Prototyping a Pavement Management System Using a Graphically Oriented Data Base Approach

M.R. WIGAN

Graphics approaches to pavement management systems (PMS) offer a substantial improvement in the early acceptance and accessibility of the road data systems presently available. Using graphics can help gain the cooperation of the critical participants—the field divisional engineering staff of the road authorities. This process has been substantially accelerated by field testing of various graphics user interfaces for PMS, which enable district and divisional staff to observe and respond to the immediate uses to which even their present data could be put, the simplicity of reexpressing it in a useful format, and the potential of maintaining an improved data base of their own area for pavement management purposes. The Apple Macintosh provided a suitable environment for flexible prototyping and field testing before implementing the final system. A commercial graphics object-oriented data base system has been applied to produce a small prototype to illustrate how this approach can be put into practice at very low cost and with little training. The approach is illustrated by some of the prototype displays for a Division of the Road Construction Authority in Victoria. The relationships are discussed between this demonstration system and the major thrust of the field PMS system now being developed at the Australian Road Research Board (ARRB) using the large-scale Oracle relational data base on MS-DOS and UNIX computer systems. These have now been selected as the initial delivery and development vehicles for PMS work at ARRB. A progressive line of development based on integrated graphics data bases for PMS is outlined. A Macintosh disk containing a self-running, commentated slide show is available from ARRB to complement this and previous papers.

A prerequisite for pavement management systems (PMS) is a solid base of continuing and comparable road condition, treatment, and inventory information. Beyond this basic need, the acceptance and usage of PMS at the operational level requires simple-to-use, but nevertheless highly sophisticated, interfaces.

Historically, information systems have been fairly complex to access and use and demanded training and familiarity before regular and enthusiastic understanding and usage could be ensured. This constrained their usefulness to operational engineers and provided little incentive for the regular access and field operational review of the data which does so much to improve data quality.

Interfaces making substantial and effective use of graphics have proved to be of considerable value, not only by lowering the resistance to new applications of computers and by substantially reducing training requirements, but also by integrating graphics as part of the control, access, and display mechanism. A much improved overall system can then be built.

The requirement for this type of interface for PMS was identified early in the current ARRB project on the development of a pavement management system, but the necessary software to implement this specification is still rare, and what is available tends to be very new and insufficiently reliable.

A useful road information system must provide the user with a fast, powerful, and easy method of interactively accessing road information, accumulating, updating, and finally assimilating such information. Such a system has a potentially valuable role to play as an effective graphics-oriented environment for a local authority or divisional offices to download and operate on the data for their own area in a familiar visual format: that of the maps and general layout of their road system and the associated installations and facilities.

This paper explores the interface and data requirements for such a system and emphasizes the value of developing and using a full prototype of the user interaction aspects of the system to work out with the users what they would prefer—on the basis of practical interaction with the interface. Changes can be quickly and easily made to a good prototype, if implemented on an appropriate system, and a considerable amount of effort at the user testing stage of the final implementation of the system can be avoided.

GRAPHICS DATA BASES

Graphics interfaces to data base systems provide the easiest and most logical way to access complex (particularly geographic) information: one picture is worth a thousand words—and quite a few spreadsheets. Despite the broad acceptance of this view, there are, as yet, very few applications built on these principles.

There are many popular small—and not so small—data base systems such as dBASE II, dBASE III, Knowledgeman, MDBS, etc. (*1*), and an equally large number of "business graphics" packages to display the results of using or querying such data bases in the form of a chart or a graph. This approach to graphics is limited almost completely to statistical summary displays and bears no direct link to the data structures in the data base, being just another (albeit excellent) way of viewing

Australian Road Research Board, 500 Burwood Highway, Vermont South, Victoria, Australia 3133.

the results of a query in a more easily understood format. Such a query posed to a PMS may show clearly that "15.6 percent of a road network is potholed to a serious extent"—but does not normally show at the same time exactly where those sections are in a geographic and spatial display.

Business Filevision is one of the few systems designed to date to retain the link between the graphics object (such as a road section or location) in direct conjunction with the data records describing the road section for the PMS (such as width, roughness or bridge and culvert appearance, and location). This direct link permits an interactive exploration of the data by working directly on the objects that make up the visual appearance of the road network. For example, a user asks: "Where are all the rough road sections?" A map with these road sections highlighted appears while the user is able to examine the usual numeric and diagrammatic data held in the data base about those sections.

Business Filevision is available only on the Macintosh, although more expensive graphics data bases are available on Xerox and other still highly priced and less common earlier generation, specialist graphics-oriented computers. User acceptance is a crucial factor in the successful installation of a new system, and the user satisfaction and understanding now being obtained by drawing on the Xerox tradition are indispensible requirements for continuing high-quality data input and updating.

