Assessing Curve Severity and Design Consistency Using Energy- and Friction-Based Measures

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Numerous published models can be used to predict curve speed based on geometric and operational characteristics like radius, superelevation rate, and approach tangent speed. Speed-based design consistency measures have also been developed to help identify which curves on a roadway are the most severe. However, the use of speed reduction alone can result in improper assessment of curve severity because drivers are more reluctant to reduce speed on roadways with higher speeds and thus accept speeds associated with higher crash risk. New measures of curve severity are suggested, based on considerations of side friction demand and kinetic energy. The increase in side friction demand above drivers’ comfort thresholds is shown to be roughly proportional to the kinetic energy reduction associated with speed reduction. Agencies can use these curve severity measures to assist in identifying curves in their jurisdictions that would most likely benefit from safety improvements.

Horizontal curves are an essential part of any highway system, but they can present safety hazards to drivers. Research has consistently shown that crash rates on horizontal curves are significantly higher than crash rates on tangent roadway segments of similar geometric design, even for curves that may appear to be relatively mild.

Numerous models published in the literature can be used to predict curve speed based on geometric factors like radius and superelevation rate, and operational factors like approach tangent speed. Models accounting for the influence of tangent speed have shown that drivers choose curve speeds that minimize their speed reduction (and travel time) while avoiding excessive amounts of side friction demand. Speed reduction is used to assess the design consistency of curves, and it is also a measure of curve severity. Larger speed reduction levels indicate that a curve is more severe, and also more inconsistent with drivers’ expectations and the design of the roadway, compared with other curves. Curve severity is a measure that reflects crash risk and the effort drivers expend to avoid risk while minimizing travel time.

In this paper, curve severity measures based on side friction demand levels and kinetic energy reduction are explored. The friction-based measure is side friction differential, measured as the difference between side friction demand at the curve speed that drivers choose and their friction comfort threshold for that speed. The energy-based measure is the amount of energy reduction that must occur for drivers to decelerate from tangent speed to their chosen curve speed. It is proposed that side friction differential and energy reduction are more closely related to driver behavior and safety, and thus better suited to assess curve severity, than speed reduction is. These measures can be used by agencies to determine which curves in their jurisdictions would most likely benefit from safety improvements.

HORIZONTAL CURVE OPERATIONS

This section discusses the factors that affect horizontal curve operations, with a focus on geometric design elements and their influence on curve speed. The relationship between side friction demand, driver behavior (i.e., choice of curve speed), and curve severity is presented.

Curve Speed and Side Friction Demand

When a vehicle traverses a horizontal curve, its tires must provide a sideways force to keep the vehicle on the curved path. The amount of lateral acceleration or side friction required to provide this force is related to curve speed and geometry. AASHTO’s A Policy of Geometric Design of Highways and Streets (Green Book) offers the following equation to quantify the relationship between curve speed, geometry, and side friction demand (1):

\[ f = \frac{2.15v_c^2}{gR} - \frac{e}{100} \]  

where

- \( f \) = side friction demand (g),
- \( v_c \) = curve speed (mph),
- \( g \) = gravitational acceleration (= 32.2 ft/s^2) (ft/s^2),
- \( R \) = curve radius (ft), and
- \( e \) = superelevation rate (%).

Equation 1 shows that side friction demand increases with increasing curve speed, decreasing radius, or decreasing superelevation rate. For the vehicle to remain safely on the curve, its tire–roadway interface must supply the amount of side friction demanded at the driver’s chosen curve speed. If the curve speed is high enough to require a side friction demand in the area of 0.50g, a passenger car will skid off the curve because its tires cannot provide more side friction. Trucks with high centers of gravity become susceptible to...
rollover at side friction demands of about 0.24 to 0.35g, depending on loading and configuration (2).

### Design-Side Friction Factors

Drivers begin to feel uncomfortable at side friction demands well below friction supply limits of tires, and they react to this discomfort by reducing speed. The Green Book recommends the design-side friction factors (see Table 1) that are conservatively below the point when most drivers begin to feel discomfort (1). In an examination of the relationship between side friction demand and driver comfort, Bonneson found that the friction factors in Table 1 generally correspond with a speed reduction of 2 to 3 mph for the 95th percentile driver (3).

The design-side friction factors decrease as curve speed increases, reflecting the fact that drivers desire less side friction demand at higher speeds. The Green Book explains that drivers begin to feel uncomfortable in high friction conditions because swerving becomes more perceptible, and more steering effort is required to stay properly within the travel lane (1, p. 135). Such conditions require increased concentration and result in the narrowing of a driver’s cone of vision. As curve speed increases, these undesirable conditions occur at lower side friction demand levels.

