Integration of Management Systems into Geographical Information Systems

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The purpose of this paper is to illustrate the use of geographical information systems (GIS) and transportation-related management systems so that a comprehensive management tool for transportation engineers can be developed. The focus of the paper is on microcomputer-based systems. A network-level culvert ranking system was attached to two GIS to illustrate the procedures and approach. It was demonstrated that when data are stored in most standard electronic formats, a significant effort is not usually required to integrate them into GIS. Base maps are readily available for many of the systems because of the TIGER files used during the 1990 census. Examples were presented to illustrate how GIS can be used to enhance the results from one type of management system. Although each system is different, other systems would work in a similar way. The use of microcomputer-based GIS has proved to be a significant time saver and could be used to improve the productivity and capability of transportation officials in the future.

The use of management systems for large transportation systems has been a fertile area of development. The principal objectives of all these management systems have been to effectively manage these large transportation systems with finite resources, optimize their performance, and set or justify current maintenance budgets so that minimum overall costs can be achieved.

Each of these management systems requires data about the transportation system, models of costs and system deterioration for conducting a network-level ranking, and a maintenance budget for each item. Once the critical items are found, many of the management systems will actually select "optimum" project-level strategies for improving the overall transportation system.

All of these management systems (pavement, bridge, and culvert) require significant amounts of data to drive them. If they can be presented clearly, these data can be useful for the management of most transportation systems. However, using standard methods, it is often difficult to determine what information is valuable, what trends are present, and what decisions are correct.

With the advent of relatively inexpensive computer power at the disposal of the transportation engineer, software engineers have been able to make GIS available. The heart of all GIS is the linkage of data and a map of a particular area of interest. This attachment of information to drawing entities is an extremely powerful capability. With many GIS, this information can be interrogated, displayed on a computer-based map, and then interpreted by the transportation official.

The purpose of this paper is to illustrate examples that combine the features of one transportation management system and GIS packages to develop a comprehensive management tool for transportation engineers. The focus will be on GIS that were developed for microcomputer-based systems.

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GEOGRAPHICAL INFORMATION SYSTEMS

Several hundred GIS are available to transportation officials for mainframe, minicomputers or workstations, and microcomputers. A few systems will work on all three computer systems, but this feature is limited among GIS developers. Many systems developed for mainframe or workstation computers have excellent features, but they are relatively expensive and require the management of large systems before they can be justified from cost considerations.

For the management of many systems, the use of a microcomputer-based GIS is an excellent choice. These microcomputer-based systems may provide support of the network environment where information can be shared among different users. In some organizations, this sharing of information can be arranged using different strategies.

When evaluating GIS, it is critical to note that although features of the system are important, the cost of the data driving the systems is usually much higher than those of hardware and software. One approach to minimizing these costs is to take advantage of the Topologically Integrated Geographic Encoding and Referencing (TIGER) (*1*) files made available through the Bureau of the Census. These files were developed by the Bureau in preparation for the 1990 Census. They provide a wealth of information about geographical entities and districts, including street-level detail for every county in the United States. Each street, waterway, railroad, city or county boundary, and so on, is digitized and stored in a standardized electronic format. Some GIS have the capability of reading the TIGER file format directly, whereas other systems must go through a data-conversion process. Privately developed base maps are also available.

The size of these TIGER files will vary depending on the development and size of the area. Because of the large amount of information stored in the TIGER files, the precensus files for 105 counties in Kansas contain more than 483 megabytes of information. The information stored in these files, which are important to transportation officials and many GIS systems, includes the beginning and ending coordinates of each line segment and type of feature (street, water, railroad, etc.). In urban locations, the TIGER files also contain the name of the segment and the address range on the left and right side of the street segments. In rural locations, the files generally do not contain this street-level information.

The focus and experience with PreCENSUS TIGER files have been primarily in the rural areas of Kansas. Many mile-long sections could have as many as three segments defining them. If only one segment per section is desired, two segments must be removed and the third one modified to contain the entire section. It is also necessary to define the names and address range associated with each segment. This could require significant coordination between several departments within the agency. It is necessary if a coordinated effort occurs within the agency.

The updating of the basic TIGER map should be considered as a necessary task before implementing GIS in rural areas. When using the TIGER files, it is important to remember that they were developed to conduct a census and not to serve as base maps for GIS. They should definitely not be used for most engineering applications.