MS-DOS is the broadest-based operating system for microcomputers and has been widely accepted by the State Road Authorities. MS-DOS has been used in the current ARRB PMS project as the framework for integrating relational data bases and graphics tools for PMS systems, using the recent Microsoft Windows environment, which now provides an emulation of the Macintosh interface and graphics facilities and provides the opportunity to move forward on the more common IBM-compatible machines.

Special care is being taken to ensure that the systems developed are as portable as possible among MS-DOS, UNIX, and other environments as a precaution against the inevitable growth in PMS systems and the steadily changing microcomputer world. IBM, which has effectively defined microcomputer standards in software simply by defining and endorsing IBM-acceptable products and specifications, has now chosen UNIX for its new RT series of engineering and graphics workstations, and thereby officially endorsed UNIX: a long-delayed, but nonetheless significant, step for anyone seeking to maintain a degree of stability in small- and medium-scale computer applications. Larger scale PMS applications are going to need UNIX or an environment very much like it.

Selecting Oracle as the main underlying data management tool for PMS implementation has a sound and conservative basis. Since the review of suitable data base systems was carried out by Kenyon (*1*), support has been strengthened by Oracle's direct presence in Australia. Oracle is available under both UNIX and MS-DOS, and offers the SQL (structured query language) made so popular by dBASE II and IBM in their products for larger machines. However, the amount of work required to overlay both Oracle and MS-DOS with the necessary graphics facilities in a good user interface soon showed that it would be very effective to set up a prototype of the user interaction facilities to be provided so that refinement (and any revisions to the design specifications) could be carried out to at least some extent early in the development period. Recent developments of object-oriented systems (such as ACTOR) under MS-DOS promise the ability to offer MS-DOS user interfaces up to the quality tested on the Macintosh.

In the course of producing a small demonstration for field testing, it became clear that the simple system had a substantial amount to offer beyond demonstration and user interface testing purposes, possibly enough to justify the acquisition of appropriate equipment and software field use in the operating divisions of road authorities.

USING A GRAPHICS DATA BASE

To show how the graphics and data base aspects can be combined in a single PMS information system, one must start with some sort of geographic representation of the area, or even a digitized map of some type. A large range of digitizers suitable for capturing map information are ever more readily available [see Wigan and Cullinan (*3*) for a partial list].

A number of other data types can now be superimposed on this background: e.g., road sections and bridges. Each data type is represented on the map by a graphics symbol and is associated with a definable record of alphanumeric and numeric data fields. This level of specification is adequate for user interface testing—and for quite a range of pragmatic tasks. But for a full graphics data base system, each graphics entity needs to be treated as an object in a large-scale data base system with all of the conventional data base facilities—and the automatic creation of graphics displays as well.

This type of system emerges naturally from recent work on object-oriented programming systems, of which Smalltalk and Common Lisp are at present the most widely known. Figure 1 is a reproduction of a screen display produced on a Xerox 1186 system running the large-scale Analyst graphics object data base system, written in Smalltalk. This display includes the detailed map of an area called up by the data base query and a series of information panels both as the responses to queries made of the system and to prompt further investigation and display of the related data.

This system is far too large and complex for the modest purposes of the PMS and interface testing, and indeed a considerable number of more up-to-date and commercialized systems of this type are under active development. It is realistic to expect that usable and economic tools of this general type will be appearing in increasing numbers in the mass marketplace.

At the modest level needed to test the resource-consuming user interface level of such systems, Business Filevision is a genuine graphics data base system with simple hierarchical levels of retrieval and data structuring. Figure 2 shows a view of the screen set up for the major roads of the Traralgon Division.

The key elements required to understand this—or indeed any other—graphics data base are

(a) Visual displays, with selection by pointing to a part of the display.

(b) A complex data record linked to each visual element in the picture.

(c) A mechanism for including images in these data records themselves.

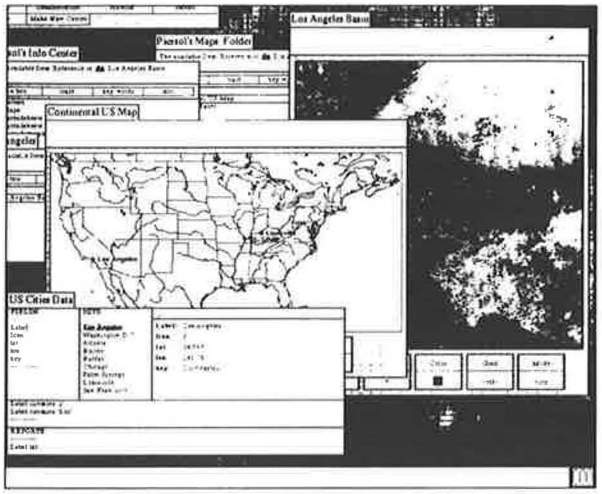

FIGURE 1 Smalltalk graphics retrieval.