An illustration of the relationship between curve speed and side friction demand is provided in Figure 1. The thick trend line represents the design-side friction factors listed in Table 1, and the thin trend lines represent the relationship between curve speed and side friction demand for two given radii, as calculated using Equation 1. At all points along the thin trend lines that fall below the thick trend line, drivers are traversing the curves at speeds below the curve design speeds, thus incurring side friction demands less than the design-side friction factors. Points near the thick trend line represent combinations of speed and side friction demand where motorists traveling at the design speed will begin to feel slightly uncomfortable, and will react by reducing speed slightly.

### Geometric and Operational Elements Affecting Curve Speed

Numerous models of the following form (or similar variations) have been developed to predict drivers’ curve speed choice (4). Models of this form are referred to as radius-based curve speed models.

\[
v_{c,85} = b_0 - \frac{b_1}{R}
\]

where

\[
v_{c,85} = 85\text{th percentile curve speed (mph)},
\]

\[
b_0 = \text{model intercept (represents average 85th percentile tangent speed across study sites (mph)), and}
\]

\[
b_1 = \text{model coefficient accounting for effect of radius on curve speed}.
\]

Equation 3 is a radius-based curve speed model developed by Fitzpatrick et al. (5). It was calibrated using data from study sites in six states. Posted speed limits at these sites ranged from 50 to 70 mph. The model intercept suggests that the 85th percentile tangent speed at most of the sites was near 65 mph.

\[
v_{c,85} = 65.1 - \frac{7.285.29}{R}
\]

In addition to the geometric design elements in Equation 1, tangent speed has been found to have a significant effect on curve speed (3). Tangent speed is the free-flow speed observed on the approach tangent to the curve, at a distance sufficiently far upstream that drivers are not yet beginning to decelerate due to the curve’s sharpness. Curve speed models accounting for the effect of tangent speed are referred to approach-based models. Using speed data from 55 study sites, Bonneson developed the following relationship between side friction demand and curve speed:

\[
f_{c,85} = 0.259 - 0.00359v_{T,85} - 0.0214\left(v_{T,85} - v_{c,85}\right)
\]

where \(f_{c,85}\) is side friction demand at 85th percentile curve speed (g) and \(v_{T,85}\) is 85th percentile approach tangent speed (mph).

Equation 4 gives the side friction demand that drivers experience for any combination of tangent speed and curve speed. It accounts for the

<table>
<thead>
<tr>
<th>Design Speed, mph</th>
<th>Design-Side Friction Factor ((f_{des})), g</th>
</tr>
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<tbody>
<tr>
<td>10</td>
<td>0.38</td>
</tr>
<tr>
<td>15</td>
<td>0.32</td>
</tr>
<tr>
<td>20</td>
<td>0.27</td>
</tr>
<tr>
<td>25</td>
<td>0.23</td>
</tr>
<tr>
<td>30</td>
<td>0.20</td>
</tr>
<tr>
<td>35</td>
<td>0.18</td>
</tr>
<tr>
<td>40</td>
<td>0.16</td>
</tr>
<tr>
<td>45</td>
<td>0.15</td>
</tr>
<tr>
<td>50</td>
<td>0.14</td>
</tr>
<tr>
<td>55</td>
<td>0.13</td>
</tr>
<tr>
<td>60</td>
<td>0.12</td>
</tr>
<tr>
<td>65</td>
<td>0.11</td>
</tr>
<tr>
<td>70</td>
<td>0.10</td>
</tr>
<tr>
<td>75</td>
<td>0.09</td>
</tr>
<tr>
<td>80</td>
<td>0.08</td>
</tr>
</tbody>
</table>

**FIGURE 1 Relationship between curve speed and side friction demand for two radii.**
Several curve severity measures identified in the literature are also the operational considerations discussed in the previous section. AND ASSESSMENT OF SEVERITY

variability. of determination (approach-based models are usually associated with larger coefficients than radius-based models do). In particular, he observed that approach-based models are usually associated with larger coefficients of determination ($R^2$), indicating that they explain more curve speed variability.

HORIZONTAL CURVE SAFETY AND ASSESSMENT OF SEVERITY

This section explains the relationship between curve severity and the operational considerations discussed in the previous section. Several curve severity measures identified in the literature are also assessed based on their ability to account for the geometric and operational factors related to curve crash risk.

