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Transportation Systems Analysis
GIS Project

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Network Pathologies

Phase 2 Report
Draft Working Paper

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1. INTRODUCTION

1.1 Background to the Report

This report is the second report prepared by GIS/Trans, Ltd. for Sandia National Laboratories GIS project, in the Transportation Systems Analysis Organization.

The work was undertaken in Working Paper format under relatively limited budget resources. It thus does not fully represent all activities that might be contained in a larger work. The Phase 1 report of this mini-study presented examples of basic "network pathologies" – that is, situations where the network feature is difficult to represent in the GIS due to topology and/or connectivity constraints. The basic pathologies included:

- Archetype network structures (i.e., overpasses and complex intersections)
- Abstract model network representations (which are coded as route-systems)
- Linear referencing pathologies (i.e., configuration of multiple LRS).

While these situations account for the majority of transportation data representations, the evolution of technologies such as Intelligent Transportation Aystems (ITS), GPS (Global Positioning by Satellite) and Transportation Simulation Models presents a number of new challenges for dynamic transportation data representation in GIS. In this respect, these "advanced pathologies" can by considered dynamic pathologies.

1.2 Report Objectives and Scope

The prime objective of this report is to provide some illustrative examples of advanced network pathologies. The Task 2 work scope specifies: *"Brief description of network integration pathologies associated with transportation model networks."* Examples of advanced network pathologies associated with these include:

- The representation of HOV lanes
- Multiple networks (e.g., on-street light rail lines)
- Contraflow systems for traffic management or transit services
- Freeway ramps
- Model networks with no corresponding network geography (i.e., zone centroid connectors, transit routes that traverse non-linear features).

Brief descriptions and diagrams of typical situations are provided in the following sections.

Following the Phase 1 Report, GIS/Trans and Sandia staff met on several occasions to discuss the findings of the Phase 1 work program, and to determine the work program for Phase 2.

1.3 Structure of the Report

Following this **Introduction**, the "intelligent" network for GIS is described in **Section 2**. Advanced network integration pathologies encountered in modelling situations are described in **Section 3**. The results of the project and directions for further research are summarized in **Section 4**.

1.4 Acknowledgment

The research for this report was undertaken by GIS/Trans, Ltd., under the direction of Dr. John Sutton, Director of Transportation Planning. The Sandia project manager was Mr. Stephen Bespalko, a Systems Specialist in the Transportation Systems Analysis Organization.

2. THE INTELLIGENT TRANSPORTATION NETWORK

2.1 Introduction

This section attempts to draw together:

- Network analysis issues from transportation planners and analysts
- Transportation modelling
- Network construction.

There is an assumption that researchers have not yet fully developed a clear "working hypothesis" or framework, for most appropriately proceeding with or viewing this research topic. This was one of the major conclusions of the Phase 1 Report. This section builds upon some of the analysis begun in Phase 1, and attempts to provide a framework or construct for assessment of GIS-T problems and issues. The focus in this section is on developing a comprehensive transportation network definition and data objects that collectively comprise the "intelligent" network.

The two initial premises given here are:

(1) A key problem for transportation modelling, planners and analysts has been the appropriate representation of networks

(2) The appropriate representation of networks varies with the modelling environments.

In other words, for example, the way a transit analyst may conceive of a network and the way that he/she may choose to disaggregate and analyze the network may be different from the way a highway engineer or an airline modeller or other type of transportation analyst views a network.

Therefore, in looking from the outset at the basic frame and the modelling of the transportation networks, we need to realize that one of the top level items is the need for analytical and modelling *flexibility*. A first part of the research is a simple analysis of the type of network modelling that is undertaken. These, as a minimum, include the networks listed in Table 2.1 below. These network examples demonstrate that modelling needs differ widely, as do the network data structures to support the model development.

The flexibility issue, with respect to different network representations, was addressed in the Phase 1 Report where we described several types of networks and "network pathologies" in GIS – situations where network connectivity/geometry does not match network topology. For a full discussion, see Section 3 on "GIS and Transportation model Network Pathologies" in the Phase 1 Report.

Table 2.1 Transportation Analysis Needs Related to Data Structures

Analysis Type	Special Needs for Spatial Data Structures	
1. Highway Network Modelling	• Divided highways • Ramps • Multiple routes on the same link	• Cul-de-sacs • Tunnels • Complex intersections • Traffic circles
2. Transit Network Modelling	• HOV lanes • Transit routes • Multiple routes on same link	• Underground links • Bus stops on one side of street
3. Freight Network Modelling	• Multi-modal links • Terminals and transfer points	• Rail and port links/nodes • Facilities with limited time of day access
4. Air Network Modelling	• Air routes • Airport hubs • Terminals and ground-side Connections	• Flight paths • Runways • Taxiways
5. Bicycle Networks	• Bicycle paths • Bicycle routes on roads or sidewalks	• Bicycle storage facilities • Facilities with limited bicycle access
6. Intermodal Networks	• Transfer points/facilities • Terminals	• Multiple links between the same nodes
7. Other Applications	• Traffic management by lanes • Simulation of turning movements at junctions	• ITS applications • GPS and AVL monitoring • Real-time routing

If we consider this need for flexibility as being a prime need for transportation planners, we may have deduced one (if not *the*) main criteria for evaluating any new modelling paradigm, such as object-oriented modelling. This point is elaborated further below, with respect to some key research questions.

2.2 Research Sub-topics

The problems and issues analysis is addressed by considering a number of key research questions which focus specifically on network definition and related issues. They are broken up in the following manner:

(1) *Research Sub-Topic #1.* Our first problem is to think of all elements that transportation networks are potentially comprised of. For example, graph theoretical networks comprise links (arcs/chains) and nodes (the abstract transportation model network is an example). In GIS, we introduce geometry and wish to display more network features and attributes. We therefore need segments and sections. Some features transcend several arcs, such as routes and the route elements, so we need route definitions. Depending upon the scale of feature representation and the purpose of the mapping or modelling exercise, we may wish to aggregate these in different ways (i.e., corridors, sub-routes or linear events).

(2) *Research Sub-Topic # 2.* Our second issue is to develop a richer hierarchy (or matrix) to allow for the construction of all the modelling elements which may be appropriate for the wide range of applications that the transportation community has.

(3) *Research Sub-Topic # 3.* Our third research issue is to clearly define the more detailed network "characteristics." These need to be further defined, but can include all network modelling elements (i.e., nodes, turn restrictions, stops, barriers, breaks, ramps, lanes) and the key characteristics associated with each.

(4) *Research Sub-Topic # 4.* A fourth research issue further develops the linkage from the theoretical model framework to the real world framework. Research sub-topic # 4 gives some examples of network "pathologies" which may exist with route construction. Several other examples were given in the Phase 1 Report. Routes may be constructed on geometric entities in many different ways. In many DOTs the construction of routes and route-details is an area which has been implemented with many local agency idiosyncrasies.

(5) *Research Sub-Topic # s 5 and 6.* The four previous research areas cover the nature of the transportation network problems and issues that GIS-T needs to address. Two additional research sub-topics are included in this section, which focus less on problems and more on what needs to be done; the fifth research issue (Section 2.2.5) addresses the requirements for constructing more flexible network definitions, and the sixth research issue (Section 2.2.6) focuses on the development of the "intelligent transportation network."

2.2.1 Research sub-topic # 1: Define all the ways in which transportation modellers define and abstract networks

An initial classification of network elements is made in Table 2.2 below. However, the network modelling situations are many, as indicated in Table 2.1 above, therefore, this list is clearly not exclusive.

The network elements are defined by type into spatial primitives (i.e., points and lines) and attributes. The attribute elements are non-topological. The topological elements form part of the standard GIS data model. GIS-T extensions such as Dynamic Segmentation allow more flexible definition or attribution of features, such as routes which cross several arcs. The super-route and corridor features can be constructed, but are not, at present, part of the GIS-T toolbox (they imply route dependencies, which are currently beyond the standard Dynamic Segmentation data model developed by GIS vendors). The most interesting concept is the super-network, which implies a mixture of topological and non-topological elements in free association. This is not a contrived concept, but rather a real manifestation of transportation network realities, especially where multimodal representations are needed.

