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;

2. To define the data needed for developing relations between (a) pavement condition, (b) axle-load weights and types and the number of each, (c) maintenance, (d) major repair, (e) environment, (f) construction costs, and (g) costs to maintain functional pavements;

3. To recommend specific data for collection to support development of multiple regression equations when long-term pavement monitoring studies are implemented; and

4. To make recommendations for planning and implementing limited pilot studies.

We have applied the experience gained in an ongoing FHWA research study, "Damage Functions for Cost Allocation" (for which we are the principal investigators), to the definition of the data needs that appear in this paper.

DEVELOPMENT OF RELATIONS AMONG PAVEMENT DISTRESSES, TRAFFIC LOADINGS, ENVIRONMENTAL FACTORS, AND OTHER IMPORTANT PARAMETERS

The common procedure for defining the relations among a group of variables for which ample data exist is a statistical analysis called linear multiple regression. Nonlinear multiple regression techniques may also be used if the linear techniques do not produce a model of sufficient accuracy. Although the use of multiple regression techniques is commonplace, their success depends heavily on the adequacy of the data base, consideration of the significant variables, and the functional form of the models used in the multiple regression. A succinct, but very thorough, discussion of the requirements for reliable predictive models may be found in a paper by Darter (1).

One purpose of proposed long-term monitoring of pavements is to produce adequate data bases to support the development of mathematical equations or models that explain the relations among the significant parameters identified in the introduction. One purpose of this paper is to identify significant variables that should be included in such data bases and to suggest means of ensuring that the data bases themselves are adequate. The significant variables are discussed in the next section of this paper. Once they have been selected, it will be critically important to ensure the adequacy of their measurement during the long-term monitoring process.

The data base that results from a long-term monitoring program must have the following characteristics if it is to provide reasonably accurate models for the relations desired:

1. It must include data for all variables that are significant to predictions of distress or performance, the maintenance or rehabilitation requirements that they generate, and the costs for that maintenance and/or rehabilitation. These variables will generally include (a) those required to define the geometry of a pavement section, (b) the engineering properties of the materials within the pavement structure, (c) the traffic and axle-load distribution imposed on the pavement, (d) the environmental conditions in which the pavement exists, (e) the time since initial construction and significant rehabilitation (such as overlays), (f) maintenance and rehabilitation histories, including identification of the distress or other parameters that generated the maintenance or rehabilitation, and (g) costs.

2. The selection of states to participate in national studies should be at least partly based on obtaining a representative sampling of the various environmental and geographic regions. The selection of test sections should include a representative sampling of (a) urban and rural areas, (b) highway functional classes, (c) traffic levels, (d) types of pavements, and (e) distribution of ages since construction or last major overlay. However, more limited pilot studies may only practically include (a) rural areas, (b) traffic levels, and (c) typical flexible and rigid pavements.

3. The data collected should be reliable and uniform from state to state or from test section to test section. There would be some advantage to the selection of test sections for which historical data have been obtained in the past, but care must be taken before this information is used in a data base to ensure that it is consistent with the long-term measurements that are to be undertaken. Reliability of the new data can be promoted by (a) use of carefully developed procedures described in sufficient detail that individual biases are hard to introduce, (b) sufficient training of survey crews to gain consistency in data gathering, and (c) maintaining equipment and keeping it calibrated (for the same reason).

4. Sufficient data should be gathered to satisfactorily "explain" the relations to be developed from these statistical analyses. In determining the sufficiency of the data, one must consider the numbers of test sections, the lengths of pavements to be included in the test sections, and the numbers of measurements to be made within these lengths ("sample sizes" are discussed later in this paper). Darter (1) has also recommended some replicate data cases (pavements of identical construction, traffic, and climate) to gain an indication of "pure error", which is taken to be a combination of random variations and repeatable errors in test equipment or observation.

A number of states have accumulated substantial data banks in pursuit of pavement management systems or improvements in programming and in project planning and design. Such data banks may offer valuable opportunities (especially if data collection is continued for a sufficient length of time) for multiple regressions to develop meaningful models within the inference space provided. That is, they apply strictly to that state or general environment only and to the range of variables included in the collection effort. A data base that includes more than 300 flexible test sections in Texas has been used to develop distress and performance predictive equations, as have others for rigid pavements (2).

