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Technical and Policy Issues Related to Semantically and Spatially Incompatible Geodata

Stephen J. Bespalko, bespalko@ttd.sandia.gov

John H. Ganter, jganter@ttd.sandia.gov

Marsha D. Van Meter, mdvanme@ttd.sandia.gov

Transportation Systems Analysis
Sandia National Laboratories

Abstract

Both the Intelligent Transportation Systems (ITS) and National Information Infrastructure (NII) efforts have ambitious goals that are expected to improve the fundamental infrastructure, commerce, and society of the United States. Achieving these goals will require rapid development and deployment of *information compatibility* methods through technical and institutional standards. These standards will have to be scaleable and flexible to support new, and as-yet-undiscovered, data. Yet they will also need to accommodate our valuable data reserves. The area of geospatial data, and thus the creation of a National Spatial Data Infrastructure (NSDI), is particularly challenging due to the profoundly different forms, evolutionary histories, and meanings attached to spatial data. We discuss technical issues resulting from the different natures and inaccuracy of existing geodata, and areas where federal policy could lead the way to greater compatibility.

NII mechanisms such as servers, catalogs, and metadata are enabling but not sufficient for sharing of geospatial data. Geospatial data have different formats, schemas (data models and structures), and semantics. 'Simple' terms such as *location* have multiple, partially-compatible meanings from the various scientific and engineering disciplines, and business areas. ITS in particular has functional and data requirements that, on close study, are quite different from those of the geographic information system for transportation (GIS-T) community, which is composed mostly of federal agencies and state Departments of Transportation (DOTs). GIS-T has built highly application-specific data structures for both broad (link-node-impedance networks) and narrow (linearly-referenced) business purposes. These structures are local referencing systems, with limited or non-existent relationships to each other or to any external reference. Error is pervasive, but unquantified. For instance, error from lack of accurate elevation data is often ignored, but it returns to cause data incompatibility. A typical error from ignoring the vertical component of a road in computing arc-length is about 1/10 %. As a result of these special applications and simplifications, some GIS-T data have low accuracy and low *geodetic coupling*. While adequate for their original, intended purposes, the data do not meet the new and unanticipated requirements of ITS.

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Despite these fundamental problems with data quality, the GIS-T community sees ITS as an important new area that they will be required to provide with data. We believe that this view is essentially correct, but naive in the details of what will be a very complex private-public sector symbiosis. Accurate new data, much of it from the private sector, will need to be made compatible with existing data. We will explore this additional complication, and options for resolving it.

For new data, the obvious source of low-cost accuracy is the Global Positioning System (GPS). GPS is being used in private vehicles, and by both public and private entities to develop highly-accurate datasets for ITS applications. For example, several firms are 'digidriving' streets in major metropolitan areas to supply base maps for commercial navigational aids. These 'data harvesters' are essentially migratory; they rapidly collect very accurate data, which become inaccurate as soon as a municipality adjusts the infrastructure by adding subdivisions, erecting traffic barricades, etc. Clearly, an NSDI requires long-term stewardship of spatial data on a local level.

Thus new, high-accuracy geodata do not solve the problem of a data infrastructure, and in fact complicate it. To make geospatial data a useful and durable asset, the NSDI must serve both functional contexts like ITS, and design, construction, and maintenance (cradle-to-grave) contexts like GIS-T. Inherently-imprecise historical data, such as pavement repair locations and underground utility rights-of-way, cannot be excluded from an infrastructure increasingly populated from high-accuracy sources.

All of the problems mentioned above lead to profound institutional issues. The private firms are very good at collecting data, but are incapable of maintaining their accuracy. The state DOTs are probably the appropriate jurisdictions to maintain high resolution data that ITS requires, but they are unlikely to be receptive to this responsibility. The current GIS-T data, as inaccurate as they are, are acceptable for most state requirements. Several alternatives exist for solving this dilemma. *We will contrast two alternatives: first, promoting an adaptive data technology that incorporates existing and historical data, and second, offering incentives that induce state DOTs to modify their methods and procedures to adapt to the high quality data that the ITS requires.* In either case, policy level intervention will be required to insure success.

