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GIS and Transportation: Status and Challenges

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Abstract

The evolution of GIS-T is characterized in three stages: the map view, the navigational view, and the behavioral view. The static nature of the map view favors applications related to inventory and description, and raises difficult questions of accuracy and interoperability. The navigational view adds concerns for connectivity and planarity, and the storage of time-dependent attributes. Navigation also raises issues of representation related to scale, including the need for lane-level connectivity. The behavioral view stems from the work of Hägerstrand, treating transportation events as dynamic and occurring within the largely static transportation space. Appropriate representations for the behavioral view have still to be worked out. In all three cases the legacies of prior technologies and perspectives are still evident. The paper presents a series of research challenges, dealing with standards, representation, unambiguous communication, economic models, response to new technologies, and application of knowledge gained from GIS-T and ITS research to other fields.

Keywords: spatial database, geographic information system, cartography, spatial behavior, navigation

1. Introduction

GIS-T, or the application of geographic information systems in transportation, dates from the very earliest interest in GIS in the 1960s. GIS is about many things, but one consistent theme in its development has been the economies of scale that derive from integrating a wide range of processing functions around a well-defined data structure representing one or more particular classes of geographic data. For example, one such structure is the familiar *layer-cake* of many co-registered representations of geographic variation over an area. If each layer uses an identical raster of rectangular grid cells, then many useful operations become possible: arithmetic combinations of layers, for example. This architecture underlies many of the software packages that have emerged over the past three decades for image processing and raster GIS, and is the basis for image algebras, Tomlin's Map Algebra [13], Geo-Algebra [12], and van Deursen's dynamic modeling language [15].

The circumstances of the first use of the term *geographic information system* are lost in the sands of time [10], [14], although several excellent histories of the field now exist [2], [4]. But it is clear that much of the initial impetus came from the group of graduate students in quantitative geography at the University of Washington in the late 1950s; and that one of these was Duane Marble, who later moved to Northwestern University and developed a rudimentary form of GIS in support of transportation studies in the Chicago area [10]. Transportation research requires a wide range of models and forms of analysis, but makes use of a comparatively small number of types of data, the vast majority of which have some form of geographic reference. Later, the Census Bureau's interest in managing data collection led to the development of the DIME structure, and later TIGER, as methods of representing street networks with a high level of internal consistency.

Although GIS-T is the subject of an annual conference in the U.S., an expanding literature, and numerous specialized software applications, there is as yet no book devoted solely to the topic. In a recent review, Waters [16] concluded that ''it is possible to state unequivocally that GIS-T has 'arrived' and now represents one of the most important application areas of GIS technology.'' In this paper I attempt to address why that should be, to identify some of the more important research issues in the field, and to point to some interesting and challenging trends. The discussion is organized according to three distinct views: the map, navigation, and behavior.

2. Three perspectives

2.1. The map view

Seen from above, the Earth's surface is an enormously complex jumble, with very little in the way of obvious order. One of the types of features most easily identified by the human eye are the linear transportation corridors: rivers, canals, railroads, and roads. Even here, however, the simple linear model breaks down. Rivers flow into lakes and seas, and people and vehicles can escape the linear road system in parking lots and other trafficable areas. Nevertheless, the linear system is relatively stable, since rivers rarely move, and roads are expected to have substantial lifetimes, and it provides a very convenient way of organizing and referencing much human activity. Homes and businesses are mostly located within short distances of the public road network, and so can be readily identified by specifying position on that network. Vehicles are mostly confined to the road network also, and trains are strictly confined to the railroad network. Moreover, as a linear system it is possible to specify location in a one-dimensional space, with a single number. One-dimensional references are inherently simpler than two-dimensional references, since only one measurement is needed, and the distance between two such linear measurements can be much easier to compute or estimate intuitively than the distance between two points in two- or three-dimensional referencing systems, especially if the points are close to each other. Thus human societies generally have chosen to identify home location by street address, and to deliver mail using that system, in preference to two-dimensional systems such as latitude and longitude, or national grids.

