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Development And Implementation Of Washington State's Pavement Management System

WA-RD 50.2

Summary
February 1983

Washington State Department of Transportation
Public Transportation and Planning
In Cooperation with
United States Department of Transportation
Federal Highway Administration

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
WA-RD 50.2		
4. Title and Subtitle: Development and Implementation of Washington State's Pavement Management System Summary		5. Report Date: September, 1982
		6. Performing Organization Code
7. Author(s): Thomas L. Nelson and R. V. LeClerc		8. Performing Organization Report No.: Materials Laboratory Report No. 177-A
9. Performing Organization Name and Address: Washington State Department of Transportation, Highway Administration Building, Olympia, WA 98504		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address: Washington State Department of Transportation, Highway Administration Building, Olympia, WA 98504		13. Type of Report and Period Covered: Final Report
		14. Sponsoring Agency Code

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

This report describes the pavement management system developed by WSDOT staff over a period of five years. Both project-level and network-level pavement management are represented within the four broad areas of data processing which combine to constitute the foundation of the system.

The design of a pavement data file is laid out together with the process of assembling it. Also shown are the methods used to analyze and convert the file data from pavement condition ratings to pavement performance curves for each project. The performance curves are then used, together with appropriate cost data, to determine the most cost-effective type and time of fix. The network-level program then summarizes the needed work for each year of a rehabilitation program. Means are provided for adjusting the program to fit budget constraints or minimum acceptable levels of average pavement condition.

It is concluded that the system, operating on biennial pavement condition ratings, provides a good solid framework for orderly analysis to estimate the economic benefits of the type, timing, and sequence of rehabilitation activities applied to a pavement.

17. Key Words	18. Distribution Statement
Pavement management, pavement data file, pavement performance	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-69)
HWY FORM 341-004 6/72

WASHINGTON STATE
DEPARTMENT OF TRANSPORTATION
MATERIALS LABORATORY

DEVELOPMENT AND IMPLEMENTATION OF WASHINGTON STATE'S PAVEMENT MANAGEMENT SYSTEM

SUMMARY

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Materials Laboratory
Report No. 177-A

September, 1982

CREDIT REFERENCE

The system described herein was developed by the Washington State Department of Transportation under project HR 557 and with sponsorship of the Federal Highway Administration. The authors wish to acknowledge with sincere gratitude the support and encouragement provided by FHWA and by all elements of the WSDOT without which this system could never have been developed. Special thanks go to Fred Finn and others at Woodward-Clyde who were responsible for producing the feasibility study which originally got us off the ground.

The authors also wish to express their sincere appreciation to Mrs. Ruth Renaud for typing, editing, re-typing, and re-editing this report; and to Dennis Crimmins whose diligence and data processing skills were invaluable in bringing this system to fruition.

DISCLAIMER

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SUMMARY

This report describes the pavement management system developed by WSDOT over a period of five years. It represents an organized approach to providing the Department's administration with the necessary information for more efficiently managing its investment in roadway pavements. Both project-level and network-level pavement management are represented within the four broad areas of data processing which combine to constitute the foundation of the system.

Functional Aspects

There are four basic components of this system:

1. Master File
2. Interpreting Program
3. Project-Level Optimizing Program
4. Network-Level Program

Master File

The foundation of this system is the Master File which combines information from five other existing data files:

1. Roadlife History (construction history)
2. Roadway Inventory (geometric data)
3. Annual Traffic File
4. Surface Friction File
5. Pavement Condition Rating File

The Master File is indexed according to milepost limits of the most recent paving contracts and is utilized in two ways:

1. To track the progression of distress over the service life of a pavement.
2. As input to the first of three computer programs in the system, the interpreting program.

Interpreting Program

The interpreting program translates the raw distress codes contained in the Master File into average ratings for each project. This is accomplished by applying weighting values to the extent and severity of each distress category. Regression analysis is then applied to the ratings to fit a performance curve which is used for predicting future pavement performance and the potential time of rehabilitation.

The output listing from the interpreting program consists of the following for each project:

1. A tabulated summary of the performance history.
2. A summary of traffic information for the project.
3. The constants for the performance equation with related statistical data.
4. A plot of average ratings with high and low ratings for each survey year shown and the performance curve fitted to the points.

The interpreting program also generates a new data processing file that contains all of the above-noted information on a project-by-project basis. This file is used in two ways:

1. To study the correlation of other parameters such as design mixes, environmental effects, traffic characteristics, etc., with trends in pavement performance.
2. As input to the second major program in the system, the project-level optimizing program.

Project-Level Optimizing Program

This program utilizes the performance equations produced in the interpreting phase to establish the most probable period of rehabilitation for each project. After selecting a set of viable alternatives and developing their associated performance equations, the program generates all possible rehabilitation strategies which might be considered within a specified period. These strategies are defined as a combination of rehabilitation alternatives designated by type, sequence, and application time. Each strategy is evaluated on the basis of economics and the best are tabulated on an output listing for each project.

Categories of cost considered in the evaluation process are:

1. Construction cost of rehabilitation.
2. Annual cost of routine maintenance.
3. Cost incurred by the highway user due to pavement condition.
4. Cost of delay time incurred by the highway user due to traffic interruption during rehabilitation.
5. Salvage value of the pavement at the end of the consideration period.

This program also generates a new data processing file which is used as input to the next program in line, the Network-Level Program.

Network-Level Program

The function of this last program is to establish a network-level six-year rehabilitation program based on the optimum strategies as determined by project-level optimizing. Through a system of aggregating the recommended rehabilitation alternatives and performance of all project segments on the network, a schedule of anticipated action, cost, and performance can be tabulated for a future number of years. By applying budget and condition-level constraints for each year, the network program will produce an entire balanced rehabilitation program. By varying the budget and condition-level constraints and tabulating the results in projected performance with proposed budgets, good comparisons are demonstrated for what can be obtained with different budget levels and most of the "what if" questions faced by administrators are answered.

The system is currently in operation within WSDOT. The performance curves produced by the interpreting phase are used to prioritize pavement sections for rehabilitation. The optimizing program and network-level program are both used by the districts to influence their decisions in preparing rehabilitation programs.

CONCLUSIONS AND RECOMMENDATIONS

It is concluded that the system, operating on biennial pavement condition ratings, provides a good solid framework for orderly analysis to estimate the economic benefits of the type, timing, and sequence of rehabilitation activities applied to a pavement. As such, it is expected to be a great aid to WSDOT in providing the citizens of the state with the best pavements for their tax dollars.

During the course of development, the importance of maintaining pavement condition ratings in their raw coded form became very obvious. By doing this, weighting values can be recalibrated as each pavement survey is completed, greater insight to the interplay of pavement distress is acquired, and the expertise in performance analysis is improved.

In this system, "optimization" is applied at the project level. All work at the network level is related to gauging the effectiveness of different programs by applying constraints--either budget or pavement condition-level. It is concluded that network optimization would involve "trade-offs" between alternatives applied on all projects in order to make the greatest gains in long-term pavement condition for the dollars available. This process was not developed in the scope of this study, but represents an objective of further research and development.

Successful development and implementation of this pavement management system were accomplished with three basic considerations:

1. The production of a feasibility study by an outside consultant which determined adequate information and expertise were available within WSDOT to develop and implement a PMS.
2. The assignment of developing the system to the Materials Laboratory which has responsibility for pavement design approval, and pavement materials and construction specifications, as well as conducting the biennial pavement condition survey.
3. The formation of a steering committee consisting of top-level management personnel was considered essential for implementation.

The data base and interpreting system provide the necessary tools for further research. The possibility exists for correlating design parameters, materials and construction methods, and surfacing types and thicknesses to such factors as projected pavement life, area under the performance curve, degree of curvature, etc.

The performance model was developed with a strong consideration for simplicity and may not be accurate in the low ranges of pavement rating (severe distress). It is recommended that typical performance curve tails be developed for specific pavement types when they approximate this low range of rating.

The cost models relating user-incurred costs are weak and based on outdated information. It is recommended that better models be developed in the future if user costs are to be a consideration.

It should be noted that the framework of this system could be utilized by any agency that has the two basic constituents for the master file:

1. A construction history file with construction dates, types of surfacing, etc.
2. A pavement rating history file that relates to severity and extent of different distress types.

With this information available, it would be possible to calibrate distress weightings to relate to any combination of distress types and to represent the genesis of pavement deterioration in almost any geographical area. Once performance curves are developed, the mechanics of the rest of this system fall into line.

THE PROBLEM

For many years highway agencies have been managing their pavements by providing well-designed and constructed pavements, proper maintenance, and timely rehabilitation. In the past, funding these activities did not present the acute problem which prevails today. The highway industry is currently being squeezed at both ends with the influx of tax revenues steadily falling off and inflation effectively reducing the work that can be accomplished with a given amount of dollars. It is no longer possible to fund highway programs at levels comparable to the past. An improved approach to managing our pavements is needed so that we can achieve the most with every dollar available and protect the investment we have made in providing today's highway network.

While managing means efficiently administering available funds, it also implies a certain degree of accountability and a required effort to gain more appropriate levels of funding if current revenues are deemed insufficient to do the job. This poses several questions for the highway engineer:

1. Can we support budget requests with solid facts and figures?
2. Are we able to demonstrate to our legislatures and the public the consequences of a given funding level in terms of future pavement condition?
3. Do we know what the present condition of our system is, or how it compares with years in the past?
4. For any given section of highway can we tell how much was spent for pavement maintenance last year?
5. Do we know the cost of all work on a pavement, including construction, reconstruction, resurfacing, and maintenance, over its entire lifetime?
6. Are our pavements giving us the service that was expected of them when they were designed?[1]

These questions represent many of the concerns faced by top-level highway administrators today. There are certainly not many agencies, if any, that can answer all of these questions with a positive "yes".

Until now, WSDOT has utilized a priority programming procedure for the selection of projects and the allocation of funds. This consists of conducting a biennial pavement condition survey, ranking all sections in a priority order according to the ratings, and implementing as many projects as possible with the funds available. A priority system is not always efficient in responding to present needs though.