(d) A mechanism for building a hierarchy of visual elements and the associated data records.
(e) A selection mechanism for data retrieval, with a visual display complement.
(f) A report generator.

Each of these elements are included in the prototype system, but little more can be expected from Business Filevision. A more powerful system, such as the Oracle relational data base, is necessary for an operational—and far more substantial—applications data base. The data-base implications are shown in diagrammatic form in Figure 3.

The basic structure required for the user interface is a bidirectional selection mechanism which can interchangeably move from the visual elements to the data records and from the data records to visual images.

The data base implications are also dependent on the same philosophy: the extension of straightforward relational data base methods to include images and their components is little more than a respecification to include compressed images or parts of images and their attributes—but does add the necessary component of a postprocessing stage once a given set of graphics elements have been retrieved. This has much in common with the treatment of graphics in expert systems, where the extraction of structures based on the context of a query is a basic and essential mechanism of those systems which include graphics at any level beyond the most basic.

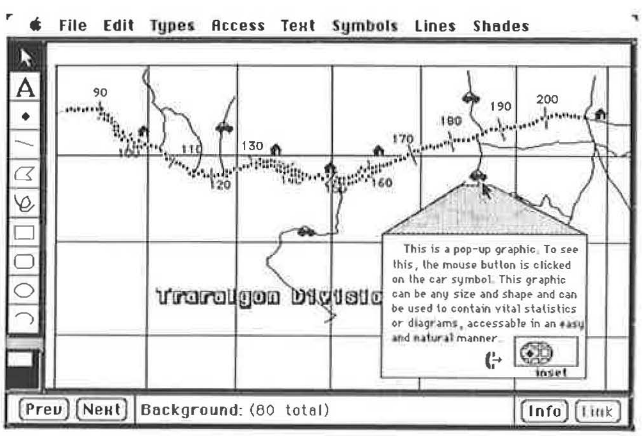

FIGURE 2 Graphics database screen.

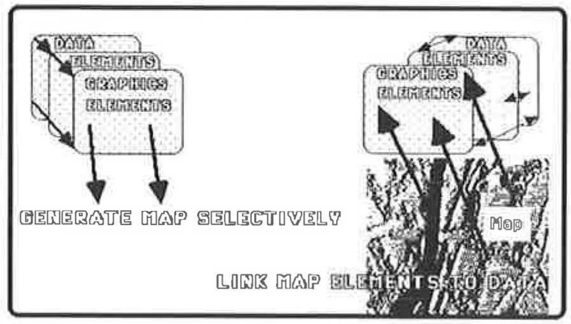

FIGURE 3 Graphics DBMS retrieval.

DEMONSTRATION PROTOTYPE

The basis that one would expect of a graphics-oriented data base would be a detailed map of the appropriate area. A digitized map can be used as the background image. Overlaid on this will be the basic diagram shown in Figure 2, which is a schematic outline of the major roads, towns, and features of the area.

This level of detail illustrates a number of interface and display points The heavy (highlighted) lines for the roads contrast with the background appearance of the towns, the coastline, and the symbols used as markers for the names of particular areas on the map. One of the symbols has a pop-up graphics resource attached to it. This display has been brought up and selected by moving the mouse to position the cursor over the icon of a car, then pressing the mouse button (this is referred to as "clicking" the mouse: two such clicks in less than a second is termed "double clicking" and causes the system to take action to get further details of the object being pointed at). House symbols are used to denote towns in a compact manner: the names and other details can be selected and brought into prominence by the same procedures.

It is also possible to be more selective in the information shown on the screen. At the top of Figure 2 is a row of menu options. If the mouse is pointed at one of these—in this case the Types menu—and the button is held down while sliding down the options on the menu table that then appears, a particular type of object can be selected for investigation.

Picking "Road Sections" from the Types menu at the top of the screen then selecting "Highlight only this type" using a similar selection process under the Access menu will cause the screen to display only the road sections in the form shown in Figure 4.

