Spatial Data Quality and Transportation Applications

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SUMMARY

The quality of spatial data can be defined as its fitness for use. Data that are appropriate for use with one application may not be fit for use with another. Different users have different perceptions as to the importance of data quality. Measures of quality of geographic information include positional accuracy, thematic accuracy, temporal accuracy, logical consistency, completeness, data status, and lineage. The primary sources of error associated with spatial data are: acquisition or measurement, processing, and presentation or visualization. Spatial data has little or no value to transportation applications without any attribute data attached to it. Positional data are used for a wide range of transportation applications including accident analysis, transportation demand modeling, infrastructure management, transportation policy analysis, commercial vehicle operations, transit operations, and intelligent transportation systems. Some applications are more sensitive to quality than others. It is recommended that statements of spatial data quality should accompany the use or transfer of all spatial data.

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1. INTRODUCTION

Spatial data refers to information that is referenced to a geographic location on the earth, and includes the three dimensions of space, time, and theme (where-when-what) (Buckley, 1997; Veregin, 1998). Spatial data include information that represents the geographic position of features as well as descriptive information about those features. Nearly all transportation data are, or can be, geographically referenced. Geographic Information Systems (GIS) provide an effective way to manage and integrate spatial data necessary for the planning, design, construction, analysis, operation, maintenance, and administration of transportation systems and facilities. Transportation agencies use spatial data to locate or describe events on a transportation system. The spatial representation of a network can be expressed in one, two, or three dimensions. All spatial data can be characterized and defined as one of three basic feature types: points, lines, or areas (Buckley, 1997; Rybaczuk, 1993).

The issue of data quality is continuing to challenge the spatial data community. Data quality is the relationship of the spatial data to the reality that it is attempting to represent (Hansen, 1997). The value of any spatial data depends less on its cost and more on its fitness for a particular purpose. Quality of spatial data, therefore, can simply be defined as its fitness for use. This definition enables users to make a judgment for each specific application, and quality is directly based on the extent to which a data set satisfies the needs of the person judging it (McGlamery, 2000). Data that are appropriate for use with one application may not be fit for use with another. A critical measure of that fitness is data quality. When used in GIS analysis, a data set's quality significantly affects confidence in the results. Unknown data quality leads to tentative decisions, increased liability, and loss of productivity. Conversely, decisions based on data of known quality are made with greater confidence and are more easily explained and defended (Minnesota DOT, 1999). The concern for spatial data quality has increased in recent years due to a number of factors, including (Veregin, 1998):

- Increased data production by the private sector and non-government agencies, which are not governed by uniform quality standards (production of data by national agencies has long been required to conform to national accuracy standards).
- Increased use of GIS for decision support, highlighting the implications of using low-quality data, including the possibility of litigation.
- Increased reliance on secondary data sources, due to the growth of the Internet, data translators, and data transfer standards, making poor quality data ever easier to get.

The primary objective of data quality standards is to help data recipients and owners evaluate the "fitness for use" of data. Definitions of "fitness for use" vary, based on environment and intended application. Therefore, a definition of "data quality" should include a sufficiently broad set of criteria to address the full range of possible data characteristics that might affect its application. Setting data quality standards and documenting data quality require considerable forethought. The investment pays off, however, when evaluating the data for use, when sharing the data, and when attempting to communicate the benefits and limits of conclusions based on the data (Minnesota DOT, 2001).

This paper discusses the issue of spatial data quality and how it relates to transportation applications. Data quality attributes are identified and the potential sources of error with specific reference to transportation applications. Sensitivity of various transportation applications to the quality of spatial data are also identified and discussed. Recommendations for minimizing the effects of spatial data errors for transportation applications are also presented.

