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Research Article

Positional Accuracy of TIGER 2000 and 2009 Road Networks

Paul A. Zandbergen
Department of Geography
University of New Mexico

Drew A. Ignizio
Department of Geography
University of New Mexico

Kathryn E. Lenzer
Department of Geography
University of New Mexico

Abstract
The Topologically Integrated Geographic Encoding and Referencing (TIGER) data are an essential part of the US Census and represent a critical element in the nation's spatial data infrastructure. TIGER data for the year 2000, however, are of limited positional accuracy and were deemed of insufficient quality to support the 2010 Census. In response the US Census Bureau embarked on the MAF/TIGER Accuracy Improvement Project (MTAIP) in an effort to improve the positional accuracy of the database, modernize the data processing environment and improve cooperation with partner agencies. Improved TIGER data were released for the entire US just before the 2010 Census. The current study characterizes the positional accuracy of the TIGER 2009 data compared with the TIGER 2000 data based on selected road intersections. Three US counties were identified as study areas and in each county 100 urban and 100 rural sample locations were selected. Features in the TIGER 2000 and 2009 data were compared with reference locations derived from high resolution natural color orthoimagery. Results indicate that TIGER 2009 data are much improved in terms of positional accuracy compared with the TIGER 2000 data, by at least one order of magnitude across urban and rural areas in all three counties for most accuracy metrics. TIGER 2009 is consistently more accurate in urban areas compared with rural areas, by a factor of at least two for most accuracy metrics. Despite the substantial improvement in positional accuracy, large positional errors of greater than 10 m are relatively common in the TIGER 2009 data, in most cases representing remnant segments of minor roads from older versions of the TIGER data. As a result, based on the US Census Bureau's suggested accuracy

Address for correspondence: Paul A. Zandbergen, Department of Geography, University of New Mexico, Bandelier West Room 111, MSC01 1110, Albuquerque, NM 87131, USA. E-mail: zandberg@unm.edu

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metric, the TIGER 2009 data meet the accuracy expectation of 7.6 m for two of the three urban areas but for none of the three rural areas. The suggested metric is based on the National Standard for Spatial Data Accuracy (NSSDA) protocol and was found to be very sensitive to the presence of a small number of very large errors. This presents challenges during attempts to characterize the accuracy of TIGER data or other spatial data using this protocol.

1 Introduction

The Topologically Integrated Geographic Encoding and Referencing (TIGER) system represents a critical element in the nation's spatial data infrastructure. TIGER data for the year 2000 were deemed of insufficient quality to support the 2010 Census. In response the US Census Bureau embarked on an effort to improve the positional accuracy of the database. These improved TIGER data were released for the entire US just before the 2010 Census. The purpose of the current study is to provide an independent evaluation of the horizontal positional accuracy of the improved TIGER data.

1.1 A Brief History of TIGER

The TIGER system has been in existence since the 1980s when it was created as part of an effort to facilitate and organize the US Census Bureau's 1990 Census of Population and Housing. At the time, TIGER was a replacement for the US Census Bureau's earlier data structure, the Dual Independent Map Encoding (DIME) system, which had been in place since the 1960s (Tomlinson 1991). In 1989, the TIGER/Line files were made available as the public version of the database created by the US Census Bureau. Due to their national level coverage and the fact that they are accessible at no charge, the TIGER files quickly gained popularity and were used as either a foundation for, or as a means of adding detail to, many of the GIS databases employed by various private and public organizations throughout the nation. The widespread acceptance and use of the dataset attested to its relevance and underscored the timeliness of the US Census Bureau's efforts to have an easily accessible way of representing census information in a digital map format.

The original TIGER database, however, was far from perfect. The database was built using "US Geological Survey 1:100,000-scale Digital Line Graphs (DLG), USGS 1: 24,000-scale quadrangles, the US Census Bureau's 1980 geographic base files, and a variety of miscellaneous maps and aerial photographs" (US Census Bureau 2005). While these source documents were known to contain large positional errors, the US Census Bureau additionally acknowledges that within the TIGER database, "files are no more complete than the source documents used in their compilation, the vintage of those source documents, and the translation of the information on those source documents" (US Census Bureau 2005).

Furthermore, the original TIGER dataset and subsequent versions are based on the adherence to one fundamental principle, that of maintaining topological integrity among all of the individual entities within the database. As a result, the major features of the TIGER/Line files (roads, railroads, hydrography, boundaries, and the areas delineated by these features) simultaneously define and are defined by the respective locations of one another. While this topological integrity is extremely useful, prioritizing this property has come at the cost of positional accuracy, as moving any one feature implicitly involves moving all of the features connected to it. As a result, the manner in which features were updated in the database (with feedback and contributions from various agencies factoring into decisions), and the lack of explicit guidelines and universal specifications for the positional accuracy of these newly updated features, the issue of positional accuracy became a problem that plagued the TIGER dataset through the 1990s.

As the TIGER dataset was edited and updated to be used again for the 2000 Census, efforts were made to assess the nature and extent of these positional errors. The internal Geography Division of the US Census Bureau developed a tool known as the GPS TIGER Accuracy Analysis Tool (GTAAT) in 2000 specifically to measure the positional accuracy of the TIGER dataset. The team gathered GPS test points at almost 7,000 different sites in eight separate study areas throughout the US and calculated the distance and azimuth difference between the GPS collected point(s) and the corresponding TIGER test points from the database (Liadis 2000). The eight sites were chosen to be representative of the different types of areas present in the TIGER database including rural and urban areas, and areas of different terrain types (Liadis 2000). Findings included that the median and mean distance between the test points and the GPS collected points were 60.8 m and 85.7 m, respectively. The set of test locations was divided into two groups: those that were created or edited before 1990 and those that were created or edited between 1990 and 2000. In a discouraging conclusion, the TIGER 2000 dataset was actually less accurate than the original version from 1989 (Liadis 2000, p. 43). This problem was attributed to differences in the way that features were added to the database (and the source documents used) in the 1990s, compared with the standards that were used in the creation of the original TIGER database. Error propagation was further compounded by "the domino effect of successive update operations, each building on the previous operation's inaccuracies" (Liadis 2000, p. 43).

Other studies have also documented the positional accuracy of the TIGER 2000 data. For example, Seo and O'Hara (2009) discuss the accuracy of TIGER 2000 data as measured against 3 m resolution satellite imagery from the Quickbird platform. In a 16 × 16 km study area in Mississippi, 103 sampling points were established resulting in a RMSE value of the X coordinates of 16 m and a RMSE value of the Y coordinates of 15.2 m (Seo and O'Hara 2009, p. 16). In another example, Zandbergen (2008) determined the accuracy of TIGER 2000 data by comparing road intersections with local street centerline data created at a scale of 1:12,000 for Orange County, FL. Based on a comparison of 1,000 intersections, the median error in the TIGER data was 29 m and the 95th percentile was 96 m.

In a project performed by the US Census Bureau's Geography Division, the Geospatial Research and Standards Staff (GRaSS) identified the need to improve the spatial accuracy of the TIGER 2000 dataset and investigated the practicality of using Digital Orthophoto Quadrangles (DOQs) to assess and improve the database (O'Grady 1990). The GRaSS team looked at two sites (Hampshire County, WV and Newberry County, SC) and detailed the importance of selecting quality "anchor" or reference points that consisted of "three or more end nodes of . . . roads, railroads, and hydrographic features" accepted as the intersecting features (O'Grady 1990, p. 5). It was pointed out that "DOQs are commonly used as source data for collecting digital information" and the study ultimately concluded that DOQs could be used as "an efficient medium for use in data collection" in the Census Bureau's efforts to improve the TIGER database (O'Grady 1990, p. 1, 8).

It should be noted here that the TIGER data structure was first and foremost a topological data structure – relative accuracy was the primary focus, not positional accuracy (Trainor 2003). A road network was created as nodes (points) and edges (polylines) that connect the nodes. Most edges consisted of straight lines and "shape points" were added selectively when the edge was unusually curved. This kept the number of vertices to a minimum while maintaining topological integrity. As a result a curved road such as a loop would be represented as a square or rectangle. This approach to representing features is very much evident in the TIGER 2000 data. One of the effects of this approach to capturing features is that the error of a randomly selected location along a road segment will typically be larger than the error for a node or shape point. Deciding which points to use in a positional accuracy assessment may therefore influence the results of the assessment.

In the last decade, the substantial positional errors of TIGER features have been widely recognized and documented (O'Grady 1990, Trainor 2003, Lee 2009, Song et al. 2006, Seo and O'Hara 2009). Song et al. (2006, p. 288) acknowledge that the "positional accuracy of TIGER 2000 is a limiting factor," noting that it "precludes more effective address lists and geographic information partnerships with those state, local, and tribal governments". Song et al. (2006) propose a new method of conflating, or transferring, the rich attribute information of TIGER 2000 data to other datasets that are more spatially accurate but that lack detailed attribution. The very nature of this approach implicitly suggests that, in at least some cases, the errors associated with the TIGER 2000 dataset make it unusable for mapping purposes.

