A Framework for Integrating GIS-T with KBES: A Pavement Management System Example

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This paper provides a framework for integrating the spatial data manipulation strengths of a geographic information system (GIS) with the interactive problem-solving capabilities of a knowledge-based expert system (KBES) through emulation of the knowledge of human experts. While the integration of a GIS with KBES has practical applications throughout the transportation profession, this study uses an Intermodal Surface Transportation Efficiency Act (ISTEA) pavement management system example to illustrate this integration. The pavement management process involves spatially-indexed information, human expertise, heuristic knowledge, and multiobjective decision making. These characteristics make a pavement management system ideally suited for implementation in an integrated GIS/KBES environment. In this application, the GIS provides spatial data as context to a KBES that makes use of the National Aeronautics and Space Administration's CLIPS rule-based expert system shell. The KBES retrieves information from the GIS as needed to produce an outcome. As the KBES works, the knowledge base is updated for future processes. In this way, the KBES is able to learn from the previous applications of the system. Once processed by the KBES, the results can be passed back to the GIS for further analysis and display.

The integration of knowledge-based expert system (KBES) technology with geographic information systems (GISs) can address some of the difficulties associated with a GIS. Many of the transportation areas where GIS technology has been or will be applied, such as pavement management, involve very dynamic, iterative processes with no "right" answers. Engineering judgment, fiscal realities, and other irreducible factors preclude the development of "black box" solutions. Because of this, the potential for integrating expert systems with GIS is promising. Furthermore, because of high turnover among engineers in state and municipal transportation agencies, expertise can be scarce, compounding the need for integration.

There are a number of areas in which knowledge-based systems could be applied. A GIS could be provided with an intelligent user interface to guide an inexperienced user through the most efficient use of the system. Better database search techniques and querying capabilities could make the search of large geographic databases more efficient by using heuristic search methods, that is, search methods based on judgmental rules, which eliminate major portions of the database from consideration as early as possible. Learning capability could allow results of computationally expensive queries to be added to the knowledge base to process frequent queries faster. Finally, intelligent graphical output capabilities could produce high-quality maps and graphs. While the above areas of integration are general and can be applied to almost any type of transportation GIS application, this study illustrates this integration through an Intermodal Surface Transportation Efficiency Act (ISTEA) pavement management system example that the Georgia Department of Transportation (GDOT) is implementing.

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PREVIOUS WORK IN GIS/KBES INTEGRATION

Very little research has been done on the integration between KBES and a vector-based GIS. Evans (*1*) describes an expert GIS that combines rule-based reasoning with vector-based spatial data representation and analysis, but the implementation is experimental. The Australian Army is using a vector GIS to display results from a soil moisture-soil strength model (*2*). While this is a production application of both KBES and GIS technology, it is not an integrated application.

There have been a number of attempts at integrating KBES with a raster-based GIS. Researchers at the University of California at Santa Barbara carried out research and development on a knowledge-based geographic information system (KBGIS) (*3*). The objective of the KBGIS system was to respond intelligently to user queries on large spatial databases stored in a raster GIS. Several other research efforts focused on using a raster GIS in conjunction with a KBES for digital image processing (*4–6*).

The most beneficial GIS/KBES platform from a transportation standpoint is vector based, because the vast majority of existing transportation-related GIS applications are in this format. The primary reasons for this are that a vector GIS can precisely model transportation facilities, such as roads, and attribute linkages are easily accomplished. Only preliminary efforts have been made in using KBES in conjunction with a transportation-related GIS. One area that has had limited success is pavement management. The state of Wisconsin has hard-coded decision trees into its GIS to help prioritize and recommend pavement rehabilitation activities, but this effort does not make use of a KBES (*7*). Researchers at the University of Ljubljana in Slovenia are working on an expert system based on GIS technology (*8*). The main goal of this system is the optimization of road maintenance from both technical and managerial standpoints.

POTENTIAL ROLES OF A GIS/KBES IN THE GDOT ISTEA PAVEMENT MANAGEMENT SYSTEM

In 1991, Congress passed ISTEA, which requires state transportation agencies to develop and maintain six management systems (*9*). One of these systems deals with pavement management. A primary goal of GDOT's ISTEA pavement management system (PMS) is to serve as a decision support tool that will help GDOT engineers and decision makers to determine when and where to spend pavement funds to enhance safety, preserve existing infrastructure, and serve commerce and the motoring public.

The specific objectives of the PMS that need to be achieved to meet the primary goal are as follows:

- Maintain a complete and up-to-date road inventory including physical features of the pavement, pavement history, pavement condition, and traffic information such as volume, vehicle classification, and load data;
- Develop and integrate systematic procedures for performing network-level analysis for projecting both short- and long-term pavement conditions across the network;
- Develop and implement prioritization schemes for investment in current and near-term projects;
- Routinely maintain and upgrade all of the components of the PMS; and
- Develop an efficient means by which the PMS interacts with other ISTEA management systems.

These objectives need to be achieved for all Federal-aid highways on the National Highway System and all roads that are maintained by GDOT.

The following sections explain how a GIS integrated with KBES technology may be incorporated into an ISTEA PMS for most aspects of the pavement management process. For each aspect we begin by describing the tasks involved in maintaining a stand-alone PMS without a GIS element, and then briefly discuss the effects of adding a GIS element. Further discussion is provided on how the addition of KBES technology may enhance completion of the task.

Data Collection and Maintenance

The first objective of the PMS is to maintain a complete and up-to-date road inventory. One type of data that needs to be collected is subjective pavement ratings that represent the condition of roadway segments. In a conventional PMS, subjective pavement ratings are coded into a database on a segment-by-segment basis and the results are displayed or printed in tabular form. By adding GIS technology with its visual display capabilities, segments could be color-coded by various attributes, which would greatly facilitate the process of data entry and editing. Omissions in the input of data would be immediately apparent from segments in the roadway showing no data. Errors in measurement or coding would also be readily apparent. Adding an intelligent user interface to the data entry process, based on KBES technology, could help to guide the user through the input process. Pavement ratings are entirely subjective and can vary greatly for a pavement depending on the judgment of the person rating the pavement. A KBES that guides the person making the rating can help to reduce the variability of these ratings. Of course this requires that the person collecting pavement ratings has a laptop computer in the field to enter the data and respond to questions of the system. Note that once the data are entered into the laptop, a simple program can be developed to transfer this data directly into the GIS database.

