Horizontal Curve Identification and Evaluation

MTC
MIDWEST TRANSPORTATION CONSORTIUM

Final Report
September 2012

ctre
Center for Transportation Research and Education

IOWA STATE UNIVERSITY
Institute for Transportation

Sponsored by
Iowa Department of Transportation
Midwest Transportation Consortium
(InTrans Project 10-369)

About the MTC

The Midwest Transportation Consortium (MTC) is a Tier 1 University Transportation Center (UTC) that includes Iowa State University, the University of Iowa, and the University of Northern Iowa. The mission of the UTC program is to advance U.S. technology and expertise in the many disciplines comprising transportation through the mechanisms of education, research, and technology transfer at university-based centers of excellence. Iowa State University, through its Institute for Transportation (InTrans), is the MTC's lead institution.

About CTRE

The mission of the Center for Transportation Research and Education (CTRE) at Iowa State University is to develop and implement innovative methods, materials, and technologies for improving transportation efficiency, safety, and reliability while improving the learning environment of students, faculty, and staff in transportation-related fields.

The preparation of this report was financed in part through funds provided by the Iowa Department of Transportation through its "Second Revised Agreement for the Management of Research Conducted by Iowa State University for the Iowa Department of Transportation" and its amendments.

Technical Report Documentation Page

1. Report No. InTrans Project 10-369	**2. Government Accession No.**	**3. Recipient's Catalog No.**	
4. Title and Subtitle Horizontal Curve Identification and Evaluation		**5. Report Date** September 2012	
		6. Performing Organization Code	
7. Author(s) Zachary Hans, Reginald Souleyrette, and Corey Bogenreif		**8. Performing Organization Report No.** InTrans Project 10-369	
9. Performing Organization Name and Address Center for Transportation Research and Education Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664		**10. Work Unit No. (TRAIS)**	
		11. Contract or Grant No.	
12. Sponsoring Organization Name and Address Iowa Department of Transportation, Office of Traffic and Safety, 800 Lincoln Way, Ames, Iowa 50010 Midwest Transportation Consortium, Institute for Transportation, 2711 S. Loop Drive, Suite 4700, Ames, Iowa 50010-8664		**13. Type of Report and Period Covered** Final Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes Visit www.intrans.iastate.edu for color PDF files of this and other research reports.			

16. Abstract

Horizontal curves are over-represented, high-frequency, high-severity crash locations. Significant opportunities exist to mitigate these crashes through relatively low-cost safety improvements such as paved shoulders, rumble strips/stripes, and improved signing and delineation.

However, the presence of horizontal curvature is not captured as part of the Iowa crash report and the Iowa Department of Transportation (DOT)-maintained database of public roadways does not identify the locations of horizontal curvature. Therefore, it is currently difficult to identify the locations of curves systematically, and particularly high-crash curves and the characteristics of these curves.

The goal of this project was to expand the Iowa Department of Transportation (DOT) effort to systematically identify high-crash and potentially-problematic horizontal curves.

The primary objective of this project was to refine the previously-developed, preliminary, horizontal-curve database, allowing specific curve parameters to be extracted and evaluated system wide. This refinement facilitates identification of not only high-crash locations but candidate sites for low-cost safety improvements.

Secondary objectives include updating the high-crash curve list, evaluating the accuracy of the geometric parameter estimates and testing the sensitivity of safety performance to errors in curve parameters.

17. Key Words crash estimation—crash mitigation—curve length—curve evaluation—curve radius—high-crash curves—horizontal curve measurement—Iowa DOT curve database		**18. Distribution Statement** No restrictions.	
19. Security Classification (of this report) Unclassified.	**20. Security Classification (of this page)** Unclassified.	**21. No. of Pages** 31	**22. Price** NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

HORIZONTAL CURVE IDENTIFICATION AND EVALUATION

Final Report
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Sponsored by
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and the Midwest Transportation Consortium
(InTrans Project 10-369)

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ACKNOWLEDGMENTS

The authors would like to thank the Iowa Department of Transportation (DOT) Office of Traffic and Safety (TAS) and the Midwest Transportation Consortium for sponsoring this research.

The authors would also like to thank the technical advisory committee on this project: Jeremey Vortherms and Michael Pawlovich (Iowa DOT TAS) and Michael Clement (Iowa DOT Transportation Data/TransData).

PROJECT SUMMARY

Introduction

Horizontal curves are over-represented, high-frequency, high-severity crash locations. Significant opportunities exist to mitigate these crashes through relatively low-cost safety improvements such as paved shoulders, rumble strips/stripes, and improved signing and delineation.

However, the presence of horizontal curvature is not captured as part of the Iowa crash report and the Iowa Department of Transportation (DOT)-maintained database of public roadways does not identify the locations of horizontal curvature. Therefore, it is currently difficult to identify the locations of curves systematically, and particularly high-crash curves and the characteristics of these curves.

Problem Statement

This project builds on the results of a previous CTRE project that identified locations of possible horizontal curvature, including high-crash sites, on high-speed, paved, rural roads. This project expands on the Iowa DOT effort to identify high-crash and potentially-problem horizontal curves, systematically, by developing a method for identifying curve locations and producing a statewide curve database. With the existence of such a database, candidate sites for low-cost safety improvements may be identified based on historic safety performance.

Objectives

The primary objective of this project was to refine the preliminary horizontal curve database that was developed as part of the CTRE Geospatial Safety Analysis for Highway Curves project, allowing the researchers to extract and evaluate specific curve parameters system wide.

This refinement facilitates identification of not only high-crash locations but candidate sites for low-cost safety improvements. The database would facilitate both development and maintenance of high-crash horizontal curve lists and identification of candidate sites for low-cost safety improvements, based on historic safety performance of curves possessing similar characteristics.

Secondary objectives include updating the high-crash curve list, evaluating the accuracy of the geometric parameter estimates and testing the sensitivity of safety performance to errors in curve parameters.

LITERATURE REVIEW

Horizontal Curve Identification

Post-processed global positioning system (GPS) data are often used to collect road and curve geometry. A 2009 study used GPS to collect data to compute curve radius and deflection angle data (Pratt et al. 2009). The researchers used a digital ball-bank indicator to measure superelevation and compiled curve data using Texas Roadway Analysis and Measurement Software (TRAMS).

The researchers collected data at 25 foot increments and calculated the curve radii. They then post-processed these data to calculate a recommended advisory speed. The researchers found this method provided accurate and precise measurements of curve radii, but that it required time- and labor-intensive data collection processes.

Imran et al. (2006) also used a GPS-based method that included GIS applications to collect and analyze horizontal curve geometry data. The researchers collected field data at 0.1 second intervals using differential GPS. Their results showed that GPS could quickly, accurately, and inexpensively produce horizontal alignment data. Their study used software developed specifically for an agency roadway database.

Sanders (2007) developed a methodology to collect statewide data on horizontal curves using GPS-derived centerlines. These researchers collected GPS data for more than 79,000 centerline miles of roadway in Kentucky, and they developed an automated process using GIS to extract curve data and to determine the roadway geometry by utilizing a GPS centerline base map that was referenced by mile point. The researchers found this GPS/GIS method provided significantly more accurate curve data than previous field-collected processes.

While these GPS- and/or GIS-based studies provided promising results, it is possible that the GPS data available to many agencies may not support the reviewed methodologies without significant modification. This condition may also be exacerbated with large databases.

Horizontal Curve Safety

Bonneson et al. (2007) developed a relationship between injury and fatal crash frequency and curve design using data for 1,757 curves in Texas. Their study found the crash rate increases sharply for curves with radii less than 1,000 feet and that crashes on longer curves are less likely to result in injuries or fatalities. However, their study did not address possible errors in the curve parameter estimation process or how these errors may have an impact on the computation of crash risk.

Pitale et al. (2009) suggested a similar relationship between crash rate and curve radii. However, their crash rates for 1,500 feet curves were twice as high as those for 2,000 feet radius curves.