Curve-Related Crashes

Research has consistently shown that crash rates on horizontal curves are significantly higher than crash rates on tangent roadway segments of similar geometric design. Zegeer et al. found that a 1,000-ft radius curve is likely to have 50% more crashes than a tangent segment of equivalent length, and a 500-ft radius curve is likely to have 200% more crashes than a tangent segment (7). Fitzpatrick et al. found that a curve requiring a 5-mph speed reduction is likely to have 90% more crashes than a tangent segment, and a curve requiring a 10-mph speed reduction is likely to have 250% more crashes (5).

Crashes related to horizontal curvature are likely to fall within two categories. The first category is related to drivers not noticing the presence of a curve. It is possible that some drivers do not detect the curve because of distraction, impairment, or sight distance restrictions, and thus do not attempt to track the curve. Such crashes can occur regardless of curve sharpness.

The second category is related to drivers underestimating the sharpness of a curve. In these cases, drivers enter the curve at a high speed and experience side friction demand well beyond their comfort limit. Perceiving an unacceptable risk, they may either overcorrect their trajectory or brake hard enough to compromise their tire side friction supply levels, and then lose control of their vehicle and run off the roadway. Such crashes are likely to occur near the beginning of the curve, where drivers first experience and react to the high side friction demand, and superelevation is not yet fully developed.

The following discussion of curve safety pertains to the second curve-related crash category. These crashes are related to drivers’ speed choice through curves and their perception of side friction demand. To reduce crashes of this type, relevant quantitative measures of curve severity should be used to identify the curves that would benefit most from safety improvements.

Quantifying Curve Risk Using Side Friction Demand

Rationale

Approach-based curve speed models such as shown in Figure 2 indicate that drivers select curve speed based on comfort and speed maintenance considerations. If the curve radius is sufficiently large, drivers will not feel uncomfortable traversing the curve at the tangent speed. In such cases, drivers do not decelerate, and the curve does not appreciably increase their crash risk.

If the side friction demand at tangent speed is above the comfortable side friction threshold for that speed, drivers will choose a curve speed that corresponds with a side friction demand above their comfort limit, but not beyond an amount they deem acceptable, given their desire to maintain speed. Thus, they avoid some crash risk by decelerating but accept some risk to maintain a desirable curve speed.

Glennon has proposed determining curve severity based on side friction demand incurred at curve speed (8). In a web-based article, he suggested the guidance shown in the first two columns of Table 2 as

![Figure 2](image-url)
Friction-Based Curve Risk Components

Given the importance of side friction demand in drivers’ curve speed choice and perception of risk, and the fact that skidding or truck rollover will occur at excessive side friction demands, it can be rationalized that curve risk can be quantified in regard to side friction comfort levels and the friction demands experienced at curve speed. The following relationships can be defined for curve risk components and side friction demand.

The maximum amount of crash risk is experienced when drivers traverse a curve without decelerating. In this case, they may incur a side friction demand well above their comfort limit. The amount by which the side friction demand at tangent speed exceeds drivers’ comfort threshold is given by Equation 5. This quantity is illustrated in Figure 3 as the vertical difference between points A and C. Equation 5 was used to calculate the side friction differential, “side friction tolerance associated with the speed reduction. This quantity is called “side friction differential,” and it is illustrated as the vertical difference between points C and D on Figure 3. Equation 7 was used to calculate the side friction comfort threshold at that speed, as follows:

\[
\text{risk avoided} \propto (f_{T,85} - f_{C,85}) + (f_{C,Des} - f_{T,Des}) = \frac{2.15(v_{T,85}^2 - v_{C,85}^2)}{gR} + (f_{C,Des} - f_{T,Des})
\]

where \(f_{C,Des}\) is side friction comfort threshold at 85th percentile curve speed (g).

The first difference in Equation 6 \((f_{T,85} - f_{C,85})\) represents the amount of side friction demand that a driver avoids incurring by reducing speed. This quantity is shown in Figure 3 as the vertical difference between points B and D. The second difference in Equation 6 \((f_{C,Des} - f_{T,Des})\) accounts for the small increase in driver side friction tolerance associated with the speed reduction. This quantity is shown in Figure 3 as the vertical difference between points A and C.

The sum of these two quantities is proportional to the amount of crash risk avoided by decelerating.