The next level of information management is to move on from selecting the general category of objects of interest to obtaining the detailed data records about a specific object. To do this, the mouse is used to point to any road section in the last diagram and clicked twice in succession. This causes the system to fetch the record associated with this section, and a printout of this record forms (Figure 5). There are only a few items on this record, just enough to illustrate some of the data items one would expect to see, and to provide an example of the ability to include a graphics record within these data records. In this case, a crude diagram indicates only the

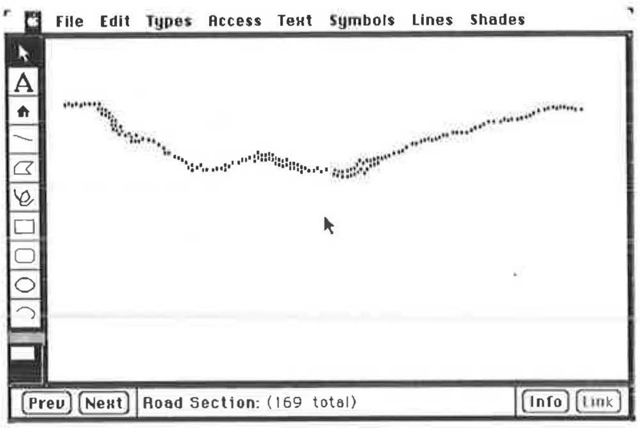

FIGURE 4 Road sections shown alone.

general type of road section, but the record could well have been a digitized photograph of a bridge at that location—or of the designer.

Simply being able to select a graphic object and examine a data record associated with it is not enough. More than this is needed to make a system useful once it becomes of any significant size, and the mechanism used to select objects (and to display visually which objects have been picked out) is shown in the subsequent figures.

The concept of selection by pointing and metaphorically tapping one's finger on the desired arrow point is a natural and easily accepted means of improving user acceptance of computer-based systems, and this simple process can be used to construct complex queries without demanding a knowledge of a query language such as SQL.

Figure 6 shows the form in which these conditions can be defined, and Figure 7 shows the result of some such conditions by highlighting the chosen road sections with an L-shaped bold mark and the sections themselves shown in bold, overlaid on the general area map which comprises the background at the top and broadest level.

The LINK field referred to at the end of the report is the name of a different file which contains a map of the section of road, has its own data records, and is the first hint of the multiple layers of description which are possible in this graphics-based approach. This information is visible in Figure 7 as a pop-up graphic display.

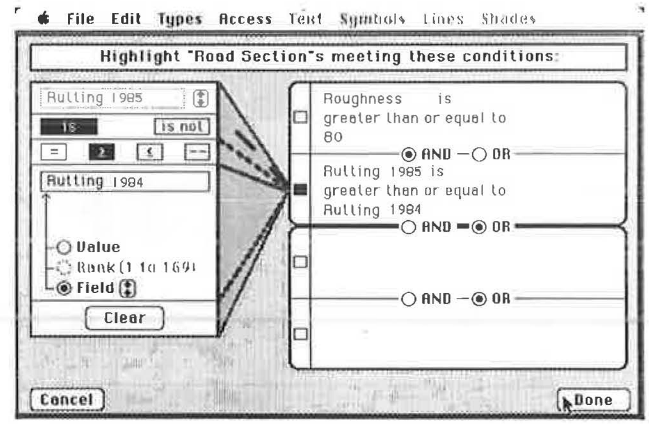

FIGURE 6 Constructing a DBMS query.

Up to this point several points have been illustrated:

(a) The basic elements of graphic selection by the user
(b) Retrieval of the associated data on items selected by the user
(c) The forms in which these graphics selection aids can be provided
(d) Construction of complex queries
(e) Graphics report production as a result of such queries
(f) Normal printed report production from complex queries

This type of extension has been added to the graphic specification of the Princes Highway through the Traralgon Division of the Victorian Road Construction Authority. Double clicking on the road section (or the block of text associated with it) between the major towns will not cause a data record to appear this time.

Instead, a new map appears (see Figure 8), showing the road as a series of three sections with markers (Permanent Reference Points, or PRPs) at the end of each. Double clicking on these markers will produce the data record typified by Figure 9. This whole new map is a separate file from the broader level picture of the general area of the Traralgon Division and is logically one layer further down in the specification and data hierarchies.

Additional layers could be added. It is this hierarchical structure that provides the really worthwhile capabilities of

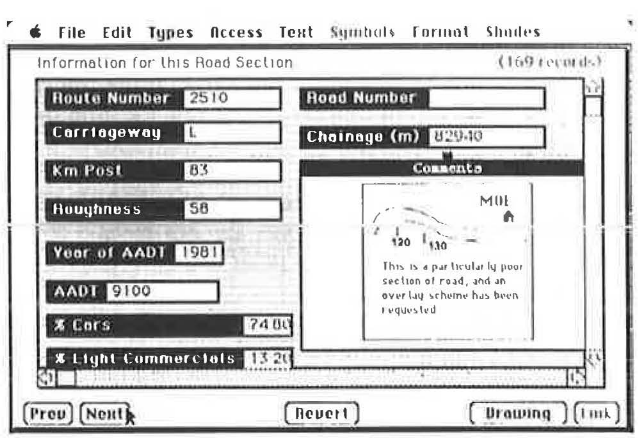

FIGURE 5 Road section data record.