Their crash rates for 1,000 feet curves were five times higher, and their crash rates for 500 feet curves, were 11 times higher.

In addition to or in the absence of quality crash data, the researchers on this project found the following factors might be indicators of safety performance at curves: curve radii, traffic volume, presence of visual traps, intersections, and proximity to other high-priority curves. While Pitale's study considered additional factors, it included only a limited number of sample curves, and didn't investigate the potential effects of estimation/measurement errors on safety performance prediction.

To estimate safety performance on horizontal curves, the American Association of State Highway and Transportation Officials (AASHTO) Highway Safety Manual (HSM) presents safety performance functions (SPFs). The results are adapted to local conditions using crash modification factors (CMFs), as shown for horizontal curves, in Equation 1 (AASHTO 2010).

$$N_{spf\ rs} = AADT \times L \times 365 \times 10^{-6}\, e^{(-0.312)} \tag{1}$$

where:

$N_{spf\ rs}$ = predicted total crash frequency for roadway segment base conditions

AADT = annual average daily traffic volume (vehicles per day) of horizontal curve segment

L = horizontal curve length (miles)

e = the base of natural logarithms

The CMFs developed for different roadway attributes help assess the relative safety performance of a particular road section. For horizontal curves, the CMF was developed to represent how the crash experience of tangent and horizontal curve segments differ, and Equation 2 shows the CMF for the safety effect of horizontal curves.

$$CMF_{curves} = \frac{(1.55 \times L_c) + \left(\frac{80.2}{R}\right) - (0.012 \times S)}{(1.55 \times L_c)} \tag{2}$$

where:

L_c = horizontal curve length (miles)

R = horizontal curve radius (ft)

S = presence of spiral transition: 1 if yes; 0 if no

This CMF and several others related to the roadway are applied to the SPF base prediction model, as shown in Equation 3, to estimate the safety performance of specific geometric features (AASHTO 2010).

$$N_{predicted\ rs} = N_{spf\ rs} \times C_r \times (CMF_{1r} \times CMF_{2r} \times \ldots \times CMF_{12r}) \quad (3)$$

where:

$N_{predicted\ rs}$ = predicted average crash frequency for a rural horizontal curve

$N_{spf\ rs}$ = predicted average crash frequency for base conditions

C_r = 1.0 for base condition

$CMF_{1r} \ldots CMF_{12r}$ = crash modification factors for roadway attribute

For this study, the equations were used to test the sensitivity of safety performance to errors in curve parameters, as derived from the proposed method. The proposed procedure combines elements from previous work to identify and evaluate horizontal curves for large roadway databases.

METHODOLOGY

Background

In a previous research project funded by the Iowa DOT, Geospatial Safety Analysis for Highway Curves project, several horizontal curve identification techniques were evaluated for a rural, paved high speed centerline network of approximately 27,000 miles. These techniques included use of both existing cartography and GPS-based coordinate traces.

A New Hampshire Department of Transportation (NHDOT) developed GIS-based algorithm was first assessed in conjunction with the Iowa DOT's Geographic Information Management System (GIMS) roadway database. The algorithm was developed to identify horizontal curves, with a radius of 2,500 feet or less, using existing centerline cartography. Upon review, the Iowa DOT's existing centerline database did not facilitate use of this algorithm, partially due to network segmentation.

GPS-based coordinate data, provided at 10 meter intervals was then evaluated. During 2004 and 2005, pavement distress data were collected on all primary and secondary rural, paved roads in the state as part of the Iowa Pavement Management Program (IPMP). As a result, a comprehensive network of coordinate data at equal intervals was available for the roads of interest, in contrast to existing cartography for which vertices were irregularly spaced.

The Imran et al. (2006) algorithm, which employed non-linear regression to fit circular curves to GPS coordinate data, was then investigated. Consistent and comprehensive application of the algorithm on a large-scale network was unsuccessful.

Since route names and chainage (mileage) values accompanied all IPMP coordinate data, GPS coordinates were sequenced, and polylines systematically created within GIS. The NHDOT algorithm was then re-evaluated using this polyline network as input. However, the vertex spacing appeared too dense for the algorithm, with many points identified as on a curve and most curves being short in length. This likely reflected the impact of lateral spatial inaccuracies (or changes) over very short longitudinal distances.

Given the results of the prior efforts, a new approach was developed to utilize the GPS-based coordinate data. The polylines created from the IPMP GPS data were simplified systematically within ArcGIS, using the Douglas-Peucker algorithm, to yield similar polylines with unnecessary vertices eliminated. This reduced the number of vertices from approximately 3.6 million to 44,000 (non-endpoints). These remaining vertices were extracted into an independent data set, which generally represented locations of changes in roadway alignment, with denser spacing along curves. Isolated vertices did exist along long tangents and locations of GPS inaccuracies.

Since the vertices of the simplified polylines were located generally on or near curves, all original GPS data within a specified spatial proximity of these vertices were selected. This was done in an attempt to capture all original data points potentially located on a curve. However, other non-curve related data points could also exist within this proximity.

Consecutive, continuous sets of GPS points were grouped and assigned unique site identifiers. Polylines representing these unique sites were created and possible curve and chord lengths were computed within GIS. The identified sited did not necessarily represent true circular curves, which was apparent through visual inspection. While some sites represented single circular curves accurately (from point of curvature to point of tangency), other sites represented reverse (or multiple) curves, partial curves, combination curves-tangents, and tangents alone.

Three primary techniques were employed to assess horizontal curvature: circular regression, Newton iteration of the modified circular curve equation, and a comparison of the results of the aforementioned techniques. A Microsoft Excel spreadsheet was developed to automate the following:

- Compute the radius of curvature from the grouped GPS coordinate pairs as well as the corresponding R^2 value (square of the correlation coefficient) through nonlinear regression
- Compute the radius of curvature and degree of curvature based on the possible curve and chord lengths through Newton iteration
- Compare the two resulting radius values

Ultimately, a combination of the values computed through the above techniques, as well as the length of the site, were used to assess whether a site was a tangent, circular curve, or "other". In general, tangent sites were identified consistently, as were the "other" sites. Identifying true circular curves proved more challenging.

Many sites returning high R^2 values and comparable radius values from both techniques often included points along the adjacent tangents. Several procedures were evaluated to systematically refine the site definition process—not relying simply on the spatial proximity of source coordinate data to simplified vertices. The success of these procedures was limited.

If only approximate locations of horizontal curves or curvilinear roadway sections were of interest, such as for high-crash location identification, the aforementioned technique is suitable. However, based on the techniques evaluated, manual refinement of horizontal curves was the most appropriate and reliable, especially if curve parameters such as radius were desired. This refinement process is outlined in the following section.

Curve Identification

As discussed in the previous section, GPS-based polylines, continuous simplified polylines, and simplified polyline vertices were created for all roads along which pavement condition data were collected, including urban streets. Given the source data were developed for presentation of pavement condition data over 10 meter intervals, each record possessed beginning and ending

GPS coordinate values. A data set of simple lines (with shape points only at the termini) was also created to represent the 10 m segments.

Given the size of these data sets, particularly the original GPS-based data, the network was parsed into adjacent county pairs to better facilitate visual inspection. These data were supplemented with the comprehensive statewide road database to provide additional context during the review/refinement process.

The roads of interest, initially all paved, two-lane roads in Iowa with a speed limit of at least 45 mph, were highlighted, helping to ensure that the appropriate roads received attention.

Figure presents a sample review interface, including inset images, from within an ESRI ArcGIS environment. The black points are the vertices remaining after polyline simplification; the green lines are the roadways of interest; and, the red lines/points are the original GPS data.