One of the problems associated with a priority approach is the time lag involved between the pavement condition survey and the start of a programmed rehabilitation project. In the Washington system there is a lag period of 2-3 years because of all the necessary steps required to assemble the rehabilitation program and receive approval from the Commission. During this period of time, other low priority segments of highway may quickly deterioriate to a worse condition and justify a higher priority at time of action. These sections lower the overall serviceability of the system and present a significant burden to maintenance forces because they are not in the rehabilitation program.

A means of predicting pavement performance would substantially cure this problem. By forecasting the pavement condition for each project, a rehabilitation program could be assembled based on the network as it would exist at the time of intended action--not two years prior when the pavement was rated.

The method of forecasting should be based on everything known about the pavements: their performance history--meaning all pavement condition surveys, not just the most recent one; their construction history--what the pavement consists of and when it was built; the loads being applied; and the environment.

Another problem with the priority approach is the lack of consideration for long-term economic benefits or consequences. One of the prime considerations (aside from structural qualities) is the long-term cost of providing pavement serviceability. Over the life of a highway facility, rehabilitation of the pavement may occur several times. Occasionally some minor routine maintenance is required to maintain serviceability until rehabilitation is effected. Once the fix becomes imminent, proper selection and accurate timing could mean an optimum return for the available funding. A variation from this "optimum" time or fix could mean substantially smaller returns for the dollars spent, i.e., rehabilitation too soon would reduce the years of service per dollar spent, and rehabilitation too late could increase the cost of fix and also increase the cost of routine maintenance. A priority approach based only on present serviceability cannot deal with this kind of problem.

THE SOLUTION

These questions, needs, and problems have generated a need for improving our approach to managing pavements. Pavement management has been defined as "a coordinated set of activities, all directed toward achieving the best value possible for the available public funds in providing smooth, safe, and economical pavements".[2] A pavement management system is thus a logically ordered arrangement of pavement management activities.

Pavement management occurs independently in most highway agencies, with pavement-related decisions taking place in many separate divisions such as design, construction, maintenance, and budgeting. To effect good pavement management, these decision-makers should have consistent, up-to-date, and well-founded information. This is one of the primary tasks of a PMS. Because the information needed involves a tremendous mass of data, it is usually the product of automated data processing, i.e., data files and computer programs. These data files and computer programs are not a pavement management system, but they do represent the core of a PMS--the roots of decisions in all pavement-related activities that form the foundation to gaining more cost-efficient pavements.

Pavement management classically exists at two levels:

1. Project level - detailed information, analysis, and decision-making relating to specific projects, usually applied at lower management levels.
2. Network level - summary information, statistics, and decisions related to system status before and after rehabilitation programs, including the assembling of a rehabilitation program. This is usually applied at upper management levels.

Some of the goals of a good pavement management system are:

1. A means for determining the most cost-effective strategy for maintaining pavement serviceability.
2. An ability to obtain the highest level of system-wide serviceability possible within budget constraints.
3. The potential for projecting the level of serviceability that can be obtained with additional revenues.
4. An ability to demonstrate the impact on network serviceability caused by delaying projects should a shortfall of funds be realized.

WASHINGTON'S PMS

The pavement management system developed by WSDOT is based on an organized approach to providing the Department's administration with necessary information for more efficiently managing its investment in roadway pavements. The system incorporates four main areas of data processing:

1. Building and updating a master file of pavement data which contains information from several different areas.
2. Interpreting or analyzing the master file, i.e., tracking pavement ratings and producing a performance curve for each project.
3. Optimizing at the project level, i.e., providing the most cost-effective time and type of pavement rehabilitation for each project.

4. Network-level programming - assembling a rehabilitation program based on forecasted effects of the overall gain in serviceability on the system.

Figure 1 is a conceptual flow chart of the operations involved in progressing from available data to the best time and type of rehabilitation for each potential project, and ultimately to a complete long-term rehabilitation program. Data files exist in all four levels with useful information potentially impacting all highway divisions involved in pavement-related decisions.

Building and Updating a Master File

To build the master file, data were required from five existing files within WSDOT:

1. Road Life History (construction history)
2. Roadway Inventory (geometric data)
3. Annual Traffic File
4. Surface Friction
5. Pavement Condition Survey (distress ratings and roughness measurements)

With data from these five areas all brought together in one file, the task of utilizing all of them in pavement analysis becomes much easier. Moreover, the potential for processing this information with computer programs is greatly enhanced.

The process of assembling the master file consists of dividing the highway network into project segments based on the limits of the most recent pavement surfacing contracts found in the Road Life History File, and then associating data from the other files, one file at a time, with each project. To do this, a hierarchical record structure was designed for three levels: all data related to the project regardless of time or specific location; all data related to the generation in time when acquired; and all data related to both generation in time and a specific location within the project.

The prime interest of this file, of course, is to relate the biennial pavement condition ratings to specific project limits. These ratings are acquired through a combination of subjective and objective evaluations: subjective, by judging the severity of a pavement distress; and objective, by measuring the actual extent of a distress. These evaluations are performed by two-man teams using the evaluation form shown in Figure 2. The ride score is obtained through objective evaluation, i.e., a modified PCA Road Meter is mounted in a vehicle to measure rear axle deflections along a pavement profile.

