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Analysis and Methods of Improvement of Safety at High-Speed Rural Intersections

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JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

ANALYSIS AND METHODS OF IMPROVEMENT OF SAFETY AT HIGH-SPEED RURAL INTERSECTIONS

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16. Abstract Since 2006, INDOT has been preparing an annual five-percent report that identifies intersections and segments on Indiana state roads that require attention due to the excessive number and severity of crashes. Many of the identified intersections are two-way, stop-controlled intersections located on high-speed, multi-lane, rural roads. Some contributing design and human factors have been identified while other factors still await investigation. Multivariate ordered probit models have been developed to help identify additional factors of the frequency and severity of crashes. These models can estimate how much different factors increase the frequency of crashes at several levels of injury severity (fatal/incapacitating, non-incapacitating/ possible, property-damage-only). They have a unique ability to account for unobserved but common conditions that affect all of the crash severity levels. Recommendations for safety countermeasures are made based on both of these research results and our study of published reports of other authors.

The statistical analysis was performed on 553 existing intersections in Indiana and 72 existing intersections in Michigan using crash data reported during a four-year period. The identified safety factors include: presence of horizontal curves within the intersection vicinity, traffic volume on the major road, land use, population of the area surrounding the intersection, and the minor road functional class (traffic volume on minor road unknown), nearby at-grade railroad crossings, intersection conspicuity to drivers on the major road, acceleration lanes for both left and right turns, median width, intersection angle, and number of intersection legs. These results are in line with other research results as documented in the literature review. Based on the results of this and other studies, recommendations are made to improve safety at new intersections as well as at existing intersections. For new intersections, construction of medians wider than 80 feet is suggested. Where this is not possible and a narrower median needs to be constructed, adding a parallel acceleration lane for vehicles turning left from the minor road is suggested. Intersections should be placed at a sufficient distance from horizontal curves and from at-grade railroad crossings. Solutions with indirect left-turn lanes (Michigan U-turns, J-turns) are recommended. At existing intersections experiencing excessive numbers of crashes involving vehicles from the minor road, median closure should be considered or a median opening should be restricted to certain maneuvers. Median acceleration lanes can be added in order to allow a two-stage maneuver for left turns from the minor road. Enhanced guide and warning signage can be used to improve intersection conspicuity; adding road illumination can especially help at night. The practice of adding left- and right-turn bays should be continued as this is a proven intersection safety improvement practice. Applying these countermeasures may help improve safety and avoid the construction of expensive grade separations. Finally, advanced intersection collision avoidance systems, such as road-side dynamic signs warning drivers on the minor road about a short gap on the major road, should be the subject of pilot studies in Indiana. Experiments in other states have indicated that these systems help drivers choose safe gaps.

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EXECUTIVE SUMMARY

ANALYSIS AND METHODS OF IMPROVEMENT OF SAFETY AT HIGH-SPEED RURAL INTERSECTIONS

Introduction

Since 2006, INDOT has been preparing an annual five-percent report that identifies intersections and segments on Indiana state roads that require attention due to the excessive number and severity of crashes. Many of the identified intersections are two-way, stop-controlled intersections located on high-speed, multi-lane, rural roads. Some contributing design and human factors have been identified, while other factors still await investigation.

Multivariate ordered probit models have been developed to help identify additional factors of the frequency and severity of crashes. These models can estimate how much different factors increase the frequency of crashes at several levels of injury severity (fatal/incapacitating, non-incapacitating/possible, and property-damage-only). They have a unique ability to account for unobserved but common conditions that affect all of the crash severity levels. Recommendations for safety countermeasures are made based on both of these research results and our study of published reports of other authors.

Findings

The statistical analysis was performed on 553 existing intersections in Indiana and 72 existing intersections in Michigan using crash data reported during a four-year period. The identified safety factors include the following: presence of horizontal curves within the intersection vicinity, traffic volume on the major road, land use, population of the area surrounding the intersection, the minor road functional class (traffic volume on minor road unknown), nearby at-grade railroad crossings, intersection conspicuity to drivers on the major road, acceleration lanes for both left and right turns, median width, intersection angle, and number of intersection legs. These results are in line with other research results as documented in the literature review.

Based on the results of this and other studies, recommendations are made to improve safety at new intersections as well as at existing intersections. For new intersections, construction of medians wider than 80 feet is suggested. Where this is not possible and a narrower median needs to be constructed, adding a parallel acceleration lane for vehicles turning left from the minor road is suggested. Intersections should be placed at a sufficient distance from horizontal curves and from at-grade railroad crossings. Solutions with indirect left-turn lanes (Michigan U-turns, J-turns) are recommended.

At existing intersections experiencing excessive numbers of crashes involving vehicles from the minor road, median closure should be considered or a median opening should be restricted to certain maneuvers. Median acceleration lanes can be added in order to allow a two-stage maneuver for left turns from the minor road. Enhanced guide and warning signage can be used to improve intersection conspicuity; adding road illumination can especially help at night. The practice of adding left- and right-turn bays should be continued as this is a proven intersection safety improvement practice. Applying these countermeasures may help improve safety and avoid the construction of expensive grade separations.

Finally, advanced intersection collision avoidance systems, such as road-side dynamic signs warning drivers on the minor road about a short gap on the major road, should be the subject of pilot studies in Indiana. Experiments in other states have indicated that these systems help drivers choose safe gaps.

Implementation

The recommendations for new intersections should be reflected in the Indiana Design Manual to help designers select solutions that may promote safety at high-speed rural intersections. The recommendations for existing intersections can be implemented as a part of the Hazard Elimination Program. The guidelines and tools for safety audits and supporting computer tools (such as RoadHAT) should include these countermeasures among its alternative improvements together with crash reduction factors and other inputs needed for an economic analysis of the benefits and costs. The below listed countermeasures need before-and-after studies to confirm their effectiveness in increasing safety and to estimate the crash reduction factors to facilitate economic analysis, which is a necessary step in the implementation of these countermeasures:

- Median acceleration lanes
- Indirect left turns (U-turns and J-turns)
- Enhanced intersection approach signage
- Intersection collision avoidance systems

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1. INTRODUCTION

Since 2006, INDOT has been identifying intersections and segments on Indiana state roads that require attention due to the excessive number and severity of crashes *(1)*. Many of the identified intersections are two-way, stop-controlled intersections located on high-speed (60 MPH speed limit), divided, multi-lane, rural roads; and any collision that occurs at these intersections could potentially be severe. Although the average numbers of crashes at rural high-speed and other intersections in Indiana are comparable (1.2 crashes per intersection per year), the percent of crashes with fatalities and incapacitating injuries are considerably higher at the high-speed rural intersections (3.5% vs. 2.3%). A literature study confirmed that this problem exists in other states as well *(2, 3)*. Due to the prevalent high speeds, any collision that occurs on a multilane rural road is potentially severe.

Roadway and human factors, as well as other factors, affect the level of safety at high-speed rural intersections. Some of these factors have been identified while others still await identification. For instance, past research in Indiana *(4)*, Iowa *(2)*, and Nebraska *(5)* has determined that intersections near horizontal or vertical curves tend to have a higher crash rate than those intersections located on tangent sections of highways. Some studies postulate that drivers may find it difficult to estimate the inter-vehicle gaps in high-speed traffic flows coming from opposite directions. Burchett et al. *(2)* indicates that many drivers turning left onto the major road have more difficulty judging gaps in the far side of traffic coming from the right, compared to the near side of traffic coming from the left. This difficulty increases at intersections located on horizontal curves where drivers find it equally difficult to find a safe gap in either direction.

Past efforts to identify effective countermeasures that would successfully increase safety at high-speed rural intersections has brought mixed results. Several traditional countermeasures have been tried with varying degrees of success, including warning signs, overhead flashers, and rumble strips *(6)*. Preston and Storm *(7)* concluded that rumble strips and flashing blinkers have not been demonstrated to consistently improve safety at two-way stop-controlled intersections. Subsequently, the Minnesota Department of Transportation *(8)* issued a new policy of removing all overhead yellow/red flashing beacons.

Many other countermeasures (typically improvements of roadway geometry) have been proposed in the past which actually improve safety; these typically include widening the median, improving the intersection angle, reducing the approach speed, staggering the cross road approaches, eliminating the median opening and replacing it with U-turns, and installing street lights. Great Britain successfully improved safety at rural intersections in the 1970s by replacing four-leg intersections with two three-leg intersections (staggering the crossing road approaches). "J-turn" intersections that eliminate crossing maneuvers from minor approaches have been installed at some locations in Maryland, which have considerably increased safety by reducing the number of severe crashes *(9)*. There are also technology-based solutions proposed in the literature that are meant to help drivers evaluate the size of a gap on the major road, but field evaluation is needed.

The available literature on the "Michigan Left" median U-turn treatment (which is similar to the J-turn) mainly focuses on signalized intersections on urban and suburban boulevards, but it insufficiently covers unsignalized intersections on rural divided highways *(10, 11, 12, 13)*. Little is known about the effects of other potential safety countermeasures applicable to rural high-speed intersections, some of which are still considered experimental.

Thus far, to the authors' knowledge, the most substantial research on the safety of high-speed rural intersections was conducted in Iowa and in neighboring Nebraska and Minnesota *(2, 3, 5)*. The authors of these studies admit that the research scope and sample size are limited, and further study on a larger sample of intersections is recommended. Burchett et al. *(2)* recommended that more comprehensive research involving more sites needs to be done to confirm their results and to identify additional safety factors and effective countermeasures. An Indiana study was limited to intersections on curved segments *(4, 14)*.

A systematic data-driven analysis of a large number of Indiana high-speed rural intersections is needed to estimate the impact of road design components and other circumstances on traffic safety at these intersections. A research study is needed to identify the safety factors and countermeasures at high-speed rural intersections through a systematic and comprehensive analysis of available data for the state of Indiana. The results of the past research will also be studied and counter-imposed against the Indiana results. More importantly, the most promising experimental solutions will be identified and recommended for application at a number of intersections for evaluation purposes with a possibility for implementation on a large scale.

1.1 Scope of Work and Research Objectives

The Indiana Five Percent Reports over the past several years have provided a convincing indication that high-speed rural intersections experience excessively frequent and severe crashes *(15)*. Given the limited body of knowledge about the safety factors at high-speed rural intersections, the primary question pertains to the causes of this hazard. Although high speed is the primary suspect, reducing the speed in the rural areas is both unacceptable to many motorists and difficult to achieve. A more practical question is then: what factors make some of the intersections on high-speed rural highways more dangerous than other intersections of the same type? Even where the basic design standards are met, there may be a combination of geometric, traffic, and other characteristics that increase the risk of crashes (e.g., horizontal curvature, presence or absence of turning lanes, lighting, signage, traffic volumes along both the main road and the crossroad). Knowing these conditions may induce ways to improve safety at such intersections by improving the existing intersections and by better designing new ones. The aim of this research is to attempt to provide some answers to these questions.

There are four research objectives for this research project:

1. Identify the factors and combinations thereof that make some high-speed intersections more dangerous than others.
2. Recommend improvements (proven to be cost-effective in practice) at existing intersections that will improve their safety.
3. Develop design recommendations for new intersections that will help avoid high-risk solutions.
4. Point out promising experimental solutions that should be considered for pilot studies in Indiana.

This research will focus on two-way stop-controlled intersections located on four-lane rural roads. A statistical analysis will be conducted to identify factors and their combinations that lead to an increased occurrence of crashes in Indiana with a special attention to severe crashes. In addition to this analysis, past research reports and other publications also will be studied to identify promising safety countermeasures. The results of the modeling effort and the literature search will be used to develop specific recommendations to improve safety at new construction and existing intersections already in operation.

1.2 Organization

The remainder of this report is organized into the following chapters:

- **Chapter 2—Literature Review.** This chapter provides an overview of the existing design practices for unsignalized intersections on high-speed rural highways and of the implemented safety treatments for existing intersections. Several promising countermeasures and the limitations of the previous studies are highlighted.
- **Chapter 3—Data Collection.** This chapter describes the intersections and the crash data collected from them for this study. A sample of 557 intersections in Indiana and 72 in Michigan were selected and data were collected on the geometric characteristics, traffic count data, population and land use surrounding the area, and other factors that may affect the frequency and/or severity of crashes. The crashes that occurred at these intersections were identified in the available datasets for Indiana and Michigan and were assigned to individual intersections. Finally, a statistical summary of the intersections and crash data are presented.
- **Chapter 4—Modeling Method.** This chapter provides an overview of the econometric modeling method utilized for this project.
- **Chapter 5—Results.** This chapter discusses the model estimation results; namely, which intersection attributes increase or decrease the crash frequency at different levels of injury severity. These severity levels include the most severe crashes (involving deaths and incapacitating injuries), the least severe crashes involving property damage only, and the crashes of moderate severity (including only minor injuries).
- **Chapter 6—Recommendations.** This chapter provides a synthesis of recommendations to improve safety based on the results of the current and other studies as outlined in the literature review. Recommendations are provided on how to improve safety at new intersections as well as at existing intersections.
- **Chapter 7—Conclusion.** This final chapter summarizes the work accomplished in this study and suggests some directions for future research.

2. LITERATURE REVIEW

It has long been recognized that intersections are the element of the roadway system that experiences the greatest number and severity of crashes; at least one-third *(16)* and as much as one-half *(17)* of all crashes occur at intersections. This is expected because different traffic streams meet and conflict with each other at intersections. Intersections involving high-speed multi-lane divided highways (also known as "expressways") and minor streets with two-way stop control *(2, 3)* are no exception. Although expressways are considered to be safer than two-lane roadways *(3)* any collision that occurs at an intersection on these types of roadways could potentially be very severe due to the high speeds. It is helpful to know the intersection characteristics on these divided highways that contribute to more crashes in order to identify safety countermeasures.

The aim of this literature review is to determine the safety-related operational deficiencies of high-speed rural intersections and to identify countermeasures that have already been tried, tested, or proposed, and which of those have been found to be effective and which ones do not improve safety.

2.1 Design of Intersections on Divided Roadways

The American Association of State Highway and Transportation Officials (AASHTO) and several states *(18, 19)* have developed design guidelines for intersections on roadways with medians.

Note that, in the case of intersections on divided highways, the median is sometimes used as a refuge space for vehicles to wait for traffic to clear in both directions, an example of which is shown in Figure 2.1. To that end, the AASHTO *Policy on Geometric Design of Highways and Streets* ("Green Book") *(20)* recommends that medians on rural divided highways be as wide as practical; a minimum median width of 25 feet is suggested so that a typical passenger car can stop safely inside it. However, the AASHTO *(20)* also suggests that median widths should be larger to accommodate longer design vehicles (i.e., at least 50 feet to accommodate a school bus and perhaps even wider (about 80 feet) to accommodate larger trucks). Harwood et al. *(21)* stated that one concern for driver confusion at wider intersections turned out to be unfounded.