The amount of crash risk that drivers accept at their chosen curve speed is proportional to the amount by which the side friction demand at curve speed exceeds the friction comfort threshold at that speed, as follows:

\[
\text{risk accepted} \propto f_{C,85} - f_{C,Des} = \left(\frac{2.15v_{C,85}^2}{gR} - \frac{e}{100}\right) - f_{C,Des}
\]

Since the quantity defined in Equation 7 is related to the amount of risk that drivers accept as they traverse curves, it can potentially be used as a measure of curve severity. This quantity is called “side friction differential,” and it is illustrated as the vertical difference between points C and D on Figure 3. Equation 7 was used to calculate the side friction differentials in the third column of Table 2, with the lowest value of side friction demand in the first column of the table (0.19 g) used as the side friction comfort threshold \((f_{C,Des})\) to be subtracted from all of the side friction demands \((f_{C,85})\) in the first column.

The bottom portion of Figure 3 provides the speed and side friction demand values defining points A to E and the numerical values for the friction-based curve risk components defined in Equations 5 to 7. Note that maximum risk (Equation 5) equals the sum of risk avoided (Equation 6) and risk accepted (Equation 7).

Speed-Based Curve Severity Measures

This section presents several curve severity measures based on the calculation of speeds on the curve and its approach tangent. These speed-based measures include speed reduction and kinetic energy reduction.

Speed Reduction

In FHWA’s Interactive Highway Safety Design Model (IHSDM), two speed reduction measures are suggested for horizontal curve design consistency evaluation (10). These measures are the difference between 85th percentile operating speed and curve design speed \((v_{C,85} - v_{C,Des})\), and the difference between 85th percentile tangent speed and 85th percentile curve speed \((v_{T,85} - v_{C,85})\). Both of these measures are based on the principle that curves requiring larger speed reductions will more likely violate drivers’ expectancies, and thus can be considered inconsistent with the general geometric and operational characteristics of the roadway.

The IHSDM’s design consistency module engineer’s manual states that crash rate has been shown to be correlated with the difference

<table>
<thead>
<tr>
<th>Side Friction Demand, g</th>
<th>Suggested Signing Treatments</th>
<th>Side Friction Differential, g</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.19 or less</td>
<td>None</td>
<td>0.00</td>
</tr>
<tr>
<td>0.20–0.23</td>
<td>Curve warning sign</td>
<td>0.01–0.04</td>
</tr>
<tr>
<td>0.24–0.27</td>
<td>Curve warning sign, advisory speed plaque</td>
<td>0.05–0.08</td>
</tr>
<tr>
<td>0.27–0.30</td>
<td>Redundant curve warning signs and advisory speed plaques</td>
<td>0.08–0.11</td>
</tr>
<tr>
<td>0.30–0.34</td>
<td>Redundant curve warning signs and advisory speed plaques, chevrons</td>
<td>0.11–0.15</td>
</tr>
<tr>
<td>0.35 or more</td>
<td>Other measures to reduce speed limit, rebuild curve, etc.</td>
<td>0.16 or more</td>
</tr>
</tbody>
</table>
between the 85th-percentile speeds on the tangent and the curve (10). Research demonstrating this correlation was documented by Fitzpatrick et al. (5) and Anderson et al. (11). Those authors developed the following relationship between speed reduction and crash rate:

$$\text{CR} = 0.26e^{-0.1(v_{T,85} - v_{C,85})}$$  \hspace{1cm} (8)

where CR is crash rate, crashes per million vehicle miles.

The IHSDM’s design consistency module assesses curve severity based on speed reduction thresholds proposed by Lamm et al. (12). These speed reduction thresholds are given in Table 3. The corresponding kinetic energy reduction ranges are also given and will be discussed in a later section.

### TABLE 3  Curve Severity Thresholds Based on Speed Reduction

<table>
<thead>
<tr>
<th>Curve Severity Rating</th>
<th>Speed Reduction Range, mph</th>
<th>Energy Reduction Range, mph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>\leq 6.2</td>
<td>\leq 706.6</td>
</tr>
<tr>
<td>Fair</td>
<td>6.2–12.4</td>
<td>706.6–1,336.1</td>
</tr>
<tr>
<td>Poor</td>
<td>&gt;12.4</td>
<td>&gt;1,336.1</td>
</tr>
</tbody>
</table>

Note: The energy reduction ranges were calculated assuming a tangent speed of 60 mph.

*Lamm et. al. referred to this designation as “design safety level” (12).