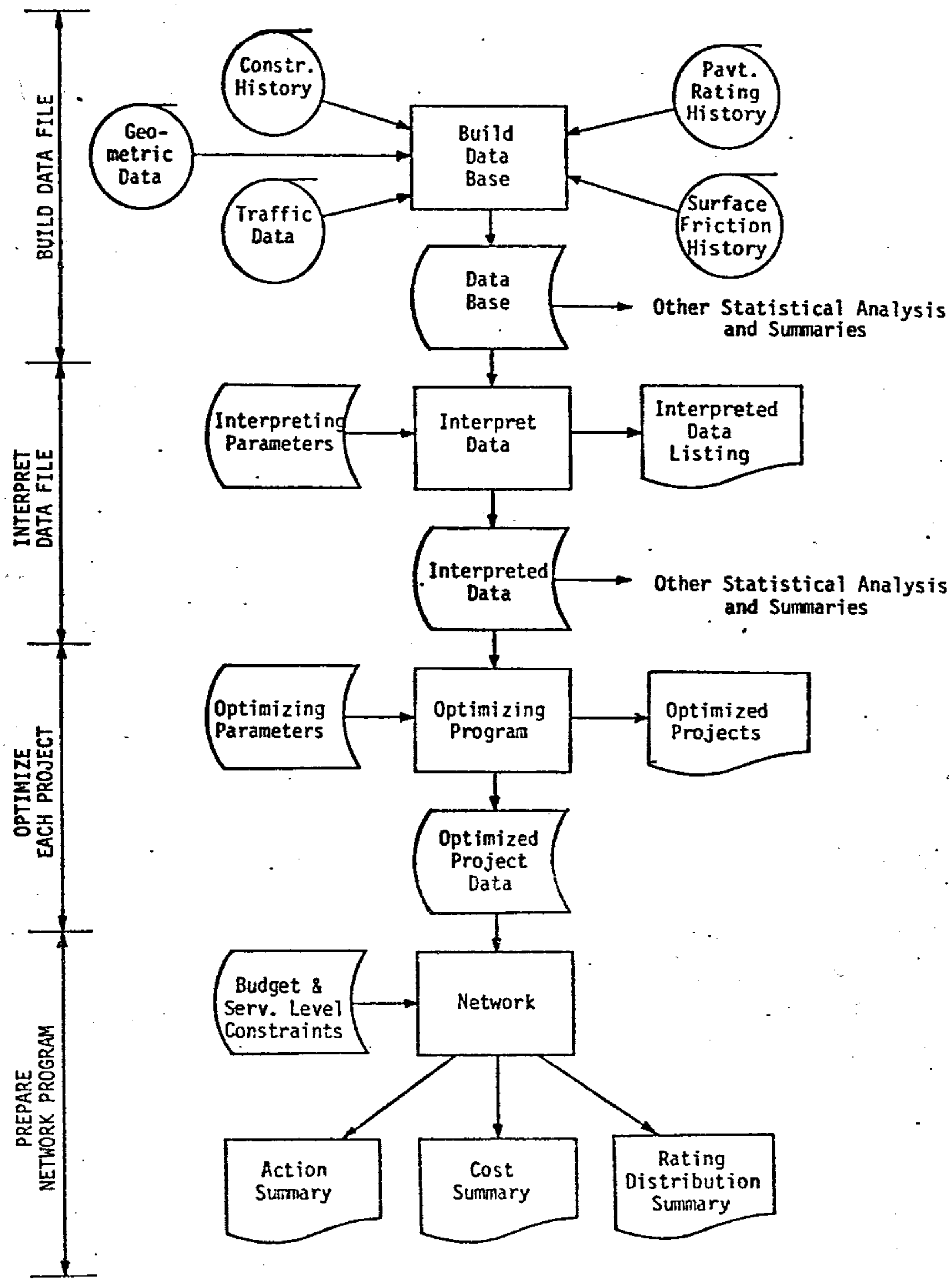


Figure 1. A Conceptual Flow Chart of PMS Operations

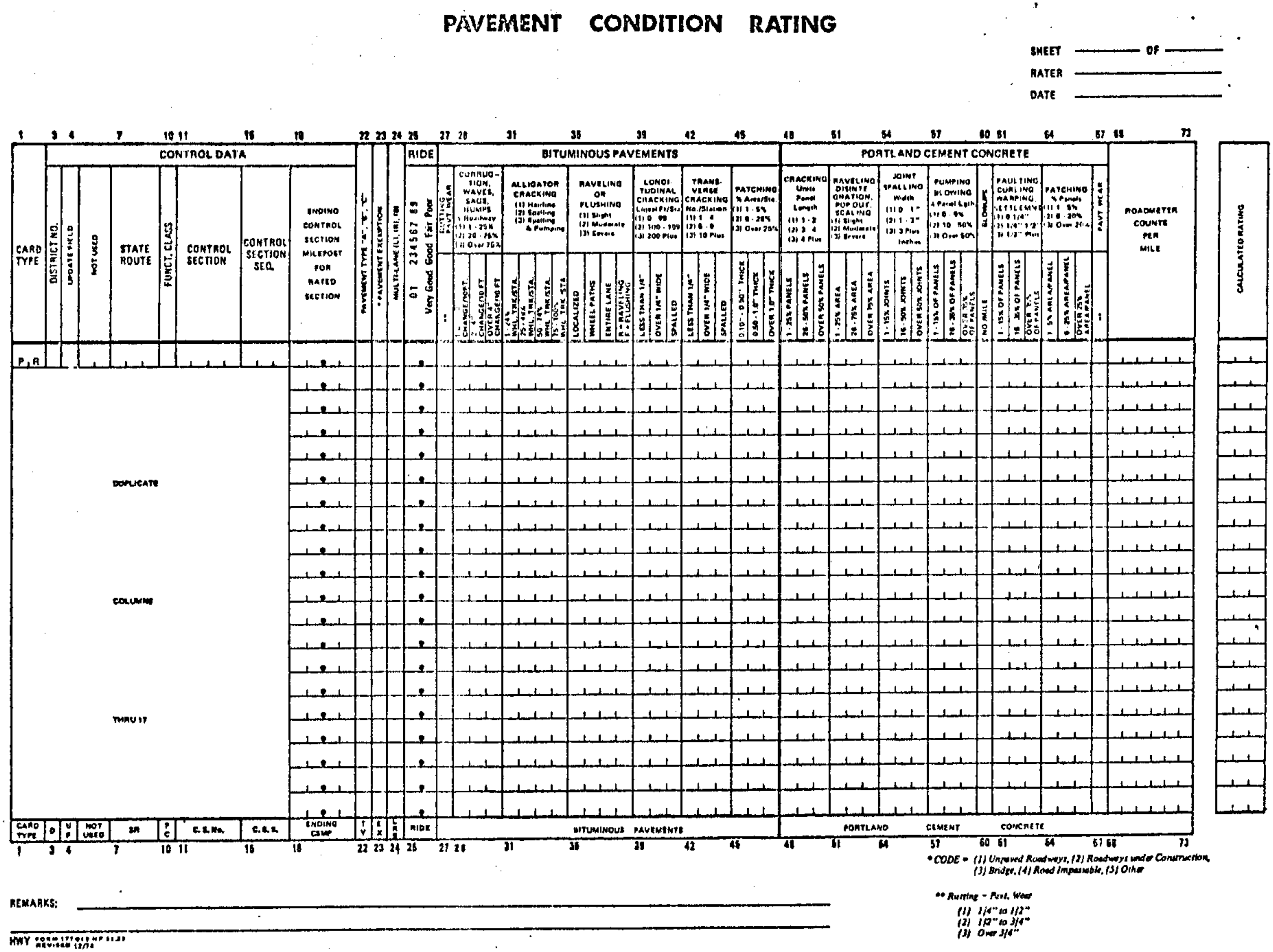


Figure 2. Pavement Condition Rating Form

Figure 3 is an example of a listing produced from the master file with information related to one project. The top line represents data describing the project. Below that are all pavement condition ratings for each year noted by milepost location within the project. The distress ratings are listed in their raw coded form to indicate trends in extent and severity from one year to the next. The first digit indicates the form column that was coded (severity in most cases), and the second number indicates the digit that was coded (extent, or percentage of area affected in most cases). An example of this coding is shown in Figure 4. To the right of the raw ratings in Figure 3 are: the raw unadjusted bump counts (ride); the speed at which the counts were acquired; an adjusted count for the speed, meter, and vehicle used; and a ride rating (scale 0.0 to 1.0) related to the bump count.

Because the master file is based on construction history and the last surfacing contracts, an update necessarily begins with recording all recently completed surfacing contracts. All other files are also updated and the whole process of combining files is repeated to produce a new generation master file. Unfortunately, an update is not achieved through a simple editing process. To update the master file, it must literally be rebuilt with updated input files.

Interpreting Phase

The second phase of this system involves analyzing the data in the master file on a project-by-project basis.

Early in development of this system, it became apparent that a step should be provided prior to optimizing the rehabilitation treatment for each project. There was an awareness that different areas of decision are necessarily related to different types of information. Maintenance and rehabilitation people, for instance, are concerned with knowing the specific types of distress present on a pavement in order to apply the proper fix. A pavement management system must have a predictive capability, however. This is something that can only be accomplished with numerical ratings which can be used to provide a serviceability vs. time relationship so that time to failure might be predicted. These numeric ratings do not have much meaning for maintenance or rehabilitation engineers other than to indicate a need for some type of action.

The interpreting phase was developed to accommodate both approaches. In using this method, raw coded data indicating severity and extent of each distress type are maintained in the master file. These data are then translated into a combined rating in the interpreting phase for tracking a project's performance. These combined ratings are calculated with the following equation:

CS	BEG	END	D	SR	BEG	END	LENG	FC	L	HT	RDW	RSH	LSH	CONT#	TY	SF	TK	M	YR	BASE	79 ADT	GRW	SU	CM
2719	0	396	3	5	13554	13950	396	US	R	34	48	10	10	08603	20	40	33	5	70	11	78300	56	4	6

GEN	SIDE	ECSMP	RUTT WEAR	WAVE SAGS	ALG CRK	RAV FLU	LONG CRK	TRNS CRK	PTCH	BUMPS	BUMP SPEED	ADJ BUMPS	RIDE RATNG
71	R	100	1	11	1N	31	1N	1N	1N	277	50	274	1.00
71	R	200	1	12	1N	31	1N	1N	1N	458	50	584	1.00
71	R	300	1	11	1N	31	1N	1N	1N	445	50	561	1.00
71	R	396	1	12	1N	31	1N	1N	1N	884	50	1312	0.98
73	R	100	1	11	1N	31	1N	1N	1N	329	50	74	1.00
73	R	200	1	11	1N	31	1N	1N	1N	357	50	96	1.00
73	R	300	1	11	1N	31	1N	1N	1N	366	50	103	1.00
73	R	396	1	11	1N	31	1N	1N	11	919	50	544	1.00
75	R	100	N	12	1N	21	11	1N	1N	291	50	291	1.00
75	R	200	N	11	1N	21	1N	1N	11	385	50	385	1.00
75	R	300	N	11	1N	21	1N	1N	1N	288	50	288	1.00
75	R	396	N	12	1N	21	1N	1N	11	853	50	853	0.99
77	R	100	N	1N	1N	1N	11	1N	1N	413	50	413	1.00
77	R	200	N	1N	1N	1N	1N	1N	1N	531	50	531	1.00
77	R	300	N	1N	1N	1N	11	1N	1N	393	50	393	1.00
77	R	396	N	1N	1N	1N	1N	1N	21	868	50	868	0.99
79	R	100	2	1N	1N	32	31	1N	1N	453	0	453	1.00
79	R	200	2	1N	1N	32	21	1N	1N	549	0	549	1.00
79	R	300	1	1N	1N	32	21	1N	1N	365	0	365	1.00
79	R	396	1	11	1N	12	21	1N	1N	1255	0	1255	0.98

Figure 3. Master File Listing

$$\text{Rating} = (100 - \Sigma D)\left(1.0 - 0.3\left(\frac{CPM}{5000}\right)^2\right) \text{ or}$$

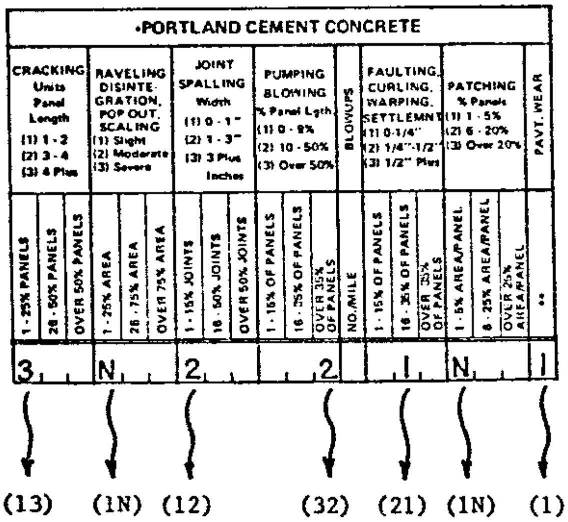
$$\text{Rating} = (\text{pavement rating})(\text{ride rating})$$

In this equation, ΣD represents the sum of weighted values for all distress categories as shown in Figure 5, and CPM represents the counts per mile for the rating section acquired with the ride meter. Since the ratings are acquired for each mile of the system and project limits occur at odd mileposts, the mean combined rating for each project is computed using length as a weighting factor. By plotting the history of combined mean ratings for each paving project, the progression of pavement deterioration is tracked with time and projected into the future. This is accomplished in the interpreting program by utilizing three different methods of producing performance equations:

1. When the project being considered does not have at least three ratings, a typical equation for the specific pavement type, surfacing depth, and geographical area is assigned. This is justifiable because the pavement would be relatively new and should not need rehabilitation for some time. The equation generated is used primarily in network analysis. Should the project have only two ratings, with the second rating falling beyond that allowed for in the typical equation, the performance equation is modified so as to reflect that rating.
2. Regression analysis is applied to all projects that have at least three ratings. This is the basic approach to fitting performance equations.
3. When regression analysis does not produce a reasonably good fit, (R^2 value less than minimum acceptable), a "typical" curve is fitted through the first and last values.

These three methods of developing performance equations are applied in the interpreting program as an algorithm for automation and can be considered a general rule that has many exceptions. They do not always produce good fitting curves with accurate equations.

