AUTOMATION IN PAVEMENT DESIGN AND MANAGEMENT SYSTEMS

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Pavement design presents a complex problem that involves a variety of loads, materials, and environments. There are also various economic criteria that must be applied and a number of design details that must be determined in solving a pavement design problem. Existing design methods are generally based on empirical procedures and use models that are based on theory and general experience.

Generally, so-called pavement design methods have concentrated on finding a combination of thicknesses of available materials that will last the intended service life of a facility without requiring rehabilitation. Little attention has been given to required maintenance schemes or to the overall economics of the designed system. Figure 1 shows the general procedural flow of such empirical design methods.

Other details that must be established for a rational design are thickness requirements of various layers, selection of materials, type of pavement and overlays, joint and reinforcement details, and seal coats and maintenance schedules. The computations that are required when these details must be determined for a large number of possible alternatives make it impossible to perform the analysis manually. The use of manual analysis is also impossible when these alternatives must be optimized to achieve the best set of solutions, or resource allocations, and when various decision criteria must be considered.

The initial phase of the overall system design problem is mathematical modeling, which is used to achieve an optimum design configuration. Implementation and feedback are the long-range planned objectives of a pavement management system. When the optimal strategy for a design procedure is implemented, it may produce results that deviate from those predicted. Thus, pavement design must involve a feedback control process that accumulates pavement data on construction, performance, and cost in a pavement system data bank, which is used to modify the pavement design system models. The result is a closed-loop pavement design and management system that can use implementation and feedback data to improve its subsystem models. Figure 2 shows the overall concept of this pavement design and management system.

Solution of the broad problem of pavement design and management requires a computer that is fast and accurate and has large storage capacity. The computer aids the pavement design engineer in several ways:

1. It allows greater use of theory and analytical techniques and, thus, restructuring of the analysis procedures;
2. With the use of suitable models, it makes feasible the consideration of a full spectrum of variables that affect pavement systems;
3. It increases the number of possible designs considered by generating a large number of alternatives;
4. It allows the use of many kinds of constraints and decision criteria;
5. It allows for various optimization techniques that can pick out favorable alternatives and simplify the decision-making process;
6. It can store a large amount of pavement behavioral data that can be analyzed to modify and improve the existing design models; and
7. It provides mechanisms for predicting and managing future designs and economic alternatives for the administrator.

Figure 1. Format of existing design procedures.

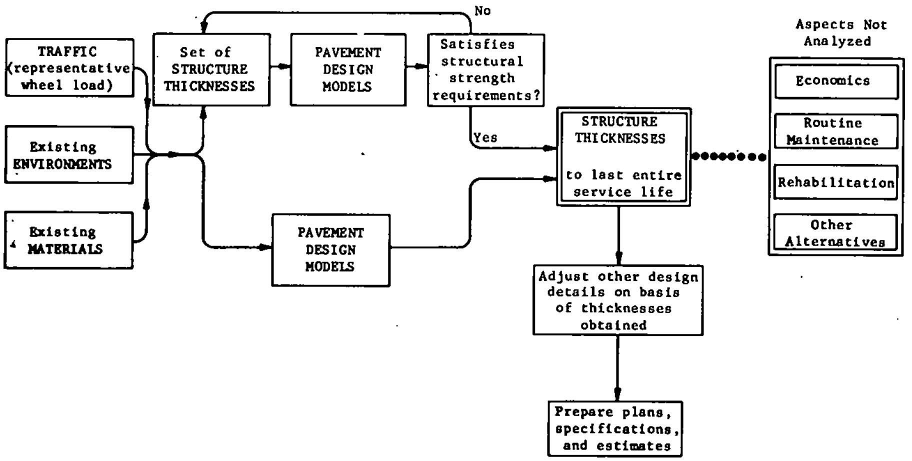
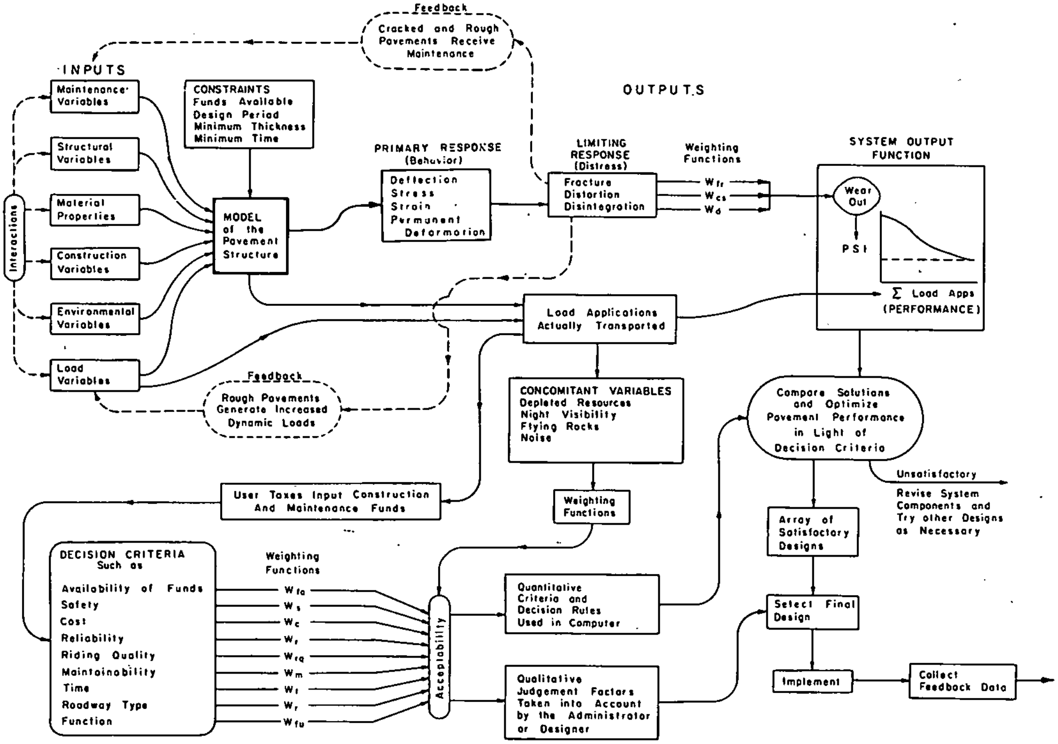


Figure 2. Conceptual pavement system.