Overview

Transportation research and development at Sandia National Laboratories has been primarily technical in nature, involving computation, high-volume spatial data management, and communications applied to the management of vehicle fleets carrying special cargoes. More recently, we have begun a project to design and prototype a 'next-generation' Geographic Information System (GIS) for utilizing the spatial data underlying many of these projects. As a result, we have been exposed to pre-emergent technologies which have been either classified or prohibitively expensive outside of defense

applications. We have thus become aware of areas where new or better methods of dealing with spatial data would benefit transportation technology.

The two issues we will present here are the need for vastly improved digital maps or 'representations' of the surface transportation infrastructure and the relative abilities of public and private entities to create and maintain such representations. We will motivate these issues with examples of current and anticipated advanced transportation projects that we believe would benefit from, or clearly require, considerably better data than are currently available from public entities, usually state departments of transportation.

Defining what we mean by improved data is central to the arguments we wish to make. The current body of spatial data is largely, and for the most part literally, digitized (or computerized) two dimensional maps. At typical scales, buildings are represented by dots, squares, and occasionally groups of lines. Roads are typically represented by a single line or possibly polygons. The roads are then differentiated with various attributes such as state or federal designations, direction, or road type. From these data, simple maps can be generated that display the attributes with mixtures of color, thickness and pattern.

Our work to implement a prototype of the next-generation computer system to manage spatial information is leading us to believe that the digital map metaphor mentioned above (sometimes referred to as the point-line-polygon model) is inadequate for many applications. Or more specifically, that many applications, including those defined by the ITS program, could be greatly improved with a three-dimensional object-oriented model.

Adding the third dimension to the spatial data would in many regards make the systems more like a Computer Aided Drafting (CAD) system used by engineers. From the standpoint of transportation systems *design*, this is already the case. We believe that the many new demands on the spatial data representing our transportation system will require many of the same characteristics that design-engineers already take for granted.

Computer systems described as 'object-oriented' organize data and procedures that access the data in ways that closely reflect their real-world counterparts. For our purposes, rather than a line or a polygon representing a road in the current systems, we believe there are inherent benefits in asserting there is an object called a road. This object includes many properties of a real road. One of these properties is how the road is rendered as a two-dimensional map at a particular scale. The other properties would include the detailed path the road follows on the surface of the earth. Most of the advantages of the design we intend to implement follow from either the inclusion of the third dimension of data, or from the object orientation of the software we will use to program the system.

Who will design, construct, and maintain these new data representations? Many of the state Departments of Transportation (DOTs) and regional organizations (county and city governments, metropolitan planning organizations [MPOs]) are far behind other organizations (both public and private) in terms of being part of the 'information

revolution.' We will demonstrate a paradox: local entities that build and maintain infrastructure for their constituents are the logical 'owners' of representations, but often least able to take on this responsibility due to fiscal limitations and short-term political pressures. Bringing these organizations into the ITS realm is therefore critical to the overall success of the advanced transportation program in general.

Assuming that our technical intuition is correct (since our project is not yet complete), several very important policy issues emerge. First, whose interest is being served by investing in technology (e.g., increasingly elaborate spatial referencing schemes) that will clearly be sub-optimal in the near future? We propose recasting the underlying designs to depend on, rather than avoid, highly-descriptive data. These data are well within the capability of current digital technology to collect, maintain, and apply to advanced transportation problems. Second, most of the emphasis and justification for the NII has been to promote electronic access to federally collected information previously available through the Freedom of Information Act. The ITS, although clearly information intensive, shares very little in common with data of this nature. Most importantly, the ITS-related data, except in limited examples such as data concerning the Interstate Highway system, are owned by the states. Third, assuming that the complexity of making this immense amount of frequently-updated data needed for the ITS and other advanced transportation projects can be surmounted, how best should the federal government bring the states into the 'information age' sufficiently to maintain and supply the data?

The balance of this paper will be in four sections. The first section will discuss some of the background of how the spatial data evolved into the current state-of-the-art. The next section will cover the data requirements of the typical state DOT in more detail. This is intended to motivate the subsequent discussion of the alternatives for promoting the state DOT participation in advanced transportation initiatives. We will also describe the recent Pooled Fund Study which was the method used by the states to adopt a common technical strategy for adopting the federally mandated ISTEA systems. Although considerably less ambitious than the changes implied by the advanced transportation projects described here, the Pooled Fund Study is a good example of how federal transportation policy can be used to stimulate significant technological change at the state level. Third, several advanced transportation projects will be described, with particular attention being given to data requirements. Fourth, we will discuss the implications of these new technologies for the two advanced transportation projects. We conclude by considering the opportunities for federal policy intervention to influence the introduction of the new technologies.