Preliminary Analysis and Interpretation

In a traditional PMS, the highway engineer transfers some of the tabular information to a base map by hand as a first step in understanding the data. For example, the engineer might construct a map showing the severity of rutting or block cracking, or create a map indicating the overall performance index. As in the situation for data editing, the GIS-PMS can integrate the database attributes describing the pavement condition with a map display of the road network; it can then create any number of illustrative visual displays of the status of the road system. For example, it would be possible to highlight all segments with block cracking greater than Condition 6.

Adding a knowledge-based system can help to standardize and automate the process of identifying problem areas. Consider a section of rutted pavement. A possible rule in the knowledge-based system may be as follows:

IF
Rutting is moderate and pavement age is less than 5 years old.
THEN
Mix is too soft.

This rule illustrates how an integrated KBES could be used to identify problem areas. The KBES could be taken one step further, and also recommend strategies to remedy the problem. Additional information pertaining to this will be presented later.

Performing Network-Level Analysis

While visual representations of the segment-by-segment status of the roadway are a valuable addition to the pavement management process, it is necessary to add analytical capabilities to assess the current status of the system as a whole, compare it with previous periods, and make predictions about the future. Doing this requires statistical and mathematical procedures, which a conventional database management system could be programmed to perform. A GIS would add the benefit of spatial querying to selectively isolate geographic regions for more detailed assessment. A network-level assessment can be reported in the form of graphical products that provide greater visual impact than tabular reports. These graphical products can be easily understood by management, politicians, and citizens' groups, helping to clarify issues and obtain needed support.

Incorporating a KBES into this task has many possibilities, since there is a great deal of subjectivity involved with network-level assessment. A KBES could be used to help interpret the output and guide the user through the process of using this output to develop the assessment. An additional possible KBES domain is automated map design, in which the system relies on heuristics to aid in the positioning of labels of spatial features.

Determination of Prioritization Strategies for Allocating Resources

Another use of the GIS-PMS is to develop and implement prioritization strategies for investment in current and near-term projects. This is where a KBES could again come into play. The determination of strategies could be based on a series of decision rules that match deficiency ratings with appropriate actions. Using these rules, a KBES could be used to identify a list of potential projects. Furthermore, a KBES could also be used to prioritize the allocation of resources to these projects.

A FRAMEWORK FOR GIS/KBES INTEGRATION

In the previous sections we have described a number of possible specific KBES applications in a GIS-PMS. The next issue is how a

KBES could be integrated with a GIS-PMS or even a standard GIS. Ideally, a KBES built into the core of the GIS would be most efficient, because the KBES would have direct access to the GIS database. Unfortunately, because of the proprietary nature of commercially available GIS products, this approach is not feasible. The intent in this study is to identify a framework that can be implemented on a wide variety of GIS platforms. The next question is how to interface with an existing GIS. This is a software question that depends on the type of GIS being used. Different GIS programs have varying capabilities for expansion. For example, ESRI's ARC/INFO product includes a large set of generic GIS tools and has extremely powerful customization capabilities that make it an attractive candidate for GIS/KBES integration.

Figure 1 presents a conceptual framework of how a GIS/KBES could be integrated. This figure shows a linkage between the GIS and the KBES. The user interface resides within the GIS. When the KBES is needed to solve a heuristic problem, the GIS would provide context (facts) to the KBES. The inference mechanism would then process the context using rules stored in the knowledge base. The results of the process can be passed back to the GIS for display. The updated context can be used in future processes which would use the KBES more efficiently. Based on this framework, the following sections present criteria that were used in the design of the pavement GIS/KBES discussed later.

The construction of a GIS/KBES requires a systematic approach to design. Design criteria, including the following points, must be rigorously applied and the rationale for each standard must be explicitly defined for each component of the GIS/KBES.

- The inference engine must be able to address the class of general problems representative of any GIS while retaining a high degree of domain independence for other specific applications.
- The knowledge base must adequately reflect the complexity of highly specialized information while remaining internally consistent and logical.
- Conclusions and explanations derived by the rules of the knowledge base must be reproducible and supportable.

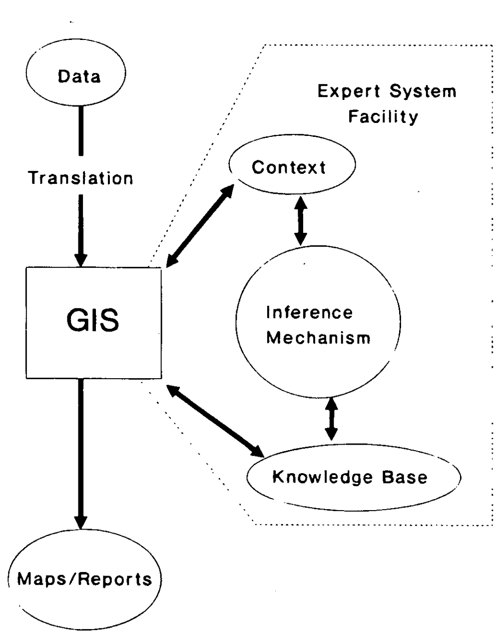


FIGURE 1 GIS/KBES conceptual framework.

- The link to the GIS and other databases must retrieve the exact information necessary to address an inquiry.
- The output must be in formats useful to the end users and decision makers, and sufficiently flexible to accommodate various needs.
- The user environment must be comfortable and encourage productivity while providing adequate power and capability to serve both experienced and novice users.
- The system must be amenable to updating and expansion in an open-ended, incremental fashion as new knowledge critical to the transportation application becomes available.

Standards for ensuring that these basic requirements are met once the system is working should be identified prior to the actual development of the system.

A number of inference algorithms were reviewed for incorporation into the GIS/KBES. These include forward chaining, backward chaining, and hybrid forward chaining with local backward-chaining inferencing. Forward chaining was chosen for this implementation because a wide range of possible scenarios can be explored in an efficient manner starting from the basic data. Thus, the system is free to draw any reasonable conclusion from the data, rather than seek out a particular conclusion or diagnosis, which is not as efficient (especially if it goes down the wrong path). Furthermore, conventional pavement management activities most closely resembles a forward-chaining decision process.

