Sandia National Laboratories
Transportation Systems Analysis
GIS Project

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Network Pathologies

Phase 1 Report

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1. INTRODUCTION

1.1 Background to the Project

This report is the result of a two-month investigation by GIS/Trans, Ltd. for Sandia National Laboratories GIS project in the Transportation Systems Analysis Organization.

GIS/Trans was requested to provide Sandia with examples of "network pathologies," based upon the company's extensive experience in working with network files in GIS. Network pathologies are defined as situations where the network feature is difficult to represent in the GIS due to topology and/or connectivity constraints. Network feature representation uses three approaches:

1. *Link-node topology:* The links and nodes provide the geographic unit or feature to which all network data is referenced. Examples include streets and transportation model links which are an abstraction of the real street network;
2. *Route-systems:* The route is a "virtual network" comprised of a series of links and nodes that may or may not begin and end at a node. This link or a partial link is called a section. The route is the network representation to which data elements are referenced. A route system can contain one or many routes. Examples include transit routes with bus stop elements and highway routes with pavement sections; and
3. *Linear referencing systems:* LRS are methods to locate network features on the earth's surface or the base map of reference. They have been proposed as a system to manage network data representation. A common method is the milepoint referencing method employed by most state DOTs where network features are referenced to/from the milepoints along a route, e.g., "Bridge 411 is 0.25 miles from milepost 155 on Rte 55".

In GIS the three methods are interconnected although all three are not necessary for network data representation: it depends upon the level of data representation required. Simple link-node models, for example, have a unique value for each link and node. All data is link defined – from_node, to_node – with a lot of data duplication. More complex data schema utilize routes which represent in a table format the order of interconnected sections related to the underlying arcs. Their existence and modification are associated with the link-nodes dynamically. This allows the network attribute data to be represented in great detail and "independent" of the link-node topology. Thus, a change in the street attribute such as pavement material does not have to be coded as a node or point but can be associated dynamically as an event on the arc rather than as a topological division.

The location of the route defined attributes on the underlying network is measured by the LRS method employed. Some GIS use base-offset methods (distance from a base point) while others use local control points. Dynamic network attribution (dynamic segmentation) in GIS needs both a LRS and a route-system to work effectively. LRS are not dependent on routes but become somewhat meaningless in GIS if linear events are not precisely located, either by a route-system/LRS methodology or by actual coordinates (x,y,z or lat.,long.). LRS are a popular method because it is a relatively simple way of referencing data to mileposts or other reference points. Emerging technologies such as GPS provide an alternative means of referencing network data either independently or in combination with LRS.

In most cases all three approaches are employed to represent complex situations. This improves the power and performance of GIS but the use of the different methods can confuse the representation of network features and associated attribute data. The compilation by FHWA of HPMS data in GIS, for instance, has been constrained by the different LRS schema and how to calibrate these at state boundaries. Methods to cross-reference the LRS through cross-classification techniques and the addition of fields which carry a correspondence attribute have been only partially successful. Even where LRS have been developed in GIS, subsequent highway realignments have been difficult to manage (Caltrans is a good example of a complex LRS that has a lot of data redundancy due to the absence of route-system definition). In Maine, the LRS used for highway inventory uses control points such as bridges which the GIS represents as nodes which is not topologically correct.

The three models are summarized in the table below.

Table 1.1 Network Representation Models

Network Representation	Spatial Feature	Spatial Attribute	Spatial Analysis
Link-node topology	Arc, node, point, polygon	Street, intersection, landmark, boundary	Polygon Overlay (buffer) Buffer by straight line distance (radii)
Route-system "virtual network"	Collection of arcs and nodes, linear and point elements, polygon	Transit route, volume data, bus stops, highway sections, route-polygon intersect	Buffer by network distance or straight line distance
Linear Referencing System	Arc, node, point	Base point, control point, anchor point, milepost	Route measurement

The problem confronting many GIS-T professionals is that the above methods of spatial representation do not provide a uniform suite of techniques that can be easily applied in all situations, and indeed there are some complex situations that appear to be beyond the scope of these representational methods as currently programmed.

These problems are recognized within the GIS community, and research and development programs have been instigated in an attempt to provide solutions. Two programs in particular are worth mentioning. The NCHRP 20-27 Project

"Adaptation of Geographic Information Systems for Transportation"[1] investigated the representational issue and spawned the first Location Data Modeling Workshop, held in Milwaukee on August 5-6, 1994[2]. The focus of the workshop was on linear referencing issues. A second workshop to consider Linear Referencing and Spatial Data Transfer Standards is being organized to coincide with the 75th Annual Transportation Research Board meeting in Washington, D.C., on January 6-7, 1996. This workshop is being sponsored by the Bureau of Transportation Statistics, U.S. Dept. of Transportation. The other relevant research project is the GIS/T–ISTEA Pooled Fund Study sponsored by the Alliance for Transportation Research and coordinated by the New Mexico State Highway and Transportation Department. This project, which involves Sandia staff, is developing object-oriented data models for GIS-T. The project aims to produce data models that vendors can utilize to develop new products that provide more robust tools and methods to represent network data.

1.2 Project Aims and Scope

The objective of this project is to describe examples of network pathologies that are commonly encountered in GIS-T applications. It is not part of the project scope to provide solutions of a specific or generic nature. The Sandia team wishes to take a fresh look at the network representation issue and it was felt that solutions that have been applied as "work arounds" elsewhere might cloud the investigation. GIS/Trans staff have held some preliminary discussions with Sandia staff which included solution approaches to resolving these problems. These briefings will continue as the project progresses: they are meant to be inform Sandia staff rather than prescribe specific approaches.

1.3 Project Specification

This project includes two tasks:

Task 1 *Brief description of transportation network topology archetypes.*

The descriptions will include: (i) location along the road network; (ii) one or two schematic drawings or maps, including 3-D sketches as appropriate; (iii) brief explanation of the nature of the topology/connectivity pathology. The focus will be on the network structures that form the basic connectivity – topology. Examples include overpasses, complex intersections, transit alignments.

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[1] Adaptation of Geographic Information Systems for Transportation. Final Report. Alan Vonderohe, Larry Travis, Robert Smith, Victor Tsai, University of Wisconsin, Madison. NCHRP 20-27. January, 1993.

[2] Location Data Modeling Workshop. Alan Vonderohe (Ed.), University of Wisconsin, Madison. NCHRP 20-27(2). August, 1994

Task 2 *Brief description of network integration pathologies associated with transportation model networks.*

The integration of base maps and model networks (conflation) presents some unusual problems. Examples 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, and model networks that do not have any corresponding network geography (e.g., zone centroid connectors, transit routes that traverse non-linear features). Brief descriptions and diagrams of typical situations are provided.

1.4 Structure of the Report

Following this **Introduction**, the network pathology archetypes are described in **Section 2**. **Section 3** describes network integration pathologies most commonly encountered. **Section 4** summarizes additional pathologies and directions for further research that are not covered in this report.

