IMPROVING SAFETY AT HIGH-SPEED RURAL INTERSECTIONS

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ABSTRACT

The Indiana Department of Transportation (INDOT) prepares annual reports that identify intersections and segments on state roads that require attention due to the excessive number and severity of crashes. Many of these identified intersections are two-way stop-controlled (TWSC) intersections on rural multi-lane roads with 55 or 60 mi/h speed limits. Various road design and human factors may contribute to the troublesome level of safety at Indiana high-speed rural intersections. Some of these safety factors have already been identified while other factors still await identification. This paper looks first at past research on safety at high-speed intersections to learn about known safety factors and to identify proven and proposed countermeasures. Next, extensive data, representing 557 Indiana TWSC intersections, are analyzed with statistical modeling to reevaluate some of the safety countermeasures found in the literature and to identify new ones. The developed trivariate ordered probit model estimates the effects of design, traffic, and land-use variables on crash severity and frequency at the studied intersections. The results are then used to estimate the possible reduction of fatal, injury, and property damage crashes associated with certain modifications of intersection geometry. Our findings show that adding acceleration lanes, increasing the intersection angle, widening medians more than 80 feet, and improving the recognizability of intersections considerably contribute to improving intersection safety.

Keywords: Intersections; transportation safety; countermeasures; crash reduction factors; road geometric improvements; Indiana.

INTRODUCTION

Roadway and human factors, as well as other factors, affect the level of safety at high-speed rural intersections. Past efforts to identify effective countermeasures that would successfully increase intersection safety have brought mixed results.

Several sources have identified factors that contribute to crash severity and frequency on high-speed divided highways. The factors that increase the frequency of crashes include traffic volume and residential and commercial development while residential and commercial development tends to increase the crash severity (Van Maren, 1977; Burchett et al., 2005). Roadway characteristics also play a significant role; intersections located on or near horizontal and vertical curves tend to have higher crash rates than intersections on tangent segments (Savolainen and Tarko, 2005; Burchett et al, 2005; Khattak et al, 2006; Van Maren, 1977).

One main concern is that drivers on the minor roadway find it difficult to evaluate gaps between vehicles on the major road due to the high speed traffic and the divided roadway. Consequently, drivers may select an unsafe gap in the major road traffic flow when performing a turning or crossing maneuver (Burchett et al, 2005). Right-angle collisions, the result of selecting a gap that is too short, account for between 36 to 50 percent of crashes at intersections on high-speed divided highways, as opposed to 28 percent of crashes at intersections on other types of roads (Alexander et al, 2007).

To improve safety at high-speed intersections, a number of safety countermeasures have been proposed, some of which have been implemented. NCHRP Report 500 summarizes these safety countermeasures. The countermeasures listed there have had varying degrees of success; some of them have been used extensively and are proven to work, while others are still in the experimental stages of study.

The first step to improving safety at TWSC intersections is to provide an adequate sight distance for drivers on the minor road to view the approaching traffic on the major road. AASHTO (2004) helps determine the minimum sight distances for various traffic maneuvers at unsignalized intersections. One proven countermeasure in NCHRP Report 500 is installing separate left-turn and right-turn lanes. These lanes allow drivers to separates themselves from the main traffic stream before slowing down and, in the case of a left turn, before stopping to yield to oncoming traffic and to turn left. This countermeasure decreases the frequency of rear-end crashes, especially where the through traffic on the major road is heavy.

One concern unique to divided highway intersections is that the left-turn paths may overlap. This can be resolved with the use of offset left-turn lanes. The Ohio Department of Transportation favors their use on their rural divided highways, and Khattak et al. (2006) found that intersections that have offset left-turn lanes have fewer crashes than intersections that do not have them. NCHRP Report 650 documents a case in North Carolina where the installation of offset left-turn lanes resulted in a decrease in crashes at an intersection with a heavy volume of left turns departing the major road. However, this solution is not preferable at intersections with high volume traffic crossing the major road due to possible confusion among drivers about the yielding rules (MoDOT, 2009).

Another geometric improvement allows two-stage crossing or turning left from the minor road by providing a sufficient refuge area inside the intersection to facilitate selection of a gap in one traffic direction at a time. There are several ways of doing this, including widening the median, using indirect left-turn treatments, and adding a median acceleration lane. Van Maren (1977) notes that a good highway design should not force drivers to make too many decisions simultaneously; therefore, it is expected that a two-stage crossing of the divided highway should result in improved safety.