GIS are different from other graphic packages, such as CAD (computer-aided design), because information attached to each drawing entity is efficiently tied to the data base. Because GIS were specifically designed for this operation, they are much faster and more efficient than most CAD-based GIS. GIS must efficiently find the street name, address range, and entity type very quickly. Most CAD systems were designed to draw lines and circles efficiently.

The more complete GIS generally support three types of drawing entities. The simplest type of data element is one that contains information about a point or object. These data are generally stored in point files, typical examples of which are data bases containing information about bridges, culverts, or sign inventories.

The next level of drawing entity supported by most GIS is a line element, which could be a street, water segment, or railroad, as previously discussed. However, it could also be a pavement segment, sewer or water line, or telephone line. Not all GIS will permit additional information to be stored with these drawing entities. Obviously, for some applications such as pavement data, transportation officials must have this capability of storing information with the line element. In this way, street level features such as material type, roughness, deterioration status, and so on, can be stored.

The highest level of drawing entities supported by most GIS are area- or boundary-type elements. In some systems, these are called boundary files. Boundary areas are excellent for determining properties associated with geographical areas; for example, state and counties define areas.

Most GIS systems allow for the evaluation of information associated with a boundary based on data found in point files. For example, to determine the average bridge rating for each district in a county, GIS could look at the bridge ratings for each bridge in the county. Each bridge would be assigned to a district and averaged with all other bridges in the district. Many GIS can provide additional statistical information for areas such as maximum and minimum values of a particular data field.

One desirable feature found in most GIS is the capability to display data-base information using different colors and symbols. If emphasis of the average bridge ratings for each district is required, a process called thematic mapping will select a different color or pattern for each district based on the average bridge rating for the district. In many systems, the ranges for selecting these colors or patterns may be predetermined or user selected.

Thematic mapping can also be used for point files. For example, bridges with good ratings could be displayed in one color and those with poor ratings in another. With paper maps, this would be called a pin map.

This thematic mapping capability is possible with GIS because the maps are efficiently tied to the vast amount of information required to drive the system. Therefore, fast computers with large hard disks, large RAM (random access memory), and good graphic cards are necessary. Fortunately, 386 and 486 computers provide sufficient computer power for most applications.

Besides the obvious graphic capability, these systems must have an efficient access to a data-base system, which could use a standard data-base format, such as dBASE, or it could be a proprietary data-base system. There are advantages to both approaches. However, what is important is that either compatibility or the capability of interfacing with an existing data base must be provided. When GIS is not dBASE compatible, the interface is generally through ASCII and LOTUS worksheet file formats.

GEOCODING

One of the most important procedures in GIS applications is attaching the data base to the computerized map; for example, attaching a bridge to a particular spot on a map can be accomplished in several ways. The specific method selected to locate each data record is dependent on the location information in the data base, capability of the software, and information stored with the map.

Location information stored in the data base could be an address, highway mile post, latitude-longitude or other coordinate system. Most GIS use latitude-longitude as the coordinate system for defining the map. If so, they will use this system for the location of point files. If addresses are available and the software and map support an address method of geocoding, the software will calculate the latitude-longitude coordinates of each point in the data base based on the address and the map data base. These latitude-longitude coordinates are usually stored in the data base in two additional fields.

Some systems also support geocoding by theme files, boundary names, and pointing. A typical example of theme-file geocoding is a point file data base containing ZIP codes. A second data base (theme file) contains records with fields for ZIP codes, and latitude and longitude coordinates. The software will look in the theme file for the ZIP code and coordinates for each record in the original data base. These coordinates will be stored in the original data base.

Boundary names can also be used to geocode a data base that contains a field with the boundary name. If the boundary map includes a field with the same boundary names, the original data base could be geocoded on the basis of the geometry of the boundary. Unfortunately, most systems will place all point file records in the boundary at the same location, usually the boundary centroid.

The last method of geocoding a point file is by pointing to the map location with a mouse or digitizing tablet. This method is simple but is labor intensive and prone to operator errors.

APPLICATION TO A NETWORK-LEVEL CULVERT RANKING SYSTEM

A network-level culvert ranking system was recently developed by Kurt and McNichol (*2*). This system was developed using dBASE III+a data-base management system. Basically, this system took eight culvert parameters and conducted a network-level ranking of each culvert in the system. The culvert management system (CMS) was developed using a level of service concept that is also popular with most bridge management systems.