AUTOMATED PAVEMENT DESIGN SYSTEMS

The concept previously described led to the formulation of working models for the pavement design system (PDS) (2). The operational systems consist of computer programs in two categories: rigid pavement system (RPS) (3) and flexible pavement system (FPS) (4, 5, 6). The programs are the first iterations of a research study and will be continually improved. The main objective of the computer programs is to use the best information from research on individual subsystems and to provide the decision-maker with a set of feasible design alternatives arranged in order of increasing overall total cost and with other pertinent information necessary for making a rational design decision.

Input and Output of Pavement Design System

A large number of numerical inputs are used for PDS programs. FPS uses about 50 different input parameters, and RPS uses well over 100 parameters. The input for the programs is in the following broad categories.

1. Program controls are used to control the operation and to exercise the options over the solutions;
2. Constraints are used to generate specific types of solutions with respect to thicknesses, time schedules, and funds and to control the number of feasible designs;
3. Traffic volume, growth, and distribution are used to describe the expected traffic that the pavement must serve during its lifetime;
4. Material properties are used to define the engineering characteristics of materials used for subgrades, subbases, bases, surfaces, reinforcements, overlays, and seal coats;
5. Performance variables are used to define the limits on serviceability indexes for an initial or overlaid structure;
6. Material costs are used for computation of the costs of materials and the costs of providing these materials (interest rate and salvage value are used to weight future investments in terms of current worth);
7. Traffic delay variables are used to analyze the costs of overlay construction due to inconvenience to traffic users;
8. Environmental variables are used in structural and maintenance subsystems of the computer programs;
9. Stochastic parameters are used to take into account regression errors of the design models as well as variations of material properties with time and space;
10. Road geometrics are used to define the overall dimensions of the facility to be designed; and
11. Seal coat variables are used to impose specific seal coat schedules for each pavement design.

An example of the inputs echo-printed by the computer for the FPS program is shown in Figure 3.

The prime decision criterion for the sélection of the optimal and nearly optimal pavement strategies is total overall cost. Availability of initial funds is another decision criterion, but it also acts as a restraint.

Solution output is intentionally arranged such that the designer can exercise his judgment. It is currently possible to use mathematical formulation to determine the relative importance to the decision-maker of various economic, social, and experience values. A set of alternative design strategies and the information pertinent to them are presented as a summary table arranged in increasing order of the present worth of total overall costs.

General Formulation of Pavement Design System

The computer programs are written to give performance, structural, and economic subsystems and arrays of designs and other pertinent information. A systematic structuring of the operational pavement design system is shown in Figure 4.

Figure 3. Input data (shown as output) for example problem.

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PROB    1                          AVERAGE PROBLEM

           THE CONSTRUCTION MATERIALS UNDER CONSIDERATION ARE

     MATERIAL              COST/C.Y.   ST.COEF.   MIN.DEPTH   MAX.DEPTH

ASPHALTIC CONCRETE           10.00        .75        1.00        6.00
CR. LIMESTONE                 5.00        .70        6.00       16.00
GRAVEL                        2.00        .40        6.00       16.00
SUBGRADE                      0.00        .25        0.00        0.00

  NUMBER OF INPUT MATERIAL TYPES                                           3
  MAX FUNDS AVAILABLE PER SQ.YD. FOR INITIAL DESIGN (DOLLARS)           4.00
  LENGTH OF THE ANALYSIS PERIOD (YEARS)                                 20.0
  INTEREST RATE OR TIME VALUE OF MONEY (PERCENT)                         5.0
  ASPHALTIC CONCRETE PRODUCTION RATE (TONS/HOUR)                        75.0
  ASPHALTIC CONCRETE COMPACTED DENSITY (TONS/C.Y.)                      1.80
  SALVAGE PERCENT AT THE END OF ANALYSIS PERIOD (PERCENT)               50.0
  MAXIMUM ALLOWED THICKNESS OF INITIAL CONSTRUCTION (INCHES)           25.00

  DISTRICT TEMPERATURE CONSTANT                                        25.00
  SERVICEABILITY INDEX OF THE INITIAL STRUCTURE                          4.2
  MINIMUM SERVICEABILITY INDEX P2                                        2.5
  SWELLING CLAY PARAMETERS -- P2 PRIME                                  1.50
                              B1                                       .1000

  ONE-DIRECTION ADT AT BEGINNING OF ANALYSIS PERIOD (VEHICLES/DAY)    10,000
  ONE-DIRECTION ADT AT END OF ANALYSIS PERIOD (VEHICLES/DAY)          20,000
  ONE-DIRECTION 20-YR ACCUMULATED NO. OF EQUIVALENT 18-KIP AXLES   4,000,000

  MINIMUM TIME TO FIRST OVERLAY (YEARS)                                  5.0
  MINIMUM TIME BETWEEN OVERLAYS (YEARS)                                  6.0
  MIN TIME TO FIRST SEAL COAT AFTER OVERLAY OR INITIAL CONST.(YEARS)     5.0
  MINIMUM TIME BETWEEN SEAL COATS (YEARS)                                5.0
  A SEAL COAT WILL NOT BE APPLIED WITHIN ONE YEAR PRIOR TO AN OVERLAY
  NUMBER OF OPEN LANES IN RESTRICTED ZONE IN O.D.                          1
  NUMBER OF OPEN LANES IN RESTRICTED ZONE IN N.O.D.                        2

  C.L. DISTANCE OVER WHICH TRAFFIC IS SLOWED IN THE O.D. (MILES)         .50
  C.L. DISTANCE OVER WHICH TRAFFIC IS SLOWED IN THE N.O.D. (MILES)       .50
  PROPORTION OF ADT ARRIVING EACH HOUR OF CONSTRUCTION (PERCENT)         6.0
  OVERLAY CONSTRUCTION TIME (HOURS/DAY)                                  8.0
  THE ROAD IS IN A RURAL AREA.

