Applying Geographic Information System Technology to Traffic Signal Coordination

WAYNE A. SARASUA

Research conducted at the Georgia Institute of Technology that investigated the use of geographic information system (GIS) technology as a support tool for coordinating traffic signals is discussed. TRANSYT-7F is the most widely used and respected macroscopic computer model for optimizing the coordination of traffic signals. Unfortunately, creating an optimum TRANSYT-7F model is very costly. The hypothesis of this research was that the use of a specialized GIS with TRANSYT-7F could enhance the process of coordinating a traffic signal system. The research resulted in the development of a GIS-based signal coordination system that operates on a microcomputer. This system is an improvement over existing methods of creating optimum TRANSYT-7F models because relationships between intersections do not have to be encoded manually. Instead, the system takes advantage of the GIS's topological data structure, which provides these relationships. The process of analyzing different network optimization scenarios is simplified with this system because the user need only to select the intersections to be coordinated from the GIS graphic display instead of cutting and pasting from existing TRANSYT-7F input files. Alternatively, the system can serve as a multipurpose signal information system and play a vital role in decision support. It can provide improved access to signal data and allows for swift identification of intersections that experience excessive delays or unacceptable levels of service.

Studies have shown that the proper coordination of traffic signals in a local street system is the most effective way to reduce delay, fuel consumption, and vehicle emissions. Because of continual changes in traffic patterns brought on by new land use developments and shifts in commuting patterns, there is a need to coordinate traffic signals on a regular basis. Unfortunately, limited resources combined with the high cost of signal coordination efforts prohibit many transportation agencies from coordinating their traffic signal systems on a regular basis (*1*).

The current practice of coordinating a signal network involves the use of computer simulation models. TRANSYT-7F is one of the most widely used and respected macroscopic tools for optimizing the performance of traffic signals (*2*). Creating an optimum TRANSYT-7F model, however, can be very time consuming. Data required by TRANSYT-7F are extensive and must be precisely formatted into an ASCII text file before they can be processed by the program.

Many attempts have been made to make data input into TRANSYT-7F easier and less costly (*3*). A telephone survey of TRANSYT-7F users from around the United States was conducted at the Georgia Institute of Technology to identify the most popular methods of creating TRANSYT-7F input files (*4*). Although novice users of TRANSYT-7F indicated a preference for using input managers, more experienced users tended to favor using a simple text editor to create and edit TRANSYT-7F networks. Most experienced users who preferred using simple text editors were familiar with a number of different input managers but preferred an editor because the input managers were considered cumbersome. Clearly, existing input managers have not gained wide acceptance among experienced TRANSYT-7F users. Recent research at the Georgia Institute of Technology examined the use of geographic information system (GIS) technology as a possible alternative to the TRANSYT-7F data input managers that are available.

APPLYING GIS TECHNOLOGY

As computer use has grown in recent years, so has the need to manage large amounts of information. A GIS is one of the latest tools that can be used to deal with this problem. GISs are computer hardware and software for the input, storage, analysis, and retrieval of spatial data and related attribute information.

The application of GIS technology in transportation (GIS-T) has become increasingly popular in the past few years. The most common areas of application include transportation logistics (*5*), pavement management (*6,7*), public transportation (*8–10*), and transportation planning (*11–13*). A potential application that has not received much attention is traffic operations. KLD Associates, Inc., has performed preliminary work with linking its HCM/CINEMA product with a personal computer (PC)-based GIS software (*14*). HCM/CINEMA performs a highway capacity manual analysis of signalized intersections using an interactive graphical user interface and presents an animation of traffic flow based on the TRAF-NETSIM traffic simulation model. Other work on GIS in traffic engineering includes preliminary efforts to use GIS as a system integrator in advanced traffic management systems (ATMSs) (*15*). That work concentrated on looking at GIS to oversee numerous components of a traffic control system including surveillance cameras, ramp meters, traffic signals, changeable message signs, signal controllers, and the communications infrastructure.

Meyer et al. (*16*) and Meyer and Sarasua (*17*) developed a prototype GIS-T to demonstrate the capabilities of GIS as a program management system for a county department of transportation. The prototype includes a traffic signal module to help automate the process of managing and maintaining the traffic signal system. The system demonstrated a number of capabilities:

1. Quick and easy access to signalized intersection information,
2. Swift identification of "troubled" intersections such as those with poor levels of service or unacceptable delays, and
3. Up-to-date maintenance activities to spot problems before they occur.

One capability not found in the prototype was automated traffic signal coordination. Signal coordination is a logical extension to a

---

School of Civil Engineering, Georgia Institute of Technology, Atlanta, Ga. 30332–0355.

traffic signal GIS-T because much of the information needed to coordinate traffic signals is found in a traffic signal GIS-T data base. This information includes data on turning movements, intersection geometry, and signal timings. In addition, other key information, such as the locations of intersections relative to each other and the distance between intersections, could also be stored in the GIS-T.

In recent years many organizations have implemented automated mapping/facilities management (AM/FM) systems. An AM/FM system is similar to a GIS in that it can manage geographical and related attribute information. The fundamental difference between a GIS and an AM/FM system, however, is that an AM/FM system has limited spatial analysis capabilities. This is because the data structures of an AM/FM system are not topological. Thus, there are not well-defined relationships between spatial information contained in an AM/FM system data base. Topology exists in many vector-based GIS, however. Topology is critical to an automated signal coordination system because of the relationships that exist between a signalized intersection (stored as point data in a GIS) and the various approaches to the intersection (stored as line data in a GIS). Furthermore, relationships between downstream intersections can be easily established in a GIS. Relationships such as the adjacency of intersections and the distances between the intersections are fundamental to a signal coordination effort.

As part of an effort to investigate the usefulness of applying GIS technology to traffic signal management, researchers at the Georgia Institute of Technology developed an integrated, fully functional GIS-based traffic signal coordination and information management system called SIG-GIS. The underlying hypothesis of the research and development of SIG-GIS was that such a system could enhance the process of coordinating traffic signals and also serve as a multipurpose signalized intersection information management system. The intent of SIG-GIS, as a tool for signal coordination, was not to replace TRANSYT-7F but to complement it by serving as a platform for the creation of optimum TRANSYT-7F models.