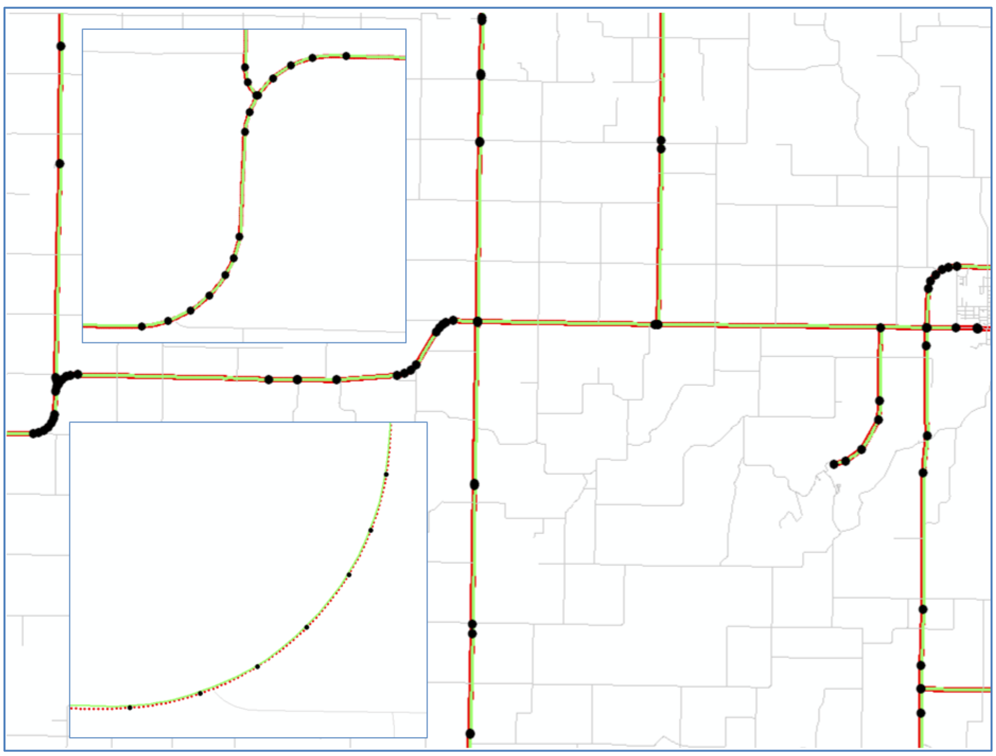

Figure 1. Review interface

Reviewers were tasked with systematically scanning the vertex locations at a standard map scale and assessing whether the vertices represented a location of curvature, route termini, or GPS spatial variations (usually on long tangents). Reviewers then magnified the locations of curvature at a standard map scale and, to the best of their abilities, selected the original 10 meter segments representing the horizontal curve from point of curvature (PC) to point of tangency (PT). This was accomplished through either heads-up digitizing of the entering/existing tangents or visual approximation of the transition locations. If present, spiral transitions were assumed part of the simple curve. Spiral transitions were generally not discernible through visual inspection. The 10 meter segments were used, instead of the discreet points, because they were found to better convey curve continuity and, in a later step, simplified curve-length computation. Geographic coordinate values were also re-projected to a planar (Cartesian) coordinate system to facilitate future chord length calculations.

A single attribute in the underlying GIS database was updated to reflect that a 10 meter segment was located on a curve and the type of curve, i.e. 1) simple horizontal curve, 2) simple compound curve, or 3) reverse curve (or sequential curves with separating tangents of negligible lengths). The vast majority of the 10 meter segments were reported as simple horizontal curves.

Data Processing

After each adjacent county pair was inspected, the underlying data were saved and converted to Microsoft Excel format. Within Excel, several steps were employed to automatically assign unique identifiers to each record reported as "on curve." Given the number of data sets reviewed, it was imperative for future integration that the identifier was unique among all data sets, not only the current one being evaluated. This was accomplished by concatenating multiple attributes provided in the original GPS data set.

The data set was then screened to eliminate all records not located on a horizontal curve. The total length of each curve, and total records associated with the curve, was computed and assigned to each record comprising the curve. The total number of records associated with the curve was an important metric because the nonlinear (circular) regression macro used in later steps required at least five records.

A new, limited data set containing only the original unique record identifiers and the new curve identifier, curve length, and record count was extracted for use in the creation of GIS-based polyline representations of each curve. This data set included all possible curve types identified previously.

Finally, the comprehensive set of simple horizontal curves, possessing at least five records, or 50 meters in length, was imported into the curve parameter computation spreadsheet.

Parameter Calculations

The curve parameter computation spreadsheet employed a Microsoft Excel add-on, Matrix and Linear Algebra for Excel v.23. The spreadsheet was developed to automatically adjust to the number of records representing each unique horizontal curve. This was necessary for regression analysis as well as computation of the chord length.

Once the appropriate data were imported, circular regression was initiated. Several values were output as part of this process, including the fitted circle's center coordinates, radius value, and coefficient of determination (R^2).

Simultaneously, the chord length was computed and, with the curve length, used as input for the second radius value calculation. Newton iteration was used in this process (referred to as the long chord method in the remainder of this report). The equation typically closed quickly and, once closed, a curve radius and degree of curvature was calculated. The concept is shown in Figure 2.

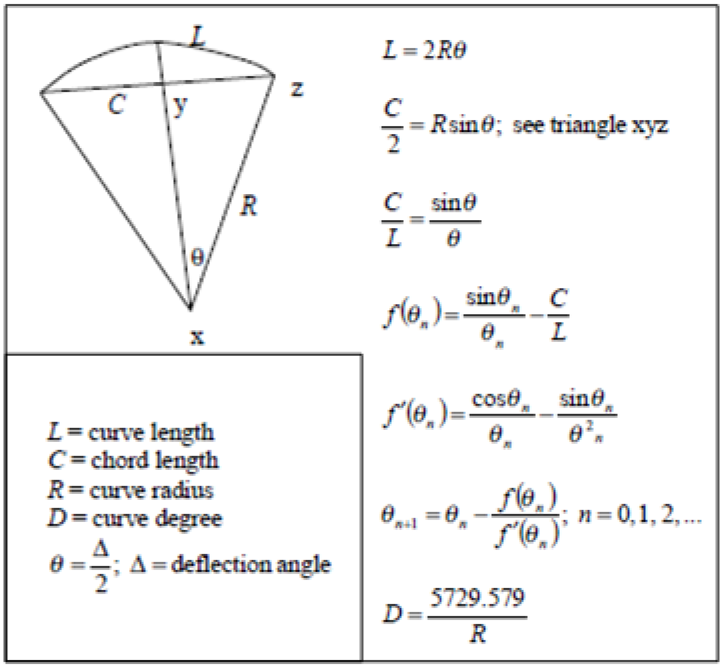

Figure 2. Newton iteration of curve radius

The output of this process was a curve identifier, radius value based on circular regression, radius value based on curve and chord lengths, absolute difference in radius values, percentage difference in radius values, curve length, chord length, coefficient of determination (R^2) from regression, and degree of curvature. These attributes were later associated with the GIS-based representations of the curves.

Spatial Data Set Assimilation

Within GIS, three data sets were merged: 1) original 10 m line segment GIS coverage, 2) tabular data set containing the original unique record identifiers and the new curve identifier, curve length, and record count, and 3) tabular data set containing the derived curve parameters.

The original 10 meter line segments were dissolved into continuous polylines based on the unique curve identifier. Several attribute fields from the original pavement distress data set were retained in the dissolve process, such as road name, county, city, and direction and lane of data collection, to provide additional depth to the curve database. The computed curve length, number of original records comprising the curve, all curve parameters and reviewers initials were also provided as attributes of the new curve database.

The aforementioned database only possessed radius values for simple curves at least 50 meters long. All shorter, simple curves were then selected and extracted from this database. The coordinate termini for each curve were derived for this subset, and the chord length computed based on the Euclidian distance between the termini.