Table 2.2 Network Elements

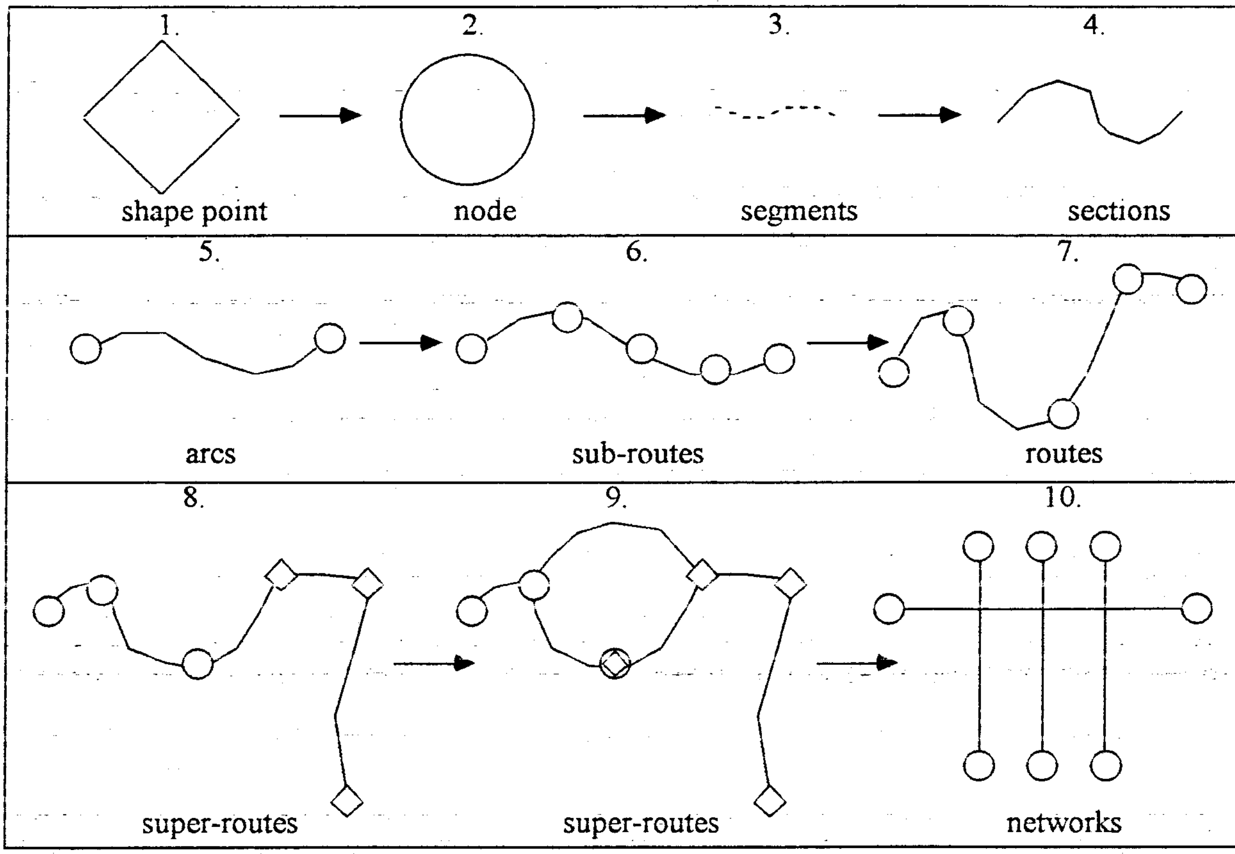
Level	Element	Type
1.	Shape points	Point
2.	Nodes	Point
3.	Segment	Line
4.	Section	Attribute
5.	Arc	Line
6.	Route	Attribute
7.	Super-route	Attribute
8.	Corridor	Attribute
9.	Network	Lines and points
10.	Super-network	Lines, points and attributes

The notes below give consideration to some elements of network construction which are key to such considerations. In Figure 2.1 below, we depict the proposed elements of the networking hierarchy listed in Table 2.2.

These include the following definitions, as examples (see Figure 2.1):

- *One segment,* which may be defined as a line between two shape points (e.g., a curve in the road or a bridge).
- *A section,* which may be defined as a part or a whole of an arc (e.g., a pavement section or speed zone outside a school). An alternate definition is the *anchor section* which lies between two *anchor points*, which in turn reference datum points (latitude, longitude and elevation). The anchor section may transcend arcs.
- *An arc,* which is defined as a set of segments between two nodes (referred to as a chain in Spatial Data Transfer Standards (SDTS), but which represents the road or other linear feature in between intersections with other roads/linear features).
- *A route,* which may be defined as a number of whole arcs or parts of arcs (e.g., I-10, State Route 145, or transit lines which use streets and which may not end at intersections).
- *A super-route,* which may be defined as a collection of routes (e.g., transit lines along a street or airline routes between a pair of cities).

Figure 2.1 Network Construction



- *A corridor,* which may be defined as a route or a super-route and its associated sub-routes or joining elements (e.g., transit lines which have sub-routes – #5, #5A / #5B, or corridor between cities that may represent several roads and railways)
- *A network,* which may be defined as a collection of arcs and nodes (i.e., TIGER street centerline file, transportation model network)
- *A super-network*, which may be defined as a collection of networks or network elements and routes or super-routes (e.g., a multimodal network where different elements represent different mode features, such as road, rail, freight and passenger, which can be represented as many networks or a single super-network: in this example, the mode networks are "virtual networks" that only exist temporarily for modelling or design purposes).

Although a relatively new concept, the *virtual network* is considered to be an important network representation in advanced transportation applications, such as ITS. Like virtual reality, the virtual network is an abstract representation which is used to model features that only exist for modelling purposes. As indicated above, the super-network may be the meta class of object that a fully developed GIS-T system needs.

The key word in the above simplistic definitions is "*may.*" It will be demonstrated below that no one construction or hierarchy elements provides for all network construction needs or opportunities that exist.

In Figure 2.1, as a working definition, it is proposed that:

- *Sections* are comprised of *segments*
- *Arcs* are comprised of *sections*
- *Sub-routes* are comprised of *arcs*
- *Routes* are comprised of *sub-routes*
- *Super-routes* are comprised of *Routes*
- *Networks* are comprised of *super-routes.*

However, segments may directly make up arcs, or routes may be placed directly on networks. The second research issue is then to define all of those elements which may be made up in some network hierarchy.

2.2.2 *Research to Sub-topic # 2: Define all those elements which may be useful for defining networks*

Figure 2.2 denotes various alternatives to construct networks, as shown in Figure 2.1.

Figure 2.2 Element Matrix

		Segment 1	Sections 2	Arcs 3	Sub-routes 4	Routes 5	Super-routes 6	Networks 7
Segment	**1**							
Section	**2**		y	y	y	y		
Arcs	**3**					y		
Sub-routes	**4**	x	x	x	x			
Routes	**5**							
Super-routes	**6**							
Networks	**7**							
		x(5) 1-4 routes can be made up of links, arcs, sections y(2) sections can be made up of links, arcs, routes						

The basic idea behind the element matrix in Figure 2.2 is to indicate which construction possibilities are feasible within the hierarchy. For example, can routes be made up of arcs, segments, or both?

In Figure 2.3, there is a brief outline of some possible hierarchies which may exist between the different network elements listed. For example, in Alternative A, it an be seen that: segments make up sections, sections make up arcs, etc.

In Alternative B, sections are not defined, and arcs are not defined by segments only.

Similarly, in Alternative C, the fourth element sub-routes may be made up of sections, sections may be made up by segments, or arcs, directly.

Figure 2.3 Alternative Hierarchies

A	1	□	2	□	3	□	4	□	5	□	6	□	7	□	8
B			1	□	3	□	4	□	5	□	6	□	7	□	8
C					3	□	4	□	5	□	6	□	7	□	8
					2										
					1										
D															

2.2.3 *Research Sub-topic # 3: Define all of the more detailed network characteristics required for their modelling. A particular focus area is routes*

A key example is the construction of routes. Routes, in a simplistic analysis, may be considered as being made up of a "collection of arcs." In reality, when we investigate the needs of transportation analysts using the route entity as a "data modelling vehicle" or entity, they may want to consider a more composite or complex generic version of a route, which meets the real operational needs of their work environment.