METHODOLOGY AND SYSTEM DESIGN

A major objective in the development of SIG-GIS was to take advantage of network relationships that are part of a GIS's underlying data structure to enhance the process of coordinating traffic signals. The first task in the design of SIG-GIS was to identify other needed technologies in addition to GIS to provide the system with the desired functionality. Tasks required to obtain these technologies included developing external programs written in C, incorporating knowledge-based expert system (KBES) technology, and interfacing with computer-aided design and drafting (CADD) software. The intent for SIG-GIS is to take advantage of the strengths of these technologies to provide the desired functionality for optimizing signal timings in a street network. Figure 1 gives a conceptual framework for SIG-GIS. The author has intentionally made Figure 1 generic because it is his opinion that the integration of these four technologies has applications outside of traffic signals.

Overview of SIG-GIS System Architecture

The actual system architecture of SIG-GIS that evolved from the conceptual framework presented in the previous section is shown in Figure 2. Figure 2 identifies six main components and shows the interaction between the components. The components are (a) the GIS platform, (b) the signalized intersection data base editor (SIDE), (c) the GIS data base generator, (d) the intelligent user interface (IUI), (e) the SIG-GIS translator, and (f) the AutoCAD DXF file generator. A brief overview of these components is given in the following paragraphs.

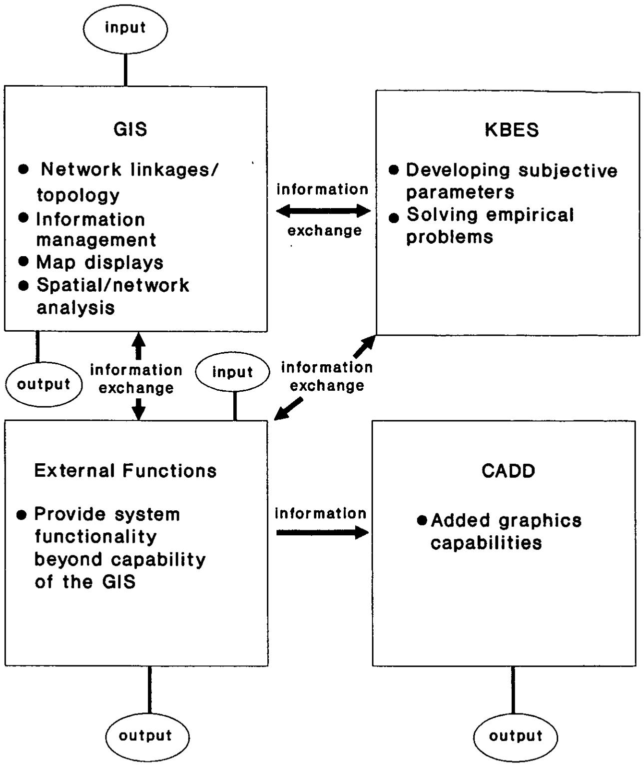


FIGURE 1 SIG-GIS conceptual framework.

GIS Platform

SIG-GIS is designed to be used with the transportation-related GIS platform TransCAD. TransCAD, developed by Caliper Corporation in 1988 (*18*), is a transportation, PC-based software package that has specialized tools for planning, management, operation, and analysis of transportation systems and facilities. SIG-GIS was designed so that it can be integrated with other PC-based GIS packages besides TransCAD with only a minimal number of modifications. A GIS must meet the following minimum criteria for integration to be possible:

- It must have network topology (e.g., connectivity),
- It must have capabilities for automation such as menu customization and a macro language or some capability to access external functions written in C,
- It must have data export and import capabilities to and from a nonproprietary format (e.g., comma-delimited ASCII), and
- It must be able to import Census Bureau topologically integrated geographic encoding and referencing (TIGER) files.

One such PC-based GIS that meets these criteria is PC ARC/INFO (*19*). PC ARC/INFO provides a robust data structure that has the necessary line (arc) topology critical for signal coordi-

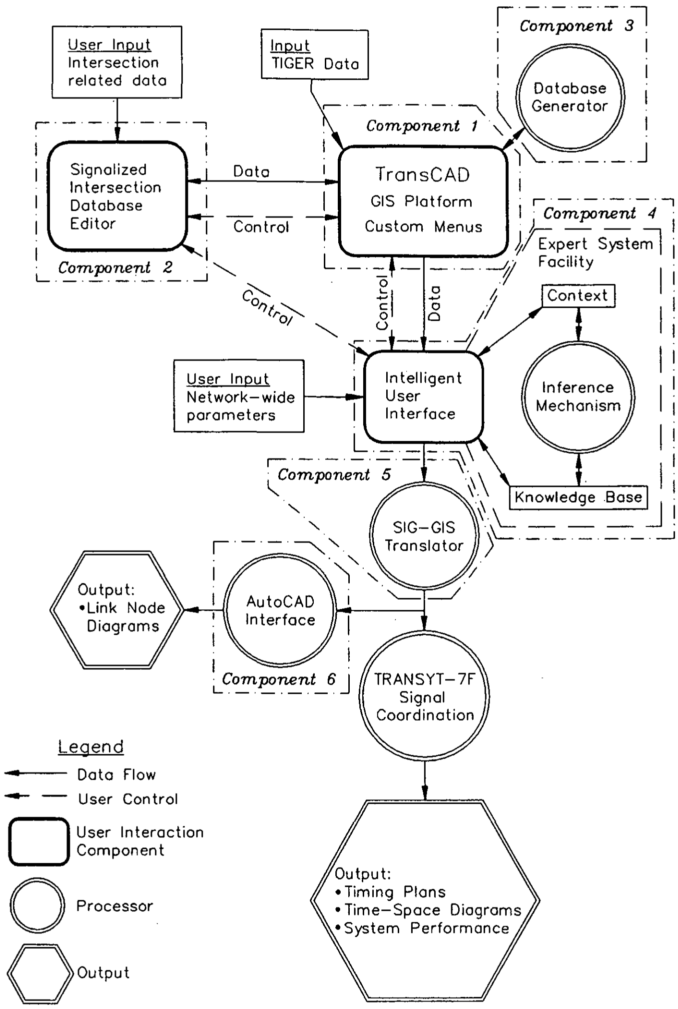


FIGURE 2 SIG-GIS architecture.

nation. Furthermore, PC ARC/INFO can read and write data in a variety of formats. The program also has a built-in macro language (Small Macro Language) that can be used to create the necessary user interface and provide functionality within the GIS.

