A Primer for Geographic Information Systems for Transportation

Volume 2:

Dynamic Segmentation

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Dynamic Segmentation of Network Data

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PREFACE

This series has been compiled by GIS/Trans in the course of its work designing, developing and implementing GIS solutions for transportation. GIS/Trans has produced this series because no similar material is currently available in texts offered in this new and growing field. We provide it as a general introduction to the subject.

Current volumes available in the GIS/Trans "A Primer for Geographic Information Systems for Transportation" Series are:

Volume 1: A Review of Location Referencing Systems

Volume 2: Dynamic Segmentation of Network Data

Each report is available for $35 US from GIS/Trans, Ltd., 675 Massachusetts Ave., Cambridge, MA 02139-3309.

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A Primer for Geographic Information Systems for Transportation

Volume 2: Dynamic Segmentation of Network Data

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1.

INTRODUCTION

Increasingly, highway agencies are employing the power of computer technology including, most recently, GIS software to manage the storage and maintenance of location reference schemes based on a variety of methods. The concept of topology is the key difference which sets GIS apart from other graphical technologies such as Computer Aided Design (CAD). *Topology* defines the relative relationships between points, arcs, and polygons in spatial layers. In effect, topology adds intelligence to the graphical model of the highway network.

Not until the recent addition of dynamic segmentation tools by a number of GIS software vendors has this technology truly begun to become facile in setting up and maintaining an on-line location reference scheme. *Dynamic segmentation* is a method of referencing road attribute data — linear or point — on demand based on a variable segmentation of a single topological network. In its essence, this technique uses measured offsets from fixed and known reference points to place attribute features on roadways. This method does not create a new topological division of the road network. Dynamic segmentation may be considered to be an "engine" to implement one or more location reference schemes on a network representation.

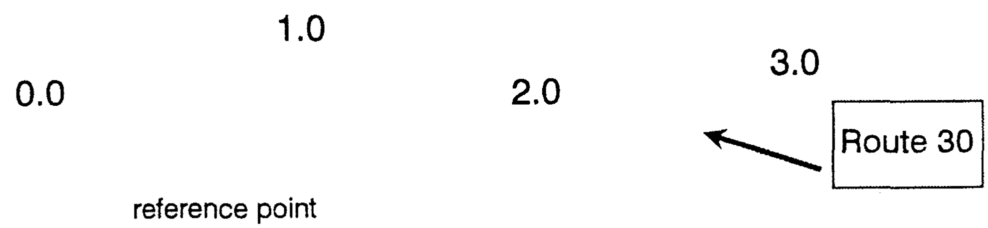
A key advantage of dynamic segmentation is that it enables *network overlay* on attribute data to be performed "on the fly" through the use of RDBMS and GIS techniques (see Figure 1.1). This dynamic overlay aspect also avoids the need to store the larger, more difficult to maintain, attribute tables associated with a fixed, or *static*, segmentation of the roadway (Figure 1.3).

Network overlay or conflation allows the graphic comparison of multiple layers of attribute data and the recording of the merged outcome of these layers into the GIS database. As line-on-line overlay can never be accomplished precisely, the solution is to transfer attributes or form a new network file with different topology as depicted in Figure 1.3. The former is technically difficult (although vendors are now offering the first versions of conflation tools) and the latter is computer processor and storage intensive. For example, Pennsylvania DOT has 50,000 miles of road, fifty database layers of tables, which would take a long time to intersect across all layers. Further, the result in terms of map display would be messy. Hence the search for a practical method of querying and displaying section data dynamically.

Figures 1.1 and 1.2 illustrate the basic problem and the simple model of the solution. In practice, user intervention is required to define the section tables and dynamic segmentation is not yet a fully automatic procedure. This book describes the basic

Fig. 1.1 DS: Example

Assign attributes along a route



Road attribute tables based on milepost measurement:

30. width

Fr	To	Val
0.0	0.5	20
0.5	1.9	25
1.9	2.0	20
2.0	3.0	22

30. condition

Fr	To	Val
0.0	0.2	A
0.2	0.7	B
0.7	0.8	A
0.8	1.7	C
1.7	2.5	B
2.5	3.0	A

30. class

Fr	To	Val
0.0	3.0	A

30. Accident

Fr	To	Val
0.6	0.6	2

30. surface

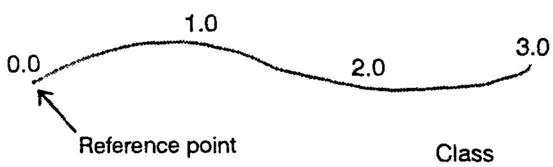
Fr	To	Val
0.0	1.4	C1
1.4	1.7	A2
1.7	2.1	C2
2.1	3.0	A1

Fr = From

Fig. 1.2 DS: Example

Width

Fr	To	Val
0	0.5	20
0.5	1.9	25
1.9	2	20
2	3	22



Class

Fr	To	Val
0	3	A

Surface

Fr	To	Val
0	1.4	C1
1.4	1.7	A2
1.7	2.1	C2
2.1	3	A1

Condition

Fr	To	Val
0	0.2	A
0.2	0.7	B
0.7	0.8	A
0.8	1.7	C
1.7	2.5	B
2.5	3	A

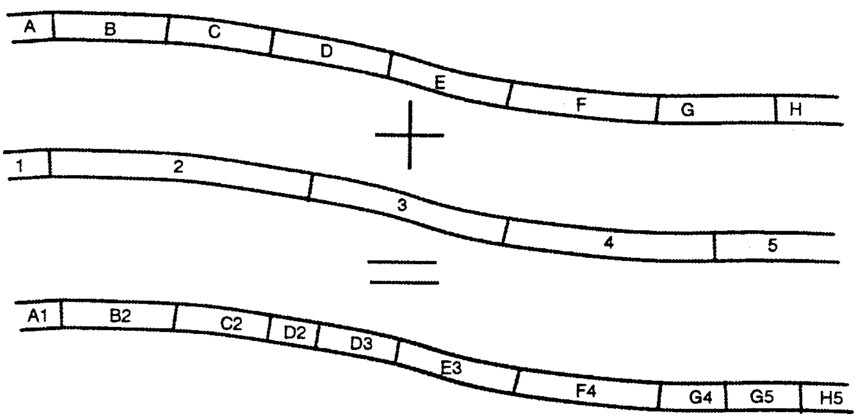
Software performs intersection between tables

"Show me the section of roadway where:
road condition = A or surface type = A2"

Selected records where COND=A or ST=A2

From	To	Cond	ST
0	0.2	A	C1
0.7	0.8	A	C1
1.4	1.7	C	A2
2.5	3	A	A1

Fig. 1.3 Network Overlay



Traditional overlay of static segments creates a new topological division.

process and discusses the relevance and importance of dynamic segmentation to GIS for Transportation, or GIS-T.

More generally, the term "dynamic segmentation" also refers to the suite of functions in the GIS software which performs the following requisite tasks:

- Assemble (and maintain) *routes* from network links;
- Calibrate a *measure system* by assigning base reference points and offsets;
- Set up and maintain attributes along routes; and
- Perform queries and analyses on route attribute data.

While certain terms used in the following conceptual discussion may appear to connote a particular vendor's dynamic segmentation terminology, this review is intended to focus on available technology in generic terms, not a comparative review of alternative vendors' solutions. No endorsement of any one company's dynamic segmentation product over others should be inferred by the reader.

2.

CONCEPTS

The main feature types involved in dynamic segmentation include:

- Links (also known as *arcs*, *line segments* or *chains*)
- Nodes (also known as *vertices*)
- Routes (also known as *network linear features*, or *polylines*)
- Route systems
- Sections
- Control points (also known as *reference markers*)
- Attribute features (also known as *events*, *occurrences*, *distributed attributes*, or simply *attributes*)

Each of these feature types will be described in turn below.

2.1 Links

Along with *points* and *polygons* (also known as *areas*), *links* are one of the fundamental topological feature types used in GIS. Together with *nodes*, links may be used to model various types of networks. In a highway network representation, for example, links indicate the road centerlines while nodes generally represent the intersections of one or more of the roads.

2.2 Nodes

Nodes, together with links, define the topology of the network model. Nodes usually represent intersections of highways with other highways or other important geographic or jurisdictional linear features (e.g., rivers, State and County boundaries) As such, nodes also often coincide with base reference points or local control points used to define the route measurement system (see below).

2.3 Routes

A *route* comprises a set of whole or partial links, generally ordered sequentially in chain-wise fashion. A route is not an independent topological entity in the GIS but, rather, is derived from the set of links to which it is related. A route may thus be said to "overlay," or "drape," on top of the existing link-node network (see Figure 2.1).

