The Minnesota Horizontal Curve Safety Improvement Project was developed to focus on the evaluation of the potential safety and speed impacts of dynamic horizontal curve warning signs (DCWSs) along rural two-lane rural roadways. This literature summary includes a brief description of the most current and/or comprehensive state-of-the-knowledge documents and research related to the following subjects:

- Curve geometrics and safety,
- Curve geometrics and speed, and
- Traditional and DCWS warning sign impacts.

In 2002 approximately 25 percent of fatal crashes in the United States occurred at horizontal curves (1). In fact, past research has also shown that the average curve crash rate is about 3 times greater than that occurring along tangents (1, 2). In addition, sharper curves have higher crash rates than those with longer radii (3). Overall, almost three quarters of the fatal horizontal curve crashes that occurred within the United States in 2002 were also in rural areas and about the same percentage of these crashes were single-vehicle run-off-the-road incidents (1).

Many lane departure and/or single vehicle run-off-the-road crashes occur on or near horizontal curves. From 2001 to 2005 approximately 32 percent of the roadway fatalities in Minnesota were single vehicle run-off-the-road incidents (4). In addition, more than 50 percent of the fatalities in the rural Minnesota (i.e., outside the Twin Cities metropolitan area) were due to lane departures (4). This percentage increases to more than 60 percent along local rural roadways in Minnesota (4). Overall, county roadways in Minnesota experience almost half the annual roadway fatalities in the state and have a fatal crash rate that is 20 percent greater than similar roadways within the state highway system (4).
CURVE GEOMETRICS AND SAFETY

A large number of research projects have either focused on the potential reason(s) crashes occur at or near horizontal curves or evaluated proposed crash countermeasures (e.g., adding chevrons, curve flattening, etc.). Several of the references uses for this technical memorandum contain summaries of some of these projects and countermeasures (1, 3, 5). Some of the characteristics that past studies have found impact curve safety include (3):

- Traffic volume and mix (e.g., percent trucks);
- Curve features (e.g., degree of curvature, length, central angle, superelevation, and/or presence of a spiral);
- Cross section features (e.g., lane width, shoulder width, shoulder type, and/or shoulder slope);
- Roadside hazard (e.g., clear zone, sideslope, rigidity and/or type of obstacles);
- Stopping sight distance on curve or curve approach;
- Vertical alignment;
- Distance to adjacent curves;
- Presence/distance to nearest intersection, driveway, bridge, etc.;
- Pavement friction; and
- Presence/type of traffic control devices (e.g., signs and delineation).

The focus of this is summary are the roadway geometrics that may impact horizontal curve safety. The Federal Highway Administration (FHWA) has developed a decision-making tool that can be used to safety and operational impacts of geometric design decisions along two-lane rural roadways (see http://www.tfhrc.gov/safety/ihsdm/ihsdm.htm). This tool is called the Interactive Highway Design Model (IHSDM).

In 2000 the methodology that generally formed the basis of the IHSDM crash prediction module was published (5). The base model for crash prediction proposed in this document includes a variable related to horizontal curves (5). The results of this model must be adjusted for the existing and/or proposed geometric design elements of the roadway segment being evaluated. This adjustment is done through the application of one or more accident modification factors (AMFs). AMFs greater than 1.0 indicate the geometric feature increases the number of predicted crashes (5).

The AMF for horizontal curves includes length, radius, and spiral presence as inputs (5, 6). It generally increases with as horizontal curve length increases and decreases as radius increases and or curve approach spirals are introduced (5, 6). In other words, the number of predicted crashes per year along a roadway segment will generally increase with increases in horizontal curve lengths or decreases in horizontal curve radii or the additional of horizontal curve spirals (5). An AMF was also proposed for horizontal curve superelevation deficiencies (5). This AMF increases the number of crashes predicted as the deficiency increases (5).
Some new horizontal curve related crash prediction research has also recently been published (7, 8). In 2009 Easa, et al. proposed several crash prediction models that attempted to take into account situations involving the three-dimensional nature of roadway curves (7). The models developed were based on Highway Safety Information System (HSIS) crash data for curved roadway segments with various horizontal and vertical characteristics or components (7). The horizontal curve characteristics that were represented by variables in the final crash prediction models included degree of curvature and length (7). It should be noted that curve radii is inversely related to and decreases with degree of curvature. In addition, these results generally agree with those previously described. The frequency of crashes predicted to occur along a roadway segment increased with degree of curvature and curve length (7). Models for truck crashes along horizontal curves were also recently developed by Schneider, et al. (8). These models also included length of curve and degree of curvature as statistically significant variables, and, not surprisingly, the number of truck crashes predicted increase with both (8).