Background: Transportation Geospatial Data at Local and State Levels

We will discuss two characteristics of state DOTs that illuminate the issues relevant here: the computer systems and data sets that the state DOTs do have tend to be treated as operational and highly application-specific tools; and second, the operational view that these agencies maintain is reflected in the most common use they have for the data—

locating and managing the transportation assets under their jurisdiction. We will describe the most common information tool used by the state DOTs, a method referred to as linear referencing.

Geographic Information Systems for transportation (GIS-T)

State DOTs have varied histories and these help to explain the very different spatial information systems that have evolved in each. Because information systems (IS) is a relatively new discipline with few formal methods, particular systems almost always reflect the personalities of those who have founded and developed them. Thus, state DOTs and similar regional organizations have different hardware, software, data formats, data structures, spatial references, etc. — sometimes even when they are in the same agencies.

Nonetheless, most state agencies utilize a data management system specialized for managing spatial data termed 'geographic information systems for transportation' (GIS-T). Such systems are used for regional transportation planning, where census data are used to develop growth projections and guesstimates of traffic on commuter thoroughfares. GIS-T supports specific applications such as corridor planning, property valuation and condemnation, environmental impact analysis, and a variety of permitting.

To understand the flow of information within a typical state agency (and ultimately why the states will have a difficult time supplying the data needed for advanced transportation systems), let us consider the information used to design and build a road. First the planners determine the rough outline of the road corridor utilizing a GIS-T. Second, the planners use the GIS-T to supply rough outlines to computer-aided design (CAD) systems in the engineer's office. CAD is then used to create detailed, multi-dimensional models where volumes of cut-and-fill, pitches of drains to carry off rainwater, and similar minute details are designed and tested before any concrete is poured. At this point the 'flow' of data and information begins to divide and disintegrate. The GIS-T and CAD systems are used to produce large paper plans which are carried into the trailers where foremen oversee construction. When construction begins, plans are marked up and modified. Later, 'as-built' drawings are created to attempt to capture the final configuration for future maintenance efforts. However, these data are often lost, because now the drawings are afterthoughts rather than immediate necessities for work to begin. The roadway goes into operation with a loose or non-existent connection to its past (where underground utility lines run, what concrete batches went where) and its future (volume counts for lanes).

GIS-T thus tends to be employed as a short-term operational tool, rather than a long-term, cradle-to-grave management system. It is typically populated with data of varying scales, collection methods, and lineages. There is seldom 'metadata' (data describing data) that quantify and track the collection over time. The highway begins to age like a car whose

owner's manual and service log have been discarded. This is unfortunate since the very information that is lost is the information that would enable many of the advanced transportation projects discussed later.

In summary, engineers utilize high quality data to design highways. Most subsequent business applications tend to use the least data possible, and often to degrade the data, to achieve their short-term goals. When viewed from a global or enterprise perspective, or from the standpoint of implementing ITS, this is clearly a costly and obsolete approach.

Linear Referencing

The maintenance and operational groups in state DOTs have become quite adept at utilizing the low resolution, and usually inaccurate, data that are made available to them. In fact, most if not all of the state DOTs have developed methods that reduce their information requirements to one-dimensional data. This is done through a method called linear referencing.

The basis of the method is that the locations of objects are established relative to some other object or location that can easily be determined. In practice these are generally intersections. Along highways where intersections are much less frequent, mileposts are located beside the roadway and locations are defined relative to the mileposts.

Linear referencing alone will not serve more sophisticated systems such as those defined in the ITS. There is also very little possibility that the states will benefit fully, at least in the short term, from more powerful location referencing systems (such as GPS) if they continue to focus on linear referencing. Therefore, we are skeptical that the states are going to see much immediate direct benefit from the introduction of new representational and transportation technologies. There will have to be other reasons for the states wanting to adopt more sophisticated methods and technologies.