It is useful to consider the positional accuracy of the TIGER 2000 data in the context of fitness for use. In a "business case analysis", the US Census Bureau articulated several reasons why the TIGER 2000 data could not support the 2010 Census and other applications (US Census Bureau 2000). For example, using high resolution remotely sensed imagery or GPS receivers in combination with TIGER data was considered impossible. The positional error of these technologies is in the order of several meters or less, i.e. much more accurate than TIGER 2000 data, severely limiting their utility for data collection and updating. In addition, efforts to create partnerships with local authorities and agencies to update address data were severely constrained since their base maps are typically of much better positional accuracy. Finally, the TIGER 2000 data were deemed insufficient to provide high quality geocoding services, one of the basic use cases of the TIGER data.

1.2 The Master Address File (MAF)

In concert with the TIGER dataset, which identifies roads, census enumeration area boundaries, railroads, water bodies, and other important geographic features, the US Census Bureau also developed the Master Address File (MAF) in the 1990s. The MAF is an electronic list of addresses and corresponding georeferenced locations for individual residences throughout the US for which census information is collected (Johnson and Kunz 2005). Using information from the 1990 Census, the US Postal Service Delivery Sequence File (DSF), and contributions from state, local, and tribal agencies, the US Census Bureau produced the MAF to help with the various activities associated with acquiring, verifying, and organizing census information (Johnson and Kunz 2005). Unlike the TIGER database itself, which is part of the public domain and widely available, the MAF is restricted from public use by Title 13 of the US Code because of the sensitive nature of its content. The MAF is only used internally by the US Census Bureau, where it is paired with TIGER via a geocoded linkage between the address information and the street features in the TIGER database. The resulting MAF/TIGER system became a cornerstone of US Census Bureau operations and enabled the organization to reliably store and manage demographic information up to and through the 2000 Census (Johnson and Kunz 2005, Marx 2000, US Census Bureau 2000).

Just as positional accuracy problems limited the utility of TIGER data for local governments, researchers and private sector users, the US Census Bureau itself recognized that the persistent problem of positional error in the database was beginning to limit its own ability to meet their goals. In the process of performing the 2000 Census, the US Census Bureau realized that it was beginning to encounter significant limitations with MAF/TIGER and that it would be necessary to implement major improvements to the database in order for it to be able to meet the needs of the next Census in 2010 (Marx 2000, US Census Bureau 2000). In addition to its lack of positional accuracy for geographic features, the MAF/TIGER database as of the year 2000 was in a state that made it very difficult for the US Census Bureau to correct known problems, impeded the ability to develop integrated and accurate address listings for map features (a prerequisite for employing GPS/hand-held computers in census data collection methods), complicated efforts to collaborate effectively with agency partners at the state, local, and tribal levels, and generally compromised the ability to provide high quality map products (US Census Bureau 2000). To an extent, all of these problems were directly or indirectly related to one large obstacle facing the US Census Bureau: the need to accurately geocode the Master Address File (MAF), an impossible task given the MAF/TIGER database's condition.

1.3 The MAF/TIGER Accuracy Improvement Project

In 2000, research began on the MAF/TIGER Accuracy Improvement Project (MTAIP), an effort to improve the positional accuracy of the database, modernize the MAF/TIGER processing environment, improve cooperation with partner agencies, implement the Community Address Updating System (CAUS), and develop standards for periodic evaluation and improvement of the database (Akers 2003, Best 2005). Additionally, the MTAIP effort was part of an attempt to streamline the exchange and management of data, something required by both the Census Address List Improvement Act of 1994 (which mandated that the Census Bureau allow tribal and local governments to "review and update the census address list before the decennial census"), and the administration's development of "geospatial one-stop e-government initiatives in compliance with the requirements of the Government Paper Work Elimination Act, OMB circular A-16, and Executive Order 12906" (Best 2005, p. 5).

In June of 2002, an eight-year contract for $200 million was signed with the Harris Corporation as the prime contractor for the US Census Bureau's MAF/TIGER Accuracy Improvement Project (Harris Corporation 2002). Using digital GIS files produced by state, tribal, and local governments as the primary source of data, the Harris Corporation was charged with correcting the MAF/TIGER database to meet a horizontal positional accuracy requirement of 7.6 meters for mapped features based on the Circular Error 95% (CE95) accuracy metric (Best 2005, US Census Bureau 2003). To supplement this data where necessary, the Harris Corporation was also charged with utilizing road centerline locations obtained with GPS collection and from high resolution imagery, as well as commercially purchased GIS files as the reference layers to update TIGER features (Best 2005). The exact nature of the updating process is not documented in detail but in general relies on integrating high quality local data from different sources (roads in particular) with the topological requirements of the TIGER data structure. These topological requirements, for example, made it impossible to simply copy high quality local data; instead correcting and updating of the TIGER data required careful adjustments while maintaining the attribute structure and topological connectivity that is at the core of the TIGER data structure. MTAIP was implemented county by county, with improved TIGER data being released gradually as counties were completed. By 2008, most US counties had been completed, in time for the 2010 Census. The US Census Bureau has carried out a comprehensive accuracy assessment of the MAF/TIGER database, but no results have been published. There have also been no published independent evaluations of the improved TIGER data, which in part has provided the impetus for the current research.

1.4 Measuring Positional Accuracy

Positional accuracy is a critical component of any geographic dataset and there is a substantial literature on measuring the positional accuracy of the point, polyline, and polygon representations of real world objects in GIS. According to Hunter (1999, p. 27), "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 as recorded in a database and its true location". Determining the true location, however, is not attainable since no measurement system is perfect and this includes determining geographic coordinates. As a result, methods of accuracy assessment focus on comparing the locations of mapped features to a reference layer of known and better accuracy.

One widely employed standard for the positional accuracy of vector data is the USGS National Map Accuracy Standard (NMAS). However, this standard provides only a very generalized methodology for quantifying the accuracy of features, and consequently, determining whether or not a dataset actually conforms to the standard is not as straightforward as it sounds (Zandbergen 2008). The more recent National Standard for Spatial Data Accuracy (NSSDA) (FGDC 1998) provides more details on how positional accuracy should be determined, but otherwise relies on the same concept. NMAS, NSSDA and some other standards rely on the concept of "well defined test points". In general, this means that test points from the dataset to be analyzed are selected and their coordinates are compared to those of reference locations of better accuracy. Reference locations can be obtained from existing data sources of better accuracy (such as aerial imagery) or through field data collection (such as real-time kinematic GPS). The positional error in the X and Y direction for a test point is then determined as the difference in the X and Y coordinates between the test point and the reference point. The horizontal positional error is represented by the Euclidean distance between the test point and the reference point. The error distribution for a number of test points can then be determined and expressed using different metrics.

In the case of road networks, "well defined test points" typically consist of intersections, which can be identified relatively easily. However, these locations may not represent the accuracy of the entire polyline feature very well, and alternative methods have emerged. Goodchild and Hunter (1997) and Hunter (1999) proposed a relatively simple buffering technique to determine the percentage of a linear feature's length that falls within a specified distance of a reference feature. Shi and Liu (2000) proposed a stochastic approach in which an error band around a linear feature is characterized based on normal error distributions of the endpoints. Seo and O'Hara (2009) developed a polyline-based assessment in which the geometry of polyline segments in vector is transformed to rasterized values to measure lengths and displacements. Frizelle et al. (2009) employed a grid-based method in which road lengths within predetermined cells are compared between different road datasets.

Despite this progress in the development of accuracy assessment methods for linear features, all commonly used accuracy standards rely on a set of individual test points. The US Census Bureau's efforts to determine the horizontal positional accuracy of its data are also based on using intersections of road centerlines. The specific accuracy metric employed by the US Census Bureau is the Circular Error 95% (CE95). The method underlying the calculation of this metric is the same as the NSSDA protocol and relies on a calculation of the Root Mean Squared Error (RMSE). The stated accuracy that the improved TIGER data is expected to achieve is a CE95 of 7.6 m. It is not clear, however, to what specific types of study areas this applies to, and whether for example this standard should be met for every individual county separately. The US Census Bureau's internal efforts to document the accuracy of improved TIGER data is referred to as the Accurate Coordinate Datasets Collection (ACDC) project. A contract of approximately $10 million was awarded in 2004 to a private company (Michael Baker Corporation) to carry out the ACDC project, but no results have been made public.

