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A Transportation Feature is a return to a more global entity than a Transportation Segment or Link, wherein attributes are referenced by a linear measure. This entity-relationship diagram reflects a paradigm shift in GIS-T to foster data exchange standards.
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From the Editors

Mapping the Journal's Future


Welcome to this special issue of the URISA Journal on transportation GIS (GIS-T). It portends a bright future for the Journal, and is the first of a series of special-focus issues that we will feature periodically.

1997 was a challenging year for the Journal and the Association. Because of a financial shortfall, the URISA Board temporarily suspended production of the Journal. Member feedback has indicated that the Journal is a vital membership service. It is a crucial feature for our academic community and others who wish to share ideas and results of their work. It provides a unique conduit for education and for the diffusion of research and ideas that practitioners rely on as a basis for application. Consequently, the editors and URISA Headquarters developed a business plan to continue Journal operation for 1998 and beyond.

The plan outlines several changes to Journal operation, format and frequency. The University of Wisconsin Press no longer acts as the Journal's publisher. The editors want to recognize UW-Press, a prestigious publisher of scholarly journals and books, for their help in establishing and operating the Journal through its formative years. Tasks that the Press performed are being internalized by the Journal's editorial staff and URISA Headquarters staff. The overall format will remain the same. The Journal will be published three times in 1998; however, the issues will be shortened to 64 pages, and the feature map and index will be suspended.

As URISA returns to financial health and sets a new strategic direction, the Journal's role and formatting will be reviewed periodically. Future plans for the Journal include discussions about expansion to quarterly publication. Alternative formats, including publication on the Web or CD-ROM, will also be explored.

On behalf of URISA, the editors would like to apologize to you for delay of the Journal. If you have suggestions or ideas, please contact us.

URISA Journal kindly acknowledges private donations in support of the Journal following persons and organizations: Steven French, Marc Armstrong, Zanetti, Will Craig, David Fletcher, William Huxhold, Ken Duiker, David Moyer, Jr. and the Minnesota GIS/LIS Consortium.
This special issue on GIS for Transportation (GIS-T) focuses on the need for integrating one-, two- and three-dimensional location referencing systems for transportation applications of GIS technology. Transportation data are normally referenced by linear referencing methods, which must be converted to Cartesian coordinates for use in GIS.

Fletcher et al. report on a small working conference to make the case for a unified linear reference system for integrating data across separate domains of transportation facility management organizations and transportation user communities.

Duerer and Butler propose a GIS-T enterprise data model to foster data sharing among transportation facility management organizations and transportation system user communities. Five appendixes provide detail on concepts for representation of linear data, external identifier issues, representation of linear data in relational databases. One recommends additions to the Spatial Data Transfer Standard to handle linear referenced data.

Two papers by Vonderohe and Heworth deal with spatial measurements made in the field to support spatial integrity of linearly referenced data. The first compares linear referencing systems with other kinds of location referencing systems. The second paper presents a design method for the field components of linear referencing systems.

**Editorial Intent**

The Refereed section of URISA Journal strives to share new knowledge in the technical, social, economic, and institutional subject areas that support information systems technology. It is the intent that this section of the Journal contain papers that are representative of URISA's membership and the broader information systems community. We encourage the participation of system designers, implementors and users as well as the educational and research community.

We hope that the refereed section will provide reliable information and new insights resulting from experience, research and scholarship. We also hope that this section will link academia, industry and the user community through the sharing of critical investigations and organized knowledge. To this end, we are seeking three forms of work: (1) Reports of current research and development pertinent to the overall information systems community; (2) systematic literature reviews of research for the research and development community; and (3) systematic reviews of applications which explain successful systems and procedures to the overall information systems community.

The refereed process consists of a "blind review." After receiving a manuscript from an author, we send it out for review to three or more persons who have been identified as being knowledgeable in the topical area. The name and affiliation of the author are removed from the paper so the reviewers can give it an impartial review; likewise, the names of the reviewers are not revealed to the author. We ask the reviewers to respond to the following: (1) Is the thesis or purpose stated early and clearly; (2) is the significance of the paper stated explicitly; (3) is the thesis argued persuasively; (4) is the writing clear, concise, straightforward, interesting, and in the active voice, where possible; (5) is the paper tied in appropriate ways to relevant literature; (6) is the paper illustrated appropriately; (7) are the methods sound and appropriate to the paper; (8) are the methods explained clearly; and (9) is the paper interesting to many different types of URISA Journal readers?

If the manuscript is accepted and does not need revising, it is sent to the managing editor for comments and final editing. If the manuscript needs revision, assistance is provided by the editors. If the manuscript is not accepted, it is returned with an explanation by the editors.

Kenneth J. Duerer
The Case for a Unified Linear Reference System

David Fletcher, John Espinoza, R. D. Mackoy, Stephen Gordon, Bruce Spear and Alan Vonderohe

Abstract: Three distinct transportation interest groups—transportation facility managers, civilian transport users, and military transport users—currently collect and maintain separate, often redundant or inconsistent, information. Some progress has been made toward integrating these data within each domain. However, the flow of information between them has received less attention.

Working groups from each domain met to explore a single location-control framework that would encompass all the domains. They concluded that a single unified system could meet the needs of all transportation users. This paper discusses preliminary user and technical specifications for a unified approach, several factors impeding the strategy, and a research agenda for moving forward.

The transportation industry demarcates its activities and data into three functionally and institutionally separate domains. Transportation infrastructure management activities (e.g., planning, design, construction and maintenance) produce the transport links (e.g., roads, rail lines, transit routes) used for travel. In contrast, civilian and military transport operations focus on finding and using the best transport links. Each of these three transportation interest groups—transportation facility managers and civilian and military transport users—currently collects and maintains separate, often redundant or inconsistent information. This information involves the status of passengers, freight, material and vehicles plus state information about the transportation system itself.

Although there has been some progress made in integrating these data within each domain, identifying and improving the flow of information between them has received less attention. Since activities initiated in one domain affect conditions in the others, defining these flows is crucial to the next generation of planners, traffic managers and transportation service users. For example, construction and maintenance activities influence civilian and military route choices and travel times. Conversely, large-scale military movements disrupt civilian travel and have potentially major effects on the infrastructure. This intertwined interest in the transportation system identifies the need for data integration not only within each sphere of interest but among the spheres as well. Although recent policy statements by the U.S. Departments of Transportation and Defense indicate a desire to share information, significant technical and institutional barriers exist.

Over the past decade, information analysts in all three domains have independently concluded that site and event locations are primary information needs and that location attributes are primary keys in developing information integration strategies. Knowing where components and events are relative to one another is essential for planning and operational decision-making. Additionally, these locations serve as a significant integrating mechanism when used as the basis for the organizing information and designing geographic information systems for transportation (GIS-T). Consequently, while there has been considerable work done in each domain to define location reference methods and standards, no one has attempted to define a unified approach applicable across all three domains.

Recognizing the fair degree of overlap among these independent efforts and the opportunity to establish a
single location-control framework encompassing all three domains, representatives from each domain met to explore such an option. Those representatives, along with several invited location experts, conducted a day and a half of technical discussions. The group concluded that a single, comprehensive approach to location control could meet the needs of public sector, civilian and military transportation users. The group also determined that this approach should be led by the federal government and supplemented by state and local transportation efforts.

The attendees also identified several factors impeding the adoption of a single, location-control strategy. They developed preliminary sets of user and technical specifications for a unified approach. They identified a research agenda addressing certain technical implications of the specifications and generated institutional recommendations for moving forward. This paper is a report of those findings.

What is a Unified Linear Datum?

The National Cooperative Highway Research Program (NCHRP) Project 20-27(2) generic data model for linear referencing systems defines a linear datum as:

...the collection of objects which serve as the basis for locating the linear referencing system in the real world. The datum relates the database representation to the real world and provides the domain for transformations among linear referencing systems and among geographic representations. The datum consists of a connected set of anchor sections that have anchor points at their junctions and termini. No (application) attributes are assigned to the datum.

(Vonderohe et al. 1995)

Figure 1 illustrates the relationships among the various objects comprising a linear reference system. Domain-specific applications determine actual transportation objects and events labeled as domain locations. Each site or vehicle can be located by various linear reference methods using combinations of field and office procedures, unique to that domain or application. Multiple application dependent topologies (i.e., transport links and nodes) can be defined and referenced to the datum as well. The key innovation offered by the universal datum is that all of the application specific objects are referenced to a single datum. This datum can also be attached to multiple cartographic representations for display purposes.

A unified linear datum encompasses national, statewide and local transportation facilities and controls infrastructure, vehicle and container locations. The significant point is that public sector transportation managers, the ITS community and the military all use the same underlying datum. This common structure will provide for the unambiguous transfer of location-based data both within and among these groups. Of course, not all applications will require every component contained in the datum. The unified approach requires only that there be exactly one anchor section controlling a specific fragment of the transportation system. This section controls all location methods that fall within its linear extent.

The control framework is not a transport systems application network. That is, the datum does not include any transport systems flow topology or application data (e.g., capacity, demand or impedance characteristics). Routes, junctions, intersections, terminals, travel links and other domain-specific objects relate to the datum; they are not parts of it. Control surveying principles, not
on-transport logic, guide the procedures for determining the locations and extents of the datum components (Vonderohe and Hepworth 1998).

The control framework is also not a unified linear reference method. That is, each domain will still continue to develop and use independent reference methods. In turn, these methods will themselves be incorporated into distinct reference systems. The control framework is used to register these multiple methods and systems in order to transform locations collected in one method into locations referenced by another method. These transformations rely on the ability to relate all locations to the datum.

Issues Impeding Linear Datum Unification

Several issues impede the progress toward a unified, surface transportation-location strategy. These are a combination of conceptual, semantic, technical and operational factors. True unification will depend on overcoming each of these.

1. There is considerable confusion over the distinctions between field, map and database “location” concepts. Field data collectors generally view locations as measurements referenced to an arbitrary number of known reference objects. Mapmakers view locations as Cartesian coordinates referenced to some planar origin. Database designers view locations as data-indexing mechanisms. Each camp uses a variety of measurement and coordinate systems. Because of the contextual differences among field, map and database views, each requires separate objects, and business rules. Field positions, map locations and database addresses are not the same attributes and will not generally have the same coordinate values. Many transportation agencies attempted to use field locations or map positions as database keys. This strategy was difficult to maintain over time because of the dynamic nature of the field locations (e.g., changes in route designations and changes in mile point values resulting from realignments). A smaller number of agencies were equally unsuccessful in their attempts to use data base keys as field locations.

2. Over the past few years there have been several national efforts aimed at producing a standard non-proprietary model specification for linear reference (Seigal et al. 1996; Vonderohe et al. 1995; Fletcher et al. 1995). However, at this time there is still a lack of “universal” consensus about these specifications. Indeed, most people in this field still do not understand the concept of an application independent linear datum used only to control the relative locations of linear objects and events.

3. Although the first linear reference software appeared more than 20 years ago, there is still a lack of technical support (i.e., products and services) of linearly referenced location data. Most software is still ad hoc and idiosyncratic. Most of these proprietary approaches have sacrificed conceptual rigor for application specific performance enhancement. To the best of the authors’ knowledge, only a few commercially available software systems can support the requirements laid out in the cited references.

4. Given the lack of a standard specification and the consequential lack of supporting technology, the final impediment to a unified approach is the lack of operational experience with developing and managing large control frameworks. There is not enough “real-world” experience to convince any but the most risk tolerant to abandon their current efforts and adopt a new strategy.

Propositions Concerning the Unified Linear Datum

The case for a unified linear datum starts with the following propositions. These propositions outline the basic technical and institutional architecture for the datum. Table 1 illustrates various control datums used in the

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Datum Name</th>
<th>Datum Object</th>
<th>Reference Object</th>
<th>Location Specification</th>
<th>Custodian</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-D</td>
<td>WGS84</td>
<td>3D Cartesian axes, origin at earth’s center of mass</td>
<td>Satellite constellation</td>
<td>X, Y, Z</td>
<td>DOD</td>
</tr>
<tr>
<td>2-D (Horizontal)</td>
<td>NAD83</td>
<td>Ellipsoid</td>
<td>Horizontal control station</td>
<td>f, l</td>
<td>NGS/States</td>
</tr>
<tr>
<td>2-D (non-mathematical)</td>
<td>PLSS</td>
<td>Section Corner</td>
<td>Monument</td>
<td>Town, Range, Section, part elevation</td>
<td>BLM/Counties</td>
</tr>
<tr>
<td>1-D (Vertical)</td>
<td>NAVD88</td>
<td>Geoid</td>
<td>Benchmark</td>
<td>TRP + offset</td>
<td>NGS/States</td>
</tr>
<tr>
<td>1-D (Linear) proposed</td>
<td>linear reference datum</td>
<td>Anchor section, Anchor point</td>
<td>Traversal reference point (TRP)</td>
<td>DOT/States</td>
<td></td>
</tr>
</tbody>
</table>

3 This Table was adopted from Vonderohe [4].
United States and serves as the basis for the following propositions:

1. The need for national (or international) surface transportation-location control is very similar to the need for geographic horizontal and vertical control. Historically, the need for navigation charts created horizontal and vertical control systems. Intermodal surface transportation navigation needs of the future justify the proposed linear datum (Seigal et al. 1996). Additionally, as Table 1 illustrates, the proposed structure of the linear datum is analogous to other established datums.

2. Federal custodianship of national datum objects used for navigational purposes has precedence as shown in Table 1. Such custodianship leads to the establishment of a national datum, plus policies and recommended procedures for expanding the datum for local purposes. In addition, public laws created each of the existing national datums. No such legal mandate for a surface transportation datum currently exists.

3. Surface transportation location control is multi-modal and multi-jurisdictional and controls regions of varying extents (e.g., international, national, corridor, statewide, regional, municipal). State and local jurisdictions will add linear datum objects to the national framework (i.e., densify the network). This proposition is consistent with the way in which control points are managed in the horizontal and vertical datums.

4. Linear datum objects can and should be tied to at least the WCS84 3D datum. Tying the linear datum to a mathematical datum provides the same benefits as tying the Public Land Survey System to a mathematical datum (e.g., reference object recovery, mapping, data fusion).

Universal Datum Specifications

The following specifications are an incomplete set of requirements for the unified linear datum. These specifications represent the datum users' expectations.

1. The purpose of the datum is to transform locations between the real-world space and data-world space(s) and to project positions between data spaces.

2. The datum needs to be a consistent, nationwide framework accessible to public and private customers.

3. Multiple public domain and proprietary databases will use the datum.

4. Although the datum itself must be in the public domain, many applications using this framework will be proprietary.

5. The datum needs to be able to control location at multiple levels of resolution (e.g., highway location, roadway location, lane location).

6. The datum needs to be able to control locations determined by many different methods (e.g., route and mile point, route and reference point, control section and offset).

7. Each functional domain has distinctly different accuracy specifications. This is a function of the smallest objects (i.e., the highest resolution) in the domain(s), the need to discriminate the relative distance between two objects or the precision of the location measurement devices.

8. Navigation and traveler information functions need 3- to 5-meter positional accuracy. The need to discriminate between or resolve the location of individual vehicles determines this requirement.

9. Datum and reference objects need to be identified easily in the field. These objects also need to be fixed, stable and recoverable over long periods of time (decades, if not longer).

10. The unified datum should be domain-content (i.e., application) neutral.

Design Specifications

The workshop participants developed a preliminary set of design specifications for the datum guided by the following design principles. A more detailed set of specifications may be obtained from the primary author.

- Field location reference objects need not be the same as datum objects. The same real world feature (e.g., an at-grade intersection) may have a number of roles and be represented in the database by multiple objects (e.g., a node, an anchor point, a traversal reference point).

- The linear datum can be expanded over time to accommodate new surface transportation facilities. The datum can also be expanded to control facilities not originally included.

- Existing and proposed applications will create additional design requirements. The initial datum design must be flexible enough to accommodate as yet unidentified applications. At the same time the design should not introduce any application biases (e.g., cost, performance).

Research Questions

Before the unified datum can become a reality, many operational questions remain. The workshop participants identified a number of issues as essential. Most of these dealt with the selection and measurement criteria for the datum components—anchor points and anchor sections. In other words, what is the required accuracy, precision and resolution of the components? Many of the questions are addressed by Vonderohe and Hepworth (1998).

Recommendations

In order for the unified linear datum to exist, it needs an institutional context. The participants agreed that the overwhelming use of the unified approach will be for ITS applications. As a result, it makes sense that the datum be established and supported by this initiative. The following recommendations are based on that assumption.

1. Synthesize a single domain model for surface transportation-location reference incorporating multiple location-
reference methods from the three existing separate domain models. This synthesis is more likely to involve adopting a consistent set of terms and definitions to describe identical concepts as opposed to having to reconcile divergent ideas.

2. Incorporate this specification into the ITS Linear Reference Standard.
3. Extend the FGDC Geospatial Positioning Accuracy Standards to include linearly referenced points.
4. Develop joint policies and procedural standards for establishing national, statewide and local datums.

Conclusion

The nation's transportation community is at a crossroads concerning its approach to providing useful location information to its customers. We can continue acting separately and according to provincial interests. Or we can combine efforts and act in the nation's interest. Establishing a single unified linear reference system would be a major step to making the transportation information system as seamless as the transportation system itself.

Notes

1. The workshop was held in Madison, Wisconsin on May 10–11, 1996.
2. The differences are related to the precision, accuracy and resolution of the data.

References


GIS-T Enterprise Data Model with Suggested Implementation Choices

Kenneth J. Dueker and J. Allison Butler

Abstract: Sharing of digital road map databases within and among organizations is dependent on translating user requirements to a data model that supports linear and non-linear location referencing systems. This paper examines issues of creating such a data model with the intent of sharing digital road map databases, and suggests implementation choices that can accommodate a range of applications. The proposal is best characterized as a GIS-T enterprise data model suitable for organizations responsible for any and all modes of transportation; e.g., aviation, highways, public transit, and railways. The proposed data model may be sufficiently robust to support ITS map database interoperability by maintaining independence among the geographic datum, the events that occur on the transportation system, the geometry to represent the system cartographically, and the paths through the system. Sample physical database designs are provided to show how the model might be implemented.

This paper describes the process of developing a universal enterprise-level data model and physical database design for geographic information systems used by transportation agencies (GIS-T). The data used by transportation agencies are fairly universal, much more so than the business processes that may be used. Thus, data are a better foundation to establish a common means of communication and GIS-T design. The data model presented here is applicable to all modes of transportation, all map scales, all software products, and all methods of data collection.

Data modes are generally unfamiliar to computer systems users, but they excel in providing a clear view of how the various things about which we want to store and retrieve information are related to each other. Those “things” are referred to in data modeling as entities. Thus, the kind of data model that is most useful for our purposes is an entity-relationship diagram (E-R diagram). An E-R diagram for a generic GIS-T design is independent of map scale, specific entity attributes, mode of travel, and location measurement methods.

Figure 1 shows the few symbols used to construct E-R diagrams. An entity is a simple box with a name. Relationships are lines with one of three symbols used to define the relationship of entities connected by the lines. The example in Figure 1 shows that people may exist without having jobs, and jobs may exist without their being filled by people. Some relationships may be mandatory, such as a road segment must have one surface type. Some relationships are unusual and must be named. Most may be viewed as equivalent to “has,” as in “an employee has a job.”

We believe that the sharing of digital road map databases within and among organizations is dependent on describing user requirements in a data model. This paper examines issues of sharing digital road map databases and proposes a data model with suggested implementation choices that can accommodate a range of applications. The proposed data model is based on the independence of:

1. geographic datum;
2. the events that occur on the transportation system;
3. the geometry to represent the system and;
4. the topology of links and nodes that make up transportation systems.

The model is constructed through a series of steps that begins with a basic version then adds components to accommodate more complex needs. This journey of steps both explains how the model was developed and presents various versions to meet differing needs—all of

Kenneth J. Dueker is director of the Center for Urban Studies and professor of urban studies and planning at Portland State University. He is a founding editor of the URISA Journal and was a founding chair of the subcommittee on GIS-T for the Transportation Research Board.

J. Allison Butler is currently the GIS manager for Hamilton County (Chattanooga) Tennessee and is responsible for the regional data center. He was previously with the Florida Department of Transportation where he developed and managed their first production GIS environment and statewide base map. He is certified by ASPRS as a mapping scientist in the fields of geographic and land information systems, and is a member of the American Institute of Certified Planners.
The Basic Model

Figure 2 shows the most basic transportation data model. It includes transportation features, the jurisdictions in which they are defined, and the events that occur on them. In this context, an event can be an attribute or physical component of the transportation feature.