**CURVE GEOMETRICS AND SPEED**

Research has shown that the difference in speed between adjacent roadway alignment segments (e.g., tangent and horizontal curve) is one approach that could be used as a surrogate to identify locations of safety concern (9, 10). Larger speed reductions for curves result in a higher number of crashes (10). In fact, the IHSDM analysis tool includes a design consistency module that uses speed-profile models to identify and “flag” these speed differences along two-lane rural roadways. These models estimate the 85th percentile free-flow passenger vehicle speed profile (using several different approaches) along existing or proposed two-lane rural roadways. The IHSDM can then identify or “flag” speed consistency concerns where there are large differences between the 85th percentile speeds of adjacent roadway segments or the 85th percentile speeds and the assumed design speed. Significant speed differences, and a particular focus in the IHSDM calculations, can occur at horizontal curves.

The basis of the speed estimates used in the IHSDM was a large research project that had its results published in August 2000 (9). This project was completed to expand upon an earlier design consistency study by Krammes, et al. and it created a series of speed prediction equations and methodologies for use in speed-profile modeling (9, 11, 12). The research used speed data from more then 200 curves in six states (9, 12) and produced several models to estimate 85th percentile horizontal curve speed (9, 12). However, although a number of geometric characteristics were considered, each model only included curve radius as the primary variable (9, 12). Different models were then produced for horizontal curves that interacted with different vertical grade situations. For example, there were speed models for horizontal curves on negative grades between -9 and -4 percent, -4 and 0 percent, 0 and 4 percent, and 4 and 9 percent (9, 12). Overall, and not surprisingly, the horizontal curve 85th percentile speed predicted by these models generally increases with the radius (9, 12). Overall, it was also concluded that the data showed that the operating speed on horizontal curves with a radius of approximately 2,625 feet (800 meters) or more were very similar to long tangent speeds (9, 12). Vehicle
speeds on the curves decreased quickly, however, when the radius was less than approximately 820 feet (250 meters) (9, 12).

The speed profile models developed by Fitzpatrick, et al. can be used within the IHSDM to assist with geometric design (9, 12). For example, the IHSDM can be told to produce a green flag for predicted differences in 85th percentile tangent and curve speeds of 6 mph (10 kph) or less, a yellow flag for differences of 6 to 12 mph (10 to 20 kph), and a red flag for differences of greater than 12 mph (20 kph) (9, 11, 12). These are referred to as “good”, “fair”, and “poor” design in an example provided by Fitzpatrick, et al. (9, 12).

The kinematics equation from the AASHTO “A Policy on Geometric Design of Highways and Streets” for curve speed includes side friction, superelevation, and radius as variables (13). The curve speed produced with this equation increases with all three of these variables. Other research projects, as reviewed by Bonneson, et al and Fitzpatrick, et al., have also shown that the following variables could also impact horizontal curve speed (9, 12, 14):

- Tangent speed,
- Vehicle type,
- Curve deflection angle,
- Curve length,
- Available stopping sight distance,
- Grade, and
- Vertical Curvature.

Bonneson, et al. have completed more recent work focused on rural horizontal curve speed prediction (14). There results and approach, however, were somewhat different than that used by Fitzpatrick, et al. (9, 12, 14). Fitzpatrick, et al. created horizontal curve speed prediction models for different vertical grade situations and they included radius as the only model variable (9, 12). The 85th percentile curve models produced by Bonneson, et al., on the other hand, were developed for several tangent approach speeds and included several variables (14). Bonneson, et al. (along with some other researchers) have concluded that this factor (i.e., approach speed) has a strong influence on horizontal curve speed choices (14). They also determined that drivers appear to adjust or modify their side friction demands with curve geometry or speed (14). Drivers appear to have lower demands on side friction for more gradual higher speed (i.e., larger radius) curves and are willing to accept higher side friction on sharper curves (14). It was also concluded that the impact of superelevation on horizontal curve speed, however, was not as important as the impacts of radius and tangent approach speed (14).