Efforts to digitize the U.S. street network began in the 1960s, driven by the needs of the Bureau of the Census for an easy way of allocating individuals to reporting zones. If street addresses could be converted to coordinates, then simple routines could be used to identify any of the complex hierarchy of reporting zones: blocks, census tracts, counties, cities, or states. The same function—conversion of one-dimensional street address to two-dimensional coordinates—found abundant applications in market research and led in part to the growth of the field we now know as geodemographics, since it could be used to convert lists of customer addresses to areal counts. But the structure chosen for the Bureau's DIME files for the 1970 census reflects what in retrospect seems like an odd choice: to see the street network as a collection of nodes and links. The traditional view of a street is reflected in our naming system, which assigns the same name to a roughly linear feature running through multiple intersections. But DIME chose to break this feature into a series of individual links. The advantage lies in the ability to institute checks of logical consistency, because all of the links surrounding a block must form a closed figure. But it has a number of significant disadvantages:

- Dependence on the precise definition of an intersection (what to do about traffic circles, or intersections not at grade, or intersections with laneways that may not count as streets).
- Sensitivity to creation of new intersections, which may require extensive modifications to the database.
- Conflict with traditional ways of thinking about street networks.
- Redundancy since street names must be repeated for each link.

Despite these problems, links and nodes have remained the prevailing view of networks, driven in part by the almost mythical significance given to *topology* in the traditions of GIS.

Another major difficulty with the link/node view concerns events or features which occur at points within links, or over stretches of links that do not match their endpoints. In the simple DIME model it is possible to attach an attribute to a link or a node, but not to arbitrarily defined parts of links. *Dynamic segmentation* extends the basic link/node model by making it possible to refer to points in the linear referencing system that are not at nodes [6]. *Route and milepost* schemes model the network consistently with traditional practice, by creating a single record for every street, and a separate but appropriately linked record for every intersection.

The map view is inherently limited by the need to represent real features as one-dimensional spaces or *centerlines*. In principle positional accuracy is limited to one half of the street width transverse to the street, and is typically similar along the street; the locations of intersections are similarly subject to uncertainty. Features such as businesses and houses may have much larger offsets from the linear system, and again such information is typically lost in the map view. Important information about the *side* of the street (e.g., whether a house is on the north or south side) must be conveyed topologically, as a binary attribute, or inferred from the numbering system, since it cannot be obtained from the geometric information in such representations.

Although DIME and its successor TIGER were created by the public sector, there is sufficient business interest in street centerline databases and their applications to support a substantial private sector in most industrialized countries. This is especially true in those countries where printed street maps are not widely available or in common use, or where addressing systems are not as simple as in the U.S. and Europe (e.g., in Japan, where houses are commonly not numbered sequentially along a street). Increasingly, then, more than one database is available for an area. High quality databases can now be created by renting a vehicle suitably equipped with kinematic GPS. Since such databases inherit the imperfections in the processes used to create them, any two databases can be expected to differ by amounts comparable to their positional inaccuracies.

Church et al. [1] describe some of the problems that are emerging in GIS-T and ITS applications of street centerline databases as a consequence of such differences, and Noronha's paper in this issue explores them in greater detail. Whereas *interoperability* is normally understood in GIS to refer to the syntactic and semantic issues of definition and content that produce different databases from the same information [7], the case here adds a new dimension of accuracy, which may turn out to be the most problematic dimension of all, since it casts doubt on the basic ability of street centerline databases to support reliable conversion between geographic coordinates and linear referencing systems.

Moreover, Noronha has shown that interoperability is also impeded by high rates of failure to match features, such as occurs if a street is present in one database but not in another, or if its name is missing or in conflict. Linear addressing systems also tend to break down in rural areas, where a patchwork of efforts has attempted to replicate the simplicity of the urban system with varied success.

2.2. The navigation view

Although unimportant to the Bureau of the Census, the link/node view of a street network has a significant advantage in supporting navigation, since a path through a network is readily expressed as a series of decisions at nodes. The algorithms to find optimum paths through networks, such as the shortest path, or the path of least expected travel time, also are based on link/node structures [3], as are more complex and harder-to-solve routing problems.