The purpose of the current study is to provide an independent evaluation of the horizontal positional accuracy of the improved TIGER data. To provide a context for this accuracy assessment, the most recently released TIGER data (2009) is compared to the TIGER 2000 data. The methods employed generally follow the recommended NSSDA protocol, with some modifications to improve the robustness of the accuracy assessment procedure.

2 Methods and Data

The accuracy of TIGER 2000 and 2009 data was determined by comparing selected road intersections in both datasets to high resolution orthoimagery. The following sections describe how the sample points were selected and analyzed.

Three US counties were selected as study areas: Allen County, IN, Bernalillo County, NM and Wayne County, NC. Counties were selected based on the following criteria: (1) availability of recent (2008 or later) high resolution (6-inch) natural color orthophotos; (2) presence of both urban and rural areas in roughly equal measure to allow for sampling in both types of study areas; and (3) modest topography in most of the study area to limit the effects of terrain on the accuracy of orthoimagery. Initial screening resulted in several dozen candidate counties and the final three were selected based on having different geographic regions represented.

Natural color 6-inch orthophotos were obtained for the three counties. Metadata reports were reviewed to confirm the procedures used in collecting and processing the imagery, and to identify the reported horizontal accuracy of the final product. In the case of Allen County, IN, the orthoimagery was collected by Pinnacle Mapping Technologies, Inc. in April 2008. Although no empirical accuracy assessment was carried out, the metadata states that "The data is produced to meet National Map Accuracy

Standards. For the 6-inch pixel RGB product areas the pixels will be within 1.5' to 1.0' of their true location." The coordinate system of the orthoimagery is State Plane Indiana East NAD 83 (US survey feet). In the case of Bernalillo County, NM, the orthoimagery was collected by Bohannan-Huston, Inc. in March and April 2008. Accuracy of the imagery was tested using the process documented in chapter 3 of the National Spatial Data Infrastructure (NSDI) and was found to conform to the American Society of Photogrammetry and Remote Sensing (ASPRS) Class 1 standards for 1″ = 100′ horizontal mapping. A total of 62 sample points collected using real-time kinematic GPS was used in the accuracy assessment and resulted in a horizontal RMSE of 0.66 feet (0.20 m) and a 95^{th} percentile of 1.14 feet (0.35 m). The coordinate system of the orthoimagery is State Plane New Mexico Central NAD 83 HARN (US survey feet). In the case of Wayne County, NC, the orthoimagery was collected by EarthData International in January 2008. The metadata states that the orthophotos were found to "fully comply with a verified horizontal accuracy of 6.7 feet (2.0 m) at the 95% confidence interval as specified in the National Standard for Spatial Accuracy (NSSDA)". Based on the description of the data collection and processing procedures, however, the orthophotos are likely to be more accurate than the stated upper limit for positional accuracy. The coordinate system of the orthoimagery is State Plane North Carolina NAD 83 HARN (US survey feet).

TIGER polyline data for 2000 and 2009 were obtained from the US Census Bureau. Each dataset was projected in a State Plane coordinate system to match the coordinate system of the orthoimagery for the particular study area. A separate dataset was created with only the road features based on the appropriate flag for feature types. Primary highways were removed from the dataset based on the Feature Classification Codes (FCC) A11 through A18. Primary highways present difficulties in positional accuracy assessments since divided multiple lanes are represented in different ways based on topological considerations, making it often impossible to determine appropriate reference locations. Network topology was created for the resulting non-highway 2000 and 2009 road networks to obtain all intersections. These intersections represent the sampling universe for the positional accuracy assessment.

The procedure to obtain the final sample consisted of the following steps: (1) removal of points on steep slopes; (2) splitting the sample in urban and rural location; and (3) iterative random selection of locations based on a rule-set of appropriate locations. Each step will be described in more detail.

The positional accuracy assessment relies on the accuracy of the orthoimagery. In the process of creating the orthoimagery, relief displacement is reduced by the process of orthorectification. Despite this procedure, the positional accuracy of orthoimagery is still likely to be lower in areas of higher relief. To limit the possible effects of topography, points located on steep slopes were removed from the sample. For each study area, a 30 m Digital Elevation Model (DEM) was obtained from the National Elevation Dataset (seamless.usgs.gov). A slope grid was derived from this DEM and cells with a slope greater than 10% were selected. These cells were buffered by one cell (30 m) and any points falling inside these areas were removed.

To allow for a comparison across urban-rural gradients, the points were split into urban and rural locations. This was accomplished by using the urban areas boundary of the US Census Bureau that is part of the same TIGER data. Urban boundaries for each study area were checked against road networks and orthoimagery to determine any inconsistencies. Specifically, in a number of places the urban boundaries were extended to include newer sub-divisions, at the urban-rural interface, which have clearly been established since the creation of the urban boundaries.

The remaining sampling points (urban and rural locations for three study areas for 2000 and 2009 for a total of 12 sets of points) were used in an iterative random sampling procedure. In general, the strategy as suggested by the National Standards for Spatial Data Accuracy (NSSDA) (FGDC 1998) was followed as close as possible, with a few notable exceptions: (1) the NSSDA protocol suggest a minimum of 20 points – since it is expected that the positional errors are not normally distributed and error metrics can therefore be biased for a small sample, a sample size of 100 was employed for each sample; and (2) the NSSDA protocol suggests that sampling points should be no closer together than 1/10th of the length of the diagonal of the (rectangular) study area – this rule is impossible to achieve with a larger sample and instead a distance based on topological connectivity was employed, as described below.

The iterative random sampling procedure consisted of the following steps, applied to each of the three study areas, for both urban and rural areas:

- Step 1. Select a point from the total set of points based on the 2009 data at random using a random feature selection tool in GIS.
- Step 2. Determine whether the sampling location is appropriate, i.e. does it represent a well defined intersection, T-junction or corner, based on an overlay with the orthoimagery? Reasons for removing a location from consideration are:
  - Intersections, T-junctions or forks where the smallest angle between two segments is less than 70 degrees – this includes all merging lanes.
  - Endpoints of road segments, including cul-de-sacs and dead-end roads.
  - Rounded corners with a poorly defined breakpoint.
- Step 3. Determine whether a robust comparison between the 2000 and 2009 data and the orthoimagery is possible. Reasons for removing a location from consideration are:
  - Newer road networks that were present in 2009 but not present in 2000.
  - Road networks that have been totally altered, such as unpaved roads in 2000, which have been replaced by a new sub-division with a totally different road network layout in 2009.
  - Incorrect topology, specifically when the 2000 data is so different from the present day imagery that the road network is unrecognizable. It should be noted that in quite a number of cases the 2000 data was off by several hundred meters, but in general the road network could be matched based on network topology, and these locations were included. Where no reliable match could be made based on network topology the location was removed from consideration.
- Step 4 (does not apply to the first point). Determine the topological proximity to existing selected points for the final sample. A point has to be at least two nodes removed from the closest other point in the final sample. In other words, the shortest path (based on number of segments, not length) between two points in the final sample consists of at least three segments. This reduces the effect of spatial autocorrelation on the positional accuracy assessment.
- Step 5. For a point that meets the criteria under steps 2 and 3, flag the corresponding intersections in the 2000 and 2009 datasets using a unique ID number.
- Step 6. Remove the point selected in step 1 (whether deemed appropriate or not) from further consideration.

Steps 1 through 6 were repeated until a total of 100 sample points was reached. This procedure was applied separately to the urban and rural locations within each study area. It should also be noted that steps 2, 3 and 4 were carried out manually through careful visual inspection, since automated procedures to apply the criteria were deemed insufficient. To ensure consistency between individual analysts (three total) a detailed protocol was developed describing the criteria employed in steps 2, 3 and 4, including a large number of screen captures with examples. In addition, all resulting sample points were double-checked by a second analyst, with corrections made as needed.

Figure 1 shows the distribution of the final set of sampling locations for the three study areas. For clarity, only the TIGER 2009 road network and the sample points based on this network are shown – at the display scale employed in Figure 1 the differences between the sets of points from the 2000 and the 2009 data would not be clearly visible. In certain areas the points appear somewhat clustered, but this is related to the display scale – closer inspection of the results would reveal that the topological distance of at least two network nodes applies consistently. Other areas visually appear somewhat under-sampled, especially in rural areas. This resulted in large part from the fact that in certain areas the TIGER 2000 data was so poor in terms of positional accuracy and network topology that no robust comparison was possible. A number of locations in rural areas were also removed due to the topographical constraints applied.