So, for example, a highway engineer responsible for managing highway data may, in modelling a route, wish to include :

- Ramps
- HOV Lanes
- Run-offs

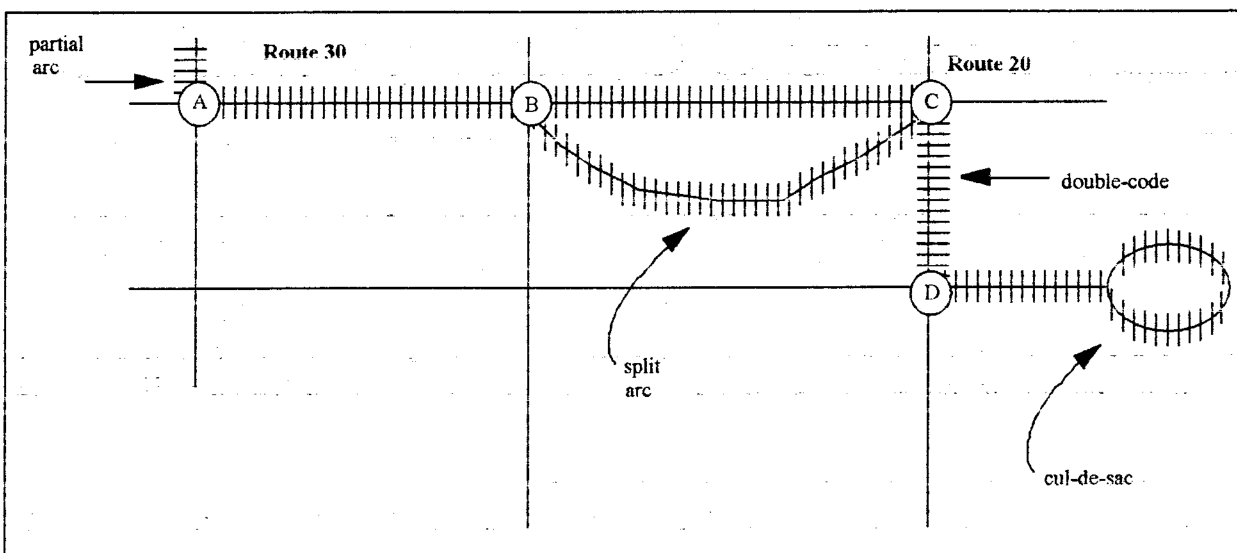
- Rest areas
- Highway spurs
- Associated route elements (e.g., I-95, I-295)
- Alternative routings.

Other elements may be associated. For example, transit lines ("routes") that use the HOV lanes or other reserved right-of-way. The modelling of linear features within networks is a growing area of activity in, for example, ITS applications and junction modelling.

2.2.4 Research Sub-topic # 4: Define ways it is possible to translate or conflate between different networks that attempt to represent in different ways common real-world realities

Figure 2.4 attempts to take this concept one step further. Here the question is effectively asked: "If we use the concept of objects as useful for maintaining data within a network environment, can we then create "constructors" to create these network objects?"

Figure 2.4 Route Network Pathologies



Assuming that attribute data is route-based, Link C-D in Figure 2.4 may, for example, maintain route attributes for Route 20, Route 30, or both.

The above is a short, sketched background of:

(1) Some of the different ways that analysts have represented networks

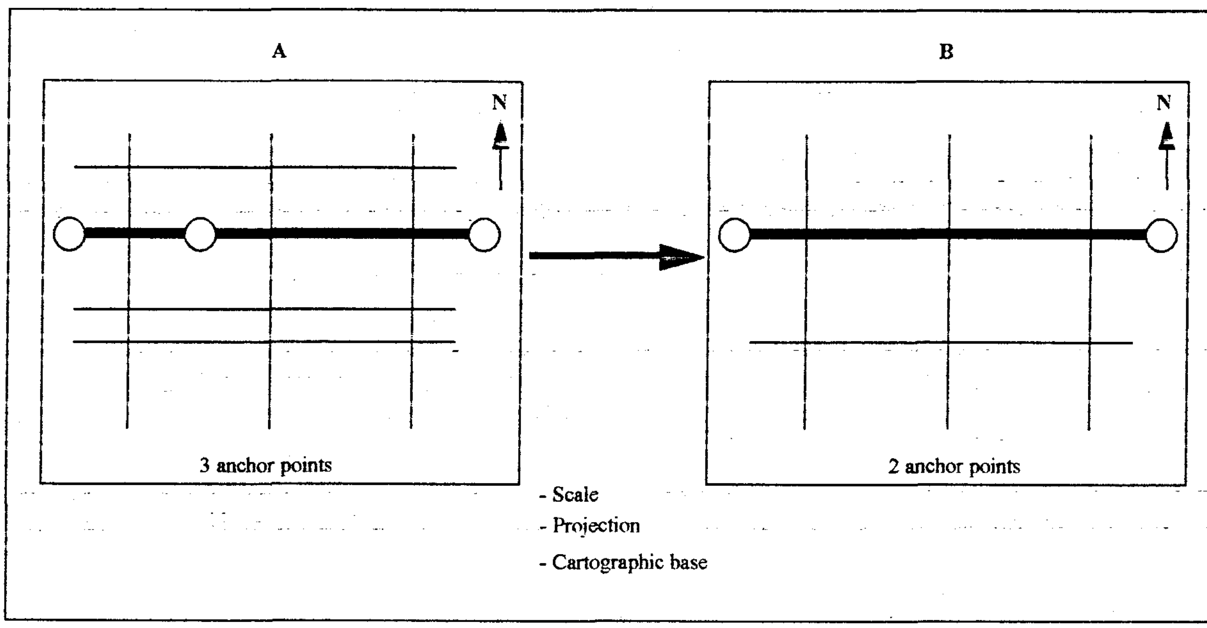
(2) The wide variety of ways that people may conceive of and carry out analysis on networks.

A key issue is *how to provide translation between different representation of what may essentially be the same physical real-world network.* This representation is sometimes (but not all commentators) referred to as "network generalization."

At a higher level of abstraction, the *meta element* level, we need to determine what are the common features that tie the various spatial elements together and establish the relationship between them. Traditionally, the topology and spatial primitive have been principally used to perform this role. In the object oriented realm of feature based representation, it is suggested that topology and element relationships can be redefined in a more flexible way. How is this accomplished?

In Figure 2.5, for example, there is a route which crosses three roads.

Figure 2.5 Network Linear Referencing System Translation



In A, there are three "anchor points," and in B, two "anchor points." The two representations of these networks may have a different scale, projection and basis. However, we may wish to be able to translate between "Representation A" and "Representation B."

A key research question then becomes, *"Can we find a way of defining an object in environment A that can be more readily translated into environment B, through the concept of objects?"*

2.2.5 Research Sub-topic # 5: What are the possible/desirable set of network constructors? How would they operate?

For example, in Figure 2.6, we may have to formulate a "route object constructor" or network object constructor, to build geometry. These constructors would need to build topology, which may require building *anchor points* or building *routes*. The use of these constructors may themselves facilitate translation between network representatives.

Figure 2.6 Object Oriented Constructors

Build Geometry:					
	Build	□	Route	□	Object
	Build	□	Network	□	Object
	Build	□	Corridor	□	Object
Build Topology:					
	Build	□	Anchor points		
	Build	□	Route (section, arcs)		
	Build	□	Metaroute		

Figure 2.7 further extends these language tools to such concepts as "construct network," "construct routes," "attribute to route" and "change route." These are by no means exhaustive and other language tools may be defined.

Figure 2.7 Network Linear Referencing Language

Construct	□	Network
Construct	□	Route
Attribute	□	Route
Change	□	Route

Figure 2.8 indicates some of the object constructors previously referred to.

Figure 2.8 Object Constructors

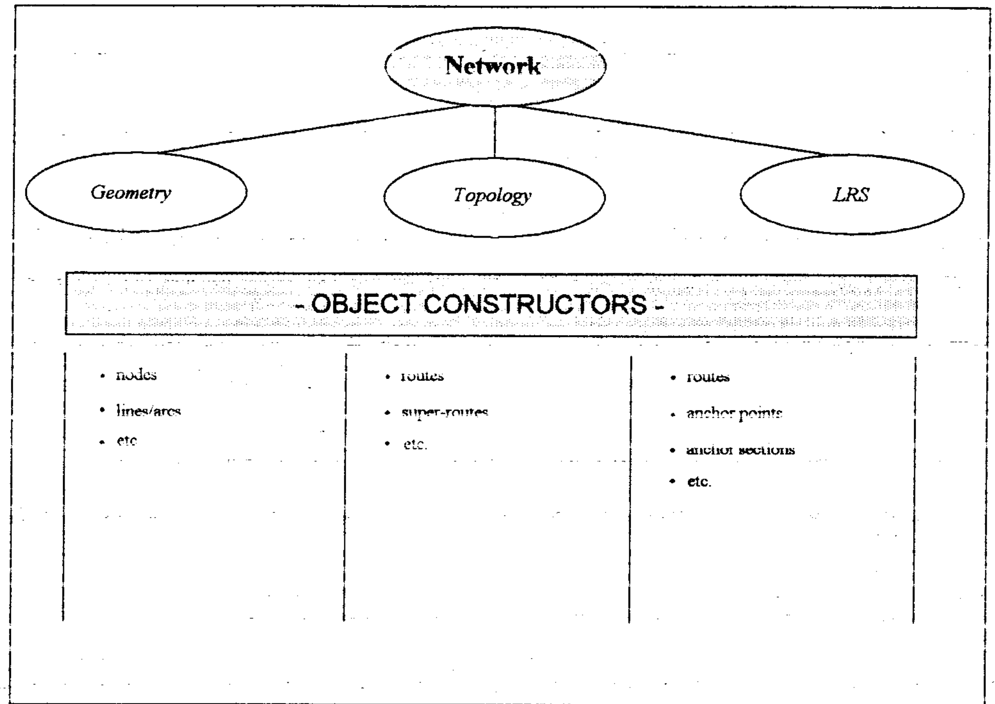


Figure 2.9 indicates the importance of specifying the appropriate or necessary characteristics of objects in various parts of the network. Different applications may have use of different types of object properties. Points, arcs, etc. may be the main attributes. It should be noted that, in OO programming, these attributes are typically internalized within the object definition as feature classes, thus allowing a more flexible interchange of network components. In the procedural programming approach, the network elements are independent properties that have attributes associated with them.