1.5 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. TASK 1. TRANSPORTATION NETWORK TOPOLOGY ARCHETYPES

2.1 Overview

The examples cited in this section are typical of network files created in GIS, such as Census Bureau TIGER files and commercial digital street centerline files such as Thomas Brothers, ETAK and GDT. Not all of the pathologies are present in each product and there are variations on each theme between street centerline files, but the examples used are fairly typical of the genre. It is also worth noting that the pathologies cited are not critical in all situations.

One particularly critical piece of information is consistently missing: the directionality of the streets. There is often a lack of consistency in network definition: for example, some minor streets are labeled one-way; two two-way links are used to represent divided highways; access ramps are labeled as being two-way. An additional difficulty in routing is working with links that are labeled as one-way switchable (e.g., contraflow transit lanes, peak hour HOV lanes). In Denver, for instance, the new *Ride* Light Rail Line has part of the line downtown traveling on the street in the opposite direction to the road traffic (cars and buses). In Honolulu, the central lane is switched to accommodate the morning (in-bound) and afternoon (out-bound) peak traffic, which includes restricting turn movements to side streets at different times of the day. Such links are rare but are likely to grow as intelligent transportation systems evolve.

2.2 Network Topology Archetypes

2.2.1 Topological Accuracy: Basic Premises

GIS networks normally have topology built by the GIS which establishes the relationships between the spatial features, but does not recognize differences between lines that represent different link types. For example, a highway passing over another road on a bridge would be connected to that road, even though it would not be a legal routing connection. These topology problems are important for transportation modeling and routing purposes. There are different approaches to dealing with these problems.

A basic difference in the approaches is to distinguish between (i) those solutions that alter the topology to represent more accurately the connectivity between spatial features; and (ii) those solutions that use special attributes to code the network connectivity arrangements. Commercial GIS products, for instance, usually mark this situation with some special attribute, which we will call a *structure* attribute, with both simple overpass links and multiple grade bridges marked as such.

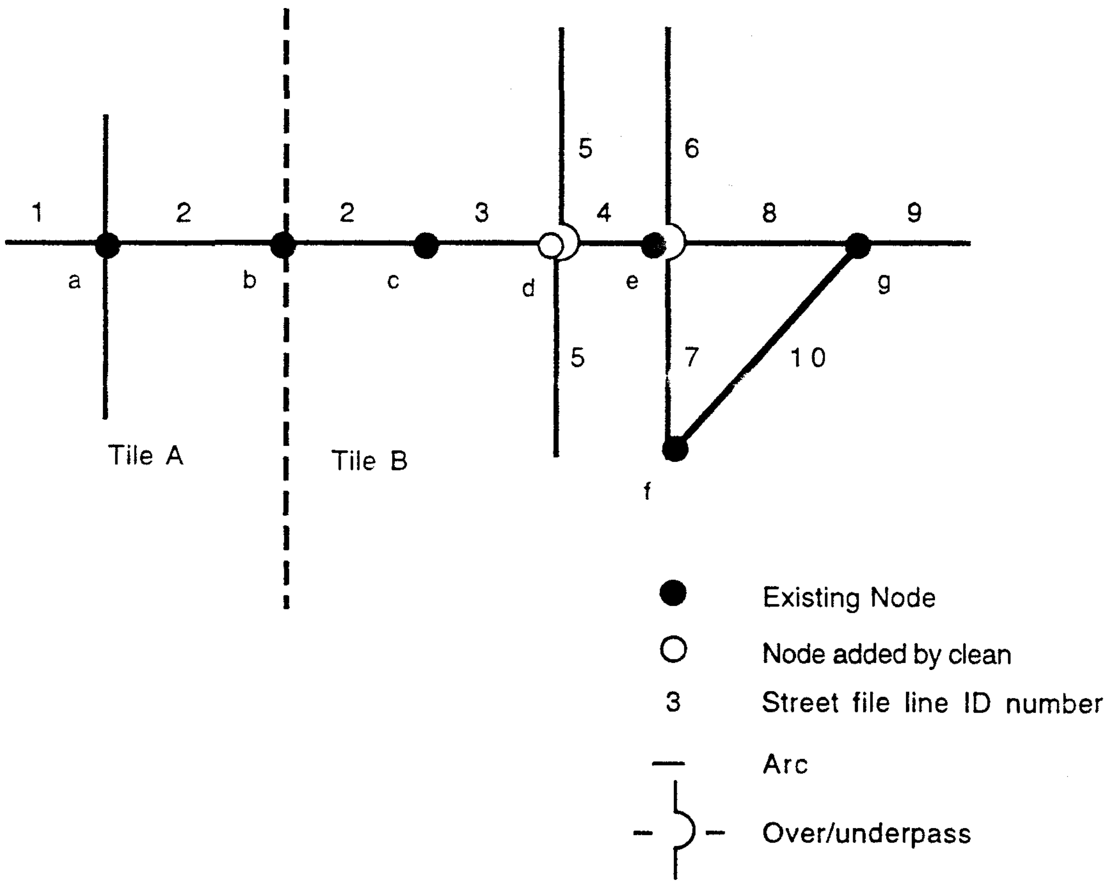
Examples of both methods are illustrated in the following sections.

2.2.2 *Validate the Network Topology*

One topology change method is to generate new nodes at such intersections, and have the overpass links connect through the new nodes (see Figure 2.1). This would circumvent the need for a large turn table, but it would take more effort to maintain. (Moreover, if you had turn impedances, you would want the turn table anyway.) One example of the increased maintenance effort is seen in the fact that network coverage could not be "cleaned" as a method of fixing nodes that were accidentally added near existing nodes, because to do so would also join the intentionally manufactured nodes. There would be additional efforts as well in upgrading the network topology when new versions of the street file are delivered.

The following diagram indicates the various cases of network topology validation issues that commonly occur in GIS.

Figure 2.1 Typical Network Topology Validation Problems



<u>Cases *a* and *c*</u>

In both of these cases, the node is correctly positioned either at an intersection of two arcs (*a*), or simply between two arcs (*c*). No processing has to be performed.

However, it should be noted that the creation of the network may cause lots of pseudo-nodes. These pseudo-nodes may have to be dissolved away, and the link ID processed as a linear event. However, this is a performance issue rather than a topology problem *per se.*

Cases *b* and *d*

Due to a number of reasons (join between tiles, cleaning etc.), extra nodes may be added to the network that split two arcs having the same link ID on either side of that node. These arcs should be joined so that the link ID is unique within the network. It is assumed that the network will be processed with either the GIS *clean* command or the *build* command with the *line* option before validation takes place. Although this may add extra nodes into the network where arcs cross, the benefits outweigh the disadvantages as methods would still be needed to remove "extra" nodes already existing in the network.

Case *e*

If a situation exists where four arcs with different link IDs intersect, but they are at the same geographic level, a node should exist and no processing is required. However, if the four arcs intersect and they are at different levels (an over/underpass), an extra node could be added to the network that is slightly offset from the existing node. The arcs should then be reassigned so that the overpass arcs are attached to one node and the underpass arcs to the other node. However, this alteration in the network topology incurs additional overhead in data maintenance, especially with upgrades.

By performing this processing, all ambiguous nodes are removed from the network simplifying future use of the network.

Note: Although most of the ambiguities can be resolved automatically, some may require manual inspection. It has even been suggested that some intersections may require site visits before the true connectivity can be resolved.