Routing problems require certain classes of attributes that may not be present in databases created from the perspective of the map view. It is important to identify one-way streets as attributes of links, and barriers to through traffic. But entirely new structures are needed to support information about turns between links, or conditions of access from one link to another [6]. ESRI's ARC/INFO, for example, extends the basic link/node structure with a *turntable* to record information about turns between links, and can use it to distinguish between intersections at grade and overpasses. More generally, use of street centerline databases to support navigation requires a more complex view of topology than that of the DIME and TIGER files, which used it simply to establish consistent representations of planar features.

Support for navigation is an indispensible part of intelligent transportation systems (ITS), where it is needed to assist drivers in designing routes, and in modifying routes in response to new information. But such effective navigation requires a massive extension of the attributes provided in the map view, to include dynamic attributes such as levels of congestion and travel speeds, temporary obstructions, and temporary turn restrictions. Few if any of these attributes are visible from above, so expensive ground-based collection is almost always required. Routes found on databases representing the map view, such as those provided by an increasing number of WWW-based services, are sometimes inaccurate or impossible because these essential attributes, and the structures needed to support them, are typically not present.

The one-dimensional perspective embedded in the map view presents numerous problems when applied to navigation. Streets may or may not have median dividers, and U-turns may or may not be legal at gaps in dividers. The advent of multi-lane freeways and turn lanes has also led to a fundamental change in the way drivers navigate. In the 19th Century gridiron city it was sufficient to tell a driver to ''turn left at First Street''. Today, a driver must anticipate left turns much earlier, in order to move into the correct lane where one is present, and must transition between intersecting freeways by taking the correct ramp. In short, it is no longer sufficient to provide navigational instructions based on a link/node view of the street network. Instead, the configuration of the street as a collection of lanes must be represented in the database, and vehicles must be tracked at the lane level of detail.

Geometric representation of lanes is much more expensive than simple representation of street centerlines, and requires a substantially higher level of positional accuracy. Goodchild [6] shows how a representation can be built that has the same level of geometric accuracy as the street centerline, but includes a topological representation of the relative positions of lanes and their connectivity. This compromise representation would be sufficient for lane-level navigation, though it would be difficult for a system using such a representation as its database to keep track of the lane currently occupied by a vehicle. The representation would be much less expensive than full lane geometry, and much of it could be built from aerial observation.

Systems to support navigation must somehow deal with two additional complications. First, people and vehicles are not necessarily confined to the linear network, and will at times depart from it, in parking lots, unrecorded or unrecognized roads, or on private property. Systems that match vehicle tracks to networks must deal with this problem (e.g., [17]), and it is a significant problem for routing also. Second, navigation often requires the use of more than one mode, or comparative evaluation of modes. For example, a commuter may combine road and rail travel to work. Few efforts have been made to create databases that combine modes, by representing both road and rail networks and their interconnections, for example, but these would be essential for multimodal routing.

2.3. The behavioral view

The map view implies an essentially static perspective, and its success is in inverse proportion to the propensity of the network to change, by adding or moving links, adding intersections, or other modifications. The navigation view assumes that information of a dynamic nature must be represented on the static geometry of the network, but does not attempt to represent moving geometry. The third view, discussed in this section, deals explicitly with the behavior of discrete objects—vehicles, people, trains, or boats—on and off the linear network.

Hägerstrand [8] was one of the first to examine the behavior of discrete objects moving in time with persistent identity. He introduced the notion of time as a third dimension, with the trajectories of objects tracing paths in this three-dimensional space, constrained such that each object had exactly one intersection with any plane of constant time, in other words, that the locational coordinates of an object at time t could be expressed as single-valued functions of t. Mark and Egenhofer [11] have termed such object trajectories *geospatial lifelines*.

