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REFERENCES

1. K. Godfrey. Heavy Trucks: How Much Damage to Pavements? Civil Engineering, Nov. 1979.
2. R. Hicks, R. Layton, and S. Glover. An Evaluation of Increased Truck Size and Weight on Pavement Life and Design Thickness. Department of Civil Engineering, Oregon State Univ., Corvallis, 1978.
3. J. Havens, H. Southgate, and R. Deen. Fatigue Damage to Flexible Pavements Under Heavy Loads. Bureau of Highways, Kentucky Department of Transportation, Frankfort, 1979.
4. J. Hardcastle and R. Lottman. A Rational Method for Establishing Spring-Thaw Load Limits on Idaho Highways. Department of Civil Engineering, Univ. of Idaho, Moscow, 1978.
5. F.H. Scrivner and others. Detecting Seasonal Changes in Load-Carrying Capabilities of Flexible Pavements. NCHRP, Rept. 76, 1969.
6. W. Phang. Flexible Pavement Design in Ontario. Engineering Research and Development Branch, Ontario Ministry of Transportation and Communications, Downsview, 1974.
7. R. McHattie, B. Connor, and D. Esch. Pavement Structure Evaluation of Alaskan Highways. Alaska Department of Transportation and Public Facilities, Fairbanks, Research Section Rept., 1980.

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State-Level Pavement Monitoring Program

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A long-term pavement monitoring program consists of the identification of specific data elements to collect, their measurement (including equipment), the sampling frequency both over time and within a pavement network and project, the efficient storage and retrieval of large amounts of data, its analysis and evaluation, and the use of the data in daily policy-level decisions and project programming. This paper describes (a) data needs for state-level management, planning, and design functions; (b) temporary data-collection activities by various states; (c) sampling strategies and data-processing strategies; and (d) key issues and problems to be considered in planning a long-term monitoring program.

There are three levels of pavement data monitoring. They correspond to three principal activities in the process of managing a state pavement network. State program management is concerned with overall planning, budgeting, and the equitable distribution of funding to political subdivisions of the state. It also includes special case studies and research needs, such as for cost allocation and improvement of design procedures. State project programming is concerned with selecting specific projects for an annual maintenance and rehabilitation program as well as for development of a projected future work plan. Project design is concerned with selecting the proper materials, layer thicknesses, and treatments for a specific project. Because the latter activity occurs on a project-by-project basis, it is not usually considered as part of a state's long-term monitoring program and will not be considered further here.

Long-term pavement data monitoring serves several important functions in state program management:

1. It provides current information on pavement condition and documents performance history on all functional systems for administrative, planning, operational, and research purposes.
2. It provides data for the projection of future funding requirements for various possible scenarios, including (a) keeping the pavement network in its current condition, (b) improving the condition of pavements on selected road networks, (c) determining the impact on network condition of a budget cut, and (d) keeping the pavement network condition stable in the event of changes in legal sizes and weights of trucks.
3. It provides accurate information to the legislature on current pavement conditions, costs, and accidents.
4. It provides information for the equitable allocation of funds to all subdivisions of the state weighted by the traffic, functional class, and occasionally the economic impact of specific road networks such as those used for hauling important products and commodities.
5. It provides information for a variety of special needs, such as studies of cost allocation or truck weight, requests from the public, state and national research projects, and data for use on the national level by the Federal Highway Administration (FHWA).

Long-term data monitoring assists in project programming in the following ways:

1. The determination of current condition and other information about specific sections of pavement to allow prioritization of and estimation of costs for required maintenance or rehabilitation and
2. The collection of condition and other data on a sufficient number of randomly sampled sections of pavement to provide the estimates and special studies that are required for state program management.

These multiple uses of a monitoring system require several types of information to be gathered and to be updated frequently. The data need to be gathered efficiently, by using sampling techniques both in time and along the length of various functional classes of highways. The purpose of sampling is to reduce to a minimum the effort that is required to collect the data. Although sampling is an essential element of a long-term monitoring program, the method of sampling must be dictated by the purposes for which the data will be used (as discussed later in this paper). In all cases, the data must be collected by reliable methods, a large number of which are currently in use in a number of states. The data must be efficiently processed, analyzed, and stored so as to be easily accessible for the variety of purposes for which they will be used.

DATA NEEDS FOR STATE PROGRAM MANAGEMENT

In general, the following types of data will be required for state program management:

1. Definition of the highway system, including designations of the functional classes of highways, a division of the highway network into standard uniform sections, and a determination of the mileage, age, surface type, and pavement depth distributions within each functional class and other subdivisions (districts, counties, etc.);
2. Traffic and capacity information, including the distribution of average daily traffic, 18-kip equivalent single-axle loads (ESALs), and volume/capacity (V/C) ratios for each functional class of highway;
3. Climatic variables, including moisture and temperature data;
4. Surface condition data, primarily the distribution of skid number by functional class;
5. General accident rates from existing accident record systems;
6. Past histories on accident rates, inflation rates, cost indexes, and unit cost distributions of maintenance and rehabilitation; and
7. Pavement condition rating distributions by functional class, including riding quality [or present serviceability index (PSI)] and significant distress types (including composite distress index).