Once the final set of sampling locations was obtained, a reference point was digitized for each location using the 6-inch orthoimagery. This was done independently of the points derived from the TIGER data. In other words, the general location of the intersection or T-junction was identified and then the TIGER data layers were removed prior to digitizing the reference point to avoid any bias. A single point was digitized, representing the best estimate of the intersection of the centerlines. Reference points were digitized using an approximate display scale of 1:250 and given a unique ID number. Corresponding intersections derived from the TIGER 2000 and 2009 data were given the same ID number. Figure 2 illustrates the result of this procedure for a single location.

State Plane XY coordinates of all points were calculated and exported to Microsoft Excel. Error statistics were calculated by comparing the coordinates of the intersections in the TIGER 2000 and 2009 data to those of the reference points. Final error statistics were converted from US survey feet to meters. Horizontal error statistics were summarized in tables and the horizontal error distributions were summarized in cumulative distribution functions for each study area.

3 Results and Discussion

A visual comparison of TIGER 2000 and 2009 data overlaid on recent orthoimagery provides a good first insight into the differences in positional accuracy. Figure 3 shows a number of typical examples from Bernalillo County, NM and Wayne County, NC. Figure 3a shows an example of a medium density residential neighborhood. The TIGER 2009 roads appear a very good match with the orthoimagery with only a few minor discrepancies. The TIGER 2000 roads, however, are a very poor match and at first glance appear totally incorrect. A closer inspection of the network topology, however, indicates that the entire road network is shifted by about 250 m to the north-northeast relative to the orthoimagery. This is the result of some type of conflation error, which is common when paper maps are poorly georeferenced. This type of error is very common in the

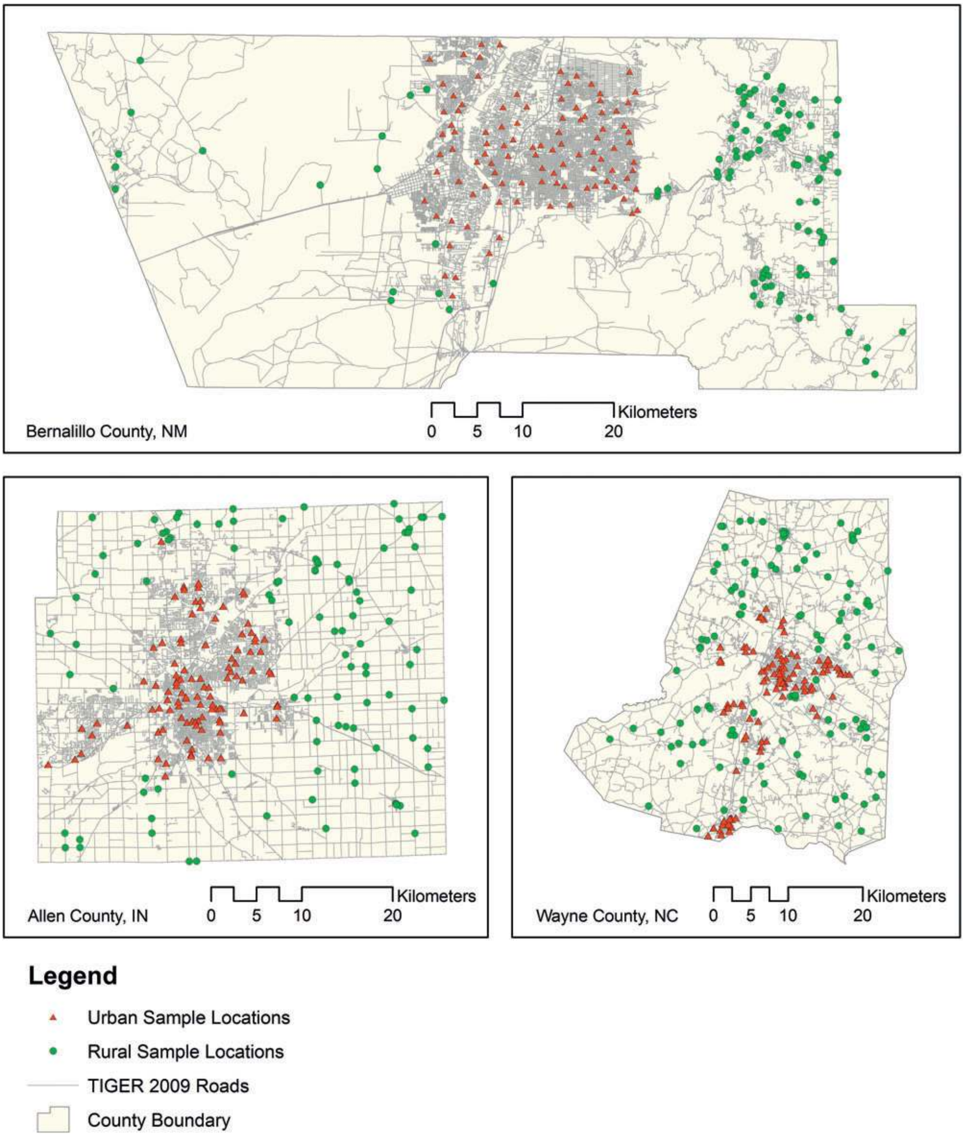

Figure 1 Distribution of sample locations in three study areas

TIGER 2000 data and reflects the historic emphasis on topological integration rather than positional accuracy. Figure 3b shows a high density commercial/industrial area. The TIGER 2009 is again a good match with the orthoimagery, although there are some roads running through city blocks where a road does not exist. Positional errors in the TIGER 2000 data are smaller than in the previous example but there is still a noticeable displacement of the data and errors of 20 to 30 m are common. There are also some odd kinks in the data from segment to segment along what visually appears to be a straight road. This is common for data originally created at a scale of 1:100,000. Figure 3c shows a low density rural residential area. The TIGER 2009 data is again a good match with

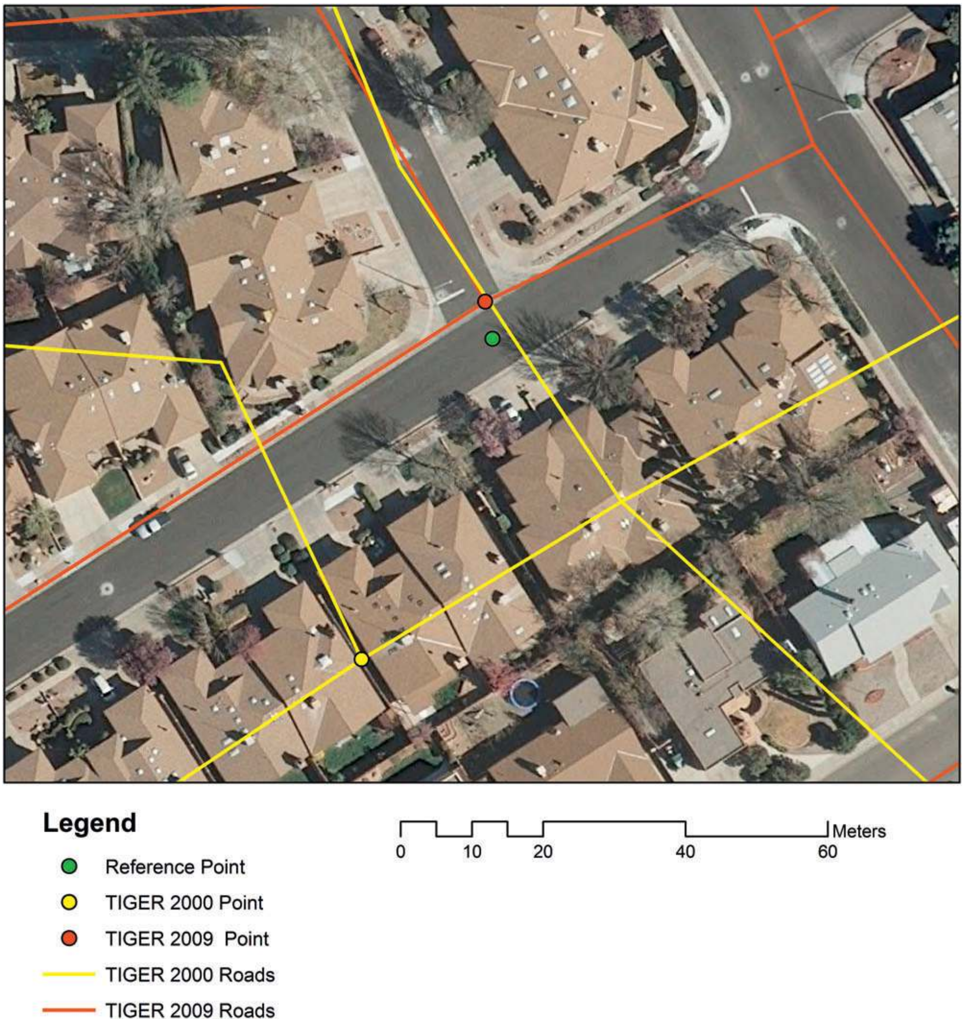

Figure 2 Close-up view of a sample location with points derived from TIGER 2000 and 2009 data compared with a digitized reference location

the orthoimagery, although not all roads are clearly visible due to canopy. The TIGER 2000 data is again a poor match. The data appears rotated by about 25 degrees and there are numerous topological inconsistencies as well. Finally, Figure 3d shows another low density residential area. The TIGER 2009 is a good match in general, with a number of inconsistencies, especially for dead-end road segments. The TIGER 2000 data is of mixed quality in this case, with some segments and intersections lining up really well and others being way off. This reflects the mixed lineage of the TIGER data, compiled from various sources and corrected and added to over time by different contributors.