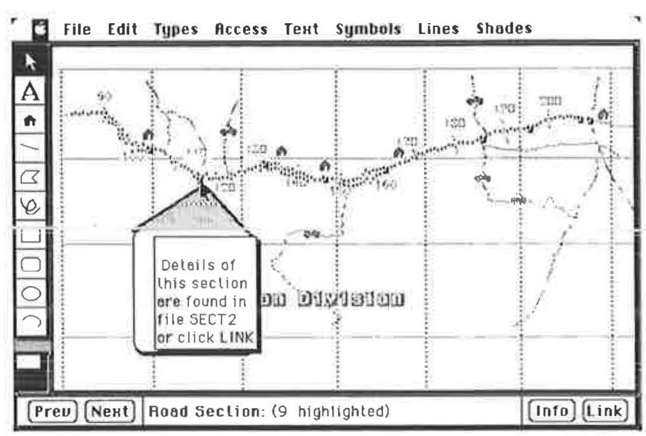

FIGURE 7 Linking to a lower level display.

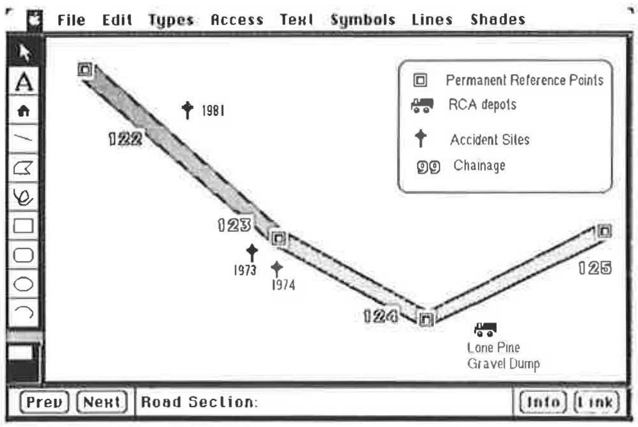

FIGURE 8 Lower level graphics display.

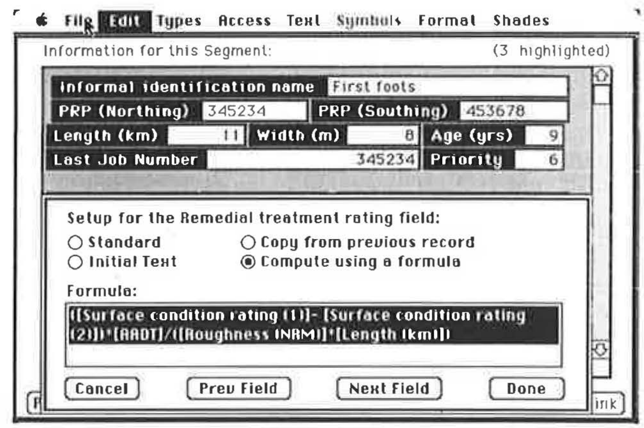

FIGURE 10 Construction of an "index."

this approach, as the short sections of road can once again be (selectively) chained to in a further level of smaller detail in exactly the same manner. A large-scale data base of some substance can be constructed that looks very simple to the user, who will be able to use the visual pinpointing and selection approach in conjunction with complex queries to interact with an immediately understandable geographic presentation of the information.

Double clicking on one of the three rectangular road "sections" in Figure 8 will produce a report as shown in Figure 9. The remedial treatment rating entry is based on a user-specified formula to relate different values in the various fields of this data record, exactly like a spreadsheet formula. Such computed fields add a substantial amount of power to this system, and a notional "performance index"—discussed in the next section—has been included as a small illustration.

Figure 10 shows how such an index can be constructed as an intrinsic part of the data record itself. One deficiency in this particular small-scale system is that it is not clear how best to pick out a history file for a road section without replicating the fields in a single record. It is possible that this could be overcome in a number of ways, but these may not be as "obvious" as the structures chosen for the demonstration, and they might lead to a complexity ill suited to the intentionally simple and straightforward specification adopted.

Using built-in formulas in records makes another major deficiency apparent when 600–1,000 sections of road are in use, and the computation of any such spreadsheet-style entry in a record format slows down the whole retrieval process remarkably—just as it does for any action in any large spreadsheet where recalculation cannot be turned off and a floating point processor is not fitted. This is important in Filevision, as the redisplay of graphics elements apparently invokes the recalculation of all of the associated records. These warnings are included here because the prototype interface system tends to generate perhaps too much enthusiasm from prospective users, and the constraints on the tools that are being used for the demonstration and prototyping stages need to be constantly reiterated.