The TransCAD component of SIG-GIS manages the specialized GIS spatial and attribute data bases that contain many of the data required by TRANSYT-7F. A data base consists of spatial and attribute information. SIG-GIS can have three or more different data bases. The key data bases are the master data base, the period data bases, and the street data base.

The main purpose of the master data base is to provide SIG-GIS with the capability of being a signal information system instead of simply being a tool for signal coordination. The master data base is a point-type data base that contains general intersection information such as an inventory of hardware and the intersection's maintenance history.

A period data base is an intersection data base (point data base) that contains much of the information needed for coordinating traffic signals. Because period data bases are temporal data bases, there can be more than one period data base for a signalized network. Typically, at least three period data bases are needed for signal coordination purposes: one for the a.m. peak period, one for the p.m. peak period, and one for the off-peak period. A period data base contains geometry information, volume information, saturation flow information, TRANSYT-7F timing information, and performance information. Some of the different types of performance information stored in a period data base include level of service (LOS) information, volume-to-capacity ratios (V/Cs), and delay information. In the case in which a new design needs to be added, the user can simply add a new record.

The street data base contains specific attribute information about the street segments between the signalized intersections. This data base includes information intended for use in signal coordination. Thus, this data base contains only a limited number of fields. Additional fields could allow this data base to be useful in other areas of transportation including pavement management and accident analysis.

Important attribute information, which is required to be part of an intersection's data structure, is used to determine the streets that feed the intersection. This information is necessary for signal coordination because the length of each street segment and the speeds of vehicles traveling on these segments are fundamental to coordinating signals. In addition to speed and distance data, the street network data base contains information that relates the different intersections. This information is vital to a signal coordination effort because traffic that passes through an intersection is generated from the different approaches of upstream intersections. Figure 3 illustrates the concept of topology for intersection and street data. In Figure 3 the current intersection is Node 22. The traffic that passes through the westbound approach of this node is generated from three different movements at Node 21. This traffic is called source flows. Source flow data are stored with the intersection from which it is generated—in this case, Node 21. The speed and distance data are stored with the street segments (e.g., Link 1). To optimize the progression along Link 1, the source flows for Node 22 from Node 21 must be known in addition to the distance between the intersections and the speed of vehicles approaching Node 22. On the basis of the topology associated with the streets and intersections, the different types of data needed to optimize the timings at Node 22 can be retrieved from the various entities where these data are stored. Thus, the importance of the point and line topology is that data can be retrieved more efficiently while being stored in a less redundant and more efficient manner. Data redundancy is reduced because there is no need to store the movement information of Node 21 (Movements A, B, and C) with Node 22.

Menu Structure

The GIS component of SIG-GIS also includes a series of custom menus that provide access to SIDE to edit the data base, to the data base generator to create new SIG-GIS data bases from a TIGER file data base (*20*), or to the IUI to create a TRANSYT-7F input file.

SIDE

SIDE, the second component of SIG-GIS, manages the intersection attribute data bases. The intent of SIDE is to make editing intersection information easier and more practical. There is a great deal of information in a period data base associated with a single intersection of a TRANSYT-7F model. Use of TransCAD's existing attribute editing capability would require the user to navigate 100 data fields to input and query information. SIDE simplifies this process by using graphical screens as a platform for entering and querying attributes.

SIG-GIS Data Base Generator

The third component, the SIG-GIS data base generator, is used to create the basic SIG-GIS data bases from Census Bureau TIGER files that are imported into TransCAD. Census Bureau TIGER files provide a means whereby roadway centerline data bases can be created quickly. Unfortunately, in its most primitive form a TIGER file imported into TransCAD is not designed for use in traffic signal optimization. Thus, the purpose of the Generate Data Bases function is to take information in a TransCAD TIGER data base and use it to generate the SIG-GIS data bases. The process of creating the necessary network data bases from a TIGER file is described in detail in the case study.

