Safety and Design Alternatives for Two-Way Stop-Controlled Expressway Intersections

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ABSTRACT

Expressways are a quickly growing segment of the U.S. highway system, and their growth is planned to continue into the future. Understanding the safety performance of two-way, stop-controlled rural expressway intersections will help corridor planners and designers include special consideration in their plans and designs for accommodating future intersection safety improvements. Such an understanding will allow the operators of existing expressway corridors to plan for accommodating special safety treatments as traffic volumes grow and as adjacent land uses change. Planning for these changes is important, as the analysis shows that intersection crash rates, crash severity rates, and fatal crash rates increase with minor roadway volume.

Keywords: divided multi-lane highways—expressways—expressway intersection safety—safety performance functions
INTRODUCTION

The conversion of two-lane rural highways into multi-lane, median-divided highways with partial or no access control (rural expressways) is one of the fastest growing parts of the country’s highway network (Maze et al. 2005). Between 1996 and 2002, the miles of expressways grew nationally by 27%. The popularity of expressways is demonstrated through a recent survey the authors conducted of 35 state transportation agencies (STAs) with the largest expressway systems (Maze, Burchett, and Hawkins 2004). Twenty-seven STAs responded, and 26 said they intended to continue expanding the expressway network in their state over the next 10 years. The reasons for building expressways are clear: expressways often operate at speeds equivalent to those of rural interstates, but cost much less. In comparison to rural interstate highways, expressways do not require the purchase of all access rights, generally require less right-of-way, and require fewer or no grade separations through expensive overhead bridges and interchanges.

It was also found that many of these same STAs are experiencing problematic crash rates at ordinary two-way stop-controlled (TWSC) expressway intersections. Almost all STAs surveyed are experimenting with treatments and design modifications to ordinary TWSC intersections, ranging from special public information and education campaigns to roundabouts and low-cost intersection grade separation strategies.

The purpose of the research described in this paper is to provide a better understanding of the safety performance of TWSC expressway intersections. By understanding the safety performance of TWSC intersections, highway professionals can better identify where safety problems are likely to occur. Under the best circumstances, if the conditions that result in the most problematic intersections are known during the corridor planning stage of an expressway’s development, highway planners and designers can avoid creating these conditions. For existing facilities, conditions that make existing intersections problematic can be identified so that traffic safety engineers can proactively identify where safety treatments should be applied and prioritize the implementation of those improvements.

To understand the safety performance of TWSC intersections, three analyses are presented in this paper. The first is a descriptive analysis using bar charts to illustrate how crash rate, crash severity, and fatal crash rate are affected by increasing intersection traffic volumes. The second analysis presents two safety performance functions (SPF) for TWSC intersections. SPFs estimate crash density (crashes per intersection per year) as a function of intersection characteristics. The third analysis uses an SPF to estimate the expected safety performance of all of the intersections, given each intersection’s traffic characteristics. The expected safety performance is then compared to the actual performance. The intersections with the poorest and best actual performances in comparison to expected performance are then examined to determine common characteristics across these intersections and the characteristics that cause deviation from the expected.

In the research report that is the basis for this paper, the STA survey helped identify 17 strategies that STAs are applying, either experimentally or routinely, to reduce crashes at expressway intersections (Maze, Burchett, and Hawkins 2004). Although it is beyond the scope of this paper to report on all 17, the continuum of strategies can generally be grouped into the following 4 categories:

- Intersection recognition strategies. These strategies alert the driver and draw attention to an approaching intersection using improved signage, approach rumble strips, warning signs, beacons, and intersection lighting.
- Speed change lane strategies. These strategies include off-set right- and left-turn lanes and left-turn median acceleration lanes.
• Low-capital–cost geometric strategies. These strategies replace movements that have a higher crash risk with those that have a lower crash risk. These generally involve indirect left-turn strategies (jug handles, loops, and median u-turns). A strategy the authors believe is very promising is shown in Figure 1. This is a directional median with a median u-turn. In this case, the higher crash risk minor road-cross and left-turn movements are replaced by a lower crash risk median u-turn. Although this strategy is commonly applied in urban areas in some states, it is not one generally applied in rural areas, and rural applications are even discouraged by AASHTO’s “Policy on Geometric Design of Highways and Streets” (the Green Book) (AASHTO 2001). One STA surveyed has been implementing this strategy at rural expressway intersections and reported excellent safety performance.