2. MEASURES OF QUALITY

Data quality can be expressed in terms of precision, accuracy, and resolution. When referencing location, it is important for the field data collector to be aware of the resolution and precision of the offset needed to report locations (e.g., 0.1, 0.01, 0.001 of a mile/kilometer), and the measurement position (e.g., along the centerline, along the shoulder lane, along the median lane). When using referenced locations for analysis, it is important for the analyst to be aware of the location resolution and precision of reference posts, points, markers, and nodes in the field (Adams et al., 1999). Previous research *(*FGDC, 1994) has identified several parameters (i.e., positional accuracy, thematic accuracy, temporal accuracy, logical consistency, completeness, data status, and lineage) as encompassing the quality aspects of geographic information. Considered together, these characteristics indicate the overall quality of a geographic database. Measures of spatial data quality are defined in the following sub-sections.

2.1 Accuracy

When referring to geographic data, the term "accuracy" is usually described with two components: 1) positional accuracy and 2) attribute accuracy. The positional accuracy of a spatial object, or a digital representation of a feature, can be defined through measures of the difference between the apparent location of the features as recorded in a database and its true location *(*Goodchild, et al., 1997).

Positional accuracy refers to the amount of offset present within a data set from the true location of the features being represented, that is, how closely the coordinate descriptions of the features compare to their actual location. This type of accuracy is typically measured directly by comparison to data known to be more accurate or by inferring the amount of error introduced from processing the data; for example, a 1:24,000 scale road network may be tested against a set of GPS-based control points. If detailed positional accuracy analyses are beyond the reach of the project being performed, the data developer should at least document the processing steps and tolerances used, and the accuracy of any source materials compiled.

Attribute accuracy refers to how well the attribute portion of the database describes the geographic features being represented. That is, how thoroughly and correctly the features in the data set are described. Before assessing attribute accuracy, it is necessary to clearly define the interpretation rules used to represent information in the database. Rigorously determining attribute accuracy requires statistical analysis. At a minimum, data developers should document steps taken to ensure the integrity of attribute data.

2.2 Resolution

Resolution, or precision, refers to the amount of detail that can be discerned in space, time, or theme. It is directly linked with accuracy, and is also used to determine how useful a given database is for a particular application. Two databases with the same accuracy levels but different levels of resolution do not have the same quality.

2.3 Data Status

Data status refers to the "currentness" of the data set. When developing data, it is important to maintain records of source material and observation dates used in the compilation. It is also important to maintain records on update cycles (Minnesota DOT, 2001).

2.4 Completeness

Data completeness refers to the degree to which the data describe the content of the source or phenomena being mapped. Completeness refers to a lack of errors of omission in spatial data. It includes consideration of holes in the data, unclassified areas, and any compilation procedures that may have caused data to be eliminated. Data completeness can be described by listing the features included in the data and whether the data are "completed" or "in progress." One might also consider what might have been omitted. For example, a particular attribute may have been collected for only part of an area, or perhaps paved roads but not gravel roads appear in a layer (Minnesota DOT, 2001).

2.5 Logical Consistency

Consistency refers to the adherence of the data to a given data structure, that is, the decisions that determine what the data set contains. Logical consistency refers to the absence of apparent contradictions in spatial data. Consistency is a measure of the internal validity of the data, and is assessed using information that is contained within the data, which typically include spatial data inconsistencies such as incorrect line intersections, duplicate lines or boundaries, or gaps in lines. These are referred to as spatial or topological errors. Consistency measures the extent to which geometric problems and drafting inconsistencies exist within the data set. For example, are attribute tables formatted identically throughout the database? Are minimum feature size criteria consistently applied? Are the data topologically correct? Do features of the same type have the same descriptive data and level of detail? Are naming conventions consistent?

2.6 Lineage

Lineage refers to a record of all data sources used to construct the spatial data set and all operations that have been taken to process the data. Thorough documentation for all spatial data is essential for determining quality. Information about appropriate ranges of use and scales at which the information is valid should be included with the original spatial data and any derived data sets. Lineage is concerned with historical and compilation aspects of the data, such as source of the data; content of the data; data capture specifications; geographic coverage of the data; compilation method of the data; transformation methods applied to the data; and use of any pertinent algorithms during compilation (Minnesota DOT, 2001).

Knowing and documenting the original source of the data and its quality, and establishing an audit trail of all transformations and changes that have been applied is essential for evaluating the overall quality of any resulting data set. The same data set that is reasonable for some applications is often not suitable for other applications where high quality is important.