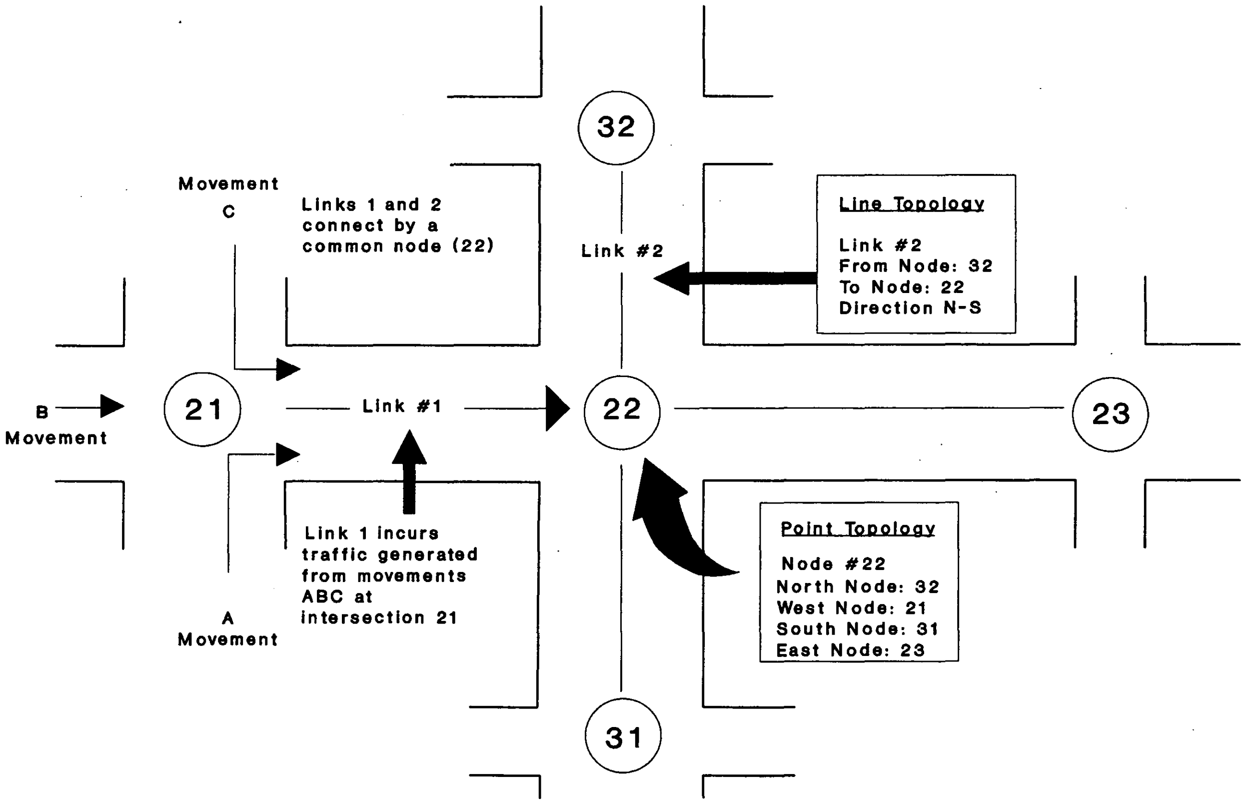


FIGURE 3 SIG-GIS network topology.

IUI

When a TRANSYT-7F input file is desired, the macros associated with the GIS custom menus will pass intersection data to the IUI. The IUI is part of the SIG-GIS help facility, the fourth component. This facility aids the user in inputting systemwide information. In addition to a conventional help system that can provide the user with information about a particular parameter, the IUI also has access to a KBES to help develop the more subjective systemwide information. The user calls the expert system facility by pressing the F2 function key after he or she highlights the parameter to be determined. The facility will prompt the user with questions and then will produce an appropriate value for the parameter based on the user's responses to the questions. Some networkwide parameters do not have expert system help associated with them because they do not require subjective or heuristic knowledge for their development and thus are not suitable for inclusion in the facility.

SIG-GIS Translator

The fifth component of SIG-GIS is the translator. The translator is written in C and is a totally separate program from the other components of SIG-GIS. Its main purpose is to correctly format input data and the systemwide parameters passed by the IUI. The translator generates an input file that can be directly processed by TRANSYT-7F without any further modification.

AutoCAD Component

The final component of SIG-GIS is the AutoCAD interface. The interface passes information from the SIG-GIS translator to AutoCAD, where a link-node diagram providing detailed network information will be generated automatically. Past discussions with public and private agencies have indicated that link-node diagrams can be a useful tool for reviewing the input into a TRANSYT-7F model and for field calibration and fine tuning. A well-designed diagram can make network information more accessible. By bringing a diagram into the field, changes during a field review can be made directly on the link-node diagram.

SYSTEM APPLICATION: A CASE STUDY

SIG-GIS is currently being implemented in Cobb County, Georgia. This section discusses a sample application of SIG-GIS for a portion of Cobb County known as the Platinum Triangle. The complete process of going from a basic Census Bureau TIGER file to a TRANSYT-7F simulation input file is discussed. A discussion is also given on how SIG-GIS can be used as a signal information management/decision support tool.

Building the SIG-GIS Data Bases

The major task before using SIG-GIS for signal coordination purposes is to create the necessary GIS data bases that describe the traffic signal network. SIG-GIS provides automation for generating a traffic signal network from a Census Bureau TIGER file. This process takes several steps, which are shown in Figure 4 and discussed in the following sections.

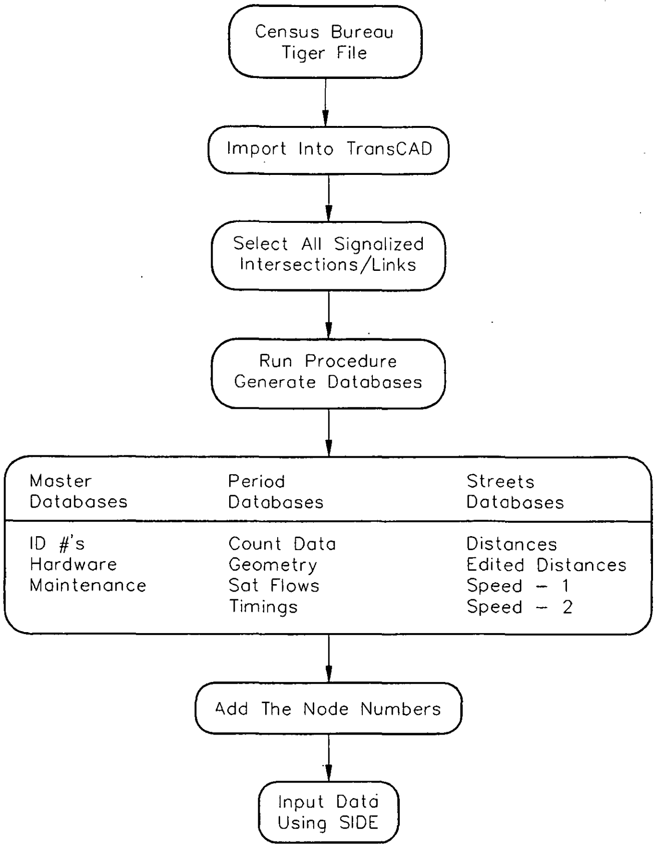


FIGURE 4 Building the GIS data bases.