Using this chord length, and previously-computed curve length, Newton iteration was employed to compute the curve radius. The resulting radius value, chord length, and degree of curvature were integrated into the comprehensive database. No regression-based radius value was populated for these curves.

Finally, the GPS data set was compared to the Iowa DOT’s most recent database of high-speed, paved, two-lane roadways. This was initiated to identify any locations that GPS traces did not exist, and where curves of interest still needed to be identified.

Through visual inspection, horizontal curves on these roadways were identified, and the associated Iowa DOT cartography clipped and extracted. Each site was assigned a unique identifier, the curve and chord lengths derived, radius computed through Newton iteration, and resulting curve integrated into the comprehensive database.

Quality Control and Assurance

Visual Inspection

Upon completion of the initial horizontal curve database, quality control and assurance was conducted. Curves were reviewed for consistency, continuity, completeness, redundancy, and accuracy. Several issues became apparent during review:

- A tangent was inadvertently coded as a curve
- Multiple GPS traces existed for an entire curve, yielding multiple representations of the same curve
- Multiple GPS traces existed for portions of a curve, yielding multiple, partial representations of the same curve
- A single curve was represented by two or more partial curves, with the partial representations sharing an endpoint
- A single curve was represented by two or more partial curves, with a discontinuity (gap) existing between the partial representations

Many of the aforementioned issues resulted from the source GPS coverage extent and underlying attribution. For example, if a route was driven multiple times, it could exist in multiple data sets and, therefore, was reviewed and captured multiple times. In addition, if a route name changed along a curve, or a chainage value was missing in the data set, the location would not possess a continuous polyline through its extent.

Each of the issues was addressed in a different manner. Specifically, the geographic representations of curves were deleted, merged, extended/trimmed, or extended/trimmed and merged. The curve parameters for all adjusted curves were then recomputed through previously-discussed techniques, and the comprehensive curve database adjusted.

Additional quality control entailed review of the estimated curve radius values. Locations possessing unrealistic, large-magnitude radius values were reviewed, and the curve either removed from the database, if appropriate, or the radius value(s) were set to null. Setting radius value(s) to null indicated that the site appeared to be a horizontal curve, but there was little confidence in the values reported. A limited number of these sites existed.

Measurements of Geometric Parameter Estimation Errors

Errors in the curve length and radius estimation methods were also identified and their effects quantified. As-built horizontal curve data were compared to the estimated curve data for a sampling of curves to recognize errors in the identification process. The Iowa DOT's Electronic Records Management System (ERMS) was used to identify as-built curve data from the historic roadway plans for primary road projects in Iowa. Secondary (county) road data, which were not available in ERMS, were not included in this evaluation.

Available curve data were extracted manually for a set of 15 counties throughout Iowa, representing a topographically-diverse sample dispersed geographically throughout the state. A total of 435 horizontal curves located on paved, two-lane, rural roadways with a speed limit of 45 mph or greater were identified.

After completing the extraction process, as-built curve data were compared with the estimated curve data to validate estimate precision. A common metric for spatial comparison, percent root mean squared error (RMSE), was used to measure the effectiveness of the curve identification process. RMSE was used to measure the deviation between the actual geometric feature value (length, radius) and the estimated geometric feature values. A large RMSE percent indicated a large deviation between the actual and estimated values.

Curve Length Estimation

As discussed previously, curve length was manually estimated during the curve identification process using the point of curvature (PC) and point of tangency (PT) location estimates. Figure 3 illustrates the distribution for the actual horizontal curve length versus the estimated horizontal curve length.

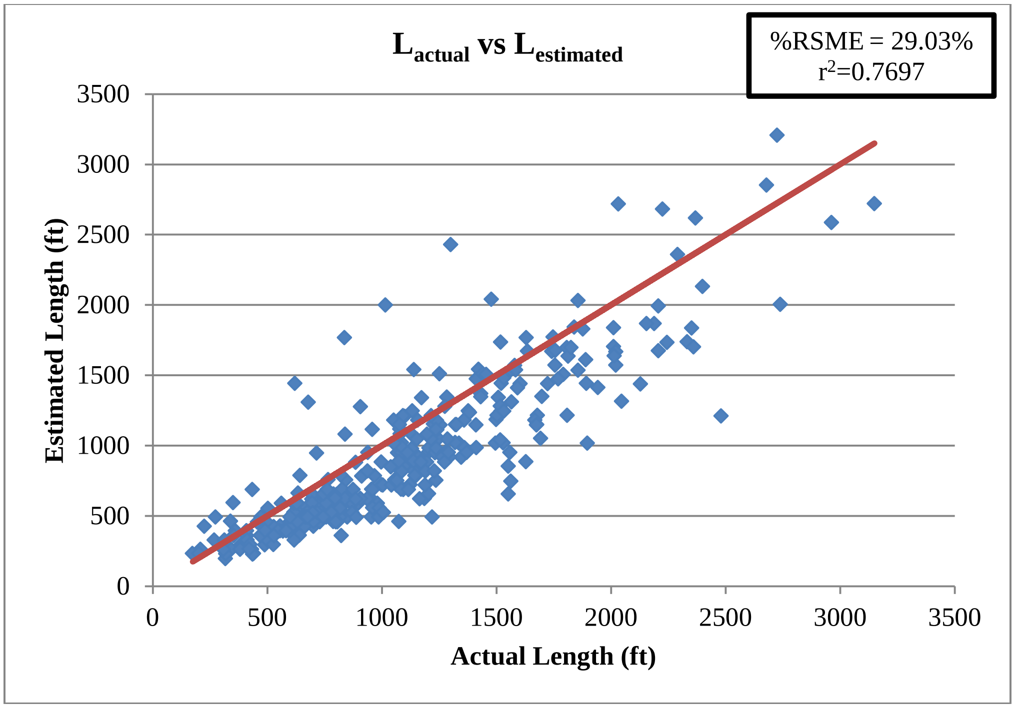

Figure 3. Actual versus estimated curve length

The RMSE of the curve length was found to be 29.0 percent. Given the manner in which curve lengths were estimated, it was difficult to identify the exact locations of curve PC and PT, explaining this length error.

Curve Radius Estimation

Two radius estimation methods were used for comparisons: circular regression and long chord.

Figure 4 illustrates the distribution of the actual, as-built curve radius versus the calculated curve radius using the circular regression method, $R_{regression}$.

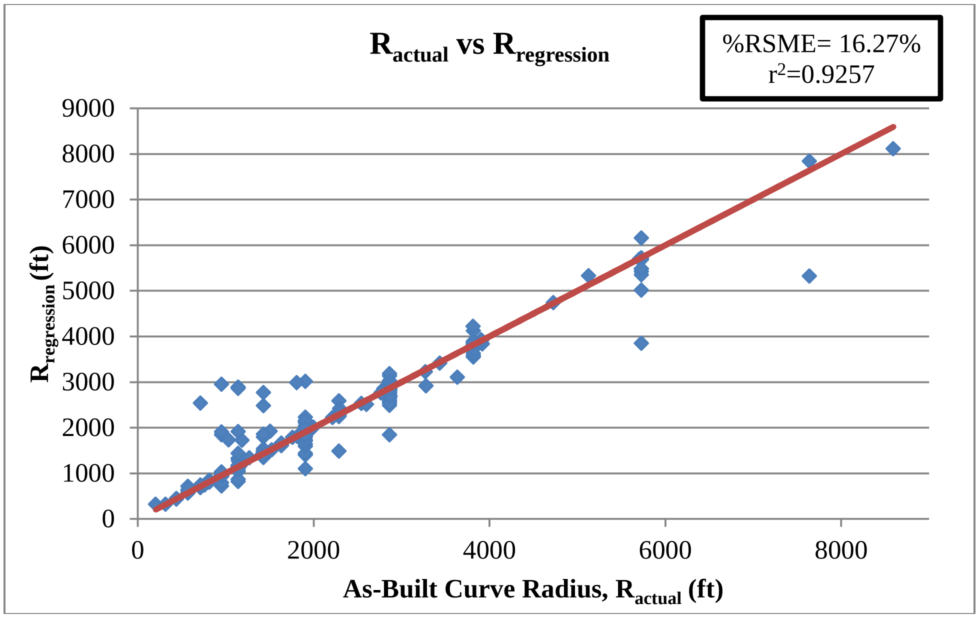

Figure 4. Actual versus circular regression estimated radius

The circular regression method was relatively precise with an RMSE of 16.3 percent and a coefficient of determination of 0.93. On average, the $R_{regression}$ was very precise with 94 percent of all curves having as-built data at an $R_{regression}$ error less than 30 percent. Moreover, more than 75 percent of all curves with as-built data have an $R_{regression}$ error equal to or less than five percent.