Routes typically may be assigned their own set of attributes, such as route number, functional class, and so forth.

Depending on the flexibility of the underlying data model and available functionality of a particular GIS product, disjoint routes, routes with multiple branches, and routes which intersect or loop onto themselves may be supported.

A required feature for all routes in implementing dynamic segmentation is some means of *measurement calibration*. This calibration equates precise geographic locations on the route with measurement values set by the user (e.g., milepoints). Once such a calibration is set to establish such a linkage between geometry and a measurement system, dynamic segmentation functions may use this linkage to place linear and point attribute data at intermediate locations along the route's geometry.

There are two means of measurement calibration commonly implemented in dynamic segmentation products, *control points* and *sections*. Each means is described in turn below.

2.4 Route Systems

A *route system* is simply a collection of routes having a common theme. Some GIS products support multiple, co-existing route systems for a particular link-node network.

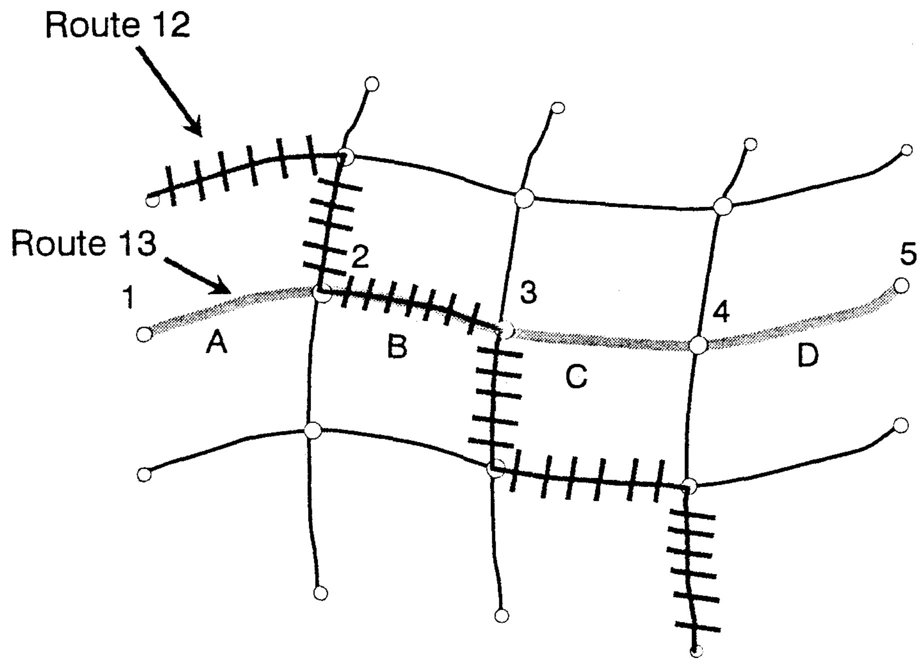
2.5 Sections

Some dynamic segmentation products use section entities as a means to link explicitly whole or partial links to one or more routes. Sections are not a separate topological division. The key reason for the use of sections is to permit partial links to be included as components of routes. Sections also allow a link (whole or part) to be represented multiple times in the sample route, thereby allowing routes to overlap onto themselves.

Sections are usually specified in a database table, independent of link and route tables, which usually contains the following columns of information:

- A unique identifier for the section record,
- The identifier of the related route,
- The identifier of the related link,
- The begin and end locations along the link delineating the portion which is included in the route,
- Measurement calibration values associated with the beginning and end of the section,
- None, one, or more user-defined attributes associated with the section.

Fig. 2.1 Routes on a road network



The relationship between begin and end measures of sections implies a sequencing of links in the route. When the sections are provided in an accessible database table, the user has the flexibility of modifying the link-route relationships.

2.6 Control Points

Control points, an alternative means of measurement calibration, are supported by some dynamic segmentation products. They are point features which equate particular geographic locations on the route with a measurement value, usually verified by a field survey. Control points constitute a separate geographic entity which generally have their own (unique) ID values and, optionally, a set of attributes.

Typically, at least two control points are placed along each route, one at each end, to define its measurement scale and orientation. More, intermediate, control points may be arbitrarily placed along the route to refine further the measurement system. Between each pair of adjacent control points along a particular route, intermediate measures are derived by interpolation, using either the graphic length, or some user-specified distance attribute, of the link(s) between the control points to scale the measure appropriately.

Placing control points on the route system, defining their identifier and measure values, and "calibrating" the route coordinate system are separate setup steps required as a prerequisite to use of dynamic segmentation.

A detailed discussion of route systems and measurement methods is contained in the review of Location Referencing Systems, Volume 1 of this series.

2.7 Attribute Features

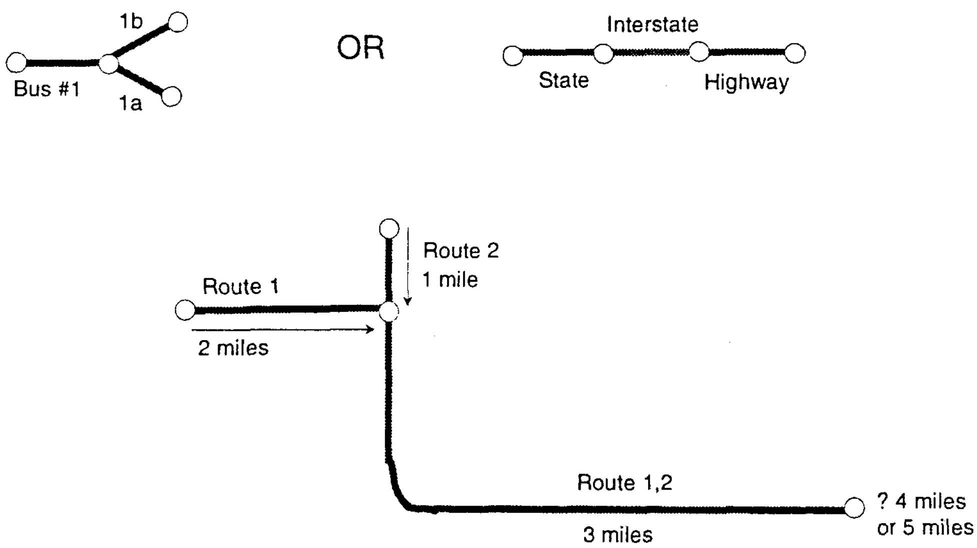
There are three main types of attribute features:

- *Point features*: Have no appreciable length, just a location along the route;
- *Linear features*: Have a distinct begin and end location;
- *Continuous features*: Have a begin location; the end location is inferred from the beginning of the following feature along this route.

It should be noted that not all of the above features are supported by all dynamic segmentation products.

To achieve the greatest flexibility, each attribute is organized into its own table of attribute features. The real power of dynamic segmentation is realized through applying relational processing to overlay attributes *on the fly* to create, display, and analyze new, more complex, network features (see Figure 2.2).

Fig. 2.2 DS Complex Routes



Implementation should allow discontinuities, e.g., loops in the route, or branching or route sharing.

Table 2.1

Route #	Link #	From Measure	To Measure	% From Position	% To Position	Bus_ID	Attributes County_ID	
1	1	0	40	0	100	99	2	Etc.
1	2	40	80	0	100	99	2	Etc.
1	3	80	100	0	100	99	2	Etc.
1	4	100	130	0	30	99	2	Etc.
1	4	130	166	30	66	99	3	Etc.
1	4	166	200	66	100	00	3	Etc.

A table like that depicted in Table 2.1 is required to contain the following information to place features along routes using dynamic segmentation:

- A primary key, typically a route ID.
- A feature begin measure. Depending on the product used, this may be specified as:
  - (1) A distance from the route's origin, *or*
  - (2) A control point ID and an offset (positive or negative) from this point, *or*
  - (3) An x,y location, which is then "snapped" to the nearest point along the route.
- A feature end measure. This is required only for linear features.
- An attribute value (which may be used, for example, to set feature display symbology).

Some vendors also allow specification of an optional secondary key, or "district" (e.g., a county ID), to identify a further subset of the route in locating attributes. This allows the measurement system to be zeroed at county or township boundaries, as is implemented in several state DOTs.

3.

OTHER DYNAMIC SEGMENTATION TECHNOLOGY OPTIONS

Several GIS vendors have released dynamic segmentation products within the past year. A comparison between the products is made difficult, in part, because of the different terminology used by different vendors in describing their product's data model, functional features, and capabilities.