Cases *f* and *g*

Currently within many commercial street files, arcs are given a level indicator that can be used to decide which turning maneuvers at a node are possible even if they are restricted. However, problems occur when processing arcs which move between levels, such as freeway ramps. If each of the proposed network validation steps were completed, each node could be assigned a level indicator to help in the process of designating valid turning maneuvers.

A methodology must be devised for deciding the level for a particular node. In most cases, as all arcs entering a node would be at the same level, the level is easily identified. In cases where the incoming arcs have different levels, a "majority" rule could be applied setting the node level to the level that most of the arcs have. Once completed, these level indicators could be used to help partially automate the tagging of ramps. This type of procedure needs further investigation.

2.2.3 *Code the Network Topology Connectivity*

An alternative method is to accept the network topology but provide information on the network connectivity. To make the network routable within GIS, turn tables have to be created that effectively prohibit improper turns at intersections onto links with a different *structure* value. This process can be accomplished using special programs. Nevertheless, there are some subtle points that must be considered in this process, as described in the examples below.

There are several tricky situations to deal with when trying to incorporate the overpass or multiple-overpass links into a non-planar topologically correct routing network (i.e. when generating the turn restriction table)[3]. These situations can be categorized by the number of links with different *Structure* values that meet at a particular node. In most commercial GIS, links of different structure values are not "connected." The basic situations are relatively easy to handle. Figure 2.2 illustrates the examples described below.

<u>Most common cases</u>

1. *Two links with different* ***Structure*** *values:* This is the beginning (or end) of a bridge or overpass. No turn restrictions are required. The node is redundant for network routing purposes;
2. *Two links with the same* ***Structure*** *value:* A simple road continuation. No turn restrictions are required. The node may be added when a road is extended or where some other feature of the road changes, such as the functional class. In this case the node is not redundant as routing may direct the route along paths of a certain functional class;
3. *Any number of links with the same* ***Structure*** *value:* This must be a normal intersection. In most cases no turn restrictions are required. However, if one of the links is a one-way street then four turn restrictions are required. If two of the streets were one-way or had some restriction such as in the peak-hour, an eight-turn restriction table would be needed. An interesting situation arises when a U-turn is permissible on one of the links but not the rest. In this case, a four-turn restriction table is required. If two links allow a U-turn, a three-turn restriction table would be needed; and

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[3] Even where turn tables are void, such as in non-routing situations where attribute data is simply displayed on the arc (e.g., traffic volumes), if the GIS arcs and nodes are corresponded to the model link and node network, and the paths to represent the model links and nodes are built in the GIS, similar issues arise.

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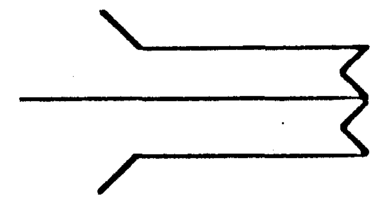
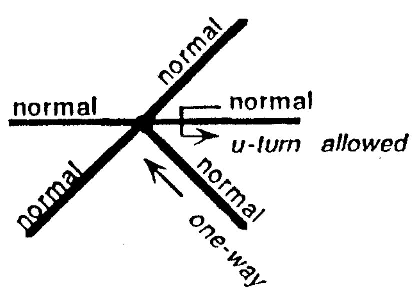
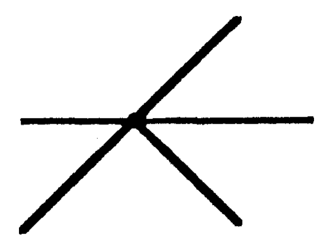
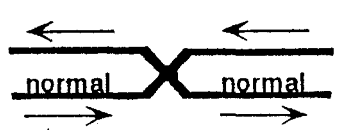
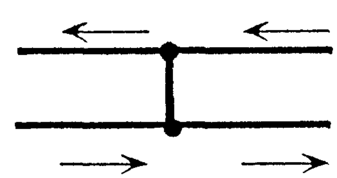
Figure 2.2 Basic Topology Archetypes

	NETWORK DATA REPRESENTATION	ACTUAL GIS NETWORK STRUCTURE	DESCRIPTION
1)			Beginning of an overpass.
2)			Simple road continuation.
3)			Normal intersection.
4)			Median u-turn along a link.

4. *A divided highway with two one-way links with the same* **Structure** *value with a one-way link between them of the same* **Structure** *value:* This is a variation of case (2). If the U-turn occurs along the link, should the U-turn be represented by a node or a link? Examples of U-turn permissible links and intersections can be found in many parts of Los Angeles.

More complex cases

Figure 2.3 illustrates more complex cases which are more problematic to deal with.

5. *Two links with one* **Structure** *value (e.g. normal grade), two links with another* **Structure** *value (e.g. overpass):* This case occurs where one road passes over another. Eight turn restrictions must be generated to signify that these links are not topologically connected.

The trickiness arises when there are different *Structure* values, but the distribution is other than two and two. For example:

6. *Two links with one* **Structure** *value (e.g. overpass), 1 link with another* **Structure** *value (e.g. normal grade):* This is probably a ramp coming up from normal grade and joining a road on an overpass. No turn restrictions are required;

7. *Three links with one* **Structure** *value (e.g. normal grade), one link with another* **Structure** *value (e.g. overpass):* This is probably two roads crossing each other, just before one starts going across a bridge. No turn restrictions are required. An example is the Longfellow Bridge which crosses the Charles River between Boston and Cambridge. On the Boston side, two roads connect with the bridge overpass: in addition, Storrow Drive, which runs alongside the Charles River, passes underneath the bridge but has a ramp connection as in case (6) above. So this is a good example of a combination of the two cases in one spot;

8. *Three links with one* **Structure** *value (e.g. normal grade), two links with another* **Structure** *value (e.g. overpass):* This is probably two roads merging, underneath an overpass. Twelve turn restrictions must be generated to signify that the overpass links are not connected to the merging links;

9. *Two links with one* **Structure** *value (e.g. normal grade), three links with another* **Structure** *value (e.g. overpass):* This is probably two overpasses merging, above another road. Twelve turn restrictions must be generated to signify that the merging overpass links are not connected to the road below;

   Cases (8) and (9) occur at freeway grade separated intersections all across the United States.

10. *More than five links, or more than two* **Structure** *values among the links meeting at one node:* This improbable situation arises in Los Angeles where freeways intersect and there are special grade separated HOV lanes or transit lanes. Even more problematic is the situation where the I-110 Harbor Freeway meets the recently constructed I-105 Imperial Freeway which not only has separate grade separated HOV lanes, but these HOV lanes connect to the transit Green Line for bus and kiss-n-ride access/egress;

    A variation on this theme is the layered or tiered road where one road lies directly on top of another one. Airport arrival and destination roads are a good example (e.g., LAX) and some bridges also have tiered roads, with some unusual access and egress ramp arrangements (e.g. Bay Bridge, San Francisco); and

11. *Two links with normal structure value:* In this case there exists a physical or administrative barrier. If an administrative barrier, such as double yellow lines, this case is a variation of case (3). However, in many situations a physical barrier is erected such as a guard rail. Examples of these are commonplace in most North American cities.