Lastly, Figure 2.10 begins to "draw together" many of the ideas which are implicit in many of the working themes above. The goal is to create objects within the network that have, for example, a further understanding of the:

- "Nestedness"
- Connectedness

within the network. We are really furthering the cause of "the intelligent transportation network."

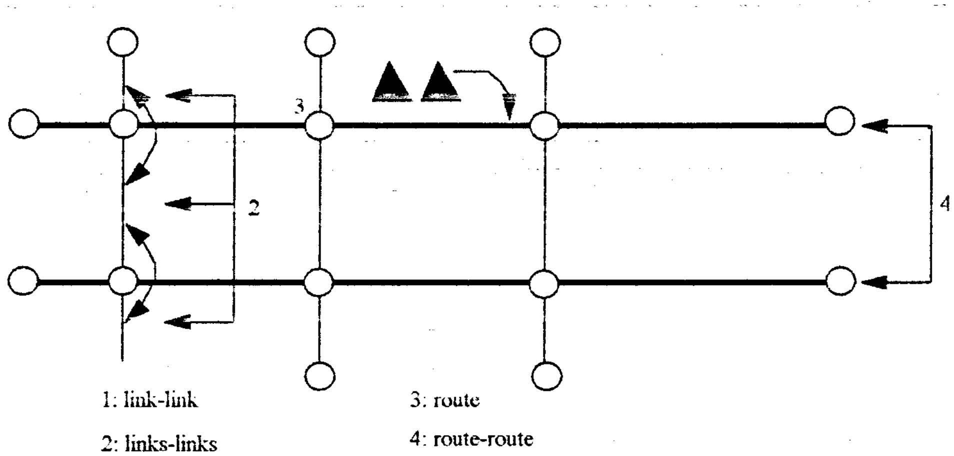
Figure 2.9 Object Properties

Routes:

- Anchor points
- Sections
- Arcs
- Name
- Attributes
- Geometric properties

Figure 2.10 The Intelligent Network

- Geometric intelligence
- Topological intelligence
- "Route" intelligence (a form of topological)



2.2.6 *Research Sub-topic # 6: What do we mean by the "Intelligent Transportation Network?" What properties does it have? What properties would be appropriate for different applications?*

Currently, we may tentatively define many network applications as having "simple intelligence." For example, they may "understand" the connectivity of objects, or that objects may have attributes. GIS topology, or "spatial intelligence," is presently arranged such that the network as a linear feature has intelligence about the other features that it connects to, for example, the left and right polygons, the connectivity of arcs and nodes, and the measurement of points along the line. However, the topology does not extend to non-planar features (3-dimensional structures) or to the directionality of the arc which is defined by the direction of digitization or by special coding.

Objects may have limited properties. However, in the proposed "fully intelligent" network, many objects in the hierarchy are given a wider set of geometric, topological, and attribute intelligence. For example, an arc might understand that it is a part of a route or routes and that it has certain properties that are part of the route. The constructors or destructors of it also behave in some intelligent fashion in their operation. Thus, when we take an arc out of a route, the system would inquire of the user, "does one realize that the topological integrity of the route has been affected?" It would also record and tell the user the topology status of the network being edited, before and after the change.

The concept of the intelligent network may be taken further. For example, one network, though different in certain parameters, may have attributes in common with another intelligent network. The transfer of attributes could occur through a "conflation" process. However, some of the intelligence to facilitate *conflation would exist through the network rather than within the conflation process (toolbox).*

Table 2.3 Levels of Network Intelligence

Level	Characteristics*
1. Simple Intelligence (basic GIS-T)	attributes, connectivity/topology
2. Extended Intelligence (existing GIS-T)	route systems, dynamic segmentation
3. Full Intelligence (future GIS-T)	route and network constructors, interactive queries for users to follow implications of network or route changes

* includes the characteristics of lower levels

At this time, the level of network intelligence is defined by the GIS data model and established by the topology between the spatial primitives. This has been extended by adding route-system characteristics to the basic model, but as indicated in Table 2.3, a more fundamental restructuring of the relationship between network topology and network elements is needed for a truly "intelligent network" to be developed.

2.3 Discussion

The research questions posed above further reinforce the findings of the Phase 1 Report. That is, at present we are only just beginning to derive a full understanding and agree and adopt frameworks of the network representation issues to then go on and build robust transportation data objects.

The "constructors" mentioned above are akin to the Map Algebra, Dynamic Graphics or other semantic tools that some vendors and researchers have begun to develop for specific applications or products. The Phase 1 Report described some of the efforts to date in developing these. It was also noted that as yet we do not have a consistent language for interpretation between different object types, as defined by different vendors, and this "standards" issue remains a significant barrier.

Arguably, however, a more problematic barrier is the semantic definition or basic understanding of what we mean by a "network feature"; it could mean two different things to different analysts, and be interpreted accordingly. Transportation professionals have developed their own lexicon to define and analyze networks and the understanding "transportation reality". There needs to be a flexible way of defining the abstract data types at the semantic and feature representation level.

Currently, these concepts are somewhat crudely sketched. They attempt to begin to more firmly suggest an appropriate set of research steps to work towards answering the following question: "How do we construct an intelligent transportation network?"

3. ADVANCED TRANSPORTATION MODEL NETWORK PATHOLOGIES

3.1 Introduction

The deployment of ITS, GPS and simulation models that simulate microscopic areas and even individual vehicle movements, presents a number of new challenges to GIS. These technologies are dynamic in that they can be used to update data in real-time. Further, the data to be updated is not fixed, like a road network, but may be a bus or auto that is being tracked. In the following sections we describe a sample of advanced network pathologies that appear to cause significant problems when these technologies are integrated with GIS. The examples given are primarily drawn from the transportation modelling field, although as ITS and GPS converge, the differentiation between an abstract network and a real street network is supposed to disappear. At least, this is the claim of those supporters of the Travel Model Improvement Program (TMIP) and the TRANSIMS (Transportation Analysis and Simulation System) project in particular: the latter aims to simulate individual vehicle movements to predict in a very detailed way the behavior of traffic in different situations.

3.2 Intelligent Transportation Systems

ITS technologies are being deployed in several regions of the USA. Examples include: ramp metering, traffic signal optimization, incident management and Advanced Traffic Management Systems (ATMS). These technologies are not necessarily new, or particularly innovative, but with modern communications and advanced computers, they are able to perform the functions more rapidly than earlier versions of the technology. They can also be integrated to work in tandem, giving more "bang for the buck". Most of these technologies utilize non-geographic Graphical User Interfaces (GUIs) to display the equipment locations or traffic flows. Even where a digital map is used more often than not this is simply for display purposes only rather than for spatial referencing or data attribution.

For illustrative purposes, the examples described below will focus on navigable databases, that is, databases that provide capabilities to handle large volumes of data (in near real-time). This is a critical area for ITS technologies and was the subject of a conference held at the University of California Santa Barbara in March, 1996, attended by Stephen Bespalko (Sandia National Laboratories) and John Sutton (GIS/Trans). The conference was hosted by the National Center for Geographic Information and Analysis (NCGIA).