General report production can be designed to automatically include graphic elements such as small maps, diagrams, or digitized pictures if these are the entries that have been stored in the data records for the relevant road sections or locations. The distinction between a text and a diagrammatic printout is therefore removed.

Figure 11 shows the results of selecting one of the Permanent Reference Points shown in Figure 8 and retrieving the data record for this PRP. The two graphics entries, one a small diagram and the other a digitized picture, will appear in any report defined for summarizing a query posed to the system which includes these fields. No special action need be taken, as graphics objects have exactly the same status as text or numbers in object-oriented graphics systems such as this.

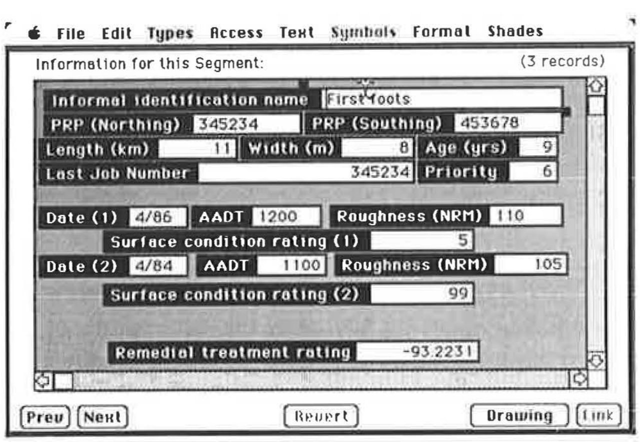

FIGURE 9 Record at the lower level.

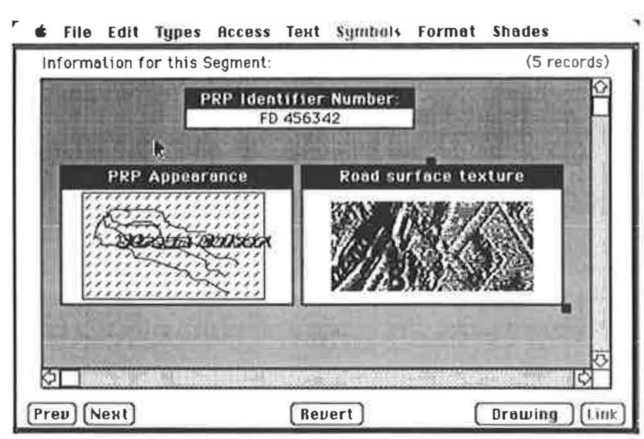

FIGURE 11 Pictures in a data record.

RELATIONSHIPS WITH LARGE-SCALE SYSTEMS

This small demonstration simply gives the perspective we wish to communicate to potential users. The complete Business Filevision files, diagrams, and records and their use for a simplified road network loosely based on the Cairns area in northern Queensland were initially reported in Wigan and Kenyon (*4*) and are now available on disk as Filevision files and as a self-running "slide show" of example frames with synthesized speech support. This is only one of the new formats that ARRB is now producing for the dissemination of research findings: the other is a Picturebase library of immediately reusable diagrams on disk, which can be searched by keywords on the text associated with the pictures in the graphics data base (*5*).

For a full-scale system, many more layers of software, larger data bases, and a high degree of machine independence must be sought under the system design evinced by these examples. SQL as a basic query language was a design decision made some time ago in this project, in accordance with these aims (*1*), and so the essential elements of graphics object inclusion in a relational data base must be followed through more rigorously to assess where one should move next on this line of attack.

The effort required to forge these powerful building blocks on the IBM PC/XT/AT range is fairly significant, mainly due to the early stage of development of the generalized multiple windowing software under MS-DOS. The same task on a Sun workstation is considerably easier, and Oracle, which has recently been ported to the Sun series of UNIX systems, is a suitable real-target system. Even so, the simplest prototyping environment is the Macintosh with the proven Business Filevision graphics-oriented data-base system, and practical experience has been gained in designing and testing appropriate user interfaces and the joint image and data storage, retrieval, and production facilities by using the Macintosh system described here.

The ability of the prototyping system to accept mass data exported from spreadsheets like Lotus 1-2-3 or data-base management systems like dBase III, means that the graphics environment for data access provided by the prototype system could play a useful role even when a full-scale data base system is operating, by downloading a large amount of condition and other data into what will be an essentially stable graphic, mapping, and images structure describing the area. The ability of Business Filevision to chain indefinitely to other files opens up the architecture of the demonstration graphics data base, and it would be quite practical to build and operate reasonably substantial and simple PMS systems entirely on the basis of this portable floppy disk-based overall system.