The examples in Figure 3 also show that the emphasis on topological integrity of early TIGER data is very much evident in the TIGER 2000 data. Relatively complex shapes are captured using nodes and edges, with most edges consisting of straight lines, and a limited number of shape points added to capture curves. As a result, using

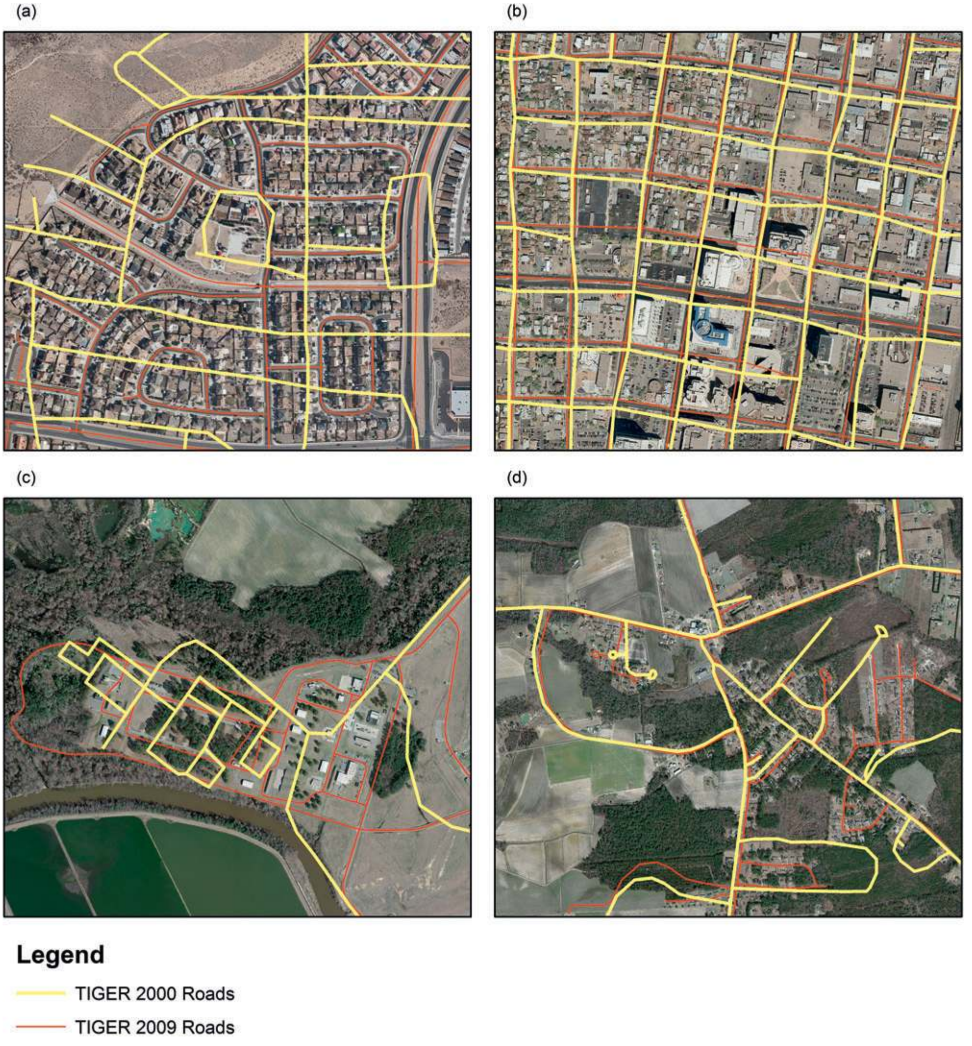

Figure 3 Examples of positional error in TIGER road data

intersections (i.e. nodes) or shape points for determining positional accuracy will likely produce a lower positional error compared to using randomly selected points. By contrast, in the TIGER 2009 data the same complex shapes are still captured using nodes and edges, but edges for curved road segments contain a large number of vertices to describe the shape and follow the actual feature much more closely. The results of a positional accuracy assessment of the TIGER 2009 data are therefore less sensitive to the selection of test locations (i.e. intersections vs. random points).

The general impression from Figure 3 is that the TIGER 2009 data is indeed much improved relative to the TIGER 2000 data, but does contain a number of flaws. It is worth noting that some of these errors (i.e. topological errors, road segments where there should not be any) are in fact not evaluated as part of the positional accuracy assessment that follows.

Table 1 provides a summary of the accuracy metrics of the TIGER 2000 and TIGER 2009 data for the three study areas. A number of typical accuracy metrics are included, including percentiles and the Root Mean Squared Error (RMSE). The statistic at the bottom reflects the error metric as recommended by the NSSDA protocol, which is derived from the RMSE value. This is the same as the CE95 error statistic referred to by the US Census Bureau.

In general, Table 1 confirms the substantial improvement of the positional accuracy of the TIGER 2009 compared to the TIGER 2000 data. In many cases, the improvement exceeds one order of magnitude. For example, the median error of TIGER 2000 data in urban areas in Allen County, IN is 23.0 m, while for the TIGER 2009 data this has been reduced to 1.0 m. Substantial improvements are observed consistently in all error metrics across both urban and rural areas for all three study areas. Despite this consistency, a number of error metrics for the TIGER 2009 data require a closer look. For example, the maximum error for TIGER 2009 data indicates that large errors of several tens of meters occur in all study areas. Values for the 95th percentile confirm that such large errors are relatively common, especially in rural areas.

In addition to the summary metrics in Table 1, the error distributions are described as cumulative distributions functions in Figures 4, 5 and 6. Combined with Table 1, these provide a more complete characterization of the positional errors. The first observation from Figures 4, 5 and 6 is that all the error distributions display non-normal behavior – this is significant since it has bearing on the robustness of certain accuracy metrics such as RMSE. This non-normal behavior also explains a peculiarity in the error metrics. The NSSDA statistic in Table 1 is derived from the value for RMSE and is assumed to represent the 95th percentile based on a normal distribution (FGDC 1998). However, the results for the NSSDA statistic are consistently different from the 95th percentile derived directly from the error distribution. The RMSE statistic (and as a result the NSSDA statistic) is sensitive to the occurrence of a small number of outliers (Zandbergen 2008). The difference between the two metrics, however, is never greater than a factor of 2 and in general the two metrics present a similar picture of the positional accuracy of TIGER data.

The second observation from Figures 4, 5 and 6, which is supported by the metrics in Table 1, is that in general the positional accuracy of TIGER data is better in urban areas than in rural areas. The only exception is the result for the TIGER 2000 data for Allen County, IN, for rural areas, which are slightly more accurate than for urban areas. For the TIGER 2009 data, the results present a strong indication that positional accuracy is consistently better in urban areas than in rural areas. By how much is hard to define since this strongly depends on which accuracy metric is employed. Figures 4, 5 and 6, however, present a clear difference between the curves for urban and rural areas anywhere above the 50th percentile, and suggest that the positional error of TIGER 2009 data in rural areas is roughly twice as large as that of urban areas.