To allow the two-stage crossing and turning left from the minor road, AASHTO (2004) recommends that the median be as wide as possible. It suggests that the median should be at least 25 feet wide to accommodate a passenger car, but may need to be significantly wider (80-150 feet) in order to store a school bus or a large truck. Not all divided highways can have an adequate median width because building a wide median may be cost-prohibitive at locations with a restricted right-of-way. One method of implementing a two-stage crossing at such locations is an indirect left-turn treatment (e.g., Michigan Left, Superstreet, or J-turn). Vehicles from the minor road, that intend to cross the major road or turn left, must turn right onto the major road instead and then make a U-turn at a median crossover downstream of the intersection (Levinson et al., 2000; Chowdbury et al., 2003). The direct left-turn movements from the major roadway may or may not be permitted depending on the intersection. An implementation of this treatment in Maryland has been extremely successful. In the three years before the implementation, there were 38 crashes; whereas there were only four crashes in the six years that followed the intersection improvement (Iowa State University, 2007; Hochstein et al., 2009; NCHRP Report 650).

Adding a parallel acceleration lane in the median is another way of implementing a two-stage left turn. This solution allows left-turning traffic to accelerate and merge in with the far-side traffic, similar to merging from an on-ramp to a freeway mainstream traffic (Maze et al., 2004; MoDOT, 2009; NCHRP Report 375; NCHRP Report 650). Parallel acceleration lanes may not be preferable at a four-leg intersection with heavy volumes of cross traffic if they reduce the median width below the minimum needed for vehicle storage.

Other safety countermeasures do not involve geometric changes and rely on enhanced signage on a high-speed road that warns drivers of an upcoming intersection. Both Nebraska and Ohio have developed different signing practices that help enhance the conspicuity of the intersection. In a case study in Minnesota, conventional signage at an intersection on a rural divided highway was replaced with larger signs. A before-and-after analysis showed that, even though the crash rate increased slightly in the 2 ½ years after the signage change compared to the three years before, there was a significant reduction in angle crashes (NCHRP 650). Some other measures have included dynamic warning signs (NCHRP 500). It should be noted that the use of overhead flashers at an intersection may confuse some drivers (observed in driving simulator study at the University of Minnesota) leading to dangerous behaviors (Preston and Storm, 2003).

A promising countermeasure is assisting drivers in selecting safe gaps in the major road traffic. One notable treatment is known as the Cooperative Intersection Collision Avoidance Systems-Stop Sign Assist (CICAS-SSA) (Gorjestani et al, 2008). The system is meant to reduce the frequency of crashes at rural expressway intersections. CICAS-SSA uses sensing technology, a computer processor, and algorithms to determine unsafe conditions. A driver interface provides timely alerts and warnings about these conditions. Although research results thus far have been encouraging, this system is still considered experimental and is undergoing further evaluation (NCHRP 650).

An ultimate solution is converting an at-grade intersection into a grade separation, possibly with connectors for movements that must be facilitated. Although this improvement may result in the safest operations, it is the most expensive solution and should therefore be considered as a last resort option. Several partial grade separation concepts also have been developed (AASHTO, 2004; MoDOT, 2009; Hochstein et al., 2010).

Even though a number of authors have investigated the problem, some of these studies have been limited in scope, and some of the identified potential countermeasures still await in-service evaluation. Therefore, a systematic data-based analysis of safety at high-speed rural intersections focused on the impacts of road design and other factors should be beneficial.

DATA

The studied sample includes 557 Indiana intersections located on nine four-lane rural highway corridors within 36 counties and within all the six Indiana districts. The intersections included in the sample are two-way stop-controlled (TWSC) intersections on rural high-speed divided highways; and all approaches from the minor road are controlled by stop signs.

GoogleEarth Professional software was used to identify intersections that matched the criteria: rural location, state route, and divided highway. These characteristics indicated that the speed limit on the state–administered highways was at least 45 mi/h (range between 45 and 60 mi/h). The aerial photography and GIS capabilities of the software assisted with collection of geometric information the GoogleEarth and link it with data from other sources. The data collected with GoogleEarth included for each intersection:

- Number of intersection legs;
- Median width measured between median markings;
- Presence of a median and/or divisional islands on the crossroad;
- Corner radii, if there was a separate right-turn bypass lane(s);
- Intersection angle;
- Number of separate left-turn lanes and right-turn lanes, both on the major road and the crossroad. This information was also recorded for each intersection approach;
- Presence of acceleration lanes and/or tapers on approaches from the minor road (recorded for each intersection approach);
- Number of approach lanes on the minor roadway;
- Presence of through-movement or turning restrictions on the minor roadway;

- Presence of closely-spaced access points or other intersections (within 300 feet) on the major or minor roadway;
- Presence of railroad crossings near the intersection (within 400 feet);
- Horizontal curvature on both the major road and the minor road, whether the intersection was on the curve or within close proximity to a curve, and the radii of such curves;
- Land uses surrounding the intersection, and, additionally, whether the intersection is a point of access into a city or town; and
- Whether the minor roadway was a state roadway or a local roadway.