Figure 2.1 Single unit truck waiting in median of rural divided highway.

However, not all medians are wide enough to accommodate this operation for all design vehicles. AASHTO *(20)* not only contains guidance on median intersection design, but also gives the lengths of various design vehicles. Table 2.1 shows the lengths of some of the more common design vehicles.

The majority of rural divided highways in Indiana have medians that are between 50 and 60 feet wide. A few have medians as narrow as 30 feet. While this may be adequate for a typical passenger car, and sometimes even a typical school bus, it can be problematic for larger trucks. If the median is not wide enough, this can result in an increase in angle crashes should a large truck attempt to use the median as a refuge, because the vehicle may extend into the travel lanes. However, larger medians can increase the expense of building a divided highway and may not be practical in areas with constrained conditions.

NCHRP Report 375 notes that crashes and other undesirable driving behavior decrease as the median width increases on rural highways *(21)*. The report presents a study on design practices by several agencies concerning median design. One agency had a policy of widening the median width to 150 feet at major intersections. Some agencies consider the use of the school bus as the design vehicle for the median width; others consider the left-turn queues in the median design. Interestingly, some agencies *intentionally* design for a narrow median so as to force waiting vehicles to cross both directions of traffic at the same time. As discussed below, this can result in a very problematic operation.

TABLE 2.1
Design Vehicle Lengths

Design Vehicle Description	Length (feet)
P (passenger car)	19
SU (single-unit truck)	30
CITY-BUS (a typical city bus)	40
S-BUS 36 (school bus)	35.8
S-BUS 40 (school bus)	40
WB-40 (intermediate semitrailer)	45.5
WB-50(intermediate semitrailer)	55
WB-62 (interstate semitrailer)	68.5
WB-67D ("double-bottom" semitrailer/trailer)	73.3
WB-65/67 (interstate semitrailer)	73.5
WB-100T (triple-semitrailer/trailer)	104.8
WB-109D (turnpike double-semitrailer/trailer)	114

Adapted from AASHTO: *A Policy on Geometric Design of Highways and Streets* (a.k.a. "The Green Book"). American Association of State Highway and Transportation Officials (AASHTO), Washington, DC, 2004.

2.2 Specific Issues that Have Been Identified

Several factors have been identified thus far that are believed to contribute to increased crash rates at two-way stop controlled rural divided highway intersections.

One of those factors considered as major is the volume of intersecting traffic. Burchett et al. *(2)* determined that intersections with higher volumes of through and crossing traffic had higher crash rates than intersections with lower traffic volumes.

Land development adjacent to intersections also has been determined to be a factor in the number and severity of crashes. Burchett et al. *(2)* concluded that multi-lane divided highway intersections in residential and commercial areas tend to have more crashes than agricultural areas. Furthermore, the crashes in residential and commercial areas tend to be more severe (injuries and fatalities) than in agricultural areas.

Roadway characteristics at and around intersections also affect the number and severity of crashes. For example, research results in Indiana *(4)*, Iowa *(2)* and Nebraska *(5)* indicate that intersections near horizontal or vertical curves have a higher crash rate than those intersections located on tangent sections of highways.

The published literature expresses a concern about drivers accepting inadequate gaps when crossing or merging onto the major road with a divided roadway. At several intersections, especially where the median is narrow, many drivers must simultaneously select gaps in high-speed traffic coming from both directions simultaneously, and this can cause difficulties and hazard for all the involved vehicles on major and minor roads. A gap of 6.5 seconds or longer is considered sufficient by AASHTO *(20)* for smaller vehicles crossing the major road and a gap as long as 10.5 seconds for large trucks. This gap is determined as the sum of the travel time needed by a vehicle to cross the major road at the design speed plus a certain buffer time. Burchett et al. *(2)* determined that many drivers have difficulty judging gaps in high-speed traffic on a multi-lane divided highway, and that drivers attempting to cross or turn left into a divided highway had more difficulty judging gaps in the far side of traffic (traffic coming from the right) than in the near side of traffic (traffic coming from the left). A possible exception occurs at intersections located on a horizontal curve, in which case many drivers had about equal difficulty with deciding which gaps are safe regardless of the direction.

Alexander et al. *(16)* found that right-angle crashes account for 36 to 50 percent of crashes at expressway intersections, which is significantly more than the 28 percent of right-angle crashes at intersections that occur at other types of roads. The predominant problem identified is that of drivers judging/safe gap lengths, while reduced intersection identification and stop sign violations have been pointed out as relatively minor factors.

In a previous study at Purdue University, Van Maren *(22)* found that one major problem at rural high-speed intersections is that "*cars entering from the minor roadway are not certain when an adequate gap exists in the far lanes of traffic. Drivers may consider stopping in the median to be unsafe, so [they may] try to go all the way across at one time. If their estimation of a safe gap is wrong, a serious accident may occur.*" His report also shows that the number of crashes increases (a) as the traffic volumes on the minor roadway increase and (b) when there is sharp curvature on the major roadway.

2.3 Potential Countermeasures

NCHRP Report 500 *(6)* lists a variety of countermeasures that can be used to improve safety at the studied types of intersections, which have had varying degrees of success. NCHRP Report 500 *(6)* categorizes them as having been proven to work (P), tried by several jurisdictions (T) with inconsistent results in practice, or experimental (E) and still under development. Table 2.2 summarizes the potential countermeasures and their overall experience, adopted from NCHRP Report 500 *(6)*. The discussion that follows outlines in depth some of the other countermeasures that have been used.

2.3.1 Sight Distance

The first step in improving intersection safety is to provide adequate sight distance to allow drivers to select adequate gaps in traffic. If the sight triangles at the intersection, as determined by AASHTO *(20)*, are not kept clear of obstructions, this can lead to crashes that occur when a minor road driver pulls into the intersection when it is not safe. Providing the required sight triangles is absolutely essential for a minor road driver to be able to watch for traffic on the major road.

2.3.2 Geometric Improvements

Several geometric improvements have been proposed to reduce the conflicts between different movements at intersections, as well as to allow drivers to seek gaps in only one direction at a time when crossing or turning left onto a divided highway.

One common and effective geometric improvement is to provide exclusive left-turn or right-turn lanes. In many cases, drivers turning off the major highway have to slow down to turn right or left; and, in the case of

TABLE 2.2
Summary of Countermeasures and Experience in Improving Safety

Objective	Countermeasures
Improve Access Management	Implement driveway or turn restrictions
Geometric Improvements	Provide left or right turn lanes (P)
	Lengthen turn lanes (T)
	Provide offset turn lanes (T)
	Provide acceleration lanes for left turns and/or right turns (T)
	Provide shoulders (T)
	Restrict turning movements with signage (T)
	Convert to offset intersection or to a single intersection (T)
	Reduce intersection skew angle (T)
	Use indirect left-turn treatments (Michigan Left, J-turn, etc.) (T)
Improve sight distance	Clear sight triangles on unsignalized intersection approaches that must stop or yield (T)
Assist drivers in finding safe gaps	Intersection decision support system (E)
	Roadside pavement markers (E)
Improve recognizability	Enhanced signage (warning or guide signage) (T)
	Add splitter islands on minor road approach (T)
	Add lighting (P)
	Add stop bar on minor road approaches (T)
	Add rumble strips on minor road approaches (T)
	Add dashed markings on major road to delineate refuge area (T)
	Add centerline and stop/yield markings on minor road (T)
Select appropriate intersection control	Avoid signalization of through roadway (T)
	Convert two-way stop control intersection to all-way stop control (T)
	Convert to roundabout intersection (T)
Reduce intersection speeds	Traffic calming with geometry or other traffic control devices (T)
	Posted advisory speed limits (T)
	Reduce the legal speed limit (T)
Enforcement	Provide enhanced enforcement (T)

Adapted from National Cooperative Highway Research Program: *NCHRP Report 500, Volume 5: A Guide for Addressing Unsignalized Intersection Collisions*, 2003.

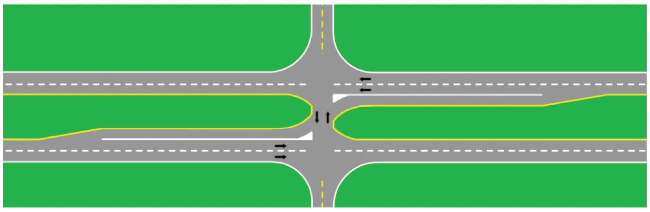

Figure 2.2 Plan view of a typical divided highway intersection with left-turn bays *(18)*.

Figure 2.3 Left-turn lane approaching a divided highway intersection in Indiana.

left-turns, may need to wait for a safe gap in the oncoming traffic. Figures 2.2 and 2.3 illustrate the use of a left-turn bay. The exclusive turning lanes remove these drivers from the high-speed main lanes before they stop to yield or slow down to make a turn. This space segregation in the presence of high-speed traffic (especially a high volume of traffic) results in a reduced occurrence of rear-end collisions. NCHRP Report 500 *(6)* considers this countermeasure to be proven effective.

Often, at intersections with wide medians, the left-turn paths overlap and cross each other twice. Perhaps one way of mitigating this problem is to introduce an offset left-turn lane for drivers turning off of the divided highway. Khattak et al. *(6)* found that intersections with offset left-turn lanes have fewer crashes than intersections that do not have the offset turn lanes. The Michigan Department of Transportation, however, has had negative experience with them *(3)*. On the other hand, the Ohio Department of Transportation tends to favor the use of offset left-turn lanes at high speed divided highway intersections. The offset left-turn lanes are illustrated in Figures 2.4 and 2.5.

NCHRP Report 650 *(23)* documents a case study in North Carolina where offset left- turn lanes were

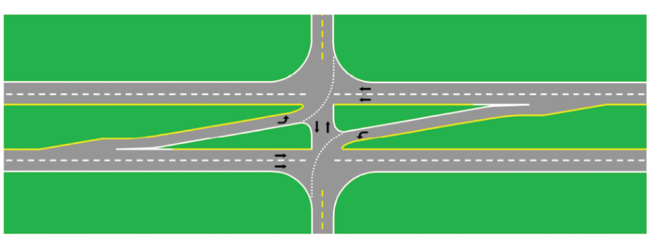

Figure 2.4 Plan view of a divided highway intersection with offset left-turn lanes *(18)*.

Figure 2.5 Offset left-turn lanes at a divided highway intersection in Ohio.

installed at locations where there was a heavy volume of left-turning vehicles departing the major road. The before-and-after study documented a decrease in severe crashes. However, offset left-turn lanes were not found to be appropriate where there is significant traffic from the minor road. This is due to the unclear yielding rules and the increase in conflicts on each side of the divided highway *(18)*.

According to Van Maren *(22)*, a highway design shouldn't force drivers to make too many decisions simultaneously. An at-grade intersection on a divided highway with a narrow median, a driver on the minor road must monitor gaps simultaneously in both streams to find a gap sufficient to cross the major highway. In some geometric solutions, conflict points are separated with sufficient distances to facilitate crossing or turning left onto the major road in stages. This solution allows drivers to monitor gaps in one direction at a time. Two countermeasures, other than widening a median, have been proposed—the median U-turn and the median acceleration lane—that remedy the situation by allowing drivers to find a safe gap in one traffic stream at a time.

In Michigan, the median U-turn treatment, commonly known as a "Michigan Left," redirects left turns to and from the divided highway—and in some cases the crossing through movements also, via a mandatory right turn on the minor roadway—to a U-turn lane downstream *(10, 12)*. After the U-turn, the minor road traffic can continue along or across the divided highway. In the cases where the minor road through movements are permitted directly across the major roadway, the median is usually wide enough to accommodate a vehicle waiting to cross the opposing direction of traffic.

Similar treatments have been implemented in other states. For example, the Maryland Department of Transportation implemented a version of the median U-turn treatment, known there as a "J-turn," that closes the median except for the left turns leaving the divided highway, and redirects all crossing and left-turn traffic onto the divided highway to a U-turn crossover downstream. Figure 2.6 illustrates these treatments. Such treatments are believed to reduce the crash rates considerably. In one outstanding case documented in

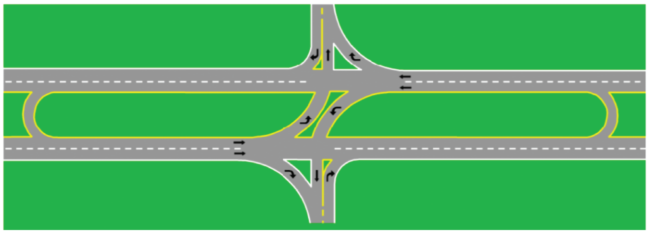

Figure 2.6 Plan view of a J-turn intersection, similar to the one constructed in Maryland *(18)*.

the published literature, 38 crashes occurred in three years (12.7 crashes/year) before the implementation of U-turns, with far-side right-angle crashes being the most common, Following implementation, only four crashes occurred in the ensuing six years (1.5 crashes/year) *(9, 23, 24)*.

Some jurisdictions in Mississippi, Missouri, and Nevada are implementing left-turn acceleration lanes in medians to help left-turning drivers accelerate and merge with the far-side traffic stream, similar to freeway on-ramps located on the left-hand side of the main-line lanes *(3, 18, 12, 23)*. Left-turn acceleration lanes apparently help drivers merge into high-speed traffic and may also provide additional space for evasive maneuvers. Nevertheless, they may not be as desirable if the volume of vehicles from the minor approaches is high. The left-turn acceleration lanes reduce the within-median storage space used by the vehicles from the minor roads.

2.3.3 Assisting Drivers with Finding Safe Gaps

Some experimental measures have been taken to help drivers identify safe gaps in the major traffic stream. For instance, the Pennsylvania Department of Transportation is currently experimenting with painted “goalposts” along the side of the roadway, to help drivers stopped on the minor roadway judge safe gaps in the cross traffic stream *(6)*.

Several jurisdictions are implementing a dynamic collision avoidance warning system. This system uses “speed trap” detectors which detect vehicles in the crossing traffic streams and relays that information to other drivers via several means. One such system, conceived in Minnesota, uses a variable-message sign that informs drivers of the speed of approaching vehicles, or how much time remains before the other vehicle on the conflicting direction enters the intersection *(3)*. The US DOT FHWA, the Minnesota Department of Transportation (Mn/DOT) and the University of Minnesota ITS Institute have developed the Cooperative Intersection Collision Avoidance Systems-Stop Sign Assist (CICAS-SSA) program. CICAS-SSA uses sensing technology, a computer processor, and algorithms to determine unsafe conditions, along with a driver interface, to provide timely alerts and warnings which are designed to reduce the frequency of crashes at rural expressway intersections *(25)*. Appendix C provides an illustration of the system’s operation. According to the authors, the system is not designed to help drivers choose safe gaps, but rather to recognize and properly respond to unsafe gap conditions (i.e., to assist drivers to reject unsafe gaps), which is accomplished by a clear indication that it is unsafe for a driver to proceed.