The following problems are common to available data bases:

1. Historical data are frequently not available over a sufficient time period or have been collected sporadically.

2. Significant data are often omitted.

3. Apparently identical items of data are recorded in totally different units or are defined differently. Examples of this include roughness measurements made with grossly varying procedures and equipment; cracking that may be measured in (a) square feet or square yards cracked in some area or length interval, (b) lineal feet of cracks, (c) percentage of total cracked, (d) percentage of slabs cracked, etc., and variation in definitions of rutting and in the length of straightedge used to measure it.

4. Traffic or loading data are inadequate.

5. Definitions of present serviceability index (PSI) differ. Among the methods used by different states are the American Association of State Highway and Transportation Officials (AASHTO) relation, modified AASHTO relations, rating panels, simple

equipment measurements correlated through the General Motors Profilometer to rating panels, and separate regression equations.

DATA NEEDS FOR DEVELOPING RELATIONS

There are two broad categories of data to be collected during long-term pavement monitoring studies. The first is basic inventory data, which includes those items that will remain constant over the monitoring period. The second is monitoring data, which includes those items that will change with time and will require periodic measurements or updating during the monitoring period.

The basic inventory data include those data necessary to (a) identify the test section, (b) describe the geometric details of its construction and the material properties of its structural constituents, (c) describe the environment in which the pavement test section exists, (d) identify the accumulated traffic and axle-load data prior to the long-term monitoring effort, and (e) identify construction costs and costs of subsequent maintenance and repair prior to the long-term monitoring effort. All of these data should remain constant throughout the monitoring period unless the pavement is resurfaced or rehabilitated during that period. If the pavement is resurfaced or rehabilitated, the test section becomes for practical purposes a new pavement structure with new surface conditions. The basic inventory data must therefore be revised to describe these new conditions while the original data are retained for reference and long-term cost analyses.

The monitoring data include distress and serviceability measurements, traffic and axle-load data, results of deflection testing, pavement maintenance costs, resurfacing costs, and restoration and rehabilitation costs during the monitoring year. These data are to be collected on an annual or other periodic basis to provide a historical data base for developing relations among distress, performance, traffic and axle loads, age, maintenance costs, and repair costs.

As discussed previously, these data must be both sufficient and reliable if satisfactory relations are to be obtained. In addition, special consideration should be given to variables that are already used as a basis for decisions by state highway agencies, providing that these variables offer sufficient statistical significance. As a further practical consideration, the number of items of data to be collected should be limited to that necessary; data that require an unusual amount of work effort or sophisticated testing should be avoided wherever possible. Specific data needs and the possibilities for limiting the items of data to be collected are discussed later in this paper.

Data That Have Significance in Multiple Regression Relations

The first logical step in the selection of items of data to be included in the proposed long-term monitoring program is to develop an organized list of all variables that could reasonably be expected to have statistical significance in the development of the multiple regression relations. Three such lists have been developed and appear below.

The following items of inventory data are used for test-section identification and/or have statistical significance for multiple regression relations:

1. Test-secton identification--Highway number, urban or rural, lanes included, functional class, and location of test section;
2. Geometric details and general information--Width of highway, number of lanes, thickness of layers, years when overlays or reconstruction occurred, identification of materials used in overlay or reconstruction, adequacy of drainage, underdrains provided, extent and severity of rigid slab cracking prior to overlay, width of shoulders, year originally constructed, identification of layer materials, overlay thicknesses (or final layer thicknesses after reconstruction), year and details of roadway widened, joint spacing, dowel bar diameter, type of load transfer (aggregate interlock or dowels), and dowel bar spacing;
3. Environmental data--General type of environment (dry-freeze, wet-no freeze, etc.), number of freeze-thaw cycles per year, highest mean monthly temperature, lowest mean monthly temperature, Thornthwaite moisture index, lowest mean solar radiation, highest mean solar radiation, annual precipitation, freeze index, ~~cloud cover, and wind speed~~;
4. Accumulated traffic and axle-load data prior to long-term monitoring effort--Mean average annual daily traffic (AADT) for prior years, accumulated 18-kip equivalent single-axle load (ESAL) (AASHTO equivalencies), weighted mean of percentage trucks for prior years, accumulated number and distribution of tandem axles, and accumulated number and distribution of single axles;
5. Material properties--(a) For subgrade soil: soil type and classification, percentage passing no. 200 sieve, ~~moisture content (inner wheel path, sample in summer), modulus of subgrade reaction~~, plasticity index, dry density, ~~resilient modulus~~, and California bearing ratio (estimate from other data if not available); (b) for base and subbase layers (unbound): soil type and classification, ~~moisture content (inner wheel path, sample in summer), resilient modulus~~, dry density, percentage modified AASHTO compaction, and percentage binder (passing no. 40 sieve); (c) for base and subbase layers (stabilized): type of treatment (cement, lime, etc.), untreated soil type and classification, dry density, ~~resilient modulus~~, percentage of stabilizing agent, and percentage modified AASHTO compaction; (d) for asphalt concrete layers: asphalt grade, asphalt content, viscosity of asphalt, ~~temperature susceptibility of asphalt~~, original stability, ~~fatigue life potential~~, penetration of asphalt (at time of basic inventory data collection), initial air voids, type of coarse aggregate, ~~polish of surface aggregate, permanent deformation potential, Lottman tensile strength ratio~~, and dynamic modulus; (e) for rigid layers: ~~modulus of elasticity~~, percentage of steel in longitudinal direction, modulus of rupture (compute from compressive strength if not available), ~~thermal coefficient of concrete~~, and type of coarse aggregate; and
6. Construction costs prior to long-term monitoring effort--Cost of initial construction, cost of each past overlay, cost of each restoration or rehabilitation project, and accumulated pavement maintenance costs (if available separated from routine maintenance).

The following items of monitoring data have statistical significance for multiple regression relations:

1. Distress and performance measurements--(a) For flexible pavements (with or without overlays): alligator cracking (fatigue), rut depth, roughness, raveling, lane-shoulder separation, low-temperature transverse or longitudinal cracking, low-temperature block cracking, skid resistance (to monitor reductions), and flushing; (b) for rigid pavements: slab cracking, D-cracking, joint faulting, pumping, lane-

shoulder separation, skid resistance (to monitor reductions), roughness, blow-ups, and deterioration of transverse joints; and (c) for rigid pavements with flexible overlays: reflection cracking, rut depth, potholes in overlays, raveling, skid resistance (to monitor reductions), roughness, flushing, and lane-shoulder separation;

2. Traffic and axle loads--AADT, number and distribution of single-axle loads, number and distribution of tandem axle loads, 18-kip ESAL for year, accumulated 18-kip ESAL, percentage of trucks, and truck lane distribution;

3. Results of deflection testing--Mean maximum deflection under load, basin parameters, and coefficient of variation of maximum deflection; and

4. Pavement maintenance costs per square yard of test section (exclusive of routine maintenance such as mowing, salting, snow removal, etc.).

The following additional data items should be collected if resurfacing, restoration, or rehabilitation occur during the monitoring year:

1. Cost of overlay per square yard;

2. Description of overlay for addition to basic inventory data--Thickness of overlay, material in overlay, asphalt grade, viscosity and penetration of asphalt, type of coarse aggregate, ~~temperature susceptibility of asphalt, Lottman tensile strength ratio~~, cost of overlay (per square yard), asphalt content, stability of mix, initial air voids, initial skid number, ~~fatigue life potential, permanent deformation potential, and polish of surface aggregates~~;

3. Cost of restoration or rehabilitation per square yard;

4. Description of pavement structure resulting from restoration or rehabilitation--Identification of layer materials, joint spacing, thicknesses of layers, dowel bar diameter, and width of joint at dowel level; and

5. Material properties--Items 5b, c, and d in the first list above for material properties of new or revised layers above the subgrade level.

The selection of the items of data that appear in these listings (including those marked through) was based partly on the experience of the project staff and partly on information reported elsewhere (2-5). The experience of the project staff includes the results of multiple regression model developments by Lytton, Darter, and others that are quite similar to those proposed. These lists are intended to identify the entire range of variables that would reasonably be considered for inclusion in the long-term monitoring project. They in effect represent a "shopping list" from which a more limited set of variables may be selected as necessary to the generation of the data bank required.