In spite of the acute needs expressed by transportation users over the past several years, dynamic segmentation has only just recently been introduced by the major GIS vendors. This is due to technological difficulties that GIS software developers have had to surmount, including:

- Preserving topological consistency after new entities — routes, segments — are introduced to the data model;
- Maintaining geometric and database integrity in response to updates on the spatial network; and
- Integrating many common but disparate location reference schemes in use by state DOTs.

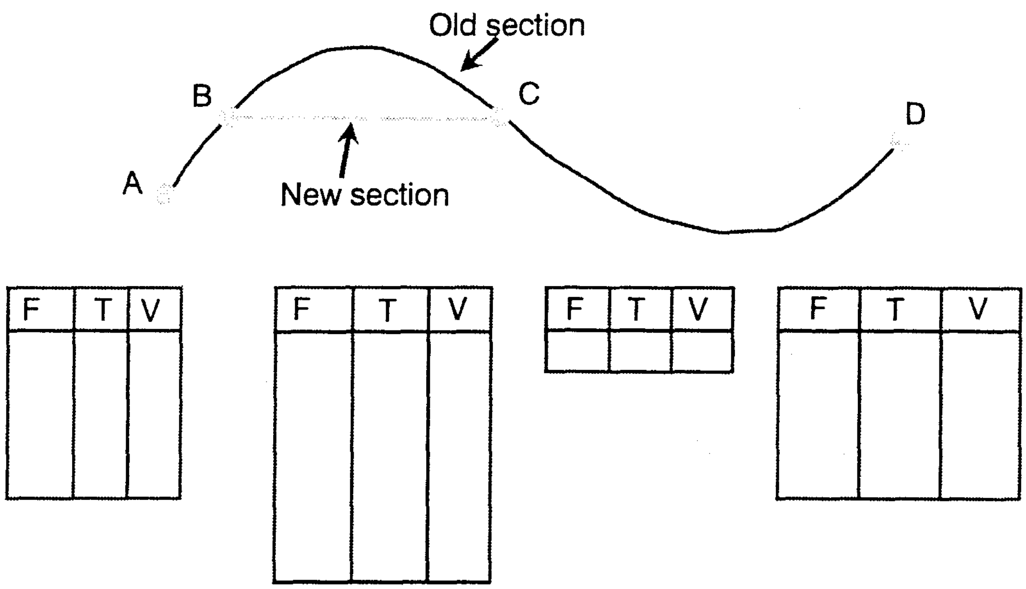
All dynamic segmentation products now available on the market are in their early stages of development of release. Consequently, many software "bugs" and other limitations still need to be resolved before this can be considered a fully off-the-shelf technology.

At present, the various GIS vendors are competing to put more robust dynamic segmentation tools in the hands of users. For instance, an important deficiency being addressed by several developers is the provision of more automated facilities for updating route measures and attribute location data in response to a change in the route's geometry (e.g., a bypass resulting in the shortening or lengthening of a route; see Figure 3.1). Other vendors are working to introduce the concept of control point features to allow more flexible placement of attributes based on local base reference locations.

A third development is the integration of dynamic segmentation technology to enhance the utility of available functions for *geocoding* — location of features on the link-node network on the basis of matching street addresses. With dynamic segmentation, for instance, the storage of building address information for a particular street segment can be calibrated more accurately to reflect the actual locations of those structures. Examples include the location of street lights or trip origins and destinations.

Other uses of dynamic segmentation include the calibration of network data from traffic or transit models, where the coarse link-node structure does not reflect local flows, and the use of the technique to define traffic analysis zone boundaries which more readily reflect trip generations and attractions along a network.

Fig. 3.1 The Problem of Geometric Update



A→B : Distances do not change
B→C (old) : Should data for this section be archived?
B→C (new) : Obtain new data
C→D : From point C, all distances subtract distance [(B - C (old)]- (B - C (new))]

4.

CASE STUDIES

4.1 Pennsylvania Department of Transportation

The Office of Planning's Development & Demonstration Division (D&D) has set up a so-called "backdoor GIS" to explore the application of GIS technology to their particular needs, based on licensed versions the Intergraph Modular GIS Environment (MGE/SX) and MGE Analyst (MGA) software products[1]. These include the MGE Network Analyst (MGNA) and MGE Segment Manager (MGSM) modules. The latter is Intergraph"s dynamic segmentation module. D&D performs GIS analysis mainly on dual-screen Model 6450 Interact, and single-screen Model 245 and Model 125, workstations.

At the time of writing, D&D has converted highway data for two counties into Segment Manager. The 1:24,000 road centerline network was divided into separate topological links corresponding to each of the over 105,000 half-mile-long Road Management System (RMS) route segments. Route features corresponding to each unique State Route ID were aggregated from these links. The primary route key also includes a direction code, used to distinguish between divided highway sections for the same State Route. These routes were further subdivided into Segment Manager districts based on the concatenated IDs for county and RMS segment. Control points were established at both ends of each segment.

A subset of fields from the A0 (root), BA (administrative data), and BB (traffic count data) records of RMS have been imported into Oracle on a local UNIX Server from the RMS database. A combination of primary key, secondary key, and begin and end offsets were used to place data on graphics. (See Map 4.1)

Problems identified with the current GIS implementation include the following:

- Segment Manager could not handle State Routes that loop onto themselves.
- Analyzing data for overlapping routes sharing the same set of links is problematic.
- When displaying one or more distributed attributes onto the highway network, the performance of the requisite dynamic segmentation tools appears to deteriorate as the number of control points increases.

The use of dynamic segmentation to implement a linear referencing system for PennDOT appears to offer significant improvements in the usefulness and

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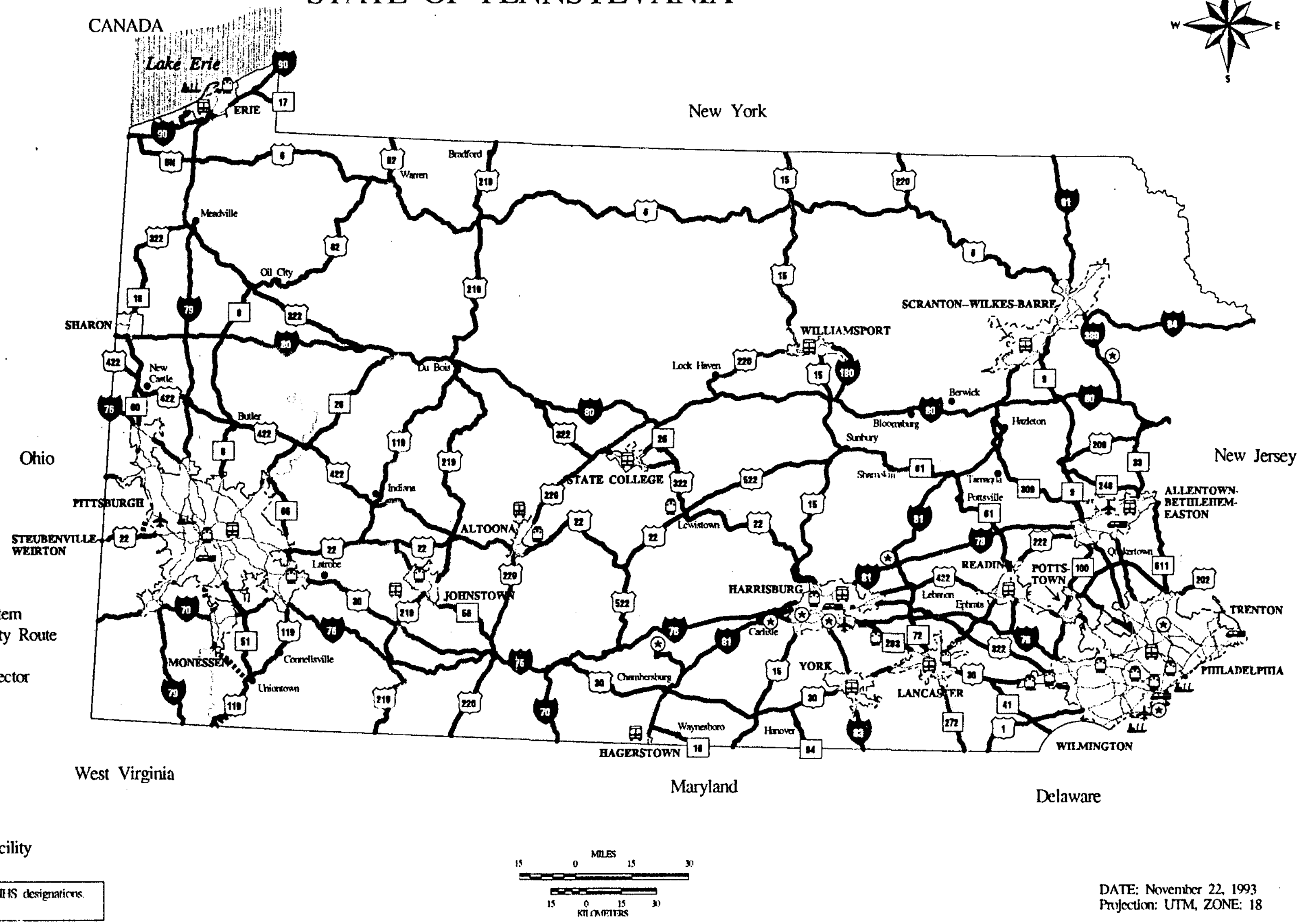
[1] Intergraph is the registered trademark of Intergraph Corp., Huntsville, AL.

maintainability of available attribute databases for highway management and analysis. The impact of converting the current highway attribute data storage is potentially very large, considering that RMS, for example, currently is estimated to require over 58 Gbytes of memory to store actual attribute data, not even counting requirements to store record index information. Research currently underway using an extract of actual PennDOT spatial and attribute data indicates that potential savings in storage may amount to one-seventh of the database.