Other systems in Maine, Virginia, and Missouri use merely a flashing light on a sign to warn of coming vehicles *(3, 6)*.

Even though research results thus far have been promising *(23)*, these measures are still considered experimental and are undergoing further evaluation.

2.3.4 Improving Recognizability

Several agencies, such as Nebraska and Ohio, have been replacing their existing signage with larger signs and also have been adding signs. This improvement gives approaching drivers on the major roadway early warning that they are approaching an intersection. These signs name the crossing road and/or the destinations to provide better guidance and help drivers decide in advance if they need to turn off at the intersection.

The Nebraska Department of Roads installed diagrammatic guide signage in advance of several at-grade intersections to make drivers on the major road more aware that they are approaching an intersection. An example of this type of signage is shown in Figure 2.7. No studies were found that confirmed the safety benefits of this type of advanced intersection signage *(23)*, but it is expected that these signs are beneficial.

In Ohio, several at-grade divided highways also have enhanced signage in advanced of intersections. Not diagrammatic and of a different design than the Nebraska example, the signs are meant to increase the conspicuity of the intersection. An advance street name sign is placed approximately one-half mile in advance of the intersection. Next, an intersection warning sign is placed about one-quarter mile in advance. Then, another advance street name sign is placed in advance of the intersection, along with lane-use signs. Finally, a large street name sign is placed at the intersection itself. This sequence of signs is codified as a standard in Ohio’s *Traffic Engineering Manual (26)*, and an example of this signage sequence is illustrated in Figures 2.8 through 2.11. By contrast, Figures 2.12

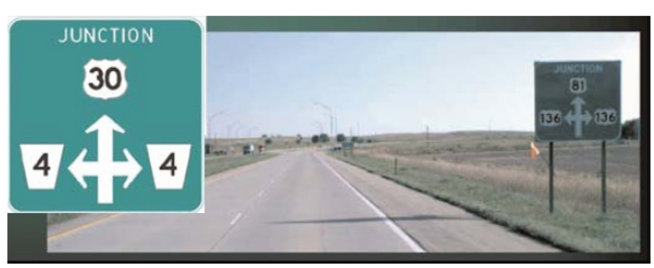

Figure 2.7 Example of diagrammatic signage for an at-grade intersection in Nebraska *(23)*.

Figure 2.8 Ohio—Advance street name notification sign (½ mile away).

Figure 2.9 Ohio—Intersection warning sign (1300 feet away).

Figure 2.10 Ohio—Advance street name and lane use signs near intersection (500 feet away).

Figure 2.11 Ohio—Signage at intersection.

Figure 2.12 Indiana—Advance warning signage.

Figure 2.13 Indiana—Advance signage before junction with a state route.

and 2.13 illustrate typical signage that is used in Indiana. Note also that some intersections in Indiana have no advance signage.

NCHRP Report 650 *(23)* includes a case study using larger, freeway-style signage. At a stretch of US-52 in Minnesota, an intersection originally having conventional route-number guide signs (similar to the sign shown in Figure 2.13) was experiencing a large number of severe crashes. There were other factors as well, such as rolling terrain, horizontal curvature, and vegetation growth that obstructed the visibility of the intersection. It was noted, however, that the original guide signs were easy to miss by drivers moving at high speeds. Larger freeway-style guide signs, similar to Ohio's signing practices for at-grade intersections, were installed. Crash data were collected for the 3 years before the installation of the enhanced signage and the 2½ years after. Overall, the crash rate increased slightly in the after period. However, there was a significant reduction of angle crashes (the most severe crash type), which were the type of crashes that the signs are meant to address *(23)*.

Another method of enhancing intersection conspicuity is adding dynamic warning signs. These are warning signs on the major roadway that alert drivers of approaching vehicles on the crossroad, either with a flasher or a variable message sign. Although considered experimental by NCHRP Report 500 *(6)*, systems that warn major road drivers of approaching traffic in Virginia, Maine, North Carolina, and Missouri *(3, 23)* have been documented to reduce the number of severe crashes at the locations where they were installed.

Overhead flashers at intersection are an example of a treatment that has met mixed opinions among safety engineers. Overhead flashers are typically installed at locations with a considerable number of crashes. NCHRP Report 500 *(6)* states that this can be an effective measure. However, Preston and Storm *(7)* came to a different conclusion about flashers; namely, they recommend that flashers should be *removed* from consideration in the Intersection Safety Toolbox because they have not been consistently effective. The authors support different mitigation strategies instead, such as using measures to assist minor road drivers in finding safe gaps in traffic, and using measures to improve intersection recognizability, some of which have been described above *(7)*. Subsequently, the Minnesota Department of Transportation *(8)* issued a new policy of *removing* all overhead yellow/red flashing beacons, with the concern that drivers on the minor road approaches are assuming that the overhead flashing beacon is signaling an all-way stop (when it is not). Instead of adding flashing warning beacons over the intersection, it may be better to install the flashing lights on the approach signage, and to have them flash only when vehicles are approaching on the minor road *(23)*.

2.3.5 Selecting the Appropriate Mode of Intersection Control

NCHRP Report 500 *(6)* mentions that there are several modes of intersection control available. One notable recommendation is to avoid signalization of the through roads; in other words, to avoid installing new traffic signals on high-speed roadways where none currently exist.

It has been well documented that adding traffic signals to unsignalized intersections will decrease angle crashes, but at the cost of increasing the frequency of rear-end crashes at the location *(3, 6)*. AASHTO *(20)* recommends that traffic signals be avoided at isolated rural intersections.

One of the major concerns with signalizing high-speed approaches is large trucks. Suppose a truck is traveling between 55 and 65 MPH on an approach to a signalized intersection, and the traffic signal turns yellow. The driver must make a quick decision between stopping the vehicle and continuing through the intersection. Suppose the truck cannot stop. It might be that the yellow change interval is designed according to the ITE guidelines but the truck with limited deceleration capabilities decelerates at a rate lower than the one assumed in the ITE formula. Truck drivers know about this issue and they typically approach signalized intersections at lower speed than other vehicles. In the considered here situation, the truck will be forced to violate the red signal. If the all-red interval is too short to accommodate this situation, this can result in an angle collision with a vehicle released from the crossroad. Another scenario is that if a dilemma zone is present at the intersection, a passenger car that decides to make a sudden stop at the signal could potentially be rear-ended by a truck which is incapable of stopping.

NCHRP Report 500 *(6)* also presents other intersection control strategies that could be used. Two of them include installing all-way stops or roundabouts at appropriate locations. Unlike the traffic signals, these two intersection controls require every vehicle to reduce speed significantly before entering the intersection, which will eliminate the sudden stop-or-go decision needed when approaching a signalized intersection that has just turned yellow. However, NCHRP Report 500 *(6)* also recommends using these intersection controls carefully and only when justified based on traffic volumes on both the major road and the cross road *(27)*. Otherwise, traffic will be required to slow down unnecessarily, causing delays and leading to aggressive driver behavior.

2.3.6 Reducing Operating Speed at Intersections and Roundabouts

Another measure that can be used to reduce the crash severity level of intersections is to reduce the speed of approaching vehicles on the major roadway. NCHRP Report 613 *(28, 13)* identifies several possible treatments to reduce vehicle speeds on approaches to high-speed intersections. The use of several different kinds of treatments is explored, including the use of static and dynamic signage, rumble strips, channelization, and narrowing of the traveled way. It also explains how different treatments could be used in different situations.

There is growing evidence that roundabouts, if properly designed, may be a good choice for high-speed rural intersections as solution safer than conventional intersections *(29)*. The case studies by Ritchie and Lenters *(29)* indicated that modern roundabouts on roadways with high-speed approaches are effective in improving safety if they are properly designed. They also warned that a roundabout will not always result in a safe intersection if its design is inadequate. They concluded that roundabouts can control speed. They also claimed that the statistical evidence of safety improvement at roundabouts located on high-speed roads in the USA is still insufficient due to limited data. Roundabouts used in other countries perform well in rural high-speed conditions. Several roundabouts evaluated examined in North America indicate positive safety performance. These roundabouts have several common elements:

- Entries are sufficiently visible to drivers.
- Entry speeds are reduced to be comparable to circulating traffic speeds.
- Splitter islands sufficiently long to allow deceleration from the approach speed to the entry speed.
- Central islands with landscaping that noticeably obstruct “seeing through.”

- Advance signage, appropriate landscaping, and a night illumination seem to contribute to safety improvement at roundabout sites on high-speed roads.

2.3.7 Grade-separated Interchange

Finally, the most expensive countermeasure is to eliminate the at-grade intersection altogether and introduce grade separation with an interchange. The need for providing connectors between the two roads should be considered. This countermeasure is not studied in the current research effort as the intent of this study is to identify countermeasures that can be implemented with lower costs and impacts. However, it is recognized that there will be some cases where the use of grade separations between the rural divided highway and the minor road can be strongly justified; namely, in cases when no other intersection treatment has adequately addressed all the operational and safety concerns at the location.

Some states, such as Illinois, use the traffic signal warrants, from the MUTCD, to plan for grade separations at existing at-grade intersections, as determined from planning studies done at the time of the construction of the intersection or the divided highway. If a traffic signal is needed within nine years at the at-grade intersection, an interchange will be built immediately; if the traffic signals will be needed within ten to twenty years after the initial construction, the right-of-way for an interchange will be reserved so that the interchange can be built later *(9)*.

Missouri, on the other hand, does not recommend building a full interchange "*unless the need is truly there*" *(18)*. Therefore, MoDOT has developed a series of median opening treatments that can help to "bridge the gap" between a traditional at-grade intersection and an interchange. Many of these countermeasures have been mentioned previously (such as the offset left-turn lanes and the J-turn intersection). However, one notable option is to use a partial grade separation. Here, one side of the divided highway intersects the minor roadway at grade. The other side of the divided highway is grade-separated over or under the minor roadway, and connecting ramps are used to allow all of the turning movements. The effect is that minor-road drivers are intersecting a one-way street *(18, 30)*. Figure 2.14 illustrates an example of this type of partial grade-separated interchange in Michigan.

Another grade-separated alternative that has been implemented, in cases where the grade separation is needed and a full interchange is not needed, is the one-quadrant interchange. This is an interchange where a ramp in only one of the four quadrants handles all of the turning traffic between the two roadways *(20)*. NCHRP 650 *(23)* illustrates two examples of one-quadrant interchanges from Iowa that were built as part of staged improvements from a traditional intersection to a full interchange. However, the conversion to a full interchange was not needed because the grade separation and one-quadrant ramp had adequately addressed the safety concerns.

Figure 2.14 Partial grade-separated intersection/interchange in Michigan *(31)*.

2.4 Limitations of the Past Research

So far, substantial research on the safety of multi-lane divided highway intersections has been performed in Iowa, Nebraska, and Minnesota, as well as some in Indiana. In fact, Burchett et al. *(2)* recommended that more comprehensive research involving more divided highway intersections needs to be done in places outside Iowa. Even though several intersection features that tend to lead to increased crash rates were identified, additional research was recommended to quantify, confirm, and complement the findings.

Many of the previous studies were very limited in scope, investigating a very limited number of intersections *(2, 3, 5)*. Many of these reports recommended further study in a larger sample of intersections. Some of the research done in Indiana *(1)* was limited to only one circumstance of intersections on curved segments.

Another limitation in the current literature is that some of these countermeasures are not evaluated for their effectiveness on safety. Maze et al. *(3)* identified several possible countermeasures that could potentially increase intersection safety. However, the authors merely discussed the implementation experiences that different state departments of transportation have had with some of these measures, and data are lacking to determine just how effective some of these countermeasures are in reducing collisions.

Finally, the literature on some of the potential countermeasures is itself limited in scope. For example, the literature on the "Michigan Left" median U-turn treatment focuses more on urban and suburban boulevards at signalized intersections, and less on rural divided highways at unsignalized locations *(10, 12, 32)*. Furthermore, much research has been conducted on this intersection treatment, albeit in a very different context. Very little is known about the effects of other potential countermeasures on intersection safety; some of them are still considered as experimental. Even though many of these alternatives described herein have shown promising results, more research is recommended *(23)*.

2.5 Summary

This literature review provided a summary of current design practices from established design guidelines, safety concerns that have been identified at existing high-speed divided highways, and several countermeasures that are being tried in different areas of the United States. A few of these countermeasures have been tried in Indiana.

The findings from this literature review and the findings from the econometric modeling described in subsequent sections of this report will both be used to develop a series of recommendations on how to improve safety at high-speed rural divided intersections.

3. DATA COLLECTION

3.1 Selection of Intersections

Van Maren *(22)* indicated that, at the time, there were 800 miles of rural at-grade intersections of multi-lane highways with minor roadways within the state of Indiana. Since then, the state highway system has changed significantly. Several four-lane rural divided highway corridors exist now that did not exist at the time of that prior study. Several segments of some of these corridors are now planned for conversion to freeway standard, most notably US-31 between Indianapolis and South Bend and SR-37/Future I-69 between Indianapolis and Bloomington. Additionally, several of the divided highways that were considered rural in that study are now located in urbanized areas, particularly along the US-40/I-70 corridor, and in the areas surrounding Gary, Valparaiso, and Indianapolis. As areas become urbanized, increasing volumes of traffic will frequently require signalization of intersections. These urban intersections do not meet the criteria for this study as the focus of this study is the safety of intersections on divided highways in rural areas that *do not* have signal control.

From all of the high-speed divided highways in Indiana, 557 intersections were selected for the sample size. This sample includes most of the rural high-speed divided highway intersections in the state, which are located in 36 counties and include nine corridors representing all six INDOT districts. Table 3.1 illustrates the corridors selected, the endpoints of the corridors, and the INDOT districts represented.

The selected intersections are mainly located on the rural divided highway corridors shown in Table 3.1. Longer corridors are more often represented in the sample because they have more intersections. The number of intersections chosen for each highway tends to be proportional to the highway corridor length.

3.2 Geometric Data Collection

Geometric data collection was mainly done using Google Earth (Professional version). This is a software program that provides GIS capabilities and aerial photographs.

Initially, intersections were matched from the GIS file used to complete the Indiana Five Percent Report *(1)*. This GIS file is compiled from two sources: the TIGER line file (U.S. Census Bureau, n.d.) and the INDOT Highway Performance Monitoring System, which provided information on all the roadway segments and classifications and information on all of the intersections between state highways and local highways. Initially, this file contained information on 30,255 intersections. Since the study subject involved only intersections on rural divided highways, it was necessary to filter out the unneeded data. The GIS program was not effective at filtering out the data; therefore, all the divided highway intersections were selected manually. Google Earth Professional was used to match the GIS information with aerial photography.