  PROPORTION OF VEHICLES STOPPED BY ROAD EQUIPMENT IN O.D. (PERCENT)     5.0
  PROPORTION OF VEHICLES STOPPED BY ROAD EQUIPMENT IN N.O.D. (PERCENT)   5.0
  AVERAGE TIME STOPPED BY ROAD EQUIPMENT IN O.D. (HOURS)                .100
  AVERAGE TIME STOPPED BY ROAD EQUIPMENT IN N.O.D. (HOURS)              .100
  AVERAGE APPROACH SPEED TO THE OVERLAY ZONE (MPH)                      50.0
  AVERAGE SPEED THROUGH OVERLAY ZONE IN O.D. (MPH)                      30.0
  AVERAGE SPEED THROUGH OVERLAY ZONE IN N.O.D. (MPH)                    40.0

  FIRST YEAR COST OF ROUTINE MAINTENANCE (DOLLARS/LANE MILE)            50.0
  INCREMENTAL INCREASE IN MAINT. COST PER YEAR (DOLLARS/LANE MILE)      20.0
  COST OF A SEAL COAT (DOLLARS/LANE MILE)                              857.0
  WIDTH OF EACH LANE (FEET)                                             12.0
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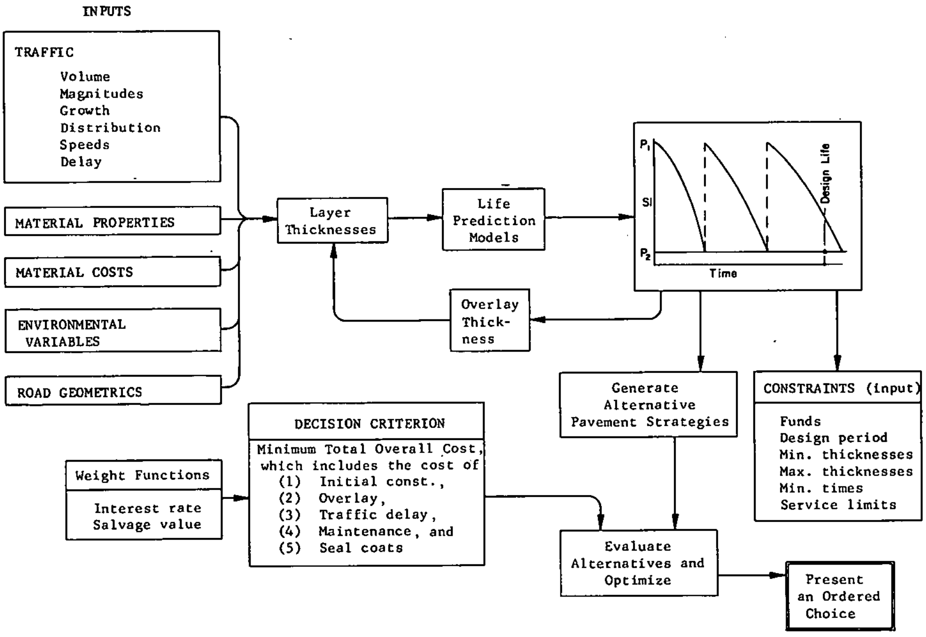
Figure 4. Structure of working pavement design system.



For initial designs, all possible combinations of the thicknesses of materials are generated, starting with the minimum values and progressing to the maximum ones. When these combinations are considered for different sets of available materials, such as cement concretes, asphaltic concretes, and bases and subbases, a large number of initial designs are produced, each of which is considered and analyzed separately. Each initial design thus produced is subjected to restraints specified by the designer. Some of the important ones are (a) maximum total thickness of initial construction, (b) minimum time to the first overlay after initial construction, and (c) maximum cost of initial construction. If an initial design does not satisfy any one of these three restraints, it is rejected. The designs that do meet these restrictions are considered to be feasible initial designs and are analyzed further. For the rigid pavement system, reinforcement and joint spacings are computed for each of the initial designs.

An initial design that does not last the analysis period but meets all other feasibility requirements is overlaid. The types of overlay provided are flexible over flexible pavements, flexible over rigid pavements, and rigid over rigid pavements. Minimum thickness of the overlay and maximum combined thickness of all overlays are specified by the program user. If a strategy requires its next overlay before the minimum specified time between overlays, it is abandoned. Figure 5 shows how the restraints are applied for the initial designs. Figure 6 shows the techniques built into PDS programs for ascertaining general overlay performance patterns but does not represent an actual problem. The relative differences in the performance patterns of initial designs with low, medium, and high structural strengths indicate that there can be numerous overlay policies for an initial design.

The cost of materials, construction, and maintenance is computed for each successful strategy that meets, along with other constraints, the requirement of lasting for the desired service life. Various costs computed for the pavement design system are as follows (cost computations for FPS and RPS are slightly different because of their structural requirements): subgrade preparation; subbases, bases, surfaces, reinforcements, joints, and tie bars; initial construction; overlay construction; traffic delay during overlay construction; maintenance; seal coat; salvage value; and design per square yard of the pavement.

All costs to be incurred in the future are discounted to their present values by using the interest rate specified by the designer. Overlay, traffic delay during overlay construction, and seal coat costs are the sums of all such costs incurred during the service life discounted separately from the time that they are incurred. Maintenance cost is the sum of each year's separately discounted maintenance cost. Salvage returns are discounted from the end of the service life.

Computer storage is a considerable problem in pavement design systems. The programs are designed to consider a large number of initial designs and overlay strategies. The large volume of pertinent information accompanying every strategy makes it necessary at times to store large arrays of data.

Scanning and optimization are time-consuming operations of the PDS solution process. Various optimization techniques have been used in different versions of FPS and RPS to optimize for the best strategies. Linear programming has been utilized in certain cases. For some versions of PDS, a bruteforce method of analysis has shown good results as compared to more advanced techniques of analysis. At present optimization is carried out with respect to costs of the strategies, but in the future other decision criteria will also be built into PDS programs.

The information that the designer must have to investigate a variety of pavement strategies is printed as an output at the end of the problem analysis. A summary table giving as many nearly optimal strategies as specified by the designer is printed. These strategies are printed in the increasing order of total overall cost. This output is the result of optimization carried out among all the designs of every possible and feasible combination tried, including the designs that do not need overlays. The first design of the summary table is therefore the most economical design possible for the given input. Figure 7 shows an example summary table for the rigid pavement system program.

Figure 5. Application of restraints to initial designs.