U.S. Department of Transportation

Federal Highway Administration

PROPOSED NATIONAL HIGHWAY SYSTEM
STATE OF PENNSYLVANIA



LEGEND

- Eisenhower Interstate System
- Congressional High Priority Route
- STRAHNET Route
- STRAHNET Major Connector
- Other NHS Route
- Waterway
- Military Base
- Airport
- Amtrak Station
- Transit Service
- Port
- Highway/Rail Transfer Facility
- Urbanized Area

Two-color lines indicate routes having dual NHS designations.
Dashed lines indicate proposed routes.

DATE: November 22, 1993
Projection: UTM, ZONE: 18

4.2 Using Dynamic Segmentation to Produce FHWA's Congressional Maps: Automated Mapping with a GIS

4.2.1 Introduction

Automated Cartography

The creation of meaningful, properly annotated maps is not an exact science. It requires judgment and a sense of aesthetics on the part of the cartographer. Although Geographic Information System (GIS) technology has dramatically improved the field of spatial data analysis in recent years, little or no attention has been paid to the aesthetic and cartographic quality of the GIS output. It is only recently that attempts have been made to utilize fully the capabilities of GIS software to produce professional quality maps in an automated fashion.

Project Description

The Federal Highway Administration (FHWA) has to produce for the U.S. Congress by January 1995 a set of maps showing the extent of the proposed National Highway System (NHS). FHWA has traditionally used time-consuming manual methods for producing these maps. To facilitate updating, FHWA decided that automation was the appropriate approach to producing these maps.

FHWA is currently in the process of setting up an agency-wide GIS. As an introductory step toward the utilization of the accumulated spatial data, it decided to produce the 1993 NHS maps using GIS software (ARC/INFO[2], in this case). A total of 458 maps (1 national map, 50 state maps, Puerto Rico, the District of Columbia and 405 urbanized area maps) needed to be produced. Examples are shown in Maps 4.2 and 4.3.

GIS/Trans, Ltd. was contracted to develop and implement this application within ARC/INFO. Also required was the delivery of the software mapping tools to enable FHWA staff to create maps in the future. The tools were to be macros developed using ARC/INFO's macro programming language (AML).

Required Map Content

The maps were to replace the manually produced versions and had to contain, at the minimum, the following cartographic elements:

- Map peripheral elements like titles, neatlines, legend, logo and north arrow
- State and urbanized area boundaries
- NHS and Principal Arterial highways

[2] ARC/INFO is a registered trademark of Environmental Systems Research Institute, Redlands, CA.

- Major airports
- Major military bases
- Major waterways
- Major highway/rail transfer facilities
- Major Amtrak stations
- Major ports
- Major cities

All the required input data were provided by FHWA, so there was no data collection phase to this project. General data issues are discussed later.

4.2.2 Issues

General GIS Issues

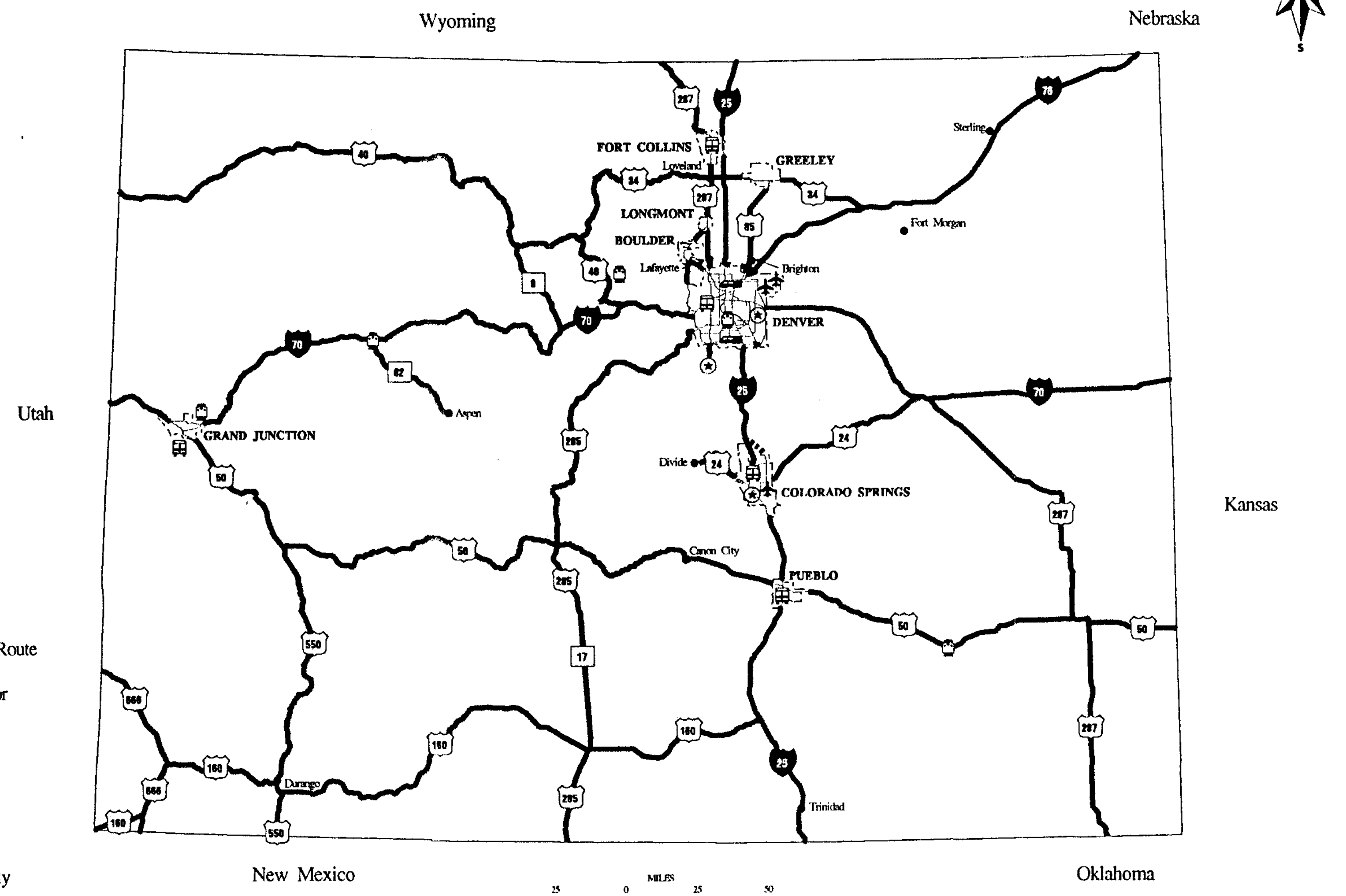
Although present day GIS packages contain toolkits that could be used for the production of quality maps, GIS are not, in general, designed for map production only. Maps are just one possible product. Many map-making functions therefore require that the user "work around" the GIS.

Data Issues

The data were provided to GIS/Trans in the form of ARC/INFO coverages, for the most part. Some attribute data would be in the form of spreadsheets and some in plain coordinate data. This meant that the data would have to be *preprocessed* in order be usable.

PROPOSED NATIONAL HIGHWAY SYSTEM
STATE OF COLORADO

U.S. Department of Transportation
Federal Highway Administration



LEGEND

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- Port
- Highway/Rail Transfer Facility
- Urbanized Area

Two-color lines indicate routes having dual NHS designations.
Dashed lines indicate proposed routes.