After the data were imported into Google Earth, the intersection locations were matched with the aerial photography to determine which intersections met the criteria: rural, divided highway, high-speed (at least 45 MPH and up to 60 MPH), and without signal control.

TABLE 3.1
Corridors Selected, Locations, and INDOT Districts

Route number	Endpoints	INDOT districts
SR-3	Three segments: I-70 north to New Castle; Muncie bypass; Fort Wayne north to US-6 at Kendallville	Greenfield, Fort Wayne
SR-37 (and future I-69 SW)	Bloomington to Indianapolis	Seymour
SR-63	Terre Haute to US-41 NW of Attica	Crawfordsville
US-24	Logansport to Fort Wayne	LaPorte, Fort Wayne
US-30	Valparaiso to Ohio state line	LaPorte, Fort Wayne
US-31	Indianapolis to South Bend	Greenfield, Fort Wayne, LaPorte
US-41	Evansville to Terre Haute; northern end of SR-63 near Attica to near Crown Point	Vincennes, Crawfordsville, LaPorte
US-50	US-41 at Vincennes to Washington	Vincennes
US-52	I-65 at Lebanon to Lafayette	Crawfordsville

It was assumed that a stop bar visible on the major roadway, according to the aerial photograph, indicated a traffic signal at that location and the intersection was dropped from the sample. Intersections were also rejected if the crossroad was clearly a driveway and not a public street.

One of the capabilities of Google Earth is the distance measurement tool. The software is capable of measuring the distance along a user-defined path between two points on the aerial photography. A path can include multiple straight segments and arcs of given radii.

For each intersection that met the criteria, several geometric attributes were collected as follows (see Appendix A for the data dictionary):

- Number of legs at the intersection.
- Median width measured between median markings. Presence of 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 to help turning traffic merge onto the major roadway. This information was also 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 (which may have an impact on the amount of turning or crossing traffic); additionally, it was documented whether the intersection is a point of access into a city or town.
- Whether the minor roadway was a state roadway or a local roadway.

Table 3.2 summarizes the geometric data.

Additional relevant data that could not be retrieved from aerial photography included the intersection controls, advanced signage, and vertical curvature, and the ability of the driver to recognize an intersection from some rational distance. This data was collected with the INDOT Video Log. Most of the data collected was from 2006 but some information was retrieved from earlier video logs. Field observations at selected locations have confirmed the correctness of the data collected with the Video Log and Google Earth.

Unlike the geometric data collected previously, it was decided that data from the INDOT Video Log would be collected for each *approach* to the intersection on the

TABLE 3.2
Intersection Geometric Data

Intersection attribute	Details	Number of intersections
Number of legs at the intersections	Number of 3-leg intersections	148
	Number of 4-leg intersections	404
	Number of intersections with 5 or more legs	1
Median widths	Wide (at least 80 ft)	11
	Between 35 ft and 80 ft	494
	Narrow (no more than 35 ft)	48
Turn lanes on major roadway	With left-turn lanes	442
	Without left-turn lanes	111
	With right turn lanes	344
	Without right turn lanes	209
Acceleration lanes (parallel design) on major roadway	With left-turn acceleration lanes	44
	With right-turn acceleration lanes	20
Acceleration lanes (taper design and shorter than the parallel lanes)	With left-turn acceleration tapers	326
	With right-turn acceleration tapers	252
Number of intersections with no crossing or turning restrictions		550
Number of intersections with curves on major road		137
Number of intersections without curves on major road		417
Number of intersections with curves on minor road		196
Number of intersections without curves on minor road		362
Number of intersections without development nearby		329
Number of intersections used as access into a city or town		96
Jurisdiction of minor road at the intersections	Intersections with INDOT roads	27
	Intersections with local roads	537
Number of intersections with railroad crossings nearby (within 400 ft)	On major road	3
	On minor road	19

major roadway, rather than for each individual intersection. This decision was made because the conditions on the major roadway on each of the two intersection approaches may be alike, or may be very different. There may be a condition that contributes to an increase of crashes in one direction that does not exist in the opposing direction. For example, an intersection may be very recognizable when approaching it from one direction on the highway, but may not recognizable in the other direction. The advance signage could be different on both approaches, for instance, there may be a severe grade on one side of the intersection while it may be very flat on the other side of the intersection.

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

- Advance signage on the intersection approach. This was grouped into five types: conventional, freeway-style, overhead, route number signage, and warning.

  - Conventional signage is the type of guide signage found on a conventional roadway, pointing the way to destinations or attractions. Such signage is generally green, blue, or brown in color.
  - Freeway-style signage is the type of guide signage that is found on freeways or on the approaches to their interchanges. Such signage is generally green in color and much larger than conventional signage.
  - Route number signage is typically found at junctions between two different state routes. This signage typically consists of stand-alone route shields, with an advanced "JCT" sign, and with cardinal directions and arrows at the point of intersection *(27)*.
  - Warning signage is typically a diamond-shaped yellow sign warning vehicles that an intersection is coming up ahead.
  - Any of this signage may or may not be mounted overhead.

- Speed limit data. Some advance warning signage warns of a posted advisory speed that is different from the legal speed limit. The advisory speed, if any, was also one of the elements collected.

  - Since there was a change in the blanket speed limit on rural divided highways from 55 MPH to 60 MPH on July 1, 2005, the video logs from 2004 and 2006 were searched to confirm which intersections had a speed limit change. All intersections that currently have a 60 MPH speed limit had a speed limit of 55 MPH before July 1, 2005. However, there are a few intersections where the speed limit, originally 55 MPH, remained 55 MPH after the change. Additionally, there were no changes in the speed limit at intersection approaches with a speed limit of ***less*** than 55 MPH before July 1, 2005. These intersections are documented in the data set.
  - Some intersections that had a warning sign in advance of the intersection also had a sign showing an advisory speed that was less than the legal speed limit. The reduced advisory speed signage may or may not have an impact on the intersection safety. To study the effects, the intersections with a reduced advisory speed were also documented and the advisory speeds collected.
  - Intersection recognizability. This is defined by the distance away from the intersection that a driver travelling along the roadway is aware that an intersection is coming up. Traffic control devices greatly aid in this regard; however, there will be some cases in which a driver may be conscious that an intersection is approaching from far away without the aid of traffic control devices, such as an intersection at the bottom of a long downgrade segment. The time to recognize the intersection before reaching it was also determined, based on both the posted speed limit and a constant speed of 100 ft/s (almost 68 MPH). The constant speed is based on the observed speeds on some of the divided highways.

- Additionally, the intersection recognizability distance was compared to the AASHTO *(20)* criteria for the decision sight distances on the major road, both for stopping (Avoidance Maneuver A based on 3.0 seconds perception/reaction time) and for a speed, path, or direction change (Avoidance Maneuver C based on the worst case 11.2-second perception/reaction time). If there was a deficiency for either criterion, it was noted.
- Surface treatment, asphalt or concrete. The type of surface may affect the friction factor.
- Grades and vertical curvature. These conditions have an effect not just on intersection visibility and recognizability, but also on the ability of a driver to stop. Information was collected on whether it was an upgrade or downgrade, whether there was a crest vertical curve or a sag vertical curve, and the distance of any vertical curve to the intersection. The INDOT Video Log provided information about the grade of the roadway.
- Presence of overhead flashers at the intersection.
- The direction of the approach concerned (northbound or southbound; eastbound or westbound; or in the case of US-52, northwest and southeast).

A summary of the intersection approaches can be found in Table 3.3.

3.3 Traffic Count Data

Traffic counts (ADT) for all of the study intersections were collected by using the traffic count maps available on INDOT's website. Data were collected from the most recent flow maps for each county. These data were then multiplied by the flow adjustment factors provided to get an estimate of the traffic counts in each year. The growth adjustment factors used were those for rural principal arterials. Flow adjustment factors were provided for all of the years 2004 through 2007.

It should be noted that the traffic flow maps only contain the traffic volume on INDOT-maintained highways. Therefore, with the exception of 28 intersections where the minor road is also an INDOT highway, traffic counts for the minor roads were not available and the traffic volumes were only collected for the major roadway at the intersection.

For crash frequency modeling (crash data organized by intersection), the average annual daily traffic for the entire study period (2004 through 2007) was also considered; for crash severity modeling, only the ADT of the year of each crash was considered.

TABLE 3.3
Approach Data Collected from Video Log

Approach attribute	Details	Number of approaches
Advance signage	Number with conventional signage	218
	Number with freeway-style (larger) signage	10
	Number with route number signage	59
	Number with overhead signage	15
	Number with warning signage	422
Speed limits	45 MPH	3
	50 MPH	68
	55 MPH*	126
	60 MPH†	899
	Number of approaches with an advisory speed less than the legal speed limit	20
Recognizability	Not recognizable in advance	24
	Recognizable less than 300 feet away	99
	Recognizable between 300 and 900 feet away	514
	Recognizable between 900 and 1200 feet away	220
	Recognizable at least 1200 feet away	344
	Approaches with inadequate stopping distance *(20)*	251
	Intersection approaches with inadequate recognizability distance for a speed, path, or direction change, 10.2 seconds reaction time *(20)*	760
	Intersection approaches with inadequate recognizability distance for a speed, path, or direction change, 11.2 seconds reaction time *(20)*	816
Surface treatment	Asphalt	1010
	Concrete	92
Number of approaches with grades	Uphill	93
	Downhill	104
	Total	220
Approach vertical curves	Crest	71
	Sag	113
Departure vertical curves	Crest	68
	Sag	88
Number of intersection approaches with overhead flashers		68

*Remained 55 MPH after July 1, 2005.
†Was 55 MPH before July 1, 2005, and changed to 60 MPH thereafter.

3.4 Crash Data

Crash data were collected for the years 2004 through 2007. For each crash, there were several data available, some of which were organized by crash, while other data were organized by each vehicle involved.

The following information was organized by crash and not pertaining to any specific vehicle:

- Number of vehicles involved.
- Weather conditions at the time of crash (clear, cloudy, rain, snow, etc.).
- Surface conditions at the time of crash (dry, wet, icy, snowy, etc.).
- Lighting conditions (daylight, dawn/dusk, or nighttime; and if the crash occurred at night, whether the intersection had lighting or not).
- Number of persons involved in the crash.
- Number of persons having different degrees of injuries. In Indiana, the KABCO scale is used to quantify the degree of injury to each person involved in the crash. For each person, the following degrees of injury were used:

  K: Killed
  A: Incapacitating injury
  B: Minor injury
  C: Possible injury
  O: No injury to the occupant

- The severity (KABCO scale) of the greatest injury also determines the severity of the crash. A fatal crash would be considered a "K" crash; whereas, a crash where no one was injured and there was property damage only (PDO) would be considered an "O" crash.
- Total amount of damage to all the vehicles (repair estimate) in dollars
- Date, time, and day of the week when the crash occurred

Following is the information that was provided for each crash organized by vehicle:

- Age of each driver.
- Gender of each driver (male or female).
- Whether the driver had been intoxicated (alcoholic beverages) at the time of crash.
- KABCO injury scale of the driver.
- Whether each driver was wearing safety belts at the time of the crash.
- Object hit by each vehicle (did the vehicle hit another vehicle; did it run off the road; did it hit a deer; etc.).
- Pre-crash vehicle action (what each driver was doing before the crash happened: going straight, turning left, turning right, making a U-turn, etc.).

- Initial impact, or the manner of collision (rear-end, head-on, sideswipe, angle, left-turn, right-turn, etc.).
- Other factors about the vehicles, drivers, or environment that might have had an impact on the collision.

Of these factors in each crash, the following were considered to be factors that could be remedied by engineering countermeasures:

- Surface conditions. While not something engineers have complete control of, some countermeasures could be implemented to counter some adverse conditions. For instance, during winter, when roads are covered with snow and ice, more crashes could occur. This could be addressed by plowing the snow and applying salt on the roads to melt the ice; however, it takes time for agencies to completely clear the roadways. Another surface condition of interest is whether there is standing water on the roadway (i.e., during or after a rain event). If a location experiences multiple crashes where flooding is a factor, one obvious countermeasure would be to improve the drainage.
- Lighting conditions. For crashes that occur at night, whether there is lighting at an intersection could have an impact on the frequency and severity of crashes. NCHRP Report 500 *(6)* documented how adding lighting at an intersection at night could reduce the frequency and severity of crashes, and the report has documented it as a "proven" countermeasure.
- Driver visibility. If the drivers reported limited visibility, this information was considered.

Table 3.4 shows the number of crashes where these factors can be taken into account out of the initial sample of 3340 crashes.

Interestingly enough, out of all of the crashes in the sample, 1014 of them involved deer. These crashes were removed from the sample because the focus of the research is improving safety at intersections, specifically looking at intersection-related crashes involving two or more vehicles to analyze the frequency and severity of crashes. By contrast, most deer crashes are single-vehicle crashes (with some crashes being multi-vehicle crashes involving a second vehicle that rear-ended the vehicle that hit the deer) and are, therefore, not intersection-related.

The final data sample contained 2326 crashes that were linked with the sample intersections. Table 3.5 shows a distribution of crashes by injury severity.

TABLE 3.4
Crashes with Notable Factors

Crash attribute	Number of crashes
Crash happened at night, intersection has lighting	105
Crash happened at night, intersection does NOT have lighting	1422
Crash happened during wintry conditions (snow and/or ice on roadway)	405
Crash where driver or officer reported limited visibility	39
Crash involving deer	1014

TABLE 3.5
Crash Distribution by Injury Severity

Severity of crash	Number of crashes in combined severity level
Fatal (K) Incapacitating injury (A)	126
Minor injury (B) Possible injury (C)	720
Property damage only (O)	1480

3.5 Data Assembly for Statistical Modeling

The statistical analysis of the safety effects used three crash counts models, one for each crash severity level, estimated simultaneously. The statistical sample supporting this analysis and including the crash counts at the three severity levels and the traffic and intersection data needed to be assembled.

Following the INDOT preferences, the fatal and incapacitating crashes (K and A) had been combined together forming a group of severe injury crashes (KA), the non-incapacitating and possible injuries had been combined together forming a light injury crashes group (BC), while property damage only crashes (PDO or O) crashes were separate.

3.5.1 Selecting Time Intervals for Analysis

Crash data reported in 2004 through 2007 were assembled in the statistical sample. The typical practice is to aggregate crash counts in multiples of whole years to reduce the effect of the crash seasonality. However, the speed limit was raised in Indiana from 55 MPH to 60 MPH at the majority of the intersections on July 1, 2005. Therefore, it was decided that an analysis by 6-month intervals would be more appropriate, so as to be able to study the effect of speed limit changes on crashes by using all the available information. Therefore, eight 6-month intervals were applied in the analysis: three 6-month intervals before the speed limit change and five 6-month intervals after the speed limit change.

