GIS Applications in Airfield Pavement Management

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Access, management, and analysis of the voluminous data associated with pavement networks at large commercial airports are critical issues constraining the effectiveness of airfield pavement management. In order to address these problems, concepts from the fields of geographic information systems (GISs) have been coupled to established pavement analysis techniques to create a network-level planning tool, the Integrated Airport Pavement Management System (IAPMS), for the management of airfield pavement management systems. The IAPMS has recently been implemented at John F. Kennedy International, LaGuardia, and Newark International airports, which are operated by the Port Authority of New York and New Jersey. These three airports collectively represent the largest and busiest air transport complex in the world. The suitability of selected GIS techniques to airfield pavement management is assessed, noteworthy features of the IAPMS software are briefly described, and the implementation experience at the New York–area airports is summarized.

Access, management, and analysis of the voluminous data associated with large-scale airfield pavement networks are critical issues constraining the effectiveness of airfield pavement management. Most of the required information has already been collected by the pavement engineering staff, but it exists in a wide variety of formats, e.g., drawings, tables, charts, narratives, and personal experience. The pavement management technical staff must organize these data into forms suitable for analysis, input the various sets of data into the engineering and forecasting models, and finally format the results for interpretation by the diverse (and often nontechnical) groups involved in the decision-making process. Constraints on time and resources inevitably limit the quality of the analyses and the consequent decisions.

In order to address these problems, selected concepts from the field of geographic information systems (GISs) have been coupled to established pavement analysis techniques to create a network-level planning tool, the Integrated Airport Pavement Management System (IAPMS), for the management of airfield pavement systems. The IAPMS not only provides immediate access to all pavement engineering data but also allows various data sets to be merged and automatically passed to the pavement analysis algorithms embedded within the system. This, combined with GIS display capabilities, enables the engineer or planner to perform parametric studies quickly and economically and to synthesize and interpret the results efficiently, leading to better and more cost-effective pavement management.

The IAPMS has recently been implemented at the John F. Kennedy International, LaGuardia, and Newark International airports located in the New York metropolitan area and operated and maintained by the Port Authority of New York and New Jersey (PANY/NJ). These three airports collectively represent the largest and busiest air transport complex in the world. The pavement conditions at these airports span an extremely wide range of pavement construction types, materials, traffic levels, and construction histories.

GIS ASPECTS OF AIRFIELD PAVEMENT MANAGEMENT

Although various definitions have been suggested for GISs (*1,2*), most full GIS implementations consist of a data base containing spatial and other attribute data, routines for performing spatial as well as conventional queries and analyses of the data base contents, and display systems for presenting the results of queries and analyses in a geographic context. Applications of the GIS to transportation engineering have been discussed by Simkowitz (*3*), Petzold and Freund (*4*), Abkowitz et al. (*5*), and others. The general benefits of a comprehensive GIS approach for transportation-related data base applications can be grouped into three categories:

- Data Integration. Most elements stored in a transportation data base are tied to a particular geographic location or topology (point, line, or area); keying all data to a common geographic reference system (e.g., latitude and longitude) permits combination of disparate data bases (e.g., road inventory, traffic accident, and population). A much richer and more powerful set of data analyses can be applied to these combined data bases than to each individually.
- Data Access and Display. In many applications, it is far simpler to query data for an individual transportation feature (e.g., pavement section) by pointing (e.g., with a mouse) to a geographic display of the transportation network than it is to issue a text-oriented query on the basis of a key identifier of the feature. More important, though, is that the visualization of results by color-coded geographic displays of the pavement network enables more powerful interpretations and syntheses than are possible from text-based reports.
- Data Analysis. A full GIS offers a rich set of tools for spatial analysis of the information stored in the data base. A partial list of these tools includes the following:

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—Map coordinate manipulation (scaling, shifting, stretching, rotating, and map registration);

—Spatial queries (nearest item to a point, all items within a specified distance or boundary, etc.);

—Statistical summaries (e.g., histograms of attribute values by area);

—Area, length, or volume calculations;

—Spatial aggregation;

—Map overlays and dissolves (intersections and unions of spatial features);

—Buffer generation;

—Three-dimensional analyses (if elevation data are included in database), including contouring, slope calculations, grading analyses, and watershed analyses; and

—Network analyses (vehicle routing, time and distance analyses, shortest path determination, etc.).

Most GIS software provides a basic set of spatial query and analysis tools and permits the addition of user-supplied analysis routines for specific applications.

A wide variety of general-purpose full-function GIS software packages currently exists (*6*), and many either can be or have been adapted to transportation engineering applications. Several states (e.g., Wisconsin, North Carolina, and Tennessee) are currently developing GIS-based applications for highway pavement management. However, little attention has been devoted to GIS-oriented applications for airfield pavement management. Airfield and highway pavement management share many features: both deal with a spatial network of pavement sections having extensive attributes of geometry (length, width, shape); structure (layer thicknesses, strengths); condition (visual distress, roughness, friction); traffic (volume, mix); and history (construction, maintenance, and repair or rehabilitation). The pavement engineering analyses are only slightly different for the two types of pavements because of the different traffic characteristics, performance requirements, and design standards.

The more significant difference between airfield and highway pavement networks for GIS applications, however, is the nature of the networks themselves. Airfield pavement networks contain many fewer pavement sections than do highway networks, and for regional- or state-wide airfield systems these sections tend to be more clumped than in the highway case, i.e., they are clustered at geographically dispersed and noninterconnected airport locations, as opposed to the more uniform geographical distribution that is characteristic of highway pavement networks. The data attributes associated with the smaller airfield pavement network also tend to be more complete and less diverse in terms of content and format than those for highways, reducing the importance of the data integration benefits of GIS.