MILES
25 0 25 50

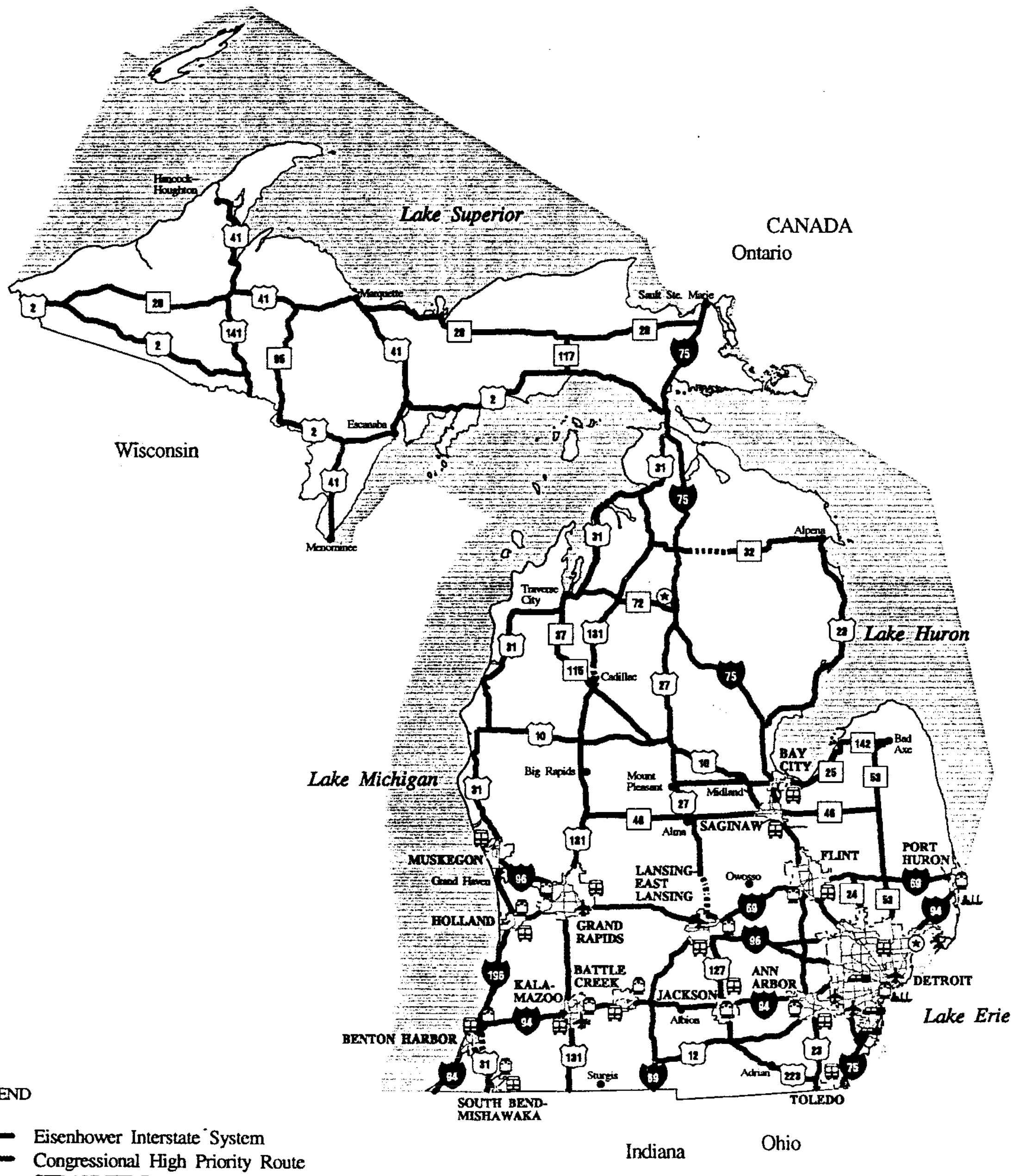
25 0 25 50
KILOMETERS

DATE: November 22, 1993
Projection: UTM, ZONE: 13

PROPOSED NATIONAL HIGHWAY SYSTEM
STATE OF MICHIGAN

U.S. Department of Transportation

Federal Highway Administration



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Two-color lines indicate routes having dual NHS designations.
Dashed lines indicate proposed routes.

MILES 30 0 30 60

KILOMETERS 30 0 30 60

DATE: November 22, 1993
Projection: UTM, ZONE: 16

Preprocessing involved the following steps and was completely automated.

1. Clip point data and project to UTM: Point data, such as for cities and military bases, was provided in the form of national coverages. These needed to be "clipped" out before coverages could be projected to Universal Transverse Mercatur (UTM), because UTM is actually a series of different projections, paralleled into UTM "zones."

2. Parse route names. Route number, type, and modifier (i.e. spur, business) were stored in one item. A C program was used to parse this out to three items in the database table.

3. Create routes. Route-systems were needed to place the route shields. One route system would be created for each type of route.

In addition to these preprocessing steps, events had to be created at points where the route shields were to be located.

Mapping Issues

There are a number of important issues involved in the automatic generation of high-quality maps. Some of the issues faced in this project are listed below:

- White Space Utilization: Optimal utilization of white space (defined as the space available on the page for the actual map) is a significant factor mainly because the shapes of the areas being depicted vary widely. Some instances require resizing the white space, while others require repositioning map peripheral elements like the legend, logo etc. to make more space available for the actual map. This decision is subjective and presents a problem for complete automation.

- Placement of Highway Route Shields: Placement of highway route shields with minimal overlapping (either with other route shields or adjacent text) was a major consideration.

- Placement of Map Peripheral Elements: The location of map peripheral elements is dependent upon the shape of the map. See point above.

A number of other issues, which were relatively less significant, also had to be dealt with.

Dynamic Segmentation

A number of approaches were evaluated before deciding that ARC/INFO's Dynamic Segmentation (DS) tools would provide the basis upon which to build the application and manage the initial placement of the highway route shields.

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DS tools provide the ability to associate data with locations on linear features without modifying the underlying topology (e.g., addition of nodes for each change in attribute value). This eliminates the need to store the same data for each arc (redundancy), in the coverage. Only the changes in attribute values would be stored – as an offset from a fixed starting point of that particular linear feature. Such an approach would not require a topological node at each change in attribute value. The linear feature would be segmented *dynamically* as opposed to *static* (or fixed) segmentation.

DS Implementation in ARC/INFO

Attributes (called "events") are stored in separate related database tables. Three different kinds of events are defined: point (a single location on a linear feature – such as a traffic accident on a road), linear (a start point and an end point – such as a measured traffic flow value), and continuous (a start location and change values – such as a speed limit sign).

This application would benefit from the use of point events to represent locations of highway route shields.

4.2.3 Technical Approach

Approximately 180 AML programs were developed to resolve the issues listed above.

Determination of Page Orientation

All of the maps could not have the same orientation (portrait or landscape) since the areas mapped were all of different shapes (for example, California state map would be portrait while Washington would be landscape). Some had greater x-dimension while others had greater y-dimension. Macros were written to set page orientation automatically. Since page orientation determines the location of map peripheral elements, this macro would also reposition these elements and make suitable adjustments to the white space.

Placement of Highway Shields

Once the route systems had been created, a complex algorithm was used to locate the event points (representing the locations of the route shields) on the routes. The algorithm would basically traverse each route from beginning to end, locating events based on a set of conditions. These conditions incorporated factors such as distance from intersections, minimum and maximum distances between route shields on the same highway, number of route shields on a particular highway, etc.

Interface

The user interface was set up to allow user-friendly creation and editing of maps. The interface had standard presentation format and the capability of interactively (and automatically, if so desired) placement of a wide variety of cartographic elements.

Figure 4.1 Preprocessing Steps and Map Generation

Highway and state boundary data are delivered in compressed ARC/INFO export files.

Perform a quality check on the data received for required INFO items and data quality.

FHWA uses the ARC/INFO generate command to convert the files of coordinates into polygon coverages.