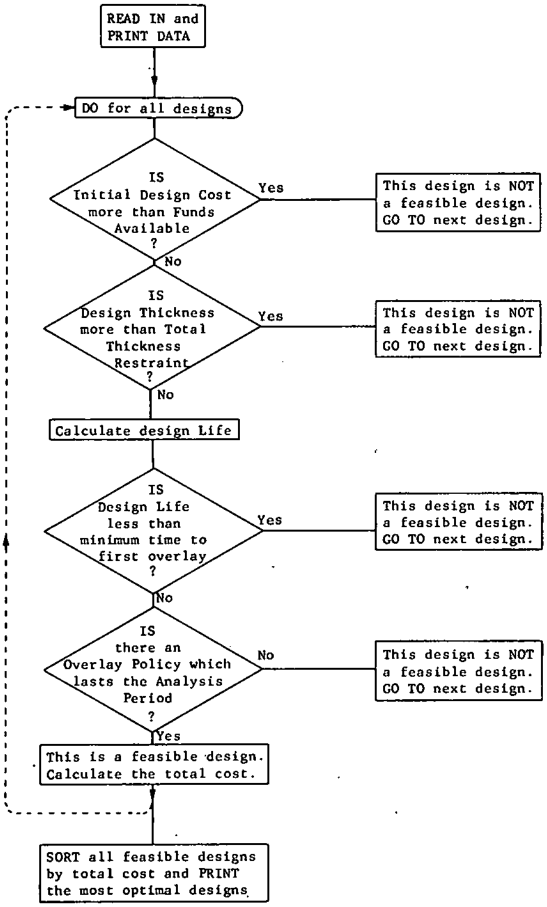
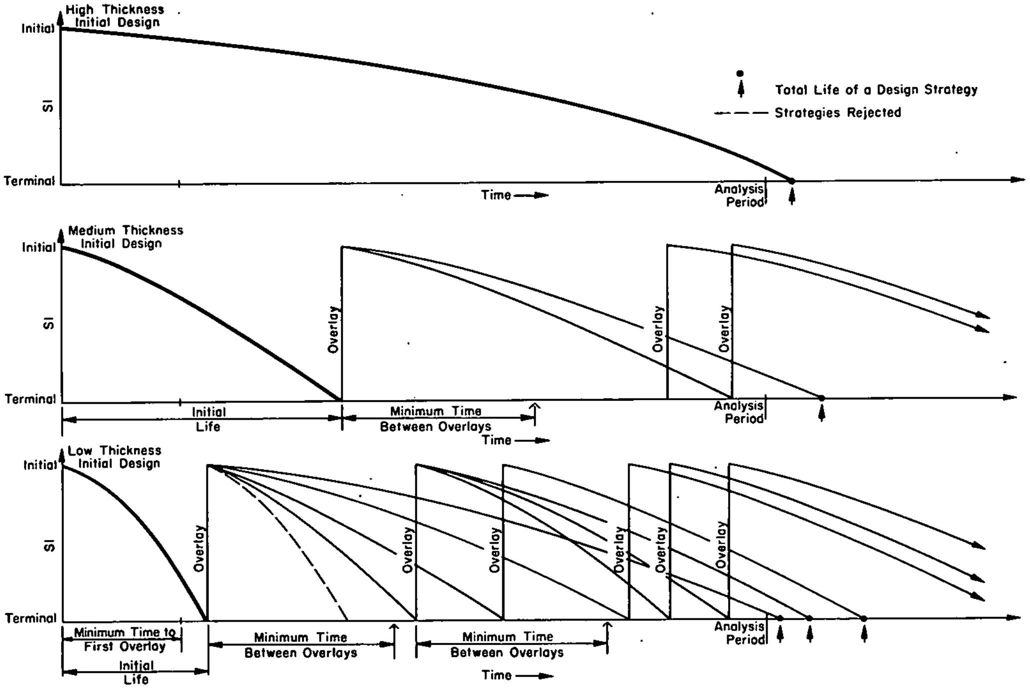


Figure 6. General performance patterns for different initial designs.



Systems Analysis of Example Problems

Nine example design problems were solved by using the flexible pavement system computer program (FPS2) given in Table 1. One is the basic example problem, and the other eight are variations obtained by holding all the variable values, except one, constant. The basic example problem was solved for the inputs shown in Figure 3. These input values are the average values for parameters that will generally be met in practice under average design conditions. Three designs were obtained as output for the basic problem and for each of the other eight problems. The first design for every problem is the optimal design for the input used. Table 1 gives the changes in variables and values and the optimal costs for each problem.

The designs have two or three layers for initial construction and one or two subsequent overlays. Each overlay requires 0.5 in. of a leveling course in addition to the overlay thickness. The number of seal coats varies from one to three. The number of feasible designs considered varies from 1 to 185. The optimal cost of initial construction for these problems varies from $1.4 to $3.1 per sq yd of pavement. The optimal design is higher for each of the example problems than for the average problem. This is as expected because each of the variations represents a stricter design condition than the average problem.

FEEDBACK DATA STORAGE AND RETRIEVAL SYSTEM

An important characteristic of an automated pavement management system is that it can continually be evaluated and updated, that is, improved by having needed changes made in the models. This iterative improvement pattern is shown in Figures 8 and 9. An important key to this improvement is the collection, processing, storage, retrieval, and analysis of appropriate data and information about the system.

