Automated Extraction of Horizontal Curve Information for Low-Volume Roads

Zhixia Li, Madhav V. Chitturi, Andrea R. Bill, Dongxi Zheng, and David A. Noyce

Rates of fatal and injury crashes on low-volume roads are much higher than those on higher-volume roads. A large proportion of crashes on low-volume roads are roadway departure crashes. Research has shown that roadway departure crashes are 1.5 to 4 times more likely at curves than on tangent sections. Therefore, knowledge of where horizontal curves are located and their geometric characteristics is key to addressing safety issues for low-volume roads. In the United States, although many states have a horizontal curve database for their state routes and Interstate highways, most states do not have such a database for non-state-owned roads, especially for low-volume rural roads, because of the lack of funds for additional data collection. A novel approach is presented that can extract curve data for both state and local roads in an accurate, cost-effective, and time-efficient manner without additional data collection. An ArcGIS add-in tool, CurveFinder, was developed by the authors previously to automatically identify horizontal curves from a selected roadway layer, classify curves, compute curve geometrics, and, finally, create a geographic information system for curve layers. CurveFinder was updated to incorporate compatibility with curve elements of FHWA's Model Inventory of Roadway Elements. Case studies are used to demonstrate the application of the updated CurveFinder on rural low-volume roads in different states and the lessons learned. Results show that none of the control curves were 100% missed by CurveFinder. False identification rates were also low. Both results validate CurveFinder. Causes of the few errors in the extracted curve data are identified, and potential solutions are explored.

The United States has more than 3 million miles of two-lane highways, 90% of which carry traffic volumes of less than 2,000 vehicles per day (*1*). Fatal and injury crash rates on low-volume roads are much higher than those on higher-volume roads (*2*). A large proportion of crashes on low-volume roads are roadway departure crashes, typically run-off-the-road crashes (*1*). Research has shown that roadway departure crashes are 1.5 to 4 times more likely at curves than on tangent sections (*3*). Knowledge of where horizontal curves are located and their geometric characteristics is key to accurate placement of curve warning signs as well as other curve safety treatments (*4*–*6*). Therefore, the availability of horizontal curve information is essential for addressing the low-volume road safety issue.

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Transportation Research Record: Journal of the Transportation Research Board, No. 2472, Transportation Research Board of the National Academies, Washington, D.C., 2015, pp. 172–184.
DOI: 10.3141/2472-20

In the United States, although many states have a horizontal curve database for their state routes and Interstate highways, most states do not have such a database for non-state-owned roads, especially for low-volume rural roads. The major reason is that collecting curve data by using traditional approaches such as GPS data collection, PhotoLog–VideoLog data collection, or satellite image processing is usually costly and time-consuming. Therefore, both the state departments of transportation and the local transportation agencies that are responsible for the low-volume roads typically do not have sufficient funds to support establishing a curve database for low-volume roads. Furthermore, Moving Ahead for Progress in the 21st Century (MAP-21), the 2012 federal highway authorization law, requires states to develop performance targets and performance plans and report on performance for operation and safety of the transportation system. MAP-21 requires the safety performance measures to assess safety on all public roads including all low-volume public roads rather than only the state highway systems (*7*). In this context, it is imperative that a novel approach that can identify location and geometric information for both state and local county highways be developed and demonstrated in an accurate, cost-effective, and time-efficient manner.

Li et al. presented an automated method for horizontal curve identification and curve data extraction from geographic information system (GIS) roadway maps and developed CurveFinder, a tool based on the ArcGIS programmable package ArcObjects (*8*). The tool automatically locates horizontal curves from a selected roadway layer, computes the length of each curve as well as the radius and curvature of each simple circular curve, and finally creates a layer that contains all the identified curve features along with their geometric information. This development means that the horizontal curve data for any road can be simply extracted without the need of additional data collection as long as the GIS roadway maps of these roads are available. Since many states have roadway GIS maps for all public roads in the state including low-volume public roads, CurveFinder becomes a potential tool for extracting horizontal curve data for all low-volume roads at minimal cost.

Since the original CurveFinder was developed, it has tentatively been made compatible with FHWA's Model Inventory of Roadway Elements (MIRE). MIRE provides a standard data model and guidance to transportation agencies on collecting consistent safety-related roadway and traffic data (*9*). Eight elements in MIRE that are related to horizontal curves include curve identifiers and linkage elements, curve feature type, horizontal curve degree or radius, horizontal curve length, curve superelevation, presence of horizontal transition and spiral curve, horizontal curve intersection or deflection angle, and horizontal curve direction. Compatibility with MIRE can facilitate integration of the curve data extracted by CurveFinder into crash analysis.

Integrating horizontal curve data into road safety analysis and modeling has always been an important and essential step toward improved road safety but also a challenging and costly task. For example, collection of curve data takes a huge portion of the effort and cost of a safety evaluation project (*10, 11*). In the United States most of the existing effort for curve data collection by different states is through analysis of GPS data points collected during the Photo-Log–VideoLog data collection. The cost for PhotoLog–VideoLog data collection reported from a California project is around $178 per mile (*12*). The updated curve data collection tool presented here addresses these issues, particularly the following:

- It substantially reduces the cost for curve data collection; this advantage makes it feasible to cover all roads including all rural roads, unpaved roads, and low-volume roads.
- It makes it possible to integrate MIRE curve elements with all curve data for rural and low-volume roads; this capability has never been realized in the United States before.
- The complete U.S. curve data set for low-volume roads, which will result from CurveFinder, can greatly facilitate statewide or nationwide safety evaluation of all low-volume roads; such an evaluation has never been feasible because of the lack of curve data for low-volume roads.

The aim of this paper is to introduce the incorporation of MIRE compatibility and demonstrate the application of the updated Curve-Finder on rural roads and low-volume roads in different states and the lessons learned.

REVIEW OF LITERATURE

Horizontal curves are a significant factor that affects low-volume road safety. Hu and Yang revealed that straight segments connected to curves with small radii are hazardous locations for drivers on low-volume roads (*13*), particularly for vehicle rollover, which mostly occurs on a combination of vertical and horizontal curves with small radii. Discetti et al. found that the 85th percentile speed at horizontal curves is correlated with the radius and length of the curve (*14*). To improve horizontal curve safety, an advisory speed sign can be set up at an upstream location from the curve, and the advised speed can therefore be determined by the curve radius and length along with other factors. Discetti and Lamberti determined that sight distance on horizontal curves is important to ensure traffic safety at curves (*15*). Cafiso et al. further recommended removing obstacles that limit sight distance on horizontal curves in order to improve low-volume road safety and stated that knowing horizontal curve locations is a necessity (*16*).