Overall, the parabolic horizontal curve speed prediction model proposed by Bonneson, et al. includes superelevation, radius, and tangent approach speed as input (14). The 85th percentile horizontal curve speed predicted by the model increases with radius for a given superelevation and 85th percentile tangent speed (14). It was found, however, that the prediction capability of the model also improved when the actual radius of the “vehicle path” was used rather than the designed or constructed curve radius (14). The actual path
of a vehicle along a circular curve is more of a spiral and vehicles shift toward the roadway centerline (14). The Bonneson, et al. model did not include the impacts of vertical grade (like Fitzpatrick, et al. above) because their database did not include curves with a wide range of this characteristic (9, 12, 14).

HORIZONTAL CURVE WARNING SIGN IMPACTS

Traditional Horizontal Curve Warning Sign Impacts

In 2004 NCHRP Report 500 (Volume 7), “A Guide for Reducing Collisions on Horizontal Curves”, was published (1). The authors of this document summarized the speed and/or crash results of several research projects focused on the implementation of traditional curve warning signs and/or curve speed advisory signs (1). The results of these studies varied. Some of the studies found no impact by the signs on vehicle speed choice by drivers along horizontal curves and one study even found an increase in vehicle speed after the sign implementation (1). Only one study that was referenced, however, attempted to evaluate the crash impacts of implementing horizontal curve warning signs and/or curve advisory speed signs (1). This study concluded that the installation of horizontal curve warning signs decreased crashes by 18 percent and that the installation of warning signs and advisory speed signs decreased crashes by 22 percent (1). Although it is not properly referenced, this same study also appears to be briefly discussed in the American Traffic Safety Services Association (ATSSA) “Low Cost Local Road Safety Solutions” document (15).

A more recent study of the impact of signing improvements was also summarized in the document entitled “Low Cost Local Road Safety Solutions” (15, 16). The signing program in Mendocino County, CA included the improvement of signing deficiencies and the use of high intensity retroreflective sheeting (15, 16). The focus at the start of the program was to improve horizontal curve signing (likely including the installation of signs at curves that did not originally have them) and eliminate nonstandard signing (15, 16). Between 1992 and 1998 the crashes along the 19 roadways reviewed and improved were reduced by 42 percent, fatalities were down by 61 percent (n = 13 to n = 5) and injuries decreased by 42 percent (15, 16). The crashes along the non-reviewed and improved county roadways, however, increased by approximately 27 percent and the crashes along the state highways in the county decreased by about 3 percent (15, 16). Not all of the signs replaced, of course, were related to horizontal curves.

In September 2007 the FHWA published the “Desktop Reference for Crash Reduction Factors” (17). This document attempted to summarize research results about the crash reductions that could be expected if the countermeasures evaluated in the studies were implemented. A large number of crash reduction factors related to roadway departure crash countermeasures were summarized (17). However, the document includes factors based on both nationally respected research studies and those that have results with a reliability considered to be “…low or very low” (17). The application of this guide, therefore, still requires engineering judgment (17). Overall, four references were summarized in the desktop reference that appeared to be related to the installation of
horizontal curve warning signs (17). The research results summarized appear to show 8 to 55 percent reductions in various crash types (e.g., all and run-off-the-road) and severities (i.e., property damage, injury, and/or fatalities) due to the installation of these signs (17). The more typical range of these crash reductions, however, appears to be between 20 and 30 percent (17). The results documented for situations when the horizontal curve warning signs are installed with a speed advisory sign, on the other hand, appear to show a crash reduction between 13 and 29 percent (17). The authors of NCHRP Report 559, “Communicating Changes in Horizontal Alignment”, also indicate that the literature, although varied, includes some studies that show a reduction in single vehicle and run-off-the-road crashes when advisory horizontal curve warning signs and/or advisory speed signs are installed (18).