Generating a GIS Data Base from a Census Bureau TIGER File

A TIGER file is an ASCII text file that must be translated before it can be used in a GIS. By using existing TransCAD tools (TCBuild), a generic Cobb County TIGER file was translated to a TransCAD-compatible line data base.

Identify the Signalized Network

By using the converted TransCAD TIGER data base, nodes in the network that represent signalized intersections are selected from the screen. The links that connect these nodes are also selected. The resulting selected nodes and links make up the signalized network. Isolated signalized intersections may also be selected, but there would not be any downstream or upstream signalized intersections associated with these intersections. Nonsignalized intersections can also be modeled.

Generating the Data Bases

When the signalized network is identified the SIG-GIS Generate Data Bases procedure is run to generate the master, period, and streets data bases. When all the general information is entered the

Generate Data Base procedure creates the three basic SIG-GIS data bases: master, period, and streets. Figure 5 illustrates the resulting intersection network for two signalized arterials. The entire Platinum Triangle is included as a background to the signalized intersection network. Signal links are highlighted.

Identify Node Numbers

The next task is to assign TRANSYT-7F node numbers to those intersections to be coordinated. For this case study only the signalized intersections on Windy Hill Road were coordinated. Node numbers are assigned by using TransCAD's attribute editing capabilities.

Input Data

Data for each of the signalized intersections are obtained by using SIDE. Figure 6 shows the inputting of traffic volumes by using SIDE. A major benefit of SIG-GIS is that much information is generated automatically. For example, source volumes, which represent traffic flows generated from downstream intersections, are calculated automatically by the system. SIDE includes a page to edit source volumes manually if the user desires. Other types of data that do not have to be input into the system include street names (included in the TIGER files), distance information (the GIS generates distances automatically), and link identifications (also generated automatically). When all data are entered, the data are saved to the GIS data base and control is passed back to TransCAD. The network is now ready to use.

Creating TRANSYT-7F Input File

Now that the data are entered the next major task is to perform a TRANSYT-7F simulation run. First, the user must select the intersections to be simulated. Only those intersections that are on the same cycle length can be selected. In this case because Windy Hill Road and Cobb Parkway are on a 120-sec cycle length, all the intersections are chosen. Next, the TRANSYT-7F GIS Module selection is chosen from the TransCAD procedure menu (Figure 7). This will bring up another menu from which the type of TRANSYT-7F model to be developed is chosen (e.g., simulation or normal optimization).

Using IUI

When the run type is selected the procedure is executed and control is passed to the IUI. Here, the user inputs the various networkwide parameters. The highlighted parameters are required to be entered, whereas the others may be skipped if the user chooses to use the program defaults. Figure 8 shows the associated help screen for the Extension of Effective Green parameter. The platoon dispersion factor was entered with the help of the expert system facility. On the basis of the responses to questions such as "Is pedestrian activity light, moderate, or heavy?," the system determines the appropriate platoon dispersion factor.

When all parameters are entered, the user can elect to generate a TRANSYT-7F input file and run TRANSYT-7F. The user must then specify a file name for the input file and may choose to generate a link-node diagram. The IUI will activate the SIG-GIS transla-

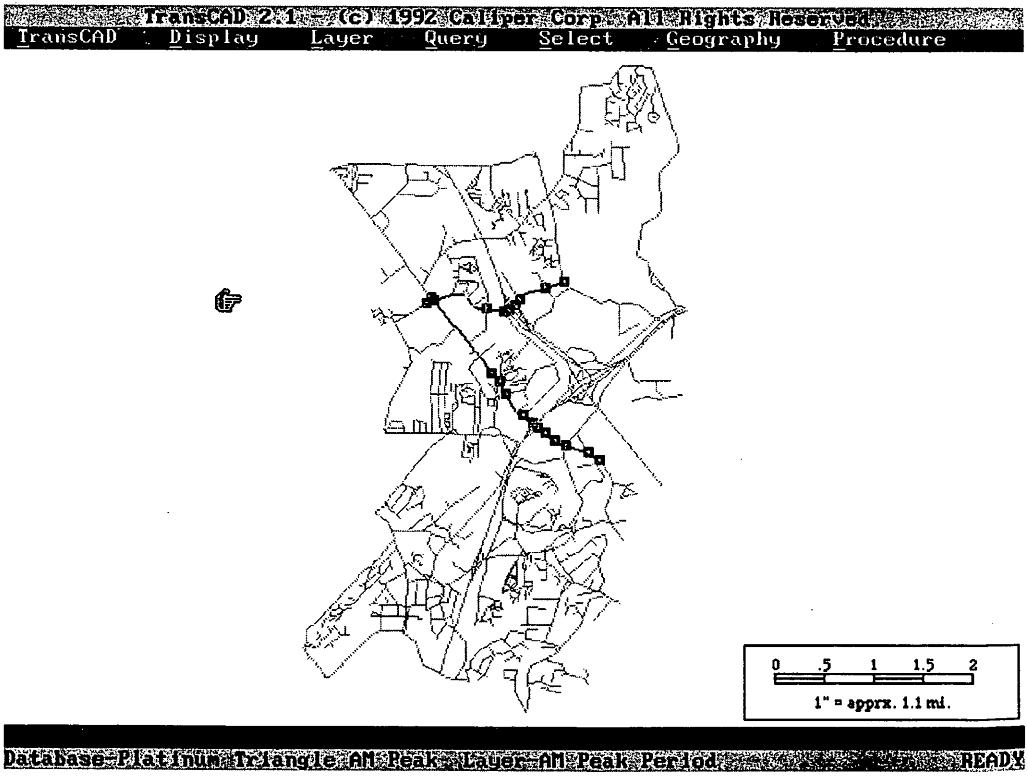


FIGURE 5 Cobb Parkway/Windy Hill signalized network.