When the metrics for positional accuracy are compared with the accuracy expectations of 7.6 m based on the CE95 metric, the results for the TIGER 2009 are somewhat discouraging. Based on the NSSDA metric, the TIGER 2009 data only meets the accuracy expectations for the urban areas in Allen County, IN (3.1 m) and in Wayne County, NC (6.9 m). Positional accuracy for the urban areas in Bernalillo County, NM (13.7 m) and for the rural areas in all three study areas does not meet the accuracy expectations. This pattern is unaltered when using the 95th percentiles instead of the NSSDA metric. Results for rural areas in Bernalillo County, NM, are particularly surprising, with a value of

Table 1 Positional accuracy metrics of sample locations for TIGER 2000 and TIGER 2009 data (m)

	Allen County, IN				Bernalillo County, NM				Wayne County, NC			
	Urban		Rural		Urban		Rural		Urban		Rural	
Accuracy metric	2000	2009	2000	2009	2000	2009	2000	2009	2000	2009	2000	2009
Minimum	2.7	0.1	1.0	0.2	2.6	0.4	10.6	0.1	2.6	0.1	2.9	0.1
Maximum	372.2	10.0	169.7	48.6	370.3	61.0	687.3	240.0	519.9	30.8	577.0	100.5
Median	23.0	1.0	11.3	1.1	34.0	2.8	77.9	4.3	19.1	0.9	25.0	1.3
68th percentile	32.1	1.4	18.0	1.7	44.9	4.0	146.2	10.2	24.6	1.2	33.5	2.0
90th percentile	99.5	2.4	46.4	5.3	111.8	7.2	357.8	59.5	70.1	2.3	144.4	17.0
95th percentile	132.3	2.9	71.8	16.0	189.2	9.8	526.1	103.8	103.7	3.8	223.8	27.1
RMSE	67.4	1.8	33.0	8.4	85.4	7.9	209.1	46.7	96.3	4.0	101.2	15.7
NSSDA / CE95	116.6	3.1	57.1	14.5	147.8	13.7	362.0	80.7	166.6	6.9	175.2	27.2

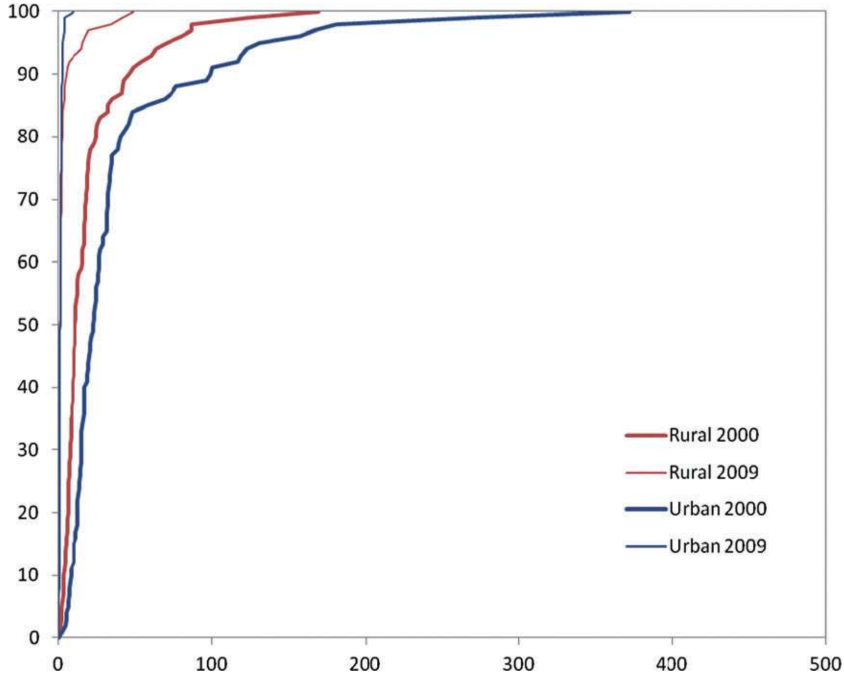

Figure 4 Cumulative distribution function of positional errors in TIGER road data for Allen County, IN

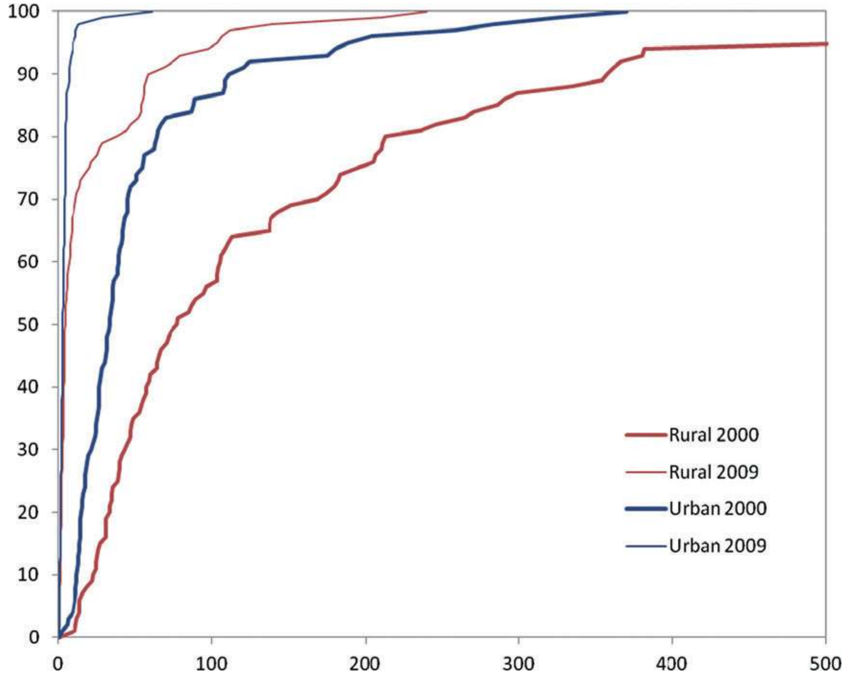

Figure 5 Cumulative distribution function of positional errors in TIGER road data for Bernalillo County, NM

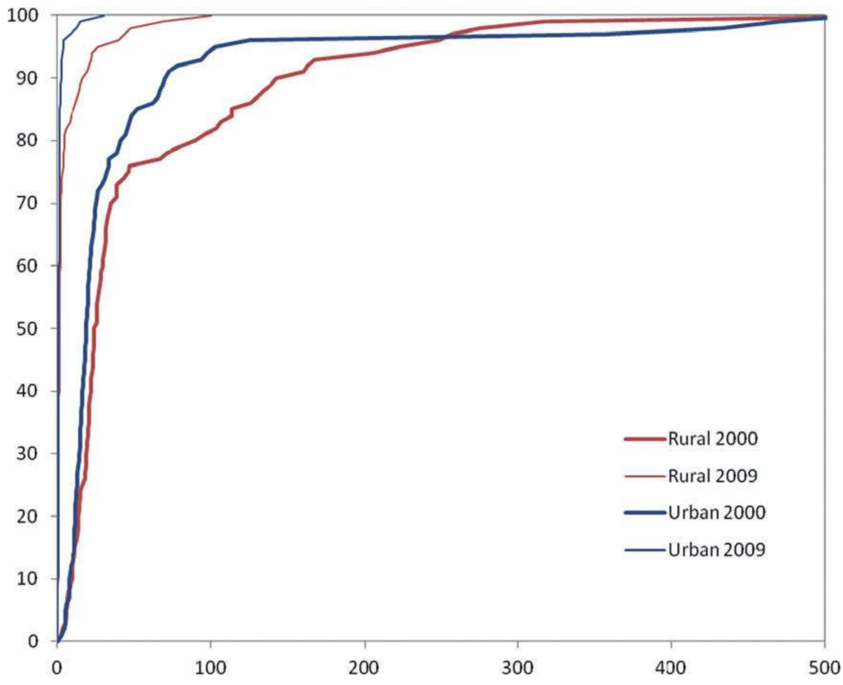

Figure 6 Cumulative distribution function of positional errors in TIGER road data for Wayne County, NC

80.7 m for the NSSDA metric. While the results for rural areas in Bernalillo County, NM, indicate a substantial improvement in positional accuracy compared with the TIGER 2000 data and a relatively small median error of 4.3 m, large errors exceeding 100 m are relatively common and account for 5% of the sampled locations.