Further complicating the situation is that in some cases individual departments in the operations groups at state DOTs have developed their own referencing systems that suit their purposes. For example, the Florida state DOT has a project underway to combine their current fourteen linear referencing methods into a single generalized method. Although this will definitely improve this DOT's ability to share data between the various groups in the department, it will do very little to prepare for the requirements of the advanced transportation projects.

Examples of Advanced Transportation Projects

Several examples of advanced transportation projects where we have identified the potential need for three-dimensional Geographic Information Systems (GIS) data are presented here. In each of the cases below we will describe briefly how the current two-dimensional data are sub-optimal for several of the more sophisticated projects. We will

describe services where improvement in two-dimensional data leads to better designs and show how three-dimensional data can achieve the improvement.

In the following sections we will describe three advanced transportation projects. To avoid the perception that the introduction of high-resolution three-dimensional data is only advantageous for long-term projects planned for deployment decades in the future, we will describe projects destined for the short-term (i.e., one to two years out), medium term (five to ten years out) and long term (perhaps twenty to thirty years out).

Short Term: The Pooled Fund Study

The Pooled Fund Study is a cooperative effort on the parts of forty states to implement the transportation management and planning systems mandated by the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). The study was initiated in November of 1993 through the Alliance for Transportation Research. This project is an important precedent from the standpoint of how the federal government can promote the assimilation of new technology into the fifty separate state DOTs (although the future of the project is in question given the current thinking on unfunded federal mandates).

A principal goal of the design team for the Pooled Fund Project is an integrated information and systems structure. The design is also intended to be extensible to provide for easy extension as new requirements are identified. The design could easily engender a new mode of state DOT organization and efficiency and, if achieved, would be a radical departure from the current practices. In particular, a cradle-to-grave approach to infrastructure and its associated information management would be instituted.

A key component of the integrated systems design was the inclusion of a general linear referencing system intended to serve as a *de facto* standard. If adopted, the system would enable all state DOTs to maintain one set of linearly-referenced data with a formal method of 'transforming' one system into another. The underlying methodology employed is to maintain an underlying 'reference system' that is of sufficient generality and spatial resolution to 'map' one coordinate system to another.

Without going into the mathematical details here, the goal of arbitrary transformation between coordinate systems is, in general, impossible using two-dimensional data. We are in the process of showing that although the transformations are possible within reasonably good approximation in most cases, the errors introduced into the data by ignoring elevation are not always negligible. For example, a typical error in Albuquerque, where the landscape gains about 1000 feet in the five miles from the river valley in the center of town up to the plateaus and mountains bounding the city is about 1/10%. This may seem like a small amount until one realizes that it translates to about 40 feet, certainly not acceptable when trying to locate objects with any precision (e.g., vehicles in a particular traffic lane).

With current two-dimensional systems, the error can be accommodated to a certain degree by using techniques that 'adjust' the data where errors are judged to be too large. The alternative that we advocate is to simply store the data needed to provide true data independence. Our analysis to date is leading us to believe that the amount of data required to analytically eliminate errors due to coordinate transformation is fairly minimal. The modern relational database management systems (RDBMSs) and even more current object oriented databases (OODBMSs) appear capable of dealing with the additional data needed to solve this problem.

A second area where three-dimensional data will help achieve the goals of the Pooled Fund Study is in providing integration and cradle-to-grave transportation management. As stated before, the information flow required for the design, construction and maintenance of a road currently goes through several transformations. The engineers already utilize highly detailed three-dimensional data in CAD systems that are discarded when the construction phase is completed. Given that there are now areas emerging where these data would be useful to clients of the transportation system, it would be highly appropriate for the data to be maintained in the system. Various applications would view the data in a format appropriate for their purposes. In this way the divergence we described before would be eliminated.

The problem with maintaining the data in a three-dimensional format is that virtually none of the state DOT business applications (at least those other than engineering) are capable of benefiting from the data. The consumers of the data will largely be outside of the state DOTs, and in some cases the clients will not exist for years or decades. Since data are so expensive to recollect, when does it become cost-effective to save the data even if there is not an immediate client identified? Unless the state DOTs shift to thinking in a longer-term perspective, it is unlikely that the data are ever going to be available for all potential advanced transportation projects.