In general, the variables in the first listing (inventory data), with the exception of material properties, will not be too difficult to obtain and must only be obtained once. However, some may not be absolutely required and may be omitted. The material properties listed include variables that would be duplicative for explaining relations through multiple regression analysis. For example, the fatigue life potential of an asphalt concrete is largely explained by asphalt content, initial air voids, and dynamic modulus. Both permanent deformation potential and original stability explain the tendency of an asphalt concrete to rut. It should be possible to eliminate some data where other data are sufficient. This is explored in another section of this paper.

Considerations for Limiting Data-Collection Requirements

The critical criterion for elimination of items of data from the monitoring study is the effect of their elimination on the sufficiency of the data bank or statistical base. It appears that all or most of the data that may be seriously considered for elimination primarily affect the development of relations between the occurrence of distress and other parameters. If this is so, decisions as to data for collection may be made on the basis of their significance to the prediction of distresses. Each of the authors has worked for many years toward development of relations between distresses and significant independent variables and have applied this experience in evaluating the effects of data elimination.

Table 1 lists as an example 13 of the 46 significant distresses and performance measures considered for flexible pavements and flexible pavements with flexible overlays and also the variables on which occurrence or prediction of these distresses depends. The intent in assigning these priorities was to recognize significance on the assumption that other data that explained much the same variance had not first been introduced into the multiple regression. Similar tables were also developed and studied for various types of rigid pavements.

It should be recognized that significance in the statistical sense is somewhat a function of the order in which the data are introduced into the regression analysis. For instance, permanent deformation potential would not generally be as significant to rutting distress if the stability of an asphalt concrete mix had already been included (due to expected correlation between permanent deformation potential and stability). Layer stiffnesses and other material properties would generally have only limited significance if they followed deflection measurements in a multiple regression analysis. Because of this, it is not enough just to decide that items with a priority of 3 may be eliminated and that those with a priority of 1 must be retained. Although data items with a priority of 3 for all distresses can probably be eliminated, some with a priority of 1 may also if other data explain similar variation (or correlate highly).

Since there may also be several different combinations of variables that may each adequately explain the variation in a relation, some discretion (and a lot of experience) must be applied in the selection of the variable combinations to retain and the variables to be eliminated. For instance, the test programs used to develop the fatigue life potential of asphalt concrete mixes are extremely sophisticated and costly. Therefore, data for other variables that are more common and easily obtained would be favored if they adequately explain the nature of the asphalt concrete mix and its effect on the occurrence of fatigue in pavements.

Data Recommended for Collection

The considerations discussed above have been used to reduce significantly the recommended data requirements for long-term pavement monitoring studies. The items marked through in the list of inventory data are those data not considered essential, and those items not marked through are the inventory data recommended for collection. None of the monitoring data listed were selected for elimination, but some data items can be eliminated from the list of additional data and these have also been marked through. It should be noted that those items of data eliminated from the third list are in all cases

Table 1. Significant variables and their relative importance to significant distresses and PSI for flexible pavements and flexible pavements with flexible overlays.

	Significant Distress								
Significant Variable	Fatigue Cracking	Reduced Skid Resistance	Rut Depth	Low-Temperature Cracking	Roughness due to Subgrade Volume Change	Raveling	Flushing	Reflection Cracking	PSI
Layer thicknesses									
AC overlay	1		1	1	3			1	1
AC surface	1		1	1	3			2	1
Base	1		1						1
Subbase	1		1						1
Layer stiffnesses									
AC overlay with temperature	1		1			3			1
AC surface with temperature	1		1			3			1
Base	2		1						1
Subbase	2		1						1
Subgrade	2		1						1
18-kip ESAL	1	3	1		3	3	2	2	1
Time since construction	3	3	3	1		3			2
Time since overlay				1				1	2
Annual precipitation			2		1	1			1

Note: 1 = essential data; 2 = moderately significant data; 3 = data have significance but explain only a limited amount of variance.

items of data eliminated from the first list also.