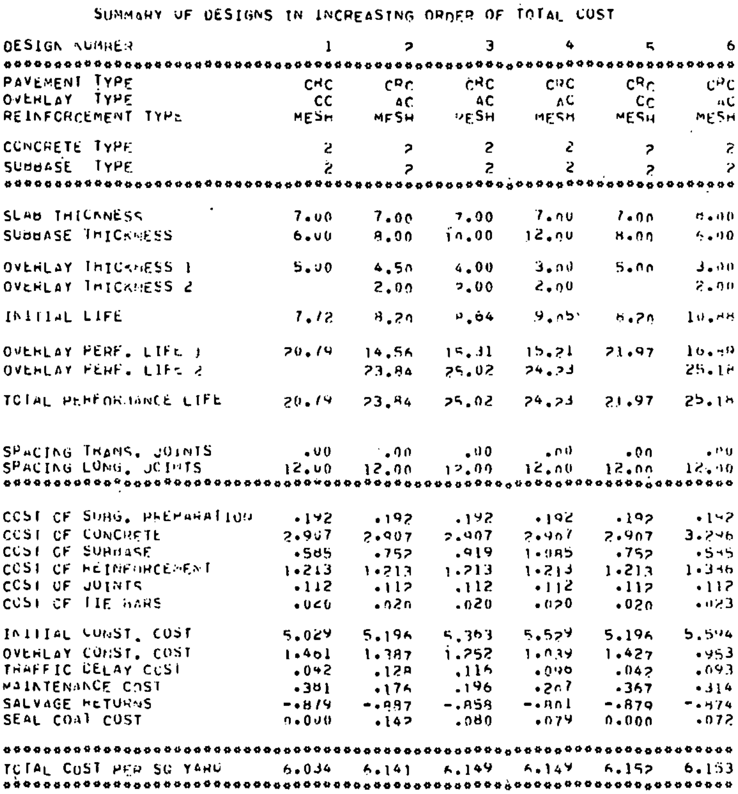
Too often in the past, pavement design has depended on manual records or general information on plan sheets several years old. Research at the Texas Transportation Institute on this problem has shown that many errors can creep into randomly kept data. The only way these data can be adequately and efficiently processed, stored, retrieved, analyzed, and used to update models is with the computer. Such a feedback-data system must be designed to include a sampling of information on every pavement of interest at each significant time step in the life of the pavement and at each major interval in the life cycle of the pavement (system correction), such as an overlay or a seal coat. A sampling unit for such a data system must be developed so that significant changes in any of the variables in the pavement management models can be adequately assessed. Because approximately 100 variables are being considered, the data storage problem can be quite large.

Design of System

In designing any such data storage system, the pavement engineer tends to make it far too complex and broad because he is "storing all possible combinations of all possible data." This immediately overloads the system with extraneous information and makes it extremely difficult to sort out the valuable data that are available. On the other hand, a simple system designed for easy use may omit the important variables involved and thus provide data that are grossly inadequate for updating models and providing maintenance management and planning and programming information. The obvious answer to this problem is to involve both the pavement design engineer and the information systems designer in a team effort to develop a proper data storage system. This approach has been used by the authors.

Figure 10 shows various kinds of data storage systems that can be used, but only a system in category 4 or 5 can handle the job of pavement management. The concept of a pavement data bank is shown in Figure 11. The general functional format of the pavement feedback-data system used in this project is shown in Figure 12. The major uses of the computer for the supplier and the user of the data are (a) processing input data, (b) updating files with new data, (c) processing output data requests, and (d) retrieving data from the data bank and other data files. The general operating plan of the computer-based data system used for this research project is shown in Figure 13.

Figure 7. Nearly optimal designs for rigid pavement design problem.



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          SUMMARY OF DESIGNS IN INCREASING ORDER OF TOTAL COST

DESIGN NUMBER                   1       2       3       4       5       6
*************************************************************************
PAVEMENT TYPE                 CRC     CRC     CRC     CRC     CRC     CRC
OVERLAY  TYPE                  CC      AC      AC      AC      CC      AC
REINFORCEMENT TYPE           MESH    MESH    MESH    MESH    MESH    MESH

CONCRETE TYPE                   2       2       2       2       2       2
SUBBASE  TYPE                   2       2       2       2       2       2
*************************************************************************

SLAB THICKNESS               7.00    7.00    7.00    7.00    7.00    8.00
SUBBASE THICKNESS            6.00    8.00   10.00   12.00    8.00    6.00

OVERLAY THICKNESS 1          5.00    4.50    4.00    3.00    5.00    3.00
OVERLAY THICKNESS 2                  2.00    2.00    2.00            2.00

INITIAL LIFE                 7.72    8.20    8.64    9.05    8.20   10.88

OVERLAY PERF. LIFE 1        20.79   14.56   15.31   15.21   21.97   16.40
OVERLAY PERF. LIFE 2                23.84   25.02   24.23           25.18

TOTAL PERFORMANCE LIFE      20.79   23.84   25.02   24.23   21.97   25.18


SPACING TRANS. JOINTS         .00     .00     .00     .00     .00     .00
SPACING LONG. JOINTS        12.00   12.00   12.00   12.00   12.00   12.00
*************************************************************************

COST OF SUBG. PREPARATION    .192    .192    .192    .192    .192    .192
COST OF CONCRETE            2.907   2.907   2.907   2.907   2.907   3.296
COST OF SUBBASE              .585    .752    .919   1.085    .752    .585
COST OF REINFORCEMENT       1.213   1.213   1.213   1.213   1.213   1.346
COST OF JOINTS               .112    .112    .112    .112    .112    .112
COST OF TIE BARS             .020    .020    .020    .020    .020    .023

INITIAL CONST. COST         5.029   5.196   5.363   5.529   5.196   5.594
OVERLAY CONST. COST         1.401   1.387   1.252   1.039   1.427    .953
TRAFFIC DELAY COST           .042    .128    .116    .096    .042    .093
MAINTENANCE COST             .381    .176    .196    .207    .367    .314
SALVAGE RETURNS             -.879   -.897   -.858   -.801   -.879   -.874
SEAL COAT COST              0.000    .142    .080    .079   0.000    .072

*************************************************************************
TOTAL COST PER SQ YARD      6.034   6.141   6.149   6.149   6.152   6.153
*************************************************************************
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Table 1. Summary of example problems solved by using FPS 2 computer program.

Design Problem	Variable Change	Value Change		Feasible Designs Considered	Optimal Cost ($/yd^2)	
		Average	Variation		Total	Initial Construction
1	None (average)			185	2.051	1.451
2	Higher swelling clay effect	0.10	0.24	19	3.318	3.134
3	Higher 18-kip axles	4 × 10^6	10 × 10^6	162	2.233	1.604
4	Lower initial serviceability index	4.2	3.8	176	2.136	1.554
5	Higher cost of surface	$10/yd^3	$15/yd^3	168	2.342	1.763
6	Lower subgrade strength coefficient	0.25	0.15	36	3.045	2.604
7	Longer time to first overlay	5 years	11 years	81	2.641	2.314
8	Higher average daily traffic	10,000-20,000	25,000-50,000	185	14.942	1.624
9	Fewer funds available for initial construction	$4/yd^2	$1.4/yd^2	1	2.092	1.381

Table 2. Schedule of expenditures required for construction and engineering on given highway systems.