The distributions of data should include a mean, a standard deviation, and the type of distribution (normal, lognormal, Beta, Poisson, etc.). This statistical information can be determined by evaluation of results by a suitable sampling scheme.

Special studies may require that additional detailed information be collected on a selected sample of test sections. These special studies may include the development of damage models for cost-allocation needs, pavement design improvement, impact of quality control on pavement performance, and other research needs. The development of special relations using multiple regression analysis is discussed in a report by Rauhut and others (1).

DATA NEEDS FOR PROJECT PROGRAMMING

Most of the same categories of information must be gathered for the purpose of project programming. However, the data must be collected on specific sections of pavement rather than on a random sampling among sections. When this specific information is stored and retrieved in a data base management system, it should remain identified by the pavement section from which it came.

The types of data needed for project programming include the following:

1. Definitions of the network by uniform sections of similar design, which should be categorized by functional class and traffic level;
2. Traffic and capacity information;
3. Skid condition data;
4. Accident rate history;
5. Pavement condition, including riding quality (or PSI) and distress; and
6. Average annual pavement maintenance expenditure.

Data items 2-6 must be updated periodically. An overall summary of these data, their level of importance, and sampling frequency is given in Table 1. The frequency of updating varies from item to item and also among pavement sections. Factors affecting the frequency include rate of change in the item, allowable maximum interval between observations, and allowable minimum value.

SYNTHESIS OF CURRENT DATA-COLLECTION MONITORING PROGRAMS

Distress

Distress monitoring includes distress type, severity, and amount. Significant distress types for flexible pavements include rutting, alligator cracking, transverse and longitudinal cracking, block cracking, potholes, bleeding, raveling and weathering, and swells and depressions. Significant distress types for rigid pavements include: slab cracking, D-cracking and reactive aggregate deterioration, pumping, joint deterioration, and blowups. Several states have developed distress identification guidelines; however, a standard distress rating manual should be used throughout the states to achieve consistency. The FHWA Highway Pavement Distress Identification Manual (2) is recommended for this purpose.

Distress is currently monitored by several states for state-level program studies, project programming, and project design. The State of Washington performs distress condition surveys on a portion of every highway section once every two years. The distress data are then used to arrive at a structural rating (3). The State of California also monitors selected distress on each highway section once every two years (4). The entire length of highway is surveyed and the data are used to determine the extent of structural damage (percentage of shattered slabs and percentage of fatigue alligator cracking). Each section of highway in Ontario is rated at least once every three years, utilizing distress identification manuals but more frequently as rehabilitation becomes imminent (5,6).

The State of Florida procedure for flexible pavements is based on selecting and surveying a typical 100-ft-long by one-lane-wide section as a representative sample of the total pavement section evaluated (7). Only three distress types are recorded: rutting, cracking, and patching. For concrete pavements, a rating team measures and records pavement distresses while driving at a reduced speed. The rating team, however, is required to stop the vehicle at a representative location of the rated section and determine the summation of faulting for five consecutive slabs (7).

A comprehensive distress survey procedure and distress identification manual was developed under NCHRP Project 1-19 (8) for plain jointed, reinforced jointed, and continuously reinforced concrete pavements (similar to the FHWA Manual for concrete pavements). A survey crew of two or three persons can survey a 2-lane-mile section in 0.5-1 h, depending on the amount of distress. A few distress types (such as swells and depressions and shattered slabs) are recorded along the entire project, but most are sampled in 0.1-mile sections randomly located within every mile. The data are recorded on specially prepared sheets that are coded for immediate keypunching and entering into a computerized data base.

The U.S. Army Corps of Engineers procedure

Table 1. Summary of data that should be collected for programming and project prioritization.

General Data Item	Level of Importance	Sampling Frequency (years)	Relative Cost Level
Description of pavement	Normal	-[a]	Low
Traffic volume	Normal	2-3	Medium
Traffic loadings	Normal	2-3	High
Skid resistance	High	3-5	Medium
Accident rates	High	2-4	Medium
Distress	High	1-4	Medium
Roughness and serviceability	High	1-4	Medium
Maintenance costs	Normal	1-2	High
Rehabilitation costs	Normal	1-2	Low

[a]Initial and after major work.

considers all distress types and uses a comprehensive distress identification manual (9). Each pavement section is divided into sample units (about 100-200 ft long). The number of sample units to be inspected in each section is a function of the objective of the survey and the desired level of reliability (10).

Distress has been traditionally measured manually by traveling slowly along the pavement. New photographic equipment now provides for rapid (40-mph) recording of all visible distress within a 12-ft-wide lane on a strip photo and also rut depth and cross slope. The automated photographic system has significant advantages over the manual surveys, including cost, speed, and safety.

Roughness and Serviceability Index

Roughness is defined as irregularities in the pavement surface that adversely affect ride quality, safety, and vehicle maintenance costs. The PSI is highly dependent on roughness. It is computed directly from roughness data by several states.

There are several different indicators of roughness, including (a) the roughness index (sum of vertical deviations of surface or car body), (b) wavelength-amplitude characteristics (actual profile measurement), (c) slope variance, (d) vertical acceleration, and (e) subjective rating by a panel.

Roughness is generally considered a very significant parameter for state-level program management and state-level project programming. It is also of value at the project design level in determining the most cost-effective repair method.