Relevant data such as intersection controls, advanced signage, vertical curvature, and intersection conspicuity could not be collected from the aerial photographs. These data were collected with the INDOT Video Log system. Most of the data collected were from 2006, but some information was retrieved from earlier video logs.

The Indiana Video Log allows "driving" along the roads included in the Video Log database, extracting the location information, and making measurements directly on the video image using built-in tools. Each intersection included in the study was viewed in the Video Log from each approach and additional data were recorded. This allowed documenting approach-specific conditions that might be different on a different approach; considerable differences were present particularly between the major and minor roadways. In some cases, opposite approaches on the major road were also different. For example, an intersection was recognizable when approaching it from one direction on the highway but not be recognizable in the other direction. In another case, a considerable grade was present on one approach to the intersection while the opposite approach was flat.

For each intersection approach, several more attributes were collected, as follows:

- The presence and type of advance signage on the intersection approach. This was grouped into five types: conventional guide signage, freeway-style (larger) guide signage, overhead signage, route number signage, and warning signage.
- Speed limit data. In some cases, a lower advisory speed was posted for the intersection, which was also noted.
- Intersection recognizability consideration in the distance and time domains. The conspicuity distance is the distance to the intersection at which there are obvious indications of the intersection presence. This distance was determined at each intersection and for both major approaches on the major road. This distance was compared with the stopping sight distance and decision sight distance (AASHTO, 2004), and any deficiencies were noted.
- The conspicuity time is the time to reach the intersection from the point where the intersection is noticeable. Two conspicuity times were calculated for each major approach by dividing the corresponding conspicuity distance by two speeds: (1) the posted speed limit and (2) a constant speed of 100 ft/s (68 mi/h). The constant speed was

used to check if the low intersection conspicuity under the assumption of excessive speed (regardless of the speed limit) was correlated with the occurrence of crashes.

- Surface treatment, asphalt or concrete.
- Grades and vertical curvature. Information was collected on whether it was an upgrade or downgrade, whether there was a crest or sag vertical curve, and the distance of any vertical curve to the intersection.
- Presence of overhead flashers at the intersection.

The correctness of the data collected with the Google Earth and the Video Log were confirmed by field visits to selected locations.

The state speed limit on rural divided highways changed on July 1, 2005, from 55 mi/h to 60 mi/h. The video logs collected in 2004 and 2006 were viewed to check which intersections had a speed limit change. It was concluded that most of the rural high-speed intersections on divided highways currently have the 60 mi/h speed limit. All of them had the speed limit of 55 mi/h before July 1, 2005. In a few cases, however, the original speed limit of 55 mi/h was unchanged. Additionally, all of the intersection approaches with an original speed limit lower than 55 mi/h have retained the 55 mi/h speed limit and are documented in the data set. We believe that in all the cases of unchanged speed limits, the primary reason for keeping the original speed limits was a safety concern. This is an important point which will be later considered when interpreting the results.

Finally, the Annual Average Daily Traffic (AADT) values were retrieved for each intersection from the most recent traffic flow maps on INDOT's website. The retrieved data were adjusted with the growth adjustment factors to convert them to the values relevant to the years with crash data (2004-2007). Only the traffic volumes for the major roads were available.

Information about crashes that happened in the 2004-2007 period at the studied intersections was extracted from the Indiana crash database. The severity of each crash was measured on the KABCO scale. The KABCO scale is an indication of the severity of each crash based on whether anyone involved in the crash was killed (K); sustained incapacitating injuries (A), minor injuries (B), or possible injuries (C); or was uninjured (O) and property damage only occurred. The most severe injury sustained in a crash determines the severity of the crash.

A total of 2,326 crashes extracted from the crash database were linked with the sample intersections, which were broken down by injury severity; Table 1 shows this distribution. Note that, following the nature of the injury-severity level of each crash and INDOT preferences, the fatal and incapacitating crashes are combined together (K and A); the minor and possible injury crashes are combined together (B and C); and non-injury/property damage only (PDO or O) crashes are kept separate.