The US Census Bureau is not specific in terms of the study areas to which the accuracy expectations should be applied. In this study both urban and rural locations for three study areas were analyzed separately. Combining these samples, however, could result in different conclusions. Table 2 represents several alternative aggregations of the sample locations for the TIGER 2009 data with the accuracy metrics recalculated for these samples. First, data for each study area are combined, resulting in three samples of 200. For all three study areas the positional accuracy of TIGER 2009 data does not meet the accuracy expectations based on the NSSDA metric. However, in the case of Allen County, IN, this metric is clearly influenced by the non-normal nature of the distribution; the 95th percentile is 5.6 m (and meets the accuracy expectations) while the NSSDA metric is 10.4 m (and fails the accuracy expectations). The results for the other two study areas are less ambiguous since in both cases the NSSDA metric as well as the 95th percentile far exceeds 7.6 m. Second, data for urban and rural areas are combined, resulting in two samples of 300. For both datasets the positional accuracy of TIGER 2009 data does not meet the accuracy expectations based on the NSSDA metric. Similar to the result for Allen County, IN, the 95th percentile of the urban sample points (7.2 m) does meet the accuracy expectations. The results also reaffirm the difference between urban and rural locations; while the median errors are similar (1.2 m vs. 1.8 m), large errors of more than 10 m are relatively common in rural areas (57 out of 300) but quite

Table 2 Positional accuracy metrics for aggregated samples of TIGER 2009 data (meters)

	Allen County, IN	Bernalillo County, NM	Wayne County, NC	All Rural	All Urban	All Combined
Accuracy metric	n = 200	n = 200	n = 200	n = 300	n = 300	n = 600
Minimum	0.1	0.1	0.1	0.1	0.1	0.1
Maximum	48.6	240.0	100.5	240.0	61.0	240.0
Median	1.0	3.4	1.0	1.8	1.2	1.4
68th percentile	1.5	4.9	1.4	3.6	2.0	2.5
90th percentile	3.0	44.8	8.6	26.7	4.5	11.3
95th percentile	5.6	61.4	19.7	55.7	7.2	31.0
RMSE	6.0	33.5	11.5	28.8	5.2	20.7
NSSDA / CE95	10.4	57.9	19.8	49.9	9.0	35.9

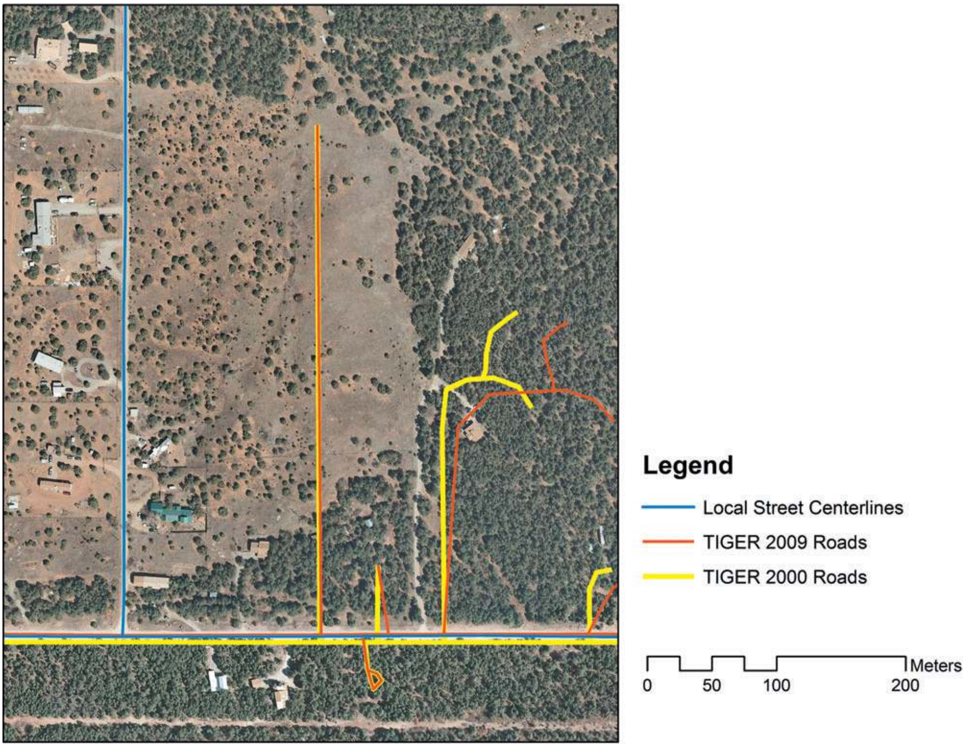

Figure 7 Comparison of TIGER data and local street centerlines for a rural area in Bernalillo County, NM

rare in urban areas (8 out of 300). For rural areas this results in very high values for the 90th percentile, the 95th percentile, RMSE and the NSSDA metric. For urban areas this results in relatively low values for the 90th and 95th percentile but the RMSE (and resulting NSSDA metric) is just large enough not to meet the accuracy expectations. Given the relatively infrequent occurrence of large errors, the NSSDA metric is very sensitive to outliers. For example, removing the single largest outlier from the urban sample (a value of 61.0 m) reduces the NSSDA value to 6.7 m, which would meet the accuracy expectations of 7.6 m. Finally, all data are combined, resulting in one sample of 600. For this dataset the positional accuracy of the TIGER 2009 data does not meet the accuracy expectations with a value of 35.9 m for the NSSDA metric.

The relatively frequent occurrence of large positional errors in the TIGER 2009 data prompted a closer inspection of these locations to determine if they followed a particular pattern. Local street centerlines obtained from the respective counties were used in a visual comparison, in addition to TIGER 2000 and 2009 data and orthoimagery. Figure 7 shows a common scenario encountered during the inspection of the locations, with a large positional error in the TIGER 2009 data. The specific example consists of a rural area in Bernalillo County, NM. For the main road running east-west, the local street centerlines and the TIGER 2009 data are a near-perfect match with the orthoimagery, and the TIGER 2000 data is off by less than 10 m. However, for the side road running north-south, the local street centerlines are a near-perfect match, but both the TIGER

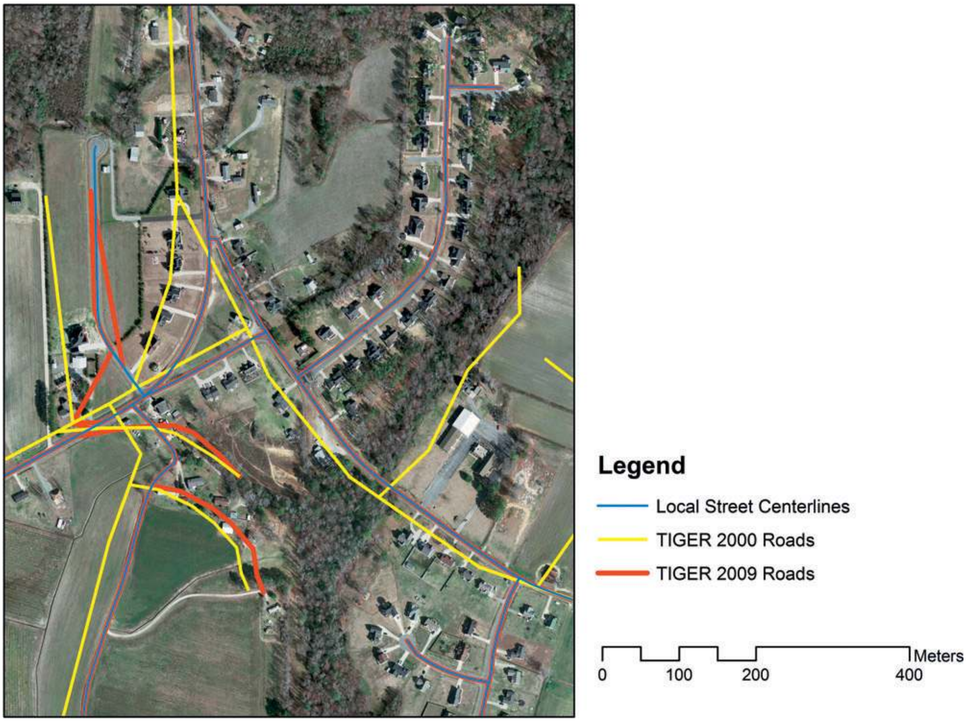

Figure 8 Comparison of TIGER data and local street centerlines for a suburban area in Wayne County, NC

2000 and TIGER 2009 data are off by about 150 m. This particular segment has not been corrected in the TIGER 2009 data and it appears to have been copied from the TIGER 2000 data without alteration. The specific T-junction in this case was one of the sample locations, resulting in a large error for both the TIGER 2000 and TIGER 2009 data. The smaller segments further to the east in Figure 7 are private driveways, which do not appear in the local street centerlines but are present in both versions of the TIGER data. While there are some differences between the TIGER 2000 and TIGER 2009 data in these segments, neither matches the orthoimagery very well. Closer inspection of the large positional errors (>10 m) in the TIGER data revealed that many of these errors consist of T-junctions as illustrated in Figure 7, where it appears that the side road off the main road has either not been corrected relative to the TIGER 2000 data, or has only been partially corrected.

A second scenario encountered in a number of locations is shown in Figure 8, using a suburban area in Wayne County, NC, as an example. In this case the local street centerlines and the TIGER 2009 data are a near-perfect match to the orthoimagery for most segments. However, one segment in the TIGER 2009 is simply poorly digitized and does not follow the topology of the road network as observed in the imagery. Two other segments consist of private driveways, which are not present in the local street centerlines. The segments roughly follow the TIGER 2000 data and do not match the orthoimagery at all. This results in an error of several tens of meters. Figure 8 illustrates the difficulties encountered when trying to match the positional accuracy of local reference data while at the same time maintaining the topological integrity present in older versions of the TIGER data. It appears that adherence to the fundamental principle of topological integrity, implemented by building on older versions of the TIGER data, has resulted in a loss of positional accuracy relative to what is commonly achieved by local jurisdictions whose data collection efforts are driven mostly by positional accuracy.