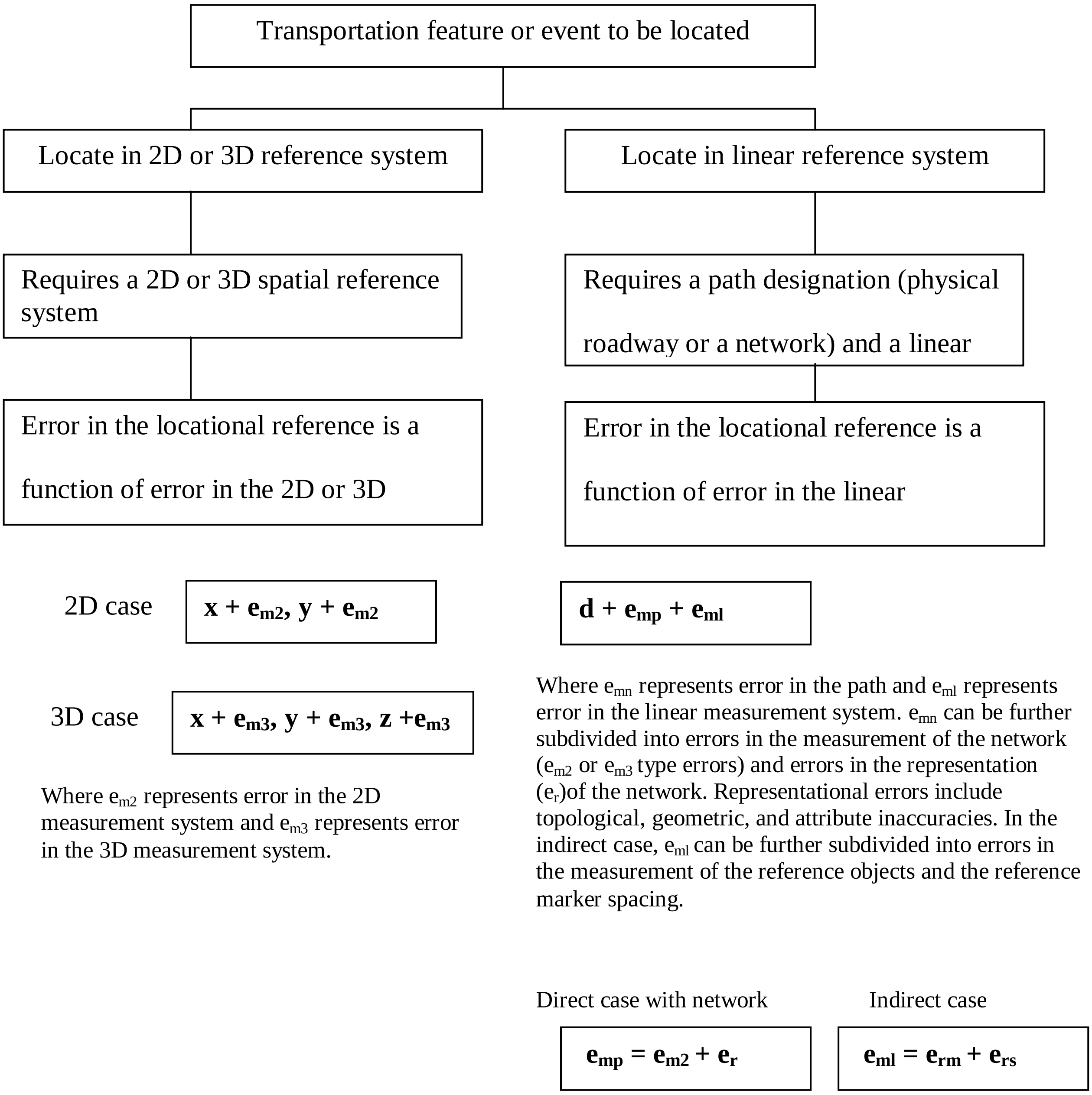
2.7 Timeliness

For certain types of spatial data that are constantly changing, such as roads, the quality of the data depends directly on the timeliness of the data. The primary data quality issues are related to authenticating and validating the data, and maintaining a detailed historical audit trail of updates for users of the data, so that quality can be verified and publications based on the data can be properly attributed.