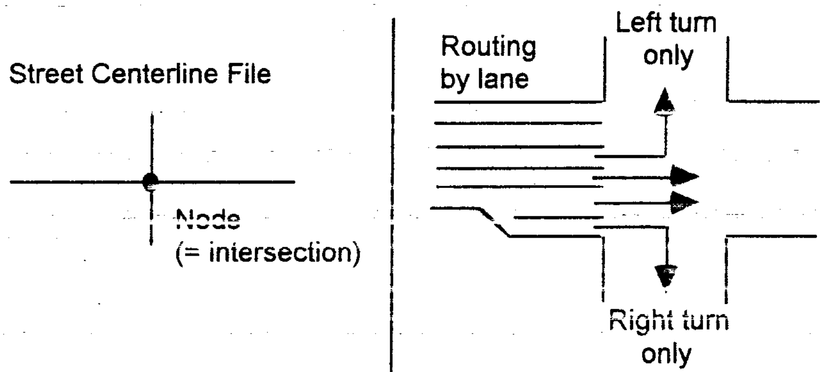
<u>Routing pathologies</u>

The following examples are commonly encountered (see Figure 3.1):

(1) *Intersection lane representation:* For navigation purposes, routing by lane is an important factor. How are lanes incorporated into street centerline files that are the main representation of networks, such as TIGER, Thomas Brothers, ETAK or other commercial vendor files?

Figure 3.1 Intelligent Transportation System Network Pathologies

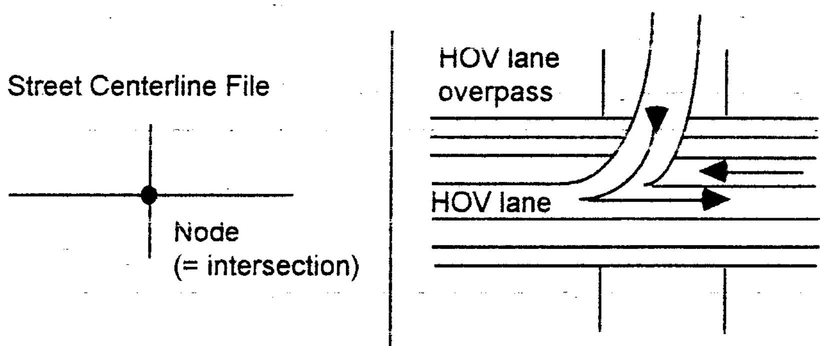
1. Intersection Lane Representation



GIS Network Representation | *Actual Network Configuration*

Lane depiction is problematic for GIS street centerline files, and routing impedances are difficult to model. GIS can have node impedance tables but these are simple look up tables that are non-dynamic. The turn prohibition may vary by time of day (e.g., downtown San Francisco).

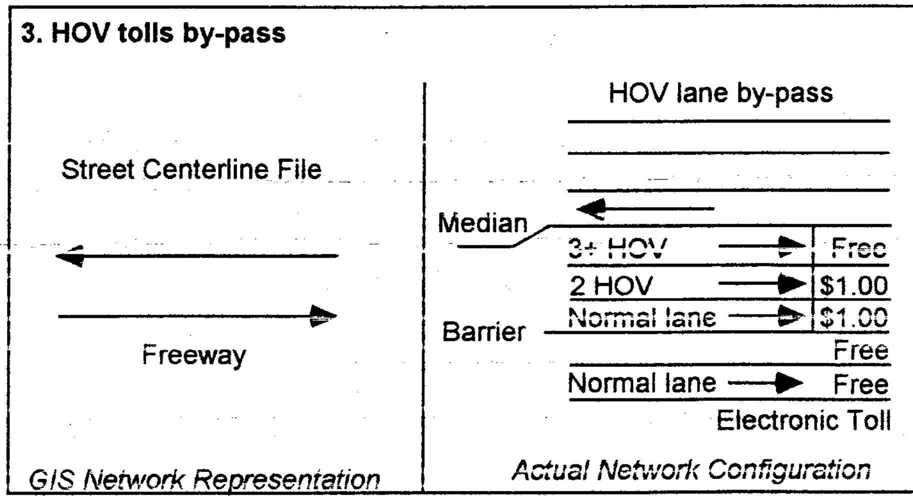
2. HOV Lane Grade Separated Junction



GIS Network Representation | *Actual Network Configuration*

HOV Lane depiction is difficult in GIS, as described in the Phase 1 report. For ITS routing, it is especially difficult as HOV lanes are now being designed to give special access between freeways with their own ramps. Thus, between two freeways there are two levels of connectivity as well as two levels of topology. Example: I-55 and I-5 interchange, Orange County, California.

Figure 3.1 Intelligent Transportation System Network Pathologies, cont.



As the lanes approach the toll facility, a special 3+ HOV lane is added to allow these autos to pass without paying. These congestion pricing experiments test the efficiency of routing traffic along special lanes which are less congested but for which a charge is made. Example: I-91 Riverside, CA.

(2) *HOV lane representation:* The basic HOV lanes representation issue was covered in the Phase 1 Report. As the control of traffic becomes more sophisticated, the variety of HOV lanes will likewise increase, including separate structures, separate lanes for different number of vehicles, etc.

(3) *HOV tolls by-pass:* An interesting experiment is occurring on the I-91 Freeway in Orange County, California, where part of the freeway is designated as a toll road. Users have an electronic device in their cars which charges them for using the toll-lanes (charges vary by time of day), but carpoolers with 3 or more occupants can use a special lane that avoids any payment.

Linear Referencing Pathologies

The majority of the LRS pathologies were covered in the Phase 1 Report. Below we focus on the proposed LRS protocol for ITS.

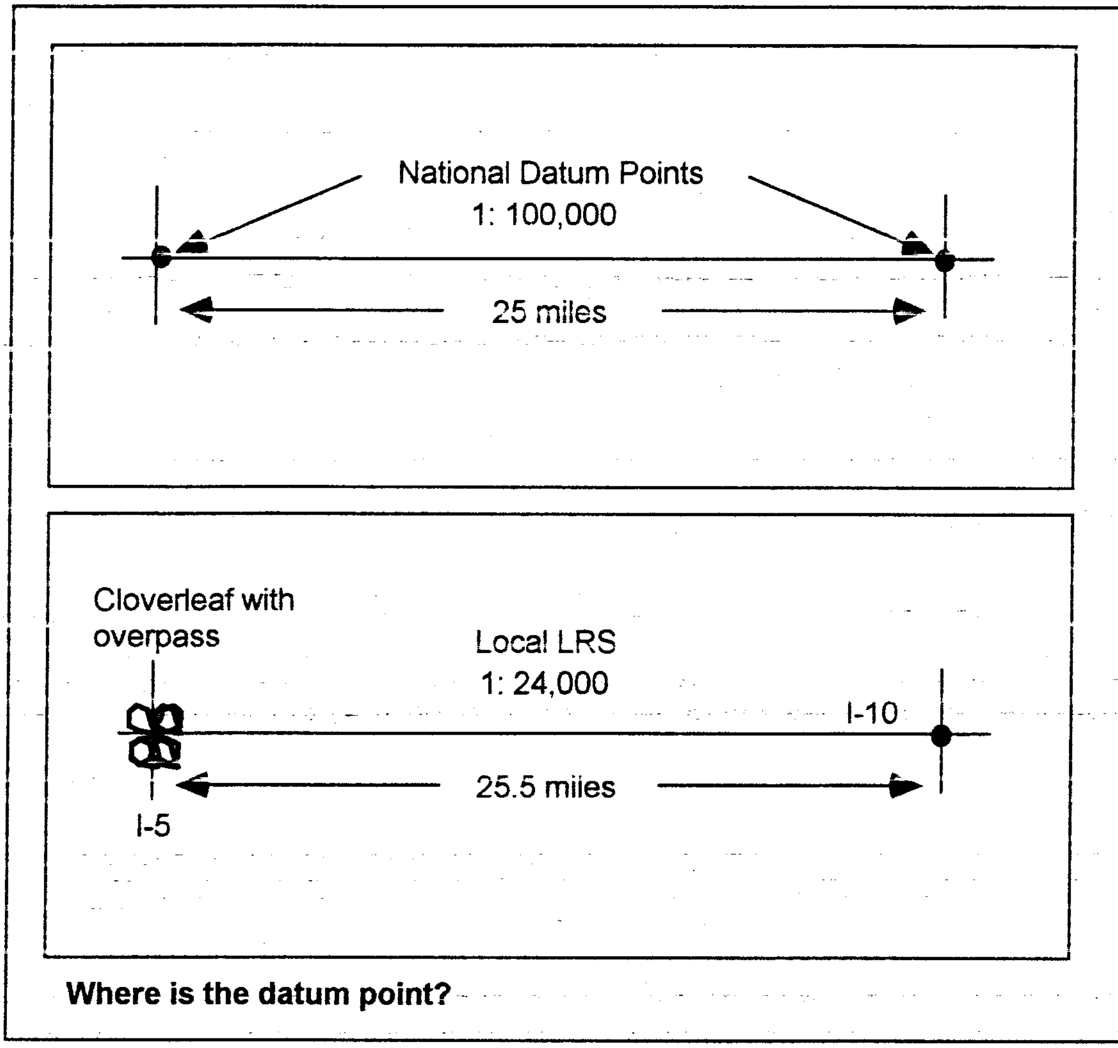
(4) *National Datum Points:* ITS research at Oak Ridge National Laboratories (ORNL) has proposed a system of national datum points, perhaps based upon intersections in the National Highway Planning Network (NHPN). For the State of Utah, for instance, there would be about 500 datum points, of which approximately 100 would be in the

Salt Lake City area. If this national LRS was adopted, how would it impact local LRS development?