Various approaches exist for identifying horizontal curve locations from different data sources. High-resolution satellite imagery is one of the most widely used sources for extracting elements of highway horizontal alignment. Different image-processing techniques have been utilized by researchers to detect roadway geometry from satellite imagery (*17–22*). Specifically, researchers from Ryerson University conducted an insightful investigation of identification of horizontal curves from IKONOS satellite images (*21, 22*). Their research proved the feasibility of deriving geometric characteristics of simple circular, compound, and spiral curves by using an approximate algorithm based on high-resolution satellite images. Meanwhile, the drawbacks of using satellite imagery are also obvious: accuracy greatly relies on image resolution and requires processing a huge amount of images. This effort is time-consuming and requires high computing power. Georeferencing after curve data extraction is another issue pertaining to image processing.

GPS data have been used to extract information on highway horizontal alignment (*23–26*). In those approaches, geographic coordinates were recorded by a GPS-equipped vehicle at uniform space intervals such as 0.01 mi. Horizontal curves were then identified and radii were computed with a customized GIS program based on the logged GPS data points. Yun and Sung installed multiple sensors in addition to GPS on the surveying vehicle to acquire real-world highway coordinates at a higher accuracy level (*27*). Other researchers equipped the surveying vehicle with laser-scanning technology to obtain the three-dimensional characteristics of horizontal curves (*28*). Although these methods usually can achieve high accuracy for curve data extraction, extensive data collection efforts are required. When these methods are applied to a larger number of roadways, enormous cost and data collection time are required.

Digital maps are another alternative data source. Researchers from the United Kingdom and Ireland succeeded in their attempts to extract highway geometry from digital maps under the Auto-CAD environment (*29, 30*). The limited availability of digital maps constrained their wide use of them as a data source for curve data extraction.

Recently, researchers have started extracting horizontal curve data using the ArcGIS roadway shapefile (*31*). The ArcGIS toolbar Coordinate Geometry provides a similar function through the command "Curve Calculator" for manual extraction of curve data from GIS roadway maps (*32*). The methods in these applications require manual identification and construction of tangent points and chord lines on the ArcGIS feature layers; this operation resulted in a large work load and lower efficiency. The Florida Department of Transportation also developed a manual method to estimate curve information under the ArcGIS environment (*33*). A tool developed by the New Hampshire Department of Transportation was found in an evaluation study conducted by North Carolina State University; the study featured a semiautomatic approach (*34*). This method extracts roadway alignment information from a geodatabase and outputs curve data into a text file (*34*). The researchers developed an executable file that retrieves roadway coordinates from a geodatabase and outputs the curve's starting and ending mileposts, radius, and number of segments to a text file. The method is specifically designed for a GIS roadway map that has a special roadway referencing system defined by mileposts. Manual creation of curve feature classes and layers based on the output curve data is also needed. The evaluation results showed that the tool can accurately measure the curve geometry; however, the method was unable to locate six of the 51 curves of interest. Besides this evaluation, no paper or evaluation report about this tool has been published directly by the developers. In addition to this semiautomatic approach, no literature documenting a fully automatic method was found. Therefore, CurveFinder is truly innovative and unique by offering the means to automatically obtain curve location and geometric information from GIS roadway maps.

WORKING MECHANISM OF CURVEFINDER

CurveFinder is an ArcGIS add-in tool developed by using ArcObjects, which implements an automatic algorithm for curve identification and extraction. Figure 1 illustrates the concept of CurveFinder. The original algorithm implemented in CurveFinder calculates the bear-

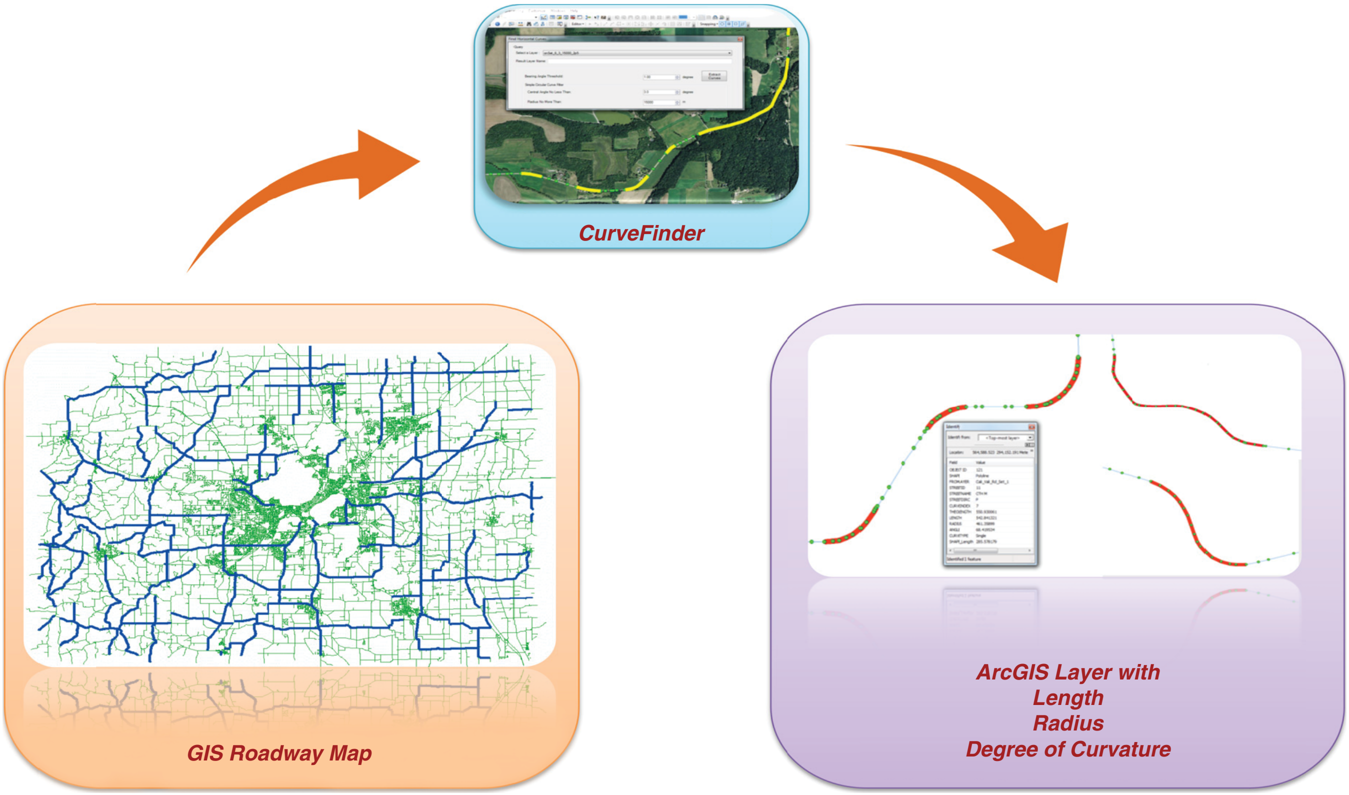


FIGURE 1 CurveFinder tool.

ing angle between consecutive vertices of the GIS roadway centerline. If the bearing angle is greater than a certain threshold, a curve begins; otherwise, a tangent section begins (*8*).