Whereas the resilient moduli of all other materials were eliminated, the dynamic modulus for the asphalt concrete layers was retained because this is a very important parameter that greatly affects the rutting potential and fatigue life of the pavement. In addition, it is not particularly difficult to obtain cores of this material when the inventory data are accumulated and to run dynamic indirect tensile tests on these cores to obtain the dynamic modulus. These tests should be run at a minimum of three temperatures that represent approximately the range anticipated. Tests should generally be conducted on the same specimens to limit variability, and testing should start with the cold temperatures first.

Data Not Recommended for Collection

It can be seen from Table 1 that less than half of the data considered was recommended for elimination from the collection effort. Although some of the data not eliminated may later be demonstrated to be statistically insignificant, it would not be appropriate to eliminate them at this time. Each of the items eliminated is discussed below.

Cloud cover and wind speed affect asphalt concrete pavement temperatures, which in turn have a strong effect on the material properties of the asphalt concrete. However, it is believed that the mean daily temperature for summer months and winter months plus the solar radiation will sufficiently explain the variations in asphalt concrete temperature for the purposes of the proposed studies.

The moisture contents for subgrade, subbase, and base layers were eliminated because these values would be very dependent on the time of year when the samples were removed and would be subject to continuing variation with time. Although moisture content has considerable effects on resilient modulus and permanent deformation potential, it is not considered practical to establish a requirement for a continuing sampling program on an annual or periodic basis. In addition, the effects of moisture content on the response of these layers to load will be represented satisfactorily by other material properties, annual precipitation, and periodic deflection measurements.

The resilient moduli for the subgrade soil, subbase, and base layers were omitted partly to avoid sampling (assuming the other material property data are available from design and construction records), partly because the resilient moduli vary seasonally with moisture content, and partly because resilient moduli are also satisfactorily explained by other material properties and by the periodic deflection measurements. The modulus of subgrade reaction was also eliminated for essentially the same reasons.

The fatigue life potential, permanent deformation potential, and Lottman tensile strength ratio are arrived at by relatively sophisticated test procedures for which few commercial or state materials laboratories are equipped. Consequently, other means for representing these data are needed. Fortunately, the fatigue life potential of an asphalt concrete has been found to be very dependent on three other material properties or factors that are included as data to be collected: dynamic modulus, asphalt content, and air voids. Other asphalt concrete material properties to be collected, such as viscosity of asphalt and type of coarse aggregate, may also offer additional "explanation" of the variation in fatigue life potential. As discussed previously, the permanent deformation potential is also correlated with the original stability of the mix used in design as well as with the other material properties discussed above.

It appears, then, that it is possible to include essentially all of the information to be gained from the sophisticated test program through other data that should be available from construction records. If these data are not available from construction records, most of them can be obtained through extraction tests on cores removed.

Polish of surface aggregates is an important factor in the rate of loss of skid resistance, but it is a difficult property to determine in the laboratory and may be adequately represented by type of coarse aggregate and skid numbers from the monitoring data. The modulus of elasticity of the concrete in rigid layers is important but does not vary over a large range, and its effects may be adequately "explained" by a combination of deflection measurements and modulus of rupture. The thermal coefficient of concrete is important to volume change in concrete, but it is very difficult to obtain and is generally negatively correlated with modulus of rupture.

It should be noted that percentage of modified AASHTO compaction is specified for uniformity for the base and subbase layers. Since standard Proctor or AASHTO compaction was frequently used for density control, it will be necessary to convert from standard to modified AASHTO compaction. For one limestone material in Texas, maximum densities were determined for a range of compactive energies. The maximum density for modified AASHTO compaction was 8 percent higher than that for standard AASHTO compaction. It is believed that this is rather typical and that little error would result if the percentage of standard AASHTO compaction were simply divided by 1.08 to convert to percentage of modified AASHTO compaction.

Temperature susceptibility of the asphalt was also proposed for elimination. It is of primary importance to the occurrence of low-temperature cracking and flushing but is not considered to be a strong parameter and will also be partly represented by other properties.