The original CMS data base was modified to add two fields to the data base so that the latitude and longitude coordinates could be stored. Because the local agency used a grid system for the county, a numerical (N/S) and alphanumeric (E/W) coordinate were already stored in the data base. A location description was also stored in the data base, but it was unrelated to the map data base and therefore was not used in geocoding.

Two different microcomputer-based GIS have been used by the author. The first is GISPlus, developed by the Caliper Corporation (*3*). The other is MAPInfo, developed by MAPINFO Corporation (*4*). Although the systems have similar features, they also contain features that are very different. One feature that both systems have in common is provision of a means for users to write their own applications so that the software can better meet their needs. GISPlus is capable of processing executable files written in most microcomputer-based languages. MAPINFO provides a *C*-based language (MAPCODE) so that users can develop applications that work within MAPINFO.

For this culvert application, a MAPCODE program was written to transform the local agency grid coordinates to a latitude-longitude coordinate system. To account for the curvature of the earth, the following transformation equations were used:

$$XCOORD = 95.056221 - \frac{XL}{69.171 * \mathrm{COS}38.738496} \qquad (1)$$

$$YCOORD = 38.738496 + \frac{YL}{69.171} \qquad (2)$$

where

$XCOORD$, $YCOORD$ = latitude and longitude of mapping system, degrees;
95.056221, 38.738496 = latitude and longitude of local coordinate system origin, degrees; and
XL, YL = local system coordinates, miles.

The local coordinate system origin was in the extreme southwest corner of the county. The positive directions of the local coordinate system are positive to the north and east. The difference in signs is because the latitude and longitude coordinates are positive to the north and west directions. The cosine term in the XCOORD term accounts for the fact that the number of miles per degree is smaller when traveling from the equator to the poles.

Because MAPCODE reads information directly from a dBASE data base, calculates latitude-longitude coordinates and stores these values in the data base, the transformation process had to be conducted only one time. With the latitude and longitude coordinates calculated, each culvert can be located on the existing computer base map of the local agency. Although a similar program was not written for the GISPlus package, it would not require a significant effort to provide identical capability.

Of course, the proof of the operation is to see a map of the local agency with the culverts displayed. Except for a few cases in which errors were observed in the original data base, all culverts were correctly located.

A brief review of the network level culvert ranking system will now be presented. The development work for this system has been presented in the TIGER/Line Precensus files (*1*). This system is based on a level-of-service concept and defines deficiency points for each culvert. These deficiency points are based on four different conditions: load capacity, hydraulic capacity, culvert width deficiency, and maintenance priority. Each condition had a priority ranking formula developed that is a function of culvert parameters, culvert parameter goals, and weighting factors. The total priority ranking formula has the form:

$$\text{Deficiency points} = \Sigma\, K_i f_i\,(a,b,c,d,\ldots) \qquad (3)$$

where

K_i = weighting factors,
$f_i\,(a,b,c,d,\ldots)$ = priority ranking formulas, and
$a,b,c,d,\ldots$ = culvert parameters.

The deficiency point formula developed for each condition is as follows:

Load Capacity

$$CP = WC * (CG - SV)/345 * ADT * DL \qquad (4)$$

where

CP = capacity priority;
WC = load capacity weighting factor;
CG = capacity goal, tons;
SV = single vehicle posting, tons;
ADT = average daily traffic; and
DL = detour length, miles.

The capacity priority (CP) may not be less than 0.

Hydraulic Capacity

$$HP = WH * (NF - NG)/365 * [(KF * ADT * DLh) + \$/\mathrm{Flood}] \qquad (5)$$

where

HP = hydraulic priority;
WH = hydraulic capacity weighting factor;

NF = number of flood days/year;
NG = number of flood days/year goal;
$KF = .062 * (SV - 3)^{.30}$;
ADT = average daily traffic;
DLh = detour length caused by flooding, miles;
SV = single vehicle posting, tons; and
$\$/FLOOD$ = average damage cost/flood day.

The hydraulic priority (HP) may not be less than 0.

Width Deficiency

$$WP = WW * [(WD^2 - WDG^2)/9380 - (WD - WDG)/338] * ADT \quad (6)$$

where

WP = width priority;
WW = width deficiency weighting factor;
WD = relative culvert width difference, ft;
WDG = relative culvert width difference goal, ft; and
ADT = average daily traffic.