Figure 2 includes six entities. Three are subtypes of a more generic-type event. Here are the entity definitions:

- **Jurisdiction.** The political or other context for designating transportation features and their names, which may be merely numerical references unique within the jurisdiction. Jurisdiction need not be the same for all transportation feature types. Airports can be named on a national basis, with streets named on a zip code basis.
- **Transportation Feature.** An identifiable element of the transportation system. A transportation feature can be like a point (interchange or bridge), a line (road or railroad), or an area (rail yard or airport).
- **Event Point.** The location where an event occurs. Event Point is defined initially as an offset distance from the beginning of the transportation feature.
- **Event.** An attribute, occurrence, or physical component of a transportation feature. Attributes include functional class, speed limit, pavement type, and state road number—things that are not tangible but describe a tangible element, such as a road. Occurrences include traffic crashes and projects. Physical components include guardrails, signs, bridges, intersections, and other tangible things that are field-identifiable elements. There are three event subtypes: a given event instance may be expressed as more than one subtype:
  1. **Point Event.** A component or attribute that is found at a single location (one event point). Point events may occur independently or on transportation features of the linear or area form.
  2. **Linear Event.** A component or attribute that is found along a segment of a linear transportation feature. Linear events are defined by two event points (beginning and ending). Linear events may occur only on linear transportation features.
  3. **Area Event.** A transportation feature component or a non-transportation entity that affects a transportation feature. Areas can be explicitly represented as polygons or implicitly represented as to where they intersect transportation features. The implicit option is called an area event and is represented through related linear and point events. For example, an area event could be a city. The city could be expressed by creating a linear event for the portion of a transportation feature located within it, or as point events
where the city limits cross a transportation feature. Another example could be a park-and-ride lot, which would be stored as a point event located where the driveway to the lot intersects the adjacent road (transportation feature). Area events may be applicable for any kind of transportation feature.

Let's look at the relationships between entities. First, we see that a jurisdiction may include one or more transportation features. Next, we see that a transportation feature may include one or more event points to define the location of point and linear events. A given event point may define the location of several point and/or linear events. For example, the speed limit on a street could change at the same point as the number of lanes. The model shows that there are two relationships between Linear Event and Event Point, one for the beginning event point and one for the ending event point. An area event may generate one or more linear and/or point events.

An obvious question is, "Why aren't there relationships between Transportation Feature and the three event entities?" It is certainly true that the transportation feature possesses the subordinate point, linear, and area events. However, that ownership is expressed only through an event's location on the transportation feature. Thus, the answer is that the Transportation Feature to Event relationships go through the Event Point entity. An event is "owned" by a transportation feature by virtue of its location on that feature; i.e., its defining event point(s).

It is equally important to look at the business rules included in the model, for data models are not independent of the business processes they serve:

- Transportation features are contained completely within a single jurisdiction. A transportation feature that exists in more than one jurisdiction must be subdivided at the jurisdiction boundaries it crosses. Transportation feature ID is unique within a given jurisdiction.
- The physical path of a transportation feature must be arbitrarily defined. While a highway transportation feature may follow the same path as a given named or numbered route, it is the physical feature, not the named or numbered route, that is being defined.
- The transportation feature name, or identification, must be independent of the named street or numbered route that may be followed. A publicly recognized name or number designation is an attribute of all or part of a transportation feature, not an identifier of a unique transportation feature. (We'll show how to construct named and numbered routes, or traversals, on pp. 16-17 and in Appendix 2.) You must use an identifier that will never change.
- Point and linear events on linear transportation features, such as roads, are located using a linear location referencing system (linear LRS) based on a distance offset from a beginning point.
- Only one linear LRS is used to relate point and linear events to transportation features.
- All events must be assigned to a transportation feature; i.e., exist on, in, at, or adjacent to a transportation feature.

The data model in Figure 2 assigns an event to one, and only one, transportation feature and each feature to one, and only one, jurisdiction. This means that a point event representing an intersection of two linear transportation features must be assigned to both; i.e., there must be two intersection point events, one for each transportation feature. For example, the intersection of Broad and Main Streets may be looked at as one event, but it is defined as two in the data model of Figure 2: one on Broad Street where Main Street crosses it, and one on Main Street where Broad Street crosses it. This is certainly a valid approach. However, one of the advantages of going to GIS-T is being able to get past the one-at-a-time limitation imposed by straight-line diagrams. We need to do one more thing to complete the basic model: add the ability to relate an intersection-type point event to more than one transportation feature. We present this in Figure 3.

Figure 3 offers the solution of adding an intersection entity (Transportation Feature/Point Event) and presents the completed basic GIS-T data model. The new business rule here is that a point event may be located on more than one transportation feature. This allows us to see the intersection of Broad and Main Streets as one event involving two transportation features. It will still

**FIGURE 3.** Adding intersections of transportation features to the initial model.
be stored as two intersection point events, one on each street. However, we now can create a single table that stores all the information about intersections, so the intersection attributes are not duplicated for each transportation feature. The two point event records store only the location of the intersection on each transportation feature, plus the fact that it is an intersection and the number assigned to the intersection. (We discuss physical database design later in this paper.)

Note that we did not, in Figure 3, simply make the relationship between the Transportation Feature and Point Event entities many-to-many; i.e., to show that a given transportation feature may include many point events and a given point event could be on more than one transportation feature. We are required to eliminate all many-to-many relationships in developing a relational database model since they cannot be directly implemented. This leads us to add a new entity, called a resolution or associative entity, to eliminate the many-to-many relationship. Essentially, we have separated the many-to-many relationship into two parts. The original one-to-many from Transportation Feature through Event Point to Point Event is still there to show that a given transportation feature can include zero, one, or more point events. The new relationship, through Transportation Feature/Point Event, shows that a point event may be part of one or more transportation features. This resolution entity functions in the real world as an intersection, or a junction in a multi-modal context; we will use the term “junction.”

Adding Topology

The next step in developing our GIS-T logical data model is to create the means to define paths through the transportation system. We will call these paths “traversals” to be consistent with NCHRP 20-27 documents and others (Vonderoehe et al. 1993, 1995). The requirement for pathfinding is that we provide topology, or information on how the various transportation features connect to one another. Adding junctions is a start on topology and, for some applications, that might be enough. But there is a better, more universal solution, which we show in Figure 4.

Five new entities are added in Figure 4. All but Traversal Member are defined in Appendix 5, but two definitions need to be repeated here:

- **Traversal.** A path or route through a portion of a transportation network consisting of one or more links. A traversal could be determined by following a state road number or looking for the best route to move a large load.
- **Traversal Segment.** An atomic component of a traversal. A traversal segment is defined by a link and its attributes. In some ways, Traversal Segment is a resolution entity between Traaversal, Link, and Linear Event. A traversal seg-

**FIGURE 4.** The model with topological (pathfinding) entities added.

A traversal is composed of traversal segments. Each traversal segment is a link in a linear transportation feature to which have been added attribute data (linear events) that provide information useful to choosing a path. Links begin and end at nodes, which may be related to point events, such as bridges or junctions. Node data include information on allowable paths leading from each node; e.g., valid turns at an intersection. The design supports travel modeling applications, with traffic analysis zones being area events expressed as centroids (nodes). Together, nodes and links create a sort of schematic circuit design of the transportation system.

Nodes and links may also define other networks, such as bus routes, that are overlaid on a physical transportation network. In such a case, the population of point events might be expanded to include bus stops, with links defining the buses that travel between stops. A traversal in the transit network could be defined for each bus’s path as it follows its route, or for a path requiring a rider to change buses at nodes to complete a trip. If transportation features can be other than roads, then this model could serve non-highway modes of travel that follow the basic linear network model; e.g., aviation (air routes), railroads, and bike paths. Nodes can be “stacked” at specific point events, such as in the case of bus stops at street intersections or highways that lead to railroad yards, but since each is on a different
network, the model shows only a one-to-many relationship between Node and Point Event. The various networks could be connected using virtual links, but we do not show that level of complexity here.

There is a many-to-many relationship between Traversal and Traversal Segment, one that shows a traversal is composed of one or more traversal segments and also that a given traversal segment may be part of many traversals. A mechanism is needed to resolve this relationship. Traversals with their own linear LRS also need a mechanism to store the beginning and ending linear LRS references. We have proposed a Traversal Member entity to meet these needs. A traversal member instance is the specific assignment of a traversal segment to a traversal.

Adding Cartography

If you want more than a text-only system—isn’t that why you are interested in GIS-T?—then the model needs to be expanded to include the cartographic data entities used to draw maps. (see Figure 5) This model defines a data model for drawing maps in a database with cartography. We have added 11 new entities to the model to support the typical cartographic elements found on transportation maps, including those created using dynamic segmentation functions in GIS software. We define all 11 entities in Appendix 5 (Area Feature is synonymous with Area in the appendix). Polygons have been provided to illustrate jurisdictions and area events. These polygons are composed of an interior area and one or more boundary rings. Base map strings are provided to cartographically describe linear transportation features. Due to the requirements of dynamic segmentation software, the relationship of base map strings and the transportation features they illustrate is one-to-one. Not all transportation features have to be illustrated, and those that are may not be represented by lines; some can be areas (e.g., rail yards) or points (e.g., bus stops). Point events are represented graphically using point symbols.

Point symbols are located on the map using a single cartographic point defined within the context of the GIS software’s cartographic datum. Line segments are located using beginning and ending points. Dynamic segmentation subdivides a base map string into segments.

FIGURE 5. The logical data model of Figure 4 with cartographic entities added.
called linear event strings in the model, that correspond
to the transportation feature segments defined by one or
more linear events. Base map strings and linear event
strings are ordered sequences of line segments.

Note that there is no data relationship expressed be-
tween Base Map String and Linear Event String except
as linear event strings are derived from base map strings
by dynamic segmentation. Once they are created, linear
event strings have no connection to the base map strings
from which they were derived. The relationship be-
tween Linear Event and Linear Event String is shown
as one-to-one, although a given string may exhibit the
values of more than one linear event. For example, line
width might represent the number of lanes, while line
color expresses traffic volume. However, this is actually
a one-to-one relationship between a linear event table
combining those attributes into a single table (perhaps
through a relational join) and the related linear event
string.

Area features have been provided as a way to carto-
graphically illustrate area events and to support the use
of area points, which are a simple way to address poly-
gons using a single coordinate pair.

Adding a Linear Datum

GIS-T researchers and users are increasingly interested
in improving data quality. One of the primary sources of
data-quality problems is the device typically used to
collect data on highway features and attributes—the dis-
tance measuring instrument (DMI). A DMI is essentially
a high-quality odometer; however, high-quality is a rela-
tive term. DMIs suffer from a number of errors, such as
changes in the vehicle to which they are attached. Such
errors are said to propagate, or get worse as the distance
of use increases. Other error sources do not propagate,
such as those associated with trying to precisely define
the middle of an intersection while driving through it.

The concept of a linear datum has been proposed
(e.g., Vonderheide and Hepworth 1998) as a way to reduce
the impact of these error sources and thereby improve
the accuracy of location data collected according to a lin-
ear LRS. The concept of a linear datum is based on a set
of well-defined and precisely located anchor points and
anchor sections to which the DMI and other linear LRS
measurement methods may be calibrated. However, the
linear datum does more than just make the data better. It
also provides a means of registering, or aligning, the
transportation features they describe to a real-world co-
ordinate system. This purpose is accomplished by locat-
ing the anchor points in many different LRSes; e.g., state
plane coordinates, the geode used by GPS, the linear
LRS, and any other LRS of interest.

As you might expect, new entities must be added to
the data model we've been developing to accommodate
the needs of the linear datum. The data model from Fig-
ure 5 has been enhanced in Figure 6 with the new enti-
ties needed to support the linear datum. A transporta-
tion feature has one or more anchor sections to provide
linear datum information, such as a highly accurate
length measure. Each anchor section is defined by a pair
of anchor points.

Anchor points may be combined to serve more than
one transportation feature, so linear LRS measurements
are not provided for them directly. Anchor sections carry
the linear LRS measurements for their beginning and
ending anchor points since those measurements are ap-
licable only within the context of the related trans-
portation feature. Anchor points are often conceptual in
nature, typically being such things as the intersection of
two road centerlines, so they must be tied to physical
objects that are more readily located. These physical ob-
jects, called reference points, can be located in all appli-
cable geographic datums. To avoid a many-to-many rela-
tionship between Reference Point and Geographic
Datum, we have added a resolution entity called Geo-
graphic Point to the model. The Geographic Point entity
carries the address of the reference point in each geo-
graphic datum. The Reference Point/Anchor Point enti-
ity allows a given reference point to locate more than
one anchor point, and for a single anchor point to be loc-
cated using more than one reference point.

The Real-world Location entity describes the actual
physical object being described. For example, a real-
world location could be "the intersection of Main St. and
Broad Ave." This could result in the related geographic
point being the exact intersection of the two street cen-
terlines defined as a latitude/longitude pair of coordi-
nates established in the North American Datum of 1983
(geographic datum), as measured from a monument in
the northwest corner of the intersection (reference
point). The intersection centerpoint would also be de-
defined as an anchor point that begins an anchor section
and defines the 0.000 milepoint (origin) of a transporta-
tion feature and may be related to cartographic points in
a cartographic datum.

Supporting Non-transportation Features

The final option we will discuss is support for non-
transportation features and the direct positioning of
transportation features. If cartographic display of these
features is adequate, the models shown in Figures 5 and
6 are sufficient. This is because the models already allow
areas, line segments, and point symbols that are not re-
lated to transportation features by virtue of their op-
tional relationships: an area feature may relate (through
events) to a transportation feature; a base map string
may relate to a transportation feature; a point symbol
may relate to a point event. GIS software functions are
available in many fully featured products to define and explore the spatial relationships between graphical objects on a map. However, we offer a more elegant solution in Figure 7 (next page) that allows non-graphical analyses and a fully integrated database. This is the complete GIS-T enterprise data model.

The only changes to the model of Figure 6 are the addition of explicit point and linear feature entities, plus a way to relate event points to geographic points. Point and Linear Feature entities support the addition of non-transportation features using points and lines in much the same way that Area Feature already supported non-transportation polygons. The last change supports both the location of event points on the surface of the earth—not just on a transportation feature—and the use of non-linear LRSs for defining the position of transportation features and their events. This facilitates the location of events using such field tools as global positioning system (GPS) receivers, in addition to the typical DMI for route/milestone linear LRSs.

All sorts of additional relationships could be defined for the entities in Figure 7. For example, Area Feature could have a one-to-many relationship with Area Event, with each area event storing an attribute of an area feature. The other non-transportation feature entities could be enhanced with a number of other entities, such as their own events. One could instead simplify the model by eliminating Transportation Feature as a separate entity and using the appropriate generic Linear, Point, and Area Feature entity to represent each transportation feature. We kept them separate here since a transportation agency is likely to treat transportation and non-
transportation features quite differently. We support the correlation of a GPS-positioned geographic point and the related linear LRS-located event point through an optional relationship. This relationship shows that one event point may relate to one or more geographic points; e.g., one each supported geographic datum.

The bottom line for database design is that the business needs of an agency should determine whether any additional entities and relationships are needed or may be eliminated. The model shown here is universal and enterprise-wide in nature. It has been subjected to extensive conceptual testing to make sure it accommodates all potential application needs; testing of the physical database design is anticipated in the near future. Recognizing that each agency should go through the data model development/validation process to ensure that the model or its derivative meets the agency’s needs, it is still useful to offer a sample physical database design process. In next several sections, we apply the same feature-based steps to developing a sample physical database design to implement the data model at a state DOT.

Implementing the Basic Model Design

Figure 8 shows what a physical database implementing the model in Figure 3 for a state highway system might look like. The format we use for physical database design uses the same entity relationship symbols, but here they refer to the relationship between relational database tables. Each box represents a table in the database, with its name given at the top (shaded area). A table’s primary key, or set of data elements that defines a unique address for each row, is underlined. Optional data elements are shown in brackets. Notice that there is not a one-to-one relationship between data model entities and database tables.
The Jurisdiction Table stores data that apply to the entire jurisdiction in which transportation features are defined. For this example, let’s assume the jurisdiction level is county. Thus, the Jurisdiction Table stores information about each county in the state, such as population, DOT district in which it is located, etc. A table could also be created to store a list of all the transportation features located within each county.

In the same way, the Transportation Feature Table stores information that applies to an entire transportation feature, which in this example is the extent of a road in a given county. Transportation feature ID is a number. Since the transportation feature ID is unique only within a jurisdiction, then both the jurisdiction ID and the transportation feature ID are needed to uniquely define a specific transportation feature. An event point is the linear LRS measure for a location on a transportation feature. The beginning event point is the origin measure, usually zero. The ending event point is the highest possible measure, i.e., the end of the feature. Transportation feature length must be explicitly stated as an attribute since it may not be the simple mathematical difference between the two defining event points. It is also a good data quality check.

We’ve created a separate Aliases Table to store the various names by which all or a portion of the transportation feature may be known. One could alternatively create a view, or virtual table, using the linear event records storing the names assigned to road segments. The primary key for this table is rather complex since more than one name may begin at a single point, e.g., a county road number and local name may both start at the county line. Note that there was no specific alias entity in the model. The decision to include a table specifically for this kind of linear event is the type of decision one must frequently make to implement a conceptual data model. Since most people know the name of a highway segment, the Aliases Table could be a convenient way to use street name as a foreign key to locate the correct road of interest and its descriptive data. A foreign key is a data element present in one table that can be used to connect to related records in another table in the database (see Appendices 2 and 4 for more information). The Aliases Table can be omitted and Event Table records used, or the Aliases Table can be constructed as an extract (subset) of the Event Table; the latter option is preferable.

The physical data model in Figure 8 shows that there may be many Event Tables, all with certain common data elements. A common structure facilitates the combination of various event tables to describe a segment of highway, so even point event tables should include an ending point reference column (which will have null values). Some tables may optionally include information on lane, side, and offset to accommodate such attributes as traffic counts (by lane), pavement types (by side of road), and signs (offset from road edge). An event ID is used to help uniquely identify a record in the event tables; event ID is unique only for a given transportation feature. Given this design, a junction would result in a record in the Event Table for each intersecting transportation feature, each with its own event ID.

We have elected to refer to the table associated with the Transportation Feature/Point Event resolution entity as the Junction/Event Table. Normally, all data elements in a resolution entity table should be part of its primary key, the various parts of which will provide foreign keys to relate to the appropriate records in other tables. The Event Table’s primary key (jurisdiction ID, transportation feature ID, and event ID) is used in the Junction/Event Table to connect to the point event(s) associated with a junction. The intersecting transportation features may be found (without regard to precise location) by using the Transportation Feature Table’s primary key.

A Junction Table stores information about the junction, such as traffic control for a road intersection. A given junction may have many attributes, and there will be one record for each intersecting transportation feature in the Junction/Event Table. This design leads to the use of a partial primary key for the Junction Table of junction ID to identify all the attribute records for a
given junction. An alternative would be to put all junction attributes in a single record, thereby eliminating the need for attribute to be part of the Junction Table’s primary key.

One should note that the Jurisdiction, Event, and Junction Tables are highly normalized in that they will provide storage space for any number of attributes without the need to deal with null values. An alternative would be to use a separate row (data element) for each attribute.

The Event Table’s design requires that event ID be different for each attribute. This may be undesirable in the case of an event described by multiple attributes. In this case, more attribute columns (data fields) could be added, or the attribute field could be added to the primary key. The full primary key for the Event Table must be included in the Junction/Event Table, so any changes to the Event Table’s primary key must be reflected in changes to the Junction/Event Table.

Incidentally, an end-to-end junction is required at the jurisdiction boundary where a transportation feature is subdivided. This means that a given junction ID will be applicable to two jurisdictions; therefore, junction ID must be unique in the entire database. Some people may question the efficiency of creating junctions where intersections do not occur except relative to a boundary. However, this approach can increase the efficiency of database maintenance by compartmentalizing the database into manageable pieces, such as for base map maintenance.

A junction need not imply the physical connection between two transportation features. For example, an overpass may define a “junction” that imposes a height restriction on one transportation feature but does not provide a physical intersection. Bridges may be universally defined as junctions, whether they carry one road across another road or a water feature. Such an approach could be useful for pathfinding applications, which we discuss in the next section.

Implementing the Topological Data Model

Figure 9 shows the new data tables needed by our sample physical database design to accommodate the new entities added in the Figure 4 data model. The Traversal Table stores information that applies to the entire traversal. Data that apply to only a part of the traversal is assigned to one or more traversal segments.

Multiple Traversal Segment Tables are shown since different ways of defining paths may need different attribute sets. One kind of path through the transportation system is the collection of linear events that all have the same route number or street name. (This is a better way to physically provide a way of tracking numbered or named routes than using the number or name as the primary key since what we call a road can easily change. A primary key should never change.) Named route traversals would only need the alias(es) of the transportation feature linear events used to create the traversal segments. Other kinds of traversals, such as to describe the route of a large vehicle, may need a lot of physical data. By including beginning and ending node numbers in the Traversal Segment Table, a separate Link Table is not required. Link direction can be expressed by including a traversal segment attribute for the information.

A Traversal Member Table provides a list of traversal segment records used by each traversal. A given traversal segment may be part of several traversals. In this design, the traversal segment ID must be unique statewide. The Traversal Member Table could also include beginning and ending measurements for a traversal-specific linear LRS, such as that used on Interstate highways. This approach is based on distance over the length of the traversal. Since a traversal segment may be part of several traversals, the Traversal Segment Table can only include linear LRS measures based on the original transportation feature events they include.

The link and node data we present here are not the same as links and nodes in such products as ARC/INFO that represent a combination of cartography and topology. This data model supports true, non-cartographic topology in a relational database. This allows pathfinding to occur using normal database queries, not complex functions in GIS software. In fact, the entire database is designed to eliminate the need for complex GIS software for all functions except to display events and their derivatives using dynamic segmentation.