In contrast, Figure 5 illustrates the distribution of the actual, as-built curve radius versus the calculated curve radius using the long chord method.

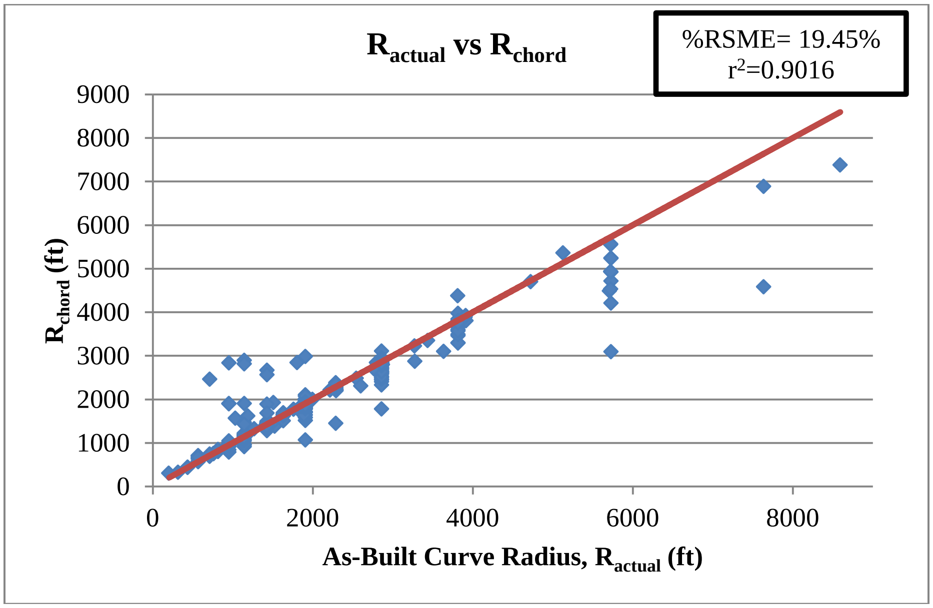

Figure 5. Actual versus long chord estimated curve radius

The long chord method was just slightly less precise than the circular regression method. The RMSE was 19.5 percent and the coefficient of determination was 0.90 using the long chord method. Analysis showed 95 percent of all estimated R_{chord} values with an error less than 30 percent and 68 percent of the values with an error less than five percent.

In general, the two radius estimation methods yielded very similar results, with the circular regression method only slightly more precise. Furthermore, a difference-of-means test comparing the two datasets showed no significant difference between the two sample sets. Therefore, no radius estimation measure could be declared more precise statistically.

Crash Assignment

In support of additional project tasks and creation of a five percent horizontal curve list for the Iowa DOT, crashes occurring from 2001 to 2009 were assigned to each horizontal curve.

All crashes within 100 meter of a horizontal curve were then extracted from the statewide data set. The initial 100 meter tolerance was employed to liberally account for possible changes in underlying Iowa DOT cartography (to which crashes are geocoded) over the analysis period, differences in spatial accuracy between the new curve database and Iowa DOT cartography, and possible spatial inaccuracies in crash geocoding. This tolerance yielded a database of manageable size. The majority of the crashes located at greater spatial distances were later eliminated from consideration through visual inspection.

Supplemental attributes were appended to the preliminary crash database to facilitate analysis. Traditionally, the Iowa DOT does not include animal or intersection crashes in horizontal curve analysis. Therefore, attributes were added to reflect if a crash involved an animal or located at an intersection.

Two animal crash-related attributes were added—one based solely on a collision with an animal as the first harmful event of a crash, which is more conservative than the Iowa DOT's derived "animal" major cause, and a second which represented the DOT's major cause definition.

Intersection crashes were based on the reported road type. A secondary "failure to yield" attribute was added to convey crashes with characteristics consistent with intersection crashes, e.g., ran stop sign, failure to yield from stop sign, but the road type was not reported as an intersection.

The total number of crashes attributed to each curve was computed, and visual inspection of sites ranked them based on this value. In other words, review began with sites with the most crashes. The two primary objectives of this review were to identify crashes of interest (limit the database to only the appropriate crashes) and conduct additional quality control and assurance of the curve database.

Crashes identified as not being located on, or reasonably proximate to, a curve were recorded for removal from the data set. This required inclusion of several versions of cartography for frames of reference and reviewer judgment. Because the state of Iowa's crash database does not contain a horizontal curve component, the location of the crash with respect to a curve, crash contributing circumstances, and crash sequence of events were taken into consideration.

Through the review process, curves were reported as reviewed (including their associated crashes) or possessing an issue requiring attention or adjustment. Curves with issues similar to those discussed previously in this report were addressed in a consistent manner, and the curve database was updated accordingly. Ultimately, all curves with at least preliminary crash data were reviewed.

Curves were also updated with the predominant unique identifier (MSLINK) from the 2008 Iowa DOT geographic information management system (GIMS) roadway database. By establishing this relationship, all roadway characteristics maintained in the GIMS database could be associated with the curve, such as shoulder type and width, surface type, lane width, speed limit, and traffic volume (AADT).

Crash Summary for Curves

The total frequency of non-animal and non-intersection crashes, by severity, for the 2001 through 2009 analysis period was summarized for each curve. In support of the Iowa DOT's five percent (most-severe needs) high crash horizontal curve list (which is accessible at www.iowadot.gov/crashanalysis/fivepercent/fivepercentneeds.htm), the total number of possible additional animal crashes (based on the Iowa DOT's major cause definition) and possible additional intersection crashes were also summarized for all curves with at least seven crashes—115 total curves. Location information, including county, route, literal description, and Google map link, was also provided for these sites.

SAFETY PERFORMANCE SENSITIVITY

A sensitivity analysis was conducted to quantify the effect of errors in the curve radius estimation. Assuming all other roadway attributes were constant and no spiral transition, the expected safety performance of horizontal curves with different radii and length values was estimated using HSM Equations 1, 2, and 3 (in the Literature Review section of this report) and the actual safety performance of these curves was compared to the estimates.

Sensitivity to Curve Radius Errors

Figures 6, 7, and 8 illustrate the change in crash frequency as errors in the estimated radius values increase for different curve lengths (500 ft, 1,500 ft, and 3,000 ft, respectively). Each figure depicts only errors in the radius estimation assuming the length is estimated correctly.