The width priority (WP) may not be less than 0.

Maintenance Priority

$$MP = WM * (MC - MG)/365 \quad (7)$$

where

MP = maintenance priority;
WM = maintenance weighting factor;
MC = maintenance cost, \$/year; and
MG = maintenance goal, \$/year.

The maintenance priority (MP) may not be less than 0.

The total number of deficiency points, DP, assigned to a culvert is the sum of four components and is given from the equation:

$$DP = CP + HP + WP + MP \quad (8)$$

where CP, HP, WP, and MP have been previously defined.

The number of deficiency points assigned to each culvert is based on eight culvert parameters, four weighting factors, and the goals selected for culvert parameters. The four weighting factors were developed so that their value should be equal to one. However, the system is flexible enough so that a local agency could use alternate weighting factors if local conditions warrant.

The number of deficiency points assigned to a culvert is not limited. However, as the number of deficiency points assigned to a culvert increases, the capacity of the culvert to meet the goals assigned to it becomes limited. A culvert with 0 deficiency points fully meets all of the goals for that particular system.

A data base program was developed on the basis of this approach to assist the user in manipulating the culvert parameters, calculating the deficiency points, sorting the results, and displaying and printing the results.

Although this approach provides the user with vast amounts of information, it is difficult to really understand the data and how they affect the performance of the system. For example, where are the reinforced concrete box culverts located in the system? How many of them are structurally inadequate and where are they located? Where are the culverts with the highest number of deficiency points actually located? Although a transportation official can answer these questions by poring over the software output and a local map, there is a better way: the use of a microcomputer-based GIS.

The largest cost in using GIS is usually the collection of the data (application and base map). Because of the TIGER files available, the base maps, with sufficient accuracy, are readily available at nominal cost. Because the culvert data must be collected in order to drive the network level ranking system, the only cost of implementing a GIS application is the geocoding and computer software.

Now, how can GIS be used in a management application? In this particular county there were approximately 1,353 culverts under the responsibility of the local agency. There are 8 different culvert types in the agency. The distribution of culverts by type is as follows: 94 were corrugated metal arch (CMMAC-1); 607 were corrugated metal pipe (CMP-2); 84 were concrete arch (CO ARCH-3); 317 were reinforced concrete box (RCB-4); 93 were reinforced concrete pipe (RCP-5); 92 were simple span (SI SPAN-6); 55 were stone arch (ST ARCH-7); and 5 were Boiler Pipe (BP-8); and several other culverts of an unknown nature. The numbers are given so that the culvert type could be numbered numerically.

After these culverts are geocoded, they are displayed on a map, as illustrated in Figure 1. The road system has not been displayed for clarity, but the roads are evident based on culvert locations. The boundaries (city and townships) are displayed. Because the northeast corner of the county is urban, the local agency does not maintain the culverts in this area.

It should be noted that each culvert type is displayed with a different type of symbol. On a color monitor, each symbol was assigned a different color for clarity. Hopefully, this figure will give a feel for the system. All culvert types can easily be located on the system.

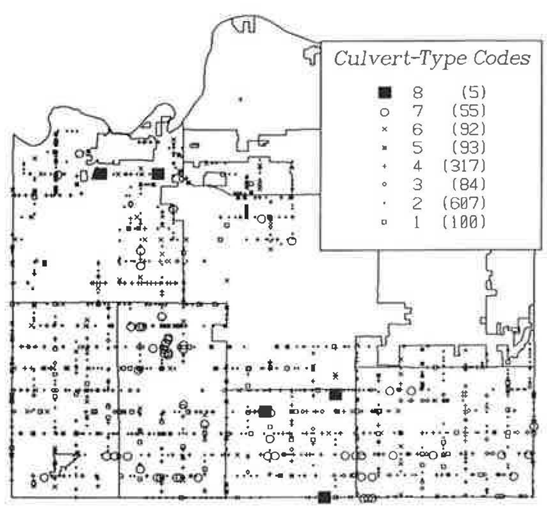

FIGURE 1 Culvert types in local agency system.