• Conflict-reducing high-capital–cost strategies. These strategies include signalization, relocating half of the intersection to create two-tee intersections, grade separating the intersection, constructing an interchange, and grade separating an entire corridor. Figure 2 shows an aerial photo of a grade-separated intersection. Although they are an unusual design, the two Iowa grade-separated intersections reduced the crash risk by one-third of the expected rate at a TWSC intersection with the same entering volumes.

The research report provides more detail on the continuum of strategies and identifies expected benefits and attributes of locations where the strategies are most appropriate.
DESCRIPTIVE ANALYSIS

The expressway intersection database that was developed to study the safety performance of TWSC rural expressway intersections includes five years of crash data (1996–2000) for 644 intersections on rural expressways in Iowa. The majority of these intersections have very low volumes and many experienced extremely low crash densities (crashes per intersection per year). Of the 644 intersections in the dataset, the minor roadways at 155 intersections are gravel-surfaced. The mean crash rate is 0.15 crashes per million entering vehicles (MEV) and the median crash rate is 0.068 crashes per MEV, indicating that the crash rate distribution is skewed towards intersections with very low crash rates and very low traffic volumes.

CRASH RATE ANALYSIS

In prior work conducted by the authors, it was observed that crash rates on expressways increased with increasing volumes (an upward-sloping safety performance function) (Maze et al. 2005). For example, crash rates on Iowa expressways with a daily traffic volume of less than 7,000 vehicles per day (VPD) averaged a crash rate of 0.79 crashes per million vehicle miles, while expressways with more than 10,000 VPD averaged 1.0 crashes per million vehicle miles. It was also observed that as volumes grew, the percentage of crashes at intersections grew. On expressways with fewer than 7,000 VPD, 21% of the crashes were at intersections, and when the volume increased to more than 10,000 VPD, crashes at intersections almost doubled to 39%. When a similar comparison was made with Minnesota data, where expressways experienced much higher traffic volumes than those in Iowa, the trend of higher crash rates and more intersection-involved crashes was even stronger. The new data from 644 intersections are used to determine the factors driving the trend toward more intersection-involved crashes.
Figure 3 graphs the crash rate, the crash severity rate (a system where the crash severity index for the intersection is divided by MEV per year), and the fatal crash rates for all intersections, summarized by increasing minor roadway volume. A simple severity index is used that applies a weight of five for a fatal crash, four for a major injury crash, three for a minor injury crash, two for a possible injury/unknown crash, and one for a property damage-only (PDO) crash.

It was expected that the average crash rate and the crash severity index would increase as the minor roadway volume increased. In other words, as crossing traffic volumes increase, the crash rate increases and crashes become more severe. The fatality rate also increases as minor roadway volume increases; the fatality rate is calculated using 100 million entering vehicles. Because each of these rates increases across increasing minor roadway volumes, the safety performance of the intersection declines as minor roadway traffic volumes increase. When a similar plot was created and stratified by increasing major roadway volume, the crash rates and severity rates did not tend to increase with increasing major roadway volumes.

Figure 3. Crash rate, crash severity rate, and fatal crash rate vs. increasing minor roadway volume

Crash Type

To help understand the relationship between crash type and volume on the minor and major roadways, Figure 4 was created. Figure 4 stratifies crash rates by minor roadway volume and excludes all PDO collisions. It was expected that as volumes increase, the proportion of right-angle crashes would increase. Right-angle crashes are generally a result of a driver on the minor roadway approach failing to select an appropriate gap in traffic. Figure 4 shows that the distribution of crash types changes with increasing volume. The proportion of right-angle crashes, therefore, also increases as minor roadway volumes increase. A similar bar chart was developed for increasing major roadway volume, and no increase in right-angle crashes with increasing major roadway traffic volumes was observed. Because right-angle
crashes are likely to be more severe, increasing minor roadway volumes result in increasing crash severity, as seen in Figure 4.

