Development of Delaware Department of Transportation Pavement Management System

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Preservation of the statewide roadway network, consisting of the vast majority of Interstate primary, secondary, and local roads in the state, is a key responsibility of the Delaware Department of Transportation (DelDOT). Because the pavement surfaces are (a) the primary link between the roadway network and the efficient movement of goods and services, (b) the portion of the network most visible to the traveling public, and (c) the most significant functional and structural components of the network, a systematic approach to their management is needed to provide the engineering and analysis tools required by decision makers. The process is described by which DelDOT pavement management activities were upgraded to be consistent with the FHWA Pavement Design Policy and the AASHTO *Guidelines for Pavement Management Systems*. The customized DelDOT pavement management system is designated the Pavement Management and Planning program; key features of it include unique and unambiguous milepoint referencing, dynamic segmentation, a decision-tree process to priority rank capital improvement and rehabilitation projects for annual programs, interim pavement performance forecast models based on currently available data, multiyear planning capabilities to forecast conditions and needs, and color graphics and mapping capabilities to illustrate current pavement conditions and projected conditions for various program scenarios.

The Delaware Department of Transportation (DelDOT), Division of Highways, is responsible for the maintenance of 7668 km (4,765 mi) of the 8666 km (5,385 mi) of public roads in the state. Of this mileage, 3561 km (221 mi) are multilane highways. Only 2348 km (1,459 mi) are eligible for some type of federal financial aid. Most of the necessary funds for construction, reconstruction, rehabilitation, and maintenance of these roads are allocated from the Delaware Transportation Trust Fund.

The statewide roadway network represents a tremendous investment. The preservation and management of these facilities are vital to the economy of the state and a key responsibility of the department. Increases in traffic, both in numbers of vehicles and in wheel loads, along with rising costs and reduced resources result in a significant challenge to administrative and engineering personnel. Because pavement surfaces are (a) the primary link between the roadway network and the efficient movement of goods and services, (b) the portion of the network most visible to the traveling public, and (c) the most significant functional and structural components of the network, their preservation and management at performance levels appropriate for desired service are major activities of the department. The changing emphasis from new construction to maintenance, rehabilitation, and reconstruction (MR&R) of existing pavements must be addressed.

A systematic approach to the management of pavements is needed to provide the engineering and economic analysis tools required by decision makers in making cost-effective selections of MR&R strategies on a network basis. Such an approach has come to be known as a pavement management system (PMS). The overall benefits attained from implementing a PMS include the planning and conduct of MR&R activities in a timely manner to preserve pavement surfaces and to provide for the most effective and efficient use of available highway funds. As described in the FHWA *Federal-Aid Policy Guide*, "the analysis and reporting capabilities of a PMS are directed towards identifying current and future needs; developing rehabilitation programs; priority programming of projects and funds; and providing feedback on the performance of pavement designs, materials, rehabilitation techniques, and maintenance levels" (*1*).

In response to an invitation from DelDOT, Pavement Consultancy Services, a division of Law Engineering, Inc. (PCS/Law), submitted a technical proposal for development and implementation of the Delaware PMS. The objective was to provide DelDOT with state-of-the-art tools for cost-effective management of the entire network of paved roads and streets under its jurisdiction.

PROJECT APPROACH

Significant project concepts that enhanced prospects for the timely accomplishment of objectives included the following:

- All activities were planned and conducted as a team effort involving DelDOT and PCS/Law project personnel. This approach provided for the accurate and realistic interpretation of Delaware PMS needs and the training of DelDOT personnel as work progressed. It also facilitated implementation by maintaining the cooperation of administrative and engineering personnel.

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• Funding, administrative, and operational constraints were recognized, and corresponding short-term, intermediate, and long-term objectives were identified early in the project. Accomplishment of short-term objectives produced early benefits and provided support for future enhancements to accomplish the intermediate and long-term needs and desires of the department.

• The pavement management software was developed and organized as a set of individual modules that can easily be replaced and updated. This approach facilitated the incorporation of advances in data collection and programming technology as well as intermediate and long-term enhancements.

• The initial phase of the project concentrated on determining DelDOT pavement management needs, desires, and anticipations at all levels from top administrative officials to district maintenance engineers. A detailed work plan for future conduct of the project was prepared on the basis of the established goals of the department.

PHASE 1 RESULTS

On the basis of an extensive review of documents and information obtained by many interviews and visits with DelDOT personnel during Phase 1 of the project, it was apparent that substantial elements of a conventional pavement management process were already being used for the selection and prioritization of projects for inclusion in the annual Highway Capital Improvements Program (CIP) and MR&R program. The existing process, however, was time-consuming because the required information was in different data files and analysis required both manual and computer efforts. Major deficiencies included the inability to forecast pavement conditions and needs and the lack of graphic reporting capabilities.