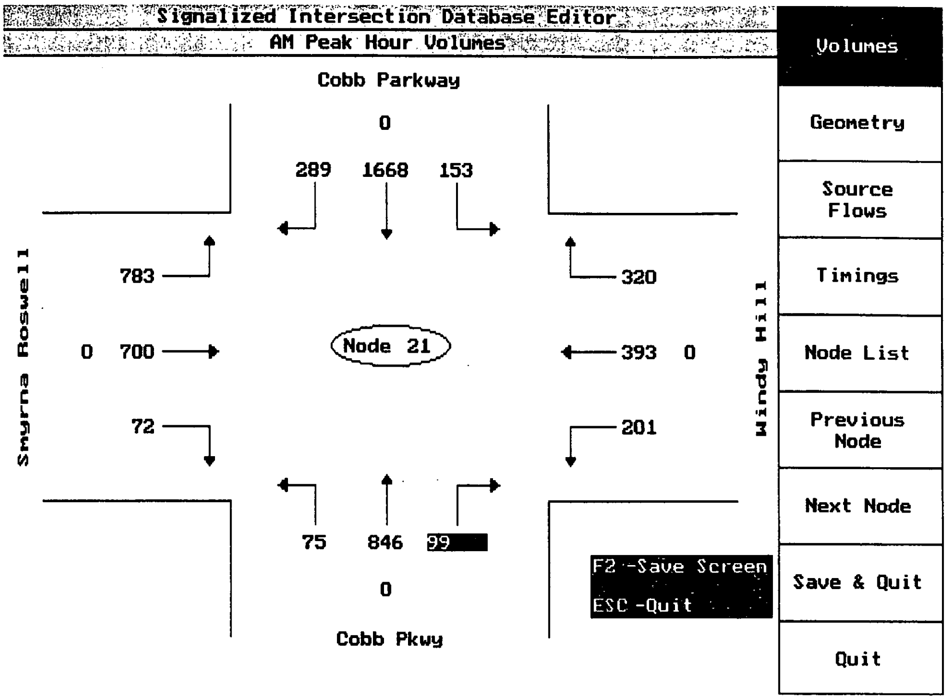


FIGURE 6 Inputting traffic volumes using SIDE.

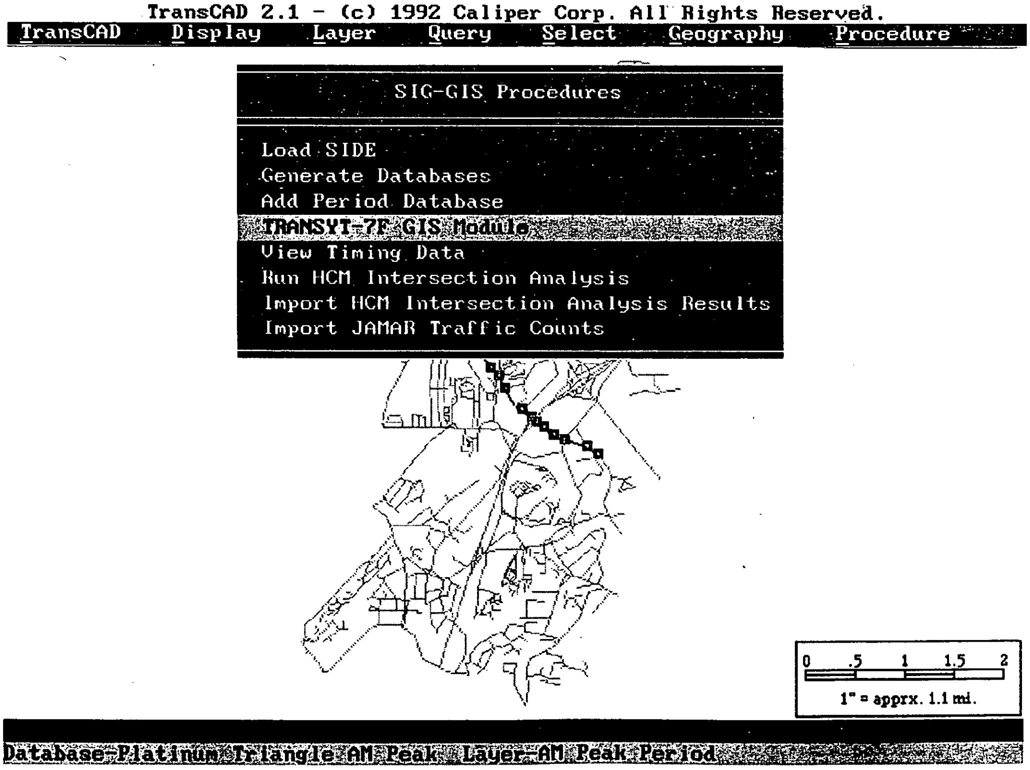
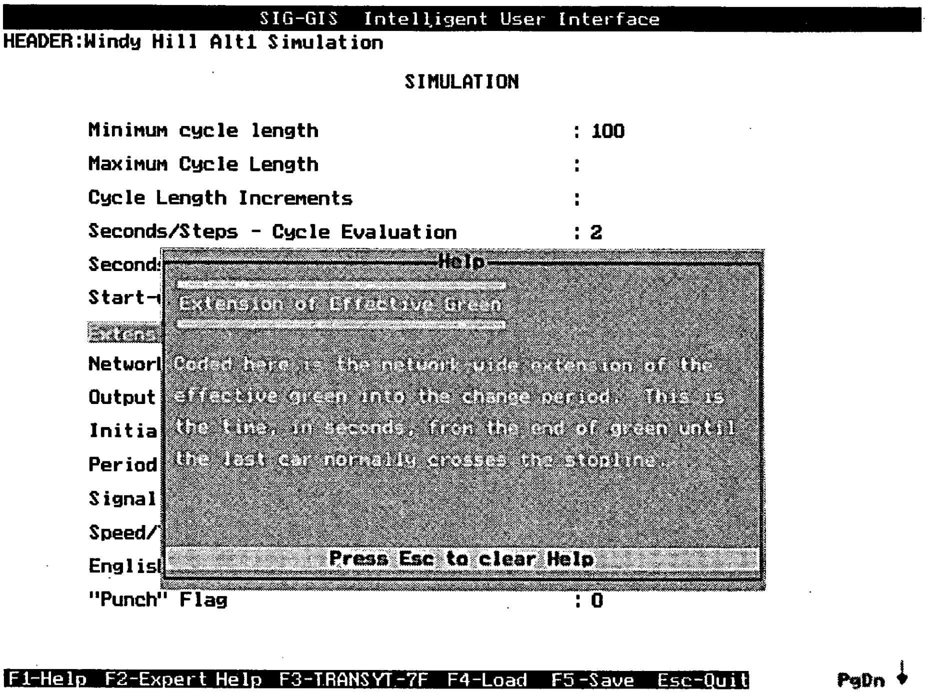