The performance of an expert system is most closely related to the content of the knowledge base. Thus, it is important that knowledge is stored in an internally consistent and logical manner.

The format of the GIS data is also important to system performance; however, like the data, it may be out of the hands of the system designer or knowledge engineer. It is important that the interaction between the GIS and the KBES be as seamless as possible and transparent to the user. The switching of different user interfaces is not very efficient. Because of the high-level rule structure of the GIS/KBES, it is preferable that GIS data be accessible to the KBES via fairly high-level calls at an operating system level. GIS query should comprise a functional description of the mapped data (e.g., asphalt overlay, no shoulder) rather than a structural description of the GIS organization (e.g., Columns 5–7 and 12). Otherwise, database information must be built into the KBES and any GIS update, change, or expansion will require a major effort.

DESIGN OF A PROTOTYPE ISTEA PAVEMENT MANAGEMENT SYSTEM GIS/KBES

The system architecture of the prototype ISTEA pavement management system GIS/KBES that evolved using the design criteria presented in the previous section is shown in Figure 2. The prototype GIS/KBES-based PMS illustrated here is designed to identify and interpret pavement distresses, evaluate the current problems of the pavements, and generate treatment or maintenance plans at the project or network level. It can be expanded to include other KBES domains such as map design, and intelligent querying to use the GIS database more efficiently. Figure 2 identifies several components that are divided into four areas. The areas are (*a*) external data, (*b*) the GIS subsystem, (*c*) the KBES subsystem, and (*d*) reporting of results. The KBES interacts with the GIS through the GIS user interface.

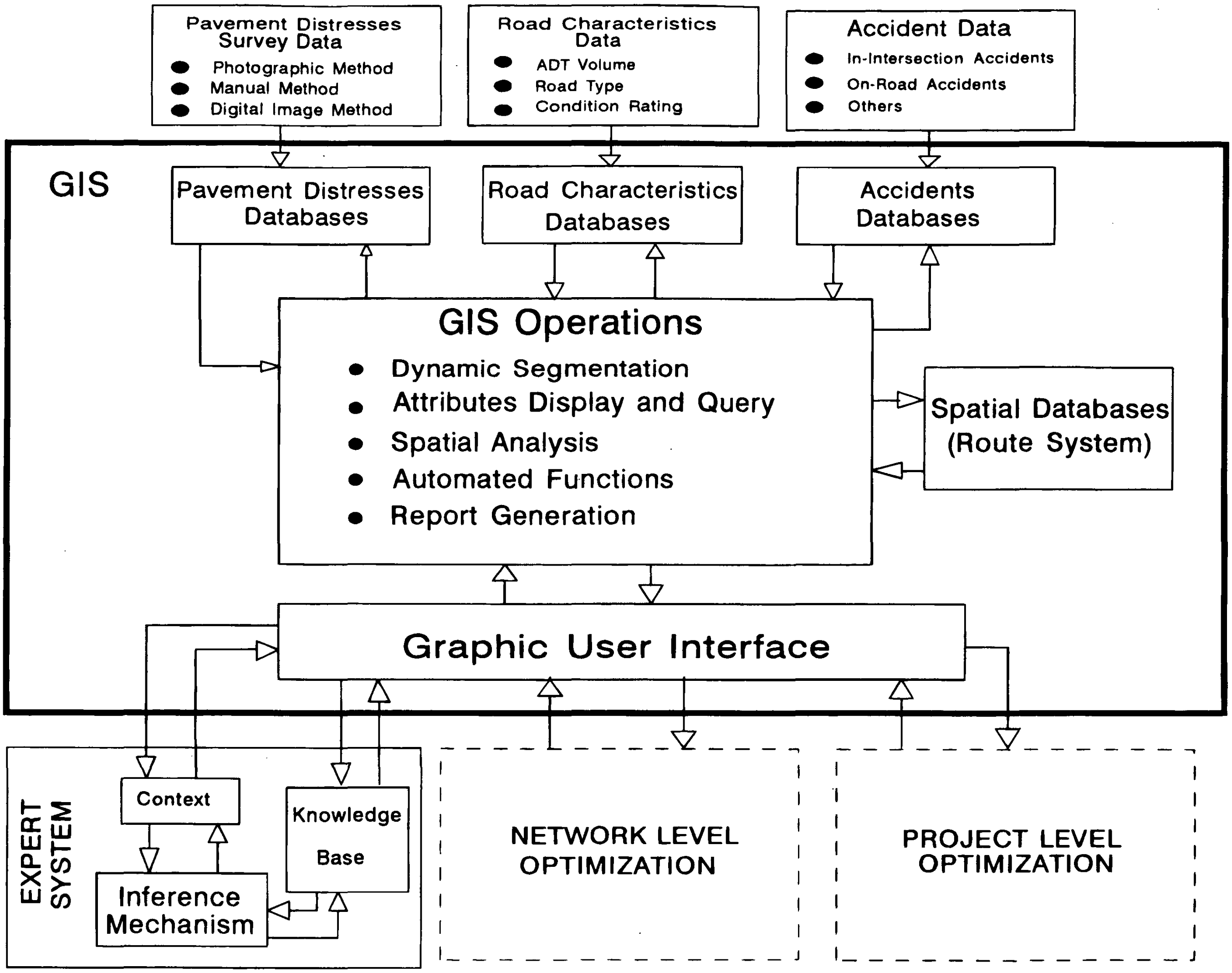


FIGURE 2 Architecture of a GIS/KBES PMS.

External Data

The external data shown in Figure 2 include pavement distress data, road characteristics data, and accident data. A series of translation programs were developed for importing these data into GIS attribute databases. The database of pavement distress attributes includes the severities and intensities of load cracking, block cracking, rutting, ravelling, and reflective cracking which were collected through biannual distress field surveys. Table 1 shows the attributes included in the pavement distress database. The road characteristics database contains average daily traffic volumes, skid factors, road types, and an overall pavement rating. The accident database currently contains only on-road accidents. It will be expanded to include accidents at intersections and the attributes associated with them. These three databases can be linked individually or in combination to the GIS route system that will be discussed in the following section. This linkage is crucial to the identification and interpretation of pavement problems. With this linkage, the pavement distresses can be graphically displayed or spatially queried on a segment-by-segment basis.