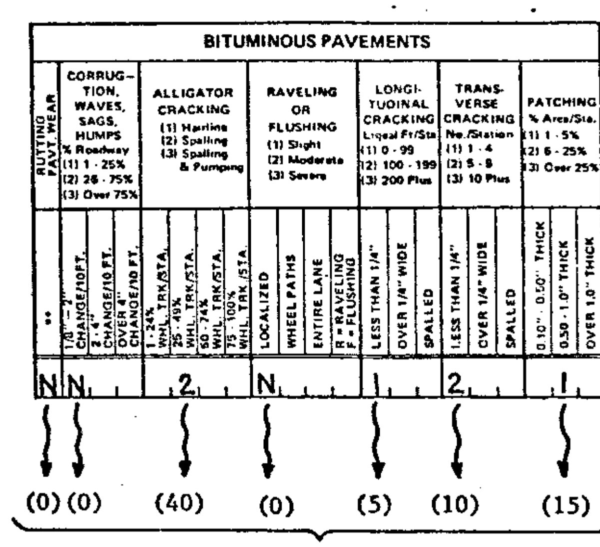
In order to be assured that the performance curves and equations for each project are reasonable and represent the best forecast of future pavement condition, the plotted ratings with fitted curves for each project are carefully reviewed one at a time. The type, thickness, and date of last surfacing are noted while inspection of the curve shape, fit, and time to failure are studied. Most projects demonstrate reasonable curve fit as analyzed by the interpreting program. Those that do not show a good fit (usually caused by a random fluctuation in ratings) are reviewed in detail in the Master File. Trends in distress are inspected carefully and engineering judgment is used to provide a performance



Coding: (AB) A = Column Coded
B = Number Coded

Note: "N" indicates no distress present.

Figure 4. Example of Coding Shown on Master File Listing



Weighting Values

$\Sigma D = 0+0+40+0+5+10+15 = 70$

Figure 5. Example of Weighting Values Assigned to Ratings

equation for predicting future pavement ratings as well as the specific type of rehabilitation. It is important to note that the equation provided with this approach is intended only to forecast future ratings and may not fit past ratings at all. Projects that fall into this category are not considered good prospects for the optimizing analysis and are routed directly to the network phase.

Another item which is addressed in this review is the amount of variance in the high, low, and mean ratings for each generation. If a high amount of variance is noted, the Master File listing and the Construction History File are studied. The Master File points out exactly where the high and low ratings are located, while the Construction History File demonstrates old surfacing contract limits that might be correlated with the high and low ratings.

If it is found that a specific portion of the project is performing substantially different from the rest, the project can be divided into two or more units with new project limits.

Figure 6 is an illustration of the model relating pavement rating (serviceability) to age that is used in the interpreting program. The general form of the performance equation adapted is:

$$R = C - mA^B$$

where C usually approximates 100, R and A represent rating and age respectively, m is a coefficient controlling the slope of the curve, and B is an exponent that controls the degree of curvature.

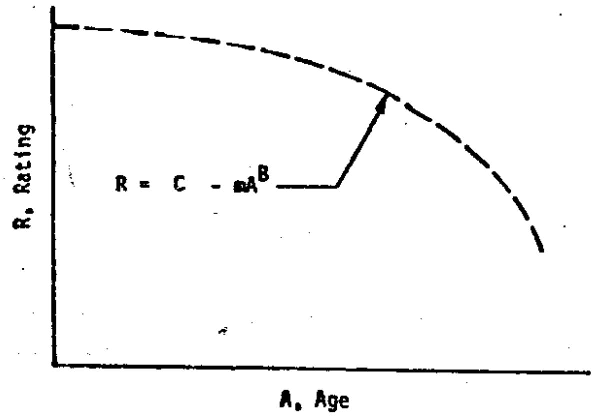


Figure 6. General Form of Performance Equation

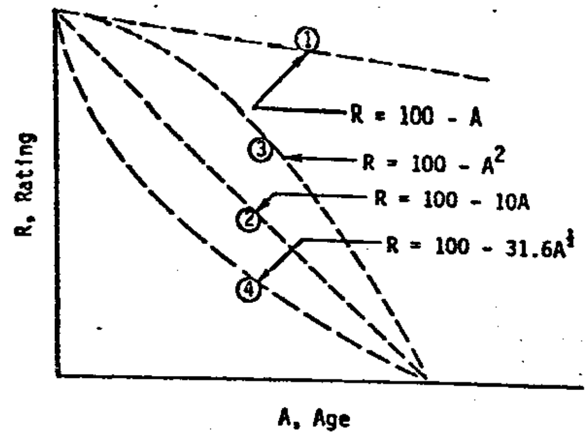


Figure 7. Example of Different Curve Shapes

Figure 7 is an example of the different shapes the curve might assume. Curves 1 and 2 are linear and demonstrate the influence of the slope, m. Curves 2, 3, and 4 demonstrate the control that B exerts on the degree of curvature. Note that exponents greater than 1 indicate curvature increasing from horizontal, while exponents less than 1 indicate curvature increasing from vertical.

In fitting the best curve to the acquired ratings with regression analysis, the program substitutes a number of different exponents (B) in order to transform the independent variable, age. The best fit is determined by the highest R^2 value (coefficient of determination) using the sum of least square method. Statistics generated with the performance equation are the R^2 value and the standard error of estimate.

Figure 8 is an example of the interpreted data listing which identifies the project across the top, similar to that on the master file. Listed under that are the performance history, approximate traffic data, and the constants used in the performance equation, with associated statistical data. Note that if regression analysis does not produce an equation with an R^2 number greater than some arbitrarily set value, say 0.75, one of the alternative methods will be applied, and the statistical data will be zeroed.

The bottom portion of the interpreted data listing is dedicated to the plot of ratings since the last surfacing activity. This plot also shows the performance curve fitted to the ratings and indicates the range of ratings for each generation with a high and low value plotted. When reviewing the performance curves for each project as described earlier, this plot is an invaluable tool.

D	SR	BEG SRMP	END SRMP	CS	BEG CSMP	END CSMP	PROJ LENG	FNC CLS	SIDE	HWY TYP	NUM LNS	RDW-RSH-LSH WIDTHS	LAST CONTR	COMPLT M-YR	CNT TYP	SURFACE TYP-THK	BASE TYPE
3	5	13554	13950	2719	0	396	396	U-5	R	3	4	48 10 10	08603	5-70	20	40 33	11

PERFORMANCE HISTORY

YEAR	71	73	75	77	79
AGE	1	3	5	7	9
RIDE RATING	0.99	1.00	1.00	1.00	0.99
STRUCR RATING	100.0	97.6	93.8	93.8	81.2
COMBD RATING	99.3	97.5	93.5	93.5	80.7
HIGH RATING	99.9	100.0	99.9	99.7	84.9
LOW RATING	97.9	89.7	89.2	84.2	69.8
HIGH FRICTION	45	45	50	50	52
LOW FRICTION	43	43	48	44	49
AVG FRICTION	44	44	49	48	50

APPROXIMATE TRAFFIC DATA

0 ADT	78300
GROWTH RATE	5.6%
SINGLE UNITS	4%
COMBINATIONS	6%
TRAFFIC INDEX	7.9
K = 11%	D = 59%
2 AXLE TRUCKS =	2.7 %
3 AXLE TRUCKS =	2.5 %
4 AXLE TRUCKS =	0.8 %
5 AXLE TRUCKS =	4.0 %

PERFORMANCE EQUATION

EQUA CONST =	98.78
EQUA COEFF =	-0.01384
EQUA POWER =	3.25
R SQUARE =	0.93744
STD ERROR =	1.99
TIME TO 60 =	11.50
TIME TO 50 =	12.34
TIME TO 40 =	13.07
TIME TO 30 =	13.72
TIME TO 20 =	14.30