FIGURE 7 Choosing the TRANSYT-7F GIS Module procedure.



```
                    SIG-GIS  Intelligent User Interface
HEADER:Windy Hill Alt1 Simulation

                                 SIMULATION

     Minimum cycle length                          : 100
     Maximum Cycle Length                          :
     Cycle Length Increments                       :
     Seconds/Steps - Cycle Evaluation              : 2
     Second ┌──────────────────Help──────────────────┐
     Start- │ Extension of Effective Green           │
     Extens │                                        │
     Networ │ Coded here is the network wide extension of the
     Output │ effective green into the change period.  This is
     Initia │ the time, in seconds, from the end of green until
     Period │ the last car normally crosses the stopline.
     Signal │                                        │
     Speed/ │                                        │
     Englis │          Press Esc to clear Help       │
     "Punch" Flag                                  : 0

F1-Help  F2-Expert Help  F3-TRANSYT-7F  F4-Load  F5-Save  Esc-Quit        PgDn
```

FIGURE 8 Associated help screen for the Extension of Effective Green parameter.

tor, which creates the TRANSYT-7F input file. The IUI will then automatically start TRANSYT-7F.

Calibrating the Simulation

Calibrating the TRANSYT-7F model ensures that the simulation run accurately represents the flow of traffic in the network. This is important to ensure that TRANSYT-7F will develop an appropriate timing plan. Calibrating a simulation is beyond the scope of SIG-GIS. It is mainly a manual exercise that involves examining TRANSYT-7F output. Comparisons must be made between modeled measures of effectiveness such as the modeled degree of saturation for a link compared with the actual degree of saturation for that link identified through field study.

Running an Optimization

After calibration of the simulation run, an optimization can be performed. The same procedures are performed for the optimization run as for the simulation run with the following exceptions:

- There is no need to choose the intersections to be optimized in TransCAD as long as they are the same as those that were selected for the simulation.
- The run type is now an optimization that must be selected from the TRANSYT-7F GIS menu.
- The network parameters need to be modified. For example, because this is an initial optimization cycle length evaluation information will need to be included in the network parameter information.

Other optimization runs can be completed in a similar fashion.

Multipurpose System

A major objective of the research described here was to design and develop a system that could also serve as a signal information management/decision support tool in addition to providing signal coordination. Thus, incorporated in the design of the data bases are specific fields geared toward information management. All the data bases are made up in part or in whole of signal information that is desirable for the everyday upkeep of the signalized infrastructure.

The intent of SIG-GIS as a multipurpose system is to help automate the process of managing and maintaining the traffic signal system. In this regard the system provides a number of capabilities.

1. It provides a means for quick and easy access to signalized intersection information.
2. It allows for swift identification of troubled intersections.
3. It can aid the traffic engineer to keep maintenance activities up to date and help spot problems before they occur.

Improved Access to Data

The signal module of the prototype GIS-T is able to provide quick and easy access to signalized intersection information, such as controller type, signal heads, detectors, sampling loops, intersection geometrics, and travel characteristics. Queries can be made by selecting an intersection from the map display. The associated text information that results from the query can be reviewed, printed, and edited.

Identification of Troubled Intersections

SIG-GIS allows for swift identification of troubled intersections. These troubled intersections may be defined as those with large V/Cs, enormous delays, unacceptable LOSs, intersections with a high number of maintenance activities in a relatively short period of time, or any combination of these variables. These troubled intersections can be displayed on high-quality thematic maps or maps that include attribute labels.

Maintenance Management

SIG-GIS has a maintenance management capability. It can be used to help the traffic engineer keep maintenance activities up to date, which can help spot problems before they occur. Included in the master data base are the type of last maintenance activity, date of last maintenance activity, and number of maintenance activities in the last year. With this information it is possible to produce, for example, a map that identifies the level of maintenance activities for all intersections during the last year.

MAJOR FINDINGS, CONTRIBUTIONS, AND RECOMMENDATIONS

A number of major findings and contributions of this research pertain to both theory and methodology. These are summarized in the following:

- Benefits of topology for signal coordination. One innovative technique used in this research is making use of capabilities inherent in GIS to determine the streets that feed into an intersection. These streets are an integral component of an intersection's SIG-GIS data structure. Because the linkages between streets and intersections are determined automatically, several tasks that would be necessary if a manual coding process was used are eliminated.
- Graphical input capabilities for point data. The development of SIDE has demonstrated that intersection-related data can be input into a GIS in a less cumbersome format than in a spreadsheet format or some other digital attribute form.
- Multipurpose. The multipurpose nature of SIG-GIS may be its most important asset. In addition to signal coordination, SIG-GIS could be used as a signal information system and could play a vital role in decision support.
- Using a GIS allows for enhanced alternative analysis. A major benefit of a GIS is that signalized intersections can be displayed graphically on a map display. With a mouse the user simply has to select the intersections from the screen that he or she would like to coordinate. In this way many alternatives for a subsystem can be analyzed quickly and easily.
- Intelligent selection of parameters. SIG-GIS provides the user with a variety of help facilities for choosing appropriate systemwide parameters. In addition to on-line help, some parameters are linked to an expert system that helps the user develop appropriate values for the parameter.
- A new application for TIGER files. This research relies heavily on the premise that Census Bureau TIGER files can provide the locational information of intersections and their relationships with one another necessary for signal coordination. The topological structure of the TIGER file provides these relationships. In evaluating TIGER files for accuracy (without making any adjustments to correct inaccuracies) it is evident that very little adjustment is needed for its use in signal coordination. This is because although positional accuracy deficiencies of TIGER files are evident (and common), distances between intersections as determined from the TIGER files are still suitable for signal coordination purposes.