Dynamic Horizontal Curve Warning Sign Impacts

In the late 1990s a dynamic curve warning system (displaying “curve ahead” or “curve ahead” and “reduce speed” in sequence) was installed along a Minnesota county roadway adjacent to a traditional horizontal curve warning sign (with a 40 mile per hour (mph) advisory speed) (19). Vehicle speeds and other horizontal curve negotiation performance measures (through the use of a video camera) were collected during a four day period to evaluate the sign impacts. Data was only collected for vehicles traveling at or above 53 mph (the choice of this speed does not seem to be documented) and the sequential sign message noted above was randomly assigned to these vehicles (otherwise just the “curve ahead” message was presented to the driver) (19). Speed data were collected on more than 2,600 vehicles and the navigation analysis was completed for 589 vehicles randomly selected from this database (19). It appears that the vehicle speeds for this project were collected approximately 700 feet upstream of the warning sign and then every 3 seconds while the vehicle remained in the radar field of view (the radar was located at the location of the dynamic and static curve warning signs) (19). Overall, the average speed decreased 12.1 and 12.3 mph for the “curve ahead” and sequential sign messages, respectively (19). The combination of a static sign with a blank dynamic curve warning sign, however, also appeared to result in an average decrease of 11.5 mph (19). The speed reductions observed (when the sign was active) were greater (up to 5 mph), however, for “higher speed” vehicles traveling 60 mph or higher (19). The videotape camera data also shows that the navigation of the curve improved when sequential sign was activated (19). The latter impact was not observed when the dynamic curve warning sign only presented the “curve ahead” message (19). A successful navigation was assigned to a vehicle if it stayed within the lane lines (19). Overall, it was concluded by the researchers that the impact of the sign was “relatively small”, but that its impact on high-speed vehicles (those most likely to experience problems at a curve) was greater than that of a typical static horizontal curve warning sign (19).

NCHRP Report 500 (Volume 7) also included pictures of some dynamic curve warning sign studies (1). In addition, it summarized the results of several studies that considered the impact of this type of sign. Many of these types of signs have been installed to reduce the number of rollover truck incidents that are occurring or may occur at very sharp curves (e.g., freeway ramps). For example, the NCHRP Report 500 (Volume 7) authors
summarize an evaluation of the impacts related to the installation of truck rollover warning signs at three ramps in Virginia and Maryland (1). This study found that 10 rollover crashes had occurred before the installation of the system and no crashes occurred during the three years after the installation (1). A summary of the speed data collected by the researchers also showed that the speed selection by “high-speed” trucks were reduced to a greater extent when the signs were activated than when they were not (20). Overall speed reductions of approximately 20 to 30 (or 1.4 to 2.9 mph) percent appear to have occurred after the installation of the signs (20).

A study that focused on the potential impacts related to dynamic curve warning signs at five locations along the California interstate system was also summarized in NCHRP Report 500 (Volume 7) (1, 21). These signs warned people of the curve ahead (and its advisory speed) and also indicated the actual speed of the vehicle (1). Overall, significant truck speed reductions (near the beginning of each curve) were found at three of the five curves after the installation of the signs and passenger vehicle speed reductions were observed at two of the five curves (1, 21). However, one of the curves only experienced a truck speed decrease during the initial data collection period (21). The speed increased during subsequent data collection activities (21). Overall, little additional explanation is provided about the reasons that might indicate why there was a lack of consistency in the speed results (1, 21). The report for this project was published in 2000 and was done too quickly after the sign installations to complete a statistically significant analysis of crash data (1, 21). The crash impacts for a dynamic curve warning system installation along the California interstate, however, is also summarized (although not properly referenced) in the 2006 FHWA “Low Cost Treatments for Horizontal Curve Safety” report (22). This report indicated that crashes were reduced by 44 percent lower during the first year after installation 39 percent lower during the second year (22). It is unknown whether the California systems summarized in NCHRP 500 (Volume 7) and the FHWA document are the same installations (1, 22).

Finally, the FHWA “Desktop Reference for Crash Reduction Factors” document that was noted above also included crash reduction factors for “Dynamic/Variable Speed Warning Signs” (17). Unfortunately, these crash reduction factors are referenced to a currently unpublished document related to the upcoming Highway Safety Manual (17). This unpublished report, however, apparently indicates that the installation of these types of signs can be expected to reduce all crashes by 46 percent and injury crashes by 41 percent (17). It should be noted, however, that the standard errors declared for these meta-analysis crash reduction summary results are 17 and 62 percent, respectively (17).

In 2004 the authors of NCHRP Report 500 (Volume 7) indicated that dynamic curve warning systems had been installed in Pennsylvania, Colorado, and Missouri (1). In addition, as summarized above, the impact of these types of installations in Virginia, Maryland, and California were also summarized (1). An ongoing national study of the impact of dynamic curve warning signs will be evaluating one or more installations in Iowa, Arizona, Washington, Florida, Ohio, and Texas.
REFERENCES