Project	Year x_1	Year x_2	Year x_3	Year x_4	Year x_5		Year x_j
001	a_1	b_1	c_1	d_1	e_1	...	z_1
002	a_2	b_2	c_2	d_2	e_2	...	z_2
003	a_3	b_3	c_3	d_3	e_3	...	z_3
004	a_4	b_4	c_4	d_4	e_4	...	z_4
005	a_5	b_5	c_5	d_5	e_5	...	z_5
006	a_6	b_6	c_6	d_6	e_6	...	z_6
⋮	⋮	⋮	⋮	⋮	⋮		⋮
n	a_n	b_n	c_n	d_n	e_n	...	z_n
Total	$\sum_{i=1}^{n} a_i$	$\sum_{i=1}^{n} b_i$	$\sum_{i=1}^{n} c_i$	$\sum_{i=1}^{n} d_i$	$\sum_{i=1}^{n} e_i$		$\sum_{i=1}^{n} z_i$

Note: Expenditures include initial construction, overlays, seal coats, and routine maintenance.

Figure 8. Iterative improvement pattern of pavement design and management system.

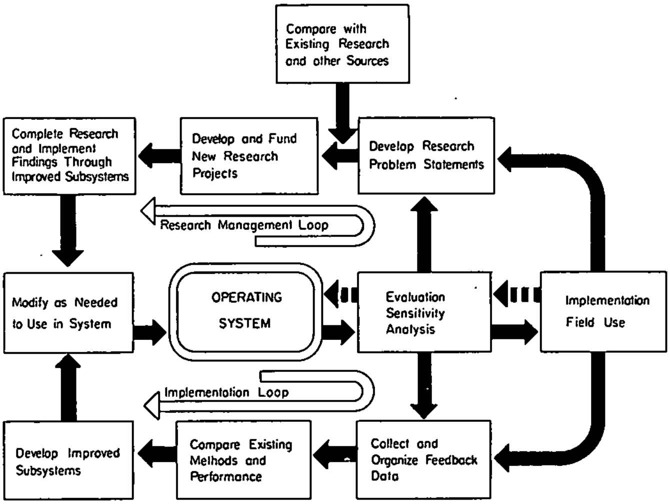


Figure 9. Staged improvements of pavement design and management system.

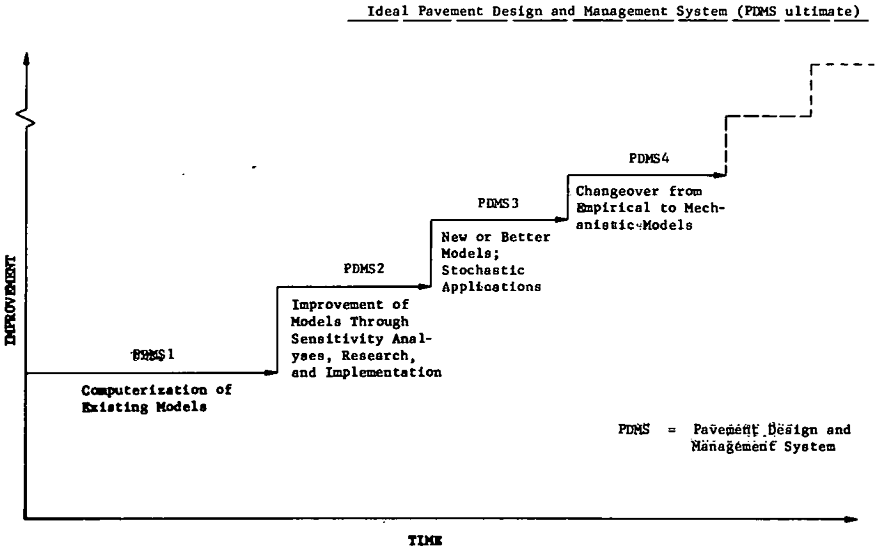


Figure 10. Types of available data storage systems in order of increasing capability.

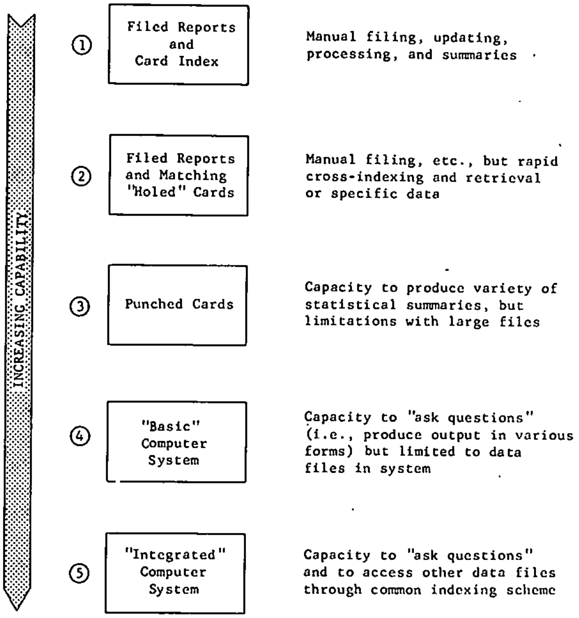


Figure 11. Inputs to pavement data bank.

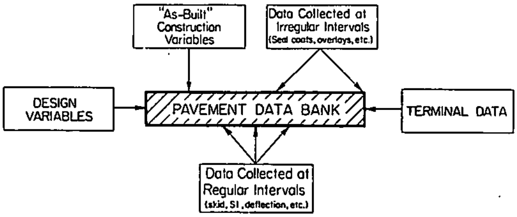


Figure 12. General functional format for pavement feedback-data system.