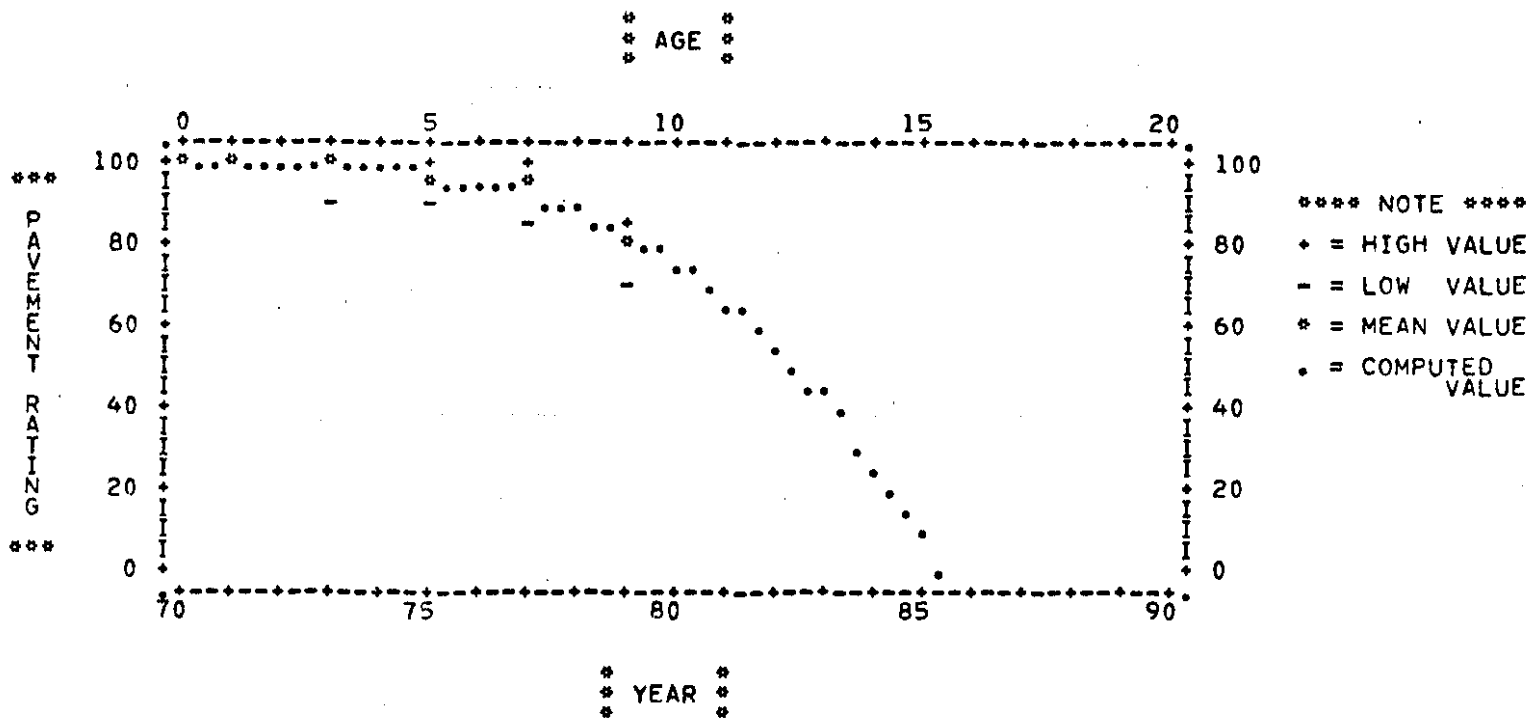


Figure 8. Interpreted Data Listing

Project-Level Optimizing

This phase utilizes the performance equations produced at the interpreting level to establish the most cost-effective rehabilitation strategy for each project.

Figure 9 is a typical performance curve relating the pavement rating (serviceability) to the age of the pavement. As a pavement ages, its condition gradually deteriorates to a point where some type of rehabilitation should be applied. This is a state of deterioration at which distress is showing, but might not yet be severe enough to call for immediate remedial action. Unfortunately, this point is all too often passed and the pavement continues to deteriorate until something must be done to rehabilitate it. These two points on the performance curve, aptly named the "should" and "must" levels, define the most probable rehabilitation period. In the event that the "must" level is surpassed without action, maintenance forces are then faced with applying temporary fixes until a major remedy can be applied. Temporary fixes tend to retard the rate of deterioration and flatten out the performance curves. However, the frequency of application and associated cost of a temporary fix are high compared to the benefit returned.

When rehabilitation treatment is eventually applied, the pavement rating increases abruptly, marking the beginning of a new cycle. Over the total existence of a pavement, many restorative actions like this occur, demonstrating a new performance cycle each time rehabilitation is applied. Obviously many different fixes are possible when the need for rehabilitation is faced, and each fix generates its own performance curve following application. Not only are many fixes possible, but a tremendous number of different combinations are possible when the timing, sequence, or type of action are changed over an extended period. A rehabilitation strategy is thus defined as a combination of rehabilitation alternatives designated by type, sequence, and application time. Figures 10a, b, c, and d illustrate this concept with a few examples of strategies.

The primary motive for improving our approach to pavement management is to minimize the cost of providing satisfactory pavement service. The methods presented here can achieve this by analyzing economically all strategies possible within a set time frame called a consideration period. Basic to the analysis is the stipulation of a minimum level of serviceability ("must level") to be maintained through the consideration period. All costs associated with each strategy can then be totaled and brought back to present worth for comparison

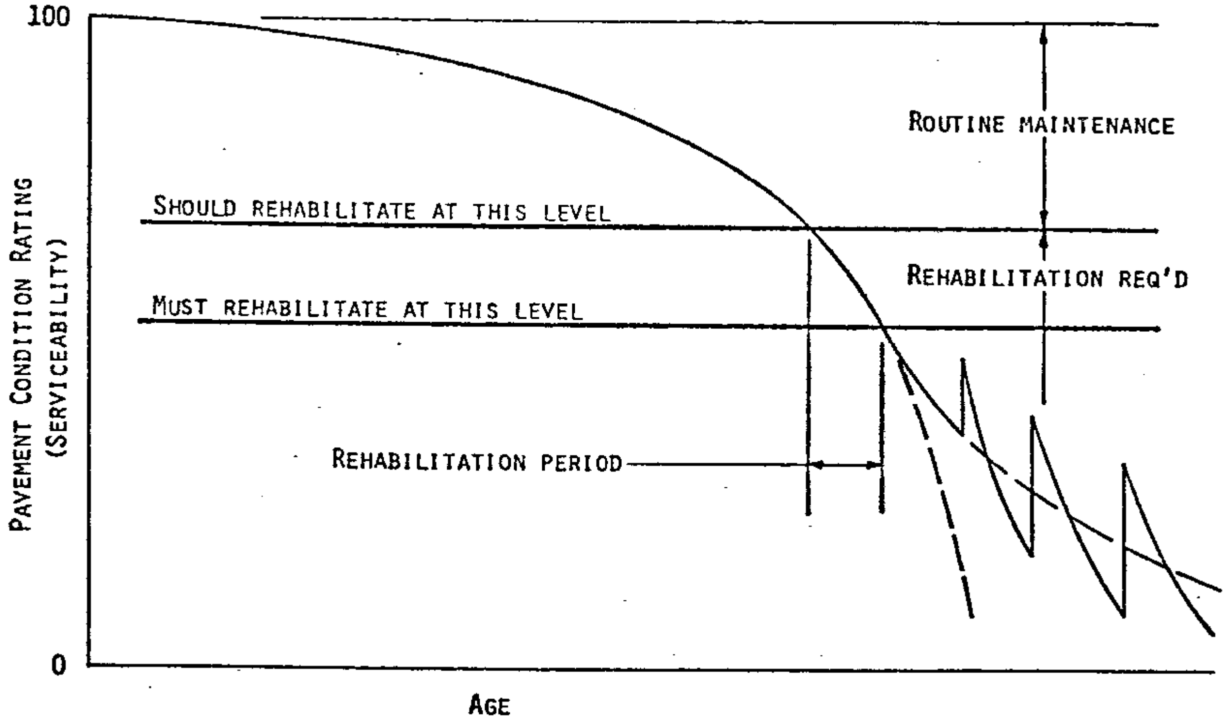


Figure 9. Typical Performance Curve

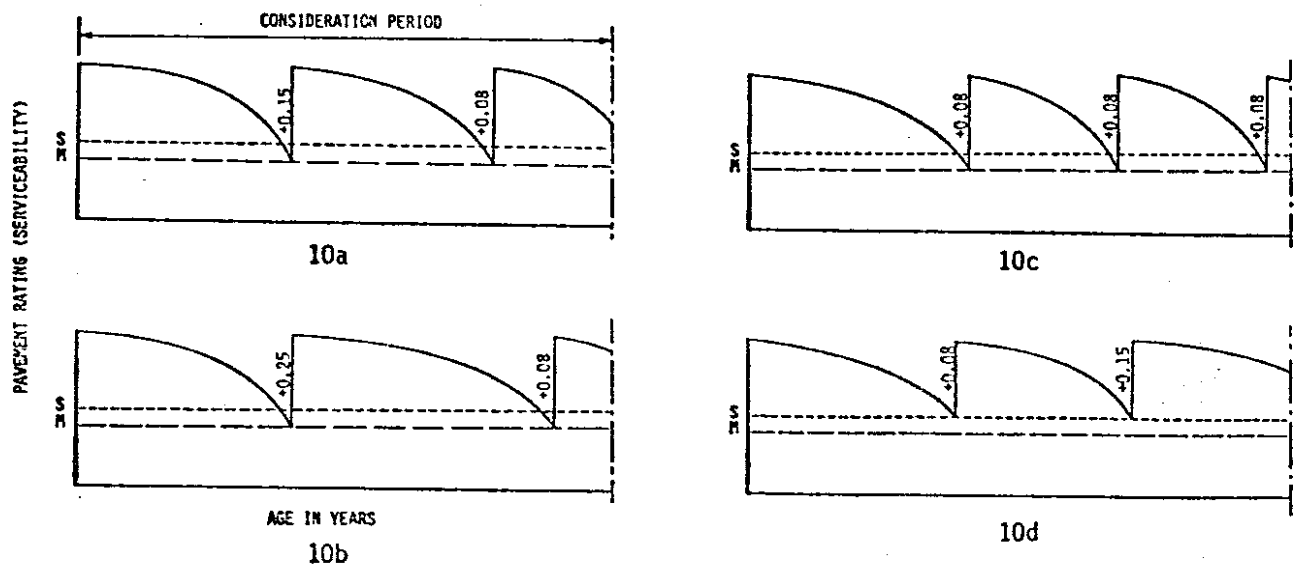


Figure 10. Examples of Different Strategies

with other strategies--the desired strategy being the one with the least total cost. Costs considered in this analysis consist of:

1. Construction costs for each rehabilitation alternative applied.
2. Routine pavement-related maintenance costs (annual).
3. User-incurred costs related to the condition of the pavement.
4. User-incurred costs related to delay during rehabilitation.
5. Salvage value of the pavement at the end of the consideration period.

It is important to note that strategies can be selected on the basis of all these costs, or any combination of them, depending on management's preference.

Figure 11 is a flow chart demonstrating the operations and work flow in the optimizing program. Each box on the flow chart represents a program module (subroutine) which can be easily replaced or modified as new data become available and expertise in each of these areas is improved.

The objective of the pavement management system is to produce cost-effective rehabilitation. To do this, performance equations developed by the interpreting program are applied in the optimizing program. This program also uses a second data set containing optimizing parameters as shown in Figure 11. Included are: constant and coefficients for the cost models; should and must trigger levels; all rehabilitation alternatives to be considered; a selection matrix for the array of alternatives to be considered for each project; and the effective interest rate (current interest less current inflation rate) to be used for discounting to present worth.

Figure 12 is an example of the output listing for one project, indicating the benefits and consequences of applying rehabilitation alternatives in certain sequences. Shown also on this listing are: all performance data as produced by the interpreting program; all optimizing parameters; a description of the rehabilitation alternatives with performance equations, construction costs, and predicted time to "should" and "must" levels after application; and a summary of the best rehabilitation strategies with their associated itemized costs.