3. SOURCES OF SPATIAL DATA ERRORS

All spatial data is inherently inaccurate, as it is only a conceptualization of the reality it represents. The degree of uncertainty associated with spatial data is affected by a variety of factors, which range from measurement error, to inherent variability, to instability, to conceptual ambiguity, to over-abstraction, or to simple ignorance of important model parameters (Rybaczuk 1993). The primary sources of error associated with positional data are: acquisition or measurement, processing, and presentation or visualization. Regardless of the measurement technique and referencing system, data will be observed with error. The method of data collection sets limitations on the selection of the measures and their metrics. Following the initial acquisition of data, a series of cartographic techniques are used to translate this acquired information into mapped information. Errors and inaccuracies introduced at the digitizing stage are largely unpredictable and random in nature. Integrating data from different sources, in different original formats (e.g., points, lines, and areas), at different original scales, and with inherent errors can yield a product of questionable accuracy (Buckley, 1997).

Every transportation feature is or can be associated with one or more spatial referencing systems. Depending on the measurement techniques utilized by a referencing system, each recorded location reference will have different error characteristics. Figure 1 outlines the error sources associated with different spatial referencing systems. The important difference in the linear referencing system is its dependency on a path definition. The path can be the physical roadway and the measurement method may be applied to the physical roadway (e.g., using DMI). Alternatively, a path can be a digital representation of the physical roadway, in which case the linear measurement may be computed from the digital representation. In this latter case, the level of the network’s spatial detail (topological and geometric) and the measurement technique will impact the measured distance and any subsequent locational references that employ this representation and measurement (Fekpe et al., 2003).



Where e_{m2} represents error in the 2D measurement system and e_{m3} represents error in the 3D measurement system.

Where e_{mn} represents error in the path and e_{ml} represents error in the linear measurement system. e_{mn} can be further subdivided into errors in the measurement of the network (e_{m2} or e_{m3} type errors) and errors in the representation (e_r)of the network. Representational errors include topological, geometric, and attribute inaccuracies. In the indirect case, e_{ml} can be further subdivided into errors in the measurement of the reference objects and the reference marker spacing.

Figure 1. Sources of Error Sources Associated with the Process of Assigning Locational References to Transportation Features (Fekpe et al, 2003)

A transportation feature or event, whose location is measured by a 2D or 3D measurement system, such as photogrammetry or GPS, is independent of the road geometry. It is also important to distinguish a direct linear measured location from an indirect measured location. The direct linear measures typically apply to the path and physical transportation assets along the path. The accuracy of indirect measurements depends on reference objects and will be influenced by the measurement errors in the reference objects and the spacing of the reference objects as indicated in Figure 1.