Turn restrictions can be especially problematic to deal with. The main administrative turn restrictions are:

- No ahead
- No left turn
- No right turn
- No U-turn
- One-way

Administrative barriers include:

- Gate (can be opened by emergency vehicle)
- Solid, double yellow lines
- Streets restricted to certain classes of vehicle, such as emergency vehicles, buses

Administrative turn restrictions can be associated with a time and may have exceptions for buses, taxis or other special vehicles.

For complete accuracy, each of these situations should be verified as correctly corresponding to the actual network. If the *structure* value rules were found to be insufficient, a further analysis could take into account the relative azimuths of the links entering and leaving a node, to connect links close to 180 degrees apart.

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Figure 2.3 Complex Topology Archetypes

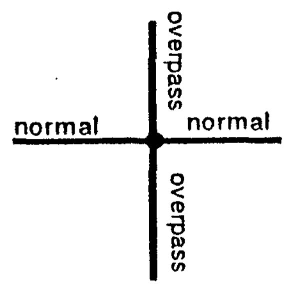
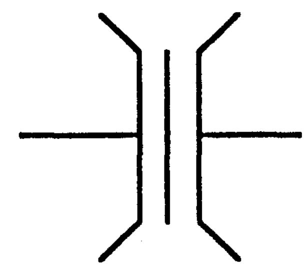
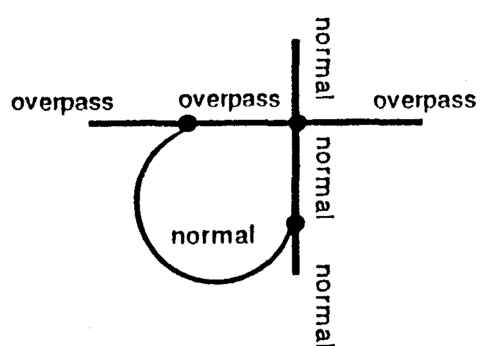
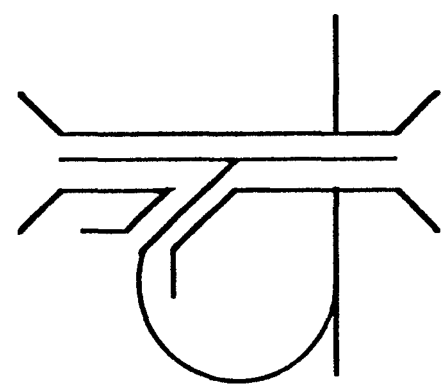
	NETWORK DATA REPRESENTATION	ACTUAL GIS NETWORK STRUCTURE	DESCRIPTION
5)			One road passing over another.
6)			Ramp joining a normal grade road to an overpass.

Figure 2.3 Complex Topology Archetypes

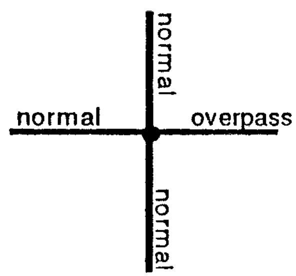
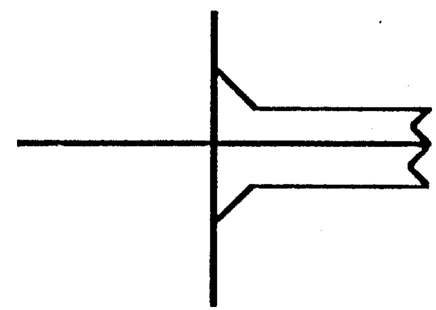
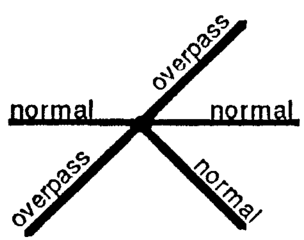
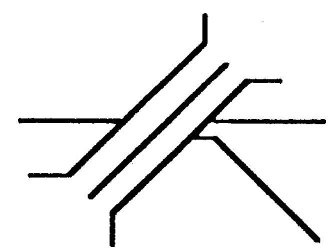
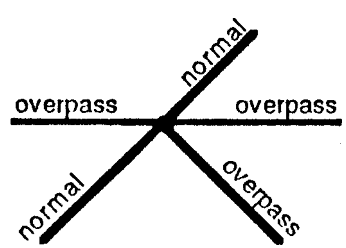
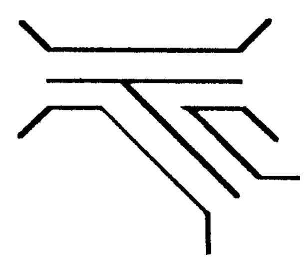
NETWORK DATA REPRESENTATION	ACTUAL GIS NETWORK STRUCTURE	DESCRIPTION
7) 		Two roads crossing just before a bridge.
8) 		Two roads merging underneath an overpass.
9) 		Two overpasses merging over a normal grade.

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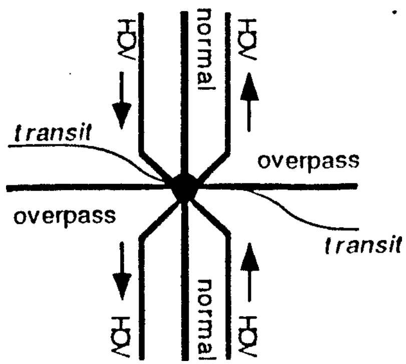
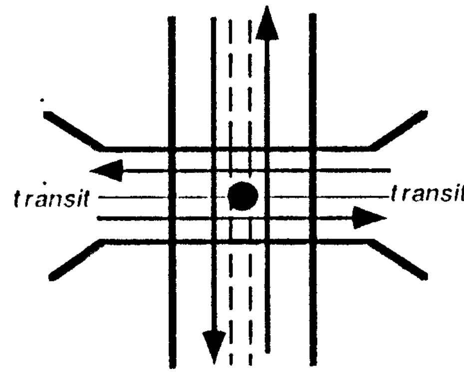
Figure 2.3 Complex Topology Archetypes

NETWORK DATA REPRESENTATION	ACTUAL GIS NETWORK STRUCTURE	DESCRIPTION

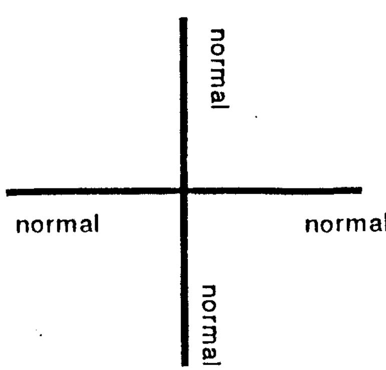
10)

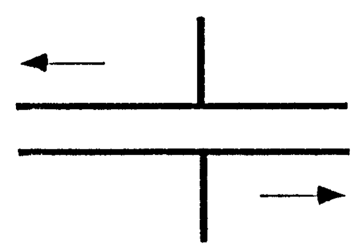




Transit line on same alignment as overpass underneath the overpass, is connected to HOV lanes on underpass freeway. Normal overpass lanes are not connected or accessible to transit.

11)





Road connectivity limited by physical or administrative lanes.