GIS Subsystem

The GIS subsystem of the prototype GIS/KBES-based PMS provides the user interface for all activities of the integrated system and is responsible for GIS-related activities such as spatial and attribute data storage, display, and analysis.

The system uses ESRI's ARC/INFO software as the GIS platform operating on a Sun SPARC workstation. The system can be ported to other hardware environments that support ARC/INFO with minimal effort. There were two reasons for the selection of ARC/INFO. First, ARC/INFO has been adopted by GDOT as its primary GIS package. Second, ARC/INFO has capabilities that are vital for GIS/KBES implementation, including the following:

- It can be customized to automate the various GIS processes that the system will use, and can access external programs such as an external KBES shell.
- Its dynamic segmentation capabilities provide the fundamental tools for linking attributes such as pavement distresses to corresponding routes or segments using a mile-point linear referencing system.

TABLE 1 **Attributes of the Pavement Distress Database**

Field name	Field Type	Field Width	# of Dec	Remarks
Trip_ID	Integer	8		Trip ID of Pavement Distress Survey
Trip_Year	Integer	12		Trip Year of Pavement Distress Survey
Survey_No	Integer	11		Pavement Distress Survey Number
Route_Id	Character	10		Route ID
Route_Number	Integer	4		Route Number
Route_Suffix	Character	2		Route Suffix
County_FIPS	Integer	3		County FIPS
MP_From	Float	5	2	Beginning (or From) Mile Post of a Segment
MP_To	Float	5	2	Ending (or To) Mile Post a Segment
Rutting_Outside	Integer	12		Rut Depth of Outside Wheelpath
Rutting_Inside	Integer	12		Rut Depth of Inside Wheelpath
Percent_LC1	Integer	12		% of Load Cracks (Severity Level 1)
Precent_LC2	Integer	12		% of Load Cracks (Severity Level 2)
Percent_LC3	Integer	12		% of Load Cracks (Severity Level 3)
Percent_LC4	Integer	12		% of Load Cracks (Severity Level 4)
Percent_BC	Integer	12		% of Block Cracking Occurrences
Severity_BC	Integer	12		Severity Level of Block Cracks
Number_RC	Integer	12		Number of Reflective Cracks
Length_RC	Integer	12		Length of Reflective Cracks
Severity_RC	Integer	12		Severity Level of Reflective Cracks
Percent_Ravel	Integer	12		Percent of the Length of Raveling
Severity_Ravel	Integer	12		Severity Level of Raveling
Percent_ED	Integer	12		Percent of the Length of Edge Distress
Severity_ED	Integer	12		Severity Level of Edge Distress
Percent_Bleed	Integer	12		Percent of the Length of Bleeding
Severity_Bleed	Integer	12		Severity Level of Bleeding
Percent_Corrug	Integer	12		Percent of the Length of Corrugations
Severity_Corrug	Integer	12		Severity Level of Corrugations
Total_Patches	Integer	12		Total Number of Patches and Potholes
Percent_Loss_S	Integer	12		Percent of the Length of Section Loss
Severity_Loss_S	Integer	12		Severity Level of Section Loss
Cross_Slope_L	Integer	12		Cross Slope in the Leftside Road
Cross_Slope_R	Integer	12		Cross Slope in the Rightside Road

• It has network overlay capabilities that allow the user to integrate data from various sources (e.g., the pavement condition data obtained from a distress survey can be overlaid with road characteristics and accident data).

GIS Route System

The route system serves as the spatial database of the GIS. It is a base map for which database attributes can be integrated and displayed. The route system used in this demonstration project contains eighteen counties in northwest Georgia. The route system was created using maps that were digitized from rectified low-level aerial photographs.

The prototype GIS/KBES-based PMS was designed largely to be independent of the route system. Thus, expansion of the route system can be integrated into the PMS with little modification. Figure 3 shows the route system in Gilmer County.

GIS Operations

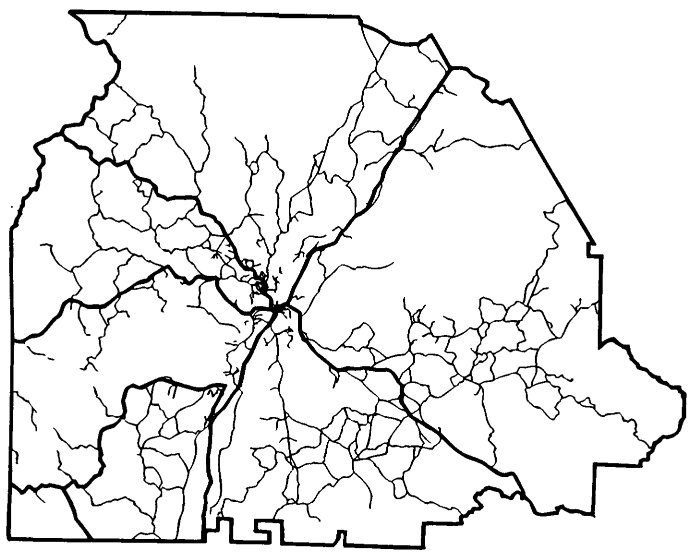
GIS operations include the graphic display and spatial query of route attributes, spatial overlay of these attributes, and the generation of reports. Figure 4 shows the user interface for creating thematic maps with the system. It includes the main menu on the left, which activates and controls the functions that implement the GIS operations. The main menu has four scroll lists that allows the user to (*a*) display and analyze road characteristics, (*b*) display and analyze pavement distress, (*c*) perform expert system analysis at both the project and network levels, (*d*) create a prioritized list of projects that includes identification of maintenance and rehabilitation treatments and the associated costs.

The road characteristics and pavement survey scroll lists include attribute items associated with the route system. One example of these attributes, or events, is the pavement condition evaluation system (PACES) rating, a subjective pavement distress rating scheme developed and used by the Georgia Department of Transportation. Once an event such as PACES rating is double-clicked or selected, a menu for the event is activated (top of Figure 4). The menu has a set of input fields, a spatial query builder, and a route-based querying and display facility.