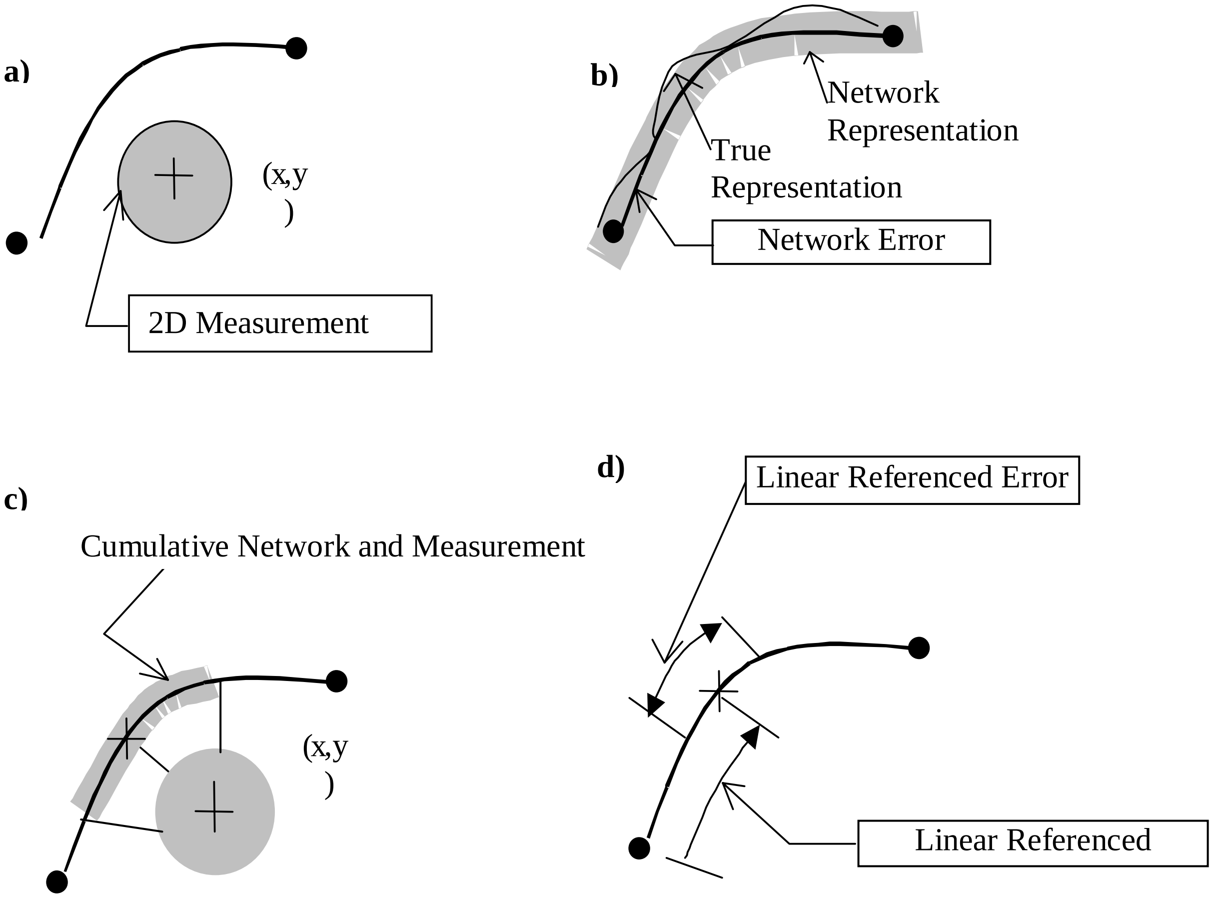


Figure 2. Schematic Representation of Positional Data Error (Fekpe et al, 2003)

Figure 2a illustrates an example of 2D measurement error. Because the measurement is independent of the road network, the measurement may be off the roadway even though in reality it is on the roadway. Transforming the 2D reference to a linear reference will place the location on the roadway but with some error that is a function of the 2D measurement error plus a linear measurement error. Conceptually, the 2D- measured location moves to the closest point on the roadway. However, given the error in the measurement, there are multiple closest points represented by the normal vectors from the circular error bound to the road centerline (Fekpe et al., 2003).

While several sources of error are involved in generating a locational reference for transportation features or events, the transformations between spatial reference systems is another source of positional error. In the transformation process, either two independent reference systems have to be combined into one new system, or one system must be transformed to the other. Both approaches raise issues of uncertainty and errors. Figure 2 is a schematic representation of three sources of errors involved in this context. Figure 2b illustrates error in the network representation. Given that the centerline position has error, the set of closest points extends to positions represented by the network error buffer. Figure 2c represents the cumulative error from these sources. Finally, Figure 2d illustrates the errors that might be present in the linear referencing system. Figure 2d illustrates potential bounds on the transformed linear position. The specific error value depends on the errors in each of the respective referencing systems. The effective result is that the 2D error transforms to a linear error in the linear referencing system (Fekpe et al., 2003).