For the purposes of the modeling approach used, each observation was determined to include all of the crashes at a single intersection during one 6-month interval. Hence the sample contained $557 \cdot 8 = 4456$ observations. Of these, 1671 observations were before the speed limit change (the speed limit was still 55 MPH throughout), and 2785 observations were after the speed limit change.

3.5.2 Crash Data per Observation

Figures 3.1 through 3.3 show a distribution of the number of crashes by each severity level.

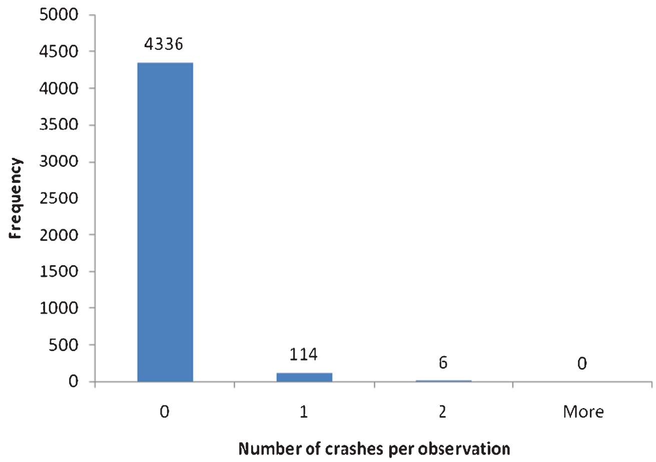

Figure 3.1 Distribution of number of observations with fatal or incapacitating injury (KA) crashes.

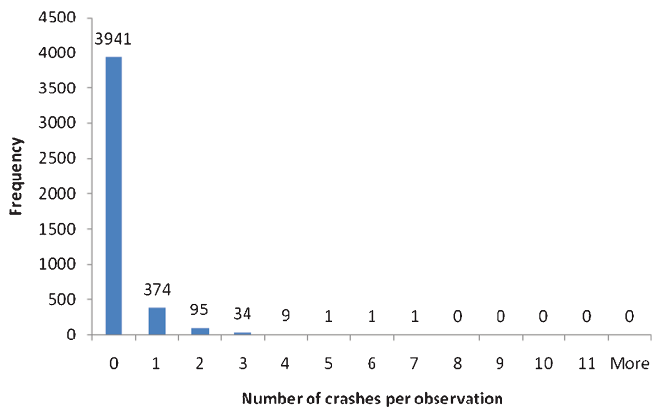

Figure 3.2 Distribution of number of observations with minor or possible injury (BC) crashes.

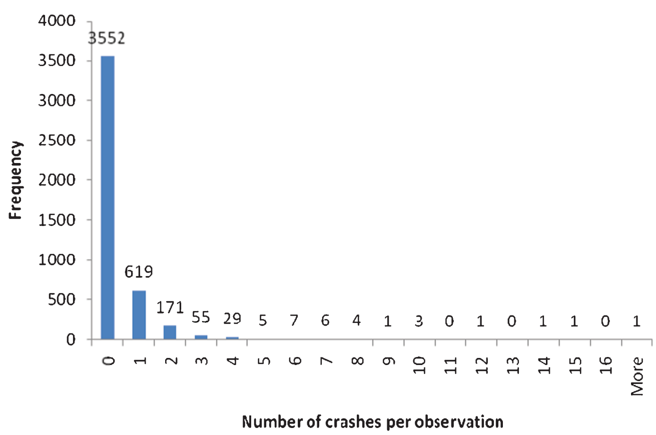

Figure 3.3 Distribution of number of observations with property damage only (PDO) crashes.

4. MODELING METHOD

4.1 Overview of the Modeling Method

The modeling strategy used is a multivariate (trivariate) ordered probit modeling scheme. The trivariate model is a relatively new modeling approach that permits the modeling of crash frequency and crash severity together. For each level of severity, the model estimates the probabilities of various crash counts given the intersection attributes. The goal of this model is to identify the factors that increase or decrease the frequency of crashes within the considered severity levels.

In Indiana, crashes are ranked in severity using the KABCO scale (K means killed; A means incapacitating injury; B means minor injury; C means possible injury; and O means there was no injury and the crash is a property damage only (PDO) crash). For the purpose of our crash analysis, these severity levels were grouped into three: fatal crashes are grouped together with incapacitating injury crashes (K and A together); minor injury and possible injury crashes (B and C) are also grouped together; and PDO crashes are kept separate from the other crashes.

The research objective is to estimate the effects of various roadway and traffic variables on the crash frequency for each of the three injury severity categories. The expected annual number of crashes is thereby estimated for each of the different levels of severity (KA, BC, and PDO), based on intersection and traffic attributes. The model takes into account the potential correlation between crashes at different severity levels. This approach is different from using three different univariate ordered probit models, which would not take into account the potential correlation between crash severities, herein assuming that there may be correlation between crashes of different severity levels. For example, if an intersection has a large frequency of PDO crashes, it is expected that the intersection will also have a high frequency of more severe crashes.

4.2 Modeling Software Used

The modeling software used is the SAS system, version 9.2 *(33)*. The procedure used is the QLIM procedure.

4.3 Modeling Procedure

As explained in Chapter 3, there are 4456 observations, each with differing geometric, traffic, and operational characteristics, and each with differing numbers of KA, BC, and PDO crashes. The distribution of crashes by severity level is as shown in Figures 3.1 through 3.3.

The dependent variable is the number of crashes at the intersection for each level of severity. This is a discrete-ordered variable, and the data were sorted into bins as shown in Table 4.1. 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.

The independent variables are the various geometric, land use, traffic, and other attributes of the crashes as

TABLE 4.1
Bins Used in Crash Frequency/Severity Modeling by Severity Level

Crash Severity	Number of crashes per bin
Fatal or incapacitating injury (K or A)	0
	1
	2
Minor or possible injury (B or C)	0
	1
	2
	3
	4
	5 or more (6.00*)
Property damage only (PDO) (O)	0
	1
	2
	3
	4
	5
	6
	7 or more (9.50*)

*Average number of crashes in the bin.

depicted in Chapter 3. A full list of the variables tested can be found in Appendix A.

The multivariate ordered probit model estimates the probability of the number of crashes for each severity level based on the values of the independent variables. Equation 4.1 shows the univariate ordered probit model formulation on which the multivariate model is based on the following *(34)*:

$$\begin{aligned} P(y=1) &= \Phi(-\beta X) \\ P(y=2) &= \Phi(\mu_1-\beta X)-\Phi(\beta X) \\ P(y=3) &= \Phi(\mu_2-\beta X)-\Phi(\mu_1-\beta X) \\ &\dots \\ P(y=I) &= 1-\Phi(\mu_{I-2}-\beta X) \end{aligned} \quad (4.1)$$

Where:

P is the probability of each outcome at each crash severity level (no crashes, 1 crash, 2 crashes, 3 crashes, etc.),

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 independent variables, as shown in Equation 4.2:

$$\boldsymbol{\beta X} = \beta_0 + \sum\nolimits_{i=1}^{n} \beta_i X_i + \varepsilon \quad (4.2)$$

Each X represents an independent variable, and each β represents the coefficient for each independent variable as estimated from the SAS software. The 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 independent variables were selected through an iterative process. Initially, all independent variables were put into the SAS software, and the model was further refined depending on whether each variable was significant or not. An independent variable was considered to be statistically significant if the t-statistic was at least 1.6, or if the p-value was not greater than 0.10.

Additionally, some variables appeared to have multicollinearity issues. These were identified when two variables were highly correlated and both statistically significant in the model, with similar t-statistics and p-values, but with opposite signs. To keep the variable that would best improve the model's statistical fit, the model was estimated with each variable separately. The variable that provided the best overall fit for the model was kept in the estimation results.

The final model contains only variables that were found to be statistically significant.

When the final model was developed with the final β coefficients and μ thresholds, sensitivity analysis was done using a Microsoft Excel spreadsheet using the multivariate ordered probit variation of Equation 4.1 to determine the probability of each outcome.

4.4 Expected Annual Number of Crashes

The expected annual number of crashes (EANOC) for each crash severity is as computed in Equations 4.3 and 4.4. Note that, since each interval is only six months, the final result must be multiplied by two in order to get the annual number of crashes.

$$EANOC\ (KA) = \sum_{i=1,2} (1 \cdot P_i(1) + 2 \cdot P_i(2)) \quad (4.3)$$

$$EANOC\ (BC) = \sum_{i=1,2} (1 \cdot P_i(1) + 2 \cdot P_i(2) + \cdots + 4 \cdot P_i(4) + 6.0 \cdot P_i(5)) \quad (4.4)$$

$$EANOC\ (PDO) = \sum_{i=1,2} (1 \cdot P_i(1) + 2 \cdot P_i(2) + \cdots + 6 \cdot P_i(6) + 9.5 \cdot P_i(7)) \quad (4.5)$$

4.5 Crash Reduction Factors

Crash reduction factors (CRF) are computed for each intersection attribute identified as a possible countermeasure. For each countermeasure variable (and some of the other variables as discussed in Chapter 5), the expected annual number of crashes was found with and without the countermeasure in effect. That is, the sample mean values of all of the other parameters were used, and the expected annual number of crashes was found with the appropriate variable set at a value that represents no countermeasure in place and also with the same variable set at a value that represents the countermeasure in place. All of the studied countermeasures are represented by binary (0, 1) variables. In most cases the 0 value represents the countermeasure's absence while the 1 value represents the countermeasure's presence.

Equation 4.6 shows the equation used to compute the crash reduction factors:

$$CRF = \frac{EANOC(with) - EANOC(without)}{EANOC(without)} \cdot 100\% \quad (4.6)$$

Where:

CRF is the crash reduction factor;

EANOC (with) is the expected annual number of crashes with the countermeasure in place;

EANOC (without) is the expected annual number of crashes *without* the countermeasure in place.

4.6 Modeling of AADT and Population Effects on Expected Annual Number of Crashes

A series of graphs was developed to illustrate the effects of the countermeasures on the expected annual number of crashes with increasing average annual daily traffic (AADT) and the population of the surrounding areas. Each graph represents the combination of the AADT or the population with one other factor.

For AADT, a range of different traffic volumes (0 through 40,000 vehicles per day in increments of 10,000) was used on the graph; the selected other independent variable (the safety countermeasure) was evaluated at 1 or 0. The sample mean values were used for all other independent variables. These values were used to calculate the expected annual number of crashes on each graph.

A similar set of graphs was developed for the population, except that the population has a range of 0 through 60,000 residents, in increments of 15,000.

5. RESULTS

The results presented in this section are from the final trivariate ordered probit model, using only the independent variables that were determined to be both statistically significant and having no multi-collinearity concerns.

Table 5.1 presents the model results with the parameter estimates of the variables that were found to be statistically significant at the 0.90 level of confidence. Note that the variables that are shown to reduce the likelihood of crashes are highlighted in **bold** type.

5.1 Variables that are Associated with the Increase in the Crash Frequency

Some of the factors that were identified as leading to an increase in the frequency of crashes at the three levels of injury severity are as follows:

- Presence of left-turn bays on major road
- Presence of right-turn bays on major road
- Presence of residential land uses at the intersection
- Presence of commercial land uses at the intersection
- Presence of schools or churches near the intersection
- Increase of annual average daily traffic (AADT) on major roadway
- Presence of, and increased population of, cities and towns along the minor roadway, within six miles of the intersection
- Reduced speed limit of 55 MPH (lower than the typical speed limit of 60 MPH)
- Minor roadway is under INDOT jurisdiction (which covers federal and state highways)
- Presence of at-grade railroad crossings near the intersection on the major roadway
- Presence of horizontal curvature along the major roadway
- Intersection not conspicuous to drivers approaching on the major roadway

Although cited as a safety countermeasure because they remove turning vehicles from the through traffic lanes *(6)*, the model results show that the existence of left-turn lanes is associated with an *increase* in crashes on the major road. This initially may seem counterintuitive, but it is due to the installation of left-turn bays at intersections where there are larger volumes of left-turning traffic. However, left-turn bays do not exist at all intersections because such left-turn bays are not typically installed at intersections that have lower volumes of left-turning traffic. Since turning movement counts were unavailable, this variable seems to be picking up that effect.

The effect of the right-turn lanes is similar to the effect of the left-turn lanes discussed above. The right-turn lane is cited as a countermeasure, removing the decelerating right-turning vehicles that form the major traffic stream *(6)*; however, since they are not installed at all intersections, right-turn lanes installed at intersections with higher volumes of turning traffic constitute an indicator of increased turning movements. It should be noted, however, that this variable is only significant for PDO crashes, whereas the presence of left-turn bays are significant for crashes of all injury severity categories.

Residential land use in the intersection area is found to be associated with the frequency of crashes in all injury-severity categories, which is intuitive due to more conflicts with resident and visitor traffic entering and leaving the residential properties, and the residents use the intersection every time they leave and return to their homes.