In the past, such data have been very costly to collect, and consequently rare. A sample of individuals in Halifax, Nova Scotia, kept daily diaries in 1971 of their activities and locations, and these data were linked to individual records of socio-economic and demographic characteristics. But although the data set has been subject to numerous analyses (e.g., Janelle et al. [9]), it remains one of a very small number of intensive samplings of individuals and their behavior. That situation is changing rapidly, however, as GPS transponders make it possible to track objects and sample locations intensively in time at reasonable cost. Other ITS sensing technologies, such as ''smart'' loops in highway pavements, may make it possible to construct detailed travel diaries of individuals. Such data raise interesting issues of privacy that will have to be dealt with. They also create the need for effective methods of representation and visualization. We also lack a suitable suite of models and analytic techniques with which to test simple hypotheses on such data.

The Halifax data, for example, were recorded as a flat file of events, defined by a change of activity, and each of these events was geocoded at its starting and ending points. In a travel event, no information was available on the route followed, and analysis had to be confined to the beginning and ending locations of the travel event. In other situations, data might consist of samples of the locations of all objects at regular time intervals (snapshots). In tracking animals, battery weight is often a constraining factor since batteries can only be replenished through recapture, so it is important to minimize the number of locations transmitted.

Hägerstrand's primary concern was with movement in continuous two-dimensional space. Similar issues arise if objects are confined to a linear network, and positions are represented in a linear system.

A GIS to support the behavioral view, and thus the modeling of complex behavior, must also deal with other data types that result from aggregation of geospatial lifelines. These include flow matrices, defined as measures of the numbers of objects moving in a given period of time between an origin area and a destination area. In such matrices all knowledge of each object's actual trajectory is lost. Numerous models exist of such aggregate origin/destination flows [5]. Another data type represents the flow in each link of the network, as used for example in modeling modal splits and in traffic assignment models.

In summary, the behavioral view requires a new series of representation methods, beyond those required by either the map or the navigation view. Many of these have been implemented in software, though it is unusual to find them all provided within the framework of a single, comprehensive GIS for transportation. Rather, GIS representations to date have tended to favor the map view, and to some extent the navigation view, reflecting the bias of the GIS software industry towards inventory and static representation rather than to analysis and dynamic modeling. In that sense, today's commercial GISs have made little progress at meeting the needs of comprehensive transportation planning or ITS.

3. Legacies

Each of these three views reflects the legacies of prior technologies, and the ways they limit our ability to think about geographic data in ways that are free of assumptions, traditions, and metaphors. The link/node approach to representing networks, for example, is grounded in the notion that streets intersect at regular intervals at grade, both familiar attributes of the design of 19th Century cities. DIME was adopted in support of an effort to count the populations of U.S. cities, which were first laid out and experienced their most rapid periods of growth in the 19th Century. The approach reflects the expectation that the population lives in discrete housing units, arrayed at regular intervals along streets, with short setbacks. It assumes that streets have single, well-established names, and that addresses are ordered along each street.

The disadvantages of this approach become obvious when conditions are encountered that violate or deviate strongly from these assumptions, as when the approach is applied to:

- Rural areas where roads do not have frequent intersections, and addresses are not numbered along streets, or not regularly spaced.
- Intersections that do not occur at grade, as frequently happens with the relatively modern concept of freeways.
- Housing units that are not located close to streets, a condition which was common in the medieval city and is increasingly common in today's *exurbs*.
- Roads that are realigned, or where new intersections are constructed.
- Areas where the concept of street is not well-defined, as in the medieval city and in condominium complexes.

The gridiron city first appeared late in the Enlightenment, when medieval areas were cleared to make way for the monumental streets of Paris, new areas were developed in Edinburgh, L'Enfant laid out the gridiron of Washington, DC, and similar simple, clean, and regular designs were applied to new cities around the globe. It began to decline in importance with the flight to the curved streets of the suburbs in the 1930s, and with the emergence of the exurbs of the 1970s. Linear addressing similarly appeared rather late in human history, simultaneously with the move to ordered city layouts and the development of mail systems in the mid-19th Century, and has been imposed in villages and rural areas only in the past few decades. Thus the system on which we base GIS applications in transportation appeared relatively recently, and is far from universal in its applicability. Moreover, linear addressing systems are notoriously difficult to standardize. There are no national standards for something as simple as odd/even numbering, and in areas where jurisdictions overlap, in the border areas between municipalities or because more than one level of government has an interest, it is common for streets to have multiple names. By contrast, there has been universal agreement on methods of two-dimensional referencing on the Earth's surface since the late 19th Century.