Although culvert type may be one way to evaluate the system, the purpose of the culvert network-level ranking system is to select the culverts that have the highest number of deficiency points. These culverts, based on this system, have high user and agency costs. Where are they located? Could this information be used to develop a comprehensive culvert management program? The use of GIS can help in these decisions.

For example, in Figure 2, the ranking of the system based on total number of deficiency points can be seen. Seventeen culverts have more than 100 deficiency points assigned to them. It can be noted that they fall on three or four east-west roads in the southern part of the county. These high-deficiency point ratings could be caused by high ADTs or low load capacity. Three of the worst culverts lie along a 2 mi section of a single road. Perhaps this is a region that warrants further investigation. If this is true, a different type of search of the data base could be conducted to test this theory.

With the search and filter features of most GIS, the original culvert data base can be reduced to locate those culverts that are reinforced concrete box culverts (Culvert Type 4). The thematic map considering reinforced concrete box culverts alone is presented in Figure 3. Again, note that many of the culverts with high deficiency points assigned to them are, in fact, reinforced box culverts.

It can now be learned whether the high number of deficiency points assigned to these reinforced concrete box culverts are caused by inadequate load capacity. Using the reinforced concrete box culverts, a thematic map is prepared based on the load-carrying deficiency point component only. Because load-carrying deficiency points are stored in the data base, a thematic mapping process on the reinforced concrete box culverts can be conducted using the load-carrying deficiency point field as the basis for the thematic map. These results are shown in Figure 4. To reduce clutter, the road system is not shown. Color is added to the screen to assist in evaluating the system.

When comparing the results shown in Figures 3 and 4, it can be seen that the majority of the total deficiency points is caused by insufficient load capacity of the reinforced concrete box culverts. It can also be seen where the most critical cul-

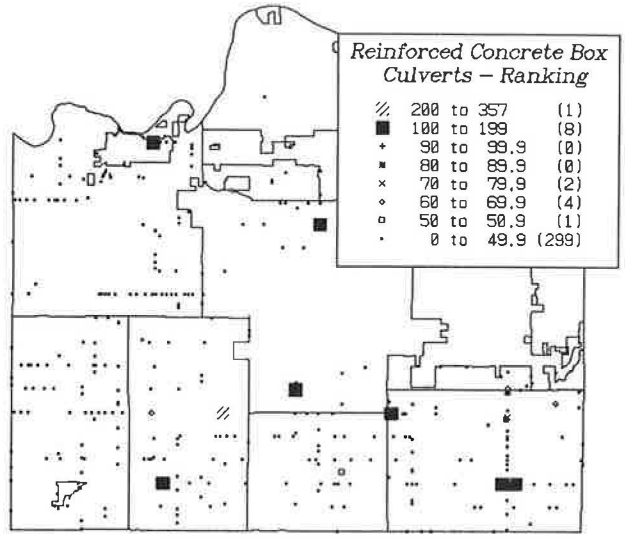

FIGURE 3 Thematic map of reinforced concrete box culverts only, based on total deficiency points.

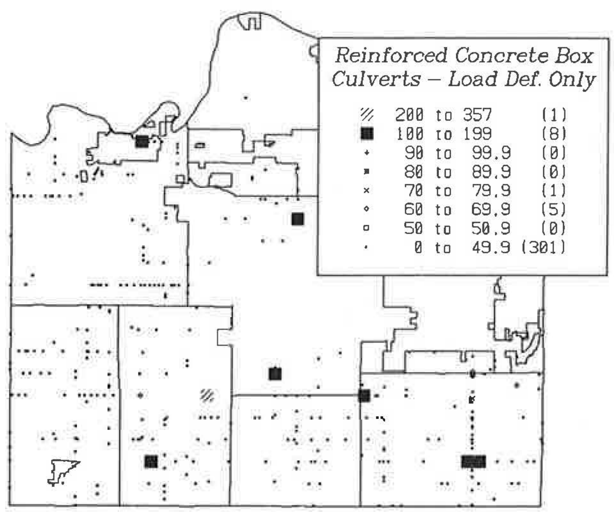

FIGURE 4 Thematic map of reinforced concrete box culverts only, based on load-carrying deficiency points only.