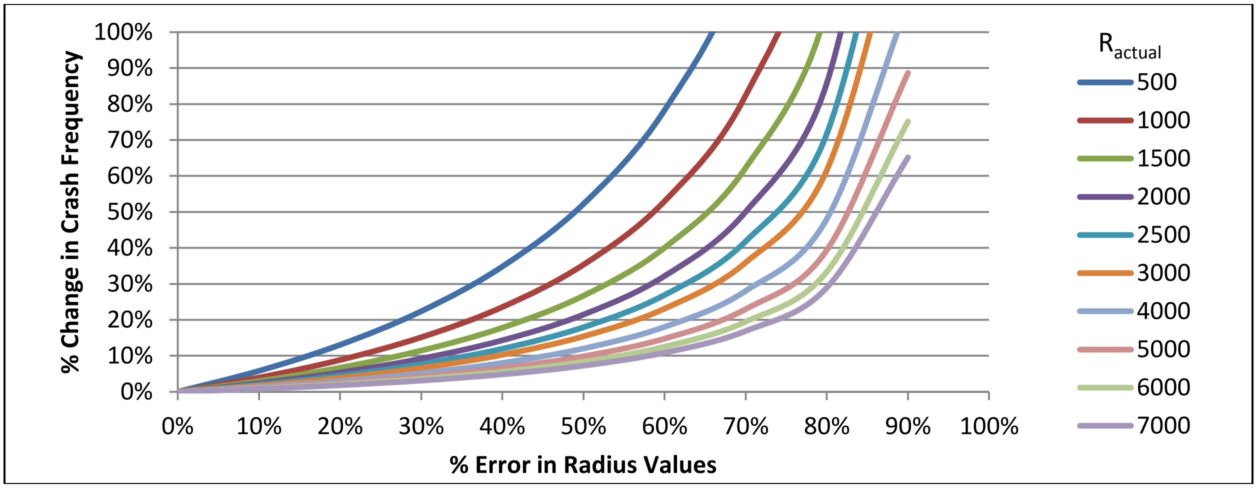

Figure 6. Safety performance sensitivity to radius estimate errors at length = 500 ft

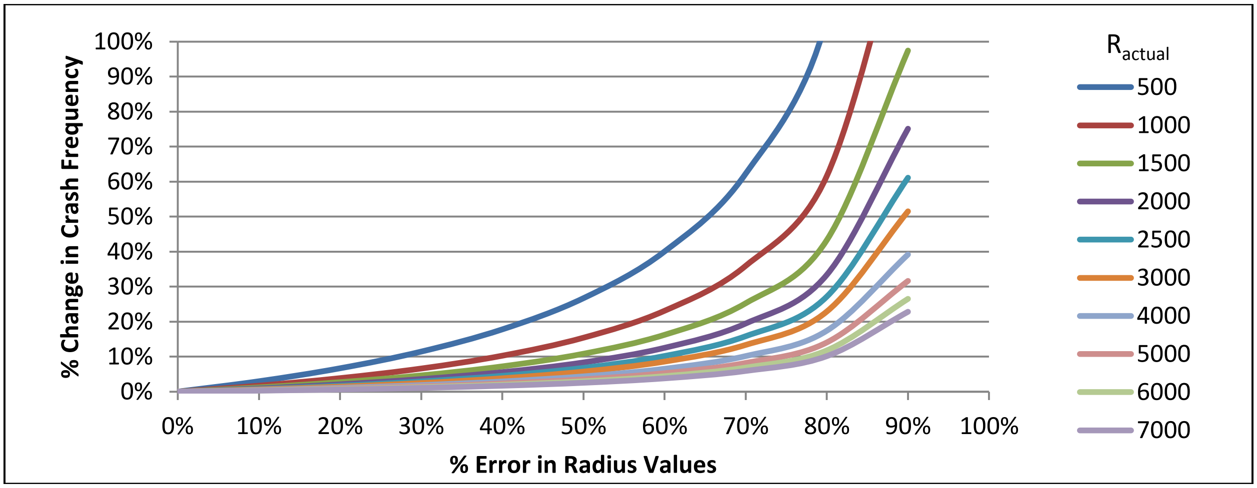

Figure 7. Safety performance sensitivity to radius estimate errors at length = 1,500 ft

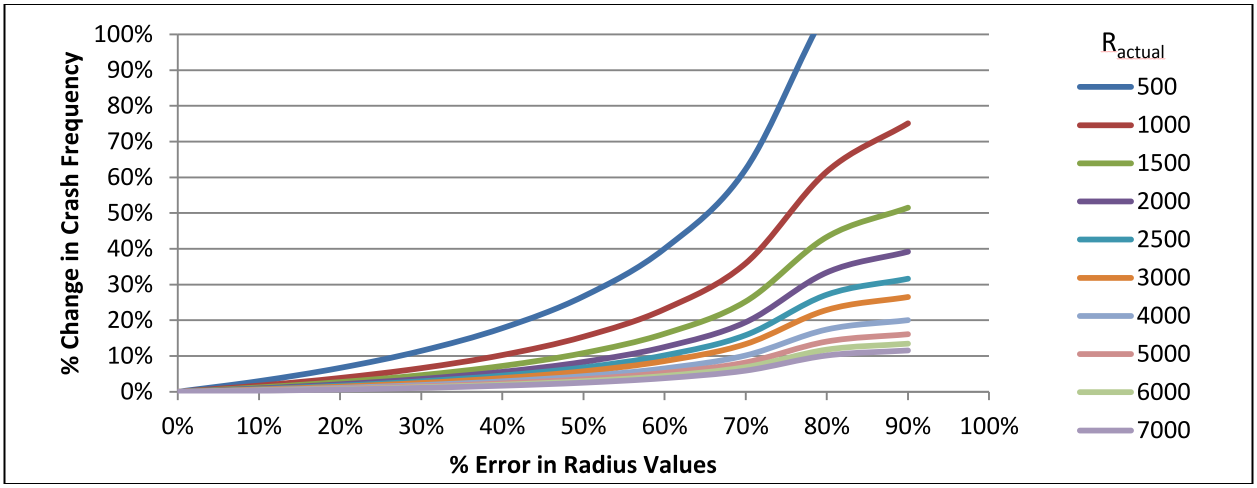

Figure 8. Safety performance sensitivity to radius estimate errors at length = 3,000 ft

Table 1 summarizes safety performance sensitivity to errors in radius estimates at the different curve lengths (500 ft, 1,500 ft, and 3,000 ft) as illustrated in Figures 6, 7, and 8 for a 1,500 ft curve radius.

Table 1. Sensitivity comparison for different curve lengths at radius = 1,500 ft

		Change in Crash Frequency (%)		
Curve Length		500 ft	1,500 ft	3,000 ft
Error in Radius (%)	0	0.0	0.0	0.0
	10	3.0	1.2	0.6
	20	6.7	2.7	1.4
	30	11.4	4.6	2.5
	40	17.8	7.2	3.8
	50	26.7	10.8	5.7
	60	40.1	16.2	8.6
	70	62.3	25.3	13.4
	80	106.8	43.3	22.9
	90	240.3	97.4	51.5

As Table 1 shows, as curve length increases, the expected change in crash frequency due to radius errors decreases. For example, a difference on a 500 ft, 1,500 ft radius curve between the actual and estimated radii of 60 percent results in a change in crash frequency of about 40 percent. Whereas, a difference on a 3,000 ft, 1,500 ft radius curve of 60 percent results in a difference of less than nine percent.

Likewise, the analysis also confirmed, as the actual radius decreases, safety performance sensitivity increases.

Sensitivity to Curve Length Errors

Figures 9, 10, and 11 illustrate the change in crash frequency plotted for percent length errors for three different radius values (500 ft, 1,500 ft, and 3,000 ft, respectively). Each figure depicts only length estimation errors, assuming the radius is estimated correctly.