Table 1 Crash Distribution by Injury Severity

Crash severity	**Number of crashes**
Fatal (K)	126
Incapacitating injury (A)	
Minor injury (B)	720
Possible injury (C)	
Property damage only (O)	1,480

STATISTICAL MODELING AND RESULTS

The state speed limit on rural roads was changed on July1, 2005, 18 months into the study period with the considered crashes. The traditional year-based aggregation could not be used and we decided to divide the four-year period into eight six-month intervals to be able to use all of the available data and to study the effect of speed limit changes on crashes. Therefore, the entire period of four years was divided into three six-month intervals before the speed limit change and five six-month intervals after the speed limit change. The 557 intersections in the sample generated 557x8 = 4,456 observations. After removing observations with missing values, 4,348 observations were used in the modeling. Our model-based statistical analysis did not detect any significant difference between the first and second halves of each year so the effect of seasonality thus could be ignored in this case.

The observations differed by geometry, traffic, operational characteristics, and KA, BC, and PDO crash totals. The traditional approach to statistical modeling of safety includes modeling crash frequency (Lord and Mannering, 2010) and severity separately given that a crash happened (Savolainen et al., 2011). Our approach differs from the traditional one. We applied a trivariate ordered probit model that allowed us to combine estimation of the frequency and severity of crash in one model. Safety at an intersection is represented by a set of crash counts distributions: one distribution for each level of severity as shown in Table 2. There are three bins for the fatal and incapacitating injury (KA) crashes, six bins for the minor and possible injury (BC) crashes, and eight bins for the property damage only (PDO) crashes.

Table 2 Bins used in crash frequency/severity modeling by severity level

Crash severity	Crash count	Number of Observations
Fatal or incapacitating injury (K or A)	0	4,230
	1	113
	2	5
Minor or possible injury (B or C)	0	3,845
	1	364
	2	93
	3	34
	4	9
	5 or more (6.00*)	3
Property damage only (PDO) (O)	0	3,464
	1	606
	2	167
	3	54
	4	27
	5	5
	6	7
	7 or more (9.50*)	18

*Average number of crashes in the bin

The multivariate ordered probit model estimated the probability of the number of crashes for each severity level based on the values of the explanatory variables. Equation 1 shows the univariate ordered probit model formulation on which the multivariate model was based (Washington et al., 2011):

$$\begin{gathered} P(y=0)=\Phi(-\boldsymbol{\beta}\boldsymbol{X}) \\ P(y=1)=\Phi(\mu_1-\boldsymbol{\beta}\boldsymbol{X})-\Phi(\boldsymbol{\beta}\boldsymbol{X}) \\ P(y=2)=\Phi(\mu_2-\boldsymbol{\beta}\boldsymbol{X})-\Phi(\mu_1-\boldsymbol{\beta}\boldsymbol{X}) \\ \dots \\ P(y=n)=1-\Phi(\mu_{n-1}-\boldsymbol{\beta}\boldsymbol{X}) \end{gathered} \tag{1}$$

Where:

$P(y=i)$ is the probability of number of crashes falling into crash bin i (i is equal to the number of crashes except the last bin, see Table 2),

Φ is the cumulative normal distribution,

μ_i is the threshold, and

$\boldsymbol{\beta X}$ is the product of the vectors of the estimated coefficients and the explanatory variables plus the error term, as shown in Equation 2:

$$\boldsymbol{\beta X} = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \varepsilon \qquad (2)$$

X_i represents explanatory variable i, and β_i represents the corresponding coefficient. The ε ~N(0,1) represents the error term of the model. The multivariate ordered probit model differs from the univariate in that it accounts for cross-equation error correlation between the levels of injury severity.

The model was estimated with SAS software (SAS, 2007). Initially, all of the explanatory variables were included in the model for estimation; and based on the results, the model was further refined depending on whether or not a variable was significant. Some variables included in the analysis were collinear or nearly collinear with each other. In such cases, the model was estimated with each variable separately and the variable that provided the best overall fit was kept in the final model. Tables 3, 4, and 5 present the obtained results. The final model includes only statically significant variables. An explanatory variable was considered to be statistically significant if the *t*-statistic was at least 1.6 (the *p*-value was less than 0.10).

Table 3 Parameter Estimates from SAS Multivariate Ordered Probit Model - fatal and incapacitating injury (K and A) crashes

Variable	Description	Coef.	Standard error	t-stat.	p-value
KAcr.Intercept	Intercept	-2.3461	0.1390	-16.87	<.0001
KAcr.INDOTrd	1 if minor road administered by INDOT, 0 otherwise	0.5765	0.1341	4.30	<.0001
KAcr.Popul	Population of city/town within 6 miles along minor road (scaled by 100,000)	1.7354	0.4343	4.00	<.0001
KAcr.LTB	1 if left-turn bays on major road, 0 otherwise	0.4678	0.1434	3.26	0.0011
KAcr.CommLU	1 if commercial area, 0 otherwise	0.3129	0.1351	2.32	0.0206
KAcr.TInt	1 if three-leg intersection, 0 otherwise.	-0.1819	0.1049	-1.73	0.0829
KAcr.RTacl	1 if parallel right-turn acceleration lane on major road, 0 otherwise	-0.4557	0.2634	-1.73	0.0836
KAcr.MjCrv	1 if horizontal curve on major road, 0 otherwise	-0.1717	0.0994	-1.73	0.0841
KACr.Limit1	Limit between 0 and 1 BC crashes	0.0000	Fixed		
KACr.Limit2	Limit between 1 and 2 BC crashes	1.1214	0.1254	8.94	<.0001