4. TRANSPORTATION APPLICATIONS OF POSITIONAL DATA

Spatial data has little or no value to transportation applications without any attribute data attached to it. Each spatial data element (a line, a point, or a polygon) has a cartographic representation as well as a unique identifier to associate attribute information with that data element. In contrast, data collected by transportation agencies may not have any cartographic representation (geo-referenced). Since the network does not require any cartographic representation (spatial data element), and attribute data are collected independently from the cartographic representation of the transportation element (highway segment), it is important to address the issue of sensitivity of applications in transforming various linear referencing measurement data to the linear datum (cartographic) representation. Different applications require spatial data at different scales. Vonderohe et al. (1993) suggested the use of four spatial database scales for transportation applications. As noted in Table 1, the transportation applications of GIS can be divided into three primary functional groups: planning, management, and engineering. Planning applications are usually at statewide and regional levels and do not require highly precise locational data. Spatial databases for these applications are at 1:500,000 to 1:000,000 scales. Management applications often require more detailed locational data that are available at regional or district levels. The spatial databases are usually in the 1:100,000 to 1:24,000 range. Engineering applications require a high level of spatial accuracy and these applications are restricted to project or corridor level. The preferred scales for engineering applications are 1:12,000 to 1:24,000. This grouping suggests that engineering applications are more sensitive to positional data quality than management applications.

Table 1. Scales and Typical Applications *(*Vonderohe et al. (1993)

Scale of Spatial Database	Precision of Spatial Database (ft)	Typical Activities or Applications
1:500,000	830	Statewide planning
1:100,000	170	District-level planning and facilities management
1:12,000 – 1:24,000	30 – 40	Engineering
1:120 – 1:1,200	0.33 – 3	Project-level activities

A different way of grouping the current and emerging applications of GIS is by transportation subject area. This concept of grouping recognizes that applications within a subject area may include planning, management, and engineering functions. Moreover, grouping by the three functional classes may conflict with the sensitivity of the individual applications to spatial data quality. For example, while accident reporting may not be classified as an engineering activity, identifying accident-prone locations is sensitive to the data quality. Similarly, highway infrastructure management may be classified erroneously as a management function, when it actually involves engineering applications. Table 2 shows the current and emerging uses of spatial data in transportation as well as the levels of sensitivity of transportation applications to spatial data quality. These levels are based practitioners' perceptions of the sensitivity of the various applications to positional data quality.

Table 2. Applications of Positional Data in Transportation (Fekpe et al., 2003)

Subject Area	**Applications**	**Sensitivity**		
		L	**M**	**H**
Safety	- Accident reporting		●	
	- Black spot/ accident prone location identification		●	
	- Traffic safety investigation		●	
	- Pedestrian and bicycle safety analysis		●	
	- Incident management			●
Transportation Planning, Impact Analysis, Policy Analysis	- Travel demand modeling	●		
	- Multi-modal freight modeling	●		
	- Hazardous materials routing		●	
	- Traffic impact analysis		●	
Transit and Public Transport Planning and Operations	- Transit planning	●		
	- Transit routing		●	
	- Handi-transit		●	
	- Real-time tracking and scheduling of buses		●	
Transportation Infrastructure Management and Operations	- Location of facilities (road, highway, airport, port)	●		
	- Pavement and asset management system		●	
	- Operation (congestion, service)		●	
	- Rail/highway information system management	●		
Transportation Design and Construction Planning	- Sources of construction materials	●		
	- Right of way			●
	- Road closure and detour		●	
	- Construction information	●		
	- Field crew scheduling	●		
	- Maintenance and operation		●	
Intelligent Transportation Systems (ITS) Applications	- Traveler Information System		●	
	- Integrated Traffic Monitoring System (ITMS)		●	
	- Web-based road condition reporting system		●	
	- Vehicle Navigation System			●
	- Applications to commercial vehicle operations regulatory enforcement activities	●		
Freight Analysis and Commercial Vehicle Operations	- Fleet management	●		
	- Vehicle tracking, dispatching, and routing applications		●	
	- Permitting	●		
	- Freight movement	●		

5. SENSITIVITY OF APPLICATIONS TO POSITIONAL DATA QUALITY

As noted earlier, knowledge of the quality associated with geographic information is critical to the effective use and credibility of geographic information systems and their outputs. The “truth in labeling” concept is aimed at providing users with information to help assess fitness for use of data. However, the lack of actual procedures for this assessment means that, in many cases, valuable data quality statements remain under-utilized. Agumya et al. (1997) discussed risk management techniques in assessing fitness for use of geographic information by translating uncertainty in the information into risk in the decision.