In the development of SIG-GIS a number of potential research areas have become apparent. They are as follows:

- Developing import capabilities of TRANSYT-7F outputs back into the GIS when signals are optimized will give the traffic engineer an enhanced ability to analyze performance information such as fuel emissions, delay, LOSs, and V/Cs. A GIS is an ideal platform for producing thematic maps that highlight problem areas based on these measure of effectiveness.
- Enhancing the expert system facility to help calibrate simulated timings and implement optimized timings. Both tasks require a great deal of engineering judgment.
- Adding real-time signal coordination capabilities to SIG-GIS. The advent of new technologies that monitor traffic volume, speed, and density data on a minute-by-minute basis has resulted in a second generation of traffic signal control. Second-generation control-type systems use real-time data to make continual changes to traffic signal settings. The addition of real-time capabilities to SIG-GIS can result in continual improvements to traffic signal settings based on traffic demand. The SIG-GIS system could thus be an integral component in an advanced traffic management system.

CONCLUSION

Use of a GIS as a tool for signal coordination shows much promise and may revolutionize how signal coordination efforts are done. A major benefit of using a system such as SIG-GIS is that several TRANSYT-7F coding tasks are reduced or eliminated, thus reducing the effort required to code a TRANSYT-7F network. The reduced level of effort may make signal coordination efforts more affordable. This may allow some jurisdictions to coordinate their traffic signals more regularly, resulting in reduced fuel consumption and improved traffic flow.

It is the author's belief that the advent of SIG-GIS along with new developments in GIS data standardization and more powerful data input tools can help pave the way toward a vastly more efficient, flexible, and powerful generation of GIS-based signal coordination and information management systems.

REFERENCES

1. Parsonson, P. S. *NCHRP Project 20-5: Signal Timing Improvement Practices,*TRB, National Research Council, Washington, D.C. 1990, pp. 11–14.
2. Wallace, C. E., et al. *TRANSYT-7F User's Manual,* Release 6. FHWA, Transportation Research Center, University of Florida, Gainesville, 1988.
3. Leonard, J. D., and W. W. Recher. Advances in the PC Interface of TRANSYT-7F Traffic Simulation Model. In *ITE 1989 Compendium of Technical Papers.* ITE, 1989, pp. 536–591.
4. Sarasua, W. A., and C. C. Hatton. *GIS-T7F: A Geographic Information System Based Data Input Module For TRANSYT-7F.* Unpublished paper. Georgia Institute of Technology, Atlanta, 1991.
5. Freund, D. Use of GIS and Related Applications in Hazardous Materials

Routing. Presented at 71st Annual Meeting of the Transportation Research Board, Washington, D.C., 1991.

6. Fletcher, D. R., et al. *Pavement Management Decision Support Using A Geographic Information System.* FHWA Report FHWA-DP-90-085-006. FHWA, U.S. Department of Transportation, 1990.
7. Simkowitz, H. J. Using Geographic Information System Technology To Enhance the Pavement Management Process. In *Transportation Research Record 1261,*TRB, National Research Council, Washington, D.C., 1990.
8. Azar, K., and J. Ferreiara, Jr. GIS For Transit Passenger Information Systems. *Proc., 1991 GIS-T Symposium.* AASHTO, 1991, pp. 257–276.
9. Dueker, K. J., and R. Vrana. GIS Applications in Urban Public Transportation: A Case Study of Tri-Met, Portland, Oregon. *Proc., 1991 GIS-T Symposium.* AASHTO, 1991.
10. Hancock, K., and M. Abkowitz. The Use of Geographic Information Systems for Customer Service in Urban Public Transportation. Presented at 71st Annual Meeting of the Transportation Research Board, Washington, D.C., 1992.
11. Lewis, S. Use of Geographical Information Systems in Transportation Modeling. *ITE Journal,* March 1990, pp. 34–38.
12. O'Neill, W. A. Developing Optimal Transportation Analysis Zones Using GIS. *Proc., 1991 GIS-T Symposium.* AASHTO, 1991, pp. 107–115.
13. Prastascos, P. Integrating GIS Technology in Urban Transportation Planning and Modeling. Presented at 70th Annual Meeting of the Transportation Research Board, Washington, D.C., 1991.
14. KLD Associates, Inc. GIS Fact Sheet. KLD Associates, Inc., Huntington Station, N.Y., 1992.
15. Insignares, M., and D. Terry. Geographic Information Systems in Traffic Control. *Proc., 1991 GIS-T Symposium,* AASHTO, 1991, pp. 205–211.
16. Meyer, M. D., et al. *Transportation Program Management for the Cobb County Department of Transportation.* Final Report. Cobb County, Ga., 1991.
17. Meyer, M. D., and W. A. Sarasua. GIS-Based Transportation Program Management. In *Transportation Research Record 1364,* TRB, National Research Council, Washington, D.C., 1992.
18. *TransCAD Reference Manual Version 2.0.* Caliper Corporation, Newton, Mass., 1990.
19. *PC ARC/INFO Starter Kit User's Manual.* Environmental Systems Research Institute, Inc., Redlands, Calif., 1987.
20. *TIGER: The Coast-to-Coast Digital Map Data Base.* Bureau of the Census, Washington, D.C., 1990.

Publication of this paper sponsored by Committee on Traffic Signal Systems.