Airfield pavement management does not require many of the spatial analysis capabilities found in a full GIS, such as contouring and slope calculations or buffer analysis. The GIS features most relevant to airfield pavement management are those dealing with data access and interpretation. The interactive geographic display of a GIS is an effective interface for selecting sets of pavement sections for data queries and analyses or for selecting sets of airfields for study from a state or regional airport system. More important, the display of pavement existing conditions and performance predictions as color-coded maps greatly assists the interpretation and synthesis of data that are distributed in both space and time. This is an important tool not only for the engineering staff responsible for maintaining the pavements but also for the management personnel responsible for setting policies and priorities and for developing multiyear budget and planning documents.

In short, airfield pavement management is a relatively well-defined and self-contained application as compared with highway pavement management. The generally complete, high-quality pavement data at most major airports permit comparatively sophisticated engineering analyses and predictions of the pavement performance. Although many features of a full GIS are not required, the spatial data query and display capabilities are valuable aids in the engineering and management decision-making process. In our work, this limited set of GIS capabilities has been combined with extensive database and pavement engineering routines to produce the IAPMS.

IAPMS OVERVIEW

The IAPMS is a self-contained software package designed to run on an i386-class desktop computer. A major consideration during the design of the software was the recognition that the system will typically be used on only an occasional basis and by a pavement engineer or planner who is not a computer specialist. Consequently, much attention was devoted to developing a consistent and easy-to-use menu-driven interface with forms-based data entry and editing screens to shorten both the initial and refresher learning curves for the system. An extensive context-sensitive on-line help system is also included to minimize the need to refer to any separate hard copy documentation.

Most data in IAPMS can be displayed in a variety of formats: tabular or text summaries, graphical displays (variations over time, etc.), and color-coded maps of the pavement network. Multiple what if? scenarios can be displayed in the same graphical format for quick side-by-side comparisons of various pavement management alternatives. Complete hard copy (text, black-and-white graphics, and color graphics) is available for all display and reporting routines on a variety of printer and plotter types.

A summary of the major IAPMS functions is shown in Figure 1. The data base management functions—data entry, editing, and display—enable the user to create a data base, enter or edit information in an existing data base, and examine the data base contents by screen or hard copy outputs. The IAPMS analysis and forecasting functions focus on key pavement management issues related to pavement condition, traffic, maintenance and rehabilitation (M&R) needs, and budget estimates. These functions, which are the core of the IAPMS system and approach, have been designed to address typical what if? scenarios such as:

> Given present pavement conditions, traffic, construction costs, and minimum pavement performance levels, what are the M&R needs and associated budgets over the next 1, 5, 10 (or more) years?
>
> What effect will budget constraint level have on M&R activities and pavement condition in the future?

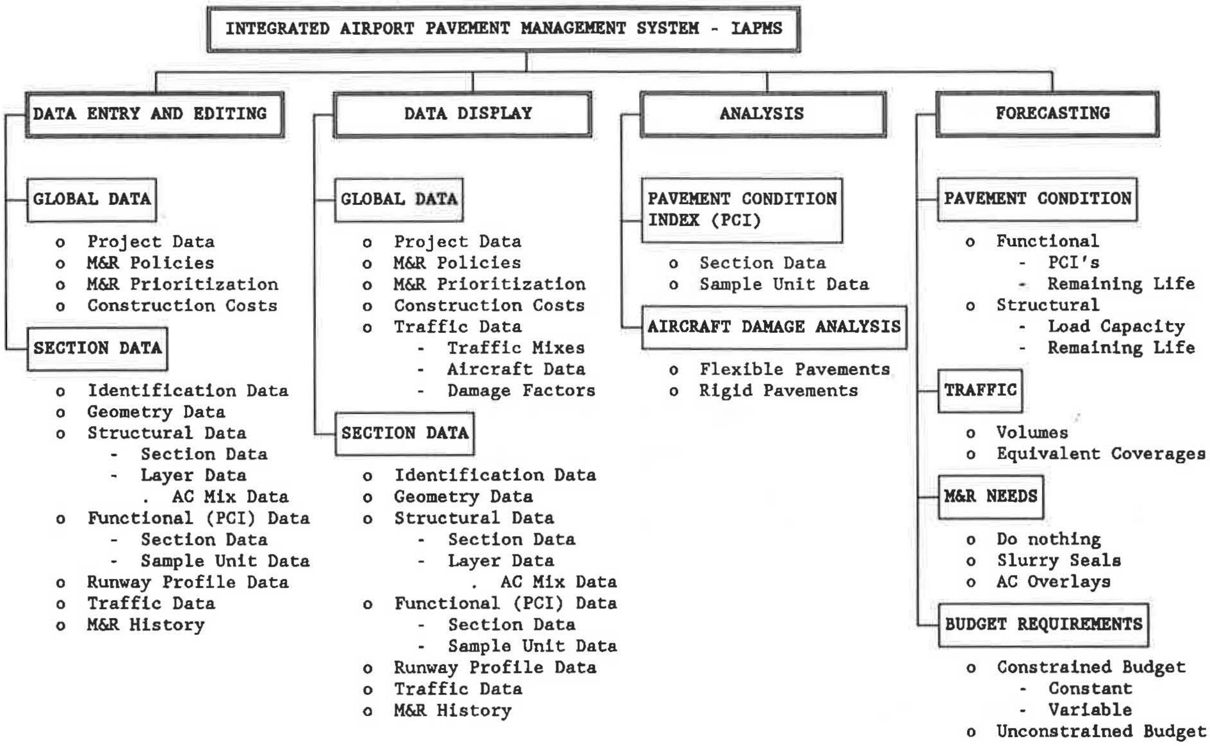

FIGURE 1 IAPMS functions.