The sensitivity of transportation applications to positional data accuracy can be assessed either by standards-based methods or by a risk-based approach. The traditional method to assess the acceptability or fitness of use – the standards-based method – compares data uncertainty with a set of standards that defines acceptable levels of uncertainty in the data (Frank, 1998). This approach measures the sensitivity of the positional data for a particular application by directly comparing the quality elements of information against a set of standards or error benchmarks that represent the acceptability of the data components. While uncertainty in spatial data is composed of several well-known elements (Guptill et al., 1995), the obvious measurable ones are map scale (resolution), currency, attribute accuracy, and percentage of completeness. However, measures of these elements are difficult to combine into a single, meaningful, composite unit (Veregin et al., 1995) and require testing the sensitivity of the application to error associated to each element. A typical example would be U.S. census TIGER street centerline spatial data, which are used for urban transportation modeling applications. There is no means of separating the individual error effects of poor map scale (e.g., positional accuracy of the street segments), logical consistency (e.g., street network topology), attribute accuracy (e.g., travel time), or completeness (e.g., missing street segments) (Agumya, 1999).

A risk-based approach, in which the sensitivity of an application is measured against the adverse impact of the ultimate decision, is based on the results of the analysis. Agumya et al. (1999) defined “risk-based approach” as a technique based on risk management practices, in which a study is made of the effect that uncertainty in the data has upon the ultimate decision to be made with it. In turn the adverse consequences of making a poor decision are quantified, and it is this information which enables a user to determine whether a data set is fit for use or not.

The sensitivity assessment of positional data under this approach would require addressing two fundamental questions *(*Agumya et al., 1997).

- What are the consequences associated with the decision, in terms of risk, in using a particular set of spatial data with error in different transportation applications?

- What are the acceptable consequences of uncertainty in terms of risk?

The first question entails the partition of spatial data error for a particular dataset into its various elements, the determination of the risk a transportation analyst may incur by making the decision based on the dataset, and the extent to which this dataset influences the decisions. If the positional accuracy of the dataset has the lesser impact on the decision, such as traffic or freight assignment using a TIGER street file, then it is reasonable to accept the risk and uncertainty associated with this particular application. However, for vehicle navigation purposes, the risk may still be too high to be acceptable.

The second question entails establishing a threshold for the risk that is considered acceptable. The acceptability of risk may vary widely among the data users and depend upon the nature of the applications. The acceptability of project-level analysis or a decision is more conservative than the planning-level transportation application. For a given spatial dataset (e.g., TIGER street file), acceptability of the positional accuracy is much higher.

6. SPATIAL DATA STANDARDS

The primary objectives of spatial data quality standards are to help data recipients and owners evaluate the "fitness for use" of data. Quality assurance is a basic requirement for reliably performing an application and all applications should be accompanied by a detailed evaluation of the fitness-of-use of the data used (to examine whether the data represent the information needed to answer the question raised by the application). A statement of accuracy generally includes a statistical determination of uncertainty and variation, as well as how and when the information was collected. Often a statement of accuracy is accompanied by the confidence level of the spatial data, which is defined as the probability that the true value of the data falls within a range of given values (FGDC, 1998).

Standards provide for consistency between data, users, and systems. Most accuracy standards for spatial data require a standard for the horizontal component of accuracy, another standard for the vertical component of accuracy, as well as a description of the method used to evaluate the accuracy. The reporting standard in the *horizontal* component is the radius of a circle of uncertainty, such that the true or theoretical location of the point falls within that circle 95 percent of the time. The reporting standard in the *vertical* component is a linear uncertainty value, such that the true or theoretical location of the point falls within plus or minus of that linear uncertainty value 95 percent of the time. The method used to evaluate accuracy such as statistical testing, least squares adjustment results, comparison with values of higher accuracy, repeat measurements, or estimation should be described.