DATA COLLECTION

Uniformity of Data

One of the biggest problems with the use of historical data (available in limited quantities in state DOTs) is the incompatibility of the data. As discussed previously, there are many methods in use among the individual states for measuring cracking, roughness, deflections, and other important pavement indicators. Without some means to successfully correlate these diverse data, there is really little hope of using them to develop reliable relations. Consequently, it is critically important that the procedures and testing requirements for this data-collection effort be uniform. It will not do to consent to a state DOT using the Bureau of Public Roads Roughometer if an accelerometer-based roughness system is selected for general use. Benkelman beam deflections are not adequate since they do not generally provide basin information. Pavements that have unusual characteristics (such as rigid pavements with unusual load-transfer devices) should be avoided since they are not representative. If the proposed monitoring efforts are not to degenerate into ineffective exercises in trying to match "apples and oranges", the inconvenience and extra expense for this standardization in the measurements must be accepted and implemented from the beginning.

All condition surveys to obtain information on distresses must use the same rating forms and must generally report severity of the distress as well as the area affected. A number of state DOTs, such as Washington and Texas, use measurements of both area and severity, but many of the states do not. The selection of forms for conducting the condition surveys will require some study in order to ensure that the data are in a form directly useful for multiple regression analyses and may be practically obtained in the field. To the extent possible, these forms should be similar to those in common use.

There is much variation in the perception of pavement engineers and technologists regarding the identification of certain distresses and assignment of severity levels. To reduce the variability in these perceptions, several manuals have been developed over the years. The latest and perhaps the most comprehensive is the manual developed by Smith, Herrin, and Darter (5), which is recommended as a standard.

Centralized Collection of Some Data

The usual approach to data collection at the national level is to levy requirements on the state DOTs and to provide some or all of the funding for collection. This is the approach planned for an FHWA pilot study and may be the approach taken for any broad, long-term monitoring studies in the future. Similar divisions of monitoring responsibilities may be made through delegation to districts within states, but centralized data collection by teams mobilized for that purpose (in-house or by contract) should be considered. The primary advantage of a centralized data-gathering effort would be uniformity in those data. It may be very difficult to get state personnel who are already committed to specific condition-measurement techniques and procedures to use some other method in a uniform manner. The trade-offs between improved data for study, management of one or more teams instead of dealing with a number of states or districts, relative costs, and the politics involved should be assessed during planning for individual data-collection efforts.

There are some data that are best collected centrally in any event. These include environmental data, which are generally available in a centralized data base, and some traffic and axle-weight distributions that are available from W-4 tables. Other traffic and axle-load distribution data will undoubtedly be required, but test sections for which traffic and weigh-station data are available should be used where possible.

Centralized Data Management

The data collected may be used by both state agencies and FHWA. These data should be controlled and stored centrally at state and/or national levels by suitable "data managers", which are software packages designed to store and process data so that they are available when needed and can be easily manipulated for the intended purposes. A number of systems are available and in use by both federal and state governments.

Pavement Maintenance Costs

Some explanation is required for definition of accumulated pavement maintenance costs as differentiated from routine maintenance. The intent is to include those costs that can be related to axle loads or to the environment and that represent correction of distresses to the pavement itself.

SAMPLE SIZES

Long-Term Pavement Monitoring Studies

As with most sampling surveys, the goal for long-term monitoring studies will be the selection of the smallest sample sizes possible that will still provide sufficient information of suitable quality to support the multiple regression analyses.

Mahoney and Lytton (6) conducted studies to establish a suitable sample size for a network analysis for the State of Texas. Their purpose was to provide valid data for use by the state highway administrator in allocating highway rehabilitation and maintenance funds. Although the purposes of other long-term studies may be different, distress and performance measures are essentially the same and much insight can be gained from the Mahoney and Lytton studies.

The type of sampling conducted was a stratified two-stage random sample over the entire state. Two-mile highway segments were used, and approximately 1 percent of the statewide total centerline mileage was sampled. Construction, traffic, climate, roughness, visually determined condition, deflection, rut depth, and skid resistance are typical of the kinds of information sampled for each of the highway segments involved. The stratification involved division of the highway network into the 25 districts. The two-stage sampling was obtained by first randomly sampling counties within each district and then randomly sampling the two-mile highway segments within each county. An average of four counties per district was used. There were a total of 250 test sections or segments, of which 21 were Interstate, 109 were U.S. and state highways, and 120 were farm-to-market roads. The percentage of centerline Interstate highway sampling was 1.8, that for U.S. and state highways was 1.0, and that for farm-to-market roads was 0.6. A mass inventory was also conducted of all the highway mileage in one district in order to study the effects of different sizes of samples.