A number of mechanical and electronic devices are used by states to measure roughness. Long-term monitoring requires that the measurement equipment be stable over many years. Several of these devices, particularly the car ride meters, change in roughness output over time as the car suspension system changes. Either careful year-to-year calibration procedures must be developed, or a device that measures the actual profile must be used.

Roughness data in California are measured with a car ride meter of the Portland Cement Association (PCA) type in order to identify when pavement corrective work should be undertaken to improve rideability (4). Critical levels of roughness were determined by use of rating panels. Raters were asked to judge whether the pavement provided a satisfactory ride or was so rough that it should be improved. A critical ride score was selected to identify those locations that should be considered for ride quality improvements. The ride score is computed separately for sections of pavement approximately 1 mile in length (this may vary from as short as 0.1 mile to more than 1 mile) and for bridge approach ride quality (approximately 100 ft approaching and leaving bridge ends). Roughness measurements are taken on every section of highway (essentially every mile) every two years.

Texas uses roughness to calculate a PSI. Mays ride meters are located in each district and periodically run on pavement sections. The Mays meters are brought back to headquarters often, where they are run over a set of test sections for calibration. The General Motors (GM) Profilometer is used to measure the roughness on the calibration test sections periodically to ensure that they do not change. Functional relations have been developed between the profile measured with the GM Profilometer and a large panel of raters. This approach is felt to be an excellent method of obtaining uniform roughness data over the long term.

Minnesota develops an annual calibration or correlation between the PCA-type ride meters and a large panel rating. A potential problem with the approach is that the panel ratings may vary from year to year.

Surface Skid Condition

Skid resistance is usually determined based on the friction coefficient between the vehicle tires and the pavement surface. Methods for measuring the friction coefficient include trailers with locked wheels, trailers with unlocked wheels making a yaw angle with the direction of travel, trailers with rolling wheels in the slip mode, portable field instruments, and laboratory equipment. The locked-wheel trailer, which complies with American Society for Testing and Materials (ASTM) standards, is the method most commonly used by the states. Values are measured in terms of skid numbers (SN), which are measured at 40 mph or converted to equivalent 40-mph values and designated SN(40).

The State of California is using the locked-wheel-trailer method and has established procedures for a continuing skid-testing program. The frequency of the skid tests is such that all Interstate highways are tested each year, other freeways and expressways are tested every two years, and all other state highways are tested every four years.

Deflection

Pavement response to loading (or deflection) is routinely used by many states to assess the structural adequacy of pavements. The following general deflection devices are in use by states (11): (a) static deflection (e.g., Benkelman beam), (b) vibratory steady-state force (e.g., Dynaflect, Road-rater), and (c) impulse (e.g., Falling Weight Deflectometer). Deflection results are most commonly used at the project design level and not often used at the state monitoring level. However, special studies for cost allocation or design verification may require deflection testing on selected sections over various seasons throughout the year.

Distress Composite Index

A meaningful pavement condition index (PCI) can be obtained by combining the effect of the individual distress types into a composite index. The index provides several uses at all three levels: program management, project programming, and project design. These uses include overall pavement condition rating, determination of needed level of maintenance and rehabilitation, project prioritization, performance modeling, computation of benefits for various repair alternatives, and budget optimization. The advantage of a distress composite index is that it indirectly combines in one number the weighted effects of important pavement condition indicators such as roughness, skid, and structural integrity. Such an index has been developed in various forms and implemented by states and agencies, including Washington, Texas, Florida, the U.S. Air Force, and the U.S. Army (3,5-7,10,12). For example, the PCI developed by the U.S. Army Construction Engineering Research Laboratory (CERL) (10) provides that the distress and level of severity be carefully and accurately defined to reduce field subjectivity. The distress deduct values are developed so that the computed PCI represents the collective judgment of experienced pavement engineers. This adds to the meaning and usefulness of the index.

Traffic

Four types of traffic data are required for long-term pavement monitoring:

1. Volume data for the 13 standard vehicle categories are typically provided by states as average annual daily traffic (AADT) and average annual daily commercial truck traffic (AADTT), including a breakdown into the basic truck categories (buses; two-axle, six-tire single unit; three-axle combinations, etc.). Typically, states sample the traffic stream annually at key locations along the highway network. These data are published as maps or in summary tables.

2. Lane distribution of trucks is required, but states do not measure or report this information (except as part of a research study). This is a very important data element for use in pavement deterioration studies and must be included.

3. With regard to axle weight distribution of trucks, states typically collect only a minimal amount of data on truck axle load (e.g., one 8-h day per year at weigh stations). These limited data are used to prepare the "W-4 tables". W-4 tables can normally be obtained for a given weigh station or over an average of all stations on a functional classification of highways (e.g., IR, IU) each year. There are typically so few weigh stations available that the axle-load distributions are averaged over an entire functional class of highways. Data from the W-4 tables can be used to compute the mean load distribution factor (or mean 18-kip ESAL per truck). All states submit the required data to FHWA each year. Much improvement in this procedure of estimating axle-load distributions is needed for the long-term monitoring system.

4. V/C ratios are determined by dividing the vehicle count by the capacity computed from the Highway Capacity Manual (12).