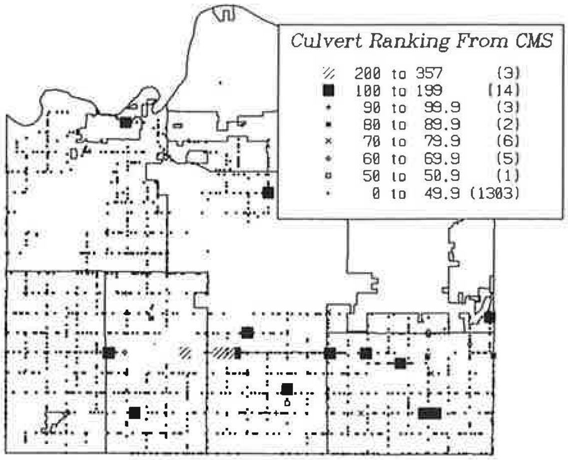

FIGURE 2 All culverts thematically mapped based on total deficiency points.

verts are located. A plan for correcting this deficiency can now be developed.

These examples of thematic mapping are fairly simple. GISPlus has the capability of showing deficiency point value for each of the four components as well as the total number of deficiency points for each culvert. This way, it would be apparent which culverts had a high level of deficiency and why they are deficient.

There are several advantages to this approach of analyzing the vast amount of data over more traditional methods of analysis. The first advantage is that because the data were already stored in electronic format, all of these examples were created in a matter of minutes. How long would it take to create these maps using manual methods? Obviously, much longer.

A second advantage is that because this information is available in electronic format, it can be used with other software packages. Both packages can create either an HPGL plot file or PCX file. This permits the output from either package to be used in many word processors or desktop publishing packages. WordPerfect and other word processors read these figures using either format, so the figures can be brought into a report. Then figures can be printed with the reports to a laser printer or other output device. Of course, if a color output device, plotter, color laser printer, or other color graphics terminal is available, then color-printed output is available for reports or presentations. This approach illustrates the flexibility built into most microcomputer-based GIS.

GIS AND VISUAL DISPLAYS

The last application to be covered is the integration of the data bases, GIS, and the visual display of graphical images. Because of recent advances of digital technology, it is now technically and economically feasible to store vast amount of information in digital format. Some applications of this technology will be presented.

With the culverts displayed on the map, it may be desirable to look at the status of a particular concrete box culvert. Earlier, a crew was sent out to videotape the culvert using standard videotape equipment found in the home. After the tape is brought into the office, the locations that are useful on the tape can be recorded and stored in a data base. Along with these locations, the structure number, or other identifying label, is stored.

A special application or procedure can then be written so that the user is prompted to point to a particular culvert. GIS will look up the identifying label, look into the tape data base, and send a signal to a special VCR to locate the portion of the tape containing this culvert. The videotape showing this culvert will be played on a television monitor. Thus, the transportation official can automatically review a videotape of every culvert in the system at the click of a button.

There are advantages and disadvantages to this type of visual display. The advantages include the capability of seeing the object without having to travel to the site. A documented status summary can be prepared if the videotape is updated periodically. Also, videotaping is relatively inexpensive. The primary disadvantage is that videotape displays are relatively slow. Unless a high use of this tool is anticipated, speed is not critical in many situations.

Another approach is to store the information in digital format on a CD-ROM. A demonstration at Caliper Corporation showed a map of a state highway system. When a segment of the highway system was selected, the author was asked how fast he wanted to travel this segment. A display of the entire segment was provided on a monitor simulating a speed of 80 mph.

Again, what makes this possible is the storage of vast amounts of information in digital format. GIS is the tool that makes all this possible and makes the system easy to use for the operator. In this application, GIS sends a signal to the CD-ROM player to locate the desired segment. The CD-ROM reader sends the signal to the monitor. The advantage of the CD-ROM technology is the vast amount of information that can be stored and accessed quickly. Its primary disadvantage is its cost.

CONCLUSIONS

In this paper, the use of GIS was illustrated in the use of a network-level culvert ranking system. However, GIS have also been successfully used in bridge, pavement, and sign inventory applications. When data are stored in most standard electronic formats, a significant effort is not usually required to integrate them into GIS. Base maps are readily available for many of the systems because of the TIGER files used during the 1990 census. The user should expect to spend some effort modifying these files for their specific applications.

Examples were presented to illustrate how GIS can be used to enhance the results from one type of management system. Although each system is different, other systems would work in a similar way. The use of these microcomputer-based GIS has proved to be a significant time saver and could help improve the productivity and capability of transportation officials in the future.

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