5 in (12.7 cm). The joints were formed at 6-ft (1.83-m) intervals skewed 45° from each side, which created a diamond pattern. The texture was obtained by scoring the surface in 4-in (10.2-cm) squares. This pavement performed well for 70 years without resurfacing and demonstrates the potential of pcc pavement. Many miles of pcc pavement were constructed in the late 1920s and early 1930s during a campaign to get Iowa out of the mud.

Iowa is a state of 56 290 miles^2 (145 791 km^2), and only eight urban areas have a population greater than 50 000. It has 112 257 miles of roadway (180 660 km), the surface types of which are given in Table 1. In 1951, excluding municipal roads, there were 8248 miles (13 274 km) of hard surfacing, 58 598 miles (94 304 km) of gravel, and 35 523 miles (57 169 km) that had no surfacing. The 94 121 miles (151 473 km) of roadway without hard surface and the belief that adequate design, high-quality material, and good construction are essential for durable concrete were the impetus for Iowa Highway research project HR-9.

Substantial research has been conducted into structural requirements. Studies of flexural fatigue as a function of design thickness were completed in the 1920s. This research was used in the development of the 1933 Portland Cement Association (PCA) design curve for pavement. The Iowa Department of Transportation is currently using the 1966 PCA design procedure.

The objective of the research project was to determine to what thickness pcc pavement could be reduced, with corresponding cost reduction, and still provide a high-quality surface of long life for low-volume secondary roadways. The objective of this report is to provide a 30-year performance evaluation of the experimental pcc roadway.

Table 1. Miles of Iowa highway by surface type, 1981.

	Iowa Highway by Surface Type (miles)			
Surface Type	Primary	Secondary	Municipal	Total
Portland cement paved	4557	4 536	3305	12 463
Asphalt concrete paved	5465	8 936	5879	20 379
Bituminous treated	88	1 514	1058	2 694
Gravel	15	68 942	1701	70 767
Not surfaced, dirt	0	5 825	127	5 954

PROJECT IDENTIFICATION

Greene County is located in central Iowa approximately 50 miles northwest of Des Moines. The project is 4 miles (6.4 km) long on County Road E-33 from IA-4 to Farlin.

Signs that show the thickness and reinforcing of the pavement were installed along the north right-of-way line of the project. They were placed at the ends of the sections, and arrows on the signs pointed to the section to which the information applied. These signs are still present on the project as an aid to observers in locating the various sections and evaluating the present condition.

A nonconformity of the signs' text and the terms used in this report is that the nonreinforced sections are listed as dowel reinforced. The dowel term noted on the signs refers to the centerline tie bars.

Preconstruction Testing

In the spring of 1951 soil borings were taken and