Figure 2*a* illustrates the bearing angle. CurveFinder also detects curve direction and computes curve radius, central angle, and length (Figure 2*b*) and estimates curve type. According to Figure 2*b,* the curve length, central angle, and curve radius can be computed when the coordinates of the point of curvature (PC), PC′, the point of tangency (PT), and PT′ are known from the following equations.

$$k_{\text{O-PC}} = \frac{x_{\text{PC}'} - x_{\text{PC}}}{y_{\text{PC}} - y_{\text{PC}'}} \tag{1}$$

$$b_{\text{O-PC}} = y_{\text{PC}} - x_{\text{PC}} \cdot \frac{x_{\text{PC}'} - x_{\text{PC}}}{y_{\text{PC}} - y_{\text{PC}'}} \tag{2}$$

$$k_{\text{O-PT}} = \frac{x_{\text{PT}'} - x_{\text{PT}}}{y_{\text{PT}} - y_{\text{PT}'}} \tag{3}$$

$$b_{\text{O-PT}} = y_{\text{PT}} - x_{\text{PT}} \cdot \frac{x_{\text{PT}'} - x_{\text{PT}}}{y_{\text{PT}} - y_{\text{PT}'}} \tag{4}$$

$$x_{\text{O}} = \frac{b_{\text{O-PT}} - b_{\text{O-PC}}}{k_{\text{O-PC}} - k_{\text{O-PT}}} \tag{5}$$

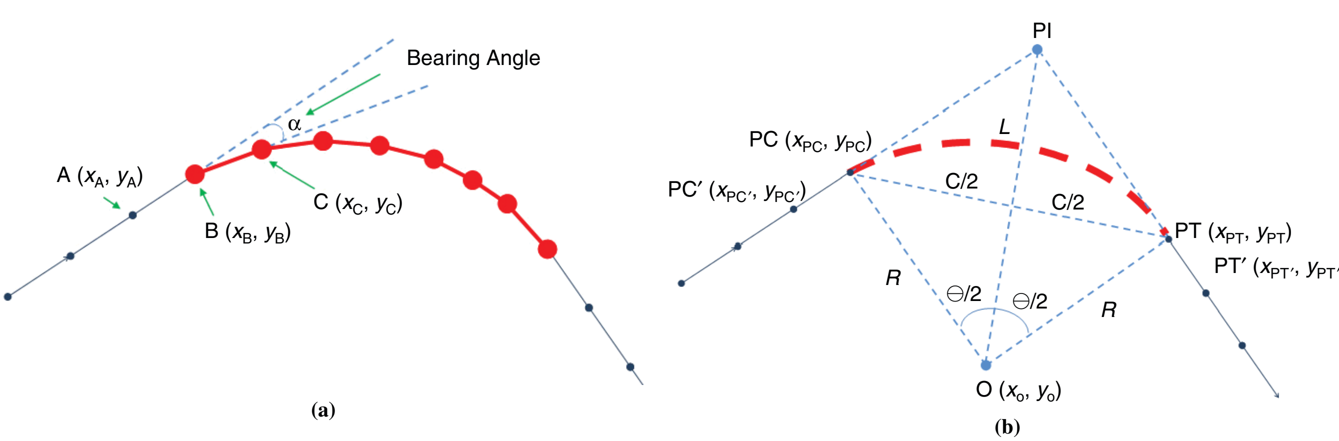


FIGURE 2 CurveFinder algorithm.

$$y_O = k_{O\text{-}PC} \cdot \frac{b_{O\text{-}PT} - b_{O\text{-}PC}}{k_{O\text{-}PC} - k_{O\text{-}PT}} + b_{O\text{-}PC} \tag{6}$$

$$R = \sqrt{(x_{PC} - x_O)^2 + (y_{PC} - y_O)^2} \tag{7}$$

$$C = \sqrt{(x_{PT} - x_{PC})^2 + (y_{PT} - y_{PC})^2} \tag{8}$$

$$\theta = 2 \times \sin^{-1}\left(\frac{C}{2R}\right) \times \frac{180}{\pi} \tag{9}$$

where

$k_{O\text{-}PC}$ = slope of line equation for line O-PC,
$b_{O\text{-}PC}$ = intercept of line equation for line O-PC,
$k_{O\text{-}PT}$ = slope of line equation for line O-PT,
$b_{O\text{-}PT}$ = intercept of line equation for line O-PT,
x_O = *x*-coordinate of curve's center point,
y_O = *y*-coordinate of curve's center point,
R = curve's radius (m),
C = length of curve's long chord (m), and
θ = curve's central angle (degrees).

Once curves are identified and information is extracted, CurveFinder generates a curve layer–shapefile that includes all identified curves along with their location and geometric information. The whole aforementioned procedure is fully automatic. An important step before running the CurveFinder algorithm is to determine the threshold of the bearing angle (as shown in Figure 2*a*). Determination of the bearing angle threshold is the calibration since CurveFinder has only one parameter to configure. The calibration requires ground-truth curve data of about 15 curves for a group of GIS roadway maps with similar vertex patterns (e.g., average distance between vertices at curves). The calibration finds the optimal bearing angle threshold that can achieve the lowest error for the roadway shapefile by comparison with the ground truth. The calibration was manual in the original CurveFinder, but automation has been partially incorporated in the current version.

INCORPORATION OF MIRE COMPATIBILITY

In the original CurveFinder algorithm, only two curve types were considered, namely, independent circular curves and compound curves (i.e., all curves except for independent circular curves). Curve geometric information was extracted for independent circular curves only. As more states adopt MIRE, incorporation of MIRE compatibility into CurveFinder becomes essential. MIRE has different definitions of curve types than the original CurveFinder. Curves are defined to be one of the following types in MIRE (*9*):

- Horizontal angle point (i.e., joining of two tangents without a horizontal curve),
- Independent horizontal curve,
- Component of compound curve (i.e., one curve in a compound curve), and
- Component of reverse curve (i.e., one curve in a reverse curve).