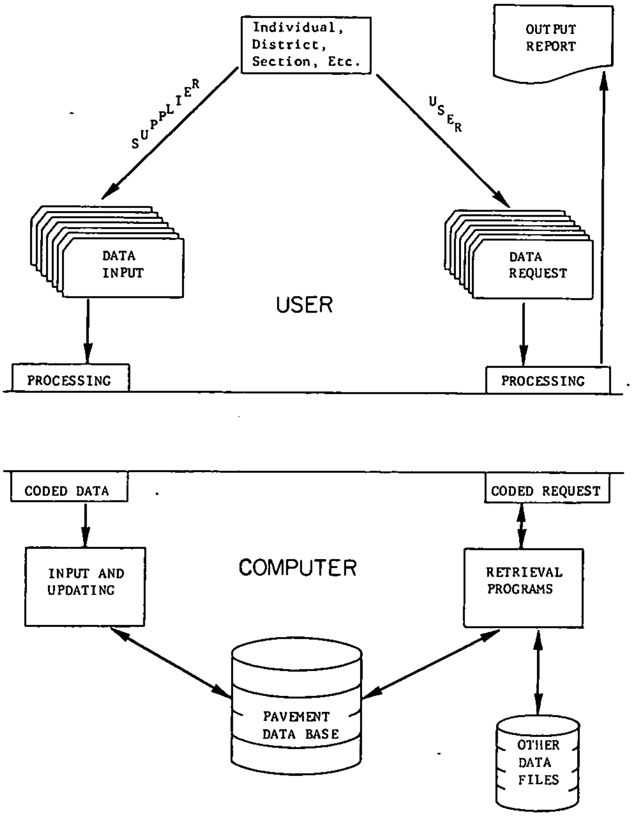


Figure 13. General operating plan of integrated, computer-based, feedback, pavement data system.

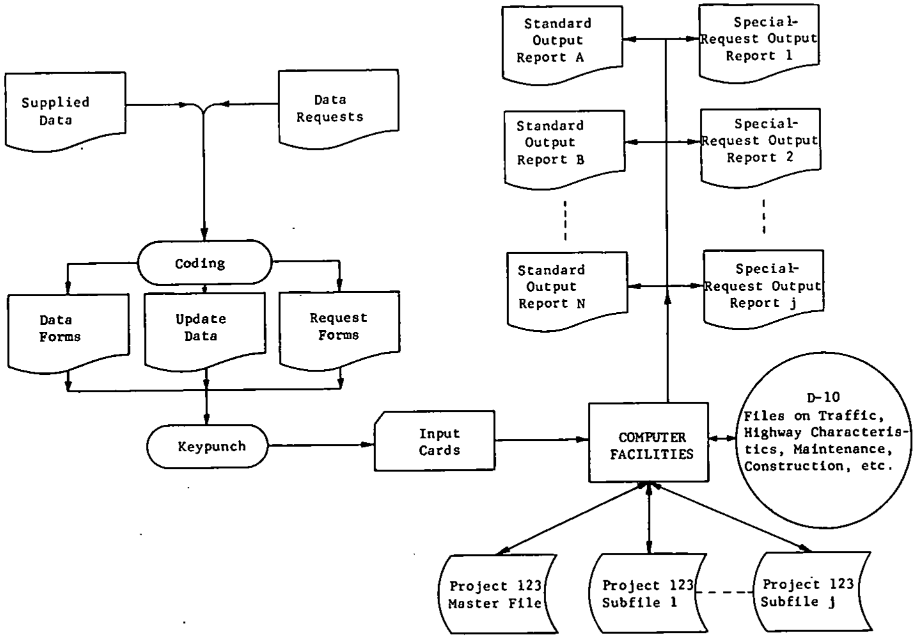


Figure 14. Computer plots of projected and observed histories.

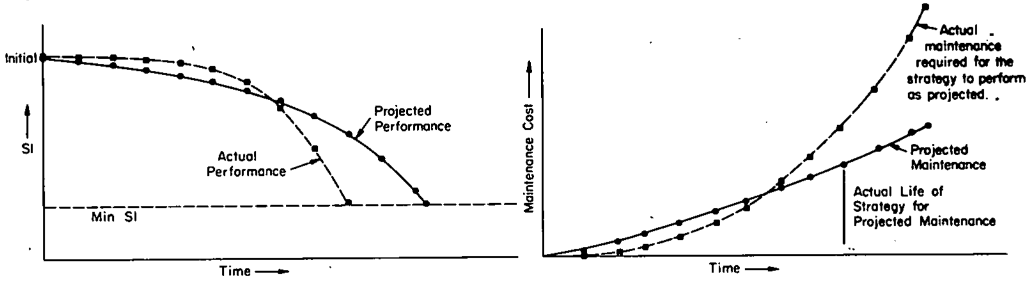
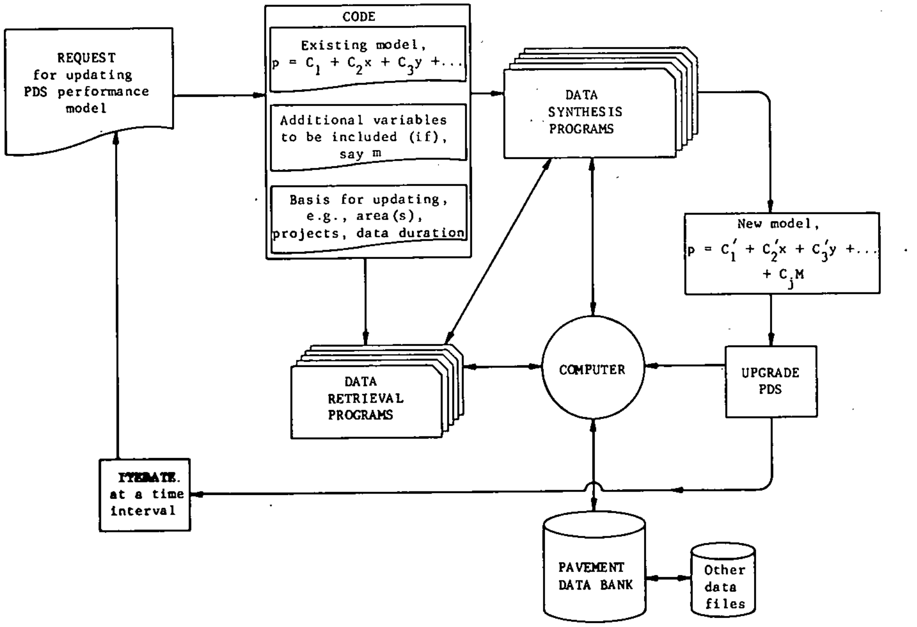


Figure 15. Format for upgrading PDS model using feedback-data system.



Uses of Feedback-Data System

The storage and retrieval of data for the administrator's use constitute one important function of a pavement feedback-data system, but it is not the prime function to a researcher. That function is to provide a useful feedback capability for improving and upgrading the existing pavement design technology. The computer operations necessary to achieve these functions are as follows:

1. Provide input data for the design of new projects;
2. Provide the administrator with data and information on trends applicable to programming and planning;
3. Evaluate the validity of the existing design subsystem models; and
4. Improve PDS models by analyzing the deviations in performance and economic histories.