The input fields require the user to specify the district, county, and route system to be analyzed. A help function is built into the menu. If a user misspells the county name, the help function can list all of the county names within the specified district for the user to choose from.

The query builder is a tool for creating conditional queries interactively. It provides a way of understanding the pavement problems at the network level. Once a user determines the query condition, the PMS will generate a thematic map based on the selected condition. Figure 4 shows an example of the use of the conditional query builder. In this figure, the user identified the query condition as "PACES rating < 65." The system will produce a thematic map that presents this information. One aspect of the system that has not yet been implemented is intelligent querying. In this scenario, information input into the query builder would be put into context. The KBES would use this information plus other information already in context to create a query that produces the desired map. This would have the benefit of querying the database more efficiently. Thus, it may be possible to eliminate large portions of the spatial database from consideration before the query is performed.

The route-based query and display facility provides a way of understanding pavement performance at the route level. It has two methods for choosing a route on which the PACES rating event can be displayed. These two alternatives are to select a route (*a*) by specifying its route number, or (*b*) by clicking on the route. Once a route is selected, the PACES rating event can be spatially linked and displayed on the route by the ARC/INFO dynamic segmentation functions. Figure 5 illustrates the route-based query and display



LEGEND

State Routes on Which a Pavement Distress Survey was Performed

Other Routes on Which a Pavement Distress Survey was not Performed

FIGURE 3 The route system of Gilmer County, 1992.

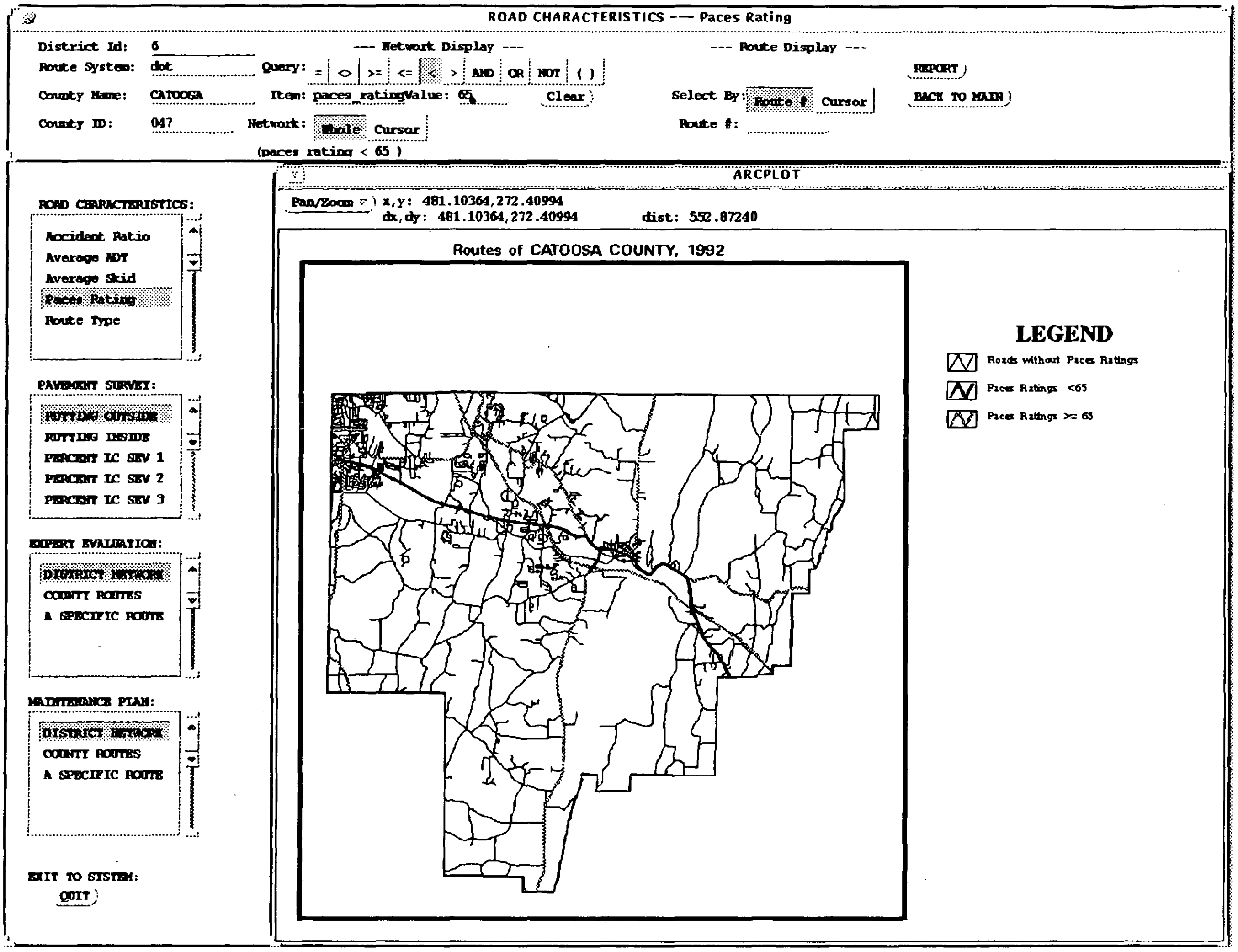


FIGURE 4 Sample thematic map creation.

facility. In this figure, the selected route is isolated in the right box for clarification. A strip map of the route is displayed with the PACES rating for each segment, and a window is displayed that includes a list of the pavement segments and their corresponding PACES ratings in tabular form. The system includes heuristics to display PACES information in a readable manner. This capability is useful when a route has too many segments to be displayed.

Knowledge-Based Expert System Design

The KBES subsystem uses NASA's CLIPS ruled-based expert system shell for the evaluation of pavement distresses and the determination of segment treatments. The CLIPS shell, written in C, can be embedded into other systems. The embedded feature allows for integration of the KBES with the GIS at the operating system level.