The examples illustrated in Figures 7 and 8 are relatively common in the three study areas considered. A review of the large errors (>10 m) in the TIGER 2009 data reveals that most of the large errors can be attributed to:

1. T-junctions where the side road off the main road has not been sufficiently corrected or not corrected at all compared with TIGER 2000 data; and
2. intersections and T-junctions where inaccurate road segments have incorrectly been carried over from the TIGER 2000 data, resulting in incorrect placement and topology.

The visual comparison with local street centerlines has also revealed some important insights:

1. for most road segments the TIGER 2009 data and local street centerlines are a very close match;
2. in many locations TIGER 2009 data are slightly less accurate than local street centerlines, mostly for minor roads; and
3. TIGER 2009 data contains many segments not present in local street centerlines, mostly consisting of private driveways and unpaved roads.

In general, the comparison with local street centerlines and orthoimagery has shown that despite the substantial improvements in the positional accuracy of TIGER data, the 2009 version still contains many remnants of the 2000 version, resulting in large positional errors. Where available and appropriate, local street centerlines are likely to provide data of better positional accuracy.

4 Conclusions

The horizontal positional errors of the TIGER 2000 data documented in this study in general correspond to those found in earlier studies (Trainor 2003, Lee 2009, Seo and O'Hara 2009, Song et al. 2006, Zandbergen 2008). Large errors of several tens of meters, sometimes exceeding 100 m, are very common. The findings represented here therefore confirm the limited positional accuracy of the TIGER 2000 data. A comparison between urban and rural areas revealed somewhat inconsistent results, with rural roads being more accurate than urban roads in one of the three study areas.

Results from this study provide strong evidence that the TIGER 2009 data are indeed much improved in terms of positional accuracy compared with the TIGER 2000 data. The improvement is at least one order of magnitude across urban and rural areas in all three study areas for most accuracy metrics. A comparison of urban and rural areas indicates that TIGER 2009 data are consistently more accurate in urban areas, by a factor of at least two for most accuracy metrics. These findings are very encouraging given the resources that were committed to the improvement of TIGER data.

Results also confirm that the positional error in the TIGER 2009 data does not follow a normal distribution, similar to what has previously been established for TIGER

2000 data (Zandbergen 2008). This has implications for the use of accuracy metrics, since non-normal distributions make traditional metrics like RMSE less robust, especially for small sample sizes (Zandbergen 2008). In the case of the TIGER 2009 data the RMSE values approximate or exceed the value for the 90th percentile as a result of a relatively small number of outliers, while for a normal distribution these values would be closer to the 68th percentile. This implies that the CE95 metric employed by the US Census Bureau and based on the NSSDA protocol should be reconsidered. The non-normal distributions complicate comparisons between studies based on a specific metric. For example, two independent studies of the same area using a different sample of test locations may derive a very different conclusion as to whether the data meets a specific accuracy standard as a result of the occurrence of one or two (valid) outliers in the data. Traditional wisdom would suggest that increasing the sample size results in more robust metrics, but this also increases the likelihood that a single very large outlier occurs, which can skew the results for a particular metric. This suggests that determining the positional accuracy of spatial data should employ multiple metrics as well as other methods to characterize the complete distribution rather than rely on a single metric.

Despite the substantial improvement in positional accuracy, large errors are relatively common in the TIGER 2009 data, especially in rural areas. For the total sample of 600 locations, 65 had a positional error greater than 10 m and seven had a positional error greater than 100 m. Most of these large positional errors identified in the TIGER 2009 data are the result of remnants of the TIGER 2000 data, which have been insufficiently corrected or not corrected at all. Most of these remnants are associated with minor road segments, often in the form of T-junctions.

As a result of these large errors, based on the CE95 metric the TIGER 2009 data only meets the accuracy expectation of 7.6 m for two of the three urban areas and for none of the three rural areas. Employing alternative accuracy metrics does not alter this general conclusion. Pooling the sample locations based on study area and urban/rural characteristics resulted in samples that did not meet the accuracy expectations. The proposed CE95 metric based on the NSSDA protocol was found to be very sensitive to the presence of outliers. For example, a single very large outlier in a sample of 300 urban locations caused the positional error of the TIGER 2009 data to exceed the accuracy expectations. This presents challenges to other studies trying to characterize the accuracy of TIGER data (or other spatial data for that matter) using the NSSDA protocol. A particular study with a certain sample size may or may not capture some of these large outliers and the presence of a single outlier in even a large sample may determine whether a specific accuracy metric is met or not. The sensitivity of the NSSDA protocol (and its equivalents in other standards) to outliers remains a persistent challenge to accuracy assessments of spatial data in general. As a minimum, any future studies on the positional accuracy of spatial data that employ the NSSDA protocol should provide a solid characterization of the error distribution and not rely on a single metric to draw final conclusions.

The current study has a number of limitations. First, only three study areas were employed, which may not be representative for the entire TIGER 2009 dataset. However, results across the three study areas are relatively consistent using a moderately large sample size, and this provides no indication that results would be very different for other regions in the nation. Second, positional accuracy was determined using only well defined intersections and more sophisticated methods to determine the accuracy of linear features were not employed. On the other hand, the methods employed follow conventional accuracy assessment procedures as described in current accuracy standards. Third, many of the large errors can be attributed to misplaced intersections. While in some cases the entire segment is misplaced (e.g. Figure 7) in other cases this represents a topological error where the segment is digitized quite accurately but the final node is not connected correctly (e.g. Figure 8). As a result, using randomly selected locations along segments instead of intersections may result in a reduction in the occurrence of large errors in the positional accuracy assessment. Fourth, reference locations were obtained from orthoimagery and no field data collection using survey grade methods was employed. However, the orthoimagery used in the study represents the highest resolution imagery currently available for large study areas and have a documented accuracy that is better than the target for the reference data (CE95 of 7.6 m).

It is important to recognize that while the current study examined TIGER roads, the results for positional accuracy have wider relevance beyond this specific dataset. By its very nature TIGER data is topologically integrated and the roads form the basis for many other boundaries in the TIGER system, including block groups, tracts, and many other units. The positional accuracy of these boundaries is somewhat harder to determine, but the results for roads in the current study provide a starting point. Earlier versions of the TIGER data have also been widely used as the basis for many other free and commercial datasets. It is likely that the improved TIGER data will be adopted in similar fashion, meaning that any errors in TIGER data will propagate through many other datasets and analyses based upon them.

Before the development of road network datasets by commercial companies like TeleAtlas and NAVTEQ, TIGER data represented the only nation-wide dataset of all roads in the US that was regularly updated. At present the improved TIGER data remains the only free dataset with consistent and up-to-date nationwide coverage. It also provides the reference data needed to create nationwide geocoding services – while not specifically addressed in the current study, the TIGER roads contain street name and address range information to support geocoding.

In addition to the specific results for TIGER roads, the current study has highlighted some findings relevant to the study of spatial data quality in general. First, there is the issue of persistent errors throughout the historical lineage of the data. Despite the substantial efforts to improve the positional accuracy of the TIGER data, some of the errors in the improved data can be traced back to earlier versions of the data, in particular in rural areas. This suggests that a certain amount of "legacy" error appears unavoidable in a large updating effort. Second, for the improved TIGER data, the positional error in rural areas is consistently larger than in urban areas. While not unexpected, these findings suggest a persistent difference in spatial data quality across urban-rural gradients. Third, spatial analyses that have employed TIGER 2000 data may need to be revisited in the light of the availability of data with much improved positional accuracy.

Future efforts to document the accuracy of the improved TIGER data should consider: (1) more sophisticated methods of spatial data quality (linear features, topological connections) that address logical functionality, not just positional accuracy; (2) additional features other than roads (hydro, rail, boundaries, etc.); and (3) more complete geographic coverage. Finally, the US Census Bureau in its own efforts to determine the accuracy of TIGER data should consider alternatives to the CE95 accuracy metric to characterize the results of accuracy assessments.

In conclusion, the positional accuracy of TIGER 2009 data is much improved compared with the TIGER 2000 data, typically by at least an order of magnitude. Unless specific research requirements dictate otherwise, any application that utilizes TIGER data for any form of spatial analysis should employ the improved TIGER data and continued uses of pre-2009 TIGER data should be discouraged. Despite these improvements, however, TIGER 2009 data may not meet stated accuracy expectations in all locations, especially in rural areas. For studies focused on relatively small study areas, local street centerlines are likely to present a more accurate alternative to TIGER 2009 data. However, local street centerlines lack national coverage and data characteristics, such as positional accuracy and attribute structure, may vary substantially between jurisdictions.

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