Figure 3 illustrates the curve types that are defined in MIRE.

MIRE has a specific subcategory for horizontal curve data, which includes the following MIRE elements (*9*):

107, Curve Identifiers and Linkage Elements,
108, Curve Feature Type,
109, Horizontal Curve Degree or Radius,
110, Horizontal Curve Length,
111, Curve Superelevation,
112, Horizontal Transition–Spiral Curve Presence,
113, Horizontal Curve Intersection–Deflection Angle, and
114, Horizontal Curve Direction.

The updated CurveFinder was designed to tentatively extract all MIRE elements from GIS roadway maps except for Element 111, Curve Superelevation, which can be obtained only from field surveys. For each curve extracted by CurveFinder, MIRE includes information on curve type, curve degree, curve radius, curve length, whether there is a transition section, the deflection angle if the curve is a horizontal angle point, and the curve direction. The attribute table of the extracted curve shapefile includes the MIRE elements' information. Table 1 gives an example of how attributes in a Curve GIS shapefile associate with the MIRE elements.

The AASHTO Green Book defines independent horizontal curves as curves separated by a tangent of at least 183 m, or 600 ft (*35*). Therefore, CurveFinder tentatively uses the AASHTO definition. If two curves are separated by a tangent of less than 183 m, these two curves are considered components of compound curves if curve directions are the same or components of reverse curves if curve directions are different. If a reverse curve and another horizontal curve are located within 183 m, both curves are considered to form

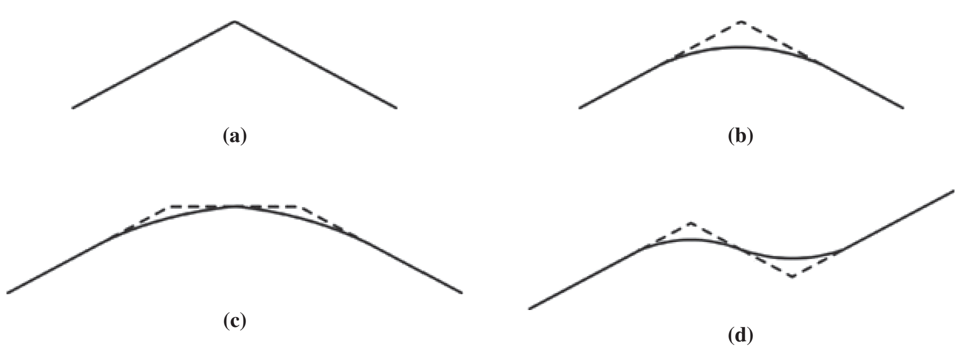


FIGURE 3 Curve types defined in MIRE (*9*): (*a*) horizontal angle point, (*b*) independent horizontal curve, (*c*) compound curve, and (*d*) reverse curve.

TABLE 1 Example of Curve Shapefile's Attributes in Association with MIRE Elements

Curve Shapefile Attribute	Associated MIRE Element	Remarks
CURVEID	107, Curve Identifiers and Linkage Elements	Unique ID of the curve
ROAD_NAME	107, Curve Identifiers and Linkage Elements	Name of the road where the curve is located
NODE_FROM	107, Curve Identifiers and Linkage Elements	Closest mile marker to the beginning of the curve
NODE_TO	107, Curve Identifiers and Linkage Elements	Closest mile marker to the ending of the curve
CURV_TYPE	108, Curve Feature Type	Horizontal angle point Independent horizontal curve Reverse curve Component of compound transition
RADIUS	109, Horizontal Curve Degree or Radius	Does not apply to horizontal angle point and transition Measured in meters
DEGREE	109, Horizontal Curve Degree or Radius	Does not apply to horizontal angle point and transition Measured in meters
CURV_LENG	110, Horizontal Curve Length	Measured in meters
HAS_TRANS	112, Horizontal Transition–Spiral Curve Presence	Transition only
INTSC_ANGLE	113, Horizontal Curve Intersection Angle	Only for horizontal angle point Measured in degrees
CURVE_DIRE	114, Horizontal Curve Direction	Left or right

a compound curve. However, according to MIRE, if two segments intersect at an angle, the two segments are classified as a horizontal angle point. CurveFinder assumes that a horizontal angle point is always independent; it is never included in a compound curve. Figure 4 shows the curve type classification algorithm implemented in the improved CurveFinder; it is based on which MIRE curve type is assigned to each identified curve.

CASE STUDIES

Case studies that use the updated CurveFinder for application of curve data extraction from GIS roadway maps are described next. Data from different states were used in the case studies. Success stories and lessons learned are discussed with a focus on application of CurveFinder on low-volume roads and the impact of the data source on curve identification accuracy.

Application of CurveFinder to Iowa Rural Road Data

Local roads in Iowa make up the majority of the rural surface transportation system, or about 90,000 mi of roads; almost 80% are unpaved. Since many rural local roads in Iowa fall into the category of low-volume roads with annual average daily traffic of fewer than 400 vehicles, applying CurveFinder to the Iowa GIS roadway data can demonstrate its applicability to extracting curve data for low-volume roads. Therefore, in this case study, rural public roadway maps for the Iowa counties of Adams and Taylor were used for curve data extraction. Figure 5 gives an overview of the identified curves from both counties.

It can be seen that all curves from the road network shown in Figure 5 are identified by CurveFinder. Figure 6 provides a more detailed view of the identified curves with different curve types. Figure 7 shows an example of the attributes of an extracted curve. Because of the lack of control curves (i.e., ground truth) for the Iowa data, the accuracy of the curve identification and data extraction could not be quantitatively evaluated. However, on the basis of a manual review of the results, all curves were completely identified and curve types were correctly classified by CurveFinder. Detection of the transition zone between a tangent and a curve section is preliminary; it currently applies only to transition zones composed of two vertices. Detection of spiral transitions that are composed of multiple vertices will be explored in future versions of CurveFinder.

Curve Identification Accuracy

In addition to the Iowa data, CurveFinder was applied to GIS data of rural roadways from other states such as Delaware, Wisconsin, and New Jersey. Since control curve data were available for Monroe County in Wisconsin and Morris County in New Jersey, curve results from these two counties were used to validate CurveFinder's accuracy in curve identification. Specifically, the curve identification accuracy was evaluated by two performance measures: identification rate (IR) and false identification rate (FIR).