The KBES subsystem consists of three main components: the knowledge base, the inference mechanism, and context. The knowledge base contains control knowledge and domain knowledge. The inference mechanism uses the control knowledge to dictate how the domain knowledge is used. The knowledge is represented as a set of rules, which were developed through interviews with GDOT engineers and the FHWA district pavement engineer. Figure 6 shows an example of an inference network, which illustrates the process by which the inference mechanism uses control knowledge and domain knowledge to infer the solution of a pavement problem, similar to the way an experienced pavement engineer does. The context is developed automatically using inputs from the GIS including the event data and their associated route or network spatial information.

The interface between the GIS and the KBES is through a set of programs written in ARC/INFO's ARC macro language (AML) and C. The interface is activated by the pavement evaluation list, which has three levels of pavement evaluation: the route level, the county level, and the district level. The route level concentrates on an individual route, evaluating it through the KBES. The county and district levels consider a set of routes selected either by the spatial query builder or by the cursor and evaluate these routes through the KBES.

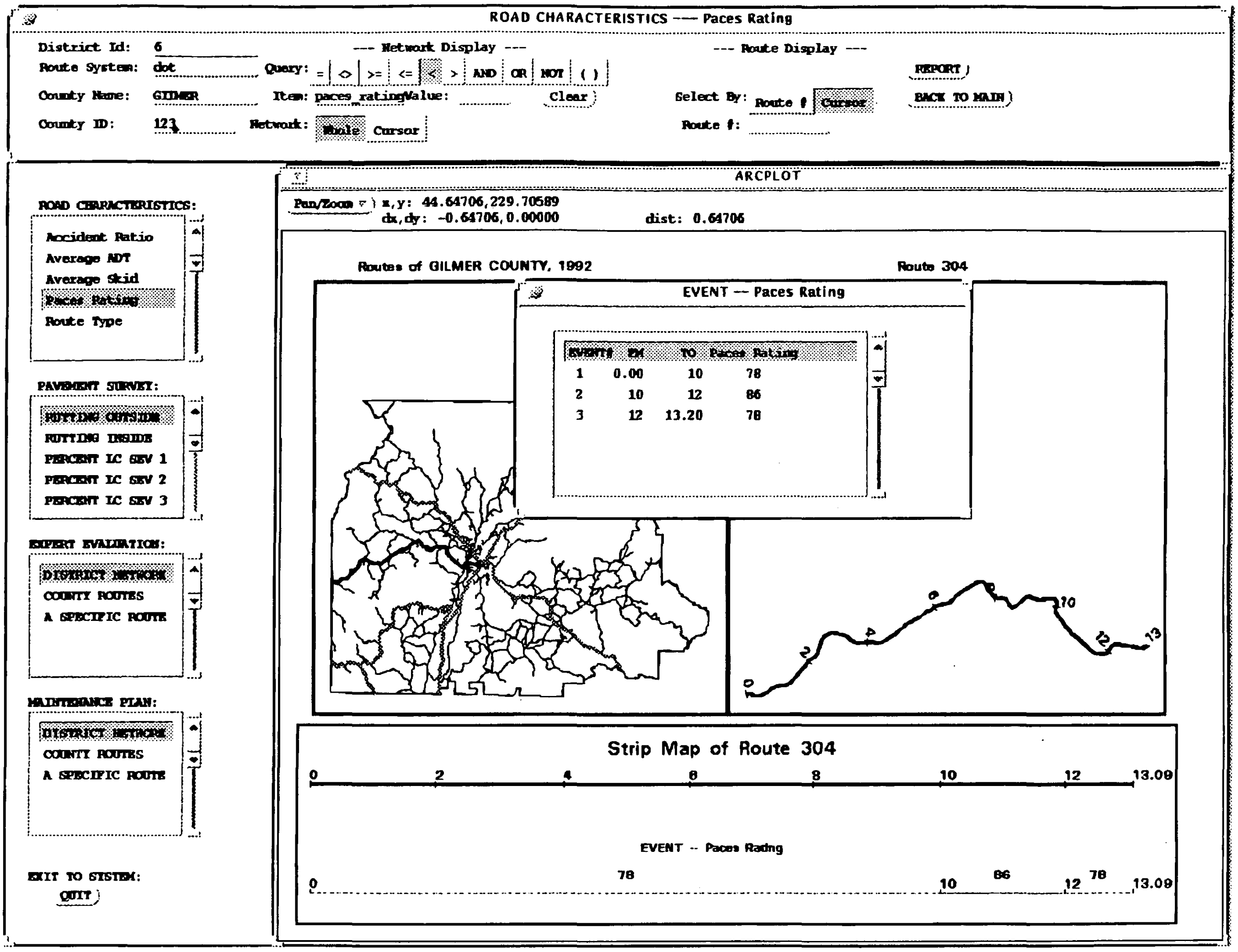


FIGURE 5 Sample route-based query.

GIS/KBES Integration

The process of integrating the KBES with the GIS-based PMS at the route level is shown in Figure 7. The figure illustrates three steps: network overlay of pavement distresses and road characteristics, the passage of control and information to and from the user interface, and the spatial display and query of segment treatment and the generation of the treatment report.

Network Overlay

Before using the KBES, the various attributes to be used in the analysis need to be overlaid. The overlay process, activated when a user selects a route with the cursor or the route number, can combine the pavement distress and other road characteristics to produce a new event database. Figure 7 illustrates the process of an event overlay. In the figure, the GIS overlays ADT with load cracking to create the new event database, which is then passed to the KBES.

Passage of Control and Information to and from the GIS

The GIS user interface calls the KBES at the operating system level using the Expert-Route button or Expert-Section button shown in Figure 8. As the KBES works, spatial and attribute data are passed from the GIS as needed to complete the process.

The Expert-Route button passes the overlaid event database for a specified route to the KBES, whereas the Expert-Section button passes a part of the overlaid event database for an individual segment. The Expert-Section button also opens a window listing the event data for all of the segments of a specified route. The window provides a visual tool for selecting segments to be passed to the KBES for analysis.

As the KBES works, system status and the segment treatment decisions are stored. This information allows the user to review how the KBES came up with a particular treatment. Status information, such as rules fired and associated explanations, can also be dynamically displayed in a window.