Comprehensive statements of spatial data quality should accompany the use or transfer of all spatial data, as it is not feasible to remove error entirely from spatial data sets, although a reduction of error is possible. The introduction and adoption of spatial data standards addresses the issue of spatial data quality, but heavy reliance on the fitness for use of the data means that most of the responsibility remains in the hands of spatial data users. An awareness of the accuracy of spatial data allows users to make a subjective statement on the quality and reliability of the information (Buckley, 1997).

7. SUGGESTED POSITIONAL DATA ACCURACY GUIDELINES

The following recommendations are intended for the practical use of positional accuracy guidelines and for the combination of transportation datasets in general:

- Avoid combining datasets with error differences larger than a factor of five. These datasets simply do not fit together and the results are unpredictable.

- For most transportation applications an accuracy of three feet is sufficient. Unfortunately, in the real world, most datasets are of much lower accuracy. Although it seems like a significant step for many agencies, upgrading from 50-foot accurate data to three-foot accurate data is feasible and affordable with today’s technology. This upgrade will become even more important as agencies use GPS in their day-to-day operations. Hand-held and real-time differential GPS receivers yield accuracies of three to ten feet. The research shows this is compatible with three-foot road centerlines; however, it is incompatible with 50-foot centerlines currently used by most agencies.

- It is highly recommended that agencies maintain linear reference systems along road centerlines. The linear reference system can be easily transferred from the inaccurate road centerline to a more accurate road centerline without expensive re-mapping of features. This means that the integration of legacy data related to mileposts on a linear reference system is much easier than matching new coordinates to old feature points and centerlines.

- Roadway information is always related to a road centerline. For most applications the location of a feature relative to the centerline is much more important than its absolute location on a map. Therefore, it is recommended that users compute mileposts and offsets (the parameters that relate a point to a road centerline) for any feature inventoried and used by a transportation agency.

- Agencies are encouraged to establish thresholds for their product specifications and applications. Data producers are expected to determine what accuracy exists or is achievable for their data. Positional accuracy can be estimated in terms of root mean squared error. Accuracy is typically reported in ground distances at the 95 percent confidence level. The preferred method for determining positional accuracy is accuracy testing using an independent source of high accuracy. The other methods include deductive estimates, internal evidence, and comparison to source. Whether data are tested by an independent source of higher accuracy or evaluated for accuracy by alternative means, metadata should describe how the test results were determined.

8. CONCLUSIONS

The primary sources of error associated with positional data are acquisition or measurement, processing, transformation, and presentation or visualization. Regardless of the measurement technique and referencing system, data will be observed with error. The method of data collection sets limitations on the selection of the measures and their metrics.

Recommendations for positional data quality standards include metadata documentation for linear datum components to assure stability and reportability of positional data quality.

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BIOGRAPHICAL NOTES

Dr. **Edward Fekpe** holds a PhD in transportation engineering from the University of Manitoba, Canada, MSc (Eng) in transport planning and engineering from the University of Leeds, UK, and BSc (Eng) Civil Engineering with first class honors from the University of Science and Technology, Ghana. Dr. Fekpe has over 22 years of professional experience in transportation engineering practice, research and education. Dr. Fekpe has worked on projects dealing with different aspects of transportation engineering in Ghana, Canada, the United States, and Uganda, including transport regulatory and policy analysis; heavy vehicle regulations and operations; highway infrastructure evaluation; freight transport regulatory policy; pavement design and highway performance evaluation. Dr. Fekpe is currently a Research Leader in Battelle's Transportation Division where he is the team leader for the transportation policy and operations group. Before joining Battelle in 1995, Dr. Fekpe was a Research Officer with the National Research Council of Canada. Dr. Fekpe lectured in highway and transportation engineering in the Civil Engineering of the University of Science and Technology, Ghana between 1985 and 1990. Dr. Fekpe's research interests include freight transportation and analysis, truck size and weight regulations and their enforcement. He has published over 55 technical papers in reputable refereed journals and conference proceedings on a wide range of transportation topics.

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