The evaluation was conducted by comparing the identified curves with the ground-truth control curves. If there is no overlapping portion between a ground-truth curve and any identified curve, the curve is considered 100% missed. Otherwise, the ratio between the overlapped length and the ground-truth curve length is calculated and recorded as the identified portion per curve (IPC). The IR is the ratio of the number of curves that are not 100% missed and the number of ground-truth curves. The FIR is the ratio of the number of tangent sections identified as curves and the number of ground-truth curves. The higher the IR and the lower the FIR, the more accurate the curve identification is. The following two equations define how IR and FIR are computed:

$$\text{IR} = \frac{m}{n} \tag{10}$$

$$\text{FIR} = \frac{l}{n} \tag{11}$$

FIGURE 4 Algorithm for MIRE curve type classification (Y = yes; N = no).

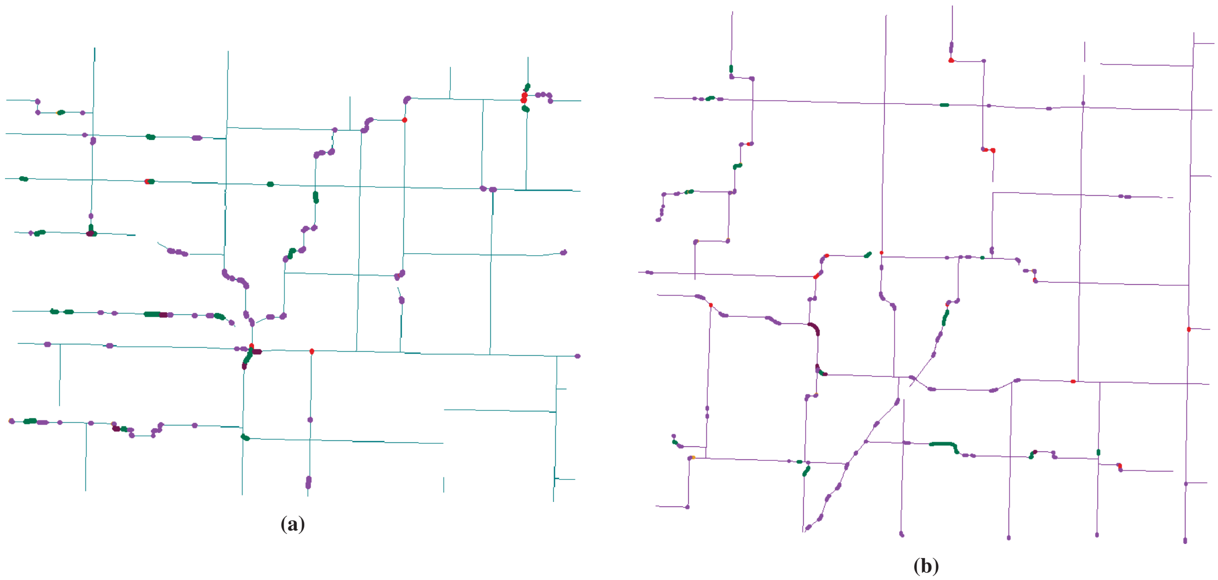


FIGURE 5 Identified curves in Iowa: (*a*) Adams County and (*b*) Taylor County.

FIGURE 6 Examples of identified curves of different types: (*a*) independent horizontal curves and reverse curves, (*b*) compound curve with transition section, and (*c*) horizontal angle point.

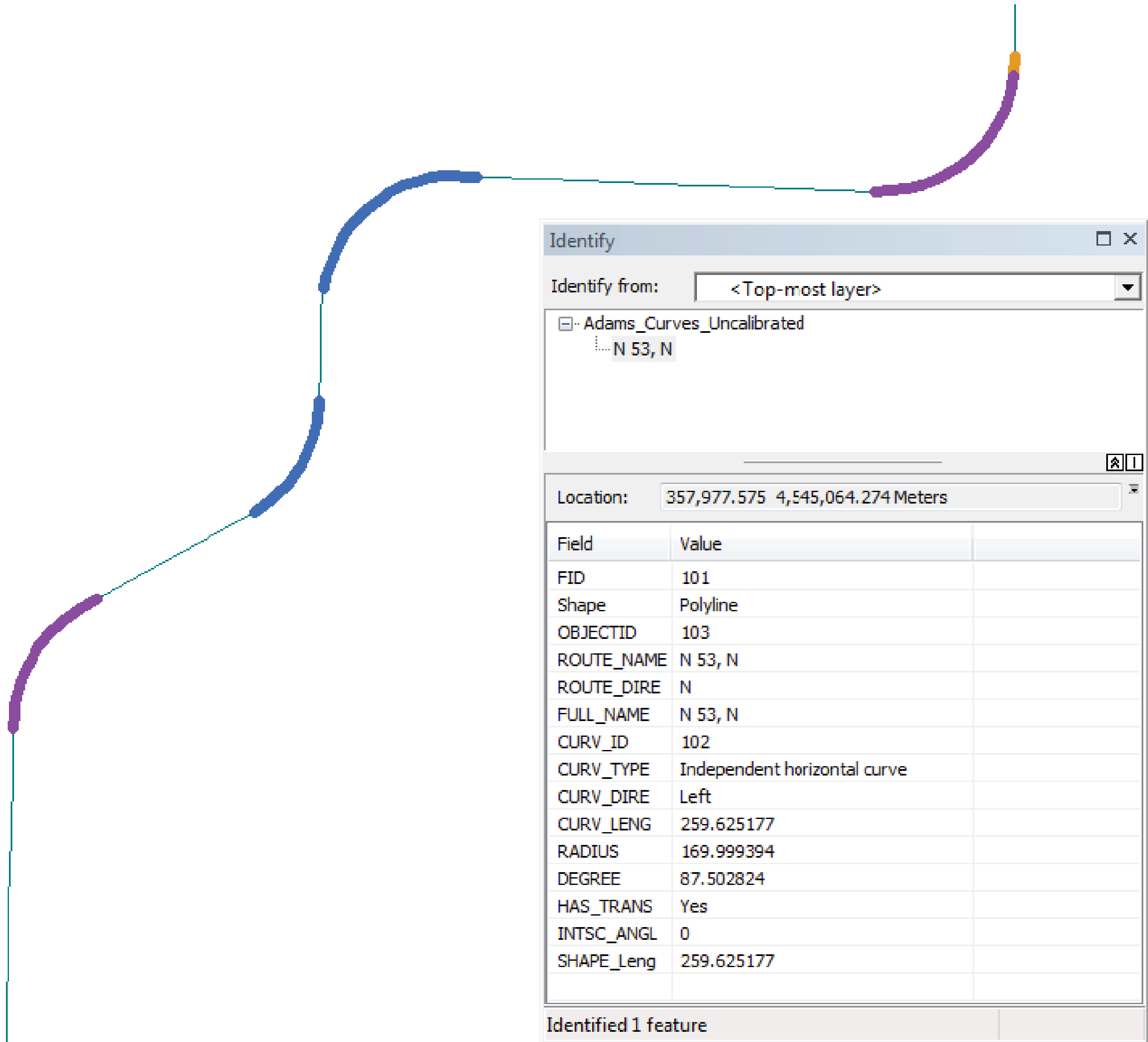


FIGURE 7 Example of attributes of extracted curve.

where

IR = identification rate (%),
FIR = false identification rate,
n = number of ground-truth curves,
m = number of ground-truth curves that are not 100% missed, and
l = number of tangent sections identified as curves.