In Figure 3.2, the national datum point occurs at a point representing the intersection of two highways. The larger scale map representing this junction shows the ramps. The following question then arises. Where does one place the datum point at the larger scale? For instance, if a vehicle is traveling South to North on I-5, and wishes to travel East on I-10, it would take the connecting ramp, thus avoiding the datum point. If the datum point is located at the intersection of the two freeway medians, and the smaller scale point encompasses all the possible points at the intersection at the larger scale, then the distance traveled will be different. This may not be a crucial issue for planning purposes, but for ITS routing it could be problematic, to say the least, and could lead to some confusion. For engineering type of applications it would also be sub-optimal.

A national system of LRS datum points may be useful for national and statewide planning purposes, including the Highway Performance Monitoring System (HPMS), but between the datum points, the problems identified in the Phase 1 Report still arise. In essence, the proposed datum points act as national calibration/reference points to which LRS developers can anchor their own local routes. This would be a good first step, and move the USA toward standardization on one or two LRSs, as occurs in Europe.

Figure 3.2 National and Local Datum Points

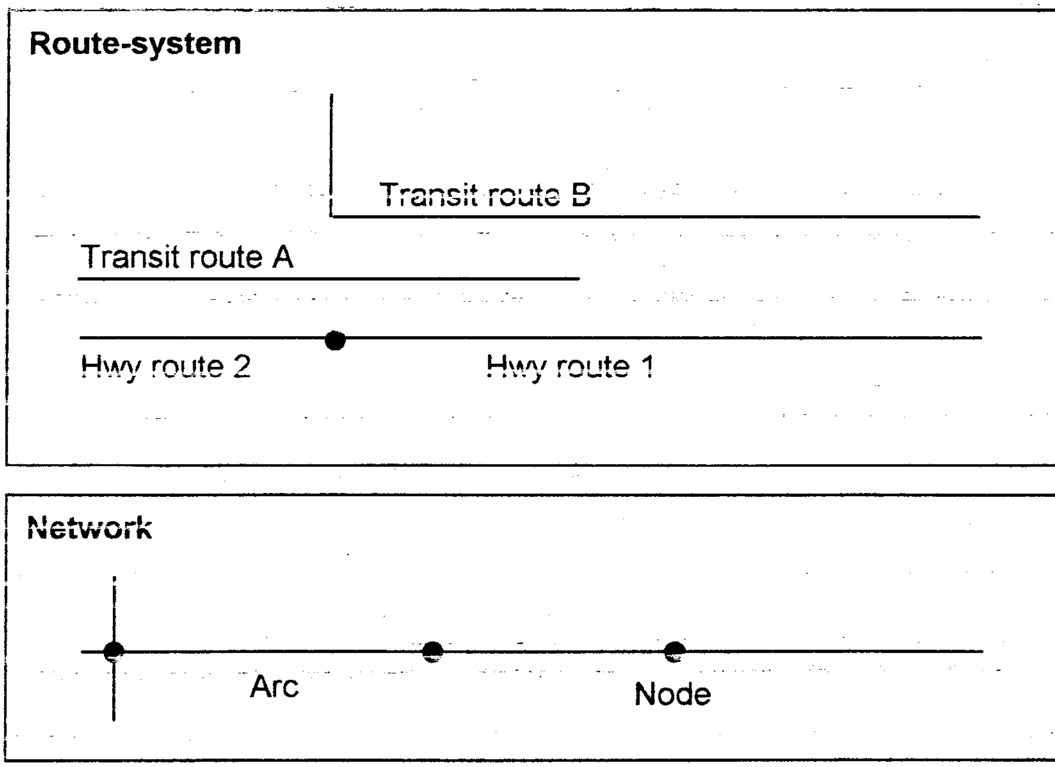


GIS Route-system pathologies

Only a few GIS products have true Dynamic Segmentation capabilities, which is perhaps the biggest pathology of all in GIS-T at this time.

(5) *Dynamic Attribution:* The Dynamic Segmentation data model allows attributes to be located *in situ* rather than referenced uniquely to the underlying arc. For example an event can occur mid-arc (see Figure 3.3). What about a situation where events not only cross arcs but also cross routes? The current Dynamic Segmentation model does not support this capability. Further, in ITS applications, for example transit, buses will be tracked as events and may well cross multiple highway-transit routes? How will this dynamic attribution be managed in GIS-ITS applications?

Figure 3.3 Dynamic Attribution/Symbolization



- Is the transit line a route or an event? If a route, how is a bus tracked across different highway routes? If an event, how are the events coded to traverse across highway routes?

3.3 Global Positioning by Satellite

Network representation issues that arise with using GPS are discussed below with reference to a rail network application.

Network Pathologies

The network files describe the position and resolution of the data according to the scale or precision at which the data is collected. For example, at 1:24,000 scale, the precision of the data is ± 12 meters, the minimum resolution (size of feature) that can be displayed on the map. Thus, a railroad feature such as a crossing or rail that is less than 12 meters across are displayed as single lines or points (nodes). At smaller scales, such as 1:100,000, even quite large structures such as bridges become points on the network. This is illustrated in Figure 3.4.

(6) *Feature Representation*: At the larger scale of 1:2,400, the network can be described in great detail, showing the tracks, bridge abutments, and railroad crossing. As the scale reduces the representation of the network features becomes more problematic, until eventually they cannot be represented at all. Note also, the loss of spatial precision, or shape, in the alignment of the network.

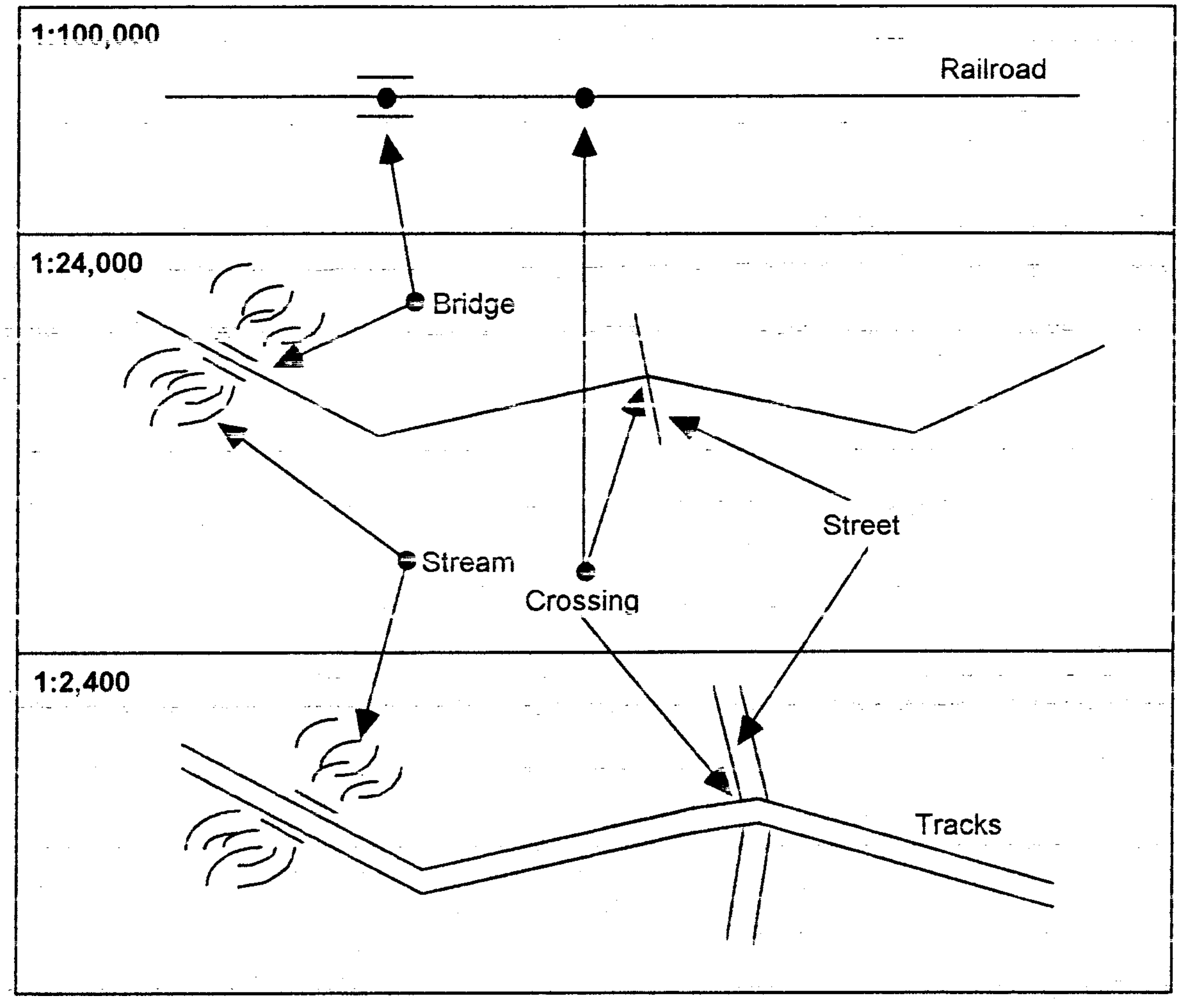
The critical issue then arises as how to move features from the large scale to the small scale. This problem is referred to as *map generalization*, and is one of the hot topics in digital mapping and GIS. Some GIS vendors, including ESRI and Intergraph, have developed algorithms and spatial processing techniques that "capture" the essence of the feature during the reduction process. One example is the rubber-sheeting tools that allow maps to be "stretched" or edge-matched to move different representations (e.g., polygons) together. At what point does a polygon or a line become a point?