Similarly, commercial land use in the intersection area is found to be associated with an increased frequency of crashes in all injury-severity categories. Most of the commercial land uses along a high-speed divided highway tend to be the type of businesses that would cater to long-distance travelers (e.g., gas stations, convenience stores, fast food restaurants, and truck stops). Drivers would be traveling along the divided highway, stopping at businesses to purchase food and fuel, rest, and use the restrooms, and then continue their trip. This situation thereby leads to an increase in turning traffic at the intersection, which in turn leads to more crashes. It should be noted that the magnitude of this effect is *stronger* than the effect of residential land uses, as indicated by the marginal effects in the

TABLE 5.1
Parameter Estimates from SAS Multivariate Ordered Probit Model

Variable description	Coefficient	Standard error	t-statistic	p-value
Fatal and Incapacitating Injury (K and A) Crashes				
Intercept	−2.356732	0.085126	−27.69	<.0001
Left-turn bays at 4-leg intersection, exist in both directions on major road (1 if yes, 0 if no)	0.518283	0.093102	5.57	<.0001
Left-turn parallel acceleration lane at 4-leg intersection, exists in both directions on major road (1 if yes, 0 if no)	−0.439734	0.248164	−1.77	0.0764
Presence of residential land uses within intersection area (1 if yes, 0 if no)	0.146471	0.086788	1.69	0.0915
Presence of commercial land uses (gas stations, fast food, convenience stores) within intersection area (1 if yes, 0 if no)	0.488063	0.130335	3.74	0.0002
Population of cities/towns within 6 miles along minor road (scaled by 100,000)	1.180839	0.428180	2.76	0.0058
Right-turn parallel acceleration lane at 3-leg intersection, exists on major road (1 if yes, 0 if no)	−0.830509	0.431399	−1.93	0.0542
Threshold 1 (μ_1)	1.129555	0.126848	8.900	<.0001
Minor and Possible Injury (B and C) Crashes				
Intercept	−1.916098	0.088304	−21.7	<.0001
Left-turn bay at 3-leg intersection, exists on major road (1 if yes, 0 if no)	0.373616	0.097792	3.82	0.0001
Left-turn bays at 4-leg intersection, exist in both directions on major road (1 if yes, 0 if no)	0.578085	0.084030	6.88	<.0001
Left-turn parallel acceleration lane at 4-leg intersection, exists in both directions on major road (1 if yes, 0 if no)	−1.078053	0.189104	−5.70	<.0001
Presence of residential land uses within intersection area (1 if yes, 0 if no)	0.185230	0.055915	3.31	0.0009
Presence of commercial land uses (gas stations, fast food, convenience stores) within intersection area (1 if yes, 0 if no)	0.383888	0.090246	4.25	<.0001
Presence of school or church within intersection area (1 if yes, 0 if no)	0.407502	0.214116	1.90	0.057
Average Annual Daily Traffic (AADT) on major road (scaled by 10,000)	0.147427	0.035949	4.10	<.0001
Population of cities/towns within 6 miles along minor road (scaled by 100,000)	0.822182	0.349211	2.35	0.0186
Speed limit 55 MPH, remained 55 MPH after 1 July 2005 (1 if yes, 0 if no)	0.238620	0.075926	3.14	0.0017
Crash occurred after speed limit change to 60 MPH (1 if yes, 0 if no)	−0.107717	0.048760	−2.21	0.0272
Left-turn taper acceleration lane at 3-leg intersection, exists in both directions on major road (1 if yes, 0 if no)	−0.132785	0.070503	−1.88	0.0596
INDOT has jurisdiction over minor roadway (1 if yes, 0 if no)	0.452492	0.060224	7.51	<.0001
At-grade railroad crossing exists on major road near intersection (1 if yes, 0 if no)	0.491397	0.253963	1.93	0.0530
Threshold 1 (μ_1)	0.731560	0.036080	20.28	<.0001
Threshold 2 (μ_2)	1.260705	0.059639	21.14	<.0001
Threshold 3 (μ_3)	1.795520	0.102719	17.48	<.0001
Threshold 4 (μ_4)	2.263089	0.177479	12.75	<.0001
Property Damage Only (PDO) Crashes				
Intercept	−1.749327	0.113623	−15.40	<.0001
Left-turn bays at 4-leg intersection, exist in both directions on major road (1 if yes, 0 if no)	0.361631	0.062504	5.79	<.0001
Left-turn parallel acceleration lane at 4-leg intersection, exists in both directions on major road (1 if yes, 0 if no)	−0.986143	0.155794	−6.33	<.0001
Driveways exist in intersection area (between 3 and 6 driveways) (1 if yes, 0 if no)	−0.443801	0.161226	−2.75	0.0059
Presence of residential land uses within intersection area (1 if yes, 0 if no)	0.097827	0.050069	1.95	0.0507
Presence of commercial land uses (gas stations, fast food, convenience stores) within intersection area (1 if yes, 0 if no)	0.427770	0.083970	5.09	<.0001
Average Annual Daily Traffic (AADT) on major road (scaled by 10,000)	0.261336	0.033147	7.88	<.0001
Population of cities/towns within 6 miles along minor road (scaled by 100,000)	1.017598	0.327884	3.10	0.0019
Speed limit 55 MPH, remained 55 MPH after 1 July 2005 (1 if yes, 0 if no)	0.368375	0.095793	3.85	0.0001
Speed limit currently 60 MPH (1 if yes, 0 if no)	0.159873	0.081872	1.95	0.0509
Intersection angle between 75 and 90 degrees (1 if yes, 0 if no)	−0.132873	0.049202	−2.70	0.0069
Median at least 80 feet wide (1 if yes, 0 if no)	−0.507819	0.203306	−2.50	0.0125
Right-turn bay at 3-leg intersection, exists on major road (1 if yes, 0 if no)	0.300094	0.065229	4.60	<.0001
Right-turn bays at 4-leg intersection, exist in both directions on major road (1 if yes, 0 if no)	0.293303	0.071444	4.11	<.0001
INDOT has jurisdiction over minor roadway (1 if yes, 0 if no)	0.534580	0.057309	9.33	<.0001
Intersection cannot be recognized from at least 1.2 times the stopping sight distance (1 if yes, 0 if no)	0.180389	0.046300	3.90	<.0001
Horizontal curvature (one curve) exists on major roadway at or near the intersection (1 if yes, 0 if no)	−0.149983	0.051422	−2.92	0.0035
Two curves (reverse curves) exist on major roadway at or near the intersection (1 if yes, 0 if no)	0.266200	0.175643	1.52	0.1296

TABLE 5.1
(Continued)

Variable description	Coefficient	Standard error	*t*-statistic	*p*-value
Right-turn taper acceleration lane, exist on either OR both approach(es) on the major road (1 if yes, 0 if no)	−0.244289	0.057251	−4.27	<.0001
Threshold 1 (μ_1)	0.764592	0.028678	26.66	<.0001
Threshold 2 (μ_2)	1.252659	0.043307	28.93	<.0001
Threshold 3 (μ_3)	1.578902	0.057029	27.69	<.0001
Threshold 4 (μ_4)	1.864568	0.073534	25.36	<.0001
Threshold 5 (μ_5)	1.940620	0.078877	24.60	<.0001
Threshold 6 (μ_6)	2.071026	0.089217	23.21	<.0001
_Rho.KAcr.BCcr	0.333164	0.045500	7.32	<.0001
_Rho.KAcr.PDOcr	0.290247	0.044865	6.47	<.0001
_Rho.BCcr.PDOcr	0.444292	0.026241	16.93	<.0001

sensitivity analysis presented in the next section, even though both are statistically significant.

The average annual daily traffic at the intersection is found to strongly affect the frequency of BC and PDO crashes, which confirms the results of past research *(23, 2, 35, 36, and many others)*. This finding is discussed in depth later in this section.

The presence of a city or town along the minor roadway leads to an increase in all injury-severity level crashes. Furthermore, it was shown that the higher the population of the city or town, the higher will be the number of crashes. This result is logical because people will be using the minor roadway to access the city, town, or any other populated area, thereby leading to higher traffic counts on the minor roadway and higher turning movement volumes and crossing traffic volumes at the intersection with the divided highway. This finding is also discussed in more detail later in this section.

The intersections where the speed limit remained unchanged at 55 MPH throughout the analysis period were found to have more BC and PDO crashes than the intersections for which the speed limit increased from 55 to 60 MPH. This finding is somewhat surprising since driving at higher speeds is known to be more accident-inducing. Normally, one would expect more crash occurrences in locations where the speed limit is higher. However, keeping the existing 55 MPH speed limit (instead of raising it to 60 MPH) at these intersections may have been dictated by safety concerns. Thus, the seemingly counterintuitive results could be caused by the endogeneity of the variable. An interesting finding, however, is that intersections that experienced the speed limit increase to 60 MPH were associated with more PDO crashes. This may still be, though, a result of the decision selection process of accident-prone intersections.

Another factor that was found to affect the crash frequency within the BC and PDO categories was whether the minor roadway was a U.S. or State roadway under INDOT jurisdiction. In other words, this could imply that there would be more traffic on the minor road, more crossing and turning maneuvers, and therefore more crashes.

The presence of railroad crossings on the major roadway was also an important factor identified in the BC category. Railroad crossings are expected to disrupt the traffic on the major roadway; sometimes, the resulting queues may impact intersection operations. If the railroad crossing is on the minor roadway, however, vehicles may not be able to clear the tracks before the arrival of a train. The presence of any at-grade railroad crossing will have a negative impact on intersection operations. This finding should be taken with caution, however, as there were only three intersections in the sample with at-grade railroad crossings on the major road.

The presence of horizontal curvature on the major roadway was found to have mixed effects on PDO crashes. It appears that one horizontal curve near the intersection reduces PDO crashes, whereas two or more (one on either side, along the major and/or minor roadway) have an increasing effect. The result obtained for a single curve contradicts other research showing that intersections on curves are less safe *(2, 14)*. Where horizontal curves exist in the intersection area, it may be difficult for drivers stopped along the minor road to find safe gaps in the traffic *(2, 6)*. Additionally, large amounts of superelevation on the curve will also have a negative impact on intersection safety *(14)*.

Finally, at intersections which are not recognizable to drivers approaching on the major roadway, who do not have to stop, there is an increased chance that, should another driver on the minor roadway enter the intersection, the driver on the major road would be unable to stop or make some other evasive maneuver to avoid a collision. Additionally, if the driver intends to turn off the major roadway and does not recognize the intersection, that driver might not be able to turn at the desired location and be forced to take another route - or worse, might brake abruptly - potentially causing a rear-end collision; or turn the corner at excessive speed, potentially running off the road or having an angle crash involving a stopped vehicle.

5.2 Factors that Reduce the Likelihood of Crashes

The factors that were found to decrease the frequency of crashes in the three injury severity levels are as follows:

- Left-turn parallel acceleration lanes on the major roadway
- Right-turn parallel acceleration lanes on the major roadway
- Intersection angle between 75 and 90 degrees
- Median at least 80 feet wide
- Intersection having three legs with minor road terminating at major road

Three-leg intersections were found to reduce crashes at all levels of injury severity. Although these intersections were not found to be specifically significant, several other variables (one left-turn bay on major road, left-turn taper acceleration lane exists in one direction only, right-turn acceleration lane exists in one direction only) do tend to reflect the three-leg intersection. These results tend to show that three-leg intersections are safer than four-leg intersections. This finding is intuitive because three-leg intersections have fewer turning movement conflicts compared to four-leg intersections, and there are no crossing conflicts as all traffic on the minor roadway must turn either left or right.

A left-turn parallel acceleration lane is a lane in the median that permits a driver 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, much like a left-side freeway entrance ramp instead of having to enter the far-side traffic stream from a full stop. Essentially, the median acceleration lane has the effect of allowing a "two-stage" left-turn maneuver, even when the median is narrower. The expected effect of this is a reduction in angle crashes, which are a major problem with high-speed intersections. NCHRP Report 650 *(23)* illustrates, with Minnesota's crash data, that angle crashes are one of the most frequent crash types at high-speed intersections, most of which involve difficulties with gap selection. Burchett and Maze *(2)* showed that the majority of angle crashes involve far-side traffic (i.e., traffic coming from the right) and involve difficulties with gap selection. Since the left-turn median acceleration lane mitigates the need to select gaps in traffic on the far side of the highway, it is expected that the acceleration lane would reduce these types of angle crashes. Another effect of the left-turn parallel acceleration lane is that it allows more space for a driver on the major road to make an evasive maneuver should that be necessary.

The effect of median acceleration lanes on crash performance is extremely strong. This effect was therefore 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 confirm that median acceleration lanes have an extremely positive impact on improving safety.

The presence of right-turn acceleration lanes on the major roadway was found to significantly reduce KA crashes. This countermeasure is also expected to reduce angle crashes because it removes the need to look for gaps in near-side traffic. Instead of having to seek gaps in the near-side traffic, drivers turning right will turn into an acceleration lane and merge (similar to merging at a freeway entrance ramp). Note also that this variable addresses the right-turn acceleration lane on *one side only*. However, this could also reflect that these acceleration lanes may have been installed mainly at three-leg intersections.

Intersections with 75- to 90-degree angles were also found to reduce PDO crashes, which is in line with the AASHTO *(20)* recommendation to avoid building intersections with a severe skew angle. AASHTO *(20)* states that intersections should have angles as close to 90 degrees as possible and angles smaller than 60 degrees should be avoided. In addition, intersections with at least 80 feet wide medians had a similar effect on 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).

Finally, the existence of driveways in the intersection area was found to reduce PDO crashes. This result is questionable. One would reasonably expect that there would be more crashes if there are more conflict points and less access control. These driveways in the intersection area typically lead to commercial and residential land uses.

5.3 Sensitivity Analysis

Figures 5.1 through 5.8 compare the crash annual frequencies at different severity levels with and without the presence of the factors identified as potential safety countermeasures.

Each bar graph shows the effects of the presence (or absence) of the selected countermeasure for each applicable severity level (fatal or incapacitating injury [KA], minor or possible injury [BC], or property damage only [PDO]), and is estimated at the sample mean. For comparison, the bars indicating the expected

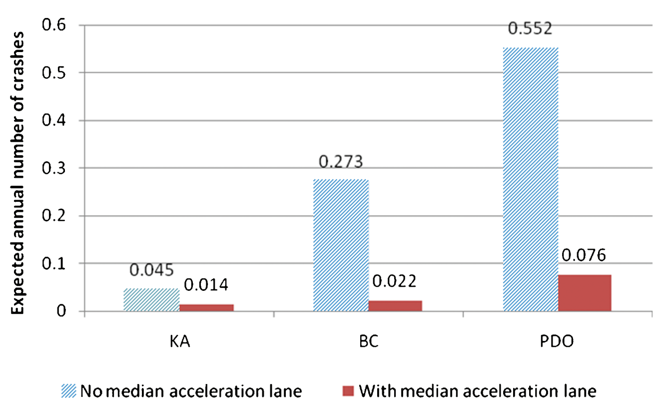

Figure 5.1 Effect of left-turn parallel acceleration lanes on expected annual number of crashes.

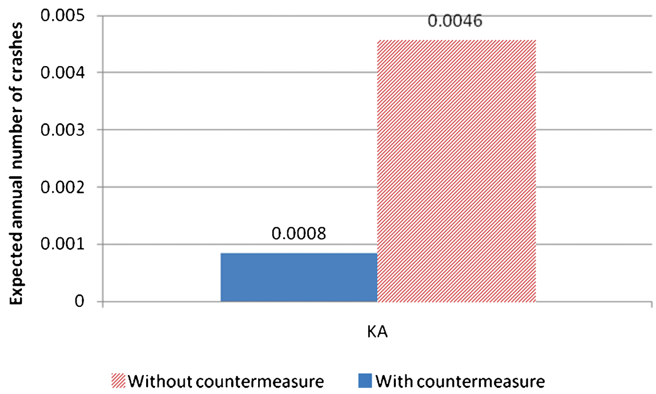

Figure 5.2 Effect of right-turn parallel acceleration lanes on expected annual number of crashes.