**Kinetic Energy Reduction**

In a study of curve signing and marking practices, Herrstedt and Greibe proposed using energy reduction as a measure of curve severity (13). The kinetic energy of a moving body is calculated as follows

$$E_{\text{kin}} = \frac{1}{2}mv^2$$  \hspace{1cm} (9)

where

- $E_{\text{kin}}$ = kinetic energy,
- $m$ = mass, and
- $v$ = speed.

As observed by Herrstedt and Greibe, the following decrease in kinetic energy occurs when a vehicle decelerates from tangent speed to curve speed (13). This quantity also represents the work associated with the speed reduction.

$$\Delta E_{\text{kin}} = c(v_{T,85}^2 - v_{C,85}^2)$$  \hspace{1cm} (10)

where $\Delta E_{\text{kin}}$ is kinetic energy reduction (ft-lbf) and $c$ is a proportionality constant (ft-lbf/mph$^2$).

The magnitude of the proportionality constant $c$ depends on the mass of the vehicle. In the following discussion, the quantity $\Delta E_{\text{kin}}/c$ is referred to as energy reduction, which has units of mph$^2$. 

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**FIGURE 3  Relationship between speeds and curve risk components.**

- **Green Book Design Factors**
- **Table 3 Curve Severity Thresholds Based on Speed Reduction**
- **Diagram showing speed vs. side friction demand**
Energy reduction differs from speed reduction in that it is proportional to the difference of the squares of the tangent and curve speeds. For a given speed reduction level, energy reduction increases as tangent speed increases, as shown in Figure 4. Similarly stated, a given energy reduction will equate with a larger speed reduction if tangent speed is lower. For example, an energy reduction of 1,500 mph² results in a speed reduction of about 12 mph from a 70-mph tangent speed, and a speed reduction of about 16 mph from a 55-mph tangent speed.

The application of energy reduction as a curve severity measure is based on the premise that small speed reductions at high tangent speeds are as dangerous as higher speed reductions at lower tangent speeds (13). This concept is based on sound physical principles. Braking involves dissipation of kinetic energy, so reducing speed by a given amount will require harder braking and more work if tangent speed is higher.

Furthermore, when drivers approach a given curve at higher tangent speeds, they must reduce their speed by a larger amount to attain their desired curve speed (see Figure 2). As a result, the energy reduction corresponding to drivers’ desired curve speeds increases rapidly as tangent speed increases. To demonstrate this point, the two example combinations of tangent speed and curve speed circled on Figure 2 are also circled on Figure 4. When drivers approach the example curve (500-ft radius, 6% superelevation rate) at 45 mph, their energy reduction required to attain desired curve speed is about 260 mph². When they approach the same curve at 65 mph, their energy reduction is about 1,550 mph².

When tangent speed is higher, drivers traverse the example curve at a higher speed because they desire to maintain the higher tangent speed as much as possible. As a result, they accept a larger side friction increase above their comfort threshold. However, to attain their desired curve speed, drivers have to decelerate more at higher tangent speeds, which requires a larger energy reduction. Thus, it seems that energy reduction and side friction differential are both similarly related to curve severity.

**Comparison of Measures**

Equation 3 was used to calculate the radius that would correspond with a range of curve speeds on a 65-mph roadway. For each combination of curve speed and approach tangent speed, the speed reduction, energy reduction (Equation 10), and side friction differential (Equation 7) were calculated. To determine the friction comfort threshold for the calculation of side friction differential, Equation 4 was used with the tangent and curve speeds set equal. Results of this comparison are shown in Figure 5. To facilitate visual comparison, the computed values for speed reduction, energy reduction, and side friction differential were multiplied by proportionality constants and plotted on an idealized y-axis. A detailed evaluation of this type was conducted by Bonneson et al. (14).

The trend lines for the curve severity measures show good agreement up to a speed reduction of about 7 mph. For higher speed reductions, curve severity increases at a slower rate when considering energy reduction or side friction differential than it does when considering speed reduction.

This behavior occurs because the amount of kinetic energy that needs to be dissipated decreases quadratically as tangent speed decreases linearly. For example, reducing speed from 65 mph to 60 mph requires an energy reduction of 625 mph². To reduce speed by an additional 5 mph, the energy reduction is only 575 mph². Each incremental amount of speed reduction from a given tangent speed results in a smaller increase in curve severity.

Given this physical trend, it seems reasonable that curve severity should not increase linearly with speed reduction for a given tangent speed. Using speed reduction to assess curve severity would likely result in overestimation of curve severity at the higher speed reduction levels. However, if speed reduction does not change but tangent speed increases, then curve severity should increase. In such cases, using speed reduction to assess curve severity would likely result in underestimation of curve severity.