What impact will traffic changes (volume and/or aircraft type/mix) have on pavement performance and M&R budgets in the future?

What are appropriate intervention levels and prioritization factors for M&R activities, given budget constraints and target pavement performance levels?

Figure 2 shows the major components of IAPMS. The following sections will describe some of the details of the database and the analysis and forecasting components and the GIS-related aspects of the user interface and display/report components.

DATA BASE STRUCTURE

The IAPMS data base is the repository of all pavement information for the airfield network. The overall design of the data base structure was based on the particular characteristics of airfield pavement networks and pavement-related data. First, in contrast to highway networks, airfield pavement networks consist of relatively few sections but with generally more complete and extensive information. Second, the pavement data are strongly hierarchical in nature; at the highest level is information pertaining to the entire airport (e.g., M&R policies, construction unit costs), with successive levels of refinement terminating at data associated with individual observations (e.g., field measurements from an individual nondestructive evaluation test). Third, the geographic layout of an airport pavement network is relatively stable; pavement sections are only rarely added or removed from the inventory. Last, historical information must be maintained for much of the data (e.g., construction activity, visual surveys), with new data being added to rather than replacing the prior data.

Given these characteristics, the IAPMS data base is organized in the hierarchical indexed structure illustrated in Figure 3. Level I contains all information common to all pavement sections at the airport. It includes data identifying the specific airport (Level IB); policies for selecting M&R activities based on pavement rank, pavement condition index (PCI), and remaining life (Level ID); unit construction costs for M&R activities (Level IE); landing gear weights and configurations for over 100 different aircraft types (Level IF), aircraft mixes for standardized predefined traffic mixes (Level IG), project priority factors based on pavement rank, PCI, and remaining life (Level IJ), and default parameters for PCI forecasting for various pavement construction categories (Level IK). Level IA provides index information for the lower levels in the hierarchical structure; specifically, it contains pointers to Level II data for each individual section.

Level II in the data base contains all data pertaining to an individual pavement section. By definition, all Level II data are explicitly linked to a specific geographic entity—a polygonal pavement section. Level II includes general inventory data for each section (Level IIA), layer thicknesses and material types (Level IIB), section PCI data, including a summary of the individual distresses found in the survey sample (Level IIC), numbers of arrivals and departures and the associated standard aircraft mixes for each pavement section (Level IID), a history of all M&R activities by contract (Level IIE), x–y coordinates defining the plan geometry of the section (Level IIF), and surface roughness data (Level IIG). In most instances, the Level II pavement section data are or-

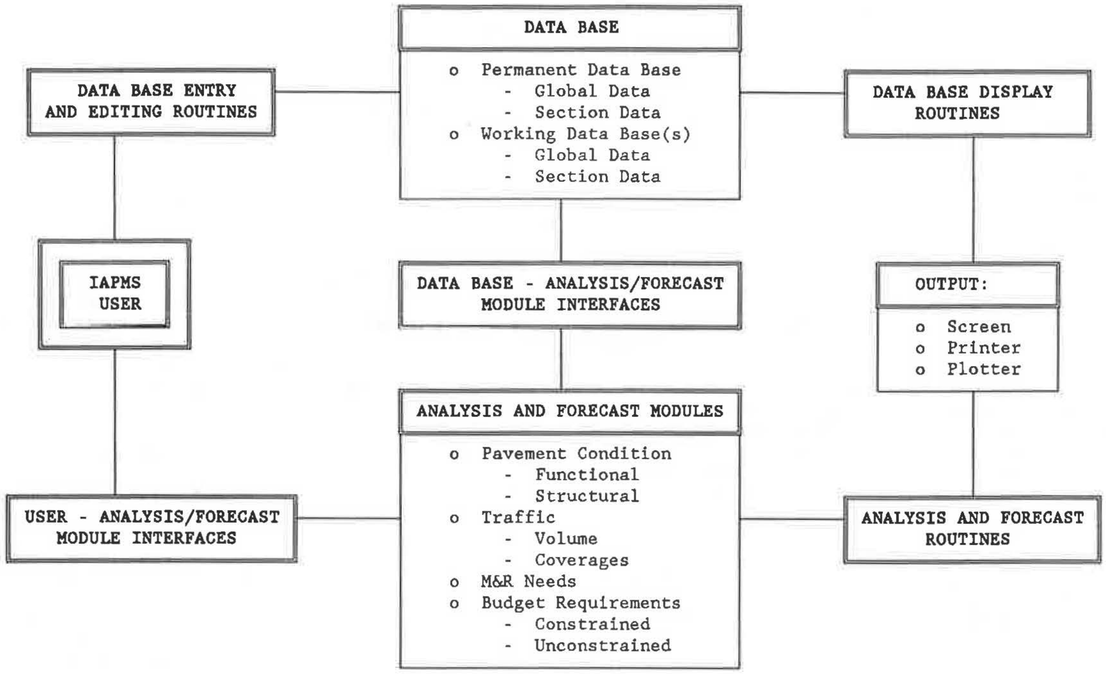

FIGURE 2 IAPMS components.