![Figure 4. Crash type by minor roadway volume without PDO](image)

### Safety Performance Function

This section describes the analysis of the intersection database using maximum likelihood to estimate parameters for a negative binomial SPF. Model parameters were estimated using the software package \textit{LIMDEP Version 7.0}. Given that the dependent variable of the model is count data (crash density = crashes per intersection per year), both Poisson and negative binomial models were considered for the analysis. Generally, crash data suffer from over-dispersion, which is a problem for the Poisson model but not the negative binomial model. Therefore, the negative binomial model was chosen.

Using the 644-intersection database, SPFs were estimated. The SPF generally involves the use of traffic volumes as independent variables and the crash density as the dependent variable.

Next, several regressions were performed using a negative binomial model. The purpose for working with the model is to obtain a general understanding of the relationships between the volumes and crashes. The authors used a Rho-squared value to demonstrate the goodness of fit of the model. Like R-squared, the Rho-squared value varies from 0.0 to 1.0 and measures the model’s ability to account for variance in the dependent variable. The closer this value is to 1.0, the better the model represents the data set (similar to an R-squared value). Rho-squared is commonly used when measuring the goodness of fit of a model that has a discrete dependent variable (such as count date) (Ben-Akiva and Lerman 1985). In Equation 1, the numbers in parentheses below each parameter represent the statistical significance of the parameter estimates (p-value). The p-value measures the chance that the parameter estimate is not statistically significantly different than zero. Therefore, the smaller the p-value, the more certain it is that the
relationship (the parameter estimate) between the independent variable and the dependent variable is statistically significant.

\[
\text{Crash density} = e^{(0.02278 + (0.00005 \times \text{Major ADT}) + (0.00042 \times \text{Minor ADT}))} \\
(0.881) \quad (0.0001) \quad (0.00001)
\]

Rho-squared value = 0.381

As expected, crash density increases with both minor and major roadway volumes. There is a strong statistical relationship between the independent variables and the dependent variable. The relatively low Rho-squared value indicates that there are important unaccounted variables, but the Rho-squared value is very good for this type of analysis. A model that also estimated the product of minor and major roadway volumes was included to test the importance of the interaction between minor and major roadways, but the interaction variable did not improve the model. The interaction term was dropped from further analysis.

In Equation 1, note that the coefficient for the minor roadway volume is nearly 10 times as large as that for the major roadway volume, indicating the stronger impact that minor roadway volume has on increasing crash density. Illustrating the relative importance of minor and major roadway volume, the crash density increases by 0.5% if the volume on the major approach increases by 100 VPD, and the crash density increases by 4% when the volume on the minor roadway increases by 100 VPD. This is interpreted to mean that crash density increases with increasing major road volume and crash rate increases with minor roadway volume.

Crash Severity Index Model

In evaluating the relationship between the intersection variables and crash severity, the intersections that experienced crashes were separated from those that did not. Three hundred twenty-seven intersections experienced at least one crash during the five-year period (1996–2000). Almost half the intersections in the dataset had no crashes. Crash severity was calculated over a five-year period for the remaining 327 intersections. The traffic volumes form the independent variable, while the crash severity index averaged over five years forms the dependent variable. Equation 2 shows the results.

\[
\text{Crash severity index} = e^{(2.10612 + (0.0000688 \times \text{Major ADT}) + (0.00040 \times \text{Minor ADT}))} \\
(0.001) \quad (0.00001) \quad (0.00001)
\]

Rho-squared value = 0.53

Equation 2 offered the best statistical properties of any statistical model estimated. In other models, other variables were included, such as median width and a dummy variable for the presence of right- and left-turn lanes at the intersection (the dummy variable is set equal to zero when no left-turn lane is present and one when a left-turn lane is present). When these variables were added, the regression resulted in lower Rho-squared values or parameter estimates that were not statistically significant.