Table 2 summarizes the results for the evaluation of curve identification accuracy for both data sets. The results reveal that none of the control curves were missed by CurveFinder, whereas there is a small number of false identifications made by mistakenly recognizing tangent sections as curves.

However, another performance measure, the distribution of identified portions per curve (DIPC), is introduced to evaluate how completely the curves are identified. DIPC is a distribution of the completeness of curve identification into 12 completeness levels: 0% identified, 1% to 9% identified, 10% to 19% identified, . . . , 90% to 99% identified, and 100% identified. Figure 8, *a* and *b,* illustrates the DIPCs for the Monroe County data set and the Morris County data set, respectively.

TABLE 2 Evaluation Results for Curve Identification Accuracy

Data Set	Number of Ground-Truth Curves	IR (%)	FIR
Monroe County, Wisconsin	40	100	0.06
Morris County, New Jersey	48	100	0.10

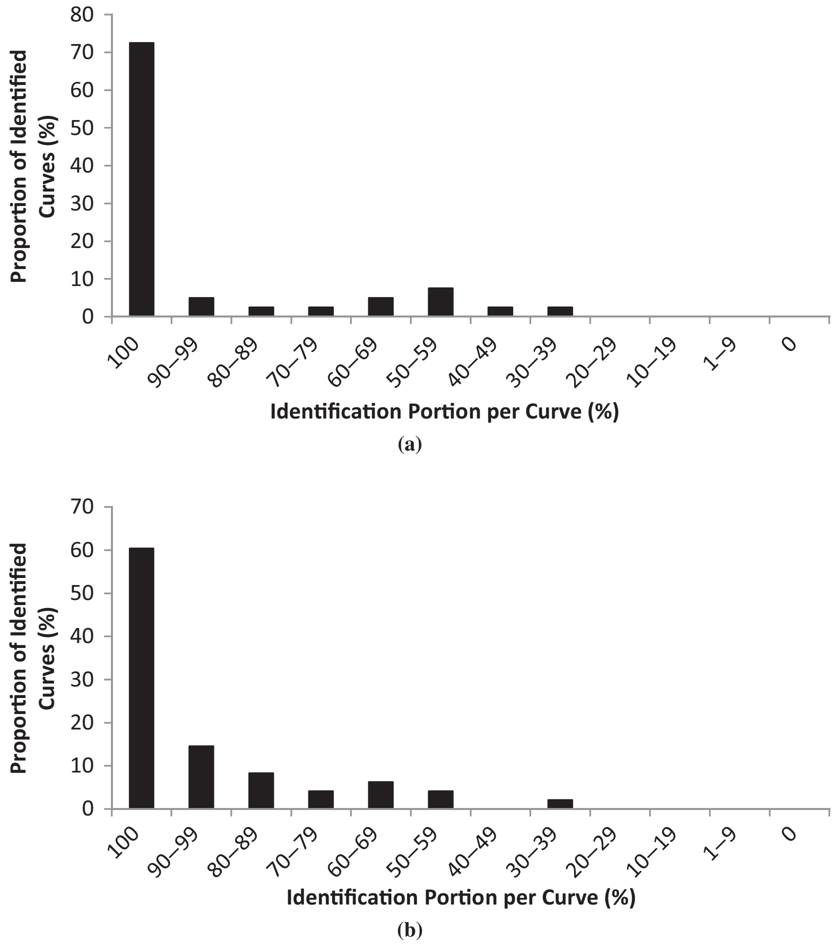


FIGURE 8 DIPC data sets: (*a*) Monroe County, Wisconsin, and (*b*) Morris County, New Jersey.

In Figure 8, the DIPCs for both data sets show a similar pattern in which the majority of the curves are 100% identified. Identification completeness of the remaining curves is almost evenly distributed within the range between 30% to 39% and 90% to 99%. None of the curves is completely missed.

Impact of Low-Quality GIS Roadway Data

During the investigation of the curve identification errors, special attention was paid to analyzing the reasons for the missing portions in the identified curves as well as the false identification of tangent sections as curves. Low-quality GIS maps as representations of roadway segments are a major cause of curve identification errors. Two typical scenarios are involved with the low-quality data:

- Scenario 1 is the roadway centerline transverse error, namely, deviation of the GIS centerline from the actual alignment. This source data error may be due to the human error in the map-digitizing phase. An example of Scenario 1 is shown in Figure 9*a.*
- Scenario 2 is the low-vertex resolution of the GIS roadway centerline to describe the actual alignment of the roadway. Figure 9*b* shows an example.

Both low-quality scenarios can be common in the GIS shapefiles for low-volume roads, since digitizing errors are likely to occur when unpaved roads are digitized. In particular, Scenario 1 is more likely to occur on low-volume roads, whereas the chance for Scenario 2 to occur is somewhat equal on low-volume roads and other roads. To ensure the accuracy of curve data extraction for low-volume roads, solutions must be investigated to improve the quality of the low-quality segments. Potential solutions include use of either GPS data or roadway satellite images to improve the vertex resolution and accuracy.

GPS data provide densely spaced vertices on both tangents and curves. These vertices can be simply converted to GIS roadway centerlines; this conversion can substantially improve the data quality. However, this method requires additional data collection effort to obtain the GPS data. Figure 10 illustrates an example of using the GPS data to improve a low-quality Wisconsin data set.

Image processing based on satellite roadway imagery is another alternative to improve the source GIS data quality. The feasibility of this alternative has been preliminarily explored by the authors. Figure 11 shows a tentative procedure for obtaining accurate and continuous centerline information by means of automated processing of satellite images. The process includes the following steps:

- Given a color satellite image of X pixels in width and Y pixels in height, convert it into a grayscale image (denoted as I_orig) of the same size (e.g., original.jpg). Then each of the X*Y pixels has an intensity value that is between 0 and 255.