Medium Term: ITS

Intelligent Transportation Systems (ITS) will use technology to re-engineer our transportation infrastructure into one that maximizes safety and minimizes harmful environmental effects. There are twenty-nine ITS user services defining the main systems in advanced transportation. These key systems are: Advanced Traffic Management Systems (ATMS), Advanced Traveler Information Systems (ATIS), Advanced Vehicle Control Systems (AVCS), Commercial Vehicle Operations (CVO), Automatic Vehicle Location (AVL), and Automatic Vehicle Identification (AVI). These systems will serve the nation by monitoring and controlling traffic on highways and streets, giving travelers specific routes to follow, eliminating drivers with autopiloting, improving the efficiency of commercial vehicle deliveries, and eliminating the need for weigh stations and toll collectors. We will discuss in more detail several of the components of these systems that are dependent upon geospatial data. Route guidance, vision enhancement, and automated

vehicle operation are some of the user services where current geospatial data, limited to two-dimensions and linearly referenced, would impose severe constraints.

Route Guidance

Route guidance provides users of private vehicles, commercial vehicles, and even pedestrians with real-time transportation information. The service will display a suggested route to help a user reach a specific destination, taking into account traffic conditions such as congestion and road closures. Information about roadway networks and transit schedules will be available in the early implementation stages.

The current technology for route guidance uses planar technology which is unable to identify changes in elevation. This becomes a problem especially near bridges and complex intersections like cloverleaves where the computer interprets the coincident road segments as being on one plane; that is having connections where none exist. The current GIS technology will tend to mislead the user by asserting that the bridge and the road beneath it are, in fact, an intersection. It is possible to manually circumvent this problem, but it is not always effective with more complex bridges and intersections, or large urban areas. By using the third dimension, the data model now incorporates an elevation coordinate and is able to discriminate the non-planar or overlapping road segments. This system will distinguish the bridge and road as two separate objects.

Route guidance technology also will benefit from spatial data that are organized in an object-oriented manner. Current GIS programmers have great difficulty when encountering different modes of transportation. Since all elements of the transportation system are represented by the same points, lines, and polygons it is very difficult to maintain and represent the difference between modes like railroad tracks, streets, bicycle paths, and subway routes. A route guidance system, like current planning models based on GIS data, frequently makes the error of routing a car onto a railroad track and pedestrians down a subway route. This is currently corrected by manually tagging the different modes with database attributes that can be translated into humanly-readable symbology such as color, line width, and graphical patterns. With object oriented technology it is much easier and significantly less error-prone to identify the routes as being strictly for trains, people, etc.

Vision Enhancement

Vision enhancement, or the projection of information concerning vehicle speed, direction, proximity of other vehicles and roadside information would be a desirable service during adverse weather conditions, and possibly while driving on congested freeways typically encountered in urban areas. Current prototypes of vision enhancement systems utilize low-power radar and object recognition technology to provide the information to the driver. The drawback of these designs is that the quality of the information available to the driver is likely dependent on the traffic conditions. If there are too many vehicles

around the driver's car, one can imagine that the information concerning the vehicle path will be questionable, since all of the information is deduced in real-time by the object recognition system.

A potentially stronger design would incorporate a three-dimensional model of the road. Assuming that the currently expensive technologies for sensing vehicle orientation could be fused with the road model, the vision enhancement would now be independent of the traffic conditions. In this new scheme there would be a constant projection of the road on the windshield (a 'heads-up display') which would let the driver see the road and other important information such as road signs which are difficult to see in the best of circumstances on busy freeways. A driver could distinguish turns and elevation differences accurately with this new technology. It would be impossible to model a three-dimensional road with a two-dimensional system or with local sensing technologies like radar.

Long Term: ITS

Automatic Piloting

Various alternatives exist for automatic piloting of vehicles. The less ambitious plans call for 'platooning,' or coordinated driving of cars to increase throughput on urban freeways, while the long-term goal of complete autopiloting is probably attainable in the thirty to forty year horizon. Thus ultimately, a rider could simply indicate a desired location and the vehicle would drive there. In either case, there are benefits derived from the availability of the high resolution geospatial data described here.