The Node Table identifies adjacent nodes, the number of which is subjective, but should be at least four, which makes this table a denormalized one. Usually, one would want to eliminate a repeating field, such as adjacent node. However, this example places them all in one record in order to improve the performance of pathfinding applications. Link direction may also be expressed here by eliminating all adjacent nodes that cannot be reached with a legal move (e.g., one shouldn’t route a vehicle the wrong way down a one-way street). A separate Node Attribute Table (not shown) could be created to store data about the node itself, such as what kind of node it was. Alternatively, this information could be added to the Node Table or stored in the Junction Table. This design creates links as they are needed to generate traversal segment records. An alternative design would be to maintain a Link Table listing all valid node pairs. However, such an alternative carries an extra burden for database maintenance as any topological data changes must be implemented in more than one table.

A Junction/Node Table shows which nodes may be located at junctions. The relationships shown support the presence of more than one node at a given junction,
as well as allowing a given node to include multiple junctions. The latter option may be useful for treating interchanges with many physical junctions as a single node for connectivity purposes, or to allow a transportation model to simplify the highway network by using a single node to represent multiple intersections.

If all you need are data about transportation features, the database is probably complete for you at this point. The model and sample implementation database design support all kinds of transportation features and services, including highways, transit, railroads, and aviation. (Of course, data about airports is not likely to utilize linear events except, perhaps, for airport runways.) Paths can be defined through the transportation system—even moving from one mode of travel to another—by supplying nodes where transportation features of all types intersect. This would include placing a node where one mode connects to another, like at the end of a highway link that accesses an airport or rail yard. Pathfinding does not require maps.

We do not offer a sample physical database implementation for cartographic entities since most cartographic databases are proprietary to each software vendor's product line. A few points, though, are worth
Implementing the Linear LRS Datum

To help visualize the linear datum entities, a sample physical database design for these entities is offered in Figure 10. Only relevant tables are included in this figure. As before, primary keys are underlined and optional data elements are enclosed in brackets. The Transportation Feature Table is the same as that shown in Figures 8 and 9. References to beginning and ending event points in this table and in the Transportation Feature/Anchor Section Table are different. In the Transportation Feature Table, the beginning and ending event points are those of the entire transportation feature. In the other table, beginning and ending event points are for the limits of the subject anchor section.

The Anchor Section Table includes the beginning and ending anchor point IDs. The related beginning and ending point linear LRS references (e.g., milepoints), anchor section length (measured in the linear LRS), and the direction of increasing linear LRS measurements are in the Transportation Feature/Anchor Section Table. These two tables could have been combined, but the illustrated approach allows one to maintain the linear LRS locations of anchor points separately from the datum entities of anchor points and anchor sections.

The Anchor Point Table includes the anchor point ID, the related reference point ID, an anchor point name, and x, y offset distances from the reference point. We assume that a single means of measuring these offsets will be used. The anchor point name, which could be something like “the intersection of Broad and Main Streets in Ourtown,” provides a real-world reference that is readily understandable to help define the location. By making reference point ID part of the primary key for the Anchor Point Table, you are able to accommodate the many-to-many relationship supported by the Reference Point/Anchor Point entity. Although a much simpler fix than using a separate table, it does have the disadvantage of requiring duplicate entries for anchor point name for each combination of reference and anchor points. This overhead is insignificant if most anchor points will be tied to a single reference point.

The Reference Point Table provides the connection to the one or more geographic points that provide the location reference defining the point on the earth. The location description field could be used to store a comment regarding the general location of the reference object, such as “SW corner of Broad and Main Streets in Ourtown.” You could include other descriptive information on the reference object itself in a separate table that had reference point ID as its primary key.

The Geographic Point Table provides a reference point’s geographic location described according to each datum in which the reference point has been located. Elevation information may be included as a z coordinate. A look-up table describing all the datums could also be included.

In order to serve as useful database registration points, we recommend that anchor points be readily located on the transportation feature base map, e.g., at intersections, bridges, and boundary crossings. The other business rule implied by this design is anchor sections are optional parts of specific transportation features, i.e., an anchor section must belong to only one transportation feature.

To provide a cartographic means of illustrating the location of anchor points and anchor sections on the base
map, they may be defined as point events and linear events, respectively. Geographic points may be mapped as geometric points using GIS software functions.

The alert reader will notice that the conceptual structure of anchor points and anchor sections is analogous to that of nodes and links. Indeed, nodes at transportation feature junctions are likely to coincide with anchor points. However, the physical implementations are substantially different, anchor points and nodes are likely to be maintained by separate functional areas within a given agency, and nodes often do not correspond with a precise physical location while anchor points always do. Node and link data elements in GIS-T software products should not be used to represent anchor points and anchor sections. No topological information, save for the beginning and ending anchor points defining a given anchor section, should be provided in the linear datum.

Conclusion

We have shown how one can progress from a simple model of transportation data to a more complex one supporting topology, cartography, and non-transportation data. We have illustrated how the logical data models could be implemented using sample physical database designs. Users should pick and choose the appropriate entities and relationships they need to meet existing and anticipated needs. However, we suggest that the use of an overall, universal data model by all transportation agencies has a number of advantages. Among these are the ability to more readily exchange data, to speak with one voice when expressing the needs of GIS-T users to software vendors, and to better utilize the experiences of other agencies in developing and supporting GIS-T systems. The complete data model we offer is shown in Figure 7, which includes all entities and is governed by the business rules discussed in the paper.

The appendices contain extensive technical data describing the various entities, concepts, and business rules expressed in the model. Appendix 5 on the Spatial Data Transfer Standard proposes changes to that document which could implement the new concepts and entities presented in this paper. In addition to this content, you are invited to review the listed references for background information for more details on underlying concepts.

Appendices

Appendix 1

General Concepts

Linearly referenced data are those data located on a linear transportation feature using an offset distance from a known point on the feature and following the feature’s path to the desired location. Linear location referencing systems are used in geographic information systems for transportation (GIS-T) to integrate linearly referenced data and geographic coordinate positional data. This approach facilitates transportation infrastructure management and applications that use digital representations of transportation systems. Nevertheless, sharing of digital road map databases within and among organizations is difficult since there are no consistent ways of representing roads and different decision rules exist as to what roads to include.

Managers of transportation infrastructure think in terms of reference points, routes, road sections, and cartographic strings, while users think of vehicles operating on paths in networks from origins to destinations. The problem is to develop data models to encompass these perspectives of transportation systems. Various references (e.g., Fletcher et al. 1998) present the results of a meeting of this community of perspectives for digital road map databases. Gordon (1996) elaborated on intelligent transportation system (ITS) needs for interoperable systems which include a comprehensive framework to handle multiple methods of referencing location in rich heterogeneous databases.

One must translate these needs to a data model as a first step to reach a consensus on transportation database design and data-sharing standards. Data sharing is a concept of decentralized control over data resources. Consequently, there is a need for a robust data model to represent the complex relationships among the components of transportation systems. This data model must be able to support legacy databases, future enhancements, and database maintenance. The purpose of this appendix is to examine issues of sharing digital transportation map databases and to propose a data model that can accommodate different applications. What is proposed is best characterized as a GIS-T enterprise data model suitable for organizations responsible for maintaining transportation systems.

Most digital transportation map databases are link-based, which poses a problem for data sharing. Parties must agree on a base network and external IDs for links to assure trouble-free data exchange. Yet, it is difficult to agree on a common base network. A more fundamental data model is needed to facilitate data sharing. We most distinctly address interoperability by adopting a nonlink-based approach.

Rich data resources exist in legacy databases that are used in GIS-T to build digital transportation map databases. The legacy databases may include data that use linear locational references in flat files or that are contained in link-based networks that are not compatible with databases to support new applications.

The data model needs to include the capacity to improve positional accuracy using larger scale cartography or data collected by a global positioning system (GPS) receiver. It also needs to handle various representation of airports, roads, intersections, and interchanges between a vicinity map and a local street map, from generalized representations to more detailed elements.
Maintenance of data is an important issue that requires independence of the entities that make up the data model. Highly integrated link-based models are difficult to maintain. A change to a roadway link may require that the whole network be recompiled. There needs to be independence among the geographic datum, the events that occur on the transportation system, the geometry to represent the system, and the traversals, links, and nodes that form networks.

A geographic datum anchors the digital transportation system to a geodetic framework. Events are attributes, occurrences, and physical components of transportation features, such as AADT, crashes, speed limits, bridges, and pavement condition. Events should be related to linear transportation features using a route/point linear location referencing system to make events independent of the cartography or network link representations, but still be defined in terms of their relative position in one-dimensional space along the transportation feature.

Geometric representations of transportation features in two and three dimensions should also be independent to facilitate cartographic improvements and more accurate positioning of roadway-related features without having to recompile other parts of the database, and to allow multiple cartographic representations to facilitate display at various map scales and roadway detail.

Traversals of networks (routes and paths) should not be dependent on particular geometric representations, though they are network-specific. Independent linear LRSs for traversals that utilize the transportation system, such as bus routes and delivery routes, also need to be supported.

Transportation features are ambiguous geographic features to digitally represent and uniquely identify because of the large number of different strategies by which they can be segmented. Cartographers segment transportation features for ease of digitizing or drawing, while pavement managers segment them by type of pavement, construction engineers by project limits, and traffic engineers at intersections. But at which intersections? Not intersections with driveways and often not with local roads. This illustrates, segmenting of roads is not clear cut. Consequently, road segments are not unambiguous geographic features that can be uniquely identified for purposes of maintaining interoperable digital transportation map databases. Similarly, intersections of transportation features are not easily defined and uniquely identified.

Nevertheless, attempts to share digital transportation map databases tend to concentrate on finding a single representation of the transportation system that can be agreed to and adopted, then permanent link IDs assigned. This strategy has been unilaterally implemented by data developer organizations, such as the U.S. Bureau of the Census in developing TIGER and by Esri Corp. in building MapBase 2.0. However, sharing of TIGER and Esri data involves a difficult conflation process because their link IDs are not compatible and their networks are not consistent. It is doubtful that the transportation community would agree to a single network representation or that the National Spatial Data Infrastructure (NSDI) would adopt any single organization’s representation. Other solutions are needed. More user-friendly external IDs, road names with defined endpoints, are proposed (Duckett 1995).

Common names of transportation features can be used as one criterion for identification, but transportation features need more permanent identifiers. Road names and route numbers, for example, need to be handled as aliases and/or traversals for external access to data. Such externally identification of transportation features is necessary to compare and share data, irrespective of the cartographic or network representation. (See Appendix 2 for more details.) Evidence in the form of two empirical studies give credence to this approach to data sharing. First, the Viggen Corp. approach to network conflation is to collect the network chains by road name and replace the nodes with linear measures to resolve differences between the databases, and then reconstruct a network that contains the desired attributes of both (Okunieff et al. 1995).

Second, in an ARC/INFO environment, Liu (1996) constructs networks from “spaghetti” cartographic strings after selecting the level of importance (arterial, arterial and local roads), using Clean and Build commands. This approach demonstrates the validity of maintaining linear data in a primitive form, and then constructing a network at the level of detail needed for a specific application.

These GIS approaches to data sharing can be facilitated by use of geographic points of registration (Vorderer et al. 1993). Anchor points in the proposed data model serve the database registration function, and must be present in all digital road map databases.

**Appendix 2**

**Advantages and Disadvantages of Road Names as External Identifiers (Foreign Keys)**

For the roadway system, transportation features are created by the complete partitioning of the system into unique, externally identified subdivisions that are commonly present in heterogeneous databases. Transportation features may also refer to things that are not roads at all. Non-road examples include air routes and railroads. Irrespective of the inherent difficulties of segmenting roadways, the problem of unique identification of roadways must be faced. Many state DOTs create control sections, while others employ unique state numbered routes. Both methods employ linear referencing to road point and linear events and attributes located on the sections or routes. Sections and routes are numbered according to the controlling agency’s methods. Unique, but arbitrary numbering facilitates data management within an organization but limits the sharing of data between systems, as one organization’s internal ID may not be a very practical external ID for others to adopt.

The key to a common solution, we believe, is to use a real-world “name” for other users to access data. Like an Internet address, users could use a publicly recognizable name while applications use the database’s actual primary key numerical reference. Using real-world names as external IDs for data exchange facilitates consistency between systems, but introduces problems, such as name changes over time and non-unique street and road names across jurisdictions. Other problems include spelling variations, aliases, and overlapping routes, which would require standardization of naming conventions and changing ambiguous names and practices, problems for which solutions are available.

First, though, a formal definition of transportation feature is needed. Our working definition is “a portion of any transportation network that is referenced by a unique identifier.” The principal criterion for defining transportation features in a roadway system is the use of a common name within a jurisdiction. However, road names that change when crossing minor jurisdiction boundaries may not warrant being broken into separate transportation features.

Transportation features are confined to the limits of a jurisdiction that forms the basic unit for subdividing larger features and to which the linear LRS is tied. Thus, each transportation feature name, or identifier (ID), need be unique only within the context of a given county, for example, if that is the basis of assigning transportation feature IDs. The total unique transportation feature ID would be the concatenation of jurisdiction ID and transportation feature ID. Other jurisdictions and area-specific data are tied to an area entity and do not control the road naming process. One or more alias names may be used for each transportation feature; these alternative names need not be unique as they can be stored as linear events or attributes of transportation features.
External references (foreign keys) may be used to extend the new GIS-T database to legacy databases. For example, one could use bridge numbers stored as a point event attribute to access a bridge inventory. Airports could be referenced by site number, and railroads by name and milepost (railroads typically have their own linear LRSs based on mileposts). Transit services do not have a uniform LRS statewide except for service provider identity; each provider uses its own route-naming convention. These local linear LRSs could be readily overlaid on the anchor section and transportation feature systems. Relating identifiers among legacy databases should be done by defining them as linear events of transportation features in the GIS-T database, whereas more ephemeral things, like delivery routes, should be defined as traversals.

It is important to distinguish between what may be considered to be a real-world name, such as Main Street, and a numerical reference, such as 04/556010024. One possible option that eliminates many of the issues associated with proper names and other real-world external IDs is the use of a numbering scheme for creating the Transportation Feature Name value. Such an option could follow an approach similar to that used for Internet addresses, with numeric codes for state, county, city, jurisdiction, or other important naming elements. Junction (intersection) codes could be created by concatenating road names, with an added sequence number to address multiple intersections of the same roads. In the example “name” shown above, ‘04’ could be the state code, ‘055’ the county code, ‘01’ the city code, and ‘0024’ the sequence number reference for a street.

The solution to the road naming problem has two organizational variations. One is to name a single organization as the czar for assignment of unique roadway and street ID numbers (transportation feature names) and agree that all other organizations will follow their lead. The second is a decentralized approach of adopting street and road naming standards. In this case, the standard name is used as the unique external ID for data sharing, allowing each organization to employ their own internal IDs for database management. Alias names may also be offered.

The shortcoming of the first approach is that the lead organization, say the State DOT, would have to become responsible for managing the assignment of unique ID numbers including those of local streets, or delegating to local governments procedures by which to do it in a consistent manner. A potential shortcoming of the second approach is the need to define transportation feature beginning and ending points, and to choose which of two or more overlapping routes is primary for use as an external ID (could allow all). Resolving these issues will require the formation and operation of an inter-organizational standards committee.

In spite of the problems with the second approach, it seems the preferable way to foster data sharing in a decentralized environment. Naming rules could be designated by many relevant agencies (e.g., USGS, U.S. DOT, and/or AASHTO) or through an SDTS Transportation Profile. The creation of those rules is outside the scope of this proposal.

Appendix 3

Linear Location-Referencing Systems

The way locations are described in a database is the location referencing system (LRS). Location descriptions external to the database are called real-world locations. LRSs include two-coordinate methods such as latitude/longitude, three-coordinate methods that also include altitude, and one-coordinate methods that show where an object is located in reference to a known point. An example of the last type is a linear location-referencing system which is related to a linear datum. To reduce confusion, “LRS” will be used to refer to the broader generic meaning while “linear LRS” will refer to the more restricted meaning of linear location referencing system.

The discussion of the previous appendix dealt with a method for achieving standards in naming methods for transportation features. Of course, just having a universal naming standard does not solve all the problems of data exchange. One must also know where the transportation facilities exist. Thus, a universal location referencing system is needed. Lat/long, state plane, and other real-world coordinate systems are often utilized for data exchange, but, in the transportation field, these systems are of limited value in expressing where features or their characteristics are located on the transportation system. For this, one needs a linear LRS.

The proposed model anticipates primarily the transportation feature/event point linear LRS that locates point and linear events along linear transportation features based on an offset distance from a point of origin. The model of Figure 7 shows that multiple LRSs and datums may be used in a GIS-T database. For example, a bridge may have both a latitude/longitude address and a transportation feature/offset point address.

While linear LRSs may locate events on linear transportation features, a means is needed to locate these features in the real world. To meet this need, it has been frequently proposed that a system of anchor points and anchor sections be established. Anchor points would be located in multiple LRSs; i.e., linear and non-linear LRSs. Anchor sections, which extend from one anchor point to another along the path of a transportation feature, have direction and length as their primary attributes. Anchor section length serves as an additional quality-control check for the accuracy of linear LRS measurements. Anchor points and anchor sections are also the geographic datum objects to which a linear LRS is tied. The anchor section is a centerline of a travelway, with anchor points being located along that centerline.

Anchor points, though, may be difficult locations to find since they are located on an abstraction of the road, i.e., the centerline. Anchor points need to be tied to reference objects, or points, which are the actual physical locations that a user can find in the field. Thus, it is really the reference object for which Vonderheide and Hepworth (1988) require an unambiguous location. Reference objects could be anything that is not readily movable, such as a curb intersection, bridge end, traffic signal post, or survey marker.

Figure 3-1 shows a highway traversing a county. The highway has been given the transportation feature ID of T55010000, which is only illustrative. The ID means the spatial object is a transportation feature (TF) located in county 55, assigned the primary identifier 010, and is the original mainline alignment, as signified by the secondary identifier 000. The secondary identifier would be different if a new segment is established (realignment or extension), or if another segment were associated with the primary feature, as in the case of limited-access highway and its related entrance/exit ramps and access roads. The county and primary identifier portions of the ID form a family name for all related transportation features. Alternatively, a random (non-intelligent) number may be used for an ID while the various elements of the suggested intelligent ID treated as transportation feature attributes.

The use of an “intelligent ID” violates one of the general rules for primary keys. A separate, “invisible” primary key may be needed with the illustrated transportation feature ID serving as a foreign key or public ID. The intelligent numbering approach is presented here mostly to emphasize the relationships between datum objects.

One numbering schema that is definitely not recommended is to use road numbers or names as a primary key. As shown in the example, T55010000 is also Route 17 for its entire length. Parts of it may also carry other names, such as Taylor Road or Route 21.
FIGURE 3-1. Transportation feature (highway) with the proposed geographic and geodetic objects.

All these designations are simply attributes and may be readily changed; however, TF55010000 should never change, even if part of the road is realigned. (The realigned portion would get a new identifier, say TF55010001.)

Anchor points may be placed at the transportation feature termini. Intermediate anchor points in this example have been placed at two major intermediate intersections. Anchor point and anchor section identifiers have also been numbered to provide a relationship between them, again, only for illustration of a possible schema. Anchor points begin with the designation “AP” and the two-digit number of the county in which they are located. Anchor sections begin with “AS” and the number of the county they are located in, followed by the two terminal anchor point sequence numbers. Anchor points have location references as mandatory attributes. Anchor sections have direction and length as mandatory attributes. Incidental anchor points for portions of the road in adjacent counties would also exist.

To be valid, a datum must be tied to physical, real-world locations that are unambiguously defined. This would seem to eliminate such field references as county lines and other jurisdictional boundaries tied to monumentation since the monuments (signs) may not be properly and/or consistently placed. However, a linear LRS will work best if its origin is the beginning point of the road in the jurisdiction. The reorganization of these two needs is to reference the jurisdictional boundary to a reference point that is unambiguously defined, i.e., make the location of the beginning anchor point and transportation feature origin 0.000 at the jurisdictional boundary, but locate the boundary (and origin) as an offset (plus or minus) from a reference point. The transportation feature is thus unambiguously tied to a datum-compatible location.

One or more anchor sections may be used to provide a geographic network reference context for a transportation feature. However, not all transportation features need to have a corresponding anchor section; some may be represented only by cartographic objects. A transportation feature not represented by an anchor section would be unavailable for direct external registration except as it related geographically to anchor points or other transportation features. Such may be the case for minor roads or planned new roads shown on a map.

A datum has been proposed for intelligent transportation system (ITS) applications which is based on the intersection of National Highway System (NHS) routes. A set of guidelines has been drafted to locate unambiguous points at or near such intersections so that their locations can be precisely surveyed and defined in a geodetic datum. These same points could serve as reference points for a national linear datum. (Goodwin 1996)

Vonderohe and Hepworth (1996) have summarized the current ITS datum proposal and provided a number of specifications for linear LRS datum of all types. The most important of these is the need to unambiguously locate anchor points within the datum. The precision required to eliminate ambiguity can be calculated from the required accuracy for linear and point event locations.

It is important to note the difference between accuracy, precision, and resolution. Resolution is the proximity of objects that can be represented as being at different locations. For example, if measurements are recorded to the nearest meter, then objects at least one-half meter apart may be tied to different locations. Accuracy refers to the closeness with which a set of measurements approximate the true value, which cannot be absolutely known. Precision refers to the repeatability of measurements. Errors in precision when precision is high can be corrected through a uniform adjustment.