Figure 14 shows the use of a data system to evaluate models by using computer graphics to plot deviations in predicted histories. Such information is extremely important to a system designer in determining the behavior of his formulated models. Figure 15 shows a functional format for a computer operation that the system designer can use to improve and update PDS subsystem models.

MANAGEMENT AND FINANCIAL PLANNING

Another important characteristic of an automated pavement system is that it allows the projected performance characteristics of the pavement to be used to predict future financial needs and manpower requirements. Too often, expenditures have been based on immediate needs, and there has been little opportunity to establish long-range plans. Thus, there may be no funds for upgrading when a pavement deteriorates below an acceptable riding quality; and it may deteriorate to such an extent that, when funds are available, excessive expenditures are required to regain an acceptable performance level. Also, in some years funds insufficient to meet current needs, and in other years they may be available for a facility that does not yet require upgrading. Thus, optimizing the expenditure of available funds is important, and the ability of an automated pavement management system to do so is highly valuable.

Management

When an engineer using an automated pavement system selects a design, he can refer to a chart, such as the one shown in Figure 16, to find when an overlay and seal coat will be required. The items are laid out on a time scale that gives the highway administrator a schedule of work that will be required for a given section of pavement on a highway system. Based on the actual performance of the pavement, the schedule of work items predicted at the time of initial design can be updated through the use of the feedback-data system previously discussed, as shown by the dashed lines in Figure 16. Thus, the schedule can reflect the most accurate information available at any given time.

Figure 17, an extension of Figure 16, shows the same type of schedule for more than one project. The schedule includes all the sections of a roadway or the total system for a district or for a state, depending on the accounting system being used. The use of such a diagram as that shown Figure 17 allows the district or state highway engineer to plan the engineering manpower needs for design, construction supervision, and maintenance for a period of 15 or 20 years. If an unusual amount of manpower will be required in a given year, plans to upgrade a given section of road can be made ahead of time to give a more orderly distribution of available manpower and thereby avoid overstaffing during peak periods.

Financial Planning

The engineer can use information such as that shown in Figures 16 and 17 to develop the expenditure requirements for each year of the time period being considered for future planning. An example is given in Table 2, which summarizes the construction cost and the engineering and design cost required through j-years for each section of

Figure 16. Schedule of work for a given project.

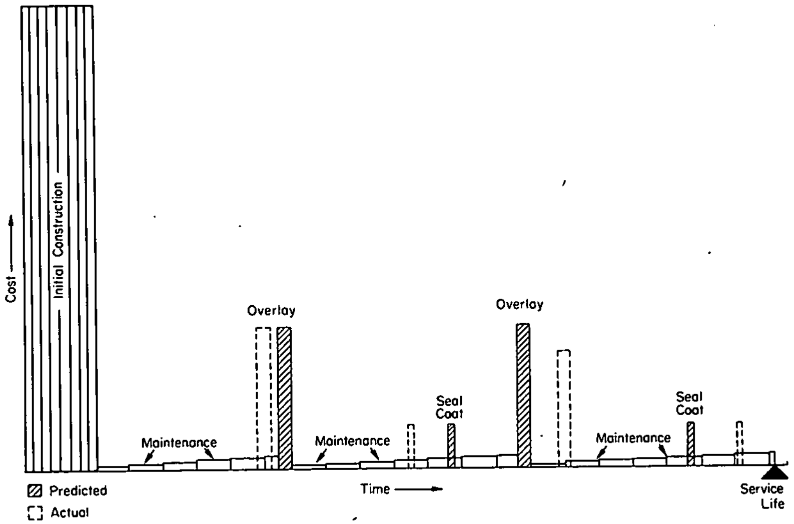
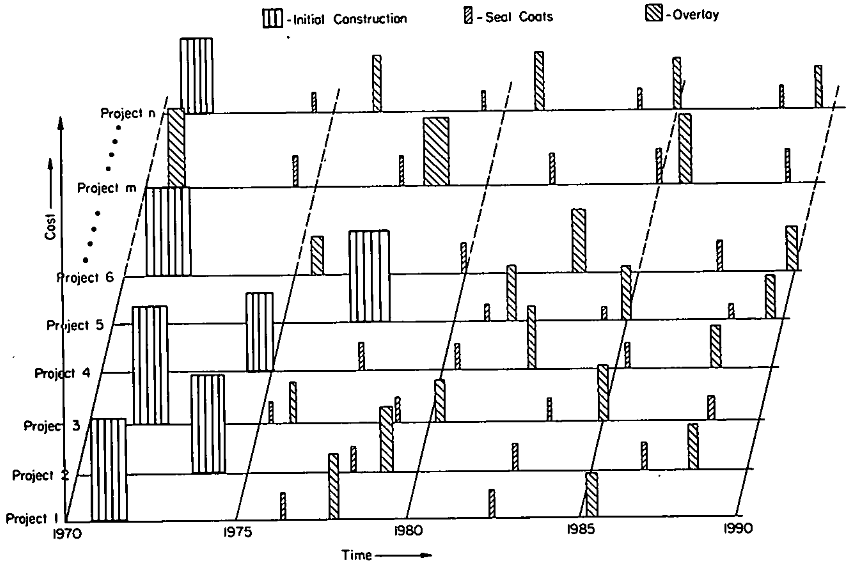


Figure 17. Schedule of work for a highway district or unit.



a project. The costs for a period of time for all the sections can be summed to give the total cost for a given period of time. If the feedback-data system shows differences between the actual performance and the predicted performance, these costs can be changed on a yearly basis. The highest degree of reliability is developed by updating the table each year.

It is apparent that an automated pavement design system is a new tool with which the highway engineer and administrator can reliably predict expenditures required for a highway system for any future period of time. As presented in this paper, a greatly expanded use of available theory and analytical techniques can be achieved by the efficient use of computer speed and storage. Therefore, it is possible to analyze the complex problems of pavement design and management systems. Automation assists in decision-making by selecting favorable alternatives based on various restraints and decision criteria. It helps modify and improve existing design models by storing large amounts of feedback data, and it provides mechanisms for managing future manpower and economic schemes for the administrator.

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