At another level our approaches to GIS-T reflect the legacy of paper maps, and the national mapping programs of the U.S. and other industrialized countries. In a world in which there was only one producer of geographic data the implications of positional uncertainty were easy to overlook: the national mapping agency was right by definition. There were no problems with what constituted a road when the national mapping agency set the semantic standards. The confusion that is a consequence of opening street centerline database production to the private sector is a direct result of this legacy, since we have no experience with working in a world in which many different databases can all simultaneously be right.

4. Research challenges

In this section I suggest six current research challenges in the field of GIS-T. They range from technical issues of representation to the social issues of economics, but all lie within the broad rubric of geographic information science, as problems motivated by applications in transportation.

4.1. Standards

The landscape is littered with the relics of past, well-meaning attempts to impose standards in systems of linear referencing. Manhattan had found a brilliant way to create an ordered city as New York grew north of its original nucleus, by laying out numbered, parallel streets at regular intervals, intersected by numbered, perpendicular avenues. But other cities faced a problem in trying to emulate this perfect system: unlike Manhattan, they were not constrained to growth only to the north. The system of San Jose, Costa Rica effects an interesting compromise by using increasing even numbers in one direction and increasing odd numbers in the other; Edmonton, Alberta chooses to start both streets and avenues at 100, presumably on the expectation that the city would never grow so large that negative numbers would be needed in the south and east. Long before that happened, however, rectilinear order fell out of fashion, as did the opportunity for supposedly wise central authorities to impose their will on urban form.

A parallel transition has occurred since the computer was introduced as a data management tool in the 1950s. In the early days, it was common for computers to impose themselves on users, requiring abbreviations of names, or truncation of years to two digits, and other forms of standardization. Today our attitudes have changed: it is no longer acceptable for computers to impose standards; rather, computers are seen as tools that can overcome the problems caused by the lack of standards in society, by implementing translations, harmonizing different practices, and generally adapting themselves to the messiness of human society. Rather than impose standard spelling on street names, for example, it is much easier to program computers to recognize multiple aliases.

But this messy world is much more difficult to represent digitally, and hence the first research challenge: to develop digital representations and processes that accommodate to the lack of standards in society, and particularly in transportation, and that exploit the power of information technology to overcome lack of positional accuracy, non-standard linear addressing, and other sources of confusion and uncertainty.

4.2. Representation

The representations implemented in today's GIS databases are rich, but fall well short of the full range needed to build a comprehensive set of GIS-T and ITS applications. I have argued that dynamic segmentation is an effort to extend the basic link/node structure to handle events located on links, and the turntable is a similar extension. But little progress has been made in implementing more elaborate structures to handle navigational applications, including lane-level detail, or to handle geospatial lifelines and their aggregations in a comprehensive fashion. More problematic are representations that include off-network locations, and merge them successfully with linear representations. Finally, the problems of interoperability discussed earlier suggest that solutions must be sought that permit the co-existence of multiple, conflicting representations. Thus the second challenge is to devise representations for the full range of information types needed for a comprehensive approach to GIS-T and ITS.

4.3. Unambiguous communication

One of the most important tasks in GIS-T and ITS is to communicate location. For example, it may be necessary to communicate the location of an accident, or the address of a delivery. Two approaches are available: linear referencing, using some variant of street address or route and milepost, and geographic referencing using a two- or three-dimensional coordinate system. Increasingly these are mixed, as when the location of an accident is determined using GPS and communicated to a dispatcher, who must translate the GPS coordinates to a street address. We have seen how this translation is supported by the map view, but with varied success because of lack of standards, positional inaccuracies, and lack of interoperability between databases.