The needs, desires, expectations, suggestions, and objectives identified from interviews with both headquarters and district personnel were grouped into two categories: those appropriate for a conventional PMS and those beyond the scope of such a program. On the basis of a careful evaluation of the needs and desires that could realistically be accomplished with the available data, developed to implementation stage immediately, and completed within available time and funds commitments, recommendations were presented in the Phase 1 report for short-term, intermediate, and long-term objectives. The short-term objectives were those recommended for accomplishment during Phase 2 of the project. The intermediate and long-term objectives were proposed for accomplishment as supplemental projects.

PHASE 2 WORK PLAN

The detailed work plan for Phase 2 of the project focused on the overall objective of developing and implementing a customized DelDOT computer software package consisting of a user-friendly data base and analysis and reporting modules with emphasis on flexibility to permit ease of modification and updating.

The detailed project work plan prepared at the conclusion of Phase 1 identified the following activities to be completed under Phase 2.

Customized Delaware PMS

A major project activity was the development of a customized computer software package consisting of a user-friendly data base and analysis and reporting modules.

• Data base: the pavement management data base is the repository for all pavement and related information required to conduct the desired analysis and reporting activities. To establish the operational data base, a data base structure responsive to DelDOT needs must be determined and access and query routines for entering, examining, and editing the data base contents must be developed.

• Analysis and forecasting modules: the PMS must contain a powerful and versatile set of analysis and forecasting tools related to pavement condition, traffic, rehabilitation needs, and budget estimates. Specific modules developed for DelDOT included pavement analysis, traffic analysis, pavement condition forecasting, project ranking and prioritization, and multiyear budget projections.

• Report generation: the primary output (useful end products) from an operational PMS are various types of planning, priority ranking, scheduling, forecasting, and budgeting management reports. The DelDOT program contains a robust set of reporting options including tabular summaries, bar and pie charts, line graphs, and color-coded maps.

Implementation and Training

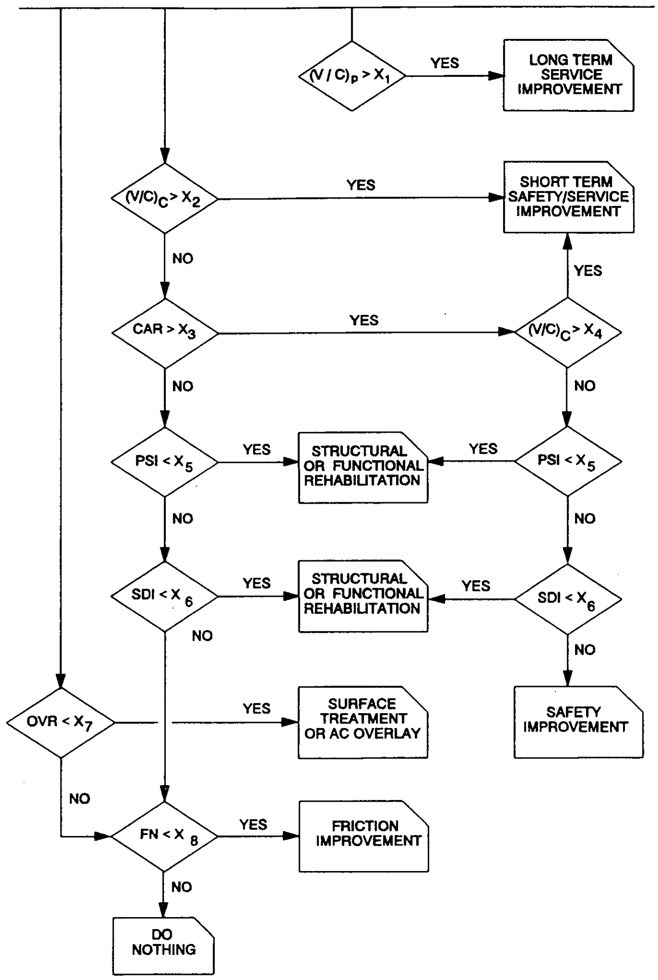
An important project goal was the maintenance of close coordination and communications between the project staff and DelDOT personnel during the program development, resulting in the implementation's being a continuous process. The implementation activities also included a review and evaluation of data collection equipment and procedures plus final software documentation and DelDOT personnel training.

DELDOT PAVEMENT MANAGEMENT FEATURES

The customized pavement management software developed under the project has been designated the DelDOT Pavement Management and Planning (PMAP) program. Customized PMAP features include:

• A decision-tree process to priority rank capital improvement and rehabilitation projects for annual programs (Figure 1),
• Development of interim pavement performance models based on currently available DelDOT data,
• Multiyear planning capabilities to forecast needs and condition trends, and
• Production of color graphic and map reports illustrating current pavement conditions and projected conditions for various programming scenarios.

This paper describes the PMAP development process including road referencing, segmentation, performance models, safety and service improvements, data collection evaluation, and reporting capabilities.



Legend: $(V/C)_P$ = volume-to-capacity ratio, planning (gravity) model projection for long-term planning
$(V/C)_C$ = volume-to-capacity ratio, current for short-term program development
CAR = critical accident ratio (number of accidents per 0.3 mi road section per year in relation to average number of accidents per 0.3-mi section of similar traffic and classification)
PSI = present serviceability index (AASHO Road Test model at 80 percent ride/roughness and 20 percent distress)
SDI = surface distress index (subjective visual rating of combined distress types)
RCI = ride comfort index (use with SDI to determine PSI)
OVR = overall condition rating (local surface-treated roads only)
FN = friction number (measured with locked wheel friction tester at 40 mph)

FIGURE 1 Delaware PMAP decision tree process.

Road Reference System

A unique and unambiguous milepoint referencing system for all roads in the DelDOT network is critical to successful operation of PMAP. At the beginning of the project there was a general perception that the existing maintenance road number milepoint referencing system would serve this purpose. However, substantial inconsistencies were found in the use of the system in the various data sources such as inventory, traffic, and condition surveys. The same physical location was not always identified by the same milepoint, roads were missing from some data sources, directionality was not always identified, and treatment of divided and multilane roads was ambiguous.

To address these problems, a new standardized scheme for specifying road references was developed and implemented as part of this project. The road reference scheme was designed to satisfy the following four objectives: to (a) provide an unambiguous milepoint location reference along the roadway, (b) permit tracking of the changes or "evolution" of milepoint references over time due to alignment and other modifications along the roadway, (c) maintain compatibility with field milepoint measurements, and (d) retain consistency with current DelDOT practice to the maximum extent possible.

The first objective simply requires that there be an unambiguous, well-defined, unique correspondence between roadway milepoint references and the corresponding geographic location along the roadway alignment. This clearly is the first and critical requirement for any road reference scheme. In the Delaware PMS this is accomplished for each roadway via a roadway milepoint table that defines the complete one-to-one correspondence between reference milepoint values in the forward and reverse directions along the roadway.

Unfortunately, roadway alignments do not stay the same over time. As a consequence of road extension, curve straightening, changes from undivided to divided travel, and other construction activities, the road alignment and its associated milepoint references will change or "evolve" over time. It must always remain possible to relate historical inventory, accident, traffic, and other data to the new milepoint references in effect after construction (assuming that the historical location remains on the roadway alignment after construction). In the Delaware system, this is done via a set of milepoint evolution tables that document the historical changes in milepoint references along the roadway and permit mapping of past milepoint references to current milepoint locations.

Dynamic Segmentation

In addition to unambiguous referencing, a PMS must include some form of road segmentation for the organization of the various pavement attributes in the data base, the forecasting of attributes, and the prioritization of rehabilitation needs. The pavement network must be subdivided into homogeneous segments/lengths within which all relevant attributes such as pavement type and design, traffic, condition, subgrade and materials characteristics, and climatic conditions are treated as uniform. The values of these attributes vary along each roadway, and in many instances the attribute values also vary over time. As a consequence, the total number of segments will become quite large and the length of each segment quite small.

Dynamic segmentation, originally developed in the context of geographic information systems, is an alternative for organizing pavement network data that eliminates many of the problems inherent in the fixed segment approach and that can be applied generally to any highway pavement network that is uniquely referenced by road number and milepoint location (*2–4*). Given these advantages, dynamic segmentation was the clear choice for implementation in PMAP. In dynamic segmentation, each pavement attribute or set of related attributes is associated with a variable length segment of pavement by specifying a road number and beginning and ending milepoints. Beginning and ending points will generally

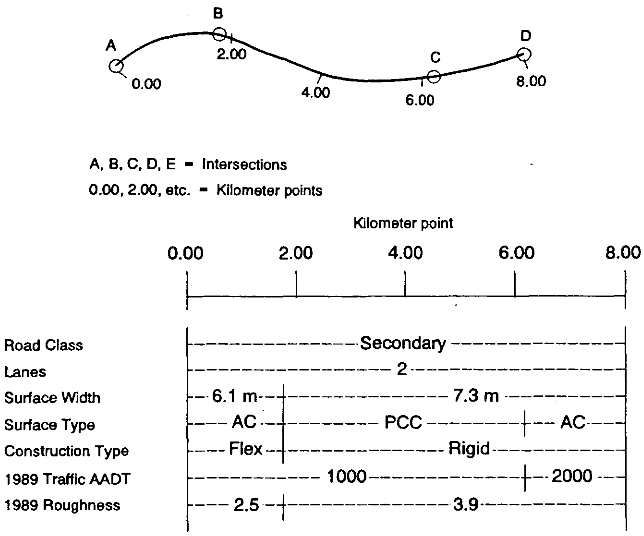


FIGURE 2 Example of dynamic road segmentation: *top*, Road 491; *bottom*, strip charts.

be different for different sets of attributes. The concept is best illustrated by an example.

Consider the hypothetical Road 491 sketched in Figure 2. (For simplicity, only a limited set of data are included in this example; for a real road, a much larger set of attributes would be stored for each segment.) The road is approximately 8.05 km (5.1 mi) long. It contains four intersections, labeled A through D in Figure 2. Road 491 was originally built as a two-lane farm-to-market road, with original construction consisting of a flexible asphalt concrete (AC) pavement with lane widths of approximately 3 m (10 ft). The length between Intersections B and D was later reconstructed as a rigid portland cement concrete (PCC) pavement with lane widths of approximately 3.6 m (12 ft). Later still, the length between Intersections C and D was overlaid with AC. Traffic and roughness are measured at 2-year intervals, 1989 being the most recent measurement year. Roughness is measured using automated equipment that records data at 0.3-km (0.2-mi) intervals. Strip charts showing the variation of an example set of pavement attributes along the length of the road are included in Figure 2.

Table 1 presents a summary of the inventory data for Road 491. Two segments are required to store the inventory data because of the change in lane widths at a point 1.93 km (1.22 mi) from the beginning. Table 2 gives the structural data for Road 491. Three segments are required here because of the change in construction type at 1.93 km (1.22 mi) and the change in surface type at 6.1 km (3.8 mi). Note that the breaks for the structural data segments need not match the breaks for the inventory data segments.

The traffic data for Road 491 are presented in Table 3. Only two segments are required because there is only one change in traffic volume along the length of the road. Note that the date of the traffic data measurement is also included in the data base to permit storage of a historical series. Table 4 gives a summary of the roughness data for Road 491. Roughness is quantified in terms of an arbitrary index ranging from 0 (poor) to 5 (good). The automated equipment used to measure roughness collects data at 0.2-mi intervals. Two segments of uniform roughness values are determined from the measured data points. The roughness values will vary along the length of the road, but the data can be aggregated into segments along which the roughness is "uniform" within a specified tolerance band.

The variable length segmentation given in Tables 1 through 4 for each set of attributes permits the pavement attributes to be organized in a more natural structure than is possible with conventional approaches. The segmentation for any one set of attributes is not necessarily congruent to the segmentation for any other set of attributes. Each set of attributes with its corresponding segmentation would be stored as a separate table under a relational data base scheme. Each table would be indexed using a sorted concatenation of the road number plus the year, if appropriate (e.g., for traffic and roughness), and the beginning milepoint.

For budget forecasting, however, the analysis algorithms still require segments along which *all* primary pavement attributes are uniform (secondary attributes—for example, curbing—can be allowed to vary along a segment). Logical segments meeting this requirement can now be easily constructed on the fly from the variably segmented pavement attribute data; this is the "dynamic" part of the dynamic segmentation scheme. Each component data table (Tables 1 through 4) is scanned to generate a master list of segment breaks for the road; this master list defines the analysis segments, and this set of segments remains in effect throughout the analyses and forecasts (and, in fact, until updates to the data base dictate regeneration of the segments). A summary of the three segments for this example is found in Table 5 (we assume here that all pavement attributes in Tables 1 through 4 are primary attributes for determining segment breaks—that is, there are no secondary attributes). Note that for each segment, all primary pavement attributes are constant.

In reality, only the segment location reference data (road number plus beginning and ending points in Table 5) would need to be stored separately for each segment, because the attribute data (all data to the right of the vertical bar in Table 5) can be extracted directly from the component data tables (Tables 1 through 4).

TABLE 1 Inventory Data, Road 491

Road Number	Kilometer Point Begin	Kilometer Point End	Road Class	Lanes	Surface Width (meters)
491	0.00	1.93	Secondary	2	6.1
491	1.93	8.05	Secondary	2	7.3

TABLE 2 Structural Data, Road 491

Road Number	Kilometer Point Begin	Kilometer Point End	Surface Type	Construction Type
491	0.00	1.93	AC	Flexible
491	1.93	6.12	PCC	Rigid
491	6.12	8.05	AC	Rigid

TABLE 3 Traffic Data, Road 491 (1989)

Road Number	Kilometer Point Begin	Kilometer Point End	Year	AADT
491	0.00	6.12	1989	1000
491	6.12	8.05	1989	2000

TABLE 4 Roughness Data, Road 491 (1989)

Road Number	Kilometer Point Begin	Kilometer Point End	Year	Roughness Index
491	0.00	1.93	1989	2.5
491	1.93	8.05	1989	3.9

Pavement Performance Models

The ability to develop annual programs based on current information and to prepare multiyear plans requires the use of forecasting models and curves. Families of models are generally developed for combinations of pavement types and designs, traffic levels, subgrade and materials characteristics, and environmental conditions. Development of the most reliable and specific models requires extensive inventory, design and construction history, condition history, climatic, and traffic data. Some of these data may be difficult to obtain, particularly the numbers of equivalent single-axle loads (ESALs) that the pavement has been subjected to since construction or rehabilitation. PMAP contains models for projecting traffic and forecasting the structural and functional condition of each pavement section based on the best available data for Delaware. Figure 3 is a family of interim models and curves to forecast surface distress index (SDI) for various types of pavements and age since new construction or last rehabilitation. Because of limitations on available data, these interim models do not distinguish between different traffic/ESAL levels. However, all PCC pavements are on roads with medium to high traffic levels, and all surface treatment pavements are on roads with low traffic levels. Provisions are included to consider low, medium, and high traffic/ESAL levels by the feedback process as future data are collected and entered in the data base.

Development of annual pavement reconstruction, rehabilitation, and resurfacing projects has been based on condition data that were 2 or more years old and might have contained some inaccurate information because previously programmed projects were not completed as programmed. And previously programmed projects were eliminated from the prioritized list manually. The PMAP program automatically updates the most recently collected traffic and pavement condition data to the program year using the forecasting models. It also automatically includes forecasted condition data for previously programmed sections. Provisions are being made for an up-to-date field inventory of completed rehabilitation and resurfacing projects by laptop computer to record actual rather than programmed details of the project.

Safety and Service Improvements

A major function of a PMAP is the capability to priority rank pavement reconstruction and rehabilitation projects for the next annual program and to forecast needs for multiyear planning purposes. The DelDOT Office of Planning prepares a Capital Improvement Program (CIP) each year that becomes the basis for the next fiscal year legislative allocations for all transportation projects. The CIP identifies multimodal planning studies; corridor/noncorridor road improvements; bridge replacement and rehabilitation projects; railway improvements; public transportation projects; pavement reconstruction, rehabilitation, restoration, and resurfacing projects; safety and drainage improvements; and aeronautics projects. Although this project was initiated to develop and implement a customized DelDOT PMS, PMAP as developed is much broader in scope. Besides ranking pavement projects, it identifies corridor/noncorridor road service needs on the basis of traffic projections and safety improvement projects. The road service needs are based on volume-to-capacity ratios computed for each segment using traffic capacity of the segment. The safety improvement projects are identified by the critical accident ratio, defined as the number of accidents per 0.3-mi road segment per year divided by the average number of accidents per 0.3 mi per year of similar traffic and road classifications. Combining these functions in PMAP avoids the programming of a pavement section for major reconstruction

TABLE 5 Pavement Management Segments, Road 491 (1989)

PMS Segment	Road Number	Kilometer Point Begin	Kilometer Point End	Road Class	Lanes	Surface Width (meters)	Surface Type	Const'n Type	AADT	Roughness Index
121	491	0.00	1.93	Sec'y	2	6.1	AC	Flex	1000	2.9
122	491	1.93	6.12	Sec'y	2	7.3	PCC	Rigid	1000	3.9
123	491	6.12	8.05	Sec'y	2	7.3	AC	Rigid	2000	3.9

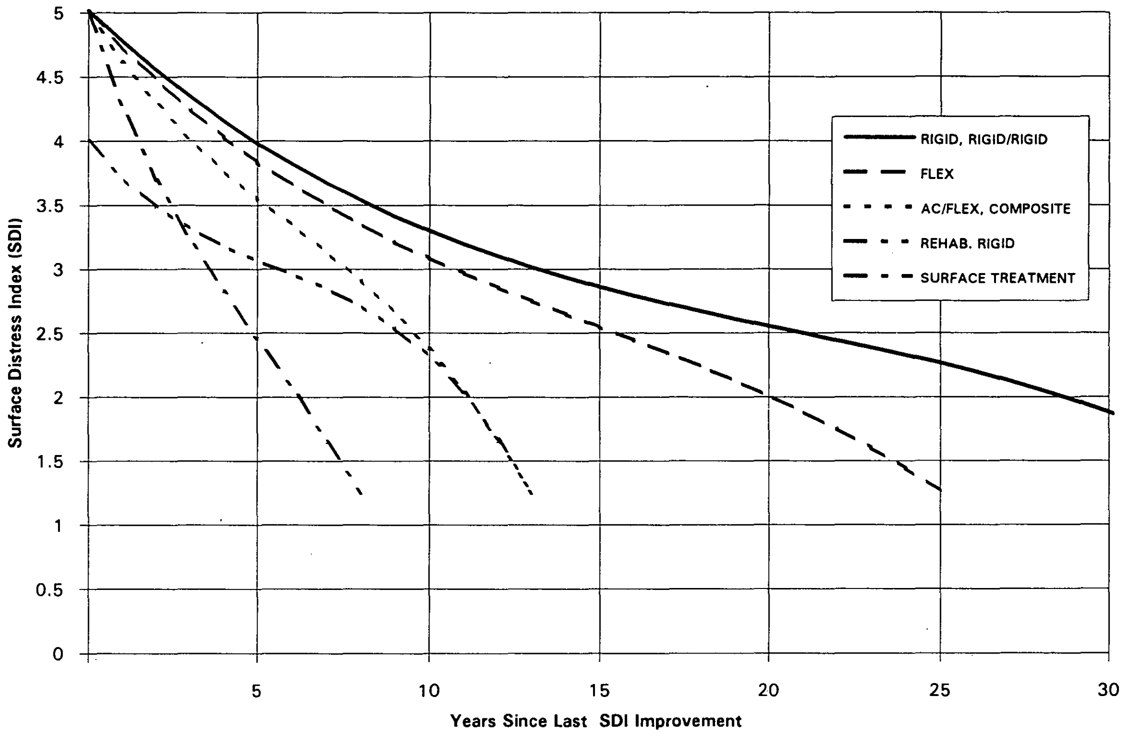


FIGURE 3 SDI forecast models.

or rehabilitation that will soon be in need of service or safety improvements.

Data Collection Evaluation

The reports produced by the PMAP are tools used by decision makers. The usefulness of these tools is greatly influenced by the quality of the data collected, entered in the data base, and used in the analysis process. The PCS/Law project included an evaluation of the current DelDOT pavement condition data collection equipment and procedures. This evaluation noted that pavement surface friction is collected with a locked-wheel trailer of the type specified by AASHTO 242-90 and that the resulting data are suitable for use in the PMAP. Pavement surface distress data are collected by visual (windshield) survey continuously. The distress type, severity, and extent are entered in a computer program by laptop keyboard and a SDI computed as a 0 to 5 statistic. The SDI data are adequate for use in the PMAP now, but use of video equipment for collection and analysis of pavement surface distress should be considered in the future.

The project identified the primary pavement condition data collection concern as the need for improved ride/roughness data for operation of the PMAP. Existing DelDOT data are the ride comfort index (RCI) collected by use of a trailer with a single accelerometer and a computer program for producing the RCI values of 0 to 5. A review of all RCI data collected in 1990 and 1991 indicates that more than half of all pavement sections in Delaware have an RCI of 1.5 or less. On the 0 to 5 scale, the 1.5 value would be a very rough riding pavement, but this is not consistent with the subjective evaluation of most roads in Delaware.

To provide some background information on ride/roughness data collection equipment and procedures, a small correlation study was conducted cooperatively between DelDOT, the University of Delaware, and PCS/Law. Thirteen pavement sections of various types and ride/roughness levels were selected for the study. Ride/roughness data were collected on each section with the North Atlantic Region Strategic Highway Research Program (SHRP) profilometer, the PCS/Law South Dakota type profiler, and the DelDOT trailer-mounted equipment using both the single and double accelerometer modes.

Various forms of international roughness index (IRI) statistics were computed from the profile data collected by all three pieces of equipment. Ride number (RN) values were also computed from the profile data collected by the SHRP profilometer and PCS/Law profiler. It should be noted that all profile data were subjected to a 152-m (500-ft) wavelength filter. The spacing between the wheelpath sensors is 165 cm (65 in.) on the SHRP profilometer and 175 cm (69 in.) on the PCS/Law profiler.

The accelerometers are mounted at the midpoint between the wheels of the DelDOT equipment, resulting in the IRI values' being based on a half-car simulation. The IRI values from profile data collected by the SHRP profilometer were calculated as left wheelpath and right wheelpath values using a quarter-car simulation and the mean of the two values used as the section IRI.

Table 6 contains the computed data for the test sections. The RCI values are computed from DelDOT data equipment operated in a single accelerometer mode and currently used by DelDOT as the pavement ride/roughness rating. Section 13 is an asphalt surface treatment pavement, and Section 16 is a rehabilitated concrete pavement. Profile data were not

TABLE 6 Computed Ride/Roughness Values

Type	Sec.	PI	RN (Eq. 1) (SHRP)	RCI (Eq. 2) (PURD)	IRI (PURD)	Mean IRI (LAW)	Mean IRI (SHRP)
Concrete	1	0.0385	2.09	0.526	4.72	4.28	5.49
	2	0.0290	2.54	1.694	3.11	3.36	3.35
	3	0.0336	2.32	0.710	3.87	4.20	4.01
	4	0.0340	2.30	0.589	3.06	3.44	3.22
	5	0.0070	4.19	3.600	1.34	1.56	0.85
Asphalt	6	0.0067	4.22	4.221	1.64	2.27	0.87
	12	0.0103	3.88	2.808	1.39	1.44	1.48
	14	0.0285	2.59	0.823	3.27	3.95	3.38
Overlay	7	0.0194	3.16	1.242	2.40	2.83	2.48
	10	0.0360	2.20	0.187	2.68	3.28	2.65
	11	0.0662	1.17	0.002	3.46	4.17	4.23
	13	0.0435	1.88	0.225	3.77	4.96	4.77
	16	0.0262	2.72	0.543	3.84	---	4.02

collected on Section 16 by PCS/Law equipment. Calculated values are generally based on an average of five sets of data per site. As indicated in Figure 4, there is reasonable good general correlation between IRI values computed from the pavement profiles collected by SHRP and PCS/Law equipment and the DelDOT equipment.

For use in the DelDOT PMAP program, it is recommended that the RN statistic for pavement ride/roughness replace the RCI currently used. Both RCI and RN are 0 to 5 statistics.

The following table contains correlations between RN and IRI on the basis of very limited data collected and analyzed for this paper:

Pavement Ride and Roughness Range	*RN*	*IRI*
Smooth	5.0 to 3.5	0 to 2.0
Medium	2.4 to 2.5	2.0 to 3.4
Rough	< 2.5	> 3.4

It is recommended that a more extensive correlation study be conducted using future data from the PMAP data base. The same values were calculated from the PCS/Law profiler data plus a half-car simulation IRI. The RN values were computed using the model

$$RN = -1.74 - 3.03 \log (PI)$$

from *NCHRP Report 275* (*5*), in which

$$PI = \{[RMS(P_r)]^2 + [RMS(P_l)]^2\}^{0.5}$$

where

- RMS = root mean square of vertical acceleration,
- P_r = measured displacement amplitude of right wheelpath for pavement wavelengths 0.5 to 2.4 m (1.6 to 8 ft), and
- P_l = measured displacement amplitude of left wheelpath for pavement wavelengths 0.5 to 2.4 m (1.6 to 8 ft).

A Fourier analysis process was used to remove pavement profile wavelength content shorter than 0.5 m (1.6 ft) and longer than 2.4 m (8 ft).

It is acknowledged that this is a very limited study. However, Figure 5 does indicate the good correlation between RN

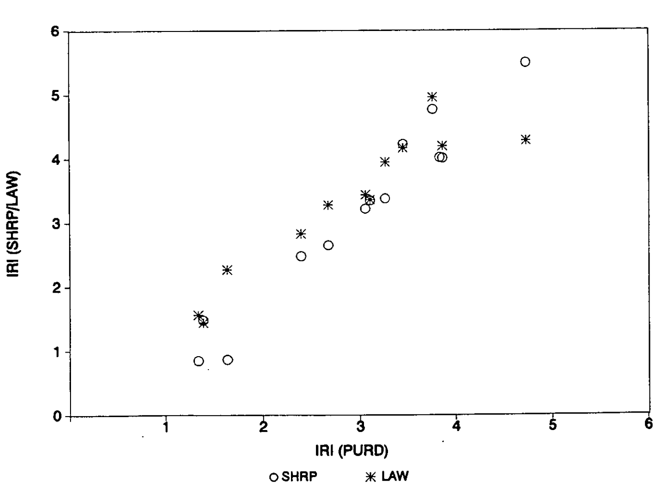


FIGURE 4 IRI from SHRP and PCS/Law equipment profiles versus IRI from DelDOT equipment profiles for all pavement sections.

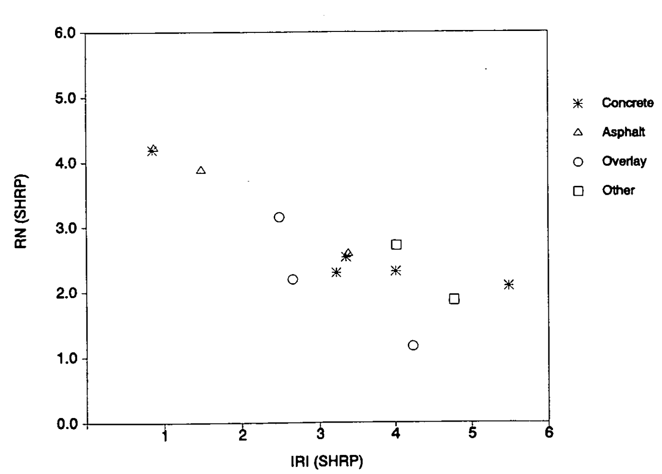


FIGURE 5 IRI versus RN values computed from SHRP profiles.

values, shown by previous NCHRP research to be highly correlated with mean panel ratings (the public perception of the ride quality) and IRI values, particularly at RN values of 2.6 and greater for different pavement types.

Report Generation

Standard reports (e.g. inventory data, budget analysis results) can be generated as tabular summary (spreadsheet) or detailed reports. In addition to standard reports, PMAP provides the capability to create "custom" reports interactively and to save the user-defined custom report formats. Any data element within the data base can be included in a custom report, and all formatting details (column headings, field widths, number of decimal places, etc.) are obtained from the PMAP data dictionary. All tabular reports can be viewed interactively on the screen, sent to the printer, and saved on disk in a form suitable for export to other programs or to other computer systems, including decentralized systems located within individual maintenance districts.

A wide range of color pie charts, bar/column charts, and *x-y* graphs can be generated within PMAP. The user has complete flexibility in defining charts: the user selects the subset of road segments to be displayed, the chart type, the parameters to be displayed along the various axes, and the details of the chart format (colors, headings, etc.). For pie charts, one data element is selected from the list, and the user specifies whether the pie chart is computed in terms of centerline miles, lane miles, or surface area (in either absolute units or percentage terms). For bar/column charts, multiple data series can be displayed on a single chart; one data element is selected for the category (horizontal) axis, and a second is selected to define the series.

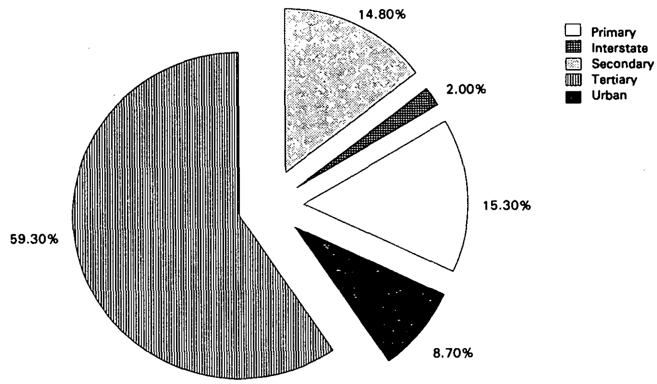


FIGURE 6 Federal aid classifications, all maintenance roads.

X-y graphs are typically used in PMAP to display forecast costs or conditions as a function of time. All charts can be viewed on the screen, sent to a color printer (e.g., HP PaintJet), and saved for later viewing or printing. Figures 6 through 8 are examples of color graphics produced by PMAP (reproduced in black and white in this paper).

Detailed color-coded maps summarizing any data in the PMAP data base can be quickly generated and examined using PMAP. The user selects the subset of road segments to be displayed, the data attributes to be displayed (e.g., "roughness index" and "AADT"), and other formatting details. Up to two attributes can be specified for each map: the first is displayed using color, and the second using line width. Complete zooming, panning, and labeling capabilities are provided. In addition, the PMAP user can point to any road segment with the mouse and activate an inquiry window summarizing the characteristics of that segment. Maps can be viewed on the screen, sent to color printer or a plotter, and saved to later viewing, printing, or plotting. Optional capa-

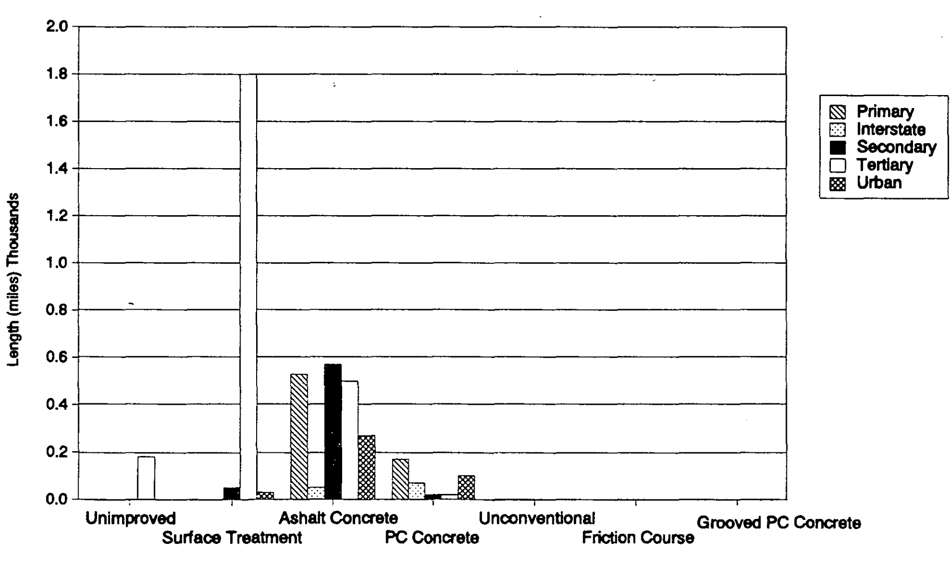


FIGURE 7 Miles of surface type by federal aid classification, all maintenance roads.

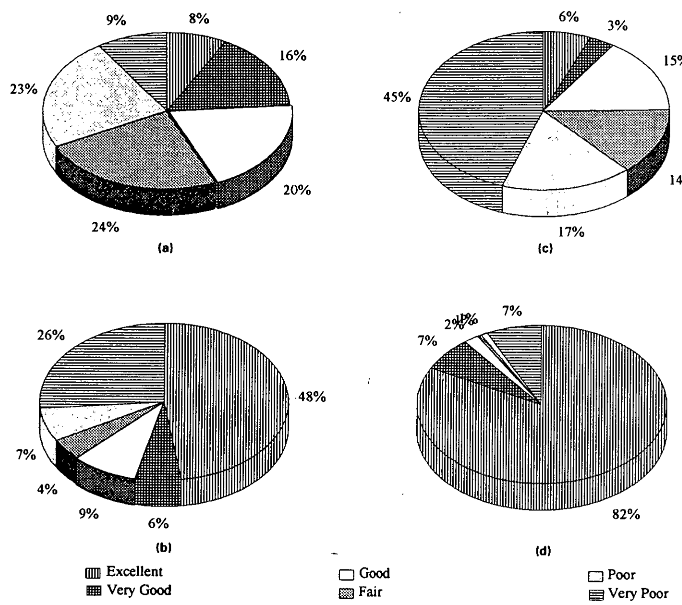


FIGURE 8 SDI, Maintenance Area 8, current condition and example funding scenarios: *a*, 1992 SDI; *b*, 1996 SDI, reallocation of funds; *c*, 1996 SDI, planned budget; *d*, 1996 SDI, increased budget.

bilities include the export of maps to other graphics and mapping programs (e.g., AutoCAD, MapInfo).

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