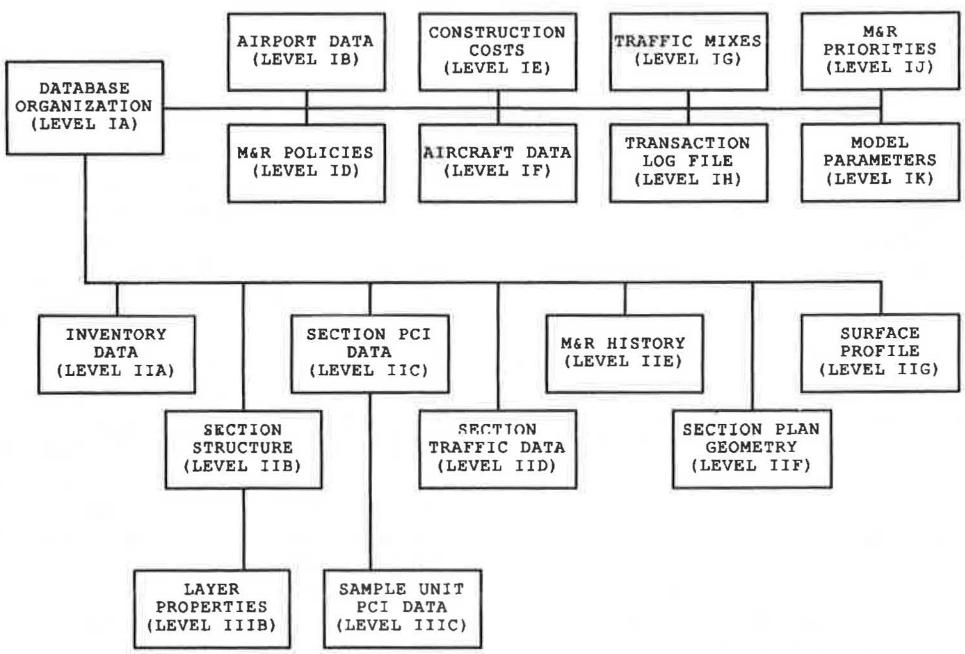

FIGURE 3 IAPMS data base structure.

ganized as linked lists to allow for changes in pavement structure, conditions, traffic, and other factors over time. The section structural and PCI subsections of the data base also contain pointers to supporting data in Level III.

Level III, currently the lowest level in the data base hierarchy, contains supporting information for the pavement section data in Level II. At present, Level III encompasses the detailed engineering properties—modulus, CBR values, variability, etc.—for each layer in the pavement structure (Level IIIB) and the sample unit data from the PCI visual distress surveys (Level IIIC). Some Level III data are intended for regular access by the IAPMS algorithms (e.g., Level IIIB), while others can be unloaded after the corresponding section-level data have been derived (e.g., Level IIIC).

Future plans include a Level IV in the data base that would contain supporting data for the Level III information. An example of this would be test data from nondestructive pavement evaluation studies; these data would be used to estimate the pavement section layer properties in Level IIIB. Level IV data would typically be georeferenced to particular locations within the pavement section.

In many instances, the information stored in the IAPMS data base includes not only the data value but also the date it was last modified, the source of the data (e.g., field tests and experience-judgment), and a cross-reference to more detailed supporting information (e.g., a particular contract or field investigation report). A complete log is maintained for all changes to the data base; this transaction log summarizes what was changed, who changed it, and when it was changed. The log assists in audits of the data base and in maintaining data base integrity.

The structure and contents of the IAPMS data base typically exist in both a permanent version and one or more temporary or working copies that are either exact or modified versions of the permanent data base. Multiple working data bases can be created for a given pavement network, permitting the user to conduct numerous what if? analysis scenarios without risk of corrupting the master data base. Although any copy of the IAPMS software can generate and modify the working copies of the data base, only the master version of the software can update the permanent data base.

ANALYSIS AND FORECASTING

The IAPMS analysis and forecasting modules provide a powerful and versatile set of tools for addressing key pavement management issues. A flowchart of the interrelationships between the various analysis and forecasting components is shown in Figure 4. The principal components can be summarized as follows:

- Pavement Evaluation Module. This module consists of two major submodules: (a) the Functional Condition Module used in analyzing visual distress survey data following the PCI approach (*7*) and forecasting of section-level visual distresses and prediction of time to functional failure; and (b) the Structural Condition Module used for evaluating the load-carrying capacity of the pavement (*8*) and, together with the Traffic Mix Module, for determining the structural remaining life, the structural condition factor, and the time to structural failure.
- Traffic Mix Analysis Module. This module is used to convert a mix of aircraft types (weights, gear configurations, and frequencies) to equivalent standard aircraft coverages for a given pavement structural capacity and foundation support value; it is applied to the complete traffic history to determine the loading history for the pavement.
- M&R Analysis Module. This module is used to select appropriate M&R activities given a set of pavement conditions and intervention levels; if a structural overlay is required, it determines the overlay thickness following FAA procedures.
- Budget Analysis Module. This module is the combination and culmination of all of the other analysis and forecasting modules; it is used to estimate project costs for activities selected in the M&R Analysis Module and to rank projects according to user-specified M&R priority factors. Budget analyses can be performed in either an unconstrained (i.e., needs assessment) or constrained (i.e., limited-budget) mode; in a constrained budget analysis, low-priority projects may be postponed to subsequent years (with consequent continuing deterioration of condition).