Intersections with High and Low Crash Severity Rates

To identify intersections where the safety performance was worse or better than expected, the model of the intersection crash severity index (Equation 2) was used to estimate the expected five-year crash severity index for all intersections that experienced a crash. Inputting the actual major and minor roadway volumes into the model provides an estimate of the safety performance expected. Because some variables

Maze, Burchett, Welch, Hawkins
are not accounted for in the model, some intersections will perform worse than expected (intersections with a higher crash severity index) and some will perform better than expected. Next, 10 intersections for which the expected severity index exceeded the actual by the greatest amount (intersections with a low crash severity) and the 10 intersections for which the actual severity index exceeded the expected by the greatest amount (intersections with a high crash severity) were identified. The 10 intersections with the highest severity indexes and the 10 with the lowest severity indexes represented extremes in our data set. The next step was to look for characteristics to explain why the intersection’s performance deviated from what was expected.

Table 1 shows the average of the traffic volumes on the minor and major roadways for the 10 intersections with the highest and lowest severity rates and for the overall average (all 327 intersections). The authors were surprised to find that several of the intersections with low severity rates were on expressway segments with some of the highest volumes in Iowa. The same intersections with low severity rates have relatively low minor roadway volumes, which is consistent with expectations. Conversely, the intersections with high severity rates have relatively high minor roadway volumes, which is also consistent with expectations.

Table 1. Average daily traffic on approaches of high- and low-severity TWSC

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<tr>
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<th>ADT on major roadway</th>
<th>ADT on minor roadway</th>
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<tbody>
<tr>
<td>Low severity rate intersections</td>
<td>20,360</td>
<td>424</td>
</tr>
<tr>
<td>High severity rate intersections</td>
<td>11,490</td>
<td>2,300</td>
</tr>
<tr>
<td>Average for all intersections with at least one crash</td>
<td>10,840</td>
<td>1,362</td>
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Horizontal and vertical curves and intersection skewness (where intersecting roads meet at an angle other than 90 degrees) create situations where sight angles make it difficult to judge a gap across the median and appear to result in poorer safety performance. For example, 8 of the 10 most poorly performing intersections involve one or a combination of the following: 1) intersection skewness values of 15 degrees or more, 2) location on a horizontal curve of 3 degrees of curvature per one hundred feet or more, and/or 3) location on a vertical curve with a grade of 4% or more. One of the two remaining intersections is mildly skewed (less than 15 degrees) and is located immediately after a horizontal curve. All intersections with high severity rates are on expressways that are primary rural commuter routes, creating peaked intersection volumes, resulting in periods of congestion and delay and causing aggressive driving.

Figure 5 compares the types of crashes at the intersections with high crash severity rates and low crash severity rates. The difference in the distribution of crash type is stark. Sixty-six percent of the crashes at intersections with high severity crash rates are right-angle crashes, while only 13% are right-angle crashes at intersections with low crash severity rates. The high proportion of right-angle crashes indicates the difficulty that motorists have in judging safe gaps in traffic.
Figure 5. Crash type distributions for high and low crash severity intersections

CONCLUSION

The data analysis shows that TWSC expressway intersection crash rates, crash severity rates, and fatal crash rates increase with increasing minor roadway traffic volumes. Therefore, for intersections at which the minor roadway has high volumes (say, more than 2,000 VPD) or is expected to have high volumes, design engineers should examine the feasibility of special safety treatments instead of designing ordinary TWSC intersections.

Although future research must be done to further quantify the impacts of horizontal and vertical curves and intersection skewness, the preliminary findings presented in this paper suggest that these geometric features create problems for drivers trying to judge acceptable gaps in traffic. If curvature and skewness are related to safety performance as strongly as they appear to be, designers should work during corridor planning and preliminary engineering to avoid placing intersections where these conditions exist.
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REFERENCES