With linear data (e.g., networks) such primitive tools are only partially useful. For example, rubber sheeting the 1:24,000 and 1:100,000 networks in Figure 3.4 would "pull" part of the networks together but "push" other parts further apart. What is needed is a more comprehensive set of tools that work on individual network features – segments and nodes – to match them correctly along the whole network. This process of network data integration is called *network conflation*.

Network Data Referencing Options

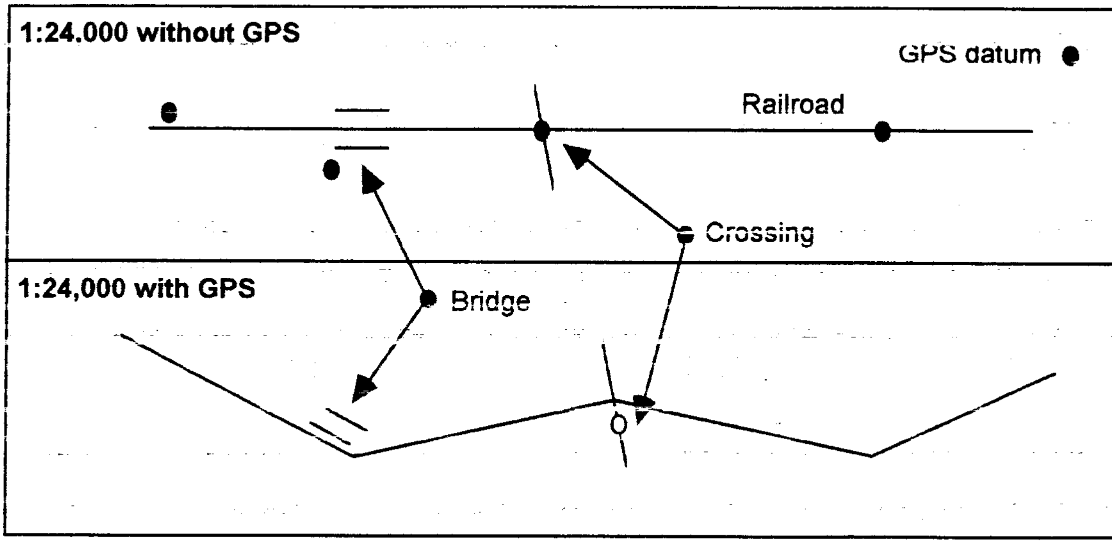
Improving the positional accuracy (e.g., precision) of the network features is being made easier with the availability of GPS equipment. The coordinates captured by these devices can be downloaded to GIS software. The reasons for utilizing GPS are many, and not simply related to a desire to improve the base map. For example, in railroads the utilization of Automatic Vehicle Location (AVL) technology with GPS needs greater precision to pinpoint the train, especially in an accident situation. Using a 1:100,000 scale network file could show a derailment 100 feet or more from the track – this could be critical if the train was carrying hazardous material. Improving the precision of the network data raises a number of issues that need to be addressed in any network development program. These are summarized below.

Figure 3.4 Levels of Network Representation



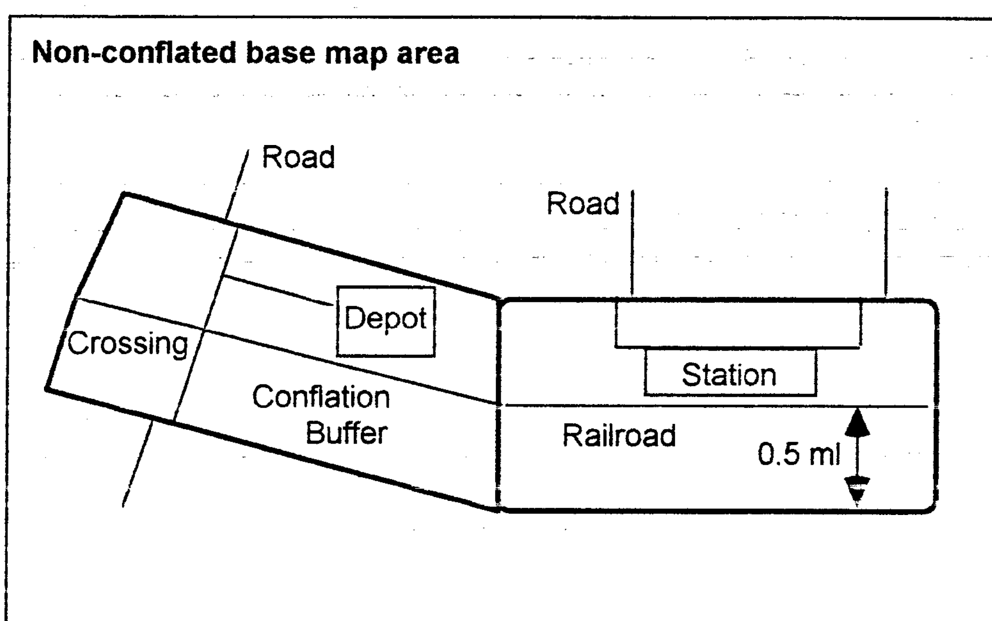
(6) *GPS Datum points.* The traditional method of applying GPS is to collect a number of datum points (see Figure 3.5). While these improve the precision of the datum locations, a large number of datum points need collecting to produce a highly accurate network. This is possible by continuous geocoding of the network but other problems arise when performing this. For example, is the alignment of the data collection vehicle consistent? Forces such as braking and acceleration affect the quality of the data. On a railroad such issues may be less of a problem but still need to be taken into account.

Figure 3.5 Network Shape before and after GPS



(7) *Realign the Railroad.* If one part of the base map is improved, how does it relate to the rest of the map? In Figure 3.5, the relocation of the railroad to more precise datum points means that the other features are offset and the map appears out of shape. There is an issue, therefore, of whether it is beneficial to enhance only part of the transportation data layer. This network integrity issue is therefore a key factor in determining the extent to which maps are improved by GPS.

Figure 3.6 Network Conflation Buffer Zone



(8) *Realign the transportation data layer inside buffer*. It is unlikely that the railroad will improve the base map and all its associated features surrounding the right-of-way. However, the corridor of the railway, which includes the right-of-way and associated land owned by the railroad is a feasible buffer area in which to rectify the transportation network data layer using conflation techniques. An example is illustrated in Figure 3.6.

Linear Referencing Pathologies

Depending upon the type of application, it may be necessary to keep several different levels of network representation. For example, inventory of land ownership and facilities may need to be precisely located by latitude and longitude, whereas for long-distance routing of trains the network description can be much simpler and smaller scale. However, the two representations will still need to be cross-referenced in many cases, such as a hazmat incident.

(9) *Multiple LRS methods*: Two or more networks can be corresponded using linear referencing methods. Assuming that the railroad adopts a standard Linear Referencing System, the location of any point (or linear event) on the network can be determined and then displayed on any network of choice. This solves the location issue on the railroads, although it will not resolve other issues of comparable network data representation, such as local roads (unless they also use the same base map).

The Federal Highway Administration (FHWA) in collaboration with other agencies, such as ORNL, are presently considering a national system of datum points based upon the NHPN and the NTA rail network. The NHPN, for instance, contains approximately 48,000 datum points. The idea is that these would serve as local datum points for local, regional and national linear referencing systems, such that some degree of correspondence can be maintained in terms of spatial precision.