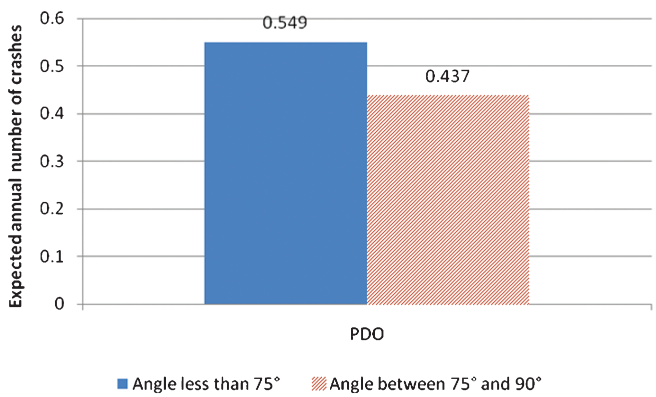

Figure 5.3 Effect of intersection angle on expected annual number of crashes.

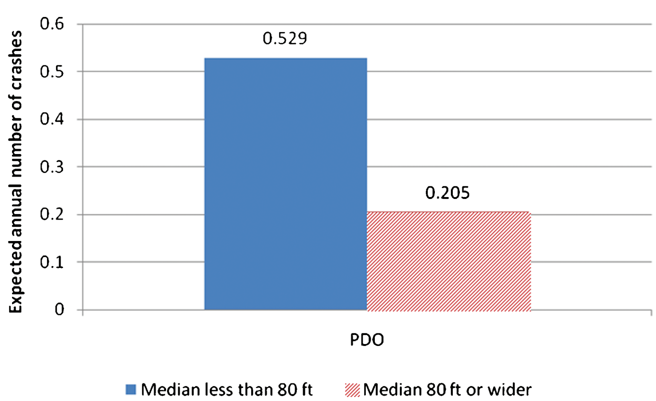

Figure 5.4 Effect of median width on expected annual number of crashes.

annual number of crashes with and without the effect are located next to each other. The numbers on the top of each bar are the expected annual number of crashes.

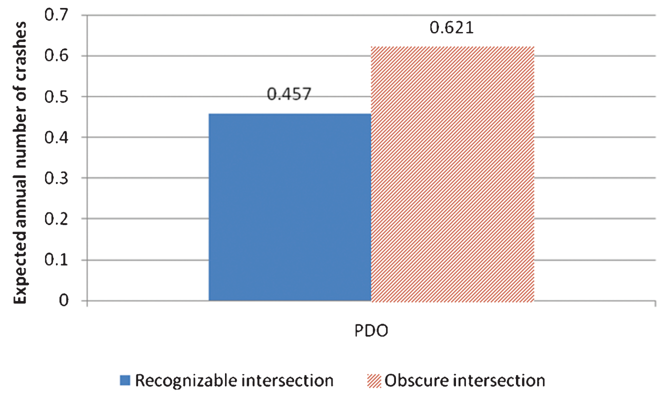

Figure 5.5 Effect of intersection recognizability on expected annual number of crashes.

NOTE: For this graph, the measure used is whether the intersection is recognizable at 1.2 times the AASHTO stopping sight distance, which is taken at the posted speed limit. The intersection is considered recognizable when a driver is made aware of the intersection when at least that far away from it.

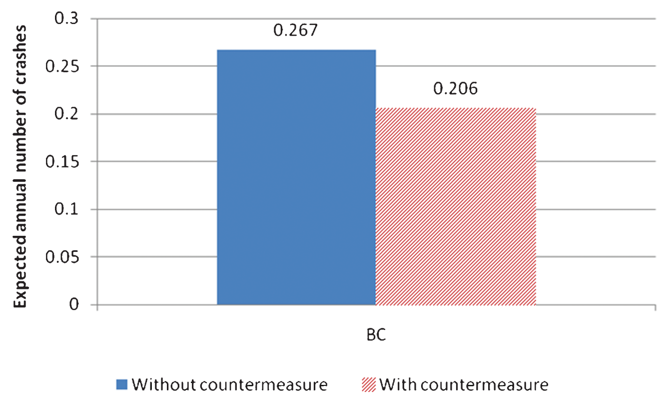

Figure 5.6 Effect of left-turn taper acceleration lanes on expected annual number of crashes.

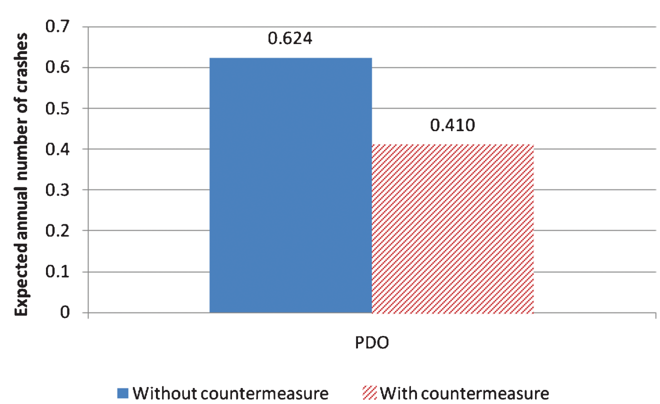

Figure 5.7 Effect of right-turn taper acceleration lanes on expected annual number of crashes.

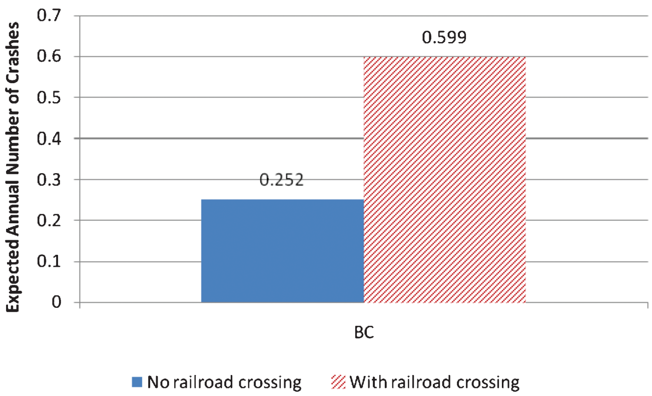

Figure 5.8 Effect of railroad crossings across major road on expected annual number of crashes.

5.4 Selected Safety Impacts under Various AADT and Population

Figures 5.9 through 5.37 present a series of graphs illustrating the effects of the significant variables on the expected annual number of crashes combined with increases in the average annual daily traffic. Each effect is shown one at a time. Figures 5.38 through 5.59 show a similar series of graphs documenting the effects of the variables combined with population increases.

Notice that, in all cases, when the average annual daily traffic increases on the major roadway, the number of crashes will also increase. Similarly, as the population of surrounding cities and towns increases, the number of crashes at the intersection will also increase in all cases.

5.4.1 Graphs of AADT and Intersection Effects

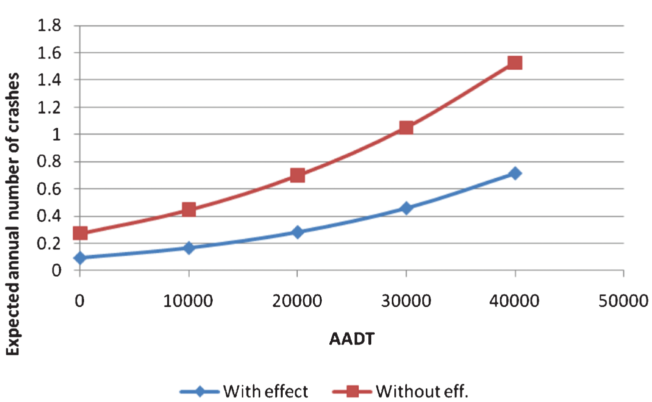

Figure 5.9 Effect of one left-turn bay on major road on expected annual number of BC crashes with AADT increase (that is, a left-turn bay in one direction but not the other, typically at a 3-leg intersection).

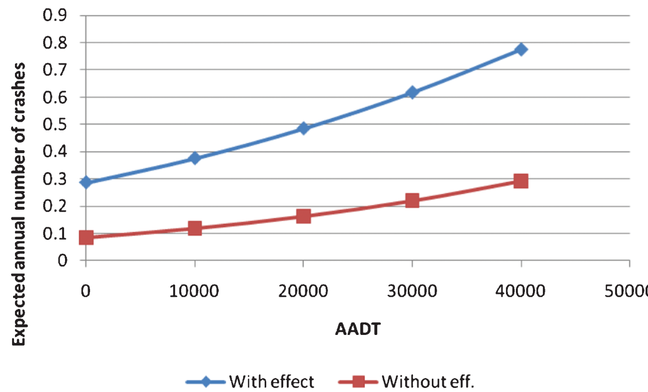

Figure 5.10 Effect of two left-turn bays on major road on expected annual number of BC crashes with AADT increase.

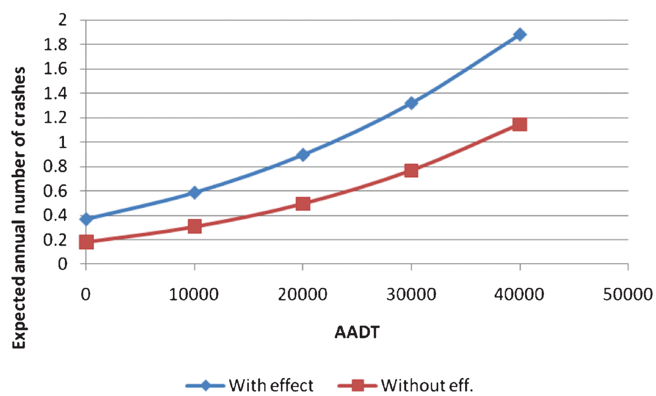

Figure 5.11 Effect of two left-turn bays on major road on expected annual number of PDO crashes with AADT increase.

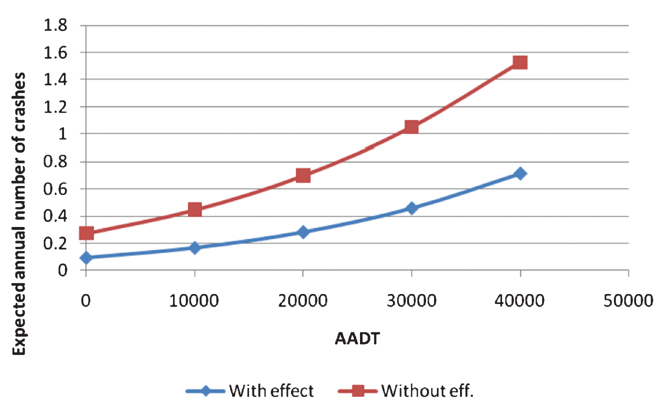

Figure 5.12 Effect of wide median (median at least 80 feet wide) on expected annual number of PDO crashes with AADT increase.

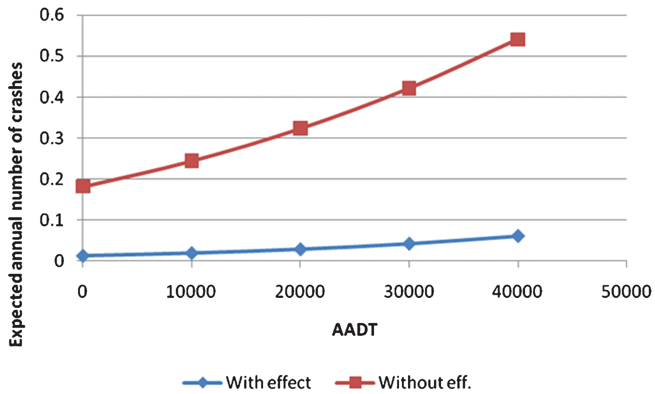

Figure 5.13 Effect of median left-turn parallel acceleration lanes (in both directions) on Expected Number of BC crashes with AADT Increase.

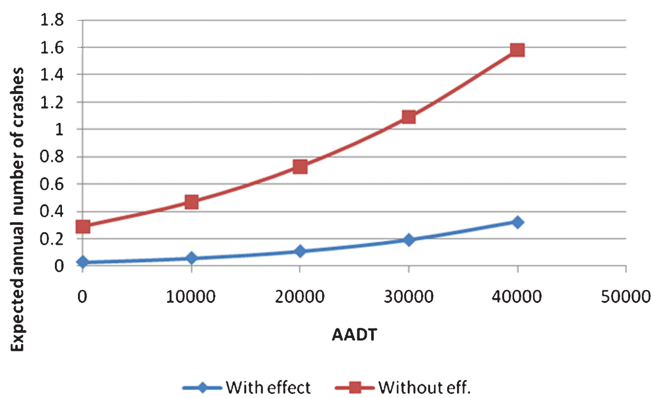

Figure 5.14 Effect of median left-turn parallel acceleration lanes (in both directions) on Expected Number of PDO crashes with AADT Increase.

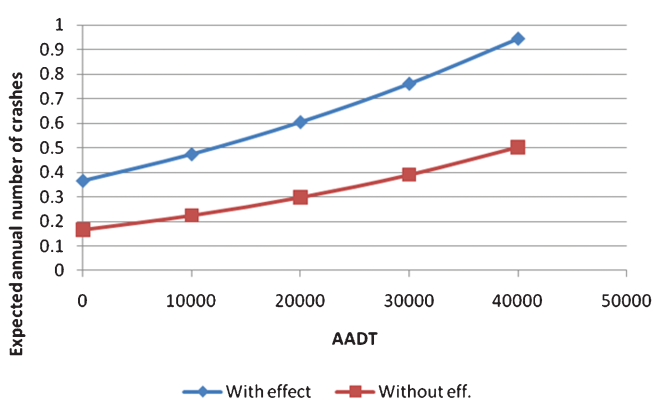

Figure 5.15 Effect of school or religious land uses on expected annual number of BC crashes with AADT increase.

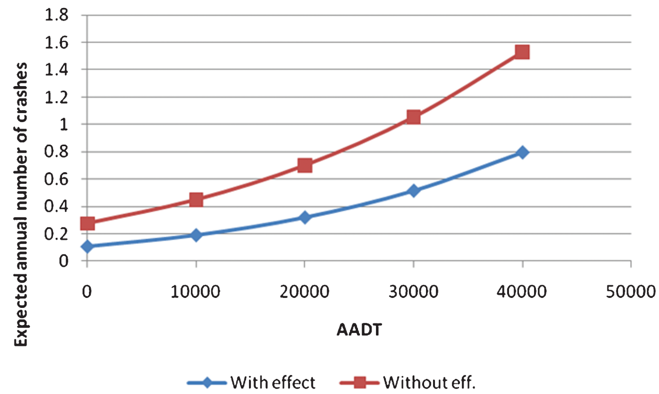

Figure 5.16 Effect of driveways in intersection area on expected annual number of PDO crashes with AADT increase.

NOTE: This result of driveways in the intersection area has been called into question in the description above.