Table 4 Parameter Estimates from SAS Multivariate Ordered Probit Model - minor and possible injury (B and C) crashes

Variable	Description	Coef.	Standard error	t-stat.	p-value
BCcr.Intercept	Intercept	-1.9252	0.0858	-22.44	<.0001
BCcr.AADT	Average Annual Daily Traffic (AADT) on major road (scaled by 10,000)	0.1476	0.0358	4.12	<.0001
BCcr.INDOTrd	1 if minor road administered by INDOT, 0 otherwise	0.7134	0.0961	7.43	<.0001
BCcr.Popul	Population of city/town within 6 miles along minor road (scaled by 100,000)	1.4826	0.3388	4.38	<.0001
BCcr.LTB	1 if left-turn bays on major road, 0 otherwise	0.5395	0.0844	6.39	<.0001
BCcr.ResidLU	1 if residential area, 0 otherwise	0.1413	0.0529	2.67	0.0076
BCcr.CommLU	1 if commercial area, 0 otherwise	0.3102	0.0880	3.52	0.0004
BCcr.TInt	1 if three-leg intersection, 0 otherwise.	-0.1196	0.0604	-1.98	0.0477
BCcr.SchlChLU	1 if school or church near intersection , 0 otherwise	0.4212	0.2050	2.05	0.0399
BCcr.RXRmaj	1 if railway crossing on major road, 0 otherwise	0.4360	0.2509	1.74	0.0823
BCcr.MedGT80	1 if median wider than 80 feet, 0 otherwise	-0.4240	0.2212	-1.92	0.0553
BCcr.LTacl	1 if parallel left-turn acceleration lane on major road, 0 otherwise	-0.2297	0.0946	-2.43	0.0152
BCcr.MjCrv	1 if horizontal curve on major road, 0 otherwise	-0.1453	0.0596	-2.44	0.0147
BCCr.Limit1	Limit between 0 and 1 BC crashes	0.0000	Fixed		
BCcr.Limit2	Limit between 1 and 2 BC crashes	0.7131	0.0352	20.27	<.0001
BCcr.Limit3	Limit between 2 and 3 BC crashes	1.2270	0.0581	21.12	<.0001
BCcr.Limit4	Limit between 3 and 4 BC crashes	1.7496	0.1003	17.45	<.0001
BCcr .Limit5	Limit between 4 and 5+ BC crashes	2.2009	0.1724	12.76	<.0001

Table 5 Parameter Estimates from SAS Multivariate Ordered Probit Model – property damage only (PDO) crashes

Variable description	Description	Coef.	Standard error	t-stat.	p-value
PDOcr.Intercept	Intercept	-1.5609	0.0740	-21.08	<.0001
PDOcr.AADT	Average Annual Daily Traffic (AADT) on major road (scaled by 10,000)	0.2604	0.0314	8.28	<.0001
PDOcr.INDOTrd	1 if minor road administered by INDOT, 0 otherwise	0.8392	0.0882	9.52	<.0001
PDOcr.Popul	Population of city/town within 6 miles along minor road (scaled by 100,000)	1.5065	0.3144	4.79	<.0001
PDOcr.LTB	1 if left-turn bays on major road, 0 otherwise	0.3376	0.0735	4.59	<.0001
PDOcr.RTB	1 if right-turn bays on major road, 0 otherwise	0.2163	0.0610	3.54	0.0004
PDOcr.CommLU	1 if commercial area, 0 otherwise	0.2660	0.0787	3.38	0.0007
PDOcr.TInt	1 if three-leg intersection, 0 otherwise.	-0.1873	0.0528	-3.55	0.0004
PDOcr.ang75a90	1 if intersection angle between 75 and 90 degrees, 0 otherwise	-0.1047	0.0482	-2.17	0.03
PDOcr.Any12sdf		0.1523	0.0456	3.34	0.0008
PDOcr.MedGT80	1 if median wider than 80 feet, 0 otherwise	-0.5986	0.2060	-2.91	0.0037
PDOcr.LTacl	1 if parallel left-turn acceleration lane on major road, 0 otherwise	-0.1937	0.0819	-2.37	0.018
PDOcr.RTtpr	1 if tapered right-turn acceleration lane, 0 otherwise	-0.1803	0.0539	-3.35	0.0008
PDOcr.MjCrv	1 if horizontal curve on major road, 0 otherwise	-0.1478	0.0518	-2.85	0.0043
PDOcr.Limit1	Limit between 0 and 1 PDO crashes	0.0000	Fixed		
PDOcr.Limit2	Limit between 1 and 2 PDO crashes	0.7460	0.0280	26.68	<.0001
PDOcr.Limit3	Limit between 2 and 3 PDO crashes	1.2166	0.0419	29.01	<.0001
PDOcr.Limit4	Limit between 3 and 4 PDO crashes	1.5284	0.0549	27.83	<.0001
PDOcr.Limit5	Limit between 4 and 5 PDO crashes	1.7985	0.0704	25.53	<.0001
PDOcr.Limit6	Limit between 5 and 6 PDO crashes	1.8703	0.0755	24.76	<.0001
PDOcr.Limit7	Limit between 6 and 7+ PDO crashes	1.9942	0.0855	23.31	<.0001