Accident Rates

For long-term pavement monitoring, the main emphasis regarding accident rates is to identify locations that have high rates and determine whether pavement condition might be a cause. Most states have well-developed accident reporting system outside the highway department.

Many states have computerized roadway information files that can be matched with reported accident files to develop numbers of reported accidents by numerous roadway and traffic characteristics. This will allow the development of generalized accident rates for both programming and project development. These computerized accident and highway files can also be used to determine numbers of reported accidents by year for specific highway sections. By sampling large numbers of sections that have different pavement characteristics and numbers of accidents, accident rates (by severity) can be related to pavement characteristics. Such statistical studies can be used to provide predictive relations for analyzing the benefits of alternative pavement strategies. In addition to general statistical analyses, computerized accident files that can be matched with highway files can also be used to develop accident histories on each specific section of highway covered by the files. These data on specific sections can be used as inputs in specific pavement programming-level decisions. Data can also be developed for several years on specific accident types such as wet-weather accidents, by severity. Because of the extra burden of incorporating accident reporting into a pavement monitoring system, only accident rates developed from existing accident record systems should be used.

Maintenance and Rehabilitation Costs

The details of systems for recording and reporting maintenance cost vary considerably from state to state. In an NCHRP study reported in 1977 (13), 11 states were surveyed and the following general characteristics were found. All states use automated data storage and reporting of routine maintenance cost information, although none record the lane in which the maintenance was done or the type of pavement (flexible or rigid). States record maintenance activities either by milepost, highway segments of variable length, highway, or district. In order to be useful for project programming, recording by either milepost or highway segment is essential. Any of these levels of reporting are adequate for program management purposes, but even here the more detailed systems are preferable.

Estimates of maintenance costs must be derived from unit costs of the various maintenance activities, the number of which varies between about 40 and 500. The aggregated maintenance costs in 1977 ranged between $1000 and $4500/lane mile or between $10 and $50/vehicle/year. The approximate cost of the recording and reporting of maintenance costs was about 0.5 percent. Table 2 (13) gives more detail on each state surveyed.

The costs of major maintenance, rehabilitation, and other such activities can be obtained more directly from bid summaries or from specific project codes. In any case, average costs are desirable in order to make projected estimates of project and networkwide funding needs.

SAMPLING STRATEGIES

It is essential to have a carefully planned strategy for data collection for each of the two state-level long-term monitoring purposes. The minimum amount of data that is necessary should be collected each year in order to reduce the amount of personnel, equipment, and other resources used in this effort.

When a long-term monitoring program is initiated, there is a need to obtain detailed project programming data on 100 percent of the entire highway

Table 2. Typical state maintenance recording systems in 1977.

State	No. of Maintenance Activities	Location Identified	Maintenance Cost ($) Per Lane Mile	Maintenance Cost ($) Per Vehicle per Year	Percentage of Maintenance Budget for Recording and Reporting
California	470	Milepost	3400	11.40	0.4
Hawaii	36	District	4550	20.90	-
Illinois	49	Highway segment	2100	13.30	0.6
Louisiana	124	Highway segment	2400	41.80	0.4
Minnesota	Many	Highway segment	1800	21.60	0.5
Nevada	72	Milepost	1300	35.50	0.2
North Dakota	63	Highway segment	950	29.30	1.0
Pennsylvania	218	District	2660	29.50	-
Tennessee	71	Numbered highway in county	1600	15.40	-
Washington	373	Highway segment	2400	16.90	0.3
Wyoming	46	Milepost	1160	51.00	0.5

network within a reasonably short period of time, such as two years. This means that approximately one-third or one-half of the network will be sampled in any one year. Once the initial condition of each section of the network is known, future sampling rates can be reduced based partly on numerical studies of sampling patterns and partly on experience, as discussed later. Under any circumstances, the level of effort that can be maintained over the long term will necessarily be controlled by the level of funding and the number of trained personnel available for the survey.

Once the initial condition data are collected, the sampling strategies for the two purposes become different. In general, the number of sections from which state program management data are drawn is considerably smaller than the number of sections needed for project programming. However, the state program management data must be collected in strict accordance with a carefully executed random, stratified, or cluster sampling plan since every effort must be expended to eliminate bias in these samples of data.

Data-Collection Strategies for Program Management

Data collection for program management purposes must be done systematically in accordance with a sampling plan. Careful attention should be applied to the design of the sampling process in order to gain an optimal compromise between the cost of collecting the data and the information gained from the survey.

A brief description and example of some of the available methods of survey sampling follow:

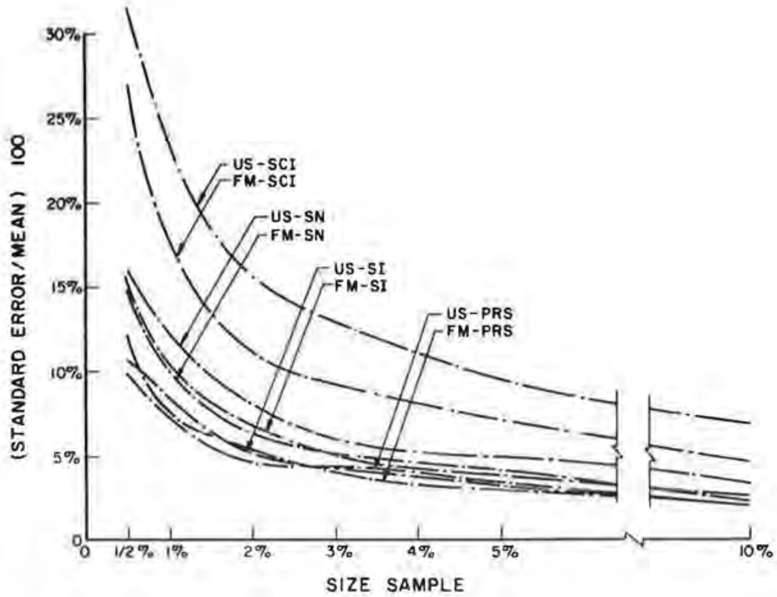
1. Simple random sampling provides that every sample has an equal probability of being chosen from a population. For example, if all highways in a given geographic area were divided into equal lengths (segments), then each highway segment would have an equal choice of being chosen for the required sample size.
2. Stratified random sampling is the sampling process whereby a population is divided into strata and then random samples are obtained within the described strata. For example, if a given state is divided into a number of highway department districts and data estimates were required for each district, then each district could be considered a stratum and individual highway segments could be randomly selected within each district.
3. In one-stage cluster sampling, elements within a population are first grouped together and then the elements are randomly sampled. For example, if data estimates are required for a state, counties could be randomly selected throughout the state. Within each selected county, all highway segments would be sampled. The pavement segments surveyed are considered to be "clustered" within the selected counties.
4. Multistage cluster sampling (multistage sampling) is similar to one-stage cluster sampling but takes the process further. Multistage clustering allows for larger areas to be clustered together and then randomly sampled. The elements within these clusters are also randomly sampled. As in the previous example, if data estimates are required for a given state, counties within a district can be randomly selected and within those selected counties pavement segments may be randomly selected. This would constitute a two-stage cluster sample. A three-stage sample would involve randomly selecting highway department districts within a state, then counties within the selected districts, then pavement segments within the selected counties.
5. In systematic random sampling, every kth element of a set of data is sampled. The first element is selected at random between 1 and k. For example, data estimates are required for a state that has 100 counties. It is determined that 10 counties should be surveyed. The interval k is determined as 100/10 = 10. The first county is selected at random between 1 and 10--say, 3. The counties to be surveyed are therefore 3, 13, 23, 33, ..., 93. Within each county selected, all highway segments would be sampled in the data-collection effort.

In addition, combinations of these five methods can be created.

Each sampling survey method has its own formulas for estimating means and standard deviations of the entire population or of specific functional classes of highways. The formulas can be found in standard reference books on sampling techniques (14,15). It is advisable to perform a study of each data type by using actual data to determine the precision of different sampling rates before selecting a specific sampling rate.

There are two approaches to determining the sample size. The first draws sample data from a small number of pavement segments in order to obtain a reliable estimate of the mean and standard deviation of each functional class of highway. Changes in the condition of these classes may be predicted by using regression models of distress and performance and a knowledge of the distribution of pave-

Figure 1. Coefficient of sample variation versus sample size for Texas highway district 21 (1975 data).



ment age and traffic within each class. This approach requires sample sizes on the order of 2-3 percent, as can be observed in Figure 1 (16), which is based on a detailed numerical study on PSI, SN, composite distress score or pavement rating score (PRS), and Dynaflect measurements (surface curvature index). As Figure 1 shows, virtually no increase in precision, as measured by the ratio of standard error to mean, can be expected with sample sizes greater than about 2 or 3 percent. The exception to this appears to be the Dynaflect data, which seem to reach a plateau at a sampling rate of about 5-10 percent.

The second method attempts to detect changes from one year to the next strictly by sampling without the use of regression equations as in the first method. In the second approach, the size of the sample is determined by the percentage change in pavement condition that it is desirable to detect and the level of confidence that is required of the result. The Highway Performance Monitoring System (HPMS) suggests that a 10 percent change in the mean value should be detectable at an 80 or 90 percent level of confidence (17). A simple formula for estimating the number of sections required is given by the following equations:

$$\eta_0 = 0.5 z^2/(p_1 - p_2)^2 \quad (1)$$

$$\eta = \eta_0/[1 + (\eta_0/N)] \quad (2)$$

where

η = number of samples required to detect a change in proportions ($p_1 - p_2$) in a functional class of pavement;
p_1 = at time period t_1, the percentage of the total mileage of a functional class of pavement that has distress greater than an acceptable level, riding quality lower than a specified minimum, or SN lower than a minimum level;
p_2 = same as above for time period t_2;
($p_1 - p_2$) = percentage change that can be detected;
N = total number of sections of pavement in a functional class; and
p = normal variable for a specific level of confidence, as given below:

Level of Confidence (%)	z
50	0.00
70	1.40
80	1.29
90	1.65
95	1.96

For example, for a 10 percent change in the mean value of distress with 90 percent confidence,

$$\eta_0 = (0.5)(1.65)^2/(0.10)^2 \quad (3)$$

Since z = 1.65 for a 90 percent confidence level, then η_0 = 136. For a functional class that contains 500 sections of pavement, the sample size is η = 136/[1 + (136/500)] = 107. If an 80 percent confidence level is acceptable, the sample size drops to 71 sections.