3.4 Simulation Models

Simulation models differ from traditional transportation demand models in two important respects:

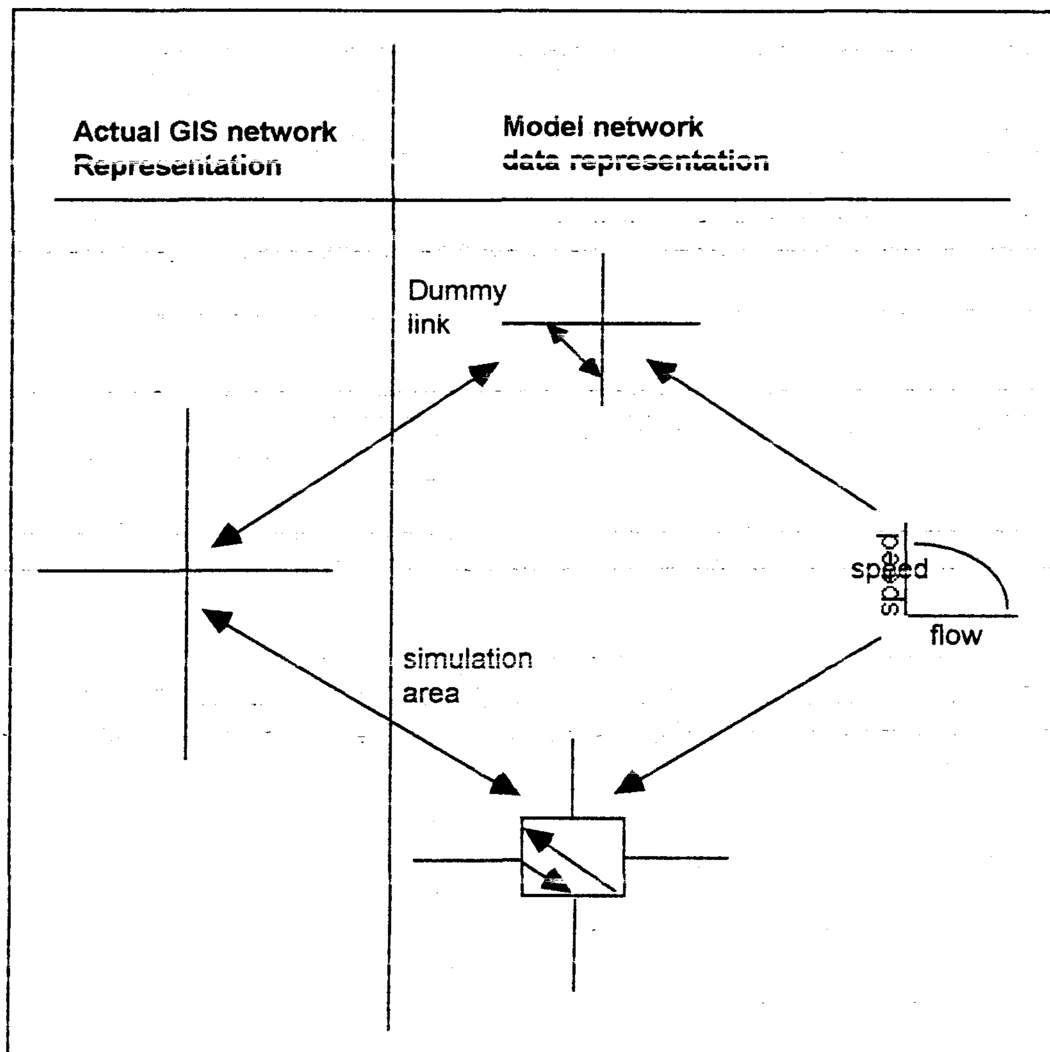
- They aim to simulate traffic movements at the micro scale, for example simulating turning movements at junctions
- They disaggregate the model time period into micro units of seconds or minutes, thus allowing the micro effects to be studied in great detail.

Travel demand models typically model a single time period, such as the peak hour, so the results reflect the average conditions pertaining throughout this period. In practice, significant variations in traffic flow can occur between say the 'peak' 15 minutes within the peak hour and the 15 minute periods at the 'shoulder' of the peak hour. Modern congestion assignment algorithms can manage these types of variations and model individual flows and turning movements in short pulses, such as 5 seconds or 5 minutes.

In order to model these effectively, simulation models may need to introduce dummy links or other features ("junction holding areas") to accommodate the level of detail being modelled.

(10) *Dummy links in the model network*: Two examples are presented in Figure 3.7. In the first example, a fictitious link is coded to represent the turning movement. The flow along the link is determined by the speed-flow curve of the opposing traffic flow. In the second example, the flow is measured inside the turning movement 'box', as a simple look-up table. These movements become more complex in a rotary.

Figure 3.7 Simulated model links



With the advent of ITS and GPS, simulation modellers will most likely develop even more sophisticated procedures for dealing with complex situation, in real-time. Another trend worth mentioning is that these models are becoming more specialized, for example, lane weaving models, junction turning models, transit headway scheduling models. In transit operations, some properties already adopt service deviation strategies, such as turning a bus around before the end of a route, and operating "virtual routes" of transit service.

More flexible transit services, such as paratransit – dial-a-ride, shared taxi, van pools, etc. – are becoming more popular. While these do not pose any network problems per se, their flexible routing and scheduling presents a number of challenges to monitoring and planning their representation in a GIS context.

3.5 Summary

This section has focused on the pathologies associated with advanced network pathologies, especially the representation of ITS, GPS and simulation model networks.

These present a number of new challenges to GIS, not simply from a network definition perspective, but in terms of the interface between the network and the object data to be attributed. Capabilities for performing dynamic attribution and map generalization are somewhat limited in existing GIS products. The development of object oriented GIS technology and databases may help in this respect, but more fundamentally the data model issues of how to manage real-time data and abstract network representations remain problematic. As noted in Phase 1, linear referencing methods appear to have little to contribute to overcoming many of these pathologies.

4. CONCLUSION

4.1 Advanced Pathologies: Network Modelling and ITS

This report has reviewed some of the advanced network pathologies that arise with ITS, GPS and simulation models. ITS and modelling applications are more detailed than traditional link-node structures of traditional transportation models and street centerline files. For example, they need to take account of highway lanes, signalized intersections, simulated dummy links in models, more sophisticated routing algorithms and a number of other features that are not represented in GIS data models. ITS technologies are already experimenting with Artificial Intelligence programs such as dynamic graphics that can represent changes in the network status in real-time. The advanced network pathologies associated with the ITS applications and simulation models, and how these are presently represented in GIS, are briefly described above.

These examples demonstrate the need for a more flexible network data model. GIS technology is making advances in addressing some of the issues, but fundamentally, the network constructor tools required to build flexible network data objects is some way off from becoming a reality. Arguably, the GIS technology paradigm needs shifting into a more flexible model that takes full advantage of object-oriented programming techniques and object-oriented database management systems. These technologies provide more flexible tools to build the network. Even so, an object-oriented network data model will still need to be designed. This is a key area for research alongside the specific research issues identified in Section 2.

The advanced pathologies introduce some new dynamic problems to network representation. Technologies such as GPS have tremendous potential to solve location problems, *in situ*, but issues arise with configuring the more precise positional data with other map representations at different scales. It is possible, using linear referencing methods, to correlate features between maps at different scales. However, where vehicle tracking or other real-time applications are being used, updating the location on the less precise map introduces a number of performance issues. If many vehicles are being tracked, perhaps on multimodal networks, not only the performance but the actual representation of objects becomes a major issue. The technology, such as dynamic graphics and 3-D graphics, is only just beginning to address some of these issues. The question remains, however, of how to apply the technologies in convergent ways that most efficiently meet user needs?

The type of pathologies described in this report, and the previous one, are not even recognized as problematic by many developers of ITS, GPS and simulation models. They would possibly even regard the network pathologies as a GIS problem. This has been the premise of this project. We have explored the range of pathologies and described current limitations as well as reviewing some possible solutions. But are these problems all GIS defined? Should not the modellers be utilizing real street networks if the technology is available? And are we trying to re-engineer GIS to accommodate an existing method of network representation when the simpler solution would be for the modellers to adopt GIS as the network description? A similar argument could be made for ITS applications. The answer probably lies somewhere in between these extremes. There are network model situations that need abstract representation, just as there are ITS network depictions that need precise location (e.g., GPS). As well as thinking about the technology, we need to understand the applications, the user environment and the organizational setting in which this technology is deployed. This is beyond the scope of this project, but an equally important issue for understanding how to best develop GIS-T technology.