GIS/Trans has had occasion to consider these situations previously for other projects, and we have produced code that deals appropriately with almost all of these situations. Even so, it is recognized that some of these solutions are non-elegant "work arounds" that are site specific and difficult to generalize to all situations.

2.2.4 *Road Feature Representation*

Data providers often have their own way of constructing the road network. For example, Caltrans uses a different road classification scheme from the one used in Thomas Brothers Maps or ETAK.

The first issue is to decide what details a network must have. Very often this work starts from the classification of real world roads:

1. *Road types:* ownership, management class;
2. *Road status:* existing or proposed roads, vehicle or pedestrian only, barriers, one-way traffic, turn restriction (etc.);
3. *Road details:* divided highways, cross-overs, slip lanes, service roads, freeway, ramps, forks, bridges (etc.);
4. *Separators:* traffic islands, refuges, strips, medians, and grade separations such as underpasses and overpasses (etc.);
5. *Intersection details:* "nearly adjacent" intersections, rotaries, complex intersections;
6. *Road attributes:* names, address ranges, political boundaries, and road history; and

Although not a map feature, scale and map details (resolution) often play important roles in network feature representation. For example, road intersections are difficult to portray at less than 1:24,000 scale.

<u>Linear Referencing of Road Features</u>

The authors of the 20-27 Report, and the GIS-T/ISTEA Pooled Fund study team, have proposed a LRS model to deal with the situations described above. The basic premise is that all LRS, and by extension linearly referenced data, can be cross-referenced once an appropriate unifying LRS data model is constructed. Their proposed "meta LRS" is independent of the base map topology and can therefore represent within its schema all the representational problems described above.

A brief discussion of the merits of LRS to network pathology problems follows.

Determination of the link *structure* value can be assisted by LRS where the street network file contains attributes to classify the road network. For example, in vehicle routing the primary route may use freeways only, otherwise some devious routes can be generated that use local streets.

The *Street Type* or *Functional Class* attribute, if one exists, is an appropriate attribute to use to extract a subset of links, as it contains different values for freeways, highways, primary roads (arterials), secondary roads (residential collectors), and minor residential roads. Care needs to be taken to include roads which have a railway right-of-way within them, if desired, as these roads are often labeled with a different value. Examples include streets with light rail lines associated with them.

The various parts of the *Street Name* attribute can be indexed using a table of standard values. This is very helpful in network classification and building linear referencing systems. For example, some values include:

Prefixes	Suffixes	Cardinal Directions
Corte del	Avenue	East
Street of the	Boulevard	Southwest
Paseo los	Junction	Central
Plaza	Square	Key Peninsula North

This standardization should aid in address matching and in street name reporting and maintenance.

While a LRS can be very useful for feature classification and attribution there are many cases where it will not be applicable for network representation. The most obvious case is where there are no linear attributes to develop a LRS. An example is a highway model network that simply uses anode, bnode identifiers. Corresponding the spatial features is impossible by linear referencing alone, and the correspondence has to employ *conflation* techniques that can match corresponding nodes and links by spatial matching, not linear referencing.

Problems will also arise in vehicle routing where the problem is not just one of representing *where* the feature is but *what* type of feature it is (such as a u-turn permissible intersection). In many of the examples cited earlier, the schema to code the non-planer connectivity in a planar graph GIS representation, is independent of the topology, and *independent of any linear referencing*.

The sophisticated LRS models developed by the Pooled Fund Study may be able to deal with many of these situations but the complexity involved in resolving these cases with LRS remains a problematic issue, especially for practitioners who are seeking a simple solution. A key issue, is how different LRS are corresponded in GIS to the meta-LRS. New technologies such as GPS that accurately record location by latitude, longitude or with reference to some x,y,z coordination system may provide a more direct way of referencing datum? GPS is increasingly being used by cartographers, planners and transportation practitioners. It is already adding a new dimension to LRS construction and many believe it has the potential to be a unifying location referencing method.

2.3 Conclusion

Most street centerline files are less than perfect in their topological quality, even where they have good positional accuracy and reasonable attribution. In all cases they require further enhancement for use in GIS for network representation, routing or modeling purposes.

Most network file data clean-ups employ a mixture of topology verification and attribute classification techniques, such as the use of *structure* values. These are cumbersome and in many cases situation specific. Examples of network pathologies are illustrated that demonstrate the limitations of current approaches. LRS methods may be appropriate to some situations but are not considered applicable in many cases.

More generic methods are needed that address network topology and connectivity issues independent of data attribution. New technologies such as GPS may offer a solution but these have yet to be fully tested.

3. TASK 2. GIS AND TRANSPORTATION MODEL NETWORK PATHOLOGIES

3.1 Overview

The multiple representation of transportation networks of a region is a key issue in GIS-T and likely to become more critical as the use of GIS in transportation grows. To date, users have been content – or confined – to attributing data to a given street centerline file and referencing their data to the network by a combination of linear referencing and route-systems that employ dynamic segmentation techniques. However, these techniques are not adequate on their own to deal with network representations that are positionally inaccurate and have non-corresponding attributes. A good example is the integration of model networks and street centerline files.

3.2 Network Conflation

The resolution of the feature and attribute cross-correspondence is referred to as conflation, and is an emerging issue in GIS-T. In practice, conflation techniques employ a multitude of methods to accomplish the correspondence between the files including linear referencing, shortest path routing, rubber-sheeting and special matching programs. Although many of these methods can be automated, the development of programs to fully automate the process is constrained by data definition and logic (i.e., choice) problems encountered in the matching process. In many of the cases cited below, interpretation by the knowledgeable user is still required, although ultimately an expert system solution would be desirable in many cases.

For consistency with previous definitions, the problems are classified into three classes: topology pathologies, linear referencing pathologies and routing pathologies.

Model network pathologies

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

1. *Intersection node representation:* In this case, a single node represents a complex grade separated intersection. Even applying the *structure* values defined above with turn tables is only a partial solution as it is not always clear which ramps are being represented or where exactly the node should be located on the real network;
2. *Zone centroid connectors:* Transportation models aggregate trips to zones and these trips are then assigned to the network. The zone centroid connection to the network may be a dummy link that is difficult to identify in the real world network. In some instances the centroid connector represents a corridor of several alternate links. Where the zone centroid link connects to the network may not be a real node, and a

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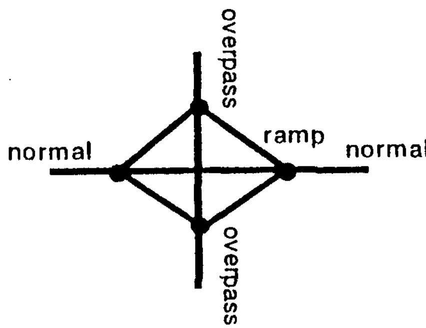
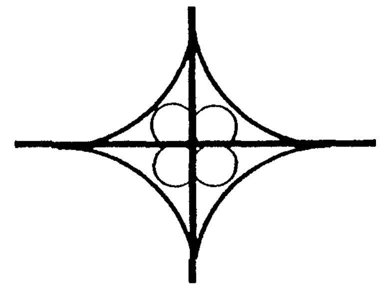
Figure 3.1 Model Network Pathologies

MODEL NETWORK DATA REPRESENTATION | **ACTUAL GIS NETWORK STRUCTURE** | **DESCRIPTION**

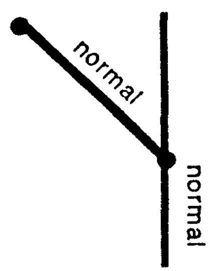
1)

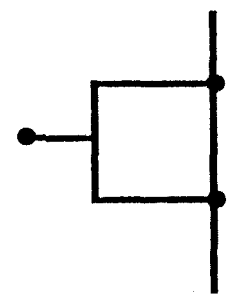




Complex closer low grade separated intersectionwith one-way ramps is modeled as single diamond with two-way ramps. Node location is difficult to validate.