The random sampling technique applied to selecting the test sections within a county did not always produce all three of the types of highways nor even a distribution. Consequently, a larger sampling of Interstate highways was selected for subsequent studies.

The simulation studies conducted on the mass inventory for the one district indicated that the optimum sample lies between 1.5 and 6.6 percent of the centerline mileage, depending on the ranges of utility weights applied to different attributes. As an example, the optimum sampling rate would be 1.5 percent if the costs of conducting the survey were weighted three times as heavily as sampling variability. If both attributes were weighted the same, an optimum sampling rate of 2.3 percent would result.

It appears that combinations of multiple stratification and staged random sampling are appropriate for long-term monitoring studies. The first stratification for a national study would logically be selection of all environmental regions, and then a random sample of the states within each region could be made. The next level of stratification might then be highway functional classes, and a third level would be urban and rural highways. The fourth level of stratification should then be type of highway (rigid or flexible). The selection of test sections could then be random and based on some selected length. The test sections selected would then include combinations of geographic regions, states, functional classes, rural or urban locations, and types of pavements. For a single state, a random sampling of districts might be appropriate as the first step in sample selection.

The overall sample size should ideally start at a relatively high level of the apparent required range--say, 5 percent of the centerline mileage of pavements within a state and of a specific functional class, rural or urban location, and pavement type. Simulations of partial data could then be conducted to determine what the effect on the data would have been if a smaller sample had been obtained the first year. After the second set of monitoring data has been received and the results are analyzed, it may be appropriate to cut the sample size down further to, say, 2 or 3 percent. For economic reasons, it may be necessary to start with a smaller sample and reduce it to, say, 1 percent, although some loss in accuracy may result.

The frequency of sampling for some data (such as deflection tests and cores) must also be established but will depend on test-section lengths and other considerations. Test-section samples of 10-20 percent have been used successfully for condition surveys.

Pilot Studies or Other Studies of Limited Scope

FHWA is currently implementing a pilot study that was initially to include the monitoring of a minimum of some 50 test sections located in five states. The five states to participate (seven were actually selected) were to be selected on the basis of interest, availability of useful existing data, proposed approach to the monitoring task, and environmental conditions. With only 50 sections and the further limitation that they be divided among five states, it is apparent that the sampling techniques discussed above for the broad study could not generally be applied. In addition, the limited size of the factorial requires that some levels of discrimination be determined.

We recommended for this limited study that only rural highways be considered and that there be no direct consideration of functional class or location in a state. The actual distribution of the average of 10 test sections in a state could be in terms of type of pavement and combined traffic and axle loads. Assuming that only typical flexible and typical rigid pavements are included (total of two types), an average of 5 test sections per state, or a total of 25, may be monitored for each pavement type. The selection of actual numbers of test sections for each pavement type within a state could also reasonably reflect the percentage of total mileage within that state for each type.

The test sections for each pavement type should include a distribution of traffic levels and axle loads--i.e., highways with low, moderate, and high traffic levels and a more or less typical distribution of axle-load magnitudes. As traffic and axle-load data are very important, test sections should be selected where relatively accurate and comprehensive data exist.

When a limited factorial is planned, the test sections selected should be "screened" to the extent possible to ensure that they are representative and will not reflect nontypical problems, such as stripping of asphalt concrete or abnormal joint problems in rigid pavement caused by deficient design or construction practice rather than loads or environment. In addition, only one type of rigid pavement--jointed reinforced or plain jointed--should be included.

An alternative approach to designing this limited study might have been selection of one state, a "cluster sample" in one part of the state, and a combination of stratified and random sampling within the cluster. Although this would have offered some advantages in testing sample design techniques and allowed consideration of urban test sections and functional classes, it would not have allowed any environmental discrimination or broad state participation.