Programming the Optimized Projects at the Network Level

The last phase in this system is network-level programming which is based on the optimum rehabilitation strategy (or alternatively one of the other strategies) as determined and projected by the project-level optimizing program. By aggregating the recommended rehabilitation actions in each year and tracking the performance and cost of all project segments on the network, a schedule of anticipated action, cost, and performance can be tabulated for a future number of years.

The network level program generates three summaries for each year of the proposed program:

1. Action Summary
2. Cost Summary
3. Rating Distribution Summary

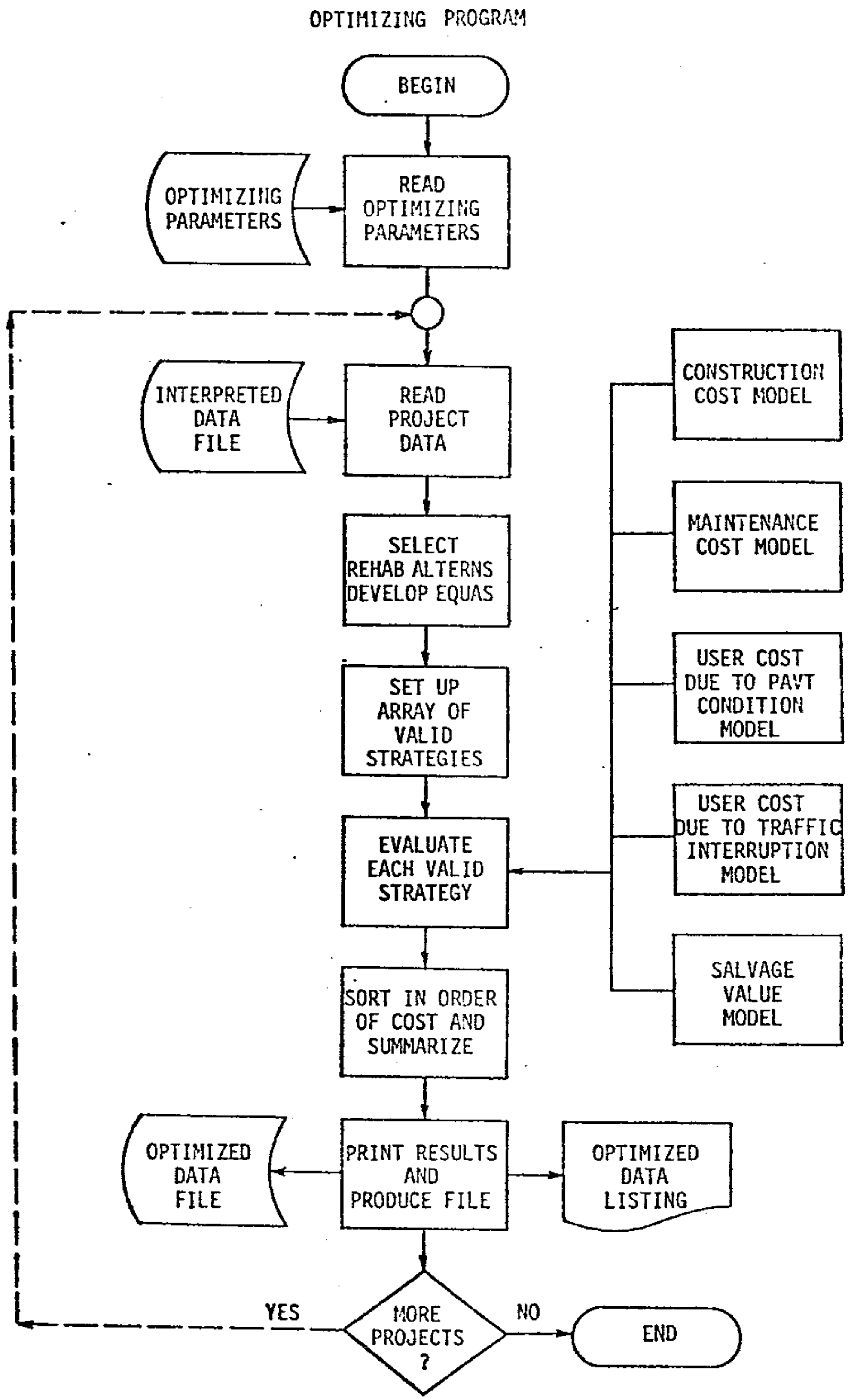


Figure 11. Flow Chart of Optimizing Program

D	SR	BEG SRMP	END SRMP	CS	BEG CSMP	END CSMP	PROJ LENG	FNC CLS	SIDE	HWY TYP	NUM LNS	ROW-RSH-LSH WIDTHS			LAST CONTR	COMPLT M-YR	CNT TYP	SURFACE TYP-THK		BASE TYPE
3	5	13554	13950	2719	0	396	396	U-5	R	3	4	48	10	10	08603	5-70	20	40	33	11

PERFORMANCE HISTORY

YEAR	71	73	75	77	79
AGE	1	3	5	7	9
RIDE RATING	0.99	1.00	1.00	1.00	0.99
STRUCR RATING	100.0	97.6	93.8	93.8	81.2
COMBD RATING	99.3	97.5	93.5	93.5	80.7
HIGH RATING	99.9	100.0	99.9	99.7	84.9
LOW RATING	97.9	89.7	89.2	84.2	69.8
HIGH FRICTION	45	45	50	50	52
LOW FRICTION	43	43	48	44	49
AVG FRICTION	44	44	49	48	50

APPROXIMATE TRAFFIC DATA

79 ADT	78300
GROWTH RATE	5.6%
SINGLE UNITS	4%
COMBINATIONS	6%
TRAFFIC INDEX	7.9
K = 11%	D = 59%
2 AXLE TRUCKS =	2.7 %
3 AXLE TRUCKS =	2.5 %
4 AXLE TRUCKS =	0.8 %
5 AXLE TRUCKS =	4.0 %

PERFORMANCE EQUATION

EQUA CONST =	98.78
EQUA COEFF =	-0.01384
EQUA POWER =	3.25
R SQUARE =	0.93744
STD ERROR =	1.99
TIME TO 60 =	11.50
TIME TO 50 =	12.34
TIME TO 40 =	13.07
TIME TO 30 =	13.72
TIME TO 20 =	14.30

SHOULD REHABILITATE AT 70.0 WHICH WILL OCCUR IN 1980
MUST REHABILITATE AT 50.0 WHICH WILL OCCUR IN 1982
CONSIDERATION SPAN = 20 PERIODS, EACH PERIOD = 1.0 YEARS
EFFECTIVE INTEREST RATE = 0.0% FACTORS : 67.0% 83.0% 100.0%

DESCRIPTION OF THE ALTERNATIVES	PERFORMANCE EQUATIONS	CONSTRCT COST 12' LANE MILE	MIN LIFE AT SHUD	MAX LIFE AT MUST
ALTERNATE 1 ROUTINE MAINTENANCE	R = 98.78 - 0.01384 P ** 3.25	0	10.49	12.34
ALTERNATE 2 OVERLAY 0.06 CLASS D	R = 100.00 - 0.30752 P ** 2.25	23100	7.66	9.61
ALTERNATE 3 OVERLAY 0.15 CLASS B	R = 100.00 - 0.10225 P ** 2.50	35800	9.70	11.90
ALTERNATE 4 RECYCLE + 0.06 CLASS D	R = 100.00 - 0.01695 P ** 3.00	68100	12.10	14.34

ITEMIZED COSTS / **STRATEGY DESCRIPTION** (ALTERNATIVE - PRD APPLIED)

ROUT MAINT COST +	COST OF CONSTR INCL PR +	COST OF TRAFFIC INTERPT +	USER COST -	SALVAGE VALUE =	EXPECTED TOTAL COST	NUMB POSS 155	1ST REHAB	2ND REHAB	3RD REHAB	4TH REHAB
160135	1633477	0	1321989	435064	2680537	40	2-81	2-89	2-98	
201764	1660535	0	1332744	497216	2697827	50	2-82	2-90	2-99	
173062	1405090	0	1324666	123127	2779691	29	3-82	2-93		
159419	1378032	0	1322639	61563	2798527	18	3-81	2-92		
104796	2093552	0	1307378	181594	3324132	9	4-81	2-94		
143095	2120610	0	1314792	242125	3336372	9	4-82	2-95		

Figure 12. Optimizing Program Listing for One Project

Figure 13 is an example of the Action Summary generated. Since different "should" and "must" levels can be applied for different functional classes of highway, the particular levels used to develop the schedule of action are indicated at the top. Below that is a summary of all projects required in that year defined by state route number and inclusive milepost limits, with a description of the action required and the associated cost--both in present dollars and dollars inflated to the respective year. The costs shown on the Action Summary and Cost Summary include only the construction and preparation costs since the other costs considered in the optimizing program would not enter into budget considerations.

Figure 14 is an example of the Cost Summary. This summarizes by functional class the gain in average pavement rating on the system to be expected by funding (and constructing) the project itemized on the Action Summary, and indicates the total demand on budget dollars for that year. Three types of dollars are shown: present dollars, inflated dollars, and discounted dollars. Inflated dollars are used to indicate the cost expected at the time of construction. Present dollars are used as a direct comparison to current-day funding levels, and the discounted dollars are shown to gauge the effect of interest and inflation on the particular time of expenditure.

The last listing produced by the network program on a yearly basis is the Rating Distribution Summary shown on Figure 15. This listing indicates how many lane-miles are present in each pavement condition rating group before and after the proposed rehabilitative action for that year.