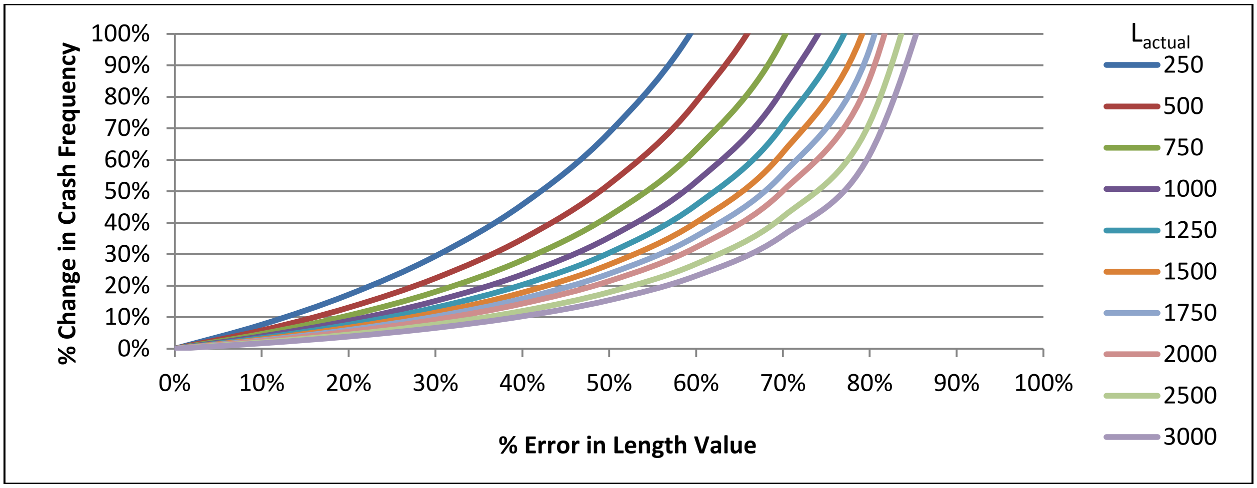

Figure 9. Safety performance sensitivity to length estimate errors at radius = 500 ft

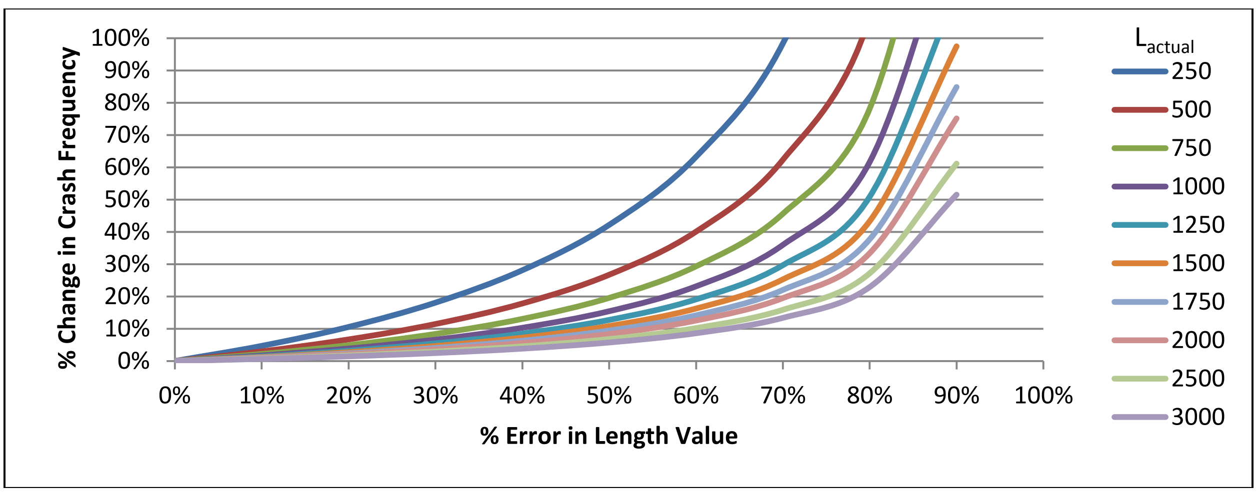

Figure 10. Safety performance sensitivity to length estimate errors at radius = 1,500 ft

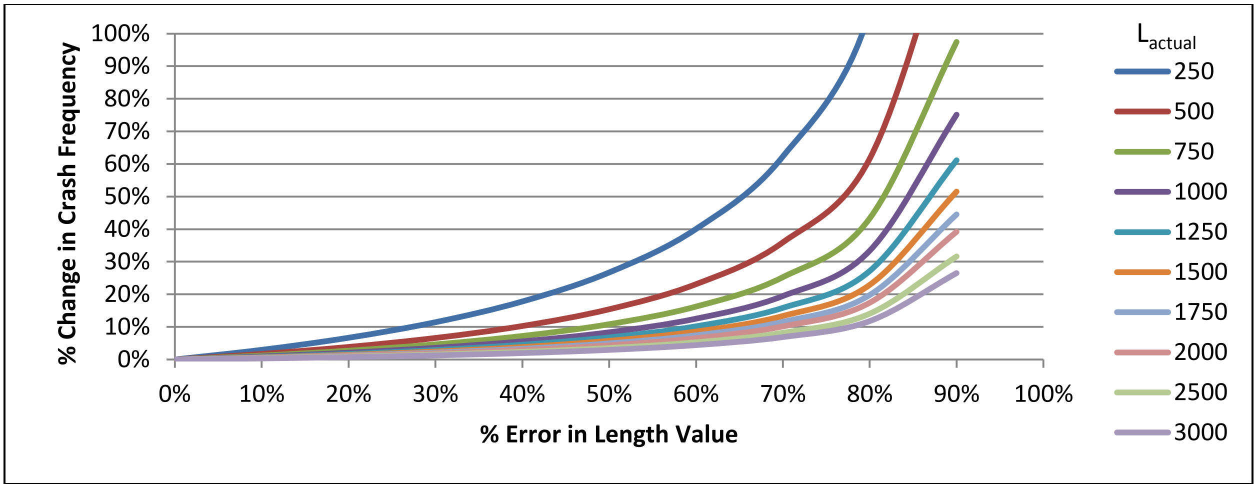

Figure 11. Safety performance sensitivity to length estimate errors at radius = 3,000 ft

Results for length estimate errors were similar to those for radius estimate errors. As the actual length decreases, the change in crash frequency increases. Table 2 summarizes the safety performance sensitivity to errors in length estimates at the different curve radii (500 ft, 1,500 ft, and 3,000 ft) as shown in Figures 9, 10, and 11, respectively, at a curve length of 2,000 ft.

Table 2. Sensitivity comparison for different curve radii at length = 2,000 ft

		Change in Crash Frequency (%)		
Curve Radius		**500 ft**	**1,500 ft**	**3,000 ft**
Error in Radius (%)	**0**	0.0	0.0	0.0
	10	2.4	0.9	0.5
	20	5.4	2.1	1.1
	30	9.2	3.6	1.9
	40	14.3	5.6	2.9
	50	21.5	8.3	4.4
	60	32.2	12.5	6.5
	70	50.1	19.5	10.2
	80	85.8	33.4	17.4
	90	193.1	75.1	39.2

Effect of Errors Due to Both Radius and Length

The figures show only the effect of estimation errors in the radius or length, assuming the other is estimated correctly. However, the analysis confirmed the geometric parameter estimation results in both length and radius errors. See Figures 12 and 13 for charts showing the compounding effect of length and radius errors, respectively.