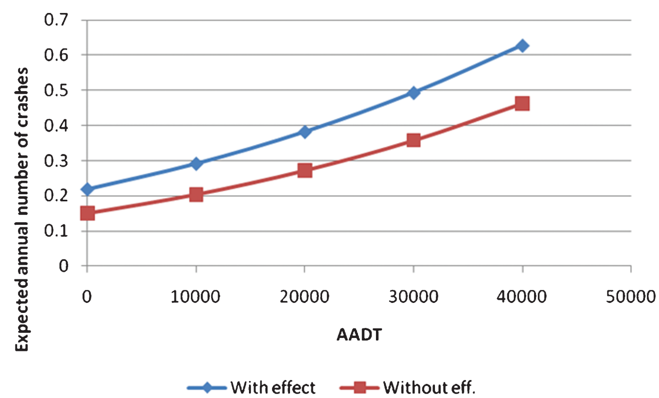

Figure 5.17 Effect of residential land uses in intersection area on expected annual number of BC crashes with AADT increase.

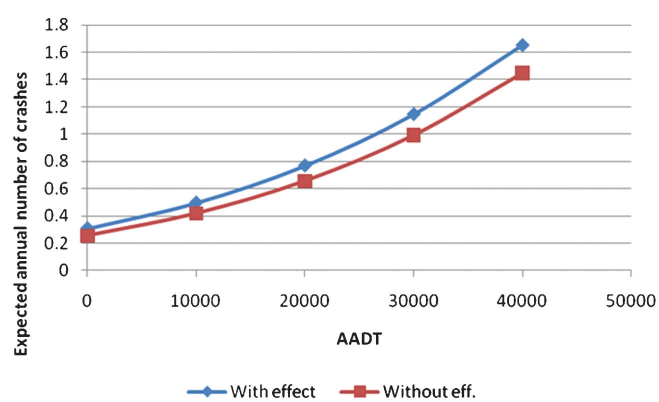

Figure 5.18 Effect of residential land uses in intersection area on expected annual number of PDO crashes with AADT increase.

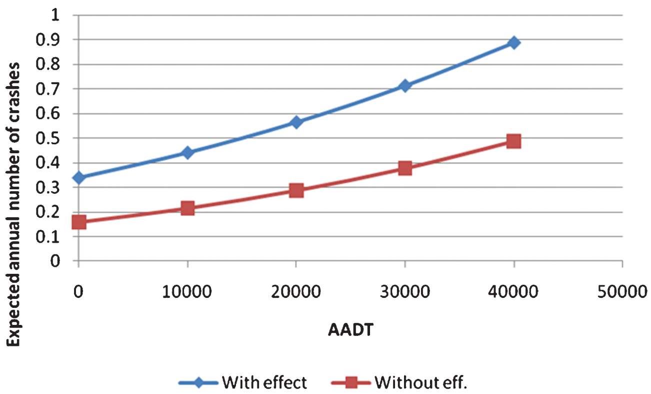

Figure 5.19 Effect of commercial land uses in intersection area on expected annual number of BC crashes with AADT increase.

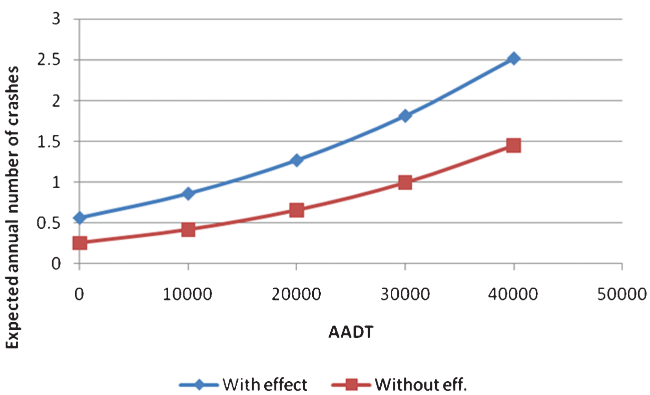

Figure 5.20 Effect of commercial land uses in intersection area on expected annual number of PDO crashes with AADT increase.

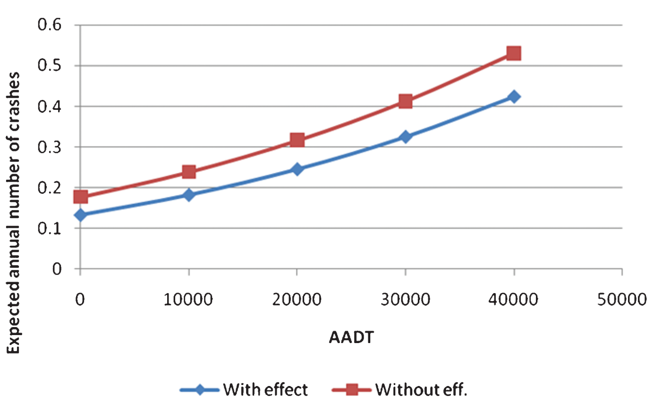

Figure 5.21 Effect of left-turn taper acceleration lane at 3-leg intersection on expected annual number of BC crashes with AADT increase.

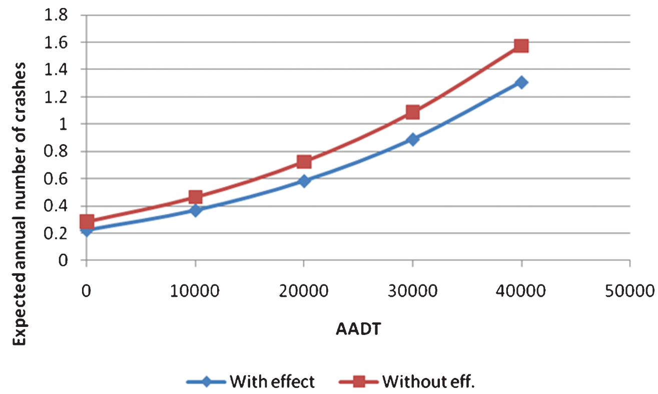

Figure 5.22 Effect of intersection angle (between 75° and 90°) on expected annual number of PDO crashes with AADT increase.

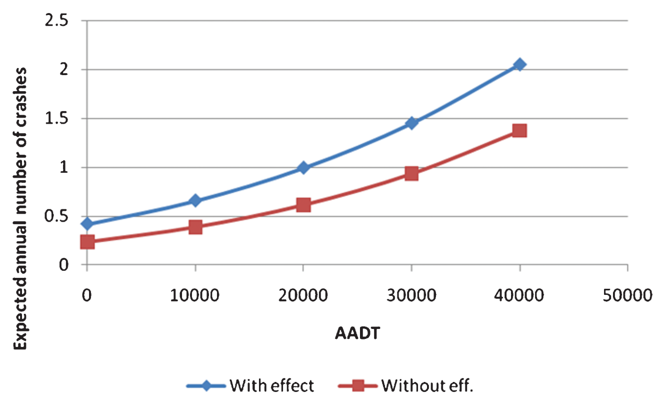

Figure 5.23 Effect of one right-turn bay on major road (one direction but not the other, as in a 3-leg intersection) on expected annual number of PDO crashes with AADT increase.

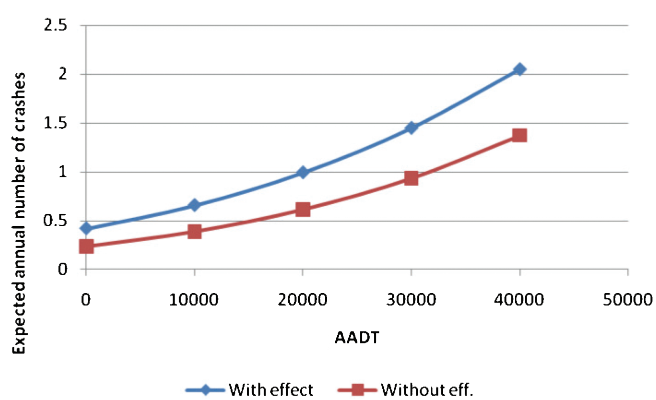

Figure 5.24 Effect of right-turn bays on major road (both directions, 4-leg intersection) on expected annual number of PDO crashes with AADT increase.

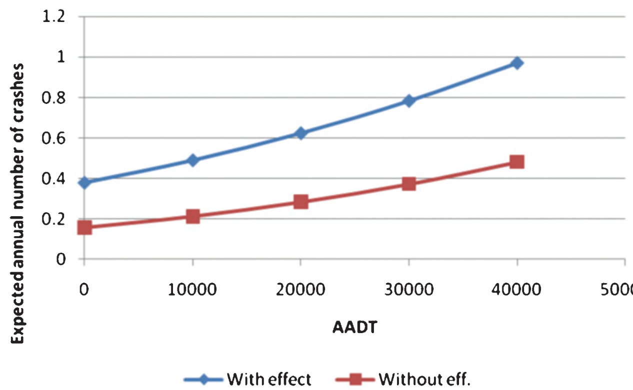

Figure 5.25 Effect of INDOT jurisdiction over minor roadway on expected annual number of BC crashes with AADT increase.

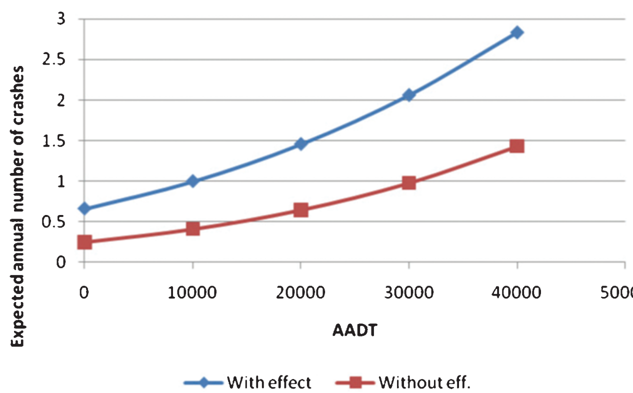

Figure 5.26 Effect of INDOT jurisdiction over minor roadway on expected annual number of PDO crashes with AADT increase.

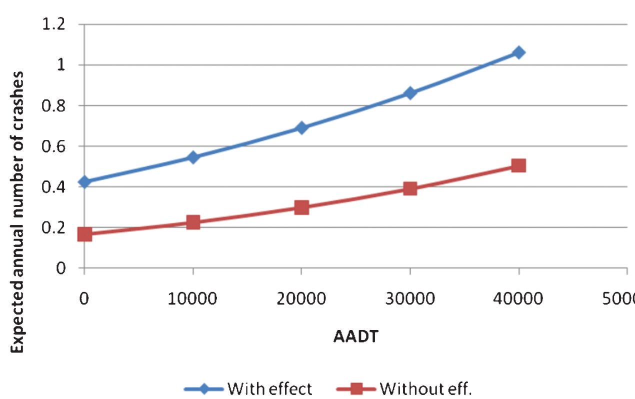

Figure 5.27 Effect of railroad crossing on major road on expected annual number of BC crashes with AADT increase.

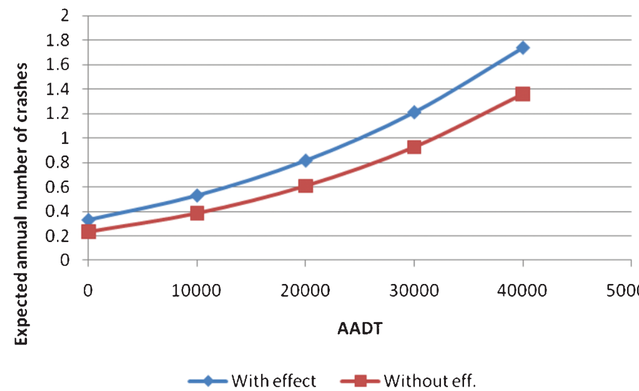

Figure 5.28 Effect of intersection recognizability deficiency (at 1.2 times AASHTO stopping sight distance) on expected annual number of PDO crashes with AADT increase.

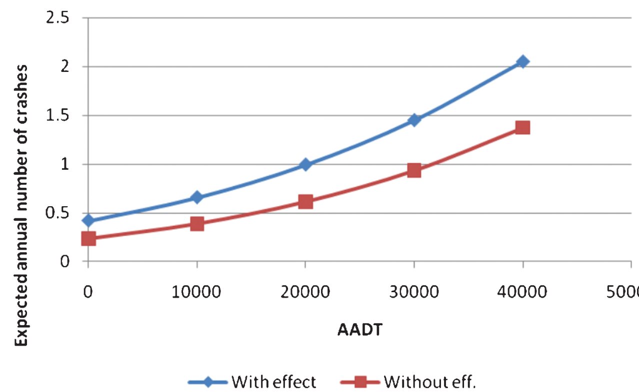

Figure 5.29 Effect of one curve on major roadway near (or at) intersection on expected annual number of PDO crashes with AADT increase.

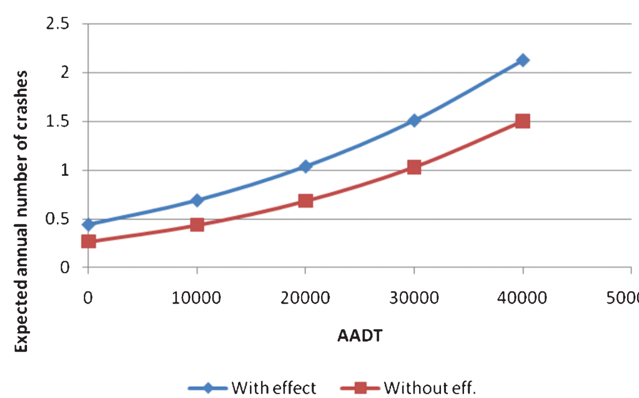

Figure 5.30 Effect of two curves on major roadway near intersection on expected annual number of PDO crashes with AADT increase.

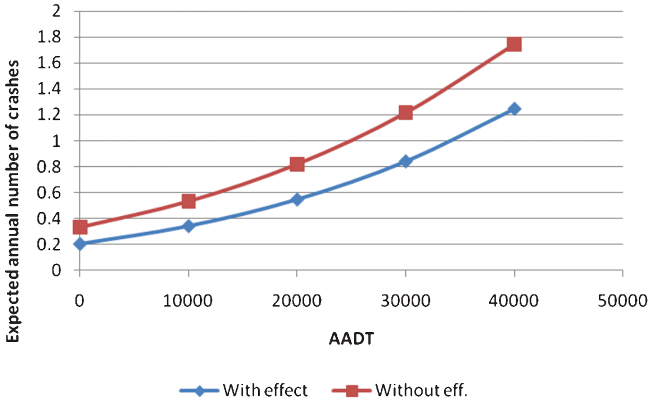

Figure 5.31 Effect of right-turn taper acceleration lane on expected annual number of PDO crashes with AADT increase.