The errors terms of the three latent variables of the ordered probit models were found to be significantly correlated with each other (Table 6). This result justified the use of the trivariate version of the ordered probit model.

Table 6 Correlation coefficients of the error terms ε

Correlation Coefficient	Coefficient	Standard error	t-stat.	p-value
Rho.KAcr.BCcr	0.3770	0.0458	8.24	<.0001
Rho.KAcr.PDOcr	0.3260	0.0437	7.45	<.0001
Rho.BCcr.PDOcr	0.4664	0.0254	18.34	<.0001

The final model was used to estimate the expected number of crashes at each level of crash severity. A sensitivity analysis of the expected number of crashes was conducted to investigate the impact of the identified safety factors.

Results

The following intersection attributes were found to be associated with the increased frequency of crashes in the various severity levels:

- Heavy traffic (AADT) on the major roadway;
- The minor roadway administered by state (intersection complexity and higher volumes);
- Considerable population (villages and towns) along the minor roadway and within six miles of the intersection (substitute for traffic volume on the minor road);
- Left-turn bays on the major roadway (substitute for considerable left-turn volumes);
- Right-turn bays on the major roadway (substitute for considerable right-turn volumes);
- Residential development present in the direct neighborhood of the intersection;
- Commercial development present in the direct neighborhood of the intersection;
- Schools or churches present in the direct neighborhood of the intersection;
- At-grade railroad crossings on the major roadway near the intersection; and
- Limited intersection conspicuity to drivers on the major roadway.

The following intersection attributes were found to be associated the reduced frequency of crashes:

- Left-turn parallel acceleration lanes on the major roadway;
- Right-turn parallel acceleration lanes on the major roadway;
- Close to normal intersection angle (within 75 - 90 degrees)
- Median at least 80 feet wide;
- Minor road terminating at the intersection (T-intersection); and
- Horizontal curvature on the major roadway.

As the major road traffic increases along the major road, there is also an increase in crashes because of the increased difficulty for minor road traffic to find suitable gaps, which has been confirmed with many other studies (NCHRP Report 650; Savolainen and Tarko, 2005; Burchett et al., 2005; and many others).

Traffic volumes on minor roads, most of which are local roads, were not available. Several variables were used as proxy variables to measure this effect. These variables included the presence of residential and/or commercial land uses around the intersection, the presence of a city or town along the minor road, the population of the city or town, and whether the minor road was under INDOT jurisdiction (U.S. or state route). All of these factors are associated with the increased traffic and turning movements from crossing roads and, not surprisingly, all of these factors increase the estimated frequency of crashes. In particular, the increase in crashes was the strongest with the presence of commercial land uses at the intersection. The presence of a city or town accessible via the intersection also led to an increase in crashes, with the effect growing stronger as the population increased.

The model shows that the presence of left-turn lanes was associated with an increase in the number of crashes, which is due to left-turn bays tending to be present at intersections with considerable left-turning traffic. As left-turn volumes were not available, the presence of left-turn bays were considered as a substitute for left-turning volumes and higher exposure to crashes. Apparently, the exposure effect of turning volumes is stronger than the possibly positive effect of turning bays.

A similar result was obtained with the presence of right-turn bays, with their presence also associated with more crashes. Here again, this is only indicative of heavier volumes of right-turn traffic, since right-turn bays are only installed where the need exists. However, the effect was not as strong and was only significant for the PDO crashes.

The presence of a railroad crossing at the intersections was associated with a higher frequency of crashes. Railroad crossings disrupt traffic on a roadway, and queues sometimes may impact a nearby intersection.