The trend line for side friction differential similarly starts to flatten at speed reductions of about 7 mph. This trend is expected for side friction differential because side friction demand is proportional to the square of curve speed. As speed reduction increases linearly, curve speed decreases linearly, and side friction demand decreases quadratically. Side friction differential stops increasing at a speed reduction of about 20 mph. This occurs because the side friction demands experienced at this point are approaching the point of skidding or skidding conditions.
rollover failure (0.35 to 0.50g), so side friction differentials beyond this level would be physically unattainable.

Of the three measures compared in Figure 5, energy reduction is suggested for curve severity assessment. The speeds used to calculate energy reduction can be estimated using speed profile models. In particular, the curve speed should be estimated using an approach-based curve speed model. Radius-based curve speed models do not account for the trade-off that drivers make between comfort and maintenance of desired speed at a variety of tangent speeds (see Figure 2).

Implications for Curve Severity Assessment

It has been shown that larger speed reduction will result in a higher crash rate (5, 11). However, using speed reduction as a curve severity measure without sensitivity to tangent speed can result in incorrect assessment of curve severity. When assessed using the measures of energy reduction and side friction differential, curves associated with a given speed reduction will be considered more severe if located on roadways with higher tangent speeds, or less severe if located on roadways with lower tangent speeds.

To illustrate these points, the speed reduction and energy reduction thresholds provided in Table 3 are plotted in Figure 6. The speed reduction thresholds are shown as thin lines, and the energy reduction thresholds are shown as thick lines. The energy reduction thresholds were calculated using Equation 10, assuming a tangent speed of 60 mph. As a result, the two sets of trend lines are equal for a 60-mph tangent speed, but they diverge for other tangent speeds.

As tangent speed increases, the vertical distances between the zero-speed-reduction line and the energy reduction threshold lines decrease. This means that when tangent speed increases, smaller speed reduction values will result in a curve being classified as fair or poor. In contrast, as tangent speed decreases, larger speed reduction values are needed for a curve to be classified as fair or poor. The divergence between the speed reduction and energy reduction thresholds is most significant at lower tangent speeds. For example, if the tangent speed is 40 mph, a speed reduction of 10 mph would be required for a curve to be classified as fair, and a speed reduction as high as 20 mph would be too small for the curve to be classified as poor. In contrast, a curve with speed reduction of slightly more than 10 mph at a tangent speed of 70 mph would be classified as poor.

A contour plot like the one shown in Figure 6 can be used to conduct an energy-based assessment of curve severity. This type of analysis would identify curves that are most inconsistent with the design of the overall roadway and drivers’ expectations. Once identified, the most severe curves could be considered high priority for safety improvements. These improvements could consist of traffic control devices such as chevrons, pavement treatments such as high-friction overlays, or even geometric alteration such as straightening or superelevation improvement. In fact, Herrstedt and Greibe proposed a contour plot similar to the one in Figure 6 as a basis for selecting curve signs and delineation devices (13). Evaluation tools based on proper measures of curve severity can help agencies analyze all of their roadway curves consistently and use their limited resources to target curves that would most likely benefit from treatment.

FINDINGS AND RECOMMENDATIONS

Drivers select curve speed based on their desire to minimize speed reduction while avoiding incurring excessive side friction demand. Additionally, drivers are more reluctant to reduce speed through a curve when they approach the curve at higher speed. These trends are not fully considered when speed reduction is used to assess curve severity.

Based on established relationships between curve geometry and operations, side friction differential (amount of side friction demand that drivers experience above their comfort threshold) has been identified as a curve severity measure. Side friction differential is rationally related to crash risk because drivers are more likely to panic and lose control of their vehicles when they experience side friction demand that they perceive to be excessive. This will happen at lower speed reduction levels when tangent speed is high.

Examination of kinetic energy reduction has shown that speed reductions from a higher tangent speed are also likely associated with higher crash risk. When assessing curve severity based on speed reduction, this consideration can be overlooked. Instead, curve severity should be assessed based on energy reduction, which exhibits trends similar to that of side friction differential.

To identify the most severe curves for possible treatment or reconstruction, curves should be assessed based on the energy reduction calculated from the estimated curve and approach tangent speeds. If improved to incorporate the relationship between tangent speed and curve speed, speed profile models like the IHSDM’s design consistency module could be used to estimate energy reduction for curves (10). This would allow a large number of curves to be evaluated systematically, and the most severe curves would be identified more accurately.

REFERENCES


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