Current designs call for the auto-piloted or platooned vehicles to have dedicated highway lanes strictly for their use. These vehicles would then be controlled by magnetic nails implanted into the pavement about every one-hundred feet. The vehicle turns a specific direction when polarity, as detected from the nails, changes. Control systems based on this design reduce the piloting problem into two problems: a two-dimensional lateral control problem and a one-dimensional longitudinal problem. Further, the current designs also depend on the assumption that they would only be used on divided highways like interstates, where the designer can make many simplifying assumptions about the topography that will be encountered. The interstate systems have well specified, or standardized, designs for most characteristics of the road including maximum pavement grades, lane widths, and turn radii. The advantage of this construction from the point of view of the ITS designer is simplicity. In practice, it is unclear how well these systems will work.

The magnetic nails give only approximate information about what to expect in the way of directional changes in the road. The main problem is that the telemetry derived from the nails is discrete; information is only available several times a second. Humans, by comparison, are able to use a continuous stream of information to judge when and how

much to change the direction of the vehicle. At best, systems based on the magnetic nail designs will be reliable but are probably not going to be able to achieve the smoothness of a human driver.

Here again, a three-dimensional data source would lead to a much stronger design. The magnetic nails can be used to determine speed with a very high degree of accuracy and location with a fair degree of accuracy. The three-dimensional model would be used for refining the location data and for very precise preview calculations—in other words to predict when changes in the road direction will occur. We believe that a system with these components would be able to achieve the smoothness of a human driver. Further, with the three-dimensional spatial data, it may be possible to operate these vehicles on more complex roads.

Robust geospatial representations, based on three-dimensional data and unconstrained by linear referencing systems, would be enabling for many applications in the transportation arena. Cradle-to-grave management systems that collect and preserve data throughout the lifespan of physical infrastructure could be created. User services like those discussed above, which depend on an omniscient view of locations, destinations, and points in between, would become possible.

Policy Issues

The first issue implied by the need for considerably better spatial data, available in nearly real-time, is how the data will be integrated into the NII architecture. As we observed before, the amount of data and the number and frequency of accesses far outstrip other data available on the network.

The second issue surrounds the ability of the federal government to effect transportation policy if the data required for the ITS and the other advanced transportation systems are widely available on a nationally accessible medium such as the NII. Most transportation stakeholders agree that it is overwhelmingly in the public interest to promote increased transit ridership and potentially fewer vehicles on the road. By making single-occupant driving easier, several of the projects defined by the ITS may run counter to this goal. How will these issues be resolved?

A related policy issue regarding the relationship between the advanced transportation systems and the NII is: even if these systems are ultimately deemed not in the public interest for environmental reasons, should the government allow these systems to be implemented in the open market? There seems to be considerable evidence that ITS services can be made to work, and that several would be immensely valuable to emergency response personnel. That market is certainly not going to be large compared to a scenario where every private car, truck and van is equipped with such devices. But it is clear that most citizens would benefit from the availability of such systems to emergency personnel.

The arguments made here, although highly qualitative for policy discussions, should be sufficient to raise questions about how the advanced transportation programs should be managed and funded. On one hand, the technology needed to implement even the more sophisticated features of the ITS and future projects is rapidly becoming commodity hardware. Similar systems such as the three-dimensional Sega and Sony games are functionally very close to the core electronics required for vision enhancement systems. These systems are expected to cost between one and two hundred dollars in less than two years.

From the organizational perspective, even once all of the other technical issues are surmounted, how will it be possible to bring the states into the information revolution any time soon? The states and local municipalities are the jurisdictions that clearly 'own' the data in that they are the ones chartered with building and maintaining the transportation infrastructures in the states. On the other hand, we briefly showed how they will likely not benefit directly from providing the information needed for others to implement and use advanced transportation systems. We do not see an obvious solution to this problem. The ISTEA legislation may well have provided the mechanism for inducing the states to implement new and better management systems for physical infrastructure. As we have suggested, these systems need to evolve further in order to contribute to an information infrastructure that will support NII and ITS programs. Yet this style of federal legislation to promote a mixture of top-down and bottom-up design (exemplified by the Pooled Fund Study) may no longer be possible in the present political climate. It may well be impossible to implement many of the more advanced ITS features until such time as there is a federal legislative mechanism for propagating a common set of technologies to the states.

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