NEXT STEPS

The operational testing of a system even as simple as this has some real merit: a prototype system that does not require the major programming efforts imposed by the MS-DOS environment can demonstrably help to speed up user requests and feedback. It is still necessary to continue with the Oracle systems, and indeed to ensure that the same environments can be set up for UNIX to avoid the natural—but incorrect—assumption that the PMS being developed is totally dependent on the particular—or primary—microsystem and operating system used for its development (in the case of the ARRB PMS, an IBM AT, MS-DOS, Windows, and Oracle, while a Sun 2/120 UNIX workstation is a probable subsequent target).

The user testing of the graphics retrieval system and the manner in which information is most effectively utilized is a crucial task in producing really usable and robust systems, and in this case can best be done with a simple prototyping system as exemplified by the combination of Business Filevision and the Macintosh.

The further development of the target PMS systems at ARRB will continue to be undertaken in close collaboration with operational field staff, as it has been to date. A system of the type described has the potential to save up to a full cycle of field user interaction and redevelopment while the full-scale first-round Oracle systems are being completed. The combination of graphics, windows, and data base retrieval as an interactive and practical environment for PMS systems and their use remains our goal. The work reported here provides an early opportunity to interact with and respond to such an environment in a prototype and easily modified form.

The smooth integration of this type of a graphically oriented data base specification of a district, in conjunction with a regular and standardized format for downloading data from a central data base, is worth pursuing. The two approaches have strengths and are complementary at a number of theoretical and practical levels.

The construction of a large and multilayered graphics data base for a divisional area can be used as the host for many updates of the associated data in the records and gives a highly effective mechanism for integrating descriptions of key locations and road elements that really benefit from a visual ancillary record—such as many of the permanent reference points used for road data bases—in a natural manner. Accident and other data can be simply added to this structure, with digitized pictures of the sites if subsequent identification of the location is likely to become a problem. High-quality reports can also be efficiently produced in this type of environment and include the visual results obtained in a particular session.

The key ideas which should continue to be carried forward are

(a) Using graphic objects to aid selection of data items of interest in context.

(b) Automatically generating and presenting a graphics-oriented version of complex (or simple) data base retrieval requests, as well as the raw data of the report.

(c) Continuing to ensure that PMS systems are both usable and accessible, as well as efficient in terms of data organization and response.

(d) Involving operational staff to ensure that the systems are of early and continuing practical value and to ensure good data quality.

The Traralgon Division of the Victorian Road Construction Authority is currently involved in the continuing development and use of these methods. Since the PMS Workshop at the 13th ARRB Conference held in Adelaide in late 1986, this prototyping and assessment work has moved on to equipment and software purchased and designed for the purpose, and to the implementation of a larger scale system heavily influenced by the concepts and interfaces tested using the prototype system.

Major data modelling and other issues are being addressed. The first is the issue of geographic referencing systems. At first sight, a link/node method appears to have been adopted implicitly by the approach described in this paper, however, the essential underlying process is the assembly of grid coordinates for all elements in the system.

As a direct result, it will soon be possible to visually or analytically restrict attention to a rectangular "window" into the physical area on the ground. This is much closer to a coordinate grid approach. It is clear that there is no conflict between the two methods of location specification—the representation in visual form forces both methods to encompass the coordinate data of the other at the first display stage. The design of the query system is specifically geared to easy portability to environments other than MS-DOS. With suitable design specifications, no substantial dependence on Oracle or any windowing system is needed.

Figures 12 and 13 show the appearance of the screen of the AT-based prototype display system (RoadView) using the data produced by an SQL-constructed query addressed to an Oracle data base. The pattern of user interaction has been heavily influenced by the prototyping experiences gained, and the similarities in the facilities offered are a result of field responses. RoadView is expected to be completed during 1988 under MS-DOS by the author of the software (J. A. Kenyon) and subcontractors under contract to Main Roads Department, Queensland. From the beginning of 1988, Sun and Relational Technologies (INGRESS) have combined forces to create a UNIX tool very similar to RoadView, which generates SQL queries from an interactive graphics query interface: RoadView is the full development system that followed the initial tentative displays shown in Figures 12 and 13.

The UNIX specifications have also been produced. This system will include the data analysis, projection, forecasting, and other tools required to make effective field use of the information that must be collected over a considerable period for the most effective systems pavement management.