Poor intersection recognizability may lead to an increase in PDO crash frequency (no significant effect detected for more severe crashes). At intersections that are not recognizable to drivers on the major road, there is an increased risk of a surprise should another driver on the minor roadway enter the intersection. Additionally, if a driver who intends to leave the major roadway at the intersection does not know the intersection location in advance, he or she may be forced to brake abruptly and to create a hazard.

Three-leg intersections were found to have fewer crashes at all levels of severity than four-leg intersections. This is intuitive because there are fewer turning conflicts and no crossing conflicts at a three-leg intersection than at a four-leg intersection.

The presence of a median acceleration lane for left turns was found to be associated with considerably fewer crashes than at other locations. This lane allows drivers turning left from the minor road, after crossing the near-side traffic stream, to accelerate and then merge onto the highway into the far-side traffic stream. It permits a two-stage left turn, even with a narrow median. The expected effect was a reduction in angle crashes because the need to select a gap in the far side of the highway traffic is mitigated. It also allows more space for evasive maneuvers.

The effect of median acceleration lanes on intersection safety performance is considerable. This effect was tested in combination with other factors (AADT on major road, presence of left-turn bays on major road, crashes related to each highway corridor, and crashes related to the six different INDOT districts) to determine which of these factors had a stronger impact than the median acceleration lanes on crashes. No other significant factors could be found. These tests have strengthened the evidence that median acceleration lanes have a strong positive impact on safety.

The presence of right-turn acceleration lanes on the major roadway was found to significantly reduce KA crashes. This countermeasure can be expected to reduce angle crashes because it reduces the speed difference between the vehicles on the major road and the vehicles merging to this road.

Intersections with 75- to 90-degree angles were also found to reduce PDO crashes, which is in line with the AASHTO (2004) recommendation to avoid building intersections with a severe skew angle. AASHTO (2004) recommend using intersection angles as close to 90 degrees as possible and avoiding angles less than 60 degrees.

Intersections with at least 80 feet wide medians experience fewer BC and PDO crashes. A wider median makes it easier for larger vehicles to make two-stage crossings. With a wider median, drivers will be more confident that they can cross the first half of the divided highway and be able to safely wait for gaps in the far-side traffic before completing the crossing maneuver (or left turn).

The intersections with reduced speed limits of 45 and 50 mi/h, as well as a number of intersections with a speed limit of 55 mi/h, had no speed limit increase on July 1, 2005. A separate analysis focused on the speed limit effects. A cross-sectional analysis was hampered by the endogeneity of the speed limit variable. Speed limits are posted on road sections in response to the safety concerns of engineers or road users. Speed limits might improve safety only partially and such locations with speed limits tend to be more dangerous than others. We decided not to include the speed limit variable to the discussed here model because of the mentioned endogeneity issues.

The effect of increasing the statewide speed limit on traffic safety was evaluated by using a sub-sample of the intersections where the speed limit had been increased from 55 mi/h to 60 mi/h. No significant safety effect, negative nor positive, could be detected. It is possible that the speed limit increase matched the speed behavior already present on the road (i.e., drivers most likely drove faster than 55 mi/h before the change in the speed limit). If the effect of changing speed limits is reversible and reducing a speed limit does not change safety, this would prompt careful consideration of speed limits as safety countermeasures. The tendency of lower safety at the intersections with reduced speed limits observed in our sample supports the concern about the low effectiveness of speed limits in improving safety. If used, a speed limit reduction should be accompanied by aggressive and routine police enforcement.

In our sample, nearly half of the intersections were located on a horizontal curve or at a distance less than 1,500 ft. These intersections were associated with the lower frequencies of PDO crashes. No effect on more severe crashes was detected, which was a surprising result. Horizontal curves increase the complexity of driving and can make an evasive maneuver on a major road more difficult. Furthermore, assessing gaps between vehicles moving along a curved road may be more difficult for drivers stopped on the minor road (Burchett and Maze, 2005; NCHRP Report 650). It has been concluded in past research that considerably superelevated roads on horizontal curves have a negative impact on intersection safety (Savolainen and Tarko, 2004). Our result is difficult to explain from the crash causality point of view. It could be the effect of a complex interplay between the variables in the sample and a potential omission of other variables. This interpretation is supported by the lack of association between the horizontal curve presence and the intersection safety in the sample with removed low speed limits (used to evaluate the increase of the statewide speed limit).

RECOMMENDATIONS FOR IMPROVING SAFETY

Based on the results of the modeling results and on the literature, the following recommendations are made to improve safety on both new and existing high-speed divided highways.