When humans are confronted with this problem, they resolve it by a process of negotiation. For example, an occupant of a rural home without a street address might call 911, and specify the location as ''the first house on the left after the bridge''. If that is ambiguous to the dispatcher, a discussion ensues in which additional information is requested, until the location is unambiguous.

Noronha's work with commercial street centerline databases has shown that no single method is capable of unambiguous specification of a location: linear addressing, geographic coordinates, and all of the alternative methods in the proposed Location Reference Messaging Standard are subject to uncertainty in certain circumstances. Yet that conclusion would come as no surprise to a 911 dispatcher, who knows that no single method works at the level of human communication. Thus the third research challenge is the following: to develop methods of inter-computer negotiation that produce completely reliable communication of location, emulating and outperforming the traditional practice of inter-human negotiation.

4.4. Economic models

GIS-T is inherently one of the most highly structured of GIS applications, where much should be known about the costs of producing data and making decisions. There should be simple relationships between data accuracy and the cost of data creation; and simple ways to estimate the value of a given data set in making certain kinds of decisions. For example, it is possible to know the relationship between the expected response time to an emergency, and the quality of the information on which the response is based. GIS-T thus provides a prime opportunity for the development and calibration of economic models of geographic information, something that has been discussed for a long time but never implemented in a substantial way. The fourth research challenge is to build economic models of the creation and use of GIS-T information, as an aid to the development of a healthy GIS-T industry, and as an example to other applications of geographic information.

4.5. Response to new technologies

In part, the history of GIS is the history of opportunities. Few if any of the technologies of GIS have been developed specifically in that context: most have been adopted from other, often larger application domains by researchers and developers with an ability to see and exploit opportunities. Triangulated irregular networks, for example, are the triangular meshes commonly used in computer graphics, and the georelational model is a clever use of the more general relational model.

In the next few years GIS-T and ITS are likely to be the beneficiaries of a large number of technical developments. Many of these are already apparent, while others have yet to emerge. Wireless communication may radically change practices in field data collection, and continuing miniaturization of hardware will likely impact our ability to compute in field settings. The summer of 1999 saw the first widely available products using the AutoPC standard, a derivative of Microsoft's Windows CE designed to support interaction between vehicle and driver, and a range of information processing functions including navigation and downlinking of data.

The fifth challenge is very simple: the GIS-T research community will be the potential beneficiary of a stream of new technological innovations, and must maintain the flexibility and creativity necessary to take quick advantage of them.

4.6. Application to other fields

Finally, and in a sense reversing the previous section, there is much to be gained by looking for applications of GIS-T developments in other fields. The problems of representation of moving objects are not unique to GIS-T, but are motivated by similar issues in wildlife management, health, and many other areas. GIS is a generic technology, designed to provide useful functions across a range of application areas. Similarly, GIScience is most productive when its developments and principles are generic, motivated perhaps by a single field but with implications for many other fields. The final challenge is to find fields that are substantively analogous to GIS-T, and to make research advances by taking advantage of a broadly conceived approach that sees the parallels between widely disparate applications.

Conclusion

GIS-T reflects many distinct influences. Much of the benefit of GIS derives from simple economies of scale in software, since many different processes are supported by a single database. Database designs have been influenced by a number of historical practices and traditions, and three of these have been of particular significance to GIS-T: the map, navigation, and the study of behavior. In each case, however, it has proven difficult to adapt generic GIS approaches to the specific needs of GIS-T, and various extensions have been made to the basic data model.

I have argued in this paper that true progress in GIS-T must derive from a more open analysis of need that is less dependent on legacy. Six research challenges have been identified, ranging from the technical issues of representation and unambiguous communication of location to the economic modeling of GIS-T data creation and use. These are of course merely personal choices, and one of my purposes in suggesting them is to provoke the publication of similar lists. GIS-T needs a clearer vision of its role that is less conditioned by practice and more far-sighted. I hope this paper has helped to contribute to that vision.

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