The network-level program described is actually a summarizing program that takes into account the performance of existing projects as analyzed in the interpreting program, and the recommended time of rehabilitation with a performance equation commensurate to the type of fix for each project requiring rehabilitation as determined in the optimizing program. On inspection of a six-year program, as summarized directly without any constraint (Figure 16), one quickly realizes that there is an enormous volume of work to be accomplished in the first year or two with just as large a demand placed on funding. Sufficient resources in terms of manpower or funds are simply not available to address this size of task--nor would it be desirable to do so if resources were available.

To manage a highway or transportation agency efficiently, steady workloads and rates of expenditure may be preferable to drastically fluctuating resource requirements. To "balance" this fluctuation requires a shift in timing for some of the projects. What actually occurs in network-level programming is a modification

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1981 DISTRICT 4 ACTION SUMMARY

05/14/81

	FC 1	FC 2	FC 3	FC 4	FC 5
SHUD	60	50	50	50	70
MUST	40	30	30	30	50

FC		SR	BEG SRMP	END SRMP	LENG	CS	SIDE	AFF RTNG.	PROPOSED ACTION	PRESENT COST	INFLATED COST
R	1	4	499	891	392	2506	R	41.9	BITUMINOUS SURF TREATMNT	217136	245363
R	1	4	891	935	44	3501	R	29.5	OVERLAY 0.15 CLASS B	73770	83360
R	1	4	1956	2087	131	3502	R	38.8	OVERLAY 0.15 CLASS B	213021	240713
R	1	4	2644	2697	253	3502	R	34.3	OVERLAY 0.15 CLASS B	360769	407668
R	1	4	3457	3648	161	3503	R	38.1	OVERLAY 0.08 CLASS G	169268	191272
R	1	4	5501	5599	98	804	R	1.8	OVERLAY 0.15 CLASS B	162720	183873
U	1	4	5599	5862	263	804	R	50.1	OVERLAY 0.15 CLASS B	415133	469099
U	1	4	5862	5924	62	804	R	0.0	OVERLAY 0.15 CLASS B	229493	259326
U	1	4	5924	6079	155	807	R	0.0	OVERLAY 0.15 CLASS B	573733	648317
R	5	5	3378	3465	87	801	L	60.7	OVERLAY 0.06 CLASS D	121179	136932
U	5	5	7755	7797	42	2102	R	49.2	OVERLAY 0.15 CLASS B	60127	67943
U	5	5	7797	7838	41	2103	L	29.7	OVERLAY 0.15 CLASS B	62873	71046
U	5	5	7797	7838	41	2103	R	39.3	OVERLAY 0.15 CLASS B	60563	68436
U	5	5	7838	7919	81	2103	L	0.0	OVERLAY 0.06 CLASS D	105847	119607
U	5	5	7838	7919	81	2103	R	29.9	OVERLAY 0.06 CLASS D	85592	96718
R	2	6	1956	2059	103	2507	R	0.0	OVERLAY 0.15 CLASS B	219886	248470
R	2	6	2059	2174	115	2507	R	26.3	OVERLAY 0.15 CLASS B	195127	220493
R	2	6	2174	2335	161	2507	R	0.0	OVERLAY 0.15 CLASS B	237033	267847
R	2	6	3392	3465	73	2105	R	13.6	OVERLAY 0.15 CLASS B	111727	126251
R	2	6	3536	3726	190	2105	R	46.6	OVERLAY 0.08 CLASS G	203532	229990
U	1	14	13	190	177	604	L	4.4	OVERLAY 0.15 CLASS B	260189	294013
U	1	14	13	219	206	604	R	52.3	OVERLAY 0.15 CLASS B	358685	405313
R	2	14	7582	7656	74	2001	R	0.0	OVERLAY 0.15 CLASS B	135019	152571
R	2	14	7656	8464	808	2001	R	28.8	BITUMINOUS SURF TREATMNT	579971	655366
R	2	14	8464	8614	150	2001	R	41.3	OVERLAY 0.15 CLASS B	218499	246903
R	2	14	12644	12881	237	2032	R	62.0	BITUMINOUS SURF TREATMNT	150991	170619
R	1	97	189	255	66	2006	R	0.0	BITUMINOUS SURF TREATMNT	55822	63078
R	1	97	255	274	19	2002	R	32.5	BITUMINOUS SURF TREATMNT	15287	17274
R	1	97	2399	2718	319	2005	R	41.5	OVERLAY 0.15 CLASS B	514638	581540
R	1	101	0	46	46	2511	R	0.0	OVERLAY 0.15 CLASS B	81750	92377
R	1	101	5302	5476	176	2504	R	14.4	OVERLAY 0.20 CLASS B	402325	454626
R	1	101	5826	5951	80	2505	R	47.4	OVERLAY 0.15 CLASS B	236841	267630
R	2	123	550	750	200	2113	R	35.0	OVERLAY 0.15 CLASS B	225076	254335
U	3	140	0	95	95	637	R	0.0	OVERLAY 0.20 CLASS B	154769	174888
R	3	140	195	624	429	637	R	35.0	OVERLAY 0.20 CLASS B	750359	847905
R	3	140	624	889	265	637	R	62.0	0.35' CSTC + BST	260106	293919
R	3	140	885	989	104	3030	R	62.0	0.35' CSTC + BST	102079	115349

Figure 13. One Page of Network Action Summary

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DISTRICT 3
1981 COST SUMMARY

04/09/80

	FC 1	FC 2	FC 3	FC 4	FC 5
	****	****	****	****	****
SHUD	60	60	50	50	70
MUST	40	40	30	30	50

FC	RTNG AVG REF ACTN	RTNG AVG AFT ACTN	NUMB PROJ	MILES ACTED ON	TOTAL MILES	% ACTED ON	PRESENT COST	INFLATED COST	DISCOUNTED COST
1	53	90	157	312	644	48 %	30632400	33695545	29454227
2	54	83	104	115	278	41 %	8557393	9413074	8228260
3	36	87	30	82	144	57 %	6888495	7577323	6623550
4	0	0	0	0	0	0 %	0	0	0
5	71	90	21	39	107	36 %	10969766	12066726	10547846
ALL	52	87	312	550	1174	46 %	57048054	62752668	54853883

Figure 14 - Network Cost Summary

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DISTRICT 4

1981 RATING DISTRIBUTION SUMMARY

05/14/81

	FC 1	FC 2	FC 3	FC 4	FC 5
SHUD	60	50	50	50	70
MUST	40	30	30	30	50

LANE MILES IN RATING GROUP BEFORE ACTION

FC	100-91	90-81	80-71	70-61	60-51	50-41	40-31	30-21	20-11	10 -0	AVG RTNG	TOTAL MILES
1	157.9	29.6	27.2	30.0	16.9	10.9	6.0	0.4	1.8	7.0	81.3	287.9
2	203.1	68.7	15.3	22.2	9.2	13.7	14.0	9.2	0.7	13.9	81.6	370.1
3	91.0	47.9	9.5	21.4	0.9	17.1	13.8	3.0	0.0	27.8	70.8	232.3
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	160.0	21.3	1.5	4.8	0.9	0.4	0.4	1.2	0.0	0.8	95.0	191.4
ALL	612.0	167.4	53.6	78.4	28.0	42.1	34.3	13.9	2.5	49.5	81.6	1081.7

LANE MILES IN RATING GROUP AFTER ACTION

FC	100-91	90-81	80-71	70-61	60-51	50-41	40-31	30-21	20-11	10 -0	AVG RTNG	TOTAL MILES
1	185.8	29.6	27.2	30.0	12.3	3.0	0.0	0.0	0.0	0.0	88.0	287.9
2	252.3	68.7	15.3	12.2	8.0	10.3	3.2	0.0	0.0	0.0	90.9	370.1
3	143.5	47.9	9.5	13.5	0.9	17.1	0.0	0.0	0.0	0.0	88.7	232.3
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	163.7	21.3	1.5	3.9	0.9	0.0	0.0	0.0	0.0	0.0	96.3	191.4
ALL	745.4	167.4	53.6	59.6	22.1	30.4	3.2	0.0	0.0	0.0	90.6	1081.7

Figure 15. Rating Distribution Summary for One Year

of project timing in the optimized data file prior to summarizing with the network-level program. This modification in timing is a process of selecting projects on a priority basis for the good of the system.

UNCONSTRAINED

YEAR	BEFORE	AFTER	MILEAGE % AFF.	COST*
1981	53.1	88.6	46%	$62,752,668
1982	83.6	87.6	8%	11,758,111
1983	83.3	86.4	5%	6,624,903
1984	81.4	83.4	4%	5,661,168
1985	77.2	81.9	8%	14,155,899
1986	75.4	83.1	15%	33,893,546
6-YR AVG RATING = 80.4				$134,846,295

*ALL COSTS ARE INFLATED COSTS

Figure 16

The assembling of a "balanced" rehabilitation program by shifting project timing then becomes constrained by what we are trying to accomplish. There are basically two goals in building a rehabilitation program:

1. To identify those projects that can be constructed with available funding--the budget constraint.
2. To identify those projects that must be constructed to attain some desired level of serviceability--the serviceability constraint.

For the administrator, many questions can be answered through application of these two constraints. For instance, application of the budget constraint results in a certain level of serviceability. By applying several different funding levels, the administrator gains insight on what can be accomplished with more or less funding. Figures 17 and 18 represent budget-constrained programs which can be compared with the unconstrained program in Figure 16. A plot of the average serviceability obtained with each funding level is illustrated in Figure 19.

Conversely, application of the serviceability constraint results in a certain level of funding. Through application of serviceability constraints, the administrator can determine the level of funding required to keep the network serviceability where it is today. He could also lay out an improvement schedule in terms of serviceability and determine levels of funding required as well as the percentage of the network to be acted on to attain the specified level. Figure 20 is an illustration of the figures that can be generated.