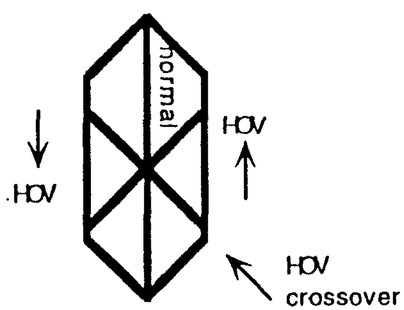
2)





The zone centroid connector is a dummy link with a pseudo-node connection to the main network.

3)



HOV is a line, not a network structure value. The crossroads have no corresponding GIS nodes or links.

Figure 3.1 Model Network Pathologies

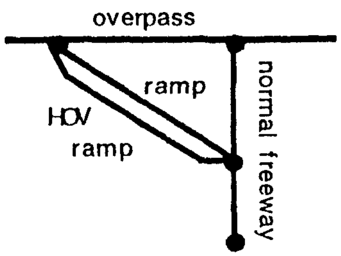
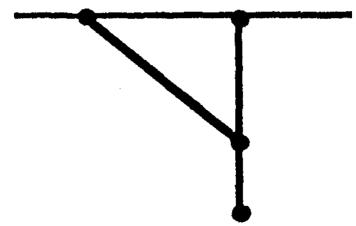
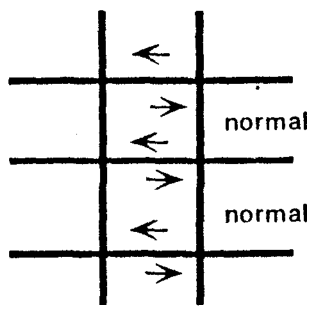
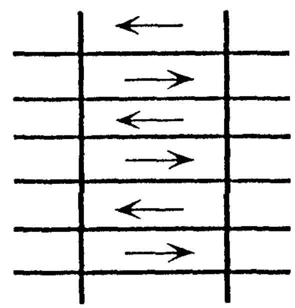
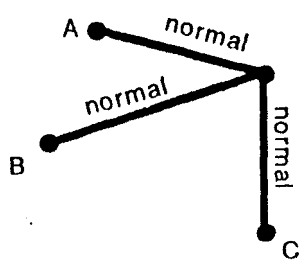
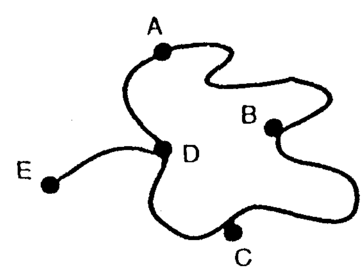
	MODEL NETWORK DATA REPRESENTATION	ACTUAL GIS NETWORK STRUCTURE	DESCRIPTION
4)			The HOV lane is represented as a separate link in the model to accommodate metered access to the freeway.
5)			Two-way streets in the model are simplified representations of one-way streets in GIS.
6)			Node D is wrongly coded on the wrong route or the model GIS route is wrong. Should B be where D is and D where E is?

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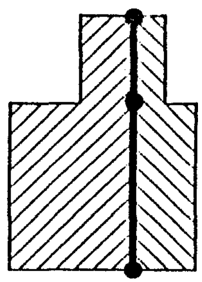
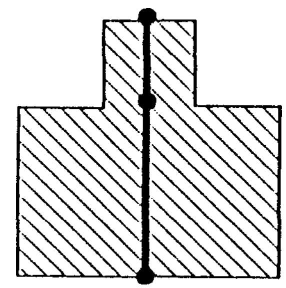
Figure 3.1 Model Network Pathologies

	MODEL NETWORK DATA REPRESENTATION	ACTUAL GIS NETWORK STRUCTURE	DESCRIPTION
7)			In GIS, directionality is not hard coded as in the model. Without special processing data is represented as a two-way flow.

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pseudo-node may be used. Moving the node to an intersection may introduce network changes such as link length which could affect routing (assignment);

3. *HOV lane representation:* In model networks HOV lanes are represented as separate links. The HOV lanes connect to the highway at places where no topological node exists in the GIS (i.e., mid-link). Should the HOV lanes be given a separate *structure* value?

4. *Metered on-ramps with HOV by-pass:* The model treats these as separate links. In some places, separate on-ramps and off-ramps are provided for HOV users. A similar situation arises with special bus lanes;

5. *Corridor links representing multiple streets:* In downtown Los Angeles, the modelers represent one-way streets as two-way streets in corridor combinations. In some suburban areas where grid patterns predominate, a model link will represent two or more parallel streets;

6. *Multiple correspondence between a single model link and several arcs in the GIS:* Finding the corresponding arcs and nodes is relatively straightforward in a downtown grid pattern area, but in hilly terrain where gradients and street patterns are irregular, determining the correspondence is more problematic. Inconsistencies also arise in model coding which result in there being no corresponding underlying arcs or nodes for the base year, and in model links that connect to a wrong node. The GIS can play a useful role in highlighting these inconsistencies but it is not so easy to resolve them because the alternate routes are not always easy to identify or rectify from the information provided;

7. *Directionality:* Transportation models code up the network as pairs of anode-bnode, bnode-anode links, and represent the links as laying on top of each other. Thus, when displaying link volumes or other model results, the directionality of the data can be represented as an offset. Generally, GIS do not code up network features in this manner and the directionality has to be added as an attribute or represented as part of the route-system.

Linear Referencing Pathologies

In representing multiple networks many of the pathologies arise from the route definition. Examples of route definition problems include:

8. *Discontinuous routes:* Routes may stop and start for various reasons, for example, a piece of intervening highway is not yet constructed, or, because of particular route coding issues. A decision needs to be made whether to milepost as if the "missing" section was in place, or to restart

the offset measurement at the start of the new section (see Figure 3.2). Usually the latter approach is adopted;

9. *Dog leg routes:* Often signed routes share common sections of highways. Does the shared section have its attributes assigned to route A, route B, or do both routes maintain characteristics for the shared sections? Choices here reflect differences in data storage schema and data update. This issue can be especially problematic in a modeling situation, as the functional class of the road will determine its speed-flow characteristics and volume-capacity ratios that impact upon the model outcome;

10. *Split road:* A particular highway may split into divided carriage-ways, which may be of unequal length. Which length is correct, or do we assume an average for linear referencing purposes? Another link length problem arises in hilly areas where the linear road length including elevation is difficult to represent in a planar graph map;

11. *Cul-de-sac:* Are cul-de-sacs linearly referenced clockwise or counter-clockwise? Lack of a conventional reference method means that offsets could be non-uniquely defined;

12. *Ramps:* How are ramps included in the system? Options include (but are not confined to):

    a. not recording ramp data
    b. recording just the position where the ramp joins the main highway central alignment
    c. creating min-routes or routlets from the ramps
    d. placing the ramps at the end of the route as if they were route additions

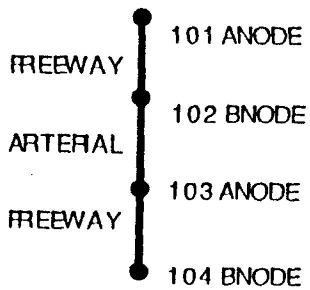
Where ramps fall between routes it must be determined whether they belong to route A or route B.