The more important functional classes of pavement, such as urban principal arterials, should require a 10 percent change to be detected with a 90 percent level of confidence. Other functional classes should require only an 80 percent level of confidence. This rule of thumb applies to all types of required data except climatic and traffic data.

Climatic data should be sampled from among the weather stations in each climatic region in a state but from no fewer than three stations. The process of traffic data collection should recognize the fact that the coefficient of variation of traffic counts varies inversely with the traffic volume. The HPMS system provides an approximate method of allowing for this variation of traffic variance with traffic volume, and that method is suggested as a practical means of determining the sample size of the sections where traffic data will be collected.

To summarize the two sampling methods described above, the first is concerned with making an accurate estimate of means and standard deviations, and the second is concerned with collecting sufficient data to detect a change in the mean value of a specified percentage. The first method only requires sample sizes of around 2-3 percent, whereas the second method, the HPMS method, may require statewide sampling rates of around 5-10 percent (excluding locals). The first method requires the use of regression equations to predict future changes in pavement condition, but the effort required to develop such models may be recovered quickly in savings of personnel over the second method.

Some numerical experimentation with the actual data will probably result in a reduction in the total number of sections where data must be collected. The pavement condition data collected for the purpose of programming specific projects should provide more than enough data each year to make reasonable assessments of the changes that occur in each of the functional classes of pavement for the purposes of statewide program planning and fund allocation.

Data-Collection Strategies for Project Programming

Programming of individual projects requires accurate knowledge of the current condition of every pavement section in the entire network. In this case, sampling takes on a different meaning. The data-collection effort for project programming purposes must satisfy three requirements:

1. It must provide data for use in state program management.
2. It must systematically update the initial condition data collected at the start of the long-term monitoring effort.
3. It must collect current condition data on specific sections of pavement that are approaching the end of their satisfactory service life.

The first requirement must be met by sampling in accordance with a carefully planned sampling plan. The second requirement is one that will ensure that the information on each section of pavement is reasonably current. This means that every section should be inspected every two to five years, even though it remains in good condition. The third requirement is to permit prioritization of pavement maintenance or rehabilitation projects. The pavement sections that need to be inspected to satisfy the first two requirements can be designated on a map each year.

An approximate annual inspection schedule to meet the third requirement can be generated by using regression models of pavement distress, performance, and skid and projecting them forward in time to the point where unacceptable levels of these pavement condition indicators are predicted. Because of the scatter that is inherent in regression equations, it is considered wise to record condition data on each section of road in the network every two to five years, regardless of condition. This will permit more accurate and useful annual inspection schedules and can help in planning the manpower effort that will be required in the annual condition survey.

Pavement sections at locations where unusual numbers of accidents have occurred should be inspected as should those special sections of the network that are affected by a sudden increase of traffic or by a haul of economically important products and commodities.

Obviously, the percentage of the highway network that needs to be inspected each year will depend on the overall condition of the pavements in the network and the rate of deterioration. For a network in good condition, data may need to be recorded on no more than 20 percent of the sections. The percentage will increase as the overall condition of the network becomes poorer.

DATA PROCESSING, STORAGE, AND ACCESSIBILITY

The data that are gathered will have multiple uses in both state program management and project programming. Because of this, the data must be stored so that they are readily accessible in a variety of forms. In general, greater accessibility requires automation and a greater capital investment. Thus, the degree of accessibility should depend primarily on how frequently the data must be used. Data that do not change rapidly or are not used often may be stored in less accessible forms.

The following methods of storing data are listed in increasing order of accessibility:

1. Decentralized manual files,
2. Centralized manual files,
3. Punched cards,
4. Magnetic tape, and
5. Computerized data base.

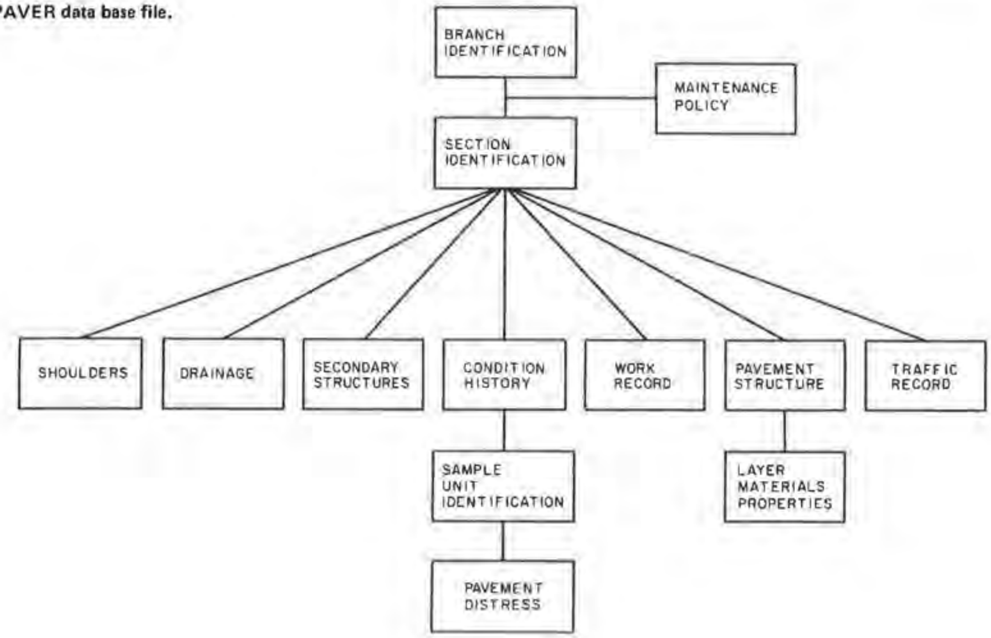
Because a substantial amount of financing and experience are required to build up and debug a computerized data base, it is best to regard the above list as the order in which a data storage system is developed. It must be realized, however, that the processing of large amounts of data on the state level as well as the accessing of the data by other agencies essentially require a computerized data base management system.