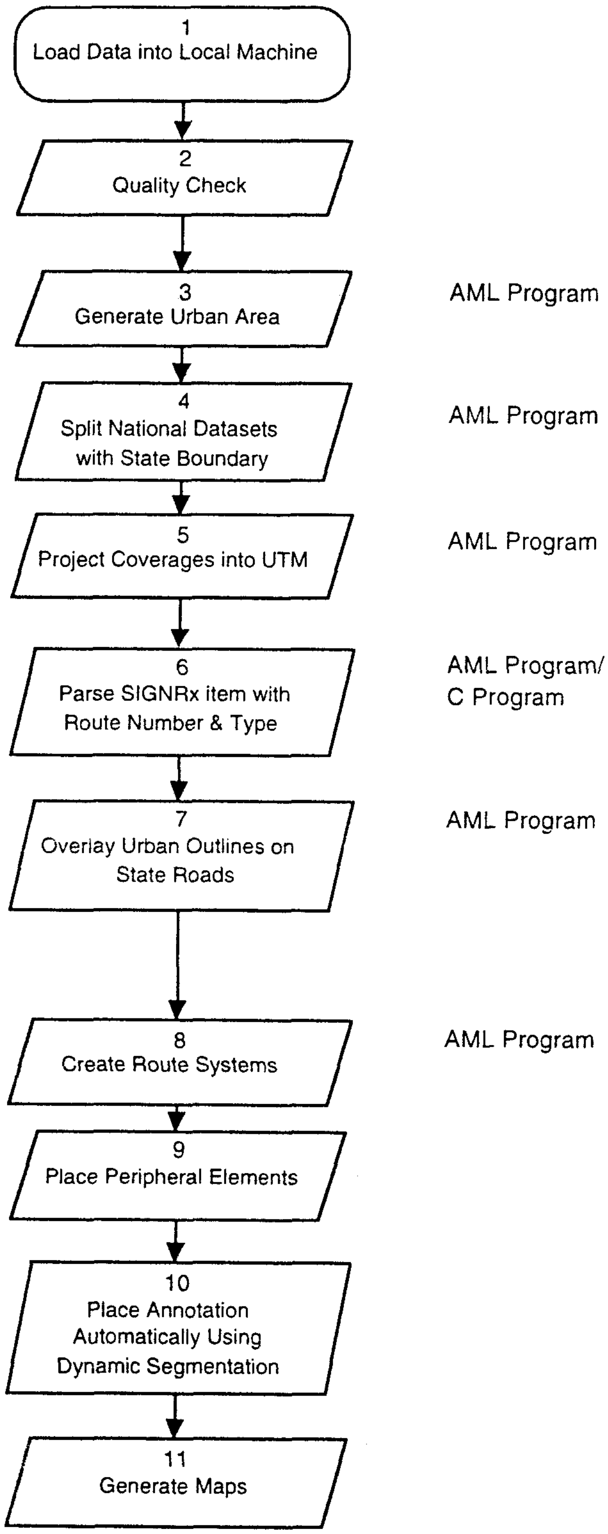
Data for military bases, airports, and cities are delivered in nationwide sets which need to be split by state boundaries

Data is delivered in long-lat (geographic projection) format and needs to be projected into UTM. A file has been created containing the UTM zone for each site.

The SignRx item in the AAT of the network coverage contains the sign route, class and qualifier. This data is parsed out and stored in individual items.

Staff at Oak Ridge National Laboratories and the University of Tennessee Transportation Center split the highway arcs at the urban area boundaries so that NHS line symbols can be differentiated inside urban areas on state maps.

The route systems are required by the program that places route shields on the map. One route system is created for each route type.



To accomplish this, the interface was split into five menus. The DISPLAY menu, for example, contained the buttons necessary for managing the general display characteristics like page size etc. while the Controls menu would have buttons to control the general map characteristics. There would be still other menus which would generate the map automatically at the push of a single button with minimal user intervention.

The user interface, consisting of approximately 180 macros and 10,000 lines of code was designed to be modular and flexible. The code is internally well documented, and a reasonably experienced AML programmer could easily customize and expand the menu system.

4.2.5 Conclusions

The mapping project involved a larger number of issues than originally expected. Some of the problems that were overcome related to methods of editing previously created maps and limitations of ARC/INFO. In the end, a robust and flexible interface for creating NHS maps was developed. Although the project did expose some limitations in the use of a GIS to produce automatically annotated maps, GIS/Trans believes that the advantages overshadow the shortcomings and that this software package will be a valuable addition to FHWA's resources. Although dynamic segmentation was only one of the procedures employed, its use saved valuable time and effort in determining placement of symbology on the map.

4.3 Vermont Agency of Transportation: Traffic Flow Mapping

4.3.1 Introduction

Transportation Mapping

Flow maps are a highly useful tool for traffic analysis. Properly designed, they provide a visual sense of traffic patterns and congestion at first glance, as well as detailed, quantified information with further study. One method of accomplishing this is to represent the traffic flows graphically as variable-width lines, while showing detailed information with text annotation, evenly spaced along road centerlines, describing the flow at that point on the road. This is the method used by the Vermont Agency Of Transportation (VAOT) for its traffic analysis maps.

VAOT has traditionally used manual cartographic techniques to produce its "State Route" and "Class Two Town Highway" Traffic Flow Maps. Starting in 1992, however, the agency began to use GIS software to facilitate mapping and transportation analysis. The initial GIS project involved creating the latest set of Traffic Flow Maps using the ARC/INFO software package. This project was not only the first in a series of proposed GIS applications, but also a test case, to determine the scope of the software, including its capabilities, its limitations, and the feasibility of its use as a transportation management tool by the state of Vermont.

The Project

GIS/Trans, Ltd. contracted with VAOT to develop this prototype application. The scope of the project included the creation of a "State Route" map and a "Class Two Town Highway" map, with 1,200 prints of each on 11" by 17" sheets, and 500 prints each on 24" by 36" sheets. Also required was the development and delivery of software mapping tools to enable VAOT staff or contractors to create future maps in the same style. The tools were to be macros developed using ARC/INFO's dedicated macro programming language, AML.

4.3.2 Background

The Data

As presented to GIS/Trans, the data sets had not yet been integrated into a single, readily usable form. While the road centerline data was in standard ARC/INFO format, as a line coverage digitized from 1:5000 scale maps, the Average Daily Traffic flows (AADTs) of the roads were in Lotus 1-2-3 spreadsheet format. Locations of much of this AADT data was presented as milepoints along routes. One type of data, however, had no reference to specific locations on the roads, merely a town name and a data value from a previous map, from which the location was to be found. The locations of the data points in the spreadsheets had to be converted into real-world spatial coordinates that could be displayed on a map. For the data that included milepoints, ARC/INFO's

Dynamic Segmentation tools were the key to integrating the data and producing a map.

Dynamic Segmentation

Dynamic Segmentation is a method of storing changing or spatially intermittent characteristics about points and linear segments on a network without storing each change as a discrete spatial element. Normally, GIS data consists of individual, homogeneous points, lines, and polygons. Each line segment, for example, has a list of characteristics that are constant for the length of the line. Dynamic Segmentation, on the other hand, allows the data to merely define a point where a characteristic changes, expressed as an offset from a fixed reference location. That way, it is only necessary to split lines where network topology requires it, as in the case of an intersection, rather than every time data values change, as happens at the dividing point between two traffic flow rates. This is a highly efficient, flexible method of spatial data management, because many layers of attribute data may reference the same spatial network.

Dynamic Segmentation, as implemented in ARC/INFO, uses data records called "events" to store attribute information, which are stored in "event tables." ARC/INFO defines three different kinds of events: the point event, which has a single location on a line, such as a traffic accident; the linear event, which has a start point and an end point, such as a measured traffic flow value; and the continuous event, which has a start location, and values that remain valid until another continuous event changes them, such as a speed limit sign. Each of these types is useful for a range of situations, though linear events are most appropriate for the data integration problem discussed above. Point events can be useful in another way, in the placement of annotation along a route, as well. This will be discussed later.

4.3.3 Tasks

The basic tasks required of GIS/Trans were data integration, map production, and interface development. The tasks were performed essentially in that order, although there was considerable overlap. The map production methods were being developed while the data was still being prepared, and the interface macros were gradually written to facilitate other tasks, which were then refined for VAOT use.

Data Integration

Dynamic Segmentation requires that routes be defined, and then calibrated by declaring the total length of the route. This gives the Dynamic Segmentation module a reference system, which it uses to place events on the network. In this particular case, that means first declaring a set of arcs to be in a given route in a given route system, such as declaring all the arcs that represent I-91 as route "91" of route system Interstate. The first step in preparing the road centerline dataset was to define the routes and route systems. For the State Routes, this was straightforward, because that information was already contained in network dataset. It only needed to be translated into a form ARC/INFO recognized. For the Class Two Town Highways, definition of the routes was not as simple. While the route information for these roads was contained in the dataset, that information was incomplete and often inaccurate. Because of this, the proper arcs had to be identified manually, on a printed road-map, and individually assigned to routes.