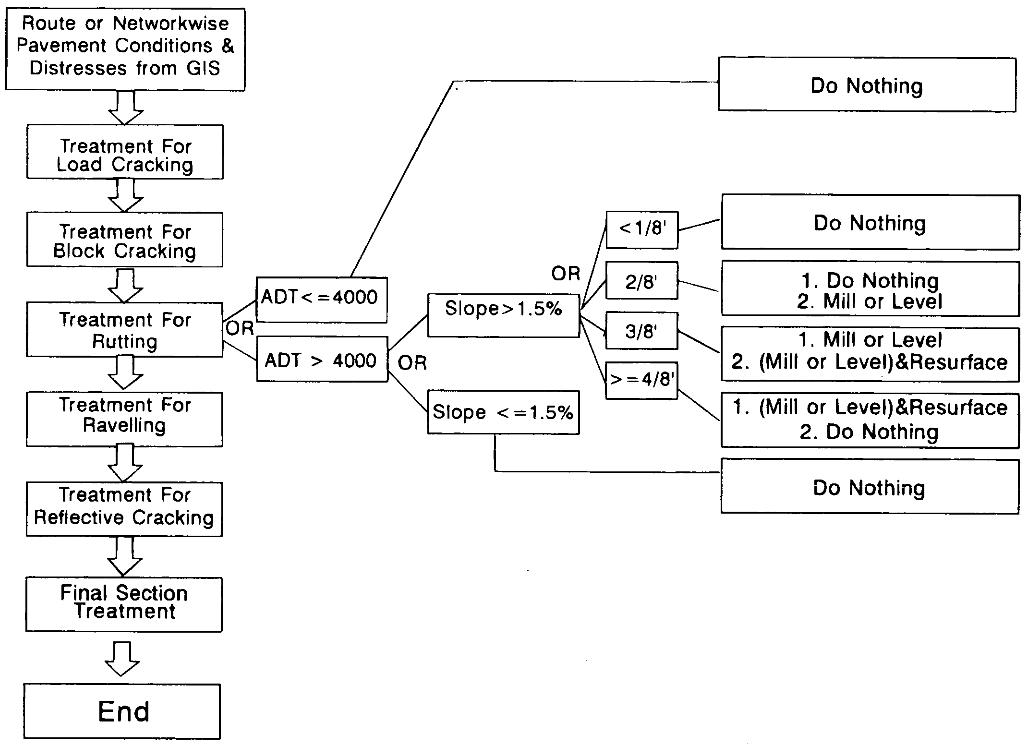


FIGURE 6 Sample inference network (rutting).

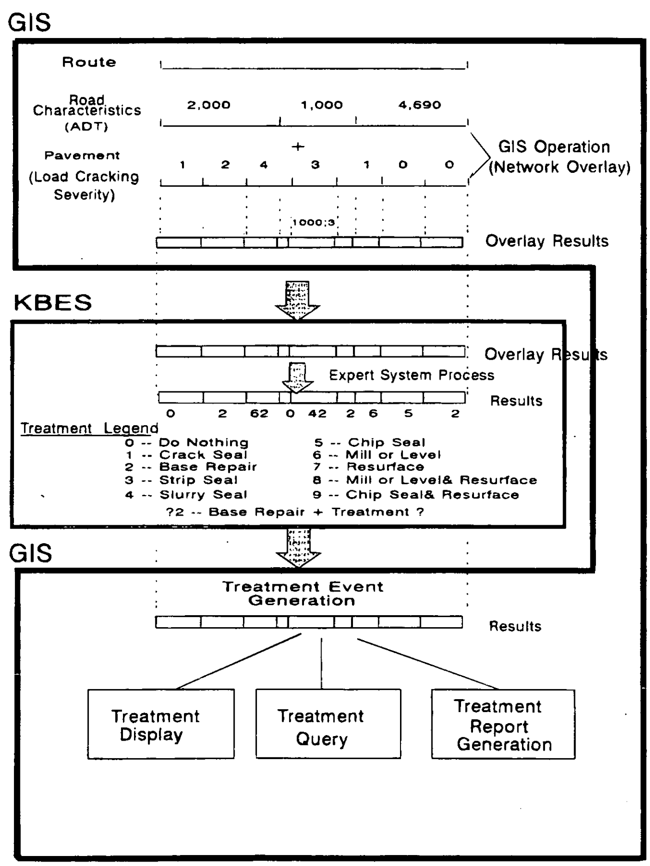


FIGURE 7 Interaction between GIS and KBES.