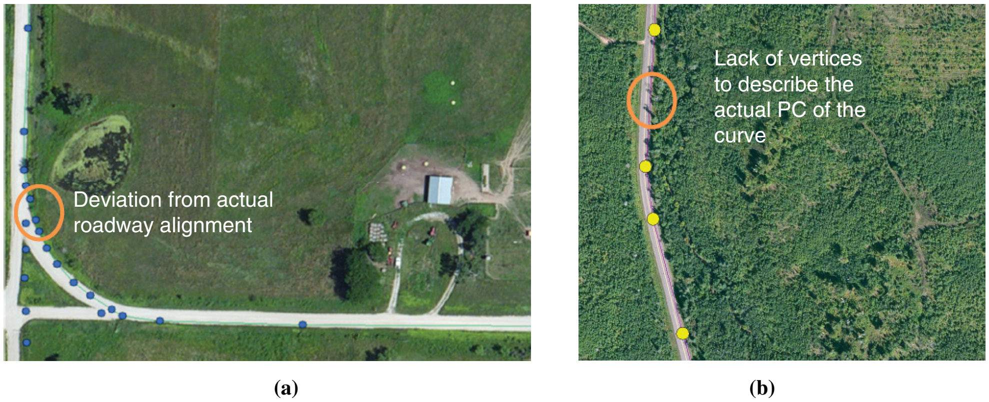
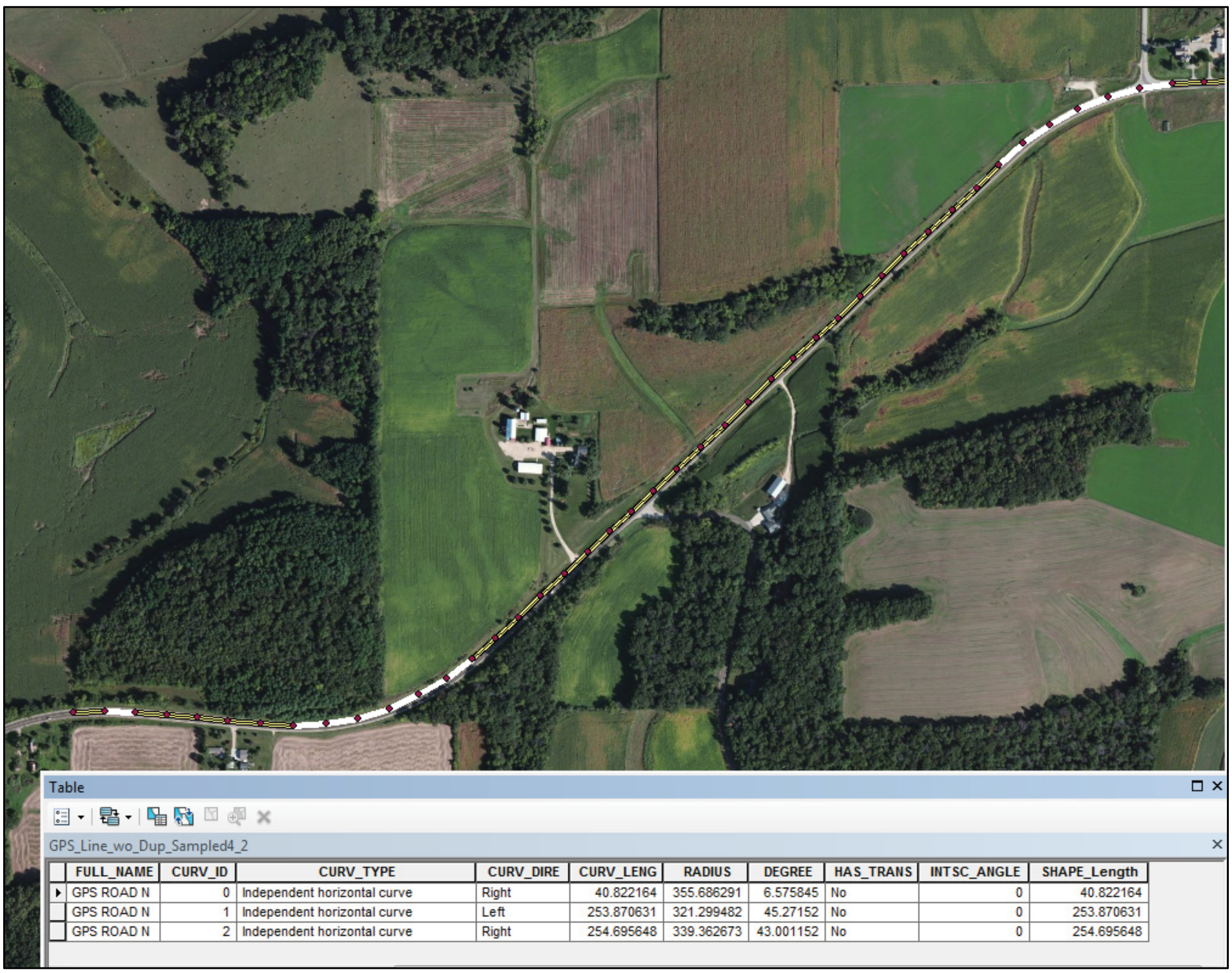
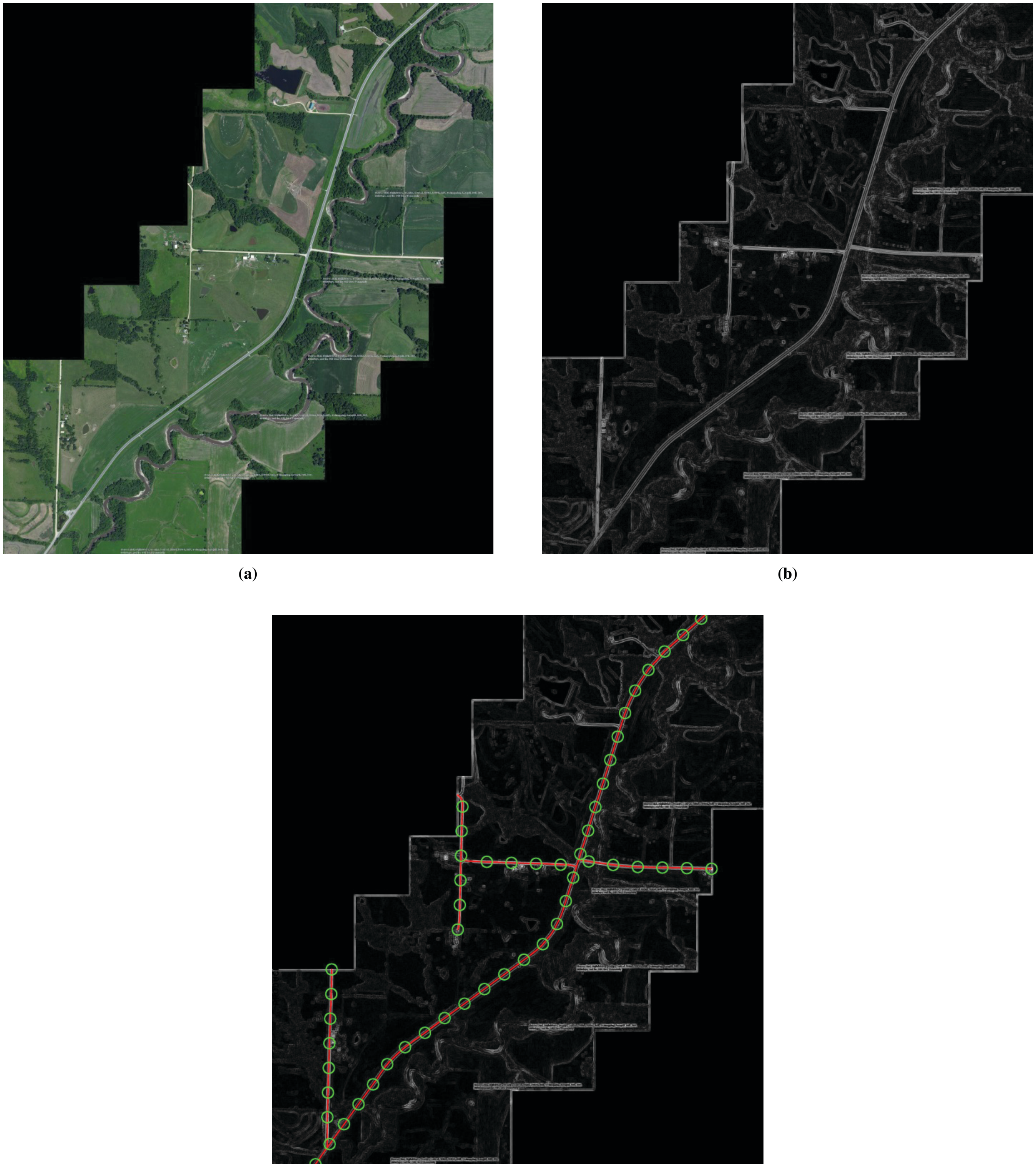