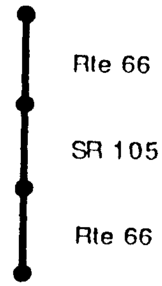
Different agencies adopt different conventions for defining the LRS. This can be problematic where multiple networks cross jurisdictional boundaries. For example, in Southern California the California Department of Transportation (Caltrans) postmile LRS is not consistent with the LRS conventions of the Southern California Association of Governments (SCAG). The research being undertaken by the GIS-T/ISTEA Pooled Fund study is addressing some of these issues and attempting to define a set of common definitions and reference datum (anchor points) to which different LRS can be referenced. However, as the above examples illustrate, not all the LRS related problems can be resolved by LRS definitions alone. Further examples and elaboration on the LRS issues for routing and network representation is reserved for the Phase 2 work program.

Figure 3.2 Linear Referencing Pathologies

MODEL NETWORK | **ACTUAL GIS** | **DESCRIPTION**

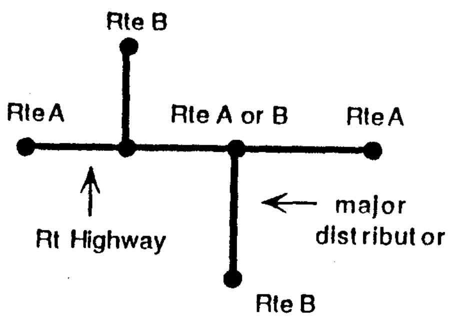
8)

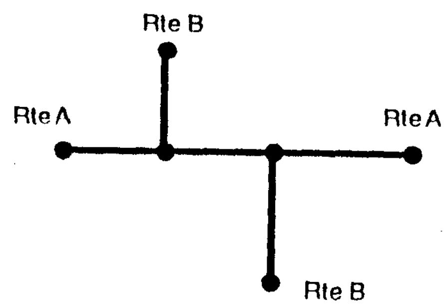




Although the GIS link exists, if it has a different structure value this will affect its routing affinity and model link class.

9)





When Route A and B merge is it a highway or a major distributor?

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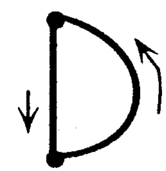
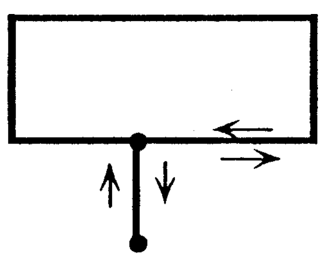
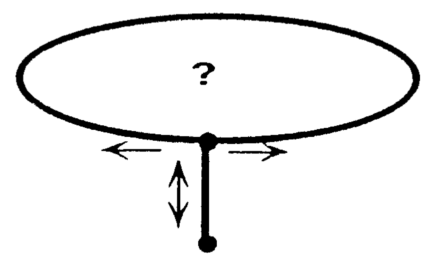
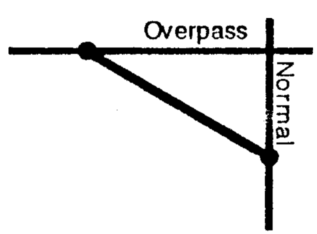
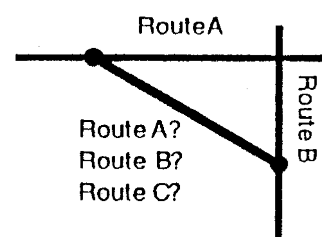
Figure 3.2 Linear Referencing Pathologies

	MODEL NETWORK DATA REPRESENTATION	ACTUAL GIS NETWORK STRUCTURE	DESCRIPTION
10)			Which is the correct length?
11)			Clockwise or counter-clockwise linear referencing?
12)			Are ramps separate or part of main highway? How do we reference them in the LRS?

GIS Route-system pathologies

A GIS route is defined as a sequence of arcs and nodes that are labeled with a unique route ID. These routes when combined in a GIS coverage comprise a route-system. The terminology is somewhat confusing as the GIS route is an artificial data model which can represent any length of road whereas in transportation a route is normally defined by functional class and administrative boundaries, for example Route 66, I-10, or State Route 5.

The GIS route is important in multiple network representation as it provides a convenient method for corresponding links and nodes, especially where a many-to-one correspondence exists, as is the case in model networks and street centerline files; it provides a mechanism for coding directionality; and it can be used to calibrate different linear referencing systems, although the capabilities for doing this latter action differ among GIS products. The route-system data model is therefore an important function in GIS-T, and is widely used in network conflation exercises.

Even so, the route-system data model has a number of weaknesses that limit its use in multiple network representation.

13. *Hierarchical route-systems:* Perhaps the biggest single weakness from a transportation modeling perspective is the lack of capability to define grandparent-parent-child relationships between route-systems. It is possible to reference multiple route-systems to the same network but not to have a route-system as a subset of another route-system. A few GIS allow a lower level of data representation, sometimes referred to as events, that are point or linear elements of a route (e.g., bus stop, pavement section), but these have not proven flexible enough to represent the complex hierarchical network relationships that exist in either the real world or the modeling world.

    Probably the best example of this is the representation of transit networks as a subset of highway networks in the INET modeling paradigm that is rapidly replacing the UNET paradigm associated with UTPS modeling procedures. The trend in transportation modeling is towards more integrated or multimodal modeling procedures which, by definition, provide an integrated network structure. Conceptually this is easy to construct, and in the modeling environment is accomplished through coding conventions, but in the real-world of GIS, the INET representation is more difficult to accomplish. There are many scenarios where in GIS this is the case and only a few are illustrated in Figure 3.3. The straightforward GIS solution is to have hierarchical route-systems but this is as yet unproven. It is a hypothesis based on the extension of current practice, but may not be ideal. Clearly, further research and testing are required;