A rough approximation of precision for this small sampling may be evaluated by using Equations 1-3 in the paper by Lytton and others in this Record. Assuming 25 test sections for a pavement type, the detectable percentage change in mileage of test sections that are experiencing unacceptable distress levels would be as follows:

Level of Confidence (%)	Detectable Change (%)
70	14.7
80	18.2
90	23.3
95	27.7

SUMMARY

This paper describes the requirements of long-term pavement monitoring studies to collect data for use in the development of multiple regression relations among pavement types, traffic loadings, environmental factors, and other important parameters. The study approach for this paper is aimed specifically at defining data requirements that would support development of multiple regression relations, but it is hoped that a reasonable amount of the data might be common to data-collection activities for other purposes, such as identifying needs for maintenance or rehabilitation, project design, and budgeting funds for these activities.

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REFERENCES

1. M.I. Darter. Requirements for Reliable Predictive Pavement Models. TRB, Transportation Research Record 766, 1980, pp. 25-31.
2. M.I. Darter, M.B. Snyder, and R.E. Smith. Development of a System for Nationwide Evaluation of Portland Cement Concrete Pavements. Univ. of Illinois, Urbana, NCHRP Project 1-19, Final Rept., 1980.
3. J.B. Rauhut, F.L. Roberts, and T.W. Kennedy. Models and Significant Material Properties for Predicting Distresses in Zero-Maintenance Pavements. FHWA, Rept FHWA-RD-78-84, June 1978.
4. M.I. Darter and E.J. Barenberg. Zero-Maintenance Pavement: Results of Field Studies on the Performance Requirements and Capabilities of Conventional Pavement Systems. FHWA, Interim Rept. FHWA-RD-76-105, April 1976.
5. R.E. Smith, S.M. Herrin, and M.I. Darter. Highway Pavement Distress Identification Manual for Highway Condition and Quality of Highway Construction Survey. FHWA, Interim Rept. FHWA-RD-79-66, March 1979.
6. J.P. Mahoney and R.L. Lytton. Measurements of Pavement Performance Using Statistical Sampling Techniques. Texas Transportation Institute, Texas A&M Univ., College Station, Rept. TTI-2-8-75-207-2, March 1978.

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Simplified Pavement Management at the Network Level

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A simplified pavement management system at the network level is presented, and an example is provided to demonstrate how this framework can be applied to produce a priority ranking on a network basis. This framework has been specifically designed to be independent of the organization of any specific highway agency. The framework is organized around the flow of information on either management level, and three major subsystems are identified at each level. Essential features of pavement management systems are identified, and specific characteristics are described for the example models and outputs. Existing pavement management practices are reviewed to demonstrate several different levels at which pavement management activities are occurring in U.S. agencies. The findings of the study suggest that implementation of simple systems can probably best begin at the network level of pavement management. These simple steps can be coordinated with later development work to recognize analysis of alternatives and optimization at the network level. A research plan and problem statements are included to address continued development and implementation at both the network and project levels.

Pavement management is a concept that involves the coordination, scheduling, and accomplishment of all of the activities performed by a highway agency in the process of providing adequate pavements for the public. The systems approach to pavement management is a rational, highly structured process that attempts to achieve the best value possible for the public funds expended to provide pavements. This is accomplished by comparing investment alternatives; coordinating design, construction, maintenance, and evaluation activities; and making efficient use of existing methods and knowledge (1). Of course, management decisions are made each day in the course of normal operations of highway agencies throughout the nation. The purpose of a pavement management system (PMS) is to improve the efficiency of this decision-making process, expand its scope, provide feedback regarding the consequences of decisions and the results of activities, and ensure the consistency of decisions made at different levels within the same organization (2).

Many agencies and individuals have conducted research into the various component models and procedures involved in pavement management. A significant portion of this work has been summarized in two recent books (1,3), which suggest that there are several major underlying considerations in pavement management:

1. Management decisions occur at several levels, ranging from investment decisions covering the network to detailed design decisions at the individual project level.
2. Periodic, in-service evaluation of existing pavements is basic to the programming of rehabilitation and maintenance, the updating of earlier design estimates, and the improvement of models.
3. A PMS must be capable of being adapted to the varying needs and resources of different agencies in order to be implemented. It must also be capable of serving the various management levels noted in item 1 above.

These considerations led to the development of a general framework for PMSs during the first phase of research under this project (2). A major finding of this study is that most PMS development and experience to date have occurred at the project level and within the areas of design or maintenance. This