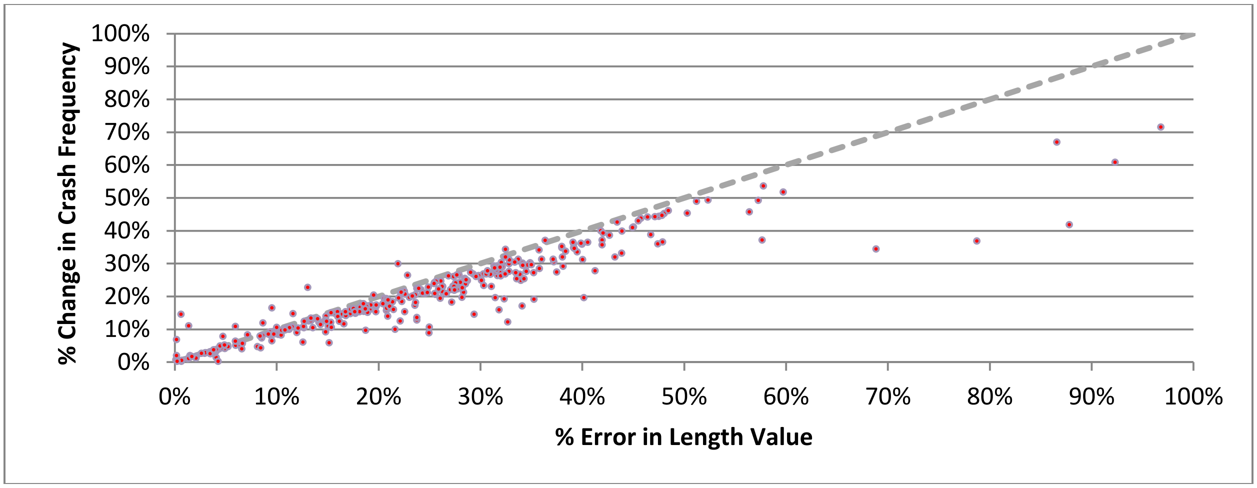

Figure 12. Crash frequency percent change versus length estimation error

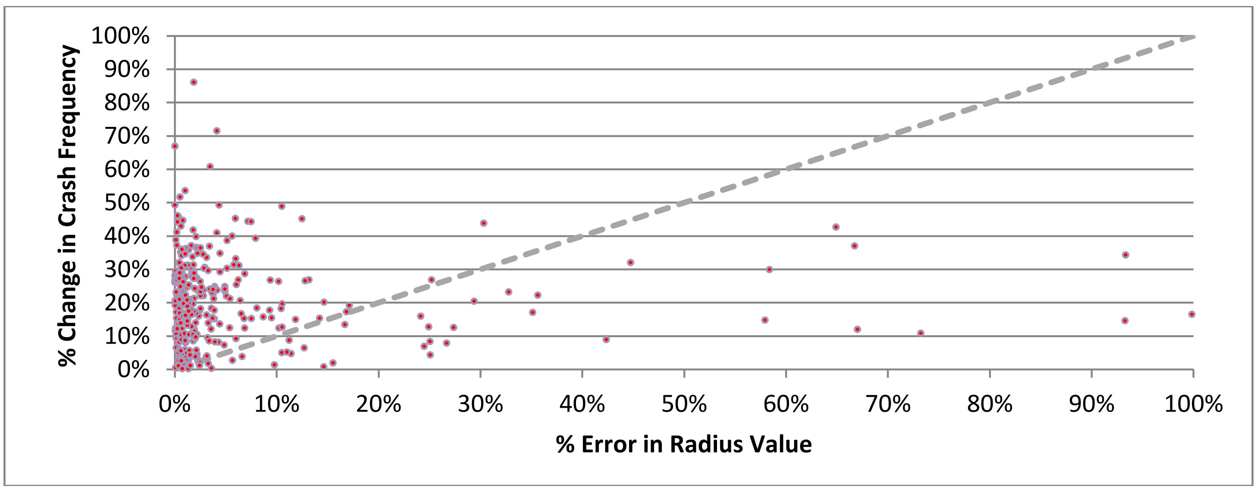

Figure 13. Crash frequency percent change versus radius estimation error

Figure 12 shows, when plotted against the percent error in length, the expected change in safety performance is nearly proportional (so, a 10 percent error in estimating length yields an expected change in crash frequency of about 10 percent). On the other hand, safety performance is very sensitive to small errors when plotted against the percent error in radius,.

Figures 12 and 13 show how curve length has a much larger effect on safety performance than curve radius using the HSM method. This study found, while radius has an effect on safety performance, its magnitude depends largely on curve length.

CONCLUSIONS

Identification and precise estimation of curve geometry is an important step in understanding and analyzing safety performance of horizontal curves. This report presents a method to identify curves and measure safety-related parameters using GPS, GIS, circular regression, chord equations, line simplification, and the HSM safety performance functions.

The horizontal curve identification method was determined to be efficient for identifying possible locations of curvature on the road network. The method can be used by agencies with GIS software and road centerline topology.

The parameter estimation method should be improved before direct use in predicting safety performance of horizontal curves.

Safety performance is sensitive to errors associated with estimating both curve length and radius. As curve radius and length decrease, the effect of estimation errors on safety performance increases.

Curve length has a greater impact on safety performance than curve radius using CMFs from the HSM. Furthermore, the magnitude of impact that radius has on curve safety performance depends largely on the curve length. However, as tangent sections near curve sections also contribute to crash risk, the prediction errors for curves in isolation may be reduced by considering both tangent and curve sections as part of a continuous route, corridor, or network.

The estimated parameters from this method should not be used to create a crash prediction model for isolated curves. However, the curve identification component remains useful in developing high-crash location lists and for implementing low-cost curve measures, such as rumble strips, warning signs, and chevrons, as the HSM-calculated effectiveness of these measures is not dependent on curve parameters.

The researchers do not recommend using this method for higher-cost strategies, such as curve flattening. (For higher-cost countermeasures, extensive and accurate planimetric data should be used in engineering analysis.)

Location errors for both crashes and roadway alignment can have a combined effect on curve safety performance estimation. Although quantifying these errors could help provide more-effective safety investments, combined effects were not addressed in this project and therefore warrant further investigation.

The work presented in this report forms an important basis for further research on improvements to the methodology.

REFERENCES

American Association of State Highway and Transportation Officials (AASHTO). 2010. *Highway Safety Manual*. Volume 2. Part C—Predictive Method. Chapter 10—Predictive Method for Rural Two-Lane, Two-Way Roads. Volume 3. Part D—Introduction and Applications Guidance. Chapter 13—Roadway Segments, 13.6 Crash Effects of Alignment Segments. pp. 10-3, 10-15, 13-27. Equations 10-2, 10-6, and 13-5 (1-3 in this report): ©2010 by the American Association of State Highway and Transportation Officials.

Bonneson, J., M. Pratt, J. Miles, and P. Carlson. October 2007. *Development of Guidelines for Establishing Effective Curve Advisory Speeds*. College Station, Texas: Texas Transportation Institute. Texas A&M University System. Report No. FHWA/TX-07/0-5439-1.

Imran, M., Y. Hassan, and D. Patterson. 2006. GPS–GIS-Based Procedure for Tracking Vehicle Path on Horizontal Alignments. *Computer-Aided Civil and Infrastructure Engineering*. 21(5):383-94.

Pitale, Jaswandi T., Craig Shankwitz, Howard Preston, and Michael Barry. December 2009. *Benefit Cost Analysis of In-Vehicle Technologies and Infrastructure Modifications as a Means to Prevent Crashes along Curves and Shoulders*. St. Paul, Minnesota: Minnesota Department of Transportation. Research Services Section. Report No. MN/RC 2009-39.

Pratt, M., Jeffrey D. Miles; and James A. Bonneson. December 2009. *Workshops on Using the GPS Method to Determine Curve Advisory Speeds*. College Station, Texas: Texas Transportation Institute. Texas A&M University System. http://tti.tamu.edu/documents/5-5439-01-1.pdf. Last access date: 11 Oct 2011. Report No. FHWA/TX-10/5-5439-01-1.

Sanders, Brandon. 2005. *Updating Horizontal Curve Data Using GPS Centerlines*. Kentucky Transportation Cabinet. Division of Planning. Presentation at the FHWA Highway Performance Monitoring System (HPMS) Data Collection Workshop. Salt Lake City, Utah. 8-10 Mar 2005.

BIBLIOGRAPHY

Federal Highway Administration. Horizontal Curve Safety - FHWA Safety Program. FHWA Safety Programs. http://safety.fhwa.dot.gov/roadway_dept/horicurves. Access date: 10 Feb 2011.

Iowa Department of Transportation. *2010 5 Percent Most Severe Safety Needs Report*. http://www.iowadot.gov/crashanalysis/fivepercent/2010/iowa_5percent_consolidatedreport_2010_final.pdf. Access date: 13 May 2011.