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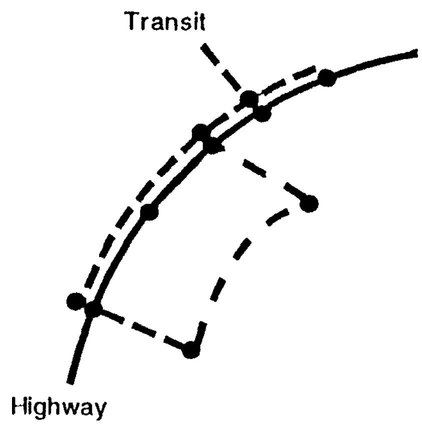
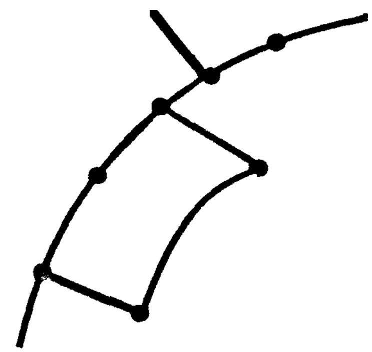
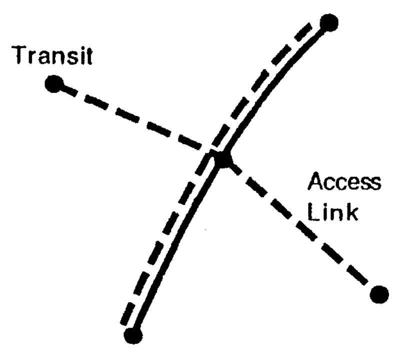
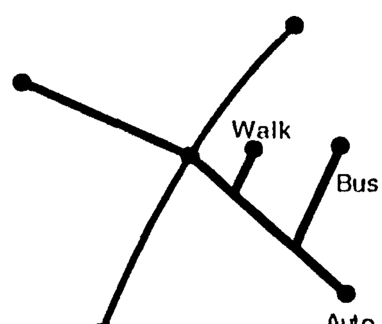
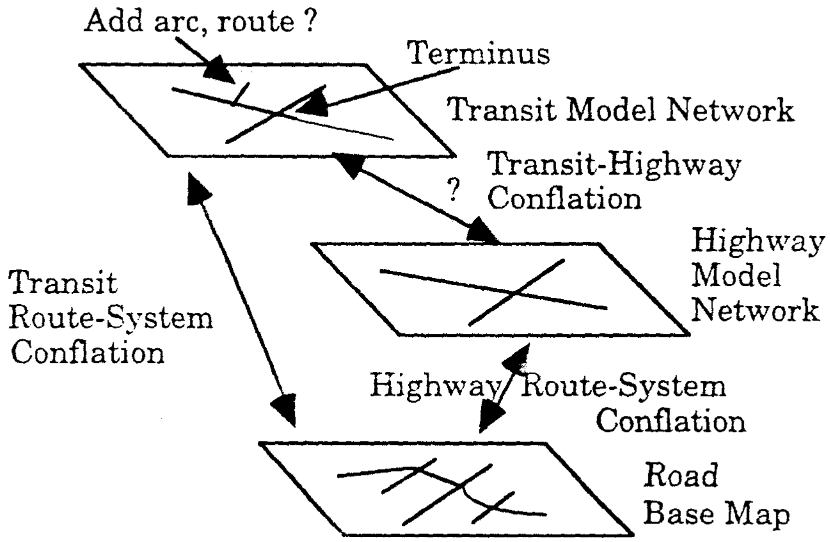
Figure 3.3 Route System Pathologies

	MODEL NETWORK DATA REPRESENTATION	ACTUAL GIS NETWORK STRUCTURE	DESCRIPTION
13)			GIS network references the base map, not model network features. Limited stop transit may miss highway nodes or use contraflow lanes.
14)			Adding a transit link means adding the underlying highway link. If the transit link is deleted, do we delete the highway? How do we deal with multimodal access links?

14. *Network Editing:* A good example of the limitation of existing techniques are the difficulties encountered when editing transit networks that overlay highway links (Figure 3.4). If the transit route changes how does this affect the highway link. For instance, addition of the transit link should result in the addition of the highway model link, but if the two networks are conflated to the base map network in GIS how is this editing correspondence established? One possible answer is to conflate the two model networks to each other as well as to the street centerline file. This double-conflation is seen currently as the best solution, but it is messy and not a trivial exercise. Clearly, better methods are needed that avoid this duplicative situation.

Figure 3.4 Hierarchical Route-System Relationships



Only a few GIS products have dynamic segmentation capabilities, and the robustness of the method varies considerably between applications. Perhaps the biggest pathology is therefore not having any capability to create route-systems that can adequately represent network data location and work with linear referencing systems.

3.3 Summary

This section has focused on the pathologies associated with multiple network representation, especially the representation of transportation model data on positionally accurate street centerline networks. Emerging techniques of network conflation are making this network integration possible for the first time and it is likely that this aspect of GIS-T will grow in importance.

Multiple networks exist because there are a multiplicity of uses and users who use networks for different purposes. The transportation modeler, for instance, has a different agenda to the transit scheduler or the trip planner. Auto drivers looking to plan commute journeys view networks differently from the traffic planner. Transportation, in short, is a rich and highly varied area of activity, but fundamentally there are common denominators that tie the different elements together. These include the basic unit of analysis – the road, route, link, section or arc – however it is defined.

For the transportation practitioner, the network is the common denominator. GIS has exposed some of the weaknesses in the network paradigm, but at heart the transport system is an immensely complex network that sometimes defies simple definition, especially at the small scale. This section has sought to illuminate some of the network pathology issues that often escape attention.

4. CONCLUSION

4.1 Summary

The above network pathology examples illustrate the range of problems that transportation users come up against when using GIS. While some of the pathologies may appear very specialized and specific to particular situations, they are manifestations of more chronic problems that arise with the traditional georelational model of GIS. This model does not take adequate account of the peculiarities of network attribution or multiple network representation of the same area. There are various ways of dealing with these pathologies, hinted at in the report, and indeed some of the solutions to emerge in GIS-T have expanded the capabilities of GIS beyond its original intention. Dynamic segmentation of network attributes is the best example of this. Intentional or not, these additional capabilities have raised expectations for GIS among transportation practitioners and their use in GIS-T is expanding. However, if these demands are to be satisfied even more dynamic and robust solutions are needed.

In this report, the nature of the network pathologies have been described. Not all network situations have been covered, but enough examples have been presented that give a flavor of the network pathologies that are commonly encountered. It is to be hoped that they illuminate the problems sufficiently to warrant further research together with action programs to evaluate potential solutions.

The trend in GIS, as in other information technologies, is towards an object oriented model of data definition and data processing. There are indications that this paradigm may provide a better data model for GIS-T. The GIS-T/ISTEA Pooled Fund study has researched object oriented methods and evaluated object data structures for transportation. In theory, at least, these appear to hold out a lot of promise. Object oriented models appear to be the model upon which the next generation of GIS is being constructed. If so, we need to understand from a theoretical and practical point of view how object-oriented programs relate to existing network pathologies and how they address the key concerns that GIS-T users have.

4.2 Advanced Pathologies: Network Routing and Intelligent Transportation Systems (ITS)

The emphasis in this report is on the network pathology fundamentals that address the key data management and planning applications for which GIS is primarily used at present. In future, it is likely that GIS will play an expanding role in routing for operational as well as for planning purposes, and in conjunction with other technologies as part of the ITS program. GIS is itself an expert system and a core technology for transportation applications.

ITS and routing applications are more detailed than 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 routing, and how these are presently represented in GIS, require further investigation.