NCHRP Project 1-19, Concrete Pavement Evaluation System (COPES) (8), used a hierarchical data base management system called SIR (17). The variables in the data base are grouped in records (historical data, distress, traffic, etc.), where each record owns many other records in a top-down or treelike structure. Data are recorded on specially prepared sheets that can be directly keypunched into a computer file and then entered into the data base. Data retrieval and analysis are easily accomplished for SIR in either batch mode or interactive mode by using a remote computer terminal. The user sitting at a computer terminal can input and execute a set of SIR commands, retrieve data files in any desired format, conduct many kinds of analyses on the data by using statistical packages such as the Statistical Package for the Social Sciences (18), print out results, etc. Automated reports, such as a summary of pavement distress in a given district, can also be developed.

The PAVER system developed by CERL is one of the best developed and implemented pavement data base management systems (10,15). The PAVER system includes a sophisticated data base manager called System 2000, specially developed user interactive input-update-change routines, and specially developed COBOL and FORTRAN programs interfaced with the data base. The PAVER data structure is shown in Figure 2. The system currently offers more than 12 preformatted reports with practically unlimited sort items.

The Arizona Department of Transportation (DOT) recently developed a computerized pavement data base system called the Information Management System (IMS) (19). The data base contains eight segments: (a) route segment (location), (b) synthesized data, (c) common data (descriptive design information), (d) skid data (Mu Meter), (e) raw ride data (Mays Meter), (f) raw Dynaflect data (deflection), (g) raw cracking data, and (h) surface history (layers, date of construction, thickness, and type). The IMS file is hierarchical in structure. Remote computer terminals can be used to execute commands and obtain results. The data base is in place and being used. The Arizona DOT estimates that the computerization of the data base has resulted in large savings of manpower.

Figure 2. Structure of PAVER data base file.



SUMMARY OF KEY ISSUES AND PROBLEMS

Pavements are an essential part of the highway transportation system. The long-term monitoring of pavements at the state level is essential to the efficient management of this huge investment in public funds. This paper presents only a brief discussion of many issues and problems involved in the long-term monitoring of pavements at the state level. Many states have recognized its importance and are currently in the process of developing pavement management systems, which require a formalized monitoring system. Some of the key issues and benefits involved in a state-level pavement monitoring program are summarized as follows:

1. A long-term pavement monitoring program consists of the identification of specific data elements to collect, their measurement (including equipment), the sampling frequency both over time and within a network and project, the efficient storage and retrieval of large amounts of data, data analysis and evaluation, and finally the use of the data in day-to-day policy-level decision and project programming.
2. The long-term pavement monitoring program is a large and costly effort that will require a firm commitment for continued support on the part of the highest level of management in the state. Many data elements are currently being collected, and they must be coordinated and brought together into a common data base (or at least compatible data bases).
3. The data-collection effort can and must be reduced to a minimum by the carefully planned use of sampling surveys and regression equations. The program should be closely coordinated with the federal HPMS.
4. Long-term data collection and evaluation will permit better management of the overall state highway program. In-service information is needed for operational decisions concerning the many design, construction, and maintenance-rehabilitation aspects of a pavement system as well as for use in making reasonably accurate pavement performance predictions for planning, budgeting, and resource allocation purposes.
5. There are numerous special studies for which a long-term pavement monitoring program will provide the required data, including cost-allocation studies, analyses of pavement deterioration to assess the relative damage attributable to traffic and environmental factors, and determination of the optimum time to rehabilitate.
6. Long-term monitoring data permit the use of optimization techniques to ensure that the most cost-effective funding and timing strategies are used on each section of pavement in the highway network.
7. Finally, a difficult question needs to be considered for which no definitive answer is now available: Can the expenditure of funds on manpower, equipment, and computer hardware and software for a long-term pavement monitoring program be recovered from real savings that are realized in a more cost-effective use of available funds? At the present time, intuition and some experience indicate that such a system will pay for itself in a reasonably short time, once it is adopted on a consistent statewide basis. Nevertheless, this question should be considered by top management in each state before the state embarks on the task of developing a state-level long-term monitoring program. It should be asked again once the program has been in operation long enough to show some tangible benefit. It is certain that a long-term pavement monitoring program can pay for itself only if it is integrated into a overall statewide pavement management process.

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REFERENCES

1. J.B. Rauhut, M.I. Darter, and R.L. Lytton. Data Requirements for Long-Term Monitoring of Pavements as a Basis for Development of Multiple Regression Analyses. TRB, Transportation Research Record (in preparation).