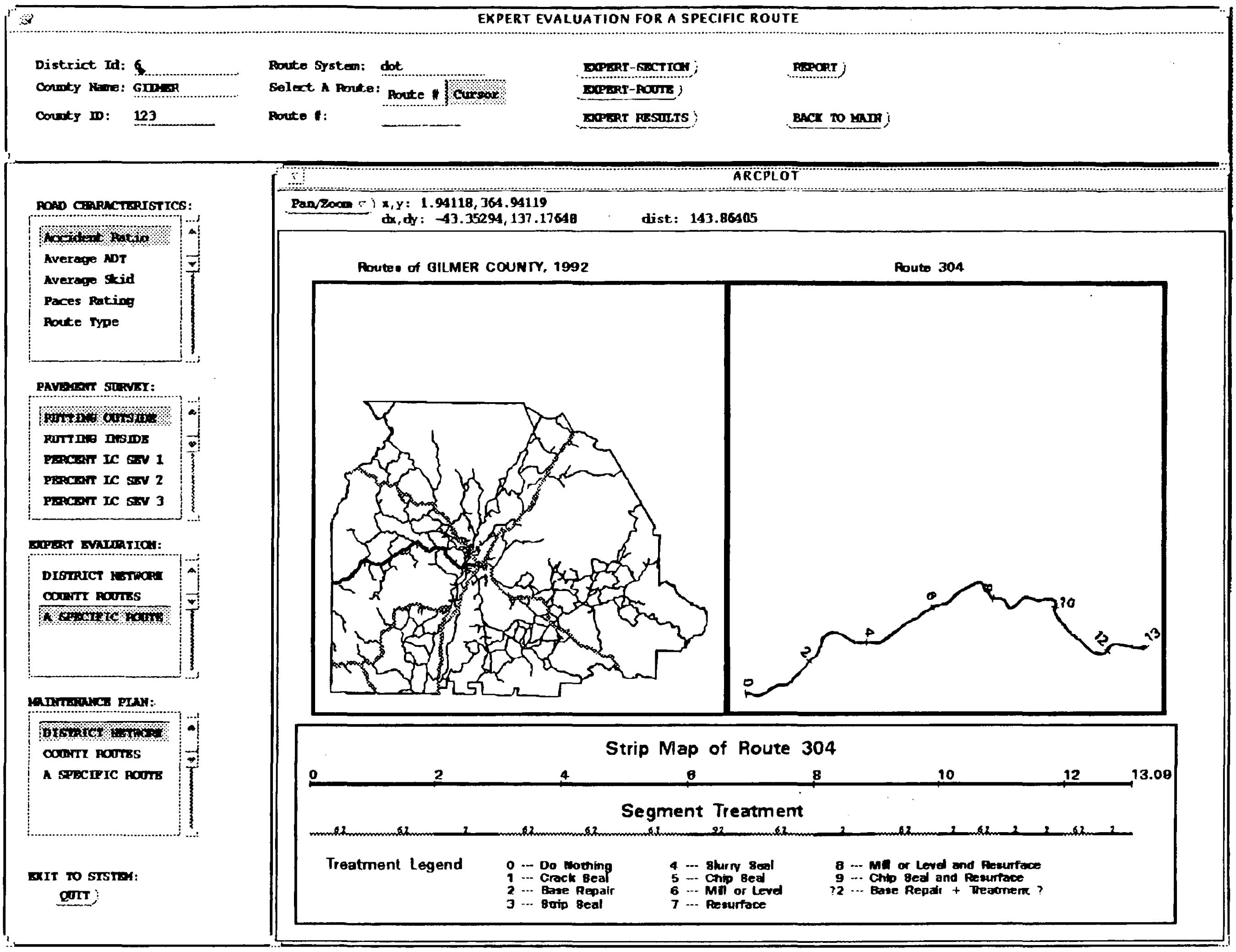


FIGURE 8 GIS/KBES route evaluation.

Segment Treatment Query, Display and Report Generation

After the segment treatment results are passed from the KBES to the GIS, the user interface can be used to spatially query and graphically display the recommended segment treatments, and to generate a treatment report. The Expert Results button invokes a strip map of the specified route and arranges the segment treatments graphically along the route (see Figure 8). The Report button activates the report generation function. Figure 9 shows a sample report.

The segment-based treatment decisions are the key to the determination of maintenance plans at the route level. Given these treatment decisions, their treatment costs, and other constraint factors, projects can be identified and prioritized into an overall maintenance plan.

FUTURE ENHANCEMENTS

The prototype GIS/KBES-based PMS presented in this paper provides users with a list of suggested roadway treatments based on the condition of the road. A future enhancement to the system includes incorporating network-level analysis and performance prediction capabilities, as required by ISTEA. From a research standpoint, there are a number of enhancements that can be made to demonstrate areas where the KBES would be beneficial. These areas include intelligent spatial querying and map design.

Further verification and validation of the prototype system based on criteria presented in this paper will be done once the system is in full implementation in GDOT.

CONCLUSION

The potential for the integration of GISs with KBESs promises to be of great value for the development of a better GIS. KBESs offer possibilities for making GISs more computationally efficient and user-friendly using expert knowledge and high-level reasoning procedures. Specific applications in transportation, such as pavement management, can benefit from KBES technology. Furthermore, many of the transportation areas in which GIS technology has been

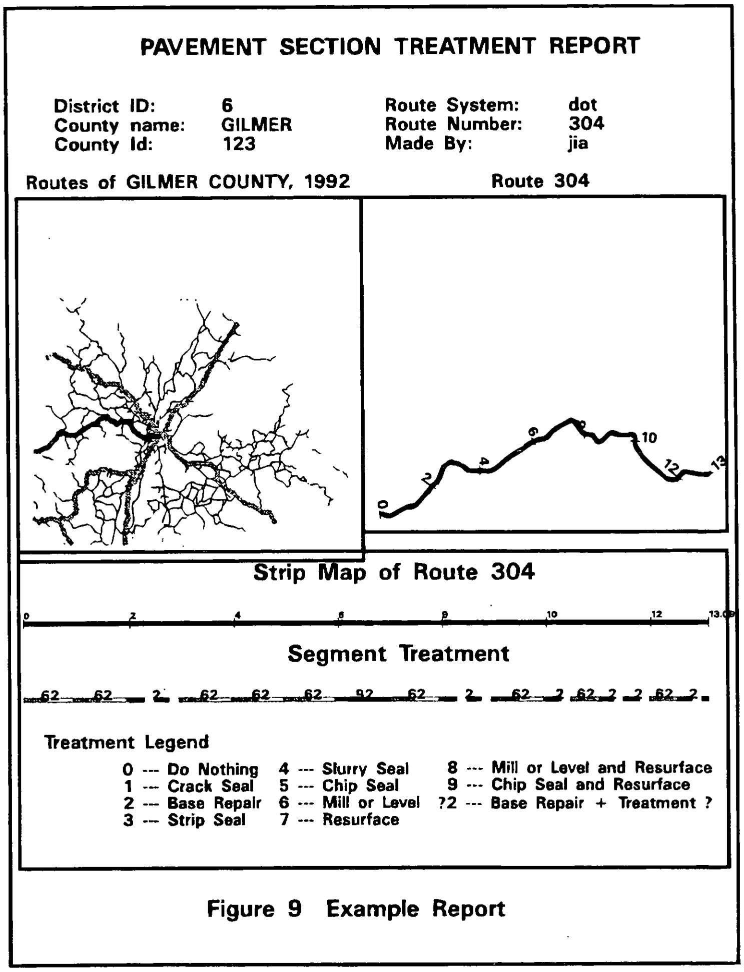


FIGURE 9 Sample report.

or will be applied involve very dynamic, iterative processes with no right answers. Numerous factors preclude the development of black box solutions; therefore, the potential for integrating expert systems with GIS is promising.

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