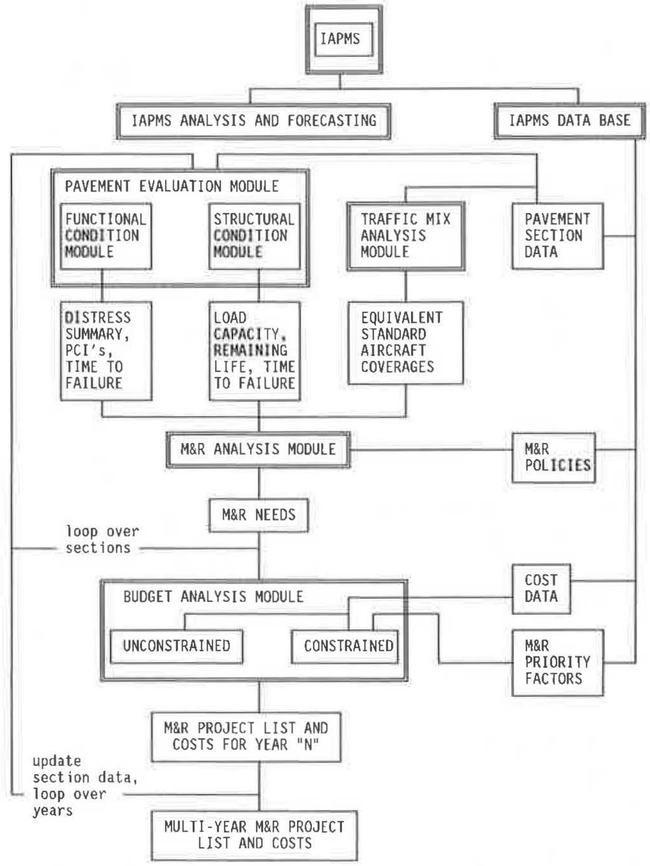

FIGURE 4 IAPMS analysis and forecasting modules.

GIS FEATURES IN IAPMS

As described previously, airfield pavement management does not require all of the capabilities found in a full GIS implementation. The GIS features of most use to airfield pavement management deal principally with selection (for query or analysis purposes) of pavement sections by geographic location and the geographic display of the data base contents and the analysis and forecasting results. Both of these operations require detailed map data for the pavement sections in the network.

Map data for Kennedy, Newark, and LaGuardia airports were developed by manually digitizing engineering drawings of the pavement network layout. Digitizing was performed after the pavement network had been delineated into homogeneous sections for pavement management purposes, so the map data could be referred directly to individual sections as Level II data in the data base. Because no consistent reference coordinate grid had been established at the airports and the map data were intended only for internal use in IAPMS, the map data were stored in arbitrary x–y coordinates. An interactive graphics editor is built into IAPMS to enable modifications of the map data and to enter geographic data for new pavement sections added to the network.

All data in the system can be displayed for a single section, for a group of sections, or for all sections in the network. Groups of sections can be selected according to feature, pavement rank, usage, construction type, or other parameters as requested by the user. For more complicated groupings, sections can be selected graphically using a mouse to pick individual sections from a map display of the pavement network. These pick operations are aided by the zoom and labeling options in the IAPMS geographic display routines.

The geographic displays of pavement data and analysis and forecasting results provide a concise and visually clear summary of the overall condition of the pavement network as well as a powerful tool for interpretation and synthesis of analysis results. Figure 5 shows an example of a geographical display of simple inventory data for the network, in this case the pavement construction types for Kennedy Airport. (The actual maps generated by IAPMS—both on screen and hard copy—are typically in color; they were generated using the cross-hatched monochrome option because of publishing constraints.) The results for current equivalent traffic volumes in terms of a standard Boeing 747 aircraft as determined from a traffic mix analysis are shown in Figure 6 for LaGuardia Airport.

Alternative pavement management policies can be easily evaluated and compared using the geographic display capabilities in IAPMS. For example, Figure 7 shows the projected overall pavement condition in terms of PCI for Newark Airport in 1995 assuming a high budget level for pavement maintenance and repair; this projection implicitly reflects all benefits resulting from the IAPMS-recommended M&R projects during the intervening period of 1990 through 1994 (i.e., the system assumes that all M&R activities recommended during all years are actually performed). Figure 8 shows the corresponding projected pavement condition for an alternative pavement management scenario of very limited M&R budgets. In addition to the spatial distribution of PCI across the network, the system also calculates an area-weighted PCI value using the geographic data.

Project grouping is a difficult problem for any pavement management system. Pavement sections recommended for M&R activities are distributed both in space and time. Neighboring pavement sections that require some type of M&R treatment over a specified time interval should be clustered and treated as a group at the same time, either with the same or different M&R procedures. Project clustering requires a generous amount of engineering experience and is thus difficult to automate. However, maps illustrating forecast M&R activities (e.g., Figure 9), when generated for a series of years in a budget forecast, can greatly aid the pavement engineer in developing project groupings.

IMPLEMENTATION EXPERIENCE

In 1980, the PANY/NJ began work to develop and implement a pavement management system for the three major commercial airports under its control. This program led to the development and pilot implementation of IAPMS by Pavement Consultancy Services of Law Engineering (PCS/Law) at John F. Kennedy International Airport in 1988. A brief description of this pilot implementation is given by Grimaldi et al. (*9*) and Rada et al. (*10*). Phase 2 implementation of