New Construction

The recommendations for new construction are as follows:

<u>Design the intersection angle at 75 to 90 degrees.</u> The Indiana study indicates a 20% reduction in crashes at intersection angles at 75 to 90 degrees than intersections more skewed.

<u>Consider J-turns (or median U-turns) at intersections</u> to allow a two-stage crossing. The J-turn is recommended where major-road left turns are relatively high; the U-turns may be a good choice with weaker turning volume.

<u>Design left-turn and right-turn bays</u> at intersections. NCHRP Report 500 reports a clear safety benefit to providing a dedicated lane for turning vehicles to decelerate away from the through traffic.

<u>Design the median at least 80 feet wide</u> in the intersection area. The Indiana study indicates that there are far fewer crashes with medians that are at least 80 feet wide than with narrower medians. Wider medians allow better opportunities to make a two-stage crossing.

<u>Limit intersections to three legs if possible</u> if the median cannot be at least 80 feet wide. The Indiana study has demonstrated that three-leg intersections are safer than four-leg intersections because of a lack of crossing traffic and fewer conflicts. Converting a four-leg intersection to two three-leg intersections requires additional analysis because short spacing between the new intersections may cause additional crashes.

<u>Consider left-turn acceleration lanes in the median</u> to reduce the difference in speed between the vehicles merging after turning left and the through traffic along the major road.

Avoid locating intersections near horizontal curves. This study agrees with other studies that intersections near horizontal curves experience more crashes than intersections on tangent segments.

Avoid locating intersections near railroad crossings. The negative effect was shown in this research. Although it should be confirmed with a larger study, it would be prudent to follow this recommendation if it is not cost-prohibitive.

Existing intersections

Recommendations for improving safety at existing intersections are as follows:

Convert direct left turns to indirect left turns. This change can be completed by closing off the median and adding U-turns in the median, which will reduce the conflicts in the median and facilitate a two-stage crossing.

Add parallel acceleration lanes in the median This study and other studies show some safety benefits with a median acceleration lane because left-turning traffic can enter the far side of the divided highway more easily. However, it will not resolve a crash problem with cross traffic.

Add larger signage to make the intersection more conspicuous, which was shown by this study and other studies to have safety benefits.

Add lighting, particularly if the majority of crashes occur at night.

CONCLUSIONS AND SUMMARY

The Indiana Five Percent Reports over the past several years identified a safety problem concerning at-grade intersections on high-speed divided highways. The current paper identified factors that tend to increase the frequency and severity of crashes at these intersections and countermeasures that can be used to improve safety.

The safety recommendations of this research were based on both a literature synthesis and a statistical analysis of 557 existing intersections in Indiana and 72 existing intersections in Michigan. Statistical analysis was performed in order to identify what factors tend to increase the frequency and severity of crashes at existing intersections. The literature review aimed to identify existing design guidelines at high-speed rural intersections, as well as the experiences of other states in terms of their crash experience, in order to recommend several promising countermeasures that could be implemented.

A number of factors were identified as causes of increases in the likelihood of crashes at the three severity levels: increased turning traffic (using the presence or absence of left and right-turn bays as a surrogate measure); horizontal curves within the intersection area; traffic volumes at the intersection on both the major and the minor roads (using surrogate measures for the minor road the land use, population of the areas immediately surrounding the study location, and the road functional class); at-grade railroad crossings in the intersection area; and lack of conspicuity. On the other hand, acceleration lanes for both left and right turns, increased median width, an intersection angle that is close to perpendicular, and the presence of three legs (instead of four) at the intersection (determined indirectly using various surrogate measures) were all factors found to decrease the likelihood of crashes in the severity categories. These results are in line with other research results as documented in the literature review.

Based on the results of this research and other studies, the following recommendations are made to improve safety at new intersections as well as at existing intersections. For new intersections, constructing wide medians is suggested; in cases where this is not possible and a narrow median needs to be constructed, reducing the legs of the intersection to three is suggested. It is also suggested that intersections be placed away from horizontal curves and at-grade railroad crossings. At existing intersections, closing off the median or restricting certain maneuvers is suggested. Median acceleration lanes can be added as well in order to provide for a two-stage crossing or left-turn maneuvers. Enhanced guide and warning signage can be used to improve conspicuity; and adding illumination can especially can help at night. The practice of adding left- and right-turn bays should be continued as this countermeasure has been proven to make intersections safer. All of these countermeasures can help improve safety without having to build grade separations, which should be used only when absolutely necessary due to the associated high costs to both the roadway agency and the traveling public.

The median acceleration lane, the J-turn (indirect left turn), U-turns, and the enhanced guide signage are all recommended for further study.

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