2. R.E. Smith, M.I. Darter, and S.M. Herrin. Highway Pavement Distress Identification Manual. FHWA, Rept. FHWA-RD-79-66, 1979.
3. R.L. Terrel and R.V. LeClerc. Pavement Management Workshop, Tumwater, WA. FHWA, Rept. FHWA-TS-79-206, Sept. 1978.
4. C. Bartell and K. Kampe. Development of the California Pavement Management System. FHWA, Rept. FHWA-CA-HM-7139-78-D3, Vols. 1 and 2, 1978.
5. G.J. Chong, W.A. Phang, and G.A. Wrong. Manual for Condition Rating of Flexible Pavements: Distress Manifestations. Ontario Ministry of Transportation and Communications, Downsview, Aug. 1975.
6. G.J. Chong, W.A. Phang, and G.A. Wrong. Manual for Condition Rating of Rigid Pavements: Distress Manifestations. Ontario Ministry of Transportation and Communications, Downsview, Aug. 1977.
7. Instructions and Procedures for the Flexible/Rigid Pavement Condition Survey. Florida Department of Transportation, Tallahassee, 1979.
8. M.I. Darter, M.B. Snyder, and R.E. Smith. Development of a Nationwide Concrete Pavement Evaluation System. NCHRP, Project 1-19, Final Rept., 1980.
9. M.Y. Shahin and S.D. Kohn. Development of a Pavement Condition Rating Procedure for Roads, Streets, and Parking Lots: Volume II--Distress Identification Manual. U.S. Army Construction Engineering Research Laboratory, Champaign, IL, Rept. M-268, July 1979.
10. M.Y. Shahin. Pavement Maintenance Management. U.S. Army Construction Engineering Research Laboratory, Champaign, IL (in preparation).
11. M.S. Hoffman. Mechanistic Interpretation of Non-Destructive Pavement Testing by Deflection. Univ. of Illinois, Urbana-Champaign, Ph.D. thesis, 1980.
12. Highway Capacity Manual. HRB, Special Rept. 87, 1965.
13. C.V. Wootan and J.A. Epps. Recording and Reporting Methods for Highway Maintenance Expenditures. NCHRP, Synthesis of Highway Practice 46, 1977.
14. M.H. Hansen, W.N. Hurwitz, and W.G. Madow. Sample Survey Methods and Theory. Wiley, New York, Vols. 1 and 2, 1953.
15. W.G. Cochran. Sampling Techniques. Wiley, New York, 1963.
16. J.P. Mahoney and R.L. Lytton. Measurements of Pavement Performance Using Statistical Sampling Techniques. Texas Transportation Institute, Texas A&M Univ., College Station, Res. Rept. 207-2, 1978, 233 pp.
17. Field Manual for the Continuing Analytical and Statistical Data Base. Office of Highway Planning, FHWA, Sept. 1980.
18. B.N. Robinson, G.D. Anderson, E. Cohen, and W.F. Gazdzik. Scientific Information Retrieval (SIR) User's Manual, 2nd ed. SIR, Inc., Evanston, IL, 1979.
19. N.H. Nie, C. Hadlai, J.G. Jenkins, K. Steinbrenner, and D.H. Bent. Statistical Package for the Social Sciences, 2nd ed. McGraw-Hill, New York, 1975.
20. G.B. Way and J. Eisenberg. Verification of Performance Prediction Models and Development of Data Base. FHWA, Rept. FHWA-AZ-80-169, 1980.

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Data Requirements for Long-Term Monitoring of Pavements as a Basis for Development of Multiple Regression Relations

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A discussion is presented concerning how data from a broad, long-term pavement monitoring study can be used to provide improved models for predicting damage to pavements, maintenance requirements, costs, etc., as functions of significant variables defining the pavement structure, its environment, and the traffic loadings imposed on it. Specific items of data are recommended for collection, and sampling techniques and sample sizes are discussed. Special considerations related to pilot studies or other studies of limited size are discussed, and specific recommendations are offered. Results are presented for a study that had the following goals: (a) to identify distress types that either generate maintenance or cause loss of performance or safety; (b) to identify environmental and traffic factors, material and geometric properties, and other properties and conditions of a pavement structure that significantly affect performance and distress; (c) to describe multiple regression techniques for developing empirical relations and the characteristics of the data banks required for successful models; (d) to develop recommended approaches to establishing sample sizes for long-term pavement monitoring studies; and (e) to develop recommendations for a planned pilot study.

The Federal Highway Administration (FHWA) and various state departments of transportation (DOTs) are considering the implementation of long-term pavement monitoring studies to support pavement management system data requirements and to produce data bases adequate for developing needed empirical relations. The relations needed include distress and performance prediction models and maintenance cost models for use in design, programming funds, project prioritization, and cost allocation. An initial pilot study is currently being implemented by FHWA in seven states. If this pilot study shows promise, funding for a much broader study may later be considered. The discussions that follow are generally in terms of comprehensive national or single-state long-term pavement monitoring studies, but compromises and recommendations specific to pilot studies or other smaller studies are also included.

The purposes of this paper are

1. To explore various approaches to long-term pavement monitoring;