FIGURE 9 Typical scenarios of low-quality GIS source data: (*a*) Scenario 1 and (*b*) Scenario 2.



FULL_NAME	CURV_ID	CURV_TYPE	CURV_DIRE	CURV_LENG	RADIUS	DEGREE	HAS_TRANS	INTSC_ANGLE	SHAPE_Length
GPS ROAD N	0	Independent horizontal curve	Right	40.822164	355.686291	6.575845	No	0	40.822164
GPS ROAD N	1	Independent horizontal curve	Left	253.870631	321.299482	45.27152	No	0	253.870631
GPS ROAD N	2	Independent horizontal curve	Right	254.695648	339.362673	43.001152	No	0	254.695648

FIGURE 10 Improved data quality by using GPS data.



(a) (b) (c)

FIGURE 11 Process for improving data quality by using satellite image processing: (*a*) original image, (*b*) extracted roadway centerline, and (*c*) reconstruction of GIS centerline vertices on basis of extracted roadway centerline.

- Next set up a range [minimum (min.), maximum (max.)], which means that the average width in pixels of the targeted highway is no less than 2 ∗ min. and no more than 2 ∗ max.
- For each value *r* in [min., max.] (with a 1-pixel interval), calculate an image whose value at pixel (*i, j*) is the standard deviation of the pixel values within a circle centered at (*i, j*) with a radius of *r* in *I*_orig. Denote each of these images as *I_r*.
- Calculate the final image by setting the value of pixel (*i, j*) as the standard deviation of the pixel values at (*i, j*) of all the intermediate images *I_r*. In addition, scale all values so that the maximum is 255.
- Reconstruct the GIS roadway centerline vertices based on the extracted centerline.

CONCLUSIONS

The case studies on Iowa, New Jersey, and Wisconsin GIS roadway maps fully demonstrate the feasibility of using CurveFinder to extract horizontal curve data on low-volume roads. The 100% identification rates and low FIRs prove the accuracy of CurveFinder. In addition, the updated CurveFinder with MIRE compatibility has successfully and correctly classified different curve types defined by MIRE despite the few errors that still exist in the extracted curve data. The reasons for errors were identified to be two typical scenarios of low-quality GIS roadway segments, which are fixable by using automated image-processing methods.

In summary, the automated curve data extraction method incorporated in the updated CurveFinder is promisingly beneficial to improving the safety of horizontal curves on low-volume roads. Its usefulness is reflected by the following aspects:

- It substantially reduces the cost for collecting curve data for curve safety evaluation; this aspect makes it feasible to cover all roads including all rural, low-volume roads;
- It makes it possible to integrate MIRE curve elements with all curve data on rural, low-volume roads; this capability has never been realized in the United States before; and
- The complete MIRE curve data set for U.S. low-volume roads that results from CurveFinder can greatly facilitate statewide or nationwide safety evaluation of all low-volume roads; this ability has never been feasible because of the lack of curve data on low-volume roads.

Future research will focus on further exploring and developing automated methods for improving the low-quality GIS data by using image processing of satellite images. The method illustrated in Figure 11 is one of the image-processing methods, which is based on centerline extraction. Methods based on curb line extraction will be explored in future research, and automated approaches for constructing centerline vertices based on the extracted curb lines will be explored. Curve extraction accuracy for both centerline- and curb line–based methods will be compared.

ACKNOWLEDGMENTS

The authors thank John Corbin and Rebecca Szymkowski of the Wisconsin Department of Transportation for their support in this research. Appreciation also goes to Michael Pawlovich of the Iowa Department of Transportation and Zach Hans of Iowa State University for provision of the GIS data and comments. Thanks also go to Yan Zhang of the University of Wisconsin, Madison, for her assistance in data processing.

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The Committee for the 11th International Conference on Low-Volume Roads peer-reviewed this paper.