BUDGET #1

YEAR	BEFORE	AFTER	MILEAGE % AFF.	COST
1981	53.1	59.3	7%	$9,050,095
1982	52.3	57.4	7%	9,048,675
1983	51.2	57.5	7%	10,299,085
1984	51.7	56.1	6%	10,300,148
1985	50.5	52.8	3%	9,449,439
1986	47.4	49.7	4%	9,449,286
				$57,596,728

6-YR AVG RATING = 53.2

Figure 17

BUDGET #2

YEAR	BEFORE	AFTER	MILEAGE % AFF.	COST
1981	53.1	62.0	11%	$12,349,188
1982	55.4	61.9	8%	12,349,691
1983	55.9	63.3	9%	14,949,463
1984	57.6	63.4	7%	14,949,477
1985	58.0	65.0	9%	17,954,686
1986	59.7	64.6	8%	17,952,927
				$90,050,432

6-YR AVG RATING = 60.0

Figure 18

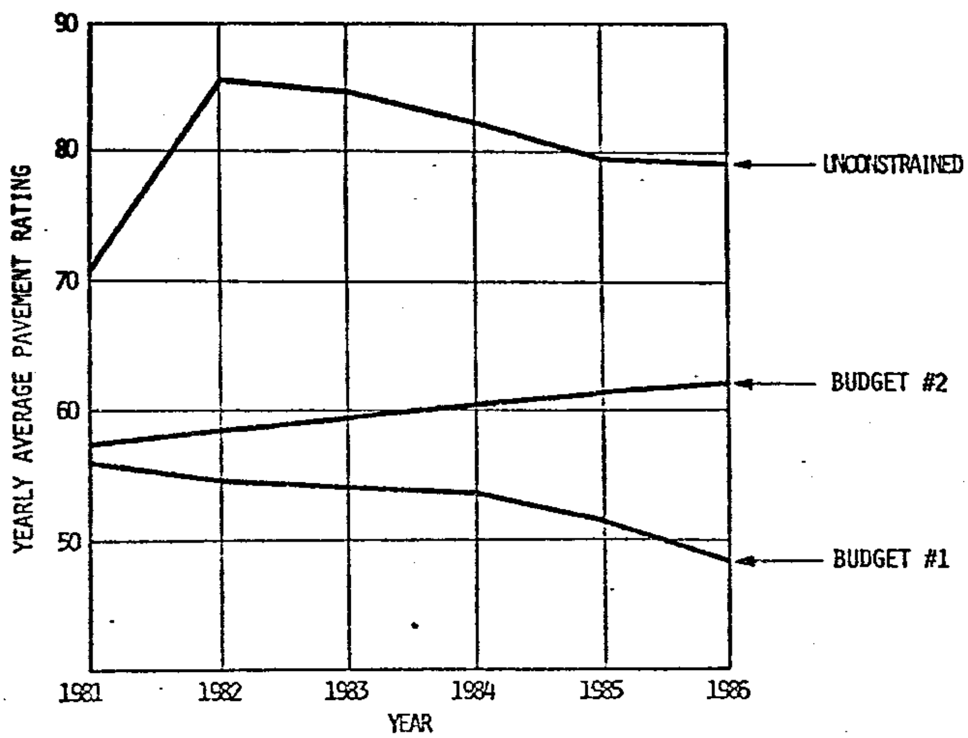
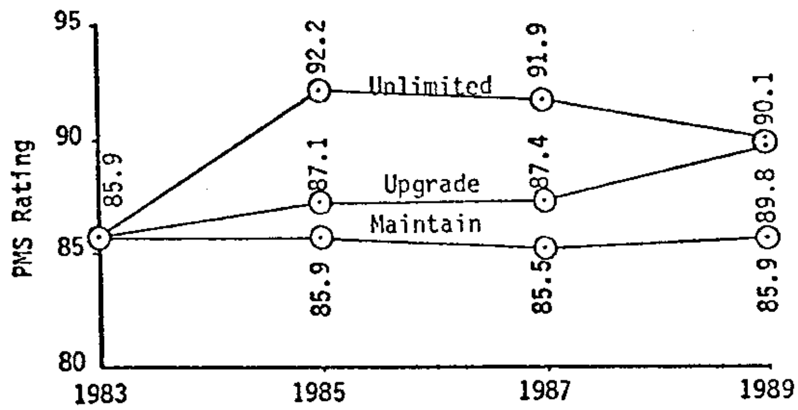


Figure 19. Plot of Average Serviceability Obtained with Budget Shown in Figures 16, 17, and 18



	1985	1987	1989
Unlimited Budget	36,114,882 (20%)	25,286,924 (13%)	28,367,426 (15%)
Upgrade Serv. Level	19,226,745 (10%)	24,439,130 (13%)	42,077,816 (22%)
Maintain Serv. Level	16,572,007 (8%)	21,205,024 (11%)	32,500,680 (16%)

Figure 20. Example of Figures Obtained by Applying Serviceability Constraints

It is important to note that the shift of project timing applied using either constraint requires a prioritizing function. It was stated earlier that projects are prioritized for the good of the system. The method used in generating the figures in this paper is called the "effect of delay". As can be seen in Figure 21, projects 1 and 2 deteriorated at significantly different rates. The effect of delaying project 1 would have far greater consequences than delaying project 2. By prioritizing projects based on a predicted rating a year after anticipated action, a better gain in serviceability is achieved.

It should be understood that this is only what was used to generate the figures in this paper. In the real world there exist several other aspects which might be considered in this type of prioritizing function. Among them are:

1. Effect of Delay - Rating (Yr. +1)
2. ADT - Functional Need
3. Effect on Maintenance Cost
4. Other deficiencies - i.e., V/C, Safety, Geometry, etc.
5. Administrative Priority - Commitment

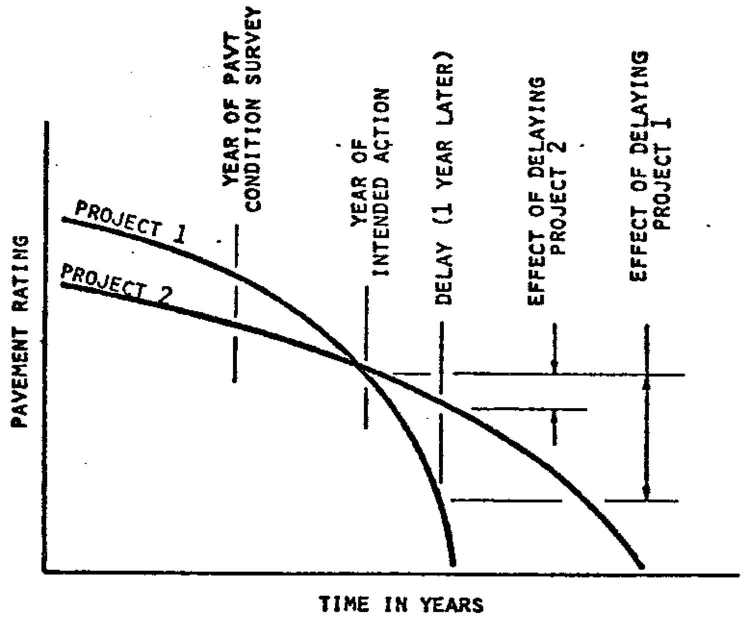


Figure 21. Effect of Delay

OTHER APPLICATIONS OF PMS

To this point, the basic framework of Washington's PMS has been described. Its use to administrators in assembling cost-effective rehabilitation programs should be immediately obvious. There are, however, many other applications of this system which impact other regions of decision-making. Data files and other computer programs exist at all levels of the PMS framework for influence in design, construction, maintenance, and pavement research. Pavement management, after all, is concerned with all facets of improving our efficiency in gaining more cost-effective pavements, as well as rehabilitation programming.

IMPACTS ON PAVEMENT DESIGN

Pavement design formulas have traditionally been related to load application, subgrade strength, frost susceptibility, and the attributes of surfacing materials used. Many of the pavement design formulas in use today were developed 20-25 years ago when materials and loading characteristics may have differed greatly. With a PMS, these design formulas can be verified or modified to reflect more current thinking. Items such as axle loadings, paving thickness, environmental conditions, and others can be correlated with pavement service life. The cost-effectiveness of new designs such as pavement recycling, sulfur-extended asphalt, stress-absorbing membranes, and open-graded friction courses can be gauged for further consideration. These represent only a few of the design-related PMS benefits--there are certainly many others.

IMPACTS ON CONSTRUCTION

It is well known that a pavement's service life is related not only to the design factors just mentioned, but also to material characteristics and its construction quality. Regardless of how well anything is designed, it must be built according to plans and specifications or it will not attain the expected service life. Some of the more obvious construction items which can be correlated with the service life of a pavement are:

1. Air void content in asphalt concrete
2. Asphalt grade and viscosity or penetration
3. Type of compaction employed and degree of compaction
4. Mix temperatures at the plant or when placed
5. Degradation values of mineral aggregate
6. Sand equivalent of crushed surfacing
7. Conformance to thickness requirements

With this system it is possible to monitor pavement performance and correlate with any recorded construction parameters, thus providing the necessary information to improve specifications and more efficiently gauge materials and construction performance.

IMPACTS ON MAINTENANCE

Applications of the pavement management system for a maintenance engineer differ greatly from those of the design or construction engineer. It should be noted that the Washington State DOT differentiates between routine pavement maintenance and rehabilitation. Routine maintenance consists of activities such as pothole patching, blade patching, minor chip seals, crack filling, pavement removal and replacement, etc. Rehabilitation is major rejuvenation of the structural and surface character through rebuilding the pavement or resurfacing.

Pavement-related maintenance problems pertain basically to three different areas:

1. Identify the specific pavement problems faced and anticipated in the future.
2. Preparing a maintenance budget to address the problem.
3. Allocating manpower, machinery, and materials to accomplish the tasks at hand.

The last two items are functions of a maintenance management system. The first item, however, is provided by the pavement management system. In providing a list of projects, the PMS identifies those which can be acted on immediately and those that, because of budget constraints, will have to wait to be fixed. This list represents all highway segments that have pavement problems and must be cared for by maintenance forces until there is enough money in the budget to fix them. The list of pavement problems can be used as direct input to the maintenance management system by identifying the pavement problems and their location.

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