The second step in preparing the road centerline data for integration was route calibration. Calibration of the route by the total length was accomplished by summing the milepoints of the flow data, found in the spreadsheets. Once the proper length of each route was known, the lengths could be used to calibrate the routes in ARC/INFO's referencing system. For the Class Two Town Highways, nothing more was required, but for the State Routes, problems began to arise.

The road centerlines were digitized from highly detailed maps. Divided highways were digitized as two lines, one for each direction. Ramps were also digitized. Unfortunately, no information was included in the data to distinguish a ramp from an interstate link, or a northbound lane from a southbound lane. This proved quite confusing for the Dynamic Segmentation module. When calibrating a route, the software traces it from start to finish. When the software reaches an intersection, and more than one of the possible connecting links is part of the route system, it does not know which link to follow, so it chooses the one that most closely approximates continuing in a straight line. If this occurs near a bend in the road, the wrong link could be chosen. As a result, several times the Dynamic Segmentation module, in tracing a route from south to north, followed a ramp instead of the highway, then turned around and traced from north to south, until another ramp turned it again. The module would continue until it had reached the northernmost point of the route, but often with highly inaccurate route measures. These problems needed to be identified, then corrected by removing the ramps from the route systems manually.

Once the routes were created and calibrated, the flow data could be fully integrated into the dataset. The basic procedure was to output the spreadsheet data to comma-delimited text files, then bring those files into INFO as data file records. These data files would then be used as event tables, to be referenced by the Dynamic Segmentation module. In this task as well, unforeseen difficulties arose.

The Dynamic Segmentation module requires that events be located by an linear offset from a fixed reference point, which is the beginning of the route on which the event is located. In the spreadsheets, the flow data was located by a linear offset from the edge of the town where the measurement was taken. Every time the route entered a new town, the milepoints would list an offset distance from the edge of that town. To translate the milepoint references contained in the spreadsheets to the format expected by ARC/INFO, the GIS/Trans staff had to sum all the milepoints, so that the distances were cumulative along the entire lengths of routes.

A second problem that arose was inaccuracies discovered in the spreadsheet data. Some of the flow values had been incorrectly entered into the spreadsheets. These problems were identified by the careful examination of test maps, looking for improbable flow rates along routes. When found, a printed version of the data was consulted. In the event of any discrepancy between the printed version and the spreadsheet version of the data, the printed data was taken to be correct, and the spreadsheets were updated.

While the procedure outlined above handled most of the flow data, one type of data needed a special method of integration. As mentioned earlier, the non-Federal Aid Secondary Class Two Town Highways did not include milepoint information. Instead, they referenced the flow value shown on a previous map, along with the town in which the flow was measured. Using that information, the exact location of each flow data point was determined, and stored as an element in a point coverage, along with the new flow value. This fit with the standard method of display for this data, which is to show only the data measurement point, annotated with the flow value. This is in contrast with the rest of the flow data, which was given as flow along whole sections of road.

Map Production

Much of the map production process involved manual placement of elements. The legend and route shields as well as state, county, and town names all had to be located by hand. However, two key elements, crucial to make the Traffic Flow Maps effective, were placed on the map by automated processing. The first was a standard technique, well implemented in ARC/INFO. The second involved an innovative use of Dynamic Segmentation, to place flow annotation automatically.

For drawing line elements, ARC/INFO uses line symbol sets containing many different line types. These symbol sets are editable, and various parameters such as color, width, and pattern can be altered by the user or a macro, and saved. ARC/INFO also has a command for drawing lines in a coverage using a value in the coverage and a lookup table to determine the symbol to use to draw each line. For example, if a line to be drawn had a AADT value of 1600, and the lookup table translated that value into symbol number 5, the line would be drawn with line symbol 5.

Using these two ARC/INFO capabilities, varying the line widths according to the AADT flow values was a fairly simple matter. Taking input from the user to determine the maximum line width, the maximum and minimum flow values, and the number of discrete widths to place between the minimum and the maximum value, a macro created a lineset with several symbols, each only differing in width. Also created was a lookup table, with the AADT flow values and their corresponding line symbols. After that was set up, the only step required was to draw the lines, using the flow value and the lookup table to determine which symbol to use to draw each line.

As discussed above, a large part of the value of this type of Traffic Flow Map is its ability to present detailed, quantified information. This is accomplished by annotating each route, at regular intervals, with the AADT flow value at that point. GIS/Trans used Dynamic Segmentation here to calculate and store the locations of the annotation.

First, for each route, the total length of the route, as defined when the route was calibrated, was determined. Then a series of point events were created, with offsets at regular intervals along the route, up the length of the route. This was repeated for each route, and all of the events were stored in an event table. The Dynamic Segmentation module was then used to determine, for each event, the coordinates of a point on each side of the route, offset perpendicularly to the line from the point defined by the event. This information was used to calculate the location and angle of the annotating text, as well as the size and orientation of an oval in which other map elements should be blanked out, so the AADT flow text will be readable. Of course, the annotation still required some manual editing to remove overlaps, but the bulk of the placement was automatic.

Interface Development

The user interface was set up to allow convenient mapping of changing data, with presentation in a standard format, and the capability of drawing a wide range of cartographic elements if desired. To accomplish this, the interface was split into two simultaneous menus. One menu, the DISPLAY menu, contains a set of generic page setup, shape and feature drawing, and map editing tools. These tools may be used to alter the maps created automatically by the macros, or generate entirely new maps, as desired.

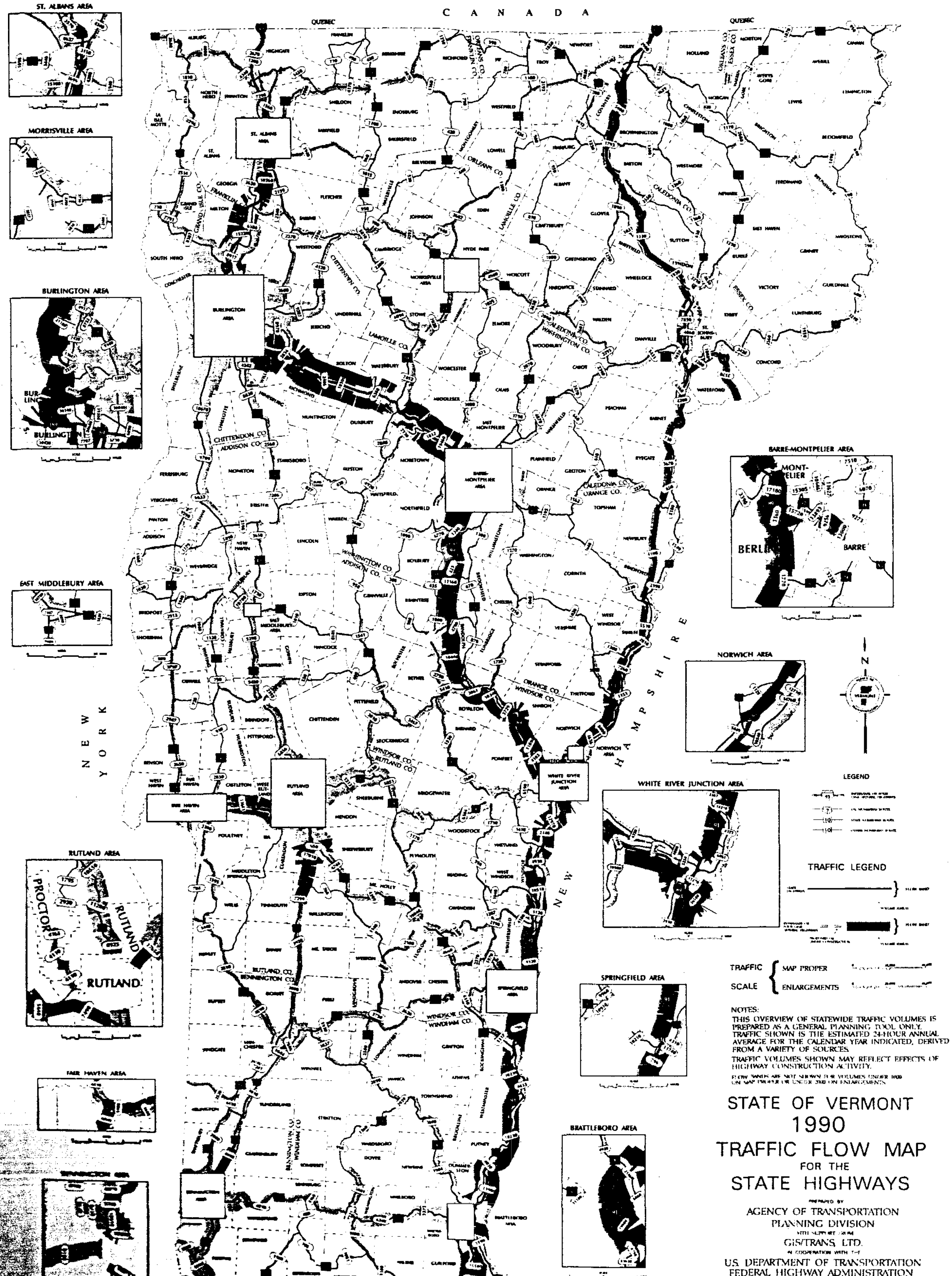
The second menu, the MAPPER menu, was set up to generate a map at the push of a single button, using a wide array of parameters set in form menus. The parameters are stored in files, and GIS/Trans included a set of default parameter files with the interface that would recreate the maps which were produced under the contract. With this method, when the data is updated and new maps must be created, only the parameters that have changed must be entered, greatly saving production time.