These projection, analytic, and exception identification tools are the real core of any management system, but the user interface issues can materially improve the quality of the data going in and being used by raising the quality of the infor-

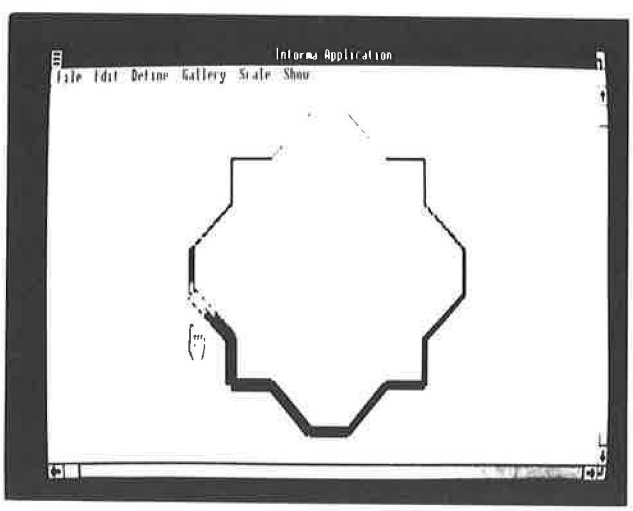

FIGURE 12 Prototype MS-DOS display.

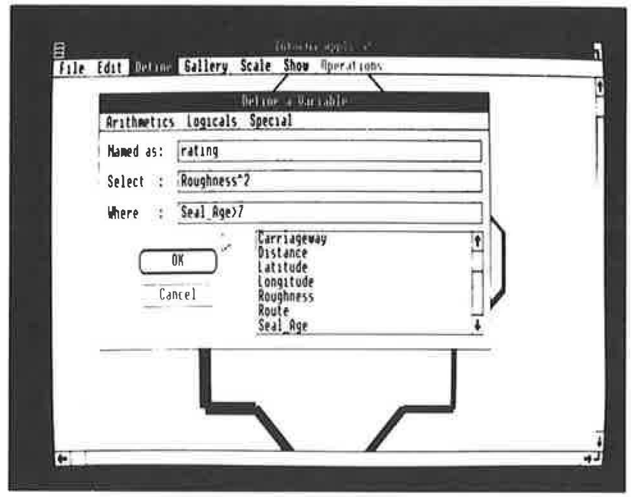

FIGURE 13 Prototype query under MS-DOS.

mation presentation and lowering the barriers to clerical and engineering input and use of the system.

While this data resource and history is building up, it is crucial to obtain and maintain the commitment of the field staff who are responsible for the quality of the data inputs. This can be materially assisted by providing effective graphics access to the geographic data as the historical weight of experience builds.

The other key issue in the refinement of the data model is the handling of different extents of data elements, and—in particular—the handling of variations in these extents at different time intervals as the system changes on the ground and the level of detail and refinement (and even measuring criteria) change for different data elements. The use of relational data base methods has enabled a reasonably satisfactory approach to be defined: it remains to be seen what level of performance this approach will deliver. The implied curtailment of the area of the data base required to be used by means of interactive visual windowing methods for user query specification plays a major role in reducing this problem in many otherwise potentially difficult cases.

The use of historical accretions of comparable information as the basis for short-run projection is a useful method for identifying exceptional variances and situations requiring attention. This requires a body of data to be available in one place in a form comparable over time, and this is still a rare occurrence in many road organizations, certainly at the local level. Until this type of local pattern can be built up, and the initial efforts of creating that data resource on a regular and valued basis are complete, the best that can be done is to apply guidelines or empirical or theoretical estimation or forecasting methods developed from an aggregation of information from many different locations.

The embodiment of both short-run projection methods (exponential smoothing and other responsive methods are easily implemented in even the simplest systems), and of the more general formulas and guidelines are requirements of any long-term PMS system. It should be realized that the operation of PMS systems and the underpinning data specification and recording procedures will quite quickly (in roading terms) produce a much enhanced basis for analyzing conditions and remedial actions that can, in their own turn, be fed back to all local areas operating such systems. The role of graphics in stimulating such a process to start with effective understanding and endorsement is a real contribution, but it is equally important to ensure that the graphics tools which make the interaction easier for the users continue to be a basic part of PMS systems in operational use.

SUMMARY

The major conclusions of this work are that

(a) Graphics-oriented methods for pavement management are appropriate to the local level, and likely to attract a high degree of acceptance.

(b) Prototyping methods of demonstration can help to achieve informed and constructive cooperation.

(c) The commitment to local data input that such systems engender may help to ensure the creation of the local information required to improve the estimation and performance equations on which the next stage of PMS must depend.

As a consequence of the work reported to date, the following actions are recommended:

(a) Operational tools of the type described and tested should be built and used in the field.

(b) The active liaison and cooperation between operational staff in road authorities and research analysts that this style of approach encourages should be built on in states initiating PMS and Pavement Information Systems programs.

(c) Management and evaluation aspects of PMS should be pursued to obtain a similar level of user understanding and interaction.

(d) Input data requirements for both graphics and numeric data now need enhancement, standardization of measures, and better decision-support procedures in a PMS framework.

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