An increase in the density and precision of locating anchor points results in an increase in linear LRS measurement accuracy. The overall accuracy of the linear LRS is limited by the precision of linear offset measurements from anchor points to locations of interest (event points) along a transportation feature. This means that even if anchor points are located to great precision, linear measurements along the transportation feature can be no more accurate than that of the measuring instrument. Measurements made with such instruments as DMI’s (distance measuring instruments) have errors that increase with distance, i.e., are said to propagate. Anchor point accuracy requirements should be determined by looking at both the needs of users and the ability of available field procedures.

A linear LRS datum design must provide a set of rules for defining, selecting, and locating anchor points and anchor sections, and for measuring the length of anchor sections. “Of particular concern are the identifiability and recoverability (persistence) of anchor points.” (Vonderohe and Hepworth 1996, p. 3) There are a number of business rules that must be defined to apply the general principles presented here and the referenced publications. For example, one must also decide whether separate anchor sections will be defined for each direction of a bi-directional highway, and how discontinuous routes, cul-de-sacs, and ramps will be addressed.

Appendix 4

Relational Database Design Principles

Relational database design is a subject sufficient to fill many books (it has!). While a full discussion of relational database design principles is clearly outside the scope of this paper, it is certainly within the scope to summarize some key points to illustrate how linearly referenced data can be stored in normalized relational tables.

The various steps in creating a “normalized” database design seek to reach a particular “normal form,” of which there are five. There are two well-known pioneers in the field who have written extensively on the subject. The first we quote is C.J. Date, who contends that all normalized relational tables must satisfy four properties (Date 1995, p. 99):

- They do not contain any duplicate rows or records.
- There is no ordering to the rows; that is handled by indexing.
- There is no ordering to attributes (columns).
- All attributes are atomic, i.e., not reducible.
It is this last requirement that Date has termed the foundation of normalization. In essence, an atomic record value is one that carries the most detailed information while avoiding redundancy. For example, if a section of highway has a speed limit of 45 mph, then there should be only one record that stores the speed limit value for that section of highway. The implication is that link-node data schemas and fixed-segmentation schemas cannot be normalized if attributes can span links or fixed-length segments. The resulting databases would be called non-normalized. This isn't necessarily a bad thing, but it is not universally good either. Most of the problems arise when updating the database in that one does not know that multiple records must be updated, i.e., the endpoints of given record cannot be guaranteed to represent the endpoints of a linear attribute.

Most designers try, at a minimum, to achieve what is known as third-normal form. The second pioneer we quote is E.F. Codd (from Date 1995), who defines the third-normal form as one where the non-key attributes are mutually independent and irreducibly dependent on the primary key. Two or more attributes are mutually independent if none of them is functionally dependent on any combination of the others. This means that each attribute can be updated independently of the others. The opposite is a non-normalized table with multiple attributes where an update of one attribute will create "new" values for other attributes on the row.

Consider, for example, a typical transportation database with attributes for highway features, such as speed limit and functional class. The primary key is formed by combining ROADWAY_ID and BEGIN_MILEPOINT. A primary key is the combination of column values that uniquely identifies a row. No other row can have the same primary key.

Table 4-1 is non-normalized in that the various attributes are not mutually independent. A change in speed limit will produce a "new" value for functional class (even if it is the same value, it is on a new row and defines a new road segment). Functional class and speed limit are mutually independent in the sense that they have nothing to do with each other. Functional class and speed limit can change according to separate rules. However, the table forces them to be dependent in that one must update speed limit (i.e., create a new record value for the row) whenever a new record is created for functional class. More importantly, from the perspective of dependency, one cannot have a functional class without a speed limit, so the independence of insert functions is lost. In addition, one cannot delete a row for functional class without also removing the speed limit.

Incidentally, END_MILEPOINT is an independent attribute and is dependent on the primary key in that it cannot be less than or equal to the primary key component of BEGIN_MILEPOINT. Some designers omit the end point attribute and derive it from the subsequent begin point or roadway origin. However, such an approach is impossible or very difficult with most relational database management systems (RDBMSs) and is discouraged.

The table also may be viewed as failing the test of atomicity in that speed limit has three consecutive entries of 55 mph due to changes in functional class. However, one can look at each row as the description of a piece of highway and, as such, is atomic for that piece of highway.

Even such a non-normalized design satisfies the requirements for first-normal form. According to Codd (1995), there is only one requirement for first-normal form, which is that the underlying domain must contain only scalar values. This means that each attribute, or column, can contain only one entry, which is the case for the tables presented here.

The failings of the first table point to a normalized solution of two tables, one for speed (Table 4-2) limit and one for functional class (Table 4-3).

These two tables are in third-normal form in that they are scalar value domains (or ranges of values), every non-key attribute is irreducibly dependent on the primary key (ROADWAY_ID and BEGIN_MILEPOINT), and all attribute entries are atomic. The second characteristic means that the values for SPEED_LIMIT and

<table>
<thead>
<tr>
<th>ROADWAY_ID</th>
<th>BEGIN_MILEPOINT</th>
<th>END_MILEPOINT</th>
<th>SPEED_LIMIT</th>
<th>FUNC_CLASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>550100000</td>
<td>00.000</td>
<td>14.577</td>
<td>55</td>
<td>01</td>
</tr>
<tr>
<td>550100000</td>
<td>14.577</td>
<td>25.575</td>
<td>55</td>
<td>02</td>
</tr>
<tr>
<td>550100000</td>
<td>23.575</td>
<td>27.950</td>
<td>55</td>
<td>01</td>
</tr>
<tr>
<td>550100000</td>
<td>27.950</td>
<td>30.475</td>
<td>45</td>
<td>03</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ROADWAY_ID</th>
<th>BEGIN_MILEPOINT</th>
<th>END_MILEPOINT</th>
<th>SPEED_LIMIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>550100000</td>
<td>00.000</td>
<td>27.950</td>
<td>55</td>
</tr>
<tr>
<td>550100000</td>
<td>27.950</td>
<td>30.475</td>
<td>45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ROADWAY_ID</th>
<th>BEGIN_MILEPOINT</th>
<th>END_MILEPOINT</th>
<th>FUNC_CLASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>550100000</td>
<td>00.000</td>
<td>14.577</td>
<td>01</td>
</tr>
<tr>
<td>550100000</td>
<td>14.577</td>
<td>23.575</td>
<td>02</td>
</tr>
<tr>
<td>550100000</td>
<td>23.575</td>
<td>27.950</td>
<td>01</td>
</tr>
<tr>
<td>550100000</td>
<td>27.950</td>
<td>30.475</td>
<td>03</td>
</tr>
<tr>
<td>ROADWAY_ID</td>
<td>BEGIN_MILEPOINT</td>
<td>END_MILEPOINT</td>
<td>ATTRIBUTE</td>
</tr>
<tr>
<td>------------</td>
<td>----------------</td>
<td>---------------</td>
<td>-----------</td>
</tr>
<tr>
<td>55010000</td>
<td>00.000</td>
<td>14.577</td>
<td>FC</td>
</tr>
<tr>
<td>55010000</td>
<td>14.577</td>
<td>23.575</td>
<td>FC</td>
</tr>
<tr>
<td>55010000</td>
<td>23.575</td>
<td>27.950</td>
<td>FC</td>
</tr>
<tr>
<td>55010000</td>
<td>27.950</td>
<td>30.475</td>
<td>FC</td>
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<td>55010000</td>
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<tr>
<td>55010000</td>
<td>27.950</td>
<td>30.475</td>
<td>SL</td>
</tr>
</tbody>
</table>

FUNCTION_CLASS are based on location, as represented by the primary key. The problems with insert and delete functions for individual characteristics go away with this revised design as each highway characteristic is stored in its own table. However, problems remain for inserts and deletes involving an entire section of roadway and all its attributes. Such actions would have to search all tables to find applicable records for modification, deletion, or (in the case of adding a section of roadway) creation. For example, to remove a segment between MP 07.954 and MP 09.388, one would have to search every table to find all the ones that had one or more attribute values for that piece of road. This search can be hard to do and take a long time; it can and should be avoided.

To avoid this problem, the separate tables can be further reduced to a single table (Table 4-4).

This design simplifies the "big" update problem by requiring the update process to look only at one table to find which rows may need to be deleted, changed, or created to implement a particular update. The primary key must be expanded to include ROADWAY_ID, BEGIN_MILEPOINT, and ATTRIBUTE in order to properly construct an index and uniquely identify each row. Sorting by the primary key components of ROADWAY_ID and BEGIN_MILEPOINT will put all the attributes for a given highway segment in order and allow an update/create/delete action to quickly identify the piece(s) of highway it needs to act upon.

A primary key may need to include other data elements. Consider the following table (4-5).

<table>
<thead>
<tr>
<th>ROADWAY</th>
<th>BEGIN_POINT</th>
<th>END_POINT</th>
<th>SIDE</th>
<th>ATTRIBUTE</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>55010002</td>
<td>02.875</td>
<td>04.532</td>
<td>r</td>
<td>speed limit</td>
<td>55</td>
</tr>
<tr>
<td>55010002</td>
<td>02.875</td>
<td>04.532</td>
<td>l</td>
<td>speed limit</td>
<td>55</td>
</tr>
<tr>
<td>55010002</td>
<td>04.532</td>
<td>07.931</td>
<td>b</td>
<td>speed limit</td>
<td>45</td>
</tr>
</tbody>
</table>

The multi-valued dependency (SIDE) has been eliminated as a repeating field; and there are no join dependencies.

If this is true, then there can be no update anomalies; i.e., there can be no data pathologies (there may still be business rule pathologies, such as cul-de-sacs). The generic Event Table we proposed in the data model uses event ID as a means of simplifying the primary key; it would replace BEGIN_POINT, END_POINT, SIDE, and ATTRIBUTE in this example table.

Using the term relation to mean table, C. J. Date stresses that:

the level of normalization of a given relation is a matter of semantics, not merely a matter of the data values that happen to appear in that relation at some particular time. It is not possible to look at the tabulation of a given relation at a given time and to say whether or not that relation is in (say) third-normal form—it is also necessary to know the meaning of the data, i.e., the dependencies, before a judgment can be made. Note that even knowing the dependencies, it is never possible to prove from a given tabulation that a relation is in third-normal form...[As long as dependency requirements are not violated,] then the tabulation is consistent with the hypothesis that the relation is in third-normal form, but that fact of course does not guarantee that the hypothesis is valid.

(Date, p. 303)

Thus, we say that linear LRs, as shown in the tables above, are consistent with the requirements of third-normal form. We will go further and state that third-normal form design is not always the best thing for good GIS-T database design. Most GIS-T applications are of the type usually associated with executive information systems, decision support systems, and data marts/warehouses. Such applications often benefit from denormalization and precalculated fields, such as showing the number of lanes and calculating lane miles in tables of characteristics that can be summed to answer questions such as, "How many lane miles of principal arterial highways are there in ____?"

If each attribute is placed in its own table, then the user must "join" the necessary tables together to analyze correlations between multiple attributes. The resulting set of records would be
denormalized in that it would look like the original one shown above. (All joins produce denormalized results with non-atomic values in the rows.) In fact, dynamic segmentation requires a denormalized table as input in order to display multiple characteristics (such as traffic volume with line width and jurisdiction with line color).

The bottom line is that third-normal form is appropriate as long as it serves the needs of an application; it is not a universal design specification. For example, we suggested a denormalized Node Table because it is considered to be a more efficient design than a normalized table. The opposite may be true for other applications in that there are times when even third-normal form may not be sufficiently normalized. In other words, business reasons, not dogma, should drive the database design process. Normalization is often justified for business reasons, such as application performance and simplicity. Date says that the valid reasons for doing normalization are (Date, p. 335):

- to eliminate certain kinds of data redundancy (note not all redundancies);
- to avoid certain update anomalies;
- to produce a design that is a 'good' representation of the real world—one that is intuitively easy to understand and a good base for future growth; and
- to simplify the enforcement of certain integrity rules.

Date also finds that dependencies are a good thing since they are reflections of business rules, and tries to design databases so the RDBMS can implement these rules by virtue of simply updating the database (Date, p. 336). SQL (the universal RDBMS access language) and RDBMS implementation rules (in the software) deal with data values, while Date’s theories deal with data meanings. There is a difference.

Database and application design must be done simultaneously to create functionally efficient GIS-T applications and databases. The comments contained in this appendix are intended to present our design philosophies, which are expressed in the sample implementations (data table designs) listed in the main text of the paper. The table designs presented here are illustrative only. Readers are encouraged to reach their own conclusions based on their specific needs.

Appendix 5

The Spatial Data Transfer Standards

This paper uses the concepts and definitions of the Spatial Data Transfer Standard (SDTS), which is described in Federal Information Processing Standard (FIPS) 173. SDTS is mandatory for all federal information systems, and has been specifically endorsed by several states, such as Florida, as a state data-sharing standard. Unfortunately, the SDTS database structure has not been defined at the physical implementation level to the extent needed to exchange all transportation data. A national user group is currently working to develop a Transportation Network Profile, or SDTS implementation method, for transmitting cartographic and topological data. However, the profile is substantially incomplete as a full database specification for other database elements. The first describes the existing SDTS. The last section offers a more complete specification for GIS-T.

The Current SDTS

SDTS uses a two-tier hierarchy of graphical items. The first is the group of elements, the basic graphic building blocks. Elements include points, line segments, strings, and areas. The second is the group of objects, complex graphic items that include "intelligent" connections to attribute data. Examples of objects include nodes, links, and chains. The relative position and connections between objects is described by topology. Topology is generally expressed within the objects themselves, not as something external. For instance, a link is defined by its terminal nodes. The connectivity of one link to another is found in their having at least one common terminal node. SDTS elements and objects are illustrated in Figure 5-1.

SDTS objects are divided into several subgroups. The two subgroups most applicable to the data model are geometric objects and geometric/topological objects. Geometric objects (a.k.a., G-type objects) are used to describe a drawing, or map, that illustrates the real-world entities being represented. Geometric/topological objects (a.k.a., GT-type objects) are used to both illustrate the physical position of real-world entities and their connections—the topology part. The specific SDTS terms used here are of both types. E-R diagram entities are used to represent each real-world item and all graphic elements and objects used to describe them in a map.

The following existing SDTS definitions are provided to show in more detail what geometric and topological aspects of the proposed model may already be satisfied. The official SDTS definitions shown here are those provided in the publicly accessible (Internet) version of the SDTS (Part 1, Logical Specifications, Section 2.3, Definition of Spatial Objects; and Section 1.4, Definitions). The published definition is shown in italics. A discussion or clarification of the meaning often follows each official definition.

Not all of the listed SDTS terms are needed for transportation features, but all potential components of a transportation database and cartographic expression are offered here to provide the full specification of a transportation transfer profile.

1. Area (Geometric)

A generic term for a bounded, continuous, two-dimensional object that may or may not include its boundary. An area is a 2-dimensional object that it has planar shape and (at a given scale) size attributes. Areas may overlap one another, with or without boundary intersections. For example, an area representing the region covered by a city may overlap another area for the county in which the city is located. Both areas would be illustrated by polygons. In its simplest cartographic expression, an area is usually bounded by a string that defines a G-polygon. Areas are typically used on transportation maps to define political jurisdictions. Areas are not generally used to describe such transportation features as highways, which

![Figure 5-1: SDTS terms illustrated.](image-url)
have been the traditional subjects of current GIS-T deployments. However, areas are appropriate for such transportation features as airports, harbors, rights-of-ways, building structures, wildlife mitigation areas, and water retention structures. Thus, areas do have a place in a transportation-transfer profile. The SDTS recognizes three area types:

a. Interior Area. (Geometric.) An area not including its boundary. For purposes of attribution and other data "handling" requirements, an area may be simplistically represented by an area point, or a geometric location within the confines of the area.

b. G-polygon. (Geometric.) An area consisting of an interior area, one outer G-ring, and zero or more non-intersecting, non-nested inner G-rings. No ring, inner or outer, shall be co-linear with or intersect another ring of the same G-polygon. The outer rings of inner G-polygons are expected to be co-linear with the inner rings of the larger G-polygon. A polygon with no inner rings is considered to be simple. One with inner rings is considered to be complex. Most displayed areas on a transportation map will take the form of simple, possibly overlapping, G-polygons, although the presence of a transportation feature inside a given area may be best expressed as an attribute of the feature. A complex polygon would be needed for a county (boundary forming the outer ring) if an included city is a "hole" within the county (boundary forming an inner ring). Such may be the case for road maintenance (i.e., if the city is responsible for only the unincorporated part) or the independent cities of Virginia.

c. GT-polygon. (Geometric and topological.) An area that is an atomic two-dimensional component of one and only one two-dimensional manifold. The boundary of a GT-polygon may be defined by GT-rings formed from its boundary chains. A GT-polygon may also be associated with its chains (either the bounding set, or the complete set) by direct reference to these chains. The complete set of chains associated with a GT-polygon may also be found by examining the polygon references on the chains. The primary difference between a GT- and a G-polygon is chiefly determined by the environment within which it exists. For example, a G-polygon may be bisected by a number of lines representing roads on a map without any change to the polygon itself. However, a GT-polygon bisected by roads described by complete chains will be subdivided into many component polygons since each bisecting chain becomes part of the boundary GT-ring of the component polygon. It is this subdivision of the large polygon that is implied by the term "atomic" in the official SDTS definition of a GT-polygon. It is also implied by the absence of any reference to inner GT-rings in the definition. GT-polygons may be useful only for traffic flow models where transportation feature links define the boundary of traffic analysis zones. Full topology for representing transportation networks to serve other applications should generally be avoided.

2. Chain (Geometric and topological)
A directed nonbranching sequence of non-intersecting line segments and/or arcs bounded by nodes, not necessarily distinct, at each end. A chain may be used as a transfer mechanism to convey geometrics and topology, which may be separately represented by different entities, such as a string (geometry) and a link (topology) in the source database. Chain types in the SDTS are:

a. Network Chain. (Geometric and topological.) A chain that explicitly references start and end nodes and not left and right polygons. It is a component of a network. A network chain is not closed and has distinct beginning and ending nodes. A path through a transportation system could be described using a sequence of network chains. A network chain may be constructed from a link, its implicit terminal nodes, and the string that defines the "shape" of the path taken to traverse the link.

b. Complete chain. (Geometric and topological.) A chain that explicitly references left and right polygons and start and end nodes. It is a component of a two-dimensional manifold. A complete chain is a directed link that includes information on adjacent polygons, i.e., serves as a boundary (GT-ring) for polygons on both sides of the chain (left and right in terms of the link direction). A county boundary could be a complete chain and a highway could be a network chain. A portion of the highway that was also a boundary of the county would be part of both chains. A given line segment may be part of multiple strings and/or chains in an SDTS-compliant file structure. However, few (if any) existing commercial GIS products can implement this "multi-owner" structure.

3. Point (Geometric)
A 0-dimension object that specifies geometric location. One coordinate pair or triplet specifies the location. Although a point location may be expressed in terms of a real-world reference system, or datum, it is actually the expression of that point within a geometric (map) context. Such a context includes aspects of map projection and cartographic datum specific to each GIS software environment. The SDTS defines three special cases of point elements. Two of these (point label and area point) are really the result of GIS software design limitations and are not necessary for transferring transportation data, except that an area point may be used to convey a traffic-analysis zone centroid:

a. Entity Point. (Geometric.) A point used for identifying the location of point features (areal features collapsed to a point), such as towers, buoys, buildings, places, etc. Entity points are the basic means for expressing such spatial features as accident site, airport, bridge, and crossing, that may be said to occur at a single place (perhaps only at smaller scale representations). If geometric and attribute information for such features is all that is required, then the existing SDTS is adequate. In our opinion, this information is usually not adequate.

b. Label Point. (Geometric.) A reference point used for displaying map and chart text (e.g., feature names) to assist in feature identification. A label point provides only map location information and does not reflect a real-world location.

c. Area Point. (Geometric.) A representative point within an area usually carrying attribute information about that area.

4. Line Segment (Geometric)
A direct line between two points. A line segment's end points need not represent anything more than the line segment termini, i.e., they do not have to be entity points. A line segment is located by referencing the two terminal point locations and "connecting them" through a mathematical function analogous to describing the slope of the line segment within the cartographic datum. Within this context, the term line segment includes the term arc, a locus of points that forms a curve defined by a mathematical expression. A line segment is a one-dimensional object in that it has only length as a mandatory attribute.

5. Link (Topological)
A topological connection between two nodes. A link may be directed by ordering its nodes. A link in which the order of nodes is important is called a directed link. A given link is not directly related to line segment(s) or string that may illustrate it, but may be related to them as a component of a chain.
6. Node (Topological)
A 0-dimension GT object that is a topological junction between two or more links or chains, or an end point of a link or chain. Multiple nodes can be related to the same point. Not all nodes need to be tied to a real-world location; some may represent conceptual locations, as in the case of traffic analysis zone centroids (e.g., area points) or simplified Interstate highway interchanges. From a topological perspective, one may move from one link to another only at nodes. In a non-planar implementation (one which recognizes that not all crossing roads intersect), nodes will not exist where non-intersecting lines cross, e.g., at a bridge overpass. Any successful transportation profile must support a non-planar data model. One may move from one coincident node to another (i.e., from one network to another) along a virtual link connecting the two coincident nodes. For example, a highway network may include a node at each airport. A separate node, also at each airport, would be present in the aviation network of air routes. A virtual link between these two nodes allows a connection to exist between the highway and aviation networks, each of which contains its own airport point event.

7. String (Geometric)
A connected nonbranching sequence of line segments specified as the ordered sequence of points between those line segments. A string may intersect itself or other strings. Linear transportation features, such as highways, airport runways, and railroads may be represented cartographically by strings.

Proposed SDTS Additions
As noted earlier, the existing SDTS elements and objects listed above do part of the job of transferring information in a transportation database. They do not complete the transfer of geometric and topological data elements, nor do they address at all the real-world reference system of anchor points and anchor sections or the geometric needs of a data model with independence of cartographic and attribute data (the current SDTS requires that attributes be directly assigned to predefined geometric objects). Having multiple cartographic representations for a single attribute, is also a problem. The current SDTS does not readily support the transmission of, for example, point symbols at small map scales and strings at larger scales for attributes such as highway bridges without duplication. Topological needs are also not being met in an entity describing complete paths across a network (tesselation) is not presently supported. These shortcomings must be corrected.

Current SDTS specifications also fail to convey linear transportation attributes in that the SDTS requires those attributes to be assigned to a cartographic element, such as a string or chain. Since many linear transportation attribution schemas rely on variable linear feature segmentation methods, a universal set of strings to which all linear attributes may be assigned cannot be efficiently defined. It is when rigid segmentation rules are attempted, such as assigning attributes to links, that many problems of database and application design appear. To avoid these problems, any proposed extension to the existing SDTS for the purposes of serving as a transportation transfer profile must avoid rigid segmentation rules.

Thus, we propose that the SDTS be extended beyond its currently limited geometric and topological content to provide a complete transportation transfer profile. To do so, we offer new and modified terms and definitions. To the extent possible, proposals by others are supported. The reference shown in parentheses immediately following each proposed term is the proposed SDTS object type. Two new ones are offered: 1) Geographic, to separate the

real-world geodetic references from the cartographic ones currently included in Geometric objects; and 2) Transportation System Characteristic, to express transportation features, the context within which they are designated (jurisdiction), and their attributes.

1. Extend the group of point types to include geometric and geographic points as the two separate aspects (cartographic and real-world addresses) of entity points:
   a. Cartographic Point. (Geometric.) The internal address reference for map cartography of an entity point. This is the cartographic address of a point. Most commercial GIS and CAD software use a proprietary internal coordinate system to locate graphical elements. This internal system is the cartographic datum.
   b. Geographic Point. (Geographic.) A 0-dimension object carrying the real-world coordinate location (e.g., latitude/longitude/elevation, or route/milepoint) of an entity point. This is the physical address of a point. The address information for a geographic point is expressed within the context of a geodetic datum and location referencing system, e.g., North American Datum 1983 and State Plan Coordinate System. (The model offered in the main text combines the geodetic datum and LRS into a single entity, Geographic Datum.)
   c. Event Point. (Geographic.) A 0-dimension object carrying the location of an event relative to its position in a transportation feature. Event points are normally defined using an offset distance from the origin of a linear transportation feature. They may be additionally or exclusively defined by geographic points.
   d. Reference Point. (Geographic.) A 0-dimension object specifying the location of the reference object to which an anchor point is tied. Reference points are normally defined as geographic points (i.e., with a real-world coordinate location) and a real-world description, such as "monument in northeast corner of Oak St. and Main St. intersection."

2. Create new linear datum objects for transportation:
   a. Anchor Point. (Geographic.) A 0-dimensional object specifying a single geographic location used for registration of databases. (The potentially equivalent term 'linear reference point' suggested in another proposal is rejected here due to the more widespread use of the term 'anchor point' in the transportation community.) In order to serve the database registration function, an anchor point must be present in all databases and locatable on a map as well as in the real world. Anchor points could be placed at prominent bridges and intersections, for example. Anchor points must be defined at least for the beginning and ending locations of anchor sections. Anchor points have only a real-world identifier, such as the name of an intersection, and are tied by x, y offsets to a readily locatable reference point. The real-world location (address) of a reference point is given by a geographic point, while its cartographic location is defined by a cartographic point. The linear LRS location of an anchor point can only be defined within the context of specified transportation features. Therefore, the linear LRS addresses of anchor points are attributes of the anchor sections they form.
   b. Anchor Section. (Geographic.) A one-dimensional object providing a logical representation of all or part of a linear transportation feature. An anchor section begins and ends at ordered anchor points and, thus, has a specified direction. This direction is the one in which linear location references are measured, not the direction of traffic flow. The relationship of anchor points to anchor sections is analogous to that of nodes to links. However.
the lack of topological attributes, such as allowable travel directions on anchor sections, or permitted “turns” at anchor points, makes them different from links and nodes.

3. Define the term, “transportation feature”:
Transportation Feature. (Transportation System Characteristic.) An element of a transportation system that may be uniquely identified in the real world and for which attributes are provided. Transportation features are confined to the limits of a jurisdiction (interior area), which forms the basic unit for providing feature names. For the roadway system, transportation features result from the complete partitioning of the system into unique, externally identified subdivisions that are commonly present in heterogeneous databases. Transportation features would serve to organize the entire database, with jurisdiction being the highest level of the organizational hierarchy. Each transportation feature name, or reference, need be unique only within the context of a given jurisdiction. Under no circumstances should the name or identifier of a transportation feature be something that may change, such as its route number or facility name. It is the physical entity that is referred to by a transportation feature ID. The total unique transportation feature ID could be the concatenation of a jurisdiction ID and transportation feature ID. (Name need not be anything other than a numeric identifier.) Other jurisdictions and area-specific data are tied to an interior area or polygon and do not control the road-naming process. One or more alias names may be used for each transportation feature; these alternative names need not be unique as they can be stored as linear or point events (attributes).

Often, the common street or road name constitutes the principal criterion by which to define the related set of transportation features. Physically continuous transportation features may be subdivided at major jurisdictional boundaries (both sides of boundary may have the same name but are within separate primary jurisdictions) or combined across minor jurisdictional boundaries (both sides of boundary may have different names but are within one primary jurisdiction). For example, if the primary jurisdiction is the county, then roads traversing multiple cities within that county may comprise a single transportation feature. Conversely, roads crossing multiple counties would be subdivided into separate transportation features, one for each county.

4. Create a term to represent the intersection of transportation features:
Junction. (Transportation System Characteristic.) A location where two or more transportation features cross or connect. The term includes both generic intersections, such as where two streets cross, and where the unique identifier of contiguous transportation features change, such as at a jurisdictional boundary. The term also includes the connection between different transportation modes, as in the case of an airport being the junction of ground and aerial transportation facilities or services. The concept of junction may also be applied to places where transportation features cross but do not intersect to meet application needs. For example, a bridge over a navigable waterway could be a non-intersection junction between the highway and waterway networks.

Junctions may relate through entity points to nodes, if applicable, and to cartographic points, geographic points, and point symbols. Junctions could also relate to strings if, for example, a highway interchange (represented fundamentally as an entity point) could be expanded at larger scales to provide additional detail by using the junction reference as a foreign key to a table of interchange drawings. The Junction entity is a place to store attributes such as traffic control, allowable turns (for pathfinding applications), turning movement counts, crashes, and similar attribute data.

The definition of junction in this paper goes beyond that of the proposed transportation data dictionary from the Ground Transportation Subcommittee (GTS) of the Federal Geographic Data Committee (FGDC) in that it is multimodal and covers the intersection of linear and point transportation features, such as highways and airports. As defined in this proposal, the term junction could include the term crossing, as it is defined in the GTS proposal. The joint use of junctions to mean road intersections and overpasses allows more efficient pathfinding. An overpass “junction” or crossing would have no allowable turns, of course, but could be used to store information on bridge loading limits and overhead clearance, for example.

Some transportation system elements belong to more than one transportation feature. For example, a bridge could be seen as part of the facility it carries and the one it crosses to form a junction (note that one need not be able to move from one transportation feature to another at a junction with the definition proposed here). Thus, junctions formed by the intersection or crossing of transportation features of different types such as rail-highway grade crossings, may be viewed as the set of multimodal objects. Paths through the transportation system may move from one node to the next only at such junctions. Of course, junctions formed by the intersection of transportation features of the same type, such as two intersecting streets, serve to move one along a path through that particular network.

5. Provide an attribute-centric way to transfer transportation system characteristics independently of the cartography:
A bridge may be viewed both as an attribute of a highway and the river it crosses, and as a transportation feature in its own right. The SDTS does not adequately convey these two aspects in that it fails to fully recognize the attribute aspect. The SDTS also fails to provide a direct way to transfer attributes without their being assigned to a specific cartographic (geometric) object. Both shortcomings can be addressed with a single solution: events.

From a logical database design perspective, we propose that all transportation feature attributes be associated with the larger feature(s) of which they are a part. For example, we have already addressed the relationship of linear transportation features and the networks they form. Here, we will address point and linear transportation system characteristics that describe or are part of larger linear transportation features. In doing so, we also address transportation feature attributes by using a common data structure.

Linear and point events are elements or characteristics of a transportation feature. Elements include tangible objects, such as bridges, signs, guardrails, and intersections. Characteristics include less tangible aspects of a transportation feature, such as a road’s speed limit, the pavement surface type, the type and width of a median, the airlines serving a particular air route, or the trains using a specific railroad track.

Most state departments of transportation have used straight-line diagrams and related attribute databases to graphically describe highways. In many ways, state DOTs look at GIS-T as an evolutionary step that puts true shape into these diagrams and allows connections (topology) between what were previously separate diagrams. Any SDTS transportation data dictionary or transfer profile must support this data structure. (See Figure 5-2)

The Linear LRS is the glue that binds transportation features to their linear and point events, as well as to the geographic datum of anchor points and anchor sections that place the transportation features on the surface of the Earth. Of course, not all transportation features are on the Earth, with aviation being the primary exception. Linear LRSs may be applicable to aviation, but since the air routes between airports are more conceptual than physical, the
aviation system may be one mode of transportation to which this glue does not stick.

In Figure 5-2, the same transportation feature has been visually described in several ways. The first is simply a straight line representing the transportation feature as a single entity. This entity has been given the identifying number 55010000. To this simple representation, a straight-line diagram will add attributes from a transportation database. The examples shown include point and linear events both on and adjacent to the road, called Transportation Feature 55010000. The tables to the right show the data used to create the straight-line diagram.

Some attributes are expressed as annotations (e.g., milepoints), others as geometry (e.g., angles of intersecting streets). Straight-line diagrams may show these attributes and objects on separate lines, as depicted here, or all on one line using various graphical methods, such as line width and pattern, or by placing tic marks across the road and labeling both sides of the mark to show what value changes at that point. Additional attributes could be provided for the entities shown, e.g., intersecting street name, sign legend, etc.

Next, the figure shows geographic datum in the form of anchor points and anchor sections. Anchor points are assigned an identifier beginning with “AP” and are described using the reference point’s location in a geodetic datum adjusted for anchor point offset from that reference point. Anchor sections are assigned an identifier beginning with “AS” and the concatenated anchor point numbers; they are also described by length. An intermediate anchor point has been placed at an intersection near the mid-point of the transportation feature, which has been defined by two whole anchor sections. (As noted earlier, the proposed rule is that anchor points must be placed at transportation feature termini.)
Below this is a cartographic representation of the road as it may appear on a map in its approximate planar image as if viewed from the air. Because of the curves, the left-to-right length of the highway string appears shorter than the straight-line objects listed above it.

Dynamic segmentation would combine these various representations using the linear LRS to place attributes on the highway string, thereby creating new strings that corresponded to the extents of the component linear attributes. Dynamic segmentation can also be used to place point symbols at the correct relative position on the highway string. Of course, there is a limit on the number of attributes that can be shown on a single map given the need to have each clearly conveyed.

To implement the concepts of linear and point events on transportation features, two new SDTS terms are proposed.

a. Linear Event. (Transportation System Characteristic) An attribute of a transportation feature that has distinct beginning and ending event points (i.e., lengths), or a means by which to relate attributes to part or all of a transportation feature. Linear events include such attributes as functional class, speed limit, pavement type, and traffic volume.

   Linear events are defined in terms of beginning and ending point events along linear transportation features, with the location of those points defined in the context of a linear location referencing system, i.e., by a distance measure (offset) from a point of origin. The use of linear events and dynamic segmentation precludes the need to aggregate attributes in accordance with a rigid transportation feature segmentation schema, e.g., link/node or fixed distance. To relate attributes defined as linear events to geometric representations of transportation features requires that the relevant geometric strings have the same end points and length measure (at scale) as the transportation features they represent. This enables interpolation along strings to locate linear events using dynamic segmentation functions in software, as shown above.

   Some transportation databases support lateral offset measurements for things such as guardrail which may not be adjacent to the road. Others may have data stored by side of road, as in the case of divided highways, in order to show attributes such as number of lanes, pavement type, and curvature. For such transportation features as air routes, linear events may be air carrier flight numbers, passenger traffic, and traffic control responsibility. Linear events occurring as part of transportation features may include attributes offset from a road edge, such as a guardrail or fence.

   Linear events may also be used to represent an area event, which is really an attribute of an area, by defining a linear event as the attribute of a transportation feature segment relative to its being inside or outside the area. For example, one could define an attribute to report whether a given location was inside or outside a city. The value of this attribute would change each time the city limits crossed the transportation feature. Such area events need not relate to a cartographic area. (While the proposed addition to the SDTS should recognize area events, this proposal does not imply that such a term needs to be formally defined separate from those area objects that currently exist in the SDTS, e.g., G-polygon.)

b. Point Event. (Transportation System Characteristic) A location where some transportation feature or attribute occurs as defined by a single event point. Examples include bridges, intersections, traffic counting sites, and similar point-like features. Some of these point-like features may alternatively or additionally be represented as linear or area events; e.g., at larger scales one may choose to show bridges as linear events. Point events may have real-world locations and positions along an anchor section, a linear transportation feature, and anywhere else within the involved geographic or cartographic space. Point events occurring on transportation features may be located cartographically in the same manner as linear events using a linear location referencing system and the dynamic segmentation function. Point events occurring as part of transportation features may include those offset from a road edge, such as a sign.

Since linear and point events are two cases of the same data entity (attribute), they may be physically implemented using a common table structure. Conceptually, point and linear events are a single entity; however, they are separated here to reflect the different relationships established between an event entity and other entities based on whether it is a linear or point event. Thus, a given transportation feature or event may be shown on a map at small scale as a point and at large scale as a line.

6. Add terms to serve as a collection of one or more links in a transportation network so that a path through a portion of that network may be defined:

a. Traversal. (Topological.) A path or route through a portion of a transportation network consisting of one or more links. Traversals may be static (defined as a stored path, such as for an entire highway across a state) or dynamic (defined "on the fly" to meet some particular set of criteria); the distinction is mainly for ease of stating system functions. Traversals may have attribute data associated with them directly, but most data will be associated through the included traversal segments.

b. Traversal Segment. (Topological.) An atomic component of a traversal comprised of one or more links and relevant attributes. Traversal segments are the result of joining linear events with links that form a path through the transportation network. Point event data would be used if they were linear events, e.g., the number of bridges on a route, or the minimum clearance of overhead structures. It is possible to show attribute data being part of link records, but the approach suggested here is to separate a simple schematic element (Link) from a richly described element (Traversal Segment). In pathfinding routines, links show the possibilities; traversal segments provide the information needed to find the links meeting the stated selection criteria. Thus, it may be desirable to separately define traversal segments as a spatial entity and traversal as a sequence of one or more traversal segments. This would be especially advantageous where a traversal segment was composed of multiple links.

c. Traversal Member. (Topological.) The assignment of a specific traversal segment to a given traversal. A traversal member table in the transfer data set would provide a list of traversal segments used by each traversal. Traversal members may be numbered in a logical sequence to define the traversal from beginning to end. This numbering may be provided by a traversal-specific linear LRS, with the values of traversal segment beginning end points being defined in that LRS as offsets from the traversal origin.

7. Recognize a standard transportation data model:

Current GIS software products implement a number of internal (and possibly different external) data models, none of which fully reflect the way transportation data are used. It is suggested that the G15 and FGDC formally recognize a standard transportation data model as a means of expressing the manner in which transportation data are organized and used by public and private agencies. The model offered in Figure 7 of the main body of the paper is a proposed starting point. The cartographic entities in the proposed data model are illustrative only and may be changed to convey more complex objects.
Two cartographic entities not previously defined are also included in the complete model. An entity for point symbols has been included as they serve as the equivalent set of cartographic objects for point events as strings do for linear events. Base map strings have been separately modeled from linear event strings to illustrate the fact that the latter exist only as expressions of the linear events described in the characteristics component of the model. Most data transfers would not actually convey both sets of strings. A user with the capability to perform dynamic segmentation would utilize only the base map cartographic strings, while a user without that software function would accept the data as line strings that were already segmented to provide a one-for-one relationship with the included linear attributes. Given the rich number of potential linear events (attributes) to be transferred, it would be much more efficient for the recipient to do dynamic segmentation rather than receive a set of maps, one for each attribute.

Notes

1. It is possible to use only a Link Table consisting of valid node pairs and then drop the Node Table—or at least restrict its use to carrying node attributes—since the Link Table could be used to find paths by looking for common end nodes. However, we anticipate that such a design would be less efficient than one using the Node Table since a second table query would be needed to find all candidate links originated from the end node. With the suggested Node Table, all valid links are already available in one record.

2. NCHRP 20-27 and subsequent work by its authors do not require anchor points to be defined for anchor section intersections. However, we believe that such intersections are most likely to be the locations that need to be properly registered during data exchanges.

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Analysis and Adjustment of Measurement Systems for Linear Referencing

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Abstract: Considerable attention recently has been devoted to conceptual data modeling and implementation of linear referencing systems in database environments. However, the field components of linear referencing systems have not been well-addressed in the literature. The spatial integrity of all linearly referenced data depends upon a system of measurements, made in the field, which not only relate events of interest to real-world objects that make up the reference system, but also relate those real-world objects to one another in such a way that reliable linear locations can be determined. This paper examines the nature of linear referencing systems by comparison with other kinds of location referencing systems; develops the basis for stochastic analysis of the quality of linear locations; and provides a mathematical model for the simultaneous adjustment of linear referencing system measurements that yields the best possible estimates for linear locations. The model also yields estimates for the accuracies and interdependencies of computed linear locations. These accuracy estimates can be propagated through functions to produce quality information on the results of spatial analysis. An example is included.

The significance of linearly referenced information to the operations of transportation agencies is being increasingly recognized. A number of agencies are beginning to establish data models and internal policies and procedures targeted at ensuring integrity and providing consistency in linearly referenced information.

Baker and Blessing (1974) articulated the concept that a linear referencing system is a set of office and field procedures that includes multiple linear-referencing methods (e.g., mileposts and engineering stationing) and support for transformations among them. Data modelers since that time established the need for the dynamic segmentation function to manage and analyze linearly-referenced data in geographic information systems (Fletcher 1987; Dueker 1987; Nyerges 1990). The data model proposed by Ries (1993) extended these ideas by including a generic topologic object (link/site) to which were linked not only multiple linear-referencing methods but also multiple cartographic representations, allowing a single set of linearly referenced data to be displayed at many scales.

Participants at a workshop sponsored by the National Cooperative Highway Research Program (NCHRP) drew upon this earlier work and derived a linear referencing system data model that includes multiple linear referencing methods, multiple cartographic representations, and multiple network representations (Vonderohe et al. 1995). The NCHRP model supports integration of data through transformations among methods, networks, and cartographic representations by association with a central object referred to as a "linear datum." The concept of a linear datum has subsequently been incorporated in further modeling efforts (Fletcher 1995; Dueker and Butler 1997).

In parallel with the data modeling work being done by infrastructure managers, the Intelligent Transportation Systems (ITS) community was also developing models for location referencing and data integration. More recent ITS work produced a location reference message specification (Goodwin et al. 1996) and a proposed ITS datum for location referencing (Siegel et al. 1996). Recognizing the commonalities among the linear referencing systems models for infrastructure management and ITS, and drawing upon expertise from the military transportation community, a recently published work calls for development of a unified linear referencing system with a common linear datum to support the transportation and navigational data needs of civilian government, the military, and the private sector (Fletcher et al. 1996).

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Collectively, these efforts and others provide a sound conceptual foundation for describing the nature of linear referencing systems in database environments. However, the data and measurements used to build such databases are collected in the real world. Certain real-world aspects of a linear referencing system (i.e., its configuration and underlying measurements) determine the spatial integrity of data referenced to it. The objective of the work reported herein was development of a mathematical model for analysis and adjustment of the underlying measurements in such a way that the best possible estimates for linear locations are obtained and their accuracies are not only known but also controlled.

Linear Referencing System Concepts

In pathfinding, routing, traffic flow analysis, and transportation planning problems, transportation facilities are often modeled as networks consisting of connected sets of links and nodes (Figure 1). Each link designates a “from” node and a “to” node and networks are generated by finding matches between nodes.

Phenomena of interest along the facility are represented as point events and linear events. Point events are zero-dimensional. Examples include traffic control signals, pipeline crossings, and accidents. Linear events have one-dimensional extent. Examples include no-passing zones, pavement segments with homogeneous characteristics, and stretches of highway under construction.

Point and linear events are located by offsets from reference points. Reference points are associated with traversals or routes consisting of ordered and directed collections of links. The direction of a traversal gives direction for the offset measures that locate events. Any given link might be included in any number of traversals. Each linear referencing method in a linear referencing system is associated with a subset of traversals. Examples of linear referencing methods include county-route-milepoint, reference post, and engineering stationing.

Nodes and traversal reference points are, in turn, located by offsets in a linear datum consisting of a connected set of anchor sections that have anchor points at their junctions and termini (Figure 2). Anchor sections have direction, specified by “from” and “to” anchor points, but this is solely for location referencing, not for representing flow. The linear datum ties the linear referencing system to the real world. Anchor points represent persistent objects along traveled ways. They must be identifiable and recoverable in the field. Anchor sections have a “distance” attribute which is the distance traveled along the facility between anchor points. Anchor section distances and offsets to nodes, traversal reference points, point events, and linear events are determined from a system of measurements, made in the field, that also establishes the accuracies and interdependencies of linear locations.

Location Referencing Systems Compared

There are established referencing systems and datums for locating phenomena of interest in one, two, and three dimensions in support of public, private, and military applications (Table 1). WGS84 is a three-dimensional referencing system, for establishing locations in space. NAD83 is a two-dimensional referencing system, for establishing horizontal locations. The Public Land Survey System (PLSS) is a two-dimensional, non-mathematical referencing system, for establishing the locations of real properties. NAVD88 is a one-dimensional referencing system, for establishing elevations. A linear referencing system (LRS) is a one-dimensional system for establishing locations along linear facilities. Following sections of

FIGURE 1. Events Located by Offsets from Traversal Reference Points
this paper compare technical aspects of these location referencing systems. Institutional and policy aspects are addressed in Fletcher et al. (1996).

Each of the location referencing systems in Table 1 have datum objects, reference objects, and location specifications. All but two of them support transformations among various location referencing methods. All of them are similar beyond the characteristics identified in Table 1 in that their designs are, or should be, based upon closed systems of redundant measurements that ensure their spatial integrity to the level required by the user community.

**Datum Objects**

A datum object provides the basis for location referencing. It is the object to which everything else in a given location referencing system is tied, either directly or indirectly. Datum objects link the referencing system to the real world. They are sometimes defined as abstractions of real objects. In other cases, they are, themselves, physical objects.

The Cartesian coordinate axes of WGS84 and the ellipsoid of NAD83 are mathematical constructs. Both of these are linked to the real world by determining the locations of their origins with respect to the Earth's center of mass and the rotations of their axes with respect to the spin axis of the Earth. WGS84 is also associated with an ellipsoid, nearly identical to that of NAD83. NAD83 is also associated with a set of three-dimensional Cartesian coordinate axes in nearly the same location and orientation as those of WGS84.

The geoid, which serves as the datum object for NAVD88, is the real gravitational equipotential surface that would be the level of the sea if the Earth's oceans were permitted to flow unrestricted within the continents and be unaffected by tides (Bornford 1980, pp.

<table>
<thead>
<tr>
<th>Name</th>
<th>Dimension</th>
<th>Datum Object</th>
<th>Reference Object</th>
<th>Location Specification</th>
<th>Transformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>WGS84</td>
<td>3 D</td>
<td>3D Cartesian Axes</td>
<td>GPS Satellite</td>
<td>X,Y,Z</td>
<td>X,Y,Z ⇔ φ,λ,h</td>
</tr>
<tr>
<td>NAD83</td>
<td>2 D (Horizontal)</td>
<td>Ellipsoid</td>
<td>Horizontal Control Station</td>
<td>φ,λ</td>
<td>φ,λ ⇔ x,y</td>
</tr>
<tr>
<td>PLSS</td>
<td>2 D (Non-Mathematical)</td>
<td>Section Corner</td>
<td>Cadastral Survey Monument</td>
<td>Township Range, Section, Aliquot Part</td>
<td>None</td>
</tr>
<tr>
<td>NAVD88</td>
<td>1 D (Vertical)</td>
<td>Geoid</td>
<td>Benchmark</td>
<td>Elevation</td>
<td>None</td>
</tr>
<tr>
<td>LRS</td>
<td>1 D (Linear)</td>
<td>Anchor Point / Anchor Section</td>
<td>Traversal Reference Point</td>
<td>Offset along Anchor Section</td>
<td>LRM₁ ⇔ LRM₁</td>
</tr>
</tbody>
</table>
Within the NAVD88 referencing system, the location of the geoid is estimated by measurements. A section corner, the datum object of the Public Land Survey System (PLSS), is a zero-dimensional location at the place of the centroid of the first monument set by the original surveyor. The original monument might be long since destroyed.

Anchor sections and anchor points, the datum objects of the linear referencing system, are low-level abstractions of a transportation facility. They represent the centerline of the traveled way and points along that centerline, respectively. The anchor section representation is solely through identification of “from” and “to” anchor points and a distance measured along the centerline of the traveled way. The linear datum is linked to the real world through a location description attribute of anchor points.

Datum objects are not dedicated to a singular coordinate system or referencing method, but allow multiple coordinate systems to be imposed upon them. A datum may be designed for a particular type of coordinate system, such as Cartesian axes, or angular coordinates, but there are different possibilities for origin, orientation and scale.

Datum objects are often described by parameters. For example, horizontal datums (e.g., NAD83) are described by ellipsoidal parameters (lengths of major and minor axes). The parameters of the linear datum are the lengths of the anchor sections.

**Reference Objects**

Reference objects are those things to which measurements are made such that coordinates for a point of interest may be computed. Reference objects have physically identifiable locations and known coordinate values referenced to the datum. They are the linear referencing system objects that are most familiar to the user community. In fact, the density and physical character of reference objects in a well-designed location referencing system should be derived from the needs of those who will be using the system in the field.

In three-dimensional satellite navigation systems the reference objects are the satellites themselves. To locate an unknown point, distances are measured to satellites whose coordinates are known with respect to the datum object (WGS84 Cartesian axes). In differential GPS applications, at least one marked location on the ground also serves as a reference object. Satellite orbital parameters are determined through a redundant ground-based network of fixed tracking stations.

The reference objects for NAD83 and NAVD88 are monumented stations of the horizontal and vertical control networks, respectively. Within each of these control networks, locations of individual reference objects are computed from an interconnected and over-determined system of measurements.

Within the PLSS, cadastral survey monuments witness the locations of section corners. Surveyors make measurements to the monuments and then use these measurements and other evidence (e.g., the physical character of the monument versus that described in the record) to decide which, if any, monuments should be accepted as representing section corners. The PLSS includes a redundant system of measurements that link adjacent section corners and which are used to provide both quality control measures and initial estimates for the sizes, shapes, and relative locations of sections of land.

The reference objects of a linear referencing system are traversal reference points, chosen for convenience and permanence in the field. The same physical object in the field (e.g., mark at the intersection of two centerlines) might represent both an anchor point (datum object) and a traversal reference point (reference object) in a linear referencing system, but there will typically be many more traversal reference points than anchor points. Traversal reference points can also be as abstract as timing points along a transit route.

During establishment of any location referencing system, the relationship between datum objects and reference objects, often expressed as coordinates, is initially unknown. These coordinates are treated as unknown parameters and estimates for them are determined from measurements.

**Location Specification**

Each location referencing system specifies location in a particular way, with a particular metric. WGS84 uses distance offsets from each of the X,Y,Z axes. NAD83 uses angular measures of latitude (φ) and longitude (λ); NAVD88 uses elevations; the PLSS uses a naming convention (Section, Township, Range, Principal Meridian); a linear referencing system uses distance offsets along anchor sections.

For all of the location referencing systems except the PLSS, the location of an unknown point can be computed from measurements of direction and distance from a known point; all that differs is the dimensionality of the direction. For WCS84, direction can be specified by direction cosines along the three-dimensional coordinate axes. For NAD83, direction is specified by a two-dimensional azimuth. For NAVD88, direction is either “up” or “down.” For a linear referencing system, direction is either “with” or “against” the direction of a traversal.
**Transformation**

Location specifications are such that there is a unique description for each location in a datum. In many cases, the location referencing datum then provides a common basis for additional coordinate systems or location referencing methods, thereby enabling transformations among them based upon calculations through a set of mathematical functions. For example, point locations in WGS84 are often published as both X, Y, Z and φ, λ, h. With NAD83, φ, λ are often transformed into rectangular coordinates (x, y or N, E) on Lambert or Mercator map projections. Transformation between map projections requires an intermediate transform to the datum. With a linear referencing system, transformations between linear referencing methods, such as reference post and milepoint, take place in a similar way. An offset from a reference post is transformed into an offset along an anchor section which is then, in turn, transformed into a milepoint.

**Redundant Measurements and Enabled Conditions**

All of the location referencing systems described above include collections of redundant measurements that establish the datum objects and determine locations of reference objects. Redundancies in the measurements allow imposition of geometric conditions that enable quality checking and provide a mathematical basis for determination of best estimates for datum and reference object parameters (Figure 3).

In horizontal referencing systems measured angles and distances form loops that impose conditions on the sums of the interior angles and the sums of the coordinate differences around the perimeters (Figure 3a). In vertical referencing systems measured elevation differences form loops that must ultimately sum to zero after adjustment of the observed values (Figure 3b). In three-dimensional referencing systems measured space vectors form loops whose sums of coordinate differences must be zero after adjustment of the observed values (Figure 3c). In a linear referencing system, measured anchor section distances that apparently form loops, as in Figure 3d, example 1, provide no redundancy and no conditions. This is because of the independence of each anchor section. However, measurements that span anchor sections or tie traversal reference points to one another or to anchor sections, as in Figure 3d, example 2, can provide redundancy and allow the imposition of conditions. In Figure 3d, example 2, the anchor section distance must be equal to the sum of its two parts after adjustment of the observed values.

**Mathematical Model for Derivation of Parameter Estimates from Measurements**

**The General Linear Model**

In Figure 3d, example 2, the unknown system parameters are the traversal reference point offset (observed value = l3) and the anchor section distance (observed value = l4). Assume that l1, l2, and l3 are 1.010, 1.020, and
2.045 miles, respectively. These measurements contain errors, as do all measurements. Imposing the known condition on them, the misclosure is

\[ mc = l_1 - l_2 - l_3 = +0.015 \text{ miles} \]  

Assuming equal reliability in the measurements, one-third of the misclosure should be attributed to each, yielding estimates of 1.015 miles for the traversal reference point offset and 2.040 miles for the anchor section distance. Estimates for the errors in the measurements, referred to as "residuals", are -0.005, -0.005, and +0.005 miles for \( l_1 \), \( l_2 \), and \( l_3 \), respectively.

In a complex system, with many anchor points, many traversal reference points, and many measurements, the full set of conditions (containing overlapping sets of measurements) is difficult to identify. An alternative approach is to build a system of "observation equations" each of which expresses a functional relationship between a single measurement and a set of system parameters (Mikhail and Gracie 1981, p. 72). In a linear system, the general form of an observation equation is

\[ l_i - \xi_i + c_i = a_{ij} x_j + a_{ik} x_k + \ldots + a_{in} x_n \]  

where \( l_i \) is the ith measurement,
\( \xi_i \) is the error in the ith measurement,
\( c_i \) is a constant,
the \( x \)'s are the unknown parameters, and
the \( a \) 's are coefficients of the unknown parameters.

A system of \( m \) observation equations may be written as

\[ L - E + C = AX \]  

where \( L \) is an \( m \times 1 \) matrix of measurements,
\( E \) is an \( m \times 1 \) matrix of errors,
\( C \) is an \( m \times 1 \) matrix of constants,
\( A \) is an \( m \times n \) matrix of coefficients, and
\( X \) is an \( n \times 1 \) matrix of unknown parameters.

If \( m > n \), the parameters are over-determined with \( m-n \) degrees of freedom. If the errors are normally distributed with means of zero (i.e., there are no systematic or gross errors present), then the solution to equation (3) that yields the best estimates for the unknown parameters is

\[ \hat{X} = (A^T PA)^{-1} A^T P (L + C) \]  

where \( P \) (a weight matrix) = \( Q_{ii}^{-1} \),

\[ Q_{ii} = \frac{1}{\sigma_i^2} \Sigma_i \]  

\( \sigma_i \) is a proportionality constant, used for scaling purposes, and can be assigned any arbitrary value often selected as one (1). \( \sigma_0 \) is interpreted as the standard deviation of a measurement with weight one. For independent measurements, \( \Sigma_i \) is diagonal and, therefore, \( Q_{ii} \) and \( P \) are diagonal. The elements of \( \Sigma_i \) may be based upon experience or derived from repetitions of individual measurements. Subsequent to the solution for \( X \), the residuals (\( V \)) can be computed from

\[ V = L + C - AX \]  

An \textit{a posteriori} estimate for the reference variance can then be computed as

\[ \hat{\sigma}_{ij}^2 = (V^T PV) / (m - n). \]  

The Chi square statistic can be used to test the hypothesis that \( \hat{\sigma}_{ij}^2 = \sigma_{ij}^2 \), providing a global indicator of the overall quality of the weights of the measurements and the measurements themselves.

The solution yields not only best estimates for the parameters but also estimates of their accuracies and interdependencies. The variance-covariance matrix of the parameters can be obtained from

\[ \Sigma_{xx} = \hat{\sigma}_{ij}^2 (A^T PA)^{-1}. \]  

The variance-covariance matrix of the residuals is given by

\[ \Sigma_{vv} = \hat{\sigma}_{ij}^2 (Q_{ii} - \Lambda (A^T PA)^{-1} A^T). \]  

(Mikhail and Gracie, 1981, p. 169)

\( \Sigma_{vv} \) can be used to examine local redundancies in the measurements, detect gross errors, determine the minimum size of a detectable gross error (internal system reliability), and determine the effects of undetected gross errors on the parameters (external system reliability) (Kuang 1996, pp. 169–173).

**Linear Referencing System Observation Equations**

All measurements within the linear referencing system are distances. Anchor sections have directions, but these are assigned, not observed. There are three kinds of distances, categorized with regard to the objects they connect: 1) connecting two traversal reference points, 2) connecting a traversal reference point and an anchor point, and 3) connecting two anchor points.

**Distance Connecting Two Traversal Reference Points**

There are three cases (Figure 4). In Figure 4a (Case 1), the traversal reference points are on anchor sections that have the same direction. The observation equation is

\[ l_0 - x = \varepsilon_0 - \varepsilon_0 = d_1 + d_2. \]  

\( \varepsilon_0 \) is a proportionality constant, used for scaling purposes, and can be assigned any arbitrary value often selected as one (1). \( \sigma_0 \) is interpreted as the standard deviation of a measurement with weight one. For independent measurements, \( \Sigma_i \) is diagonal and, therefore, \( Q_{ii} \) and \( P \) are diagonal. The elements of \( \Sigma_i \) may be based upon experience or derived from repetitions of individual measurements. Subsequent to the solution for \( X \), the residuals (\( V \)) can be computed from

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The general form of equation (11) is

$$l_r - e_r = a_0 - o_a + \sum_{i=1}^{n-1} d_i.$$  \hspace{1cm} (12)

where the first anchor section contains traversal reference point a and the nth anchor section contains traversal reference point b. If the two traversal reference points are on the same anchor section, there is no summation of anchor section distances.

In Figure 4b (Case 2), the anchor sections containing the two traversal reference points have converging directions. The observation equation is

$$l_r - e_r = -a_b - o_b + d_1 + d_2 + d_3.$$  \hspace{1cm} (13)

The general form of equation (13) is

$$l_r - e_r = -a_b - o_b + \sum_{i=1}^{n} d_i.$$  \hspace{1cm} (14)

In Figure 4c (Case 3), the anchor sections containing the two traversal reference points have diverging directions. The observation equation is

$$l_r - e_r = a_0 + o_a + d_1.$$  \hspace{1cm} (15)

The general form of equation (15) is

$$l_r - e_r = a_0 + o_a + \sum_{i=1}^{n} d_i.$$  \hspace{1cm} (16)

**Distance Connecting a Traversal Reference Point and an Anchor Point**

There are two cases (Figure 5). In Figure 5a (Case 1), the direction of the anchor section containing the traversal reference point is away from the anchor point included in the measurement. The observation equation is

$$l_r - e_r = a_b + d_1.$$  \hspace{1cm} (17)

The general form of equation (17) is

$$l_r - e_r = a_b + \sum_{i=1}^{n} d_i.$$  \hspace{1cm} (18)

where the first anchor section contains the anchor point and the nth anchor section contains the traversal reference point. If the traversal reference point is on the first anchor section, there is no summation.

In Figure 5b (Case 2), the direction of the anchor section containing the traversal reference point is toward the anchor point included in the measurement. The observation equation is

$$l_r - e_r = -a_a + d_1 + d_2.$$  \hspace{1cm} (19)

The general form of equation (19) is

$$l_r - e_r = -a_a + \sum_{i=1}^{n} d_i.$$  \hspace{1cm} (20)
**Distance Connecting Two Anchor Points**

The observation equation for a measured distance connecting two anchor points and spanning two anchor sections (Figure 6) is

\[ l_{ab} = d_1 + d_2. \]  \hspace{1cm} (21)

The general form of equation (21) is

\[ l_{ab} - e_{ab} = \sum_{i=1}^{n} d_i. \]  \hspace{1cm} (22)

**Example**

Figure 7a illustrates a configuration of three anchor sections and three traversal reference points with unknown parameters:

\[ X = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ o_a \\ o_b \\ o_c \end{bmatrix}. \]  \hspace{1cm} (23)

Figure 7b illustrates a set of measurements among the traversal reference points and anchor points. If the measured values are 5.250, 10.550, 6.410, 2.230, 1.940, 4.720, and 2.330 miles for the successive \( l_i \)’s, then the observation equations are:

\[
\begin{bmatrix}
5.250 \\ 10.550 \\ 6.410 \\ 2.230 \\ 1.940 \\ 4.720 \\ 2.330
\end{bmatrix} - \begin{bmatrix}
e_1 \\ e_2 \\ e_3 \\ e_4 \\ e_5 \\ e_6
\end{bmatrix} = \begin{bmatrix}
100 \\ 110 \\ 110-1-1 \\ 0 \\ 0 \\ 100-1 \\ 0
\end{bmatrix} \begin{bmatrix}
d_1 \\ d_2 \\ d_3 \\ o_a \\ o_b \\ o_c
\end{bmatrix}. \]  \hspace{1cm} (24)

If the measurements are independent, \( l_1 \) and \( l_2 \) have standard deviations of \( \pm 0.005 \) miles, the remaining measurements have standard deviations of \( \pm 0.010 \) miles, and \( \sigma^2 \) is assigned a value of one, then the weight matrix is:

\[
P = \begin{bmatrix}
40000 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 40000 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 100000 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 10000 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 10000 \\
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}. \]  \hspace{1cm} (25)

The solution for the parameter estimates is:

\[
\bar{X} = (A^T PA)^{-1} A^T PL = \begin{bmatrix}
5.250 \\ 5.300 \\ 4.021 \\ 2.221 \\ 1.931 \\ 1.691
\end{bmatrix}. \]  \hspace{1cm} (26)

The residuals are 0.000, -0.002, 0.010, 0.009, 0.009, 0.000, and 0.000 miles, respectively. There is one degree of freedom in the measurement system. There is no local

**FIGURE 7. Unknown Parameters and Measurements for Example**

---

**FIGURE 6. Distance Connecting Two Anchor Points**

Legend:

- 1: Anchor section "1" and two anchor points
- \( d_i \): unknown distance (length) of anchor section "1"
- \( l_{ab} \): measured distance between anchor points

---
redundancy in the measurements \( l_1, l_0, \) and \( l_7 \). The \emph{a posteriori} estimate for the reference variance is 2.769. The standard deviations (miles) in the parameter estimates are:

\[
\begin{bmatrix}
\sigma_{s_1} \\
\sigma_{s_2} \\
\sigma_{d_1} \\
\sigma_{d_2} \\
\sigma_{o_a} \\
\sigma_{o_b}
\end{bmatrix} = \begin{bmatrix} 
\pm 0.008 \\
\pm 0.011 \\
\pm 0.028 \\
\pm 0.014 \\
\pm 0.014 \\
\pm 0.023
\end{bmatrix}
\] (27)

The variance-covariance matrix for the parameter estimates is:

\[
\Sigma_{xx} = \begin{bmatrix}
\sigma_{s_1}^2 & \sigma_{s_1} \sigma_{s_2} & \sigma_{s_1} \sigma_{d_1} & \sigma_{s_1} \sigma_{d_2} & \sigma_{s_1} \sigma_{o_a} & \sigma_{s_1} \sigma_{o_b} & \sigma_{s_1} \sigma_{o_c} \\
\sigma_{s_1} \sigma_{s_2} & \sigma_{s_2}^2 & \sigma_{s_2} \sigma_{d_1} & \sigma_{s_2} \sigma_{d_2} & \sigma_{s_2} \sigma_{o_a} & \sigma_{s_2} \sigma_{o_b} & \sigma_{s_2} \sigma_{o_c} \\
\sigma_{s_1} \sigma_{d_1} & \sigma_{s_2} \sigma_{d_1} & \sigma_{d_1}^2 & \sigma_{d_1} \sigma_{d_2} & \sigma_{d_1} \sigma_{o_a} & \sigma_{d_1} \sigma_{o_b} & \sigma_{d_1} \sigma_{o_c} \\
\sigma_{s_1} \sigma_{d_2} & \sigma_{s_2} \sigma_{d_2} & \sigma_{d_1} \sigma_{d_2} & \sigma_{d_2}^2 & \sigma_{d_2} \sigma_{o_a} & \sigma_{d_2} \sigma_{o_b} & \sigma_{d_2} \sigma_{o_c} \\
\sigma_{s_1} \sigma_{o_a} & \sigma_{s_2} \sigma_{o_a} & \sigma_{d_1} \sigma_{o_a} & \sigma_{d_2} \sigma_{o_a} & \sigma_{o_a}^2 & \sigma_{o_a} \sigma_{o_b} & \sigma_{o_a} \sigma_{o_c} \\
\sigma_{s_1} \sigma_{o_b} & \sigma_{s_2} \sigma_{o_b} & \sigma_{d_1} \sigma_{o_b} & \sigma_{d_2} \sigma_{o_b} & \sigma_{o_b} \sigma_{o_a} & \sigma_{o_b}^2 & \sigma_{o_b} \sigma_{o_c} \\
\sigma_{s_1} \sigma_{o_c} & \sigma_{s_2} \sigma_{o_c} & \sigma_{d_1} \sigma_{o_c} & \sigma_{d_2} \sigma_{o_c} & \sigma_{o_c} \sigma_{o_b} & \sigma_{o_c} \sigma_{o_b} & \sigma_{o_c}^2
\end{bmatrix}
\]

\[
\begin{bmatrix}
0.693 & -0.693 & -0.693 & 0.000 & 0.000 & -0.693 \\
-0.693 & 1.330 & 0.914 & 0.222 & 0.222 & 0.914 \\
-0.693 & 0.914 & 8.144 & 1.911 & -0.859 & 5.374 \\
0.000 & 0.222 & 1.911 & 1.911 & -0.859 & 1.911 \\
0.000 & 0.222 & -0.859 & -0.859 & 1.911 & -0.859 \\
-0.693 & 0.914 & 5.374 & 1.911 & -0.859 & 5.374
\end{bmatrix} \times 10^{-4}
\] (28)

Given the linear referencing system in Figure 7 and the result in equation (28), and applying the Law of Propagation of Random Error, it is now possible to analyze the accuracies of point and linear events referenced to this system. The General Law of Propagation of Random Error (Mikhail and Gracie 1982, pp. 152-153) states that if \( y \) is a linear function of random variables \( x_i \), thus:

\[
y = a_1 x_1 + a_2 x_2 + \ldots + a_n x_n + c
\] (29)

where \( c \) is a constant,

then

\[
\sigma_y^2 = \sum_{i=1}^{n} \sigma_i^2 + \sum_{i=1}^{n} \sum_{j=1}^{n} a_i a_j \sigma_{x_i \times x_j}
\] (30)

where \( \sigma_i^2 \) is the variance in \( y \),

\( \sigma_i^2 \) is the variance in \( x_i \), and

\( \sigma_{x_i \times x_j} \) is the covariance between \( x_i \) and \( x_j \).

Measurements are typically uncorrelated (zero covariances). However, reference system parameters are typically correlated (non-zero covariances). Locations, computed from linear combinations of measurements and parameters, have variances that can be determined using equation (30).

Let point event \( z \) be located on anchor section 1 by measurement \( (l_{xz} = 0.500 \text{ mile}) \) from traversal reference point \( a \) and point event \( y \) be located on anchor section 2 by measurement \( (l_{zy} = 0.750 \text{ mile}) \) from traversal reference point \( b \) (Figure 8). If

\[
\sigma_{l_{xz}} = \pm 0.005 \text{ mile and} \quad \sigma_{l_{zy}} = \pm 0.010 \text{ mile, then}
\]

the absolute accuracy of the location of point event \( z \) is given by

\[
\sigma_{\Delta x} = [\sigma_{\Delta x}^2 + \sigma_{\Delta y}^2]^{1/2}
\]

\[
= [1.911 + 0.200]^{1/2} \times 10^{-2}
\]

\[
= \pm 0.015 \text{ mile.}
\] (33)

The absolute accuracy of the location of point event \( y \) is given by

\[
\sigma_{\Delta y} = [\sigma_{\Delta x}^2 + \sigma_{\Delta y}^2]^{1/2}
\]

\[
= [1.911 + 1.000]^{1/2} \times 10^{-2}
\]

\[
= \pm 0.017 \text{ mile.}
\] (34)

**FIGURE 8. Events on Anchor Sections 1 and 2 for Continuing Example**
The derived distance, $s_{xy}$, is given by
\[ s_{xy} = d_1 + d_2 - a_1 + l_{12} - a_2 - b_1 = 5.230 + 5.302 - 2.221 + 0.500 - 1.931 - 0.750 = 6.130 \text{ miles.} \quad (35) \]

The relative accuracy of the locations of $z$ and $y$ with respect to one another or the accuracy of the length of the linear event $zy$ is given by
\[
\sigma_{s_{zy}} = \left[ \sigma_{a_1}^2 + \sigma_{a_2}^2 + \sigma_{b_1}^2 + \sigma_{b_2}^2 + \sigma_{l_{12}}^2 + 2 \sigma_{l_{12}} \sigma_{a_1} + \sigma_{z_{12}}^2 + 2 \sigma_{z_{12}} \sigma_{a_2} - 2 \sigma_{l_{12}} \sigma_{a_1} - 2 \sigma_{l_{12}} \sigma_{a_2} - 2 \sigma_{l_{12}} \sigma_{b_1} - 2 \sigma_{l_{12}} \sigma_{b_2} + 2 \sigma_{a_1} \sigma_{a_2} \right]^{1/2}
\]
\[ = \sqrt{[0.693 + 1.330 + 1.911 + 1.991 + 0.250 + 1.000 + 2(-0.693) - 2(0.000) - 2(0.000) - 2(0.222) - 2(0.222) + 2(-0.859)]^{1/2} = \pm 0.018 \text{ miles.} \quad (36) \]

Expressed as a ratio, the relative accuracy of $zy$ is $1 : (6.15 / 0.018)$ or $1 : 340$.

**Discussion**

The mathematical model for analysis and adjustment of linear distance measurements requires a priori knowledge of the quality of the measurements, manifested as a weight matrix. The weight matrix is often taken to be the inverse of the variance-covariance matrix of the measurements. Linear distance measurements can be made in such a way that they are independent, but their variances, or at least ratios between their variances, must be known. The uncertainty of linear measurements has not been well-studied. The examples in this paper use arbitrarily assigned variances merely to illustrate mathematical principles. Intuitively, actual variances would be expected to depend upon the distances being measured. There are existing models for uncertainty in straight-line distances measured by optical techniques and by GPS that might or might not be applicable to linear measurements. Research is required. Design of experiments should account for different linear distance measurement techniques (e.g., DML, summation of chords between GPS coordinates), variation in measured distances, and variation in alignments. Reference data sets could be developed from as-built information, independent high-accuracy measurements, or engineering-scale photogrammetric mapping. If a model or models of linear distance uncertainty can be derived, it can then be used to develop the necessary a priori estimates for variances in measurements.

The assumption of normality in general regression models is sometimes problematic. However, in the case of spatial measurements, the assumption is very often supportable. The experimental research, called for above to develop a model for uncertainty in linear distance measurement, should also be used to test the assumption of normality.

**Conclusions**

A linear referencing system is similar to other kinds of location referencing systems in many ways, including the roles of its components (i.e., datum objects and reference objects) and the fundamental nature of the measurements which determine its configuration, accuracy, and fitness for use. A mathematical model was derived for the analysis and adjustment of redundant systems of linear measurements. The model is based upon the principles of geodetic science and engineering and is similar to models for geodetic network adjustment.

Systematic effects and gross errors that inevitably creep into large systems of spatial measurements can be controlled by appropriate calibration of measurement devices and adoption of standardized field procedures. Those systematic and gross errors that remain can be detected and isolated using methods based on the results of the simultaneous adjustment.

By-products of the simultaneous adjustment of linear measurements are the variance-covariance matrices of the residuals and the system parameters. The former can be used to validate a priori assumptions concerning the measurements. The latter can be used to analyze the accuracy of the referencing system and the accuracy of data referenced to it. Estimates of accuracies of linear locations and their interdependencies can be used to estimate the accuracies of derived values. The potential exists for automated delivery of quality information along with the results of spatial operations on data whose locations are referenced in this way.

Linear referencing systems of any size can be analyzed and adjusted. For very large systems, specialized methods must be used to solve the equations and produce the variance-covariance matrices. The model produces a simultaneous adjustment, so there is potential for integration of linear referencing systems across geographic extents and jurisdictional boundaries, especially for development and analysis of the linear datum, which is common to all. An accompanying paper (see Vonderohe and Hepworth 1998, page 48 in this issue) extends the adjustment model to support design of measurement systems for linear referencing in such a way that accuracy requirements of end users can be guaranteed to be met.

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References


A Methodology for Design of Measurement Systems for Linear Referencing

Alan P. Vonderohe and Todd D. Hepworth

Abstract: A method is presented for designing the field components of linear referencing systems in such a way that statistically supportable statements can be made concerning their abilities to meet the accuracy requirements of users. The method transforms end-user accuracy requirements for linearly referenced data into specifications for configuration of a linear referencing system, its underlying system of measurements, and procedures and technologies for making those measurements. The method is founded upon basic principles of geodetic science and engineering and is derived from techniques used to design geodetic networks. It ensures, a priori, that accuracies and interdependencies of linear locations, derived from analysis of a system of redundant measurements, will fall within tolerable bounds. An example is given.

Considerable effort has recently been devoted to developing conceptual data models for linear referencing systems (Ries 1993; Fletcher 1995; Hickman 1995; Okumieff et al. 1995; Scarponcini 1995; Vonderohe et al. 1995; Dueker and Butler 1997). Much of this work built upon early thinking by Baker and Blessing (1974) and subsequent research that led to recognition of the need for modeling and management of linearly referenced data in geographic information systems (Dueker 1987; Fletcher 1987; Nyerges 1990).

One of the concepts that emerged from recent data-modeling efforts was the linear datum, a collection of simple objects that provides a basis for unambiguous linear referencing and enables transformations among multiple linear-referencing methods, multiple networks, and multiple cartographic representations. A datum for ITS location referencing has been proposed (Goodwin et al. 1996; Siegel et al. 1996) and a call has been made for development of a unified linear referencing system with a common linear datum to support the transportation and navigational data needs of civilian government, the military, and the private sector (Fletcher et al. 1996).

At the same time, a number of transportation agencies, through recognition of the significance of spatially referenced data (especially, linearly referenced data) to their operations, have recently developed internal policies and standards with regard to the management of location referencing. Among them are the Departments of Transportation in Colorado (Allen and Joy 1995), Idaho (Rowell 1996), Minnesota (MinnDOT 1992, 1994), Utah (Deighton and Blake 1993), Washington (Cihon 1996), and Wisconsin (Ries 1995; WisDOT 1996).

One of the key aspects of any location referencing system is its ability to support the accuracy requirements of users. That is, a location referencing system must provide a framework of sufficient accuracy such that data referenced to it by measurements in the field will meet the most stringent requirements of the user community. Design methods, based on this criterion, have been developed and applied to geodetic networks for location referencing in one, two, and three dimensions. These methods have not yet been considered for designing linear referencing systems. The linear referencing systems of today are typically treated as collections of independent locations, determined by individual measurements. Although, in some cases, quality control measures based on repeatability have been applied (e.g., WisDOT 1996), comprehensive analysis and simultaneous adjustment of linear measurements has not been possible due to lack of an appropriate mathematical model.

An accompanying paper presents such a model (Vonderohe and Hepworth 1998). It is similar to those used for analysis and adjustment of geodetic networks. The model yields best possible estimates for linear locations from a set of redundant measurements and, at the same time, provides estimates for the accuracies and interdependencies of those locations. The model also provides global and local measures of reliability for detailed as-

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essment of the quality of its results. The objective of the work reported herein was extension of that model to address the problem of measurement system design for linear referencing. A method was sought that would enable defensible statements to be made about the ability of a linear referencing system to support the accuracy requirements of its users. The method transforms end-user accuracy requirements into specifications for configuration of a linear referencing system, its underlying system of measurements, and the technologies and field procedures to be used in making those measurements.

**Linear Referencing System Components**

The linear datum consists of anchor sections connecting anchor points (Figure 1). Anchor sections have direction, specified by “from” and “to” anchor points. The linear datum ties a linear referencing system to the real world. Anchor points represent persistent objects along traveled ways. Anchor sections have a “distance” attribute which is the distance traveled along the way between anchor points.

Traversal reference points are located by offsets from anchor points along anchor sections. They are associated with traversals (routes), consisting of ordered and directed collections of links. A given set of traversals and traversal reference points represent a single linear referencing method, such as county-route-milepoint. Another set of traversals and traversal reference points might represent a different linear referencing method, such as a reference post method. Any number of linear referencing methods can be associated with the single linear datum.

Events of interest are, in turn, located by offsets from traversal reference points. Events are the data required by end users for all applications. They consist of either point events, representing such things as signs or pipeline crossings; or linear events, representing such things as pavement segments and no-passing zones.

**The Design Problem**

It is the accuracy of locations of point and linear events, and the accuracy of results of analysis of these data, that are of concern to users. If these accuracy requirements can be clearly stated, the challenge of design is to find the least-cost configuration of the linear referencing system and its underlying measurements that guarantees a priori that those requirements will be met. The fundamental design questions are:

1. What is the optimal spacing of anchor points (and, thereby, lengths of anchor sections)?
2. What is the optimal set of measurements among traversal reference points and anchor points?
3. What is the required accuracy of those measurements?

Anchor section distances, offsets that locate traversal reference points, and offsets that locate point and linear events are all based upon a collection of measurements, each one of which contains error, and all of which contribute to the accuracy bounds of the overall system. Offsets to point and linear events are often based upon ad hoc individual measurements because data are collected and tied to traversal reference points on an as-needed and on-going basis. During design of the referencing system, it is therefore appropriate to assume that these future measurements will be made with some des-
igated accuracy. That value becomes one of the determining factors for reference system configuration, the set of remaining measurements, and their necessary accuracies. This remaining set of measurements is used to compute estimates for linear referencing system parameters (i.e., anchor section distances, and traversal reference point offsets).

Mathematical Model for Analysis and Adjustment of Linear Referencing System Measurements

The mathematical model developed by Vonderheide and Hepworth (1998) is repeated here in abbreviated form. It is based upon a system of “observation equations,” each of which expresses a functional relationship between a single measurement and a set of system parameters (Mikhail and Gracie 1981, p. 72). In any linear system, the general form of an observation equation is

\[ l_i - e_i + c_i = a_{1i} x_1 + a_{2i} x_2 + \ldots + a_{ni} x_n \]  

(1)

where

- \( l_i \) is the \( i \)th measurement,
- \( e_i \) is the error in the \( i \)th measurement,
- \( c_i \) is a constant,
- the \( x\)'s are the \( n \) unknown parameters, and
- the \( e\)'s are coefficients of the unknown parameters.

A system of \( m \) observation equations may be written in matrix form as

\[
\begin{pmatrix} L - E + C \end{pmatrix} = \begin{pmatrix} A \end{pmatrix} \begin{pmatrix} X \end{pmatrix}. 
\]

(2)

All measurements in a linear referencing system are distances. The observation equations have slightly different forms for distances connecting traversal reference points to traversal reference points, traversal reference points to anchor points, and anchor points to anchor points. The constants are zero in all cases. All coefficients are \(-1, 0, \) or \(+1\). The unknown parameters are anchor section distances and traversal reference point offsets.

If \( m>n \), the parameters are over-determined with \( m-n \) degrees of freedom. The solution to equation (2) that yields the best estimates for the unknown parameters is

\[
\begin{pmatrix} \hat{X} \end{pmatrix} = \left( \begin{pmatrix} A^T \end{pmatrix} \begin{pmatrix} A \end{pmatrix} \right)^{-1} \begin{pmatrix} A \end{pmatrix} \begin{pmatrix} L \end{pmatrix} + \begin{pmatrix} C \end{pmatrix}. 
\]

(3)

where

\[
\begin{pmatrix} Q_\theta \end{pmatrix} \text{ (a weight matrix)} = \begin{pmatrix} Q_\theta \end{pmatrix}, 
\]

(4)

\[
\begin{pmatrix} Q_\theta \end{pmatrix} = \frac{1}{\sigma_{0}^2} \begin{pmatrix} \Sigma_0 \end{pmatrix}, 
\]

(5)

\( \sigma_{0}^2 \) is the a priori reference variance, and

\( \Sigma_0 \) is the \( m \times m \) variance-covariance matrix of the measurements.

\( \sigma_{0}^2 \) is an arbitrary proportionality constant, used for scaling purposes, and can be assigned any arbitrary value often selected as one (1). \( \sigma_0^2 \) is interpreted as the standard deviation of a measurement with weight one. For independent measurements, \( \Sigma_0 \) is diagonal and, therefore, \( Q_\theta \) and \( P \) are diagonal. Subsequent to the solution for \( \hat{X} \), the residuals (\( V \)) can be computed from

\[
V = L + C - A \hat{X}. 
\]

(6)

An a posteriori estimate for the reference variance can then be computed as

\[
\hat{\sigma}_{0}^2 = \frac{\left( V^T PV \right)}{\left( m - n \right)}. 
\]

(7)

\( \hat{\sigma}_{0}^2 \), \( \sigma_{0}^2 \), and the Chi square statistic can be used to perform a global test of the overall quality of the weights of the measurements and the measurements themselves.

The solution yields not only best estimates for the parameters but also estimates for their accuracies and interdependencies. The variance-covariance matrix of the parameters can be obtained from

\[
\begin{pmatrix} \Sigma_0 \end{pmatrix} = \hat{\sigma}_{0}^2 \begin{pmatrix} A^T \end{pmatrix} \begin{pmatrix} A \end{pmatrix}^{-1}. 
\]

(8)

The variance-covariance matrix of the residuals is given by

\[
\begin{pmatrix} \Sigma_v \end{pmatrix} = \hat{\sigma}_{0}^2 \left( \begin{pmatrix} Q_\theta \end{pmatrix} - A \left( \begin{pmatrix} A^T \end{pmatrix} \begin{pmatrix} A \end{pmatrix} \right)^{-1} A^T \right). 
\]

(9)

(Mikhail and Gracie, 1981, p. 169)

\( \Sigma_v \) can be used to examine local redundancies in the measurements, detect gross errors, determine the minimum size of a detectable gross error (internal system reliability), and determine the effects of undetected gross errors on the parameters (external system reliability) (Kuang 1996, pp. 169–173).

Measurement System Design Methodology

In design problems, the reference variance is assigned a value of one. Equations (8) and (9) reduce to

\[
\begin{pmatrix} \Sigma_0 \end{pmatrix} = \left( \begin{pmatrix} A^T \end{pmatrix} \begin{pmatrix} A \end{pmatrix} \right)^{-1}. 
\]

(10)

and

\[
\begin{pmatrix} \Sigma_v \end{pmatrix} = \begin{pmatrix} Q_\theta \end{pmatrix} - A \left( \begin{pmatrix} A^T \end{pmatrix} \begin{pmatrix} A \end{pmatrix} \right)^{-1} A^T, 
\]

(11)

respectively. \( \Sigma_0 \) is established a priori with its diagonal elements expressing upper bounds on the accuracy requirements of users and its off-diagonal elements set to zero. The measurements to be made, as expressed in the \( A \) matrix by their interactions with the parameters, and their necessary accuracies, as expressed by \( P^{-1} \), are what must be determined. None of \( \Sigma_0, A, \) or \( P \), depend upon actual observed values (\( L \)). Therefore, equations (10) and (11) can be used in design to ensure a location referencing system's internal reliability, external reliability, and ability to meet the accuracy requirements of the user community before any actual measurements are made. Of course, many possible configurations and measurement schemes might provide these assurances. An optimal design provides them at least cost.
Orders of Location Referencing System Design

The geodetic community recognizes four orders (zero, first, second, and third) of location referencing system design problems (Grafarend and Sanso 1985, p. 7).

Zero-Order Design

Zero-order design can be characterized as selection of an optimum set of minimum constraints to be imposed upon the parameters (X) in order to ensure that the inverse \((A^T PA)^{-1}\) exists. Constraints on X affect A because A describes the relationship between the measurements (L) and the parameters (X).

For example, a fully observed vertical network of differential leveling cannot be used to determine elevations unless the elevation of at least one benchmark in the network is provided. In this kind of location referencing system, the unknown parameters are not observed directly. The measurements are all indirectly related to the parameters. A vertical control network with more than enough measurements to determine the elevation of each point uniquely must still be provided with constraints before the computation can be done.

In a linear referencing system, the unknown parameters (anchor section distances and traversal reference point offsets), can be observed directly. A fully observed system of measurements does not have to be constrained. This does not mean that \((A^T PA)^{-1}\) will exist for any collection of measurements. But, if it does not exist, then the system of measurements is not fully observed. For example, a sequence of traversal reference points along an anchor section could have distances measured between each successive pair Figure (2). The length (distance) of the anchor section could also be measured, as could any other distance connecting two traversal referencing points. In fact, the number of measurements in Figure 2 is equal to the number of unknowns, suggesting a unique solution. But, if there is no measurement connecting a traversal reference point and an anchor point, no traversal reference point offsets can be computed. This problem, assuring that the measurement system is appropriate, is actually more closely related to first-order design.

First-Order Design

First-order design refers to choosing the optimum configuration for the location referencing system; that is, selecting the numbers and locations of datum and reference objects and the measurements that will be made. It amounts to determining an optimum matrix A from \(\Sigma_x\) and \(P\), the former being the expression of user requirements and the latter being known for a selected measurement method.

The density of traversal reference points, for any given linear referencing method, depends primarily upon the needs of field personnel who make measurements to locate events. These needs vary with the application. For example, reference points used for highway inventory probably have a different optimal spacing than timing points for transit routes. It is feasible, although not likely, that measurement accuracies and user accuracy requirements for reference system parameters could combine to force a more dense spacing of traversal reference points than that needed for convenience in the field.

The appropriate density of anchor points and, therefore, anchor sections is not as straightforward. The minimum number of anchor points needed to define the linear datum is equal to the number of termini plus the number of odd-valence intersections (Vonderohe and Hepworth 1996). Densities of anchor points beyond this theoretical minimum are driven by the accuracies of measurement methods.

The typical precision of a distance measurement is given by:

\[
\sigma_l = (k^2 + ppm^2)^{1/2}
\]  

(Wolf and Ghilani, 1997, p. 117)

where \(k\) is a constant expressing the error in the measuring device and in positioning it with regard to the object being measured, and ppm (parts per million) is an error proportional to the distance being measured (l). For any particular measurement method, \(\sigma_l\) increases with \(l\) but the ratio \(\sigma_l : l\) decreases with \(l\) because of the presence of \(k\). This indicates that if relative accuracies are important, then longer distances and sparse anchor points are desirable. However, there might also be an upper bound on the tolerable amount of overall error in an anchor section distance, no matter the value of the distance. This, in conjunction with equation (12), would place an
upper bound on anchor section distances. The upper bound would serve as a constraint on A when determining an optimal spacing for anchor points and configuration of the linear referencing system.

Whether or not equation (12) is actually applicable to the distance measurements of a linear referencing system has yet to be determined. Experimental research is needed on the uncertainty of driven distances, measured with calibrated odometers, inertial devices, and GPS.

Second-Order Design
Second-order design involves determination of optimum accuracies of the measurements. It amounts to determining an optimum P matrix from A and \( \Sigma \). P depends upon the choice of measurement technologies and the detail of measurement procedures. Second-order design results in selection of equipment and specifications for its use. Estimates for measurement accuracies can be based upon experience, analysis of repeated measurements, or empirical formulas such as equation (12).

Clearly, first-order and second-order design are closely related. We cannot select A using P unless we know A. Neither can we select P using A unless we know A. Both A and P must be determined in an overall design. Therefore, first-order and second-order design are usually coupled in an iterative process.

Third-Order Design
Third-order design is a hybrid of first-order and second-order design, applied to the problem of improving or adding to an existing location referencing system. In third-order design, new parameters are to be added with resulting additions to \( \Sigma \) and changes to A and P. An appropriate design finds optimum changes (i.e., what new measurements to make and how well to make them so that new datum and reference objects are best integrated with those already in place).

Third-order design is clearly applicable to the problem of how to best add state and local components to linear referencing system components established at the national level, such as the proposed ITS datum. It is also applicable to the maintenance problem. New alignments and changes to existing alignments cause deletions, additions, and revisions of anchor points, anchor sections, and traversal reference points that must be managed in rigorous ways in order to ensure the continuing integrity of a linear referencing system.

Two approaches can be used when adding components to an existing location referencing system:

1. Treat existing parameter estimates as fixed and include them as absolute constraints during computation for the new parameters. This risks forcing any distortions in the existing system into the new components. The risk is minimized if the components are developed in a hierarchical fashion, with the most accurate components developed first over the widest extents. Less accurate, regional and local components can then be added in succession.

2. Treat existing parameter estimates as observations and use the inverse of their variance-covariance matrix as a weight matrix during computation for the new parameters. This risks having two sets of values for the existing parameters, the existing one and the one produced by the new computation. All databases referenced to the existing parameters would require updating with each addition to avoid confusion.

Example Design by Trial and Error
Consider the linear referencing system in Figure 3a, with parameters and derived distance, \( s_{xy} \), between point events x and y as shown. Users have stated that derived distances are to have standard deviations not exceeding ±0.015 miles. The point events are located by independent measurements, \( l_{xz} \) and \( l_{xy} \), to traversal reference points a and b, respectively. Measurements locating point events have standard deviations of ±0.010 miles. Independent measurements made to establish referencing system parameters are made with better care and technology. They have standard deviations of ±0.005 miles.

The distance, \( s_{xy} \), is derived by

\[
s_{xy} = d_1 + d_2 - l_{oa} - l_{ox} - l_{bx} - l_{by}
\]

(13)

According to the General Law of Propagation of Random Error (Mikhail and Gracie 1982 pp. 152–153), the standard deviation of \( s_{xy} \) is given by

\[
\sigma_{s_{xy}} = \left[ \sigma_{d_1}^2 + \sigma_{d_2}^2 + \sigma_{l_{oa}}^2 + \sigma_{l_{ox}}^2 + \sigma_{l_{bx}}^2 + \sigma_{l_{by}}^2 + 2\sigma_{d_1}d_2 - 2\sigma_{d_1}l_{ox} - 2\sigma_{d_2}l_{ox} - 2\sigma_{d_2}l_{by} + 2\sigma_{l_{oa}}\right]^{1/2}
\]

(14)

If the measurements \( l_{oz} \) and \( l_{oy} \) are not independent (e.g., computed from continuous odometric readings), an additional covariance term (\( \sigma_{l_{oa}l_{ox}} \)) must be included in equation (14). First-order design by trial and error will now be used to determine which measurements to make. The challenge is to find a set of measurements that will generate variances and covariances in the parameters that, when introduced in equation (14) along with the variances in \( l_{oz} \) and \( l_{oy} \), will result in a standard deviation in \( s_{xy} \) less than or equal to ±0.015 miles.

Trial 1
Consider the measurements in Figure 3b. There is no redundancy. Each parameter is determined uniquely. If the parameter vector is \( \{d_1, d_2, l_{oa}, l_{ox}, l_{bx}, l_{by}\} \) and the measurements are ordered according to their subscripts, then
The weight matrix, P, is 4x4 diagonal, with the diagonal elements having values of 40000. Equation (10) yields a variance-covariance matrix of the parameters of

$$\Sigma_{\alpha} = (A^T PA)^{-1} = \begin{bmatrix} 0.500 & 0.000 & 0.250 & 0.000 \\ 0.000 & 0.500 & 0.000 & 0.250 \\ 0.250 & 0.000 & 0.250 & 0.000 \\ 0.000 & 0.250 & 0.000 & 0.250 \end{bmatrix} 10^{-4}$$

This results in

$$\sigma_{\alpha} = [0.500 + 0.500 + 0.250 + 0.250 + 1.000 + 1.000 - 2(0.250) - 2(0.250)]^{1/2}10^{-2}$$

$$= \pm 0.0158 \text{ miles},$$

which is too large.

**Trial 2**

An overall measurement spanning the two anchor sections is added in Figure 3c. There is now one degree of freedom. The new A matrix is

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The weight matrix is now 5x5 diagonal with diagonal elements of 40000. The resulting variance-covariance matrix of the parameters is

$$\Sigma_{\alpha} = \begin{bmatrix} 0.300 & -0.200 & 0.150 & -0.100 \\ -0.200 & 0.300 & -0.100 & 0.150 \\ 0.150 & -0.100 & 0.200 & -0.050 \\ -0.100 & 0.150 & -0.050 & 0.200 \end{bmatrix}$$

This yields

$$\sigma_{\alpha} = \pm 0.0152 \text{ miles},$$

which meets the design criterion when rounded off. The effect of adding two more measurements is examined in Trial 3.

**Trial 3**

Measurements of each individual anchor section distance are added in Figure 3d. There are now three degrees of freedom. The A matrix is

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The weight matrix is now 7x7 diagonal with diagonal elements of 40000. From equation (10), the variance-covariance matrix of the parameters is

$$\Sigma_{\alpha} = \begin{bmatrix} 0.120 & -0.050 & 0.060 & -0.020 \\ -0.050 & 0.120 & -0.020 & 0.060 \\ 0.060 & -0.020 & 0.150 & -0.010 \\ -0.020 & 0.060 & -0.010 & 0.150 \end{bmatrix}$$

This results in

$$\sigma_{\alpha} = \pm 0.0130 \text{ miles},$$

We now know that if we go into the field, establish the anchor points, anchor sections, and traversal reference points as designed, and make the designed measurements with the designed accuracy, we will achieve the required accuracy in all data referenced to this system.

For larger systems, design can be facilitated by a computer tool, allowing the user to interact with a spatial representation of the system and modify elements of A.
and P at will to develop alternative designs. Design alternatives can be developed using not only $\Sigma_{xy}$, but also $\Sigma_{xx}$, thereby ensuring acceptable internal and external reliabilities in a linear referencing system in addition to acceptable variances and covariances in its parameters.

The trial and error approach, although suitable for first-third order designs, does not guarantee an optimum design from the standpoint of cost. Graefrend and Sanso (1985) and Kuang (1996) present analytical methods that solve directly for A and P and can include optimization for cost.

### Required Accuracies

The required accuracies of reference system parameters, as expressed in the $\Sigma_{xy}$ matrix, constitute the most critical factor in linear referencing system design. They determine what measurements to make and how well to make them. They can also affect the density of anchor points.

Statements of required accuracies vary widely with function. At the program planning level, concern is placed more on topological correctness than on positional accuracy. Program planners typically want highways to cross rivers at bridges but they are not terribly concerned about the accuracy of coordinates of any of those features or even about the relative accuracy of two highway intersections with respect to one another. On the other hand, highway safety analysts have been known to say that they must have the location of the start of a guard rail to "within two feet." Such statements are almost certainly expressions of relative accuracy requirements. The location of the start of a guard rail must be known relative to the location of a bridge abutment, a change in alignment, the beginning of a skid mark, or some other features of importance to highway safety. Bocskor and Toth (1995) report a need for determining coordinates with sub-meter accuracies of tracks and switches along the Burlington Northern Railroad right-of-way.

Figure 4, after Vonderhohe et al. (1993), indicates various map scales and spatial database accuracies associated with ranges of infrastructure management activities. The data are based upon the scale sizes and accuracies of GIS databases supporting various applications within transportation agencies. The accuracies in Figure 4, derived from National Map Accuracy Standards, indicate upper bounds on horizontal positional errors, to be exceeded by no more than 10 percent of tested, well-defined features on any given map.

Activities, ranging from planning through preliminary design and operations, that establish requirements for a linear referencing system are supported by source scales of 1:12,000 and smaller, with 1:24,000 being typical. A linear referencing system need not be designed for accuracies required by engineering design and construction. Rather, engineering activities produce data that might be used for development of a linear referencing system.

If we assume that well-defined, linearly referenced point events are to be compatible with spatial databases derived from 1:24,000 scale maps, an approximate upper bound on the diagonal elements of $\Sigma_{xx}$ can be readily calculated. The 90 percent accuracy of 40 feet, associated with 1:24,000 scale maps, translates to about 24 ft (approximately 0.005 mile) at the one standard deviation level. If locations of reference objects are to be 2 to 3 times as accurate as the events tied to them, then standard deviations in linear referencing system parameters should be in the range of 8 to 12 feet. Precedent for this approach lies within the accuracy requirements of control points used for making and checking topographic maps. Wolf (1983, p. 396) states that horizontal control points used for mapping should contain errors no greater than one-half the horizontal accuracy tolerance of the map. The American Society for Photogrammetry and Remote Sensing's accuracy standard for large-scale maps requires standard deviations in coordinates in the reference data set to be equal to or less than one-third of the limiting root-mean-square error selected for the map being tested (ASPRS 1990).

### FIGURE 4. Relationships among Geographic Extent, Typical Activities, and Scale and Accuracy of the Associated Spatial Database (after Vonderhohe et al. 1993)

<table>
<thead>
<tr>
<th>Geographic Extent</th>
<th>Typical Activities</th>
<th>Scale of Spatial Database</th>
<th>Accuracy of Spatial Database (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>State</td>
<td>Statewide Planning</td>
<td>1:50,000</td>
<td>30</td>
</tr>
<tr>
<td>District</td>
<td>Corridor Selection</td>
<td>1:100,000</td>
<td>170</td>
</tr>
<tr>
<td>Metro Area</td>
<td>District Planning</td>
<td>1:12,000 - 1:24,000</td>
<td>30 - 40</td>
</tr>
<tr>
<td>Project</td>
<td>Facilities Management</td>
<td>1:120 - 1:1,000</td>
<td>0.33 - 3</td>
</tr>
<tr>
<td></td>
<td>Corridor Analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Engineering Design</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Construction</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Anchor section distances and traversal reference point offsets, collected and maintained at a resolution of 0.01 miles, are not adequate for referencing events that must be compatible with 1:24,000 mapping. In fact, 0.01-mile resolution in linear referencing system parameters is barely adequate for events that must be compatible with 1:100,000 mapping. Moreover, the real-time operational functions of ITS are likely to require much higher positional accuracy than the planning and preliminary design functions previously supported by GIS spatial databases.

Statements of required accuracies are often based upon the capabilities of technology (e.g., GPS) or the availability of data (e.g., 1:24,000 scale maps, 0.01-mile odometer readings), rather than upon actual needs for decision-making. Moreover, although it might be reasonable to assume that the accuracies of linearly referenced data should be compatible with those of two- and three-dimensional data, a definitive study of error propagation through typical spatial analytical operations on linearly referenced data, and its impact on risk in decision-making, has yet to be done.

Conclusions

Most linear referencing systems in place today were never designed in rigorous ways. They merely evolved, perhaps with some attention to quality, but without comprehensive analytical methods for design. No statistically supportable statements can be made about their abilities to support the accuracy requirements of their users. This circumstance does not hold for geodetic referencing systems and mapping. Geodetic referencing systems are designed with methods that ensure their positional accuracies. Classification standards for accuracy and specifications for measurement procedures provide assurances of reliability to users of these systems. Similarly, there are well-established testing standards for the positional accuracies of maps, that serve as a basis for product development. Similar methods and standards should be developed for linear referencing systems as the significance of data referenced to them continues to increase. Moreover, such methods and standards must be developed if the vision of a unified linear referencing system, with a common linear datum, is to become a reality.

The design methodology developed herein is based upon mathematical and statistical principles of geodetic referencing system design and analysis. The methodology is driven by user requirements for accuracy in event locations, expressed as a variance-covariance matrix in linear referencing system parameters. This matrix is a by-product of a least squares adjustment of a system of measurements related to the unknown parameters. In the design process, the matrix is specified a priori and used in reverse fashion to determine an optimum configuration for the referencing system and necessary accuracies of the measurements to be made. This information can then be used to develop specifications for selecting datum and reference objects and for making measurements in the field.

The design method is statistically rigorous, both globally and locally. The method produces not only system-wide measures of reliability but also a means for determining the maximum size of an undetectable gross error in each individual measurement.

A linear referencing system, designed by the method presented in this paper, would allow managers to make statistically-defensible statements about the quality of their data, allow for computation of error in functions that operate on the data, and provide assurances to users that the spatial integrity of the data meets their needs.

The most critical inputs to the design process are 1) accuracy requirements of users, and 2) accuracies of various methods for linear distance measurement. Research is needed to establish well-founded bases for both of these. Literature on the accuracy of distance measurements along traveled ways is virtually nonexistent. And, for lack of a better approach, we base current estimates for required accuracies of linearly referenced data on source scales of existing two-dimensional GIS databases.

This research was intended to provide a theoretical basis for design of measurement systems for linear referencing. Additional practical aspects of linear referencing system design and use must be addressed to ensure long-term success. These include implementation aspects, such as selection and monumentation of anchor points and reference points, and management aspects, such as system maintenance (both field and database). These and other considerations should be more fully developed as a comprehensive and robust view of linear referencing systems continues to emerge.

Acknowledgements

The research reported in this paper was supported by Sandia National Laboratories, Project AT-4567.

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Minnesota Department of Transportation (MinnDOT). 1992. *Recommendations for Location Referencing Systems*, Location Data Standards Group, St. Paul, MN.


Wisconsin Department of Transportation (WisDOT). 1996. *Location Control Management Manual*, Madison, WI.


In this issue...

Editor Zorica Nedović-Budić continues to be the driving force behind this section. Thanks also to Ted Koch, the Journal's Feature Map editor, who reviewed the cartographic journals, and Ken Dueker, the Journal's Refereed section editor, who reviewed Transportation Research Record.

Editorial Intent

For the Review of Current Journal Literature, we have selected 20 journals of related interest to URISA members (see next page for list of journals). The Journal Literature editors scan these journals for articles they feel are relevant to the URISA audience. Selected articles are then assigned one of nine categories, which are modeled after the index categories used for the Journal and the URISA Proceedings. Several additional categories have been added. The nine categories are:

- Analysis and Modeling
- Applications
- Cartography
- Data
- Hardware/Software Technology
- Implementation and Management
- Issues
- System Concepts
- Remote Sensing and GPS

Please note that there are no clear-cut boundaries between categories, and some articles may qualify for entry in more than one. However, we decided against repetitive entries for a single article, so the reader should be advised to look in more than one category for a particular entry. Also, note that some entries list only the beginning page number of an article. These articles were retrieved online, and ending pages were not provided.

If you have suggestions or comments about our procedures or about the section, please contact us.

Zorica Nedović-Budić
Selected Journals

IJGIS  International Journal of Geographical Information Systems (monthly)
Taylor and Francis Ltd., 1. Gunpowder Square, London EC4A 3DE, UK

SLIS  Surveying and Land Information Systems (quarterly)
American Congress on Surveying and Mapping, 5410 Grosvenor Lane,
Suite100, Bethesda, MD 20814-2122

CGIS  Cartography and Geographic Information Systems (quarterly)
American Congress on Surveying and Mapping, 5410 Grosvenor Lane,
Suite 100, Bethesda, MD 20814-2122

CA  Cartographica (quarterly)
University of Toronto Press, 5201 Dufferin Street, Downsview, Ontario
M3H 5T8, Canada

PERS  Photogrammetric Engineering and Remote Sensing (monthly)
American Society of Photogrammetry and Remote Sensing, 5410 Grosvenor Lane, Suite 210,
Bethesda, MD 20814-2160

IJoRS  International Journal of Remote Sensing (monthly)
Taylor and Francis Ltd., 1. Gunpowder Square, London EC4A 3DE, UK

CG  Computers and Geosciences (monthly)
Pergamon Press Ltd., Linacre House, Jordan Hill, Oxford OX2 8DP, UK

JSM  Journal of Systems Management (bimonthly)
Association For Systems Management, 1433 W. Bagley Rd, Berea, OH 44017-2936

MISQ  Management Information Systems Quarterly (quarterly)
Carlson School of Management, University of Minnesota, 271 19th Ave.
South, Minneapolis, MN 55455

JAPA  Journal of the American Planning Association (quarterly)
American Planning Association, 122 S. Michigan Ave., Suite 1600, Chicago, IL 60603

EPB  Environment and Planning B (bimonthly)
Pion Limited, 207 Brondesbury Park, London NW2 5JN, UK

CEUS  Computers, Environment and Urban Systems (bimonthly)

LUP  Landscape and Urban Planning (bimonthly)
Elsevier Science B.V., Journal Department, P.O. Box 211, 1000 A.E.
Amsterdam, The Netherlands

EM  Environmental Management (bimonthly)
Springer-Verlag New York Inc., 175, Fifth Avenue, New York, NY 10010

JEM  Journal of Environmental Management (monthly)
Academic Press Ltd., 6277 SeaHarbor Drive, Orlando FL 32887-4900

PAR  Public Administration Review (bimonthly)
American Society for Public Administration (ASPA), 1120 G Street NW,
Suite 700, Washington, DC 20005-3885

JUA  Journal of Urban Affairs (quarterly)
JAI Press, Inc., 55 Old Post Road No.2, Box 1678, Greenwich, CT 06836-1678

TRR  Transportation Research Record
Transportation Research Board, National Research Council,
2101 Constitution Avenue, Washington, DC 20418

EDQ  Economic Development Quarterly (quarterly)
Sage Publications, 2455 Teller Road, Thousand Oaks, California 91320

JRS  Journal of Regional Science (quarterly)
Regional Science Department, University of Pennsylvania, 3718 Locust Walk, Philadelphia,
Pennsylvania 19104-6209
Review Categories

1. Analysis and Modeling


2. Applications


3. Cartography


4. Data


5. Hardware/Software Technology


6. Implementation and Management


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7. Issues


8. System Concepts


9. Remote Sensing and GPS


Parks, W., and Dial T. 1997. Using GPS to Measure Leveling Section Orthometric Height Difference in a Ground Subsidence Area in Imperial Valley, California. SLIS 57(2): 100–119.