The user interface, consisting of 53 macros and approximately 4000 lines of code, was designed to be modular and flexible. The code is internally well documented, and a reasonably experienced AML programmer could easily customize and expand the menu system.

4.3.4 Conclusions

The prototype GIS mapping project was clearly of a much larger scope than originally expected. Problems with both the storage methods of the data and the flow values themselves presented difficulties which prevented the project from being completed on time. Additional delays resulted from bugs in ARC/INFO, which were not fully corrected by a subsequent upgrade during the course of the project.

However, in the end, a set of very high quality maps were produced, and the process of overcoming obstacles had produced a large number of data processing tools, which will prove highly useful in future projects. While the project did expose some limitations in the ARC/INFO software, GIS/Trans believes that the advantages displayed by the use of GIS will make it a valuable part of the State of Vermont's transportation management tools.


C A N A D A
QUEBEC
ST. ALBANS AREA
MORRISVILLE AREA
BURLINGTON AREA
EAST MIDDLEBURY AREA
RUTLAND AREA
PROCTOR
RUTLAND
FAIR HAVEN AREA
BARRE-MONTPELIER AREA
BARRE
NORWICH AREA
WHITE RIVER JUNCTION AREA
SPRINGFIELD AREA
BRATTLEBORO AREA
NEW YORK
NEW HAMPSHIRE
MASSACHUSETTS
LEGEND
TRAFFIC LEGEND
TRAFFIC SCALE
MAP PROPER
ENLARGEMENTS
NOTES:
THIS OVERVIEW OF STATEWIDE TRAFFIC VOLUMES IS PREPARED AS A GENERAL PLANNING TOOL ONLY. TRAFFIC SHOWN IS THE ESTIMATED 24-HOUR ANNUAL AVERAGE FOR THE CALENDAR YEAR INDICATED, DERIVED FROM A VARIETY OF SOURCES.
TRAFFIC VOLUMES SHOWN MAY REFLECT EFFECTS OF HIGHWAY CONSTRUCTION ACTIVITY.
STATE OF VERMONT
1990
TRAFFIC FLOW MAP
FOR THE
STATE HIGHWAYS
AGENCY OF TRANSPORTATION
PLANNING DIVISION
GIS/TRANS, LTD.
U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
SCALE
10 MILES
MAP PROPER
ENLARGEMENTS

5.

FUTURE DEVELOPMENT

The traditional georelational data model for GIS includes software to link together in whole or part a graphics management subsystem, a relational database management subsystem, and a topology subsystem or spatial data manager. Only a few GIS provide interactive maintenance of the relations between all of the subsystems, such as automatically updating the database for all geometrically related attributes. The user is usually responsible for maintaining and updating these relationships. If the problem to be solved is simple and the data non-dynamic, the user can usually manage the task. In practice, no user can dynamically manage the complex inter-relationships of the attribute, geometry, and topology subsystems, much less any feature-to-feature relations. This is a critical problem, that requires procedures to control the input, manipulation, and interrogation of the subsystems so that no defined relationships are disturbed. However, these limit the user to the procedural approach to problem solving and effectively eliminate dynamic analysis or dynamic relationship construction and resolution.

5.1 Object-Oriented Model of Dynamic Segmentation

An alternate, more dynamic paradigm is offered by the object-oriented data model. Object-oriented programming techniques and system technologies are now being applied to the development of the next generation of Geographic Information Systems. The advantages of an object-based GIS are:

- Enhanced intelligence of objects in the GIS;
- Enhanced modeling of the relationships between the GIS objects;
- The implementation of a truly dynamic GIS model allowing interactive refinement of object behaviors, as well as the real-time presentation of external events.

The benefit from the user's perspective is that the object-GIS is a more realistic representation of how the world works than a georelational GIS which uses tables of rows and columns to store data.

In the object realm, there is no need for division of data into subsystems. The object can manage its own geometry and attributes as well as its own topology. It even offers the potential to manage its relationships with other features through inheritance procedures between classes and associated sub-classes (e.g., main roads and local streets). This is accomplished by the integration of software and data into a single point of reference the object. The object provides the ability to define and store arbitrary relationships. It then provides a single location to associate processes that manage these relationships. Spatial intelligence is modeled within the feature. The user is then free to interrogate and manipulate features with the assurance that defined relationships about the feature are maintained.

This capability to store expanded data relationships is exactly the aspect of the object model which simplifies dynamic segmentation. The key to managing linear network data is to store the attributes' values and their distributions non-redundantly and independent of any other attribute data. For example, consider the following pavement management database:

Table 5.1 Sample Pavement Management Database

Highway	Location		No. of Lanes	Lane Width	Year Repaved
	From	To			
I-95	0.0	4.9	2	14	1950
I-95	4.9	12.0	2	14	1960
I-95	12.0	15.8	2	14	1960
I-95	15.8	23.5	3	14	1960
I-95	23.5	39.0	3	12	1972
I-95	39.0	50.0	3	12	1981

The object would store them independently as follows:

number of lanes:	2 from 0.0 to 15.8 4 from 15.8 to 50.0
lane width	14 from 0.0 to 23.5 12 from 23.5 to 50.0
year repaved	1950 from 0.0 to 4.9 1960 from 4.9 to 23.5 1972 from 23.5 to 39.0 1981 from 39.0 to 50.0

The redundant data is eliminated and minimum storage achieved.

The attribute data is defined by the object in such a way that simple algorithms can provide quick answers to network queries without requiring any preprocessing. Further, locations along the object (route) can be used to define a new object which can be given all attribute information from the parent route pertaining to its location. The segments can then be dynamically segmented, since the new segment object retains the intelligence of the parent route with respect to the location where it resides. For example, if the question is "where are the two-lane sections of road along a route?" all contiguous two-lane sections will be shown as single entities, not as a number of small adjacent segments. If the non-object form of the above example is used, the answer to the two-lane question would be given in three segments:

from 0.0 to 4.9
from 4.9 to 12.0
from 12.0 to 15.8

The object answer would simply be from 0.0 to 15.8. No artificial segmentation is required.

6.2 Temporal Segmentation

Objects can store complex geometry, which opens up a number of possibilities. For example, one could store a list of geometries for an attribute, representing the shape of a road or river at increments of time. Any attribute which can be described as a function of the geometry of the feature could be stored with its functional definition, and dynamically interrogated. This opens the door for temporal analysis and even predictive modeling. Additionally, one can then consider 2D or 3D segmentation, the latter is sometimes referred to as the "spatial spreadsheet." Since the object is a single point of integration for software and data, complex relationships between the geometry and attributes can not only be stored and interrogated, but managed over time as well, so that attribute values can be immediately recalculated upon any geometric changes. The number of complex relationships that can be defined and modeled as one considers using abstract data types in the object model is theoretically infinite.

As the above discussion indicates, it is possible to use the object model to simplify the problems inherent in performing dynamic segmentation. We can define relationships between attribute values and the object's geometry and expect the object to maintain these relationships for us. In effect we can gain a completely feature-oriented access to our network data that allows full integration of other GIS data with the object model. It is even possible for the model to include dynamic maintenance of the topological relationships that provide the spatial underpinnings of our database. The object model gives us our best opportunity to describe reality.

However, to take full advantage of the object-GIS data model requires the use of object-oriented databases and as these will require data migration from traditional DBMS it is likely to be some years before object-GIS become the norm. In the meantime, object-GIS will continue to develop but in the interim offer few practical advantages to the GIS user. The georelational model has also been found to be more robust and efficient at handling topology so some further advance in the object model will be necessary.

Modeling temporal changes is one of the big challenges for GIS, especially the avoidance of data duplication between time periods. Techniques are being experimented with to update only those features which change from one time period to another. However, it is likely to be a few years before robust tools and methods are fully tested. When these do arrive they are more than likely to be object based.