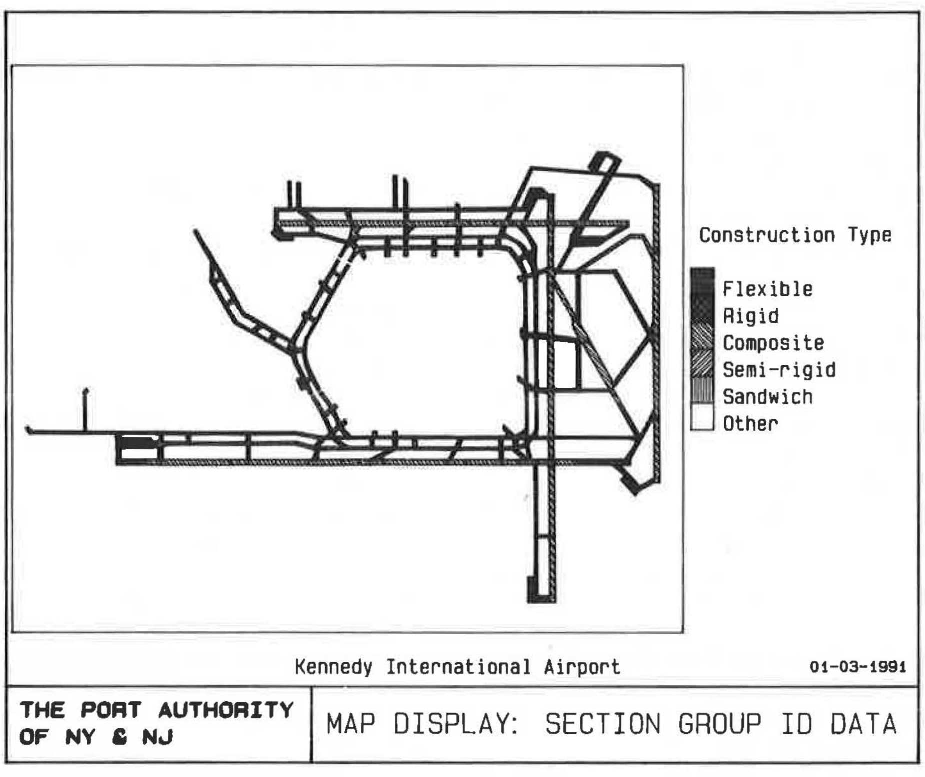

FIGURE 5 Pavement construction types for Kennedy International Airport.

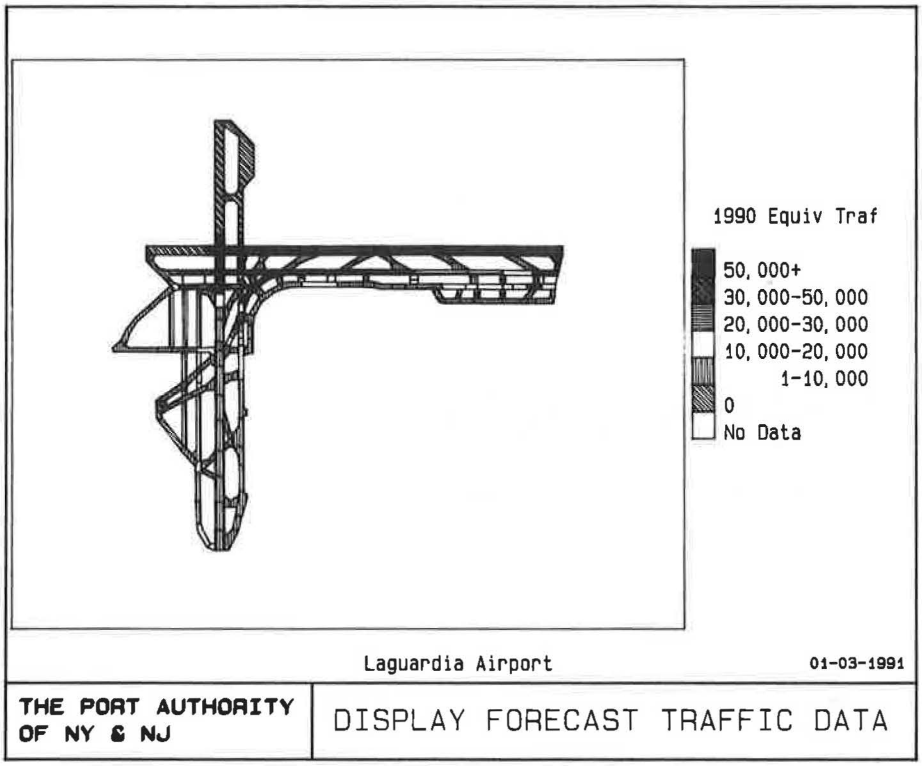

FIGURE 6 Equivalent traffic volumes for LaGuardia Airport.

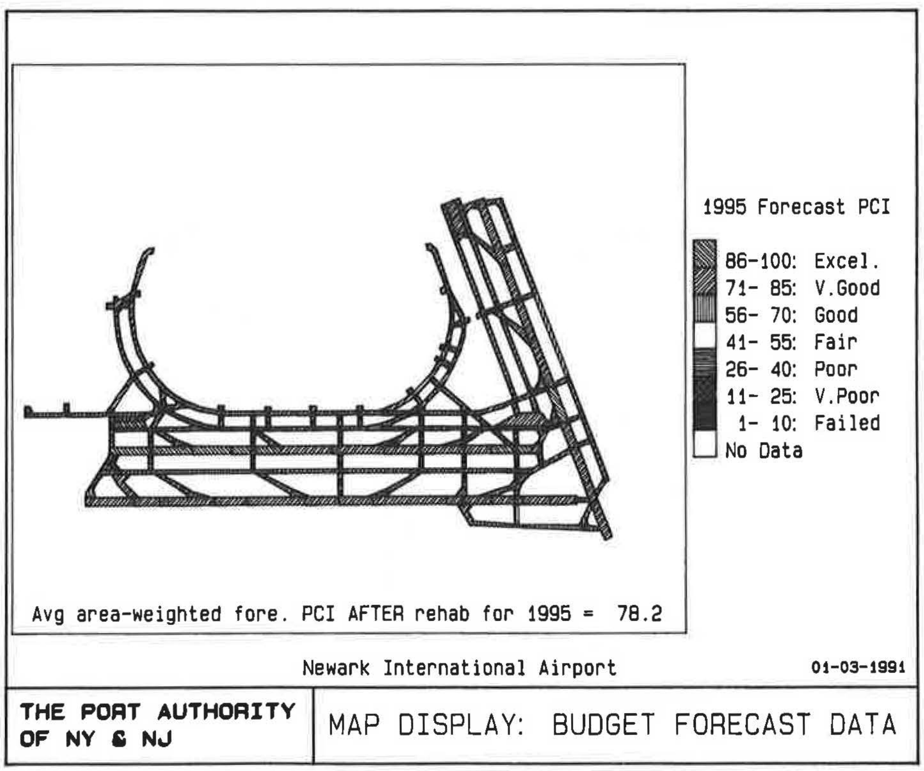

FIGURE 7 Projected 1995 PCI values for Newark International Airport: high-budget assumption.

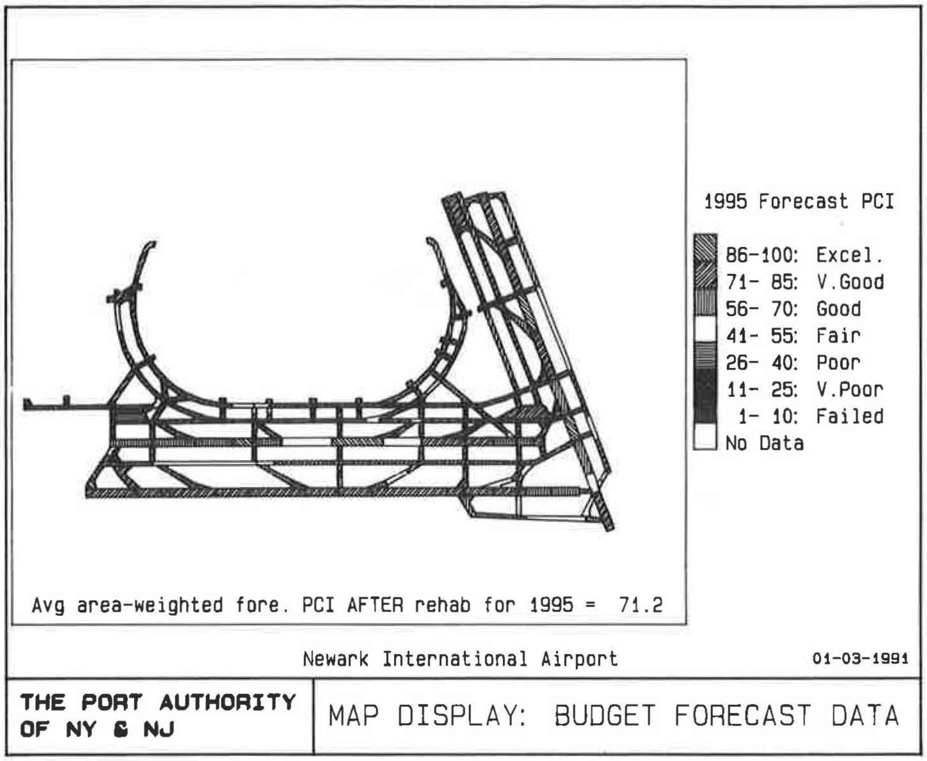

FIGURE 8 Projected 1995 PCI values for Newark International Airport: low-budget assumption.

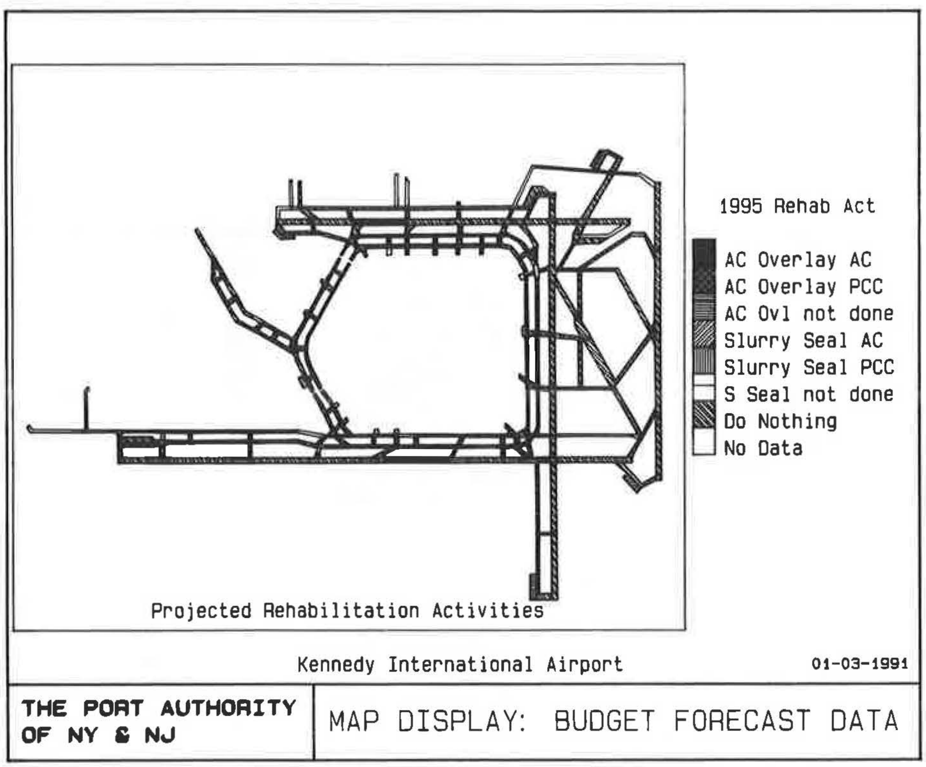

FIGURE 9 Forecast 1995 M&R activities at Kennedy International Airport.

IAPMS at LaGuardia and Newark International began in 1989 and was recently completed.

Data Availability and Quality

Historical data for any pavement network are always difficult and time consuming to gather. Through several earlier studies for PANY/NJ, PCS/Law had already compiled much of this information and was familiar with the pavement networks. However, although pavement layer thickness data were often available from the construction records, data on the engineering properties (e.g., modulus and California bearing ratio) for the layers and subgrade were often sketchy; in many instances, only very rough estimates of the required properties could be made, to be confirmed or modified later through nondestructive pavement testing. Traffic data were even more sketchy than the layer property data. Because of this, the criteria for M&R activity selection and project priorities relied heavily on the functional condition of the pavement (i.e., PCI).

The project team received invaluable assistance from the "vintage engineers" on the PANY/NJ pavement engineering staff. These "walking data bases" provided much experience-based information on pavement history and conditions that would have been unavailable otherwise. Their experience was also essential in defining the structure and intervention levels for the M&R activity decision trees and the project priority factors. The interaction with these vintage engineers was in broad terms similar to the knowledge engineering used in expert systems development.

Pavement Engineering Algorithms

An early step in implementing the IAPMS data base was the manual delineation of homogeneous pavement sections. This step was laborious and will benefit from automation within the IAPMS system itself in the future.

Because of the expected quantity and quality of the data for each section, the algorithms in the system were formulated on the assumption of complete data. Although this assumption was largely (but not entirely) justified here, it will likely be less so elsewhere. Alternative positions should be incorporated in all algorithms to handle cases in which key data items are missing from the data base.

The PCI prediction models were handicapped by limited site-specific visual distress data. At the time of the initial implementation, only one complete set of PCI data had been collected for all three airports. Visual distress surveys are now planned on a regular schedule, permitting the development of a time series of PCI data and correspondingly sharper PCI prediction models.

Additional pavement engineering issues that will be considered in future enhancements of IAPMS include automated M&R project grouping (spatially and temporally); incorporation of data variability and pavement reliability concepts; consideration of more pavement performance parameters, specifically roughness and friction (although roughness data are currently collected, they are not used in the M&R activity selection algorithms); development of a traffic flow model for automating the determination of section traffic volumes across the network; and inclusion of optimization routines to complement or supersede the project priority subsystem.

Data Base Aspects

IAPMS incorporates a large set of predefined standard queries and report formats. A more comprehensive facility is planned for the future to permit arbitrary complex queries of the data base in the style commonly found in general-purpose relational data base systems, e.g., query-by-example (QBE) or structured query language (SQL).

Only pavement-related data are included at present in the IAPMS data base. However, the data base could be easily expanded to encompass additional items such as surface and subsurface drainage, pavement markings, signs, and lighting systems.

GIS Aspects

The incorporation of GIS features has been quite straightforward, in part because only a limited set of GIS capabilities was considered and in part because the software was implemented in a computer environment that was familiar to the PANY/NJ. Our conscious strategy during the IAPMS development was to consider GIS capabilities as a natural extension of other pavement management functions, rather than to implement pavement management as additional to a primarily GIS application.

At a more detailed level, the adoption of an arbitrary x–y geographic coordinate reference system for the map data makes it somewhat difficult to georeference field test locations (for falling weight deflectometer and roughness measurements, etc.) within an individual section. However, this problem can be easily remedied through straightforward map coordinate transformations. Additional future enhancements include improved digitizing and graphics editing routines and the ability to transfer map data to and from computer-aided drafting systems.

Overall Observations

The initial implementation of the IAPMS focused only on taxiways and runways. However, the system framework is flexible enough to permit extensions to apron areas and to land side pavement assets (access roads and parking facilities). Regardless of the scale of the implementation, continual update of the pavement data base is essential if the system is to remain accurate and useful.

The development and implementation of the IAPMS required considerable coordination and interaction among all members of the project team through an extensive series of meetings, presentations, demonstrations, and reviews. However, the early meetings during the project are the most crucial for ensuring success. It is essential to define clear project objectives during the initial meetings between the client and developer. These objectives should be organized into short-, medium- and long-term time frames. The system should not be designed to simply automate the current pavement management methods in place in the organization but rather to provide a framework for incorporating improved pavement management methodologies both initially and in the future. Clear lines of communication between the client and the developer are necessary for the definition and successful implementation of these objectives.

Training is always a critical concern. Some of this training can take place as part of the collaboration between the client and developer during the system implementation. However, more formal training is also required. For the PANY/NJ implementation, for example, PCS/Law conducted a multiday seminar with computer-based workshops for hands-on training. PCS/Law is also providing PANY/NJ continuing support for the system.

CONCLUSIONS

IAPMS couples accepted pavement analysis techniques to powerful information management technology to provide an extremely versatile tool for the efficient management of large-scale airport pavement networks. Specific benefits from the IAPMS include the following:

- Easy access to all pavement data—inventory, construction history, geometric, structure, traffic, and condition;
- Replacement of the earlier approach of ad hoc experience-based maintenance by rational and systematized evaluation of pavement condition and performance and the associated required M&R;
- Codification of knowledge possessed by experienced senior engineers prior to their retirement;
- Reduced manpower requirements for performing routine engineering studies, multiyear capital budget forecasts, etc.;
- Quick response to typical questions such as the effects on pavement performance of new aircraft types;
- Easy evaluation of possible impacts on pavement condition caused by changes in capital expenditures, M&R policies, project ranking criteria, and traffic volumes, mix, and patterns, etc.

The development of the IAPMS started with a desired set of pavement management functions that were then supplemented with the relevant GIS capabilities, as opposed to appending pavement management capabilities to a generic GIS software package. The approach permits the users of the IAPMS to focus on their primary objective—pavement management—while still having available the advantages and convenience of GIS-style graphical display and query facilities.

The IAPMS data base and analysis capabilities enable the engineer or planner to make the kinds of rational predictions of future pavement conditions and performance that are essential for accurate budget forecasting and sound management. The net effect is the preservation of investment in airfield pavement infrastructure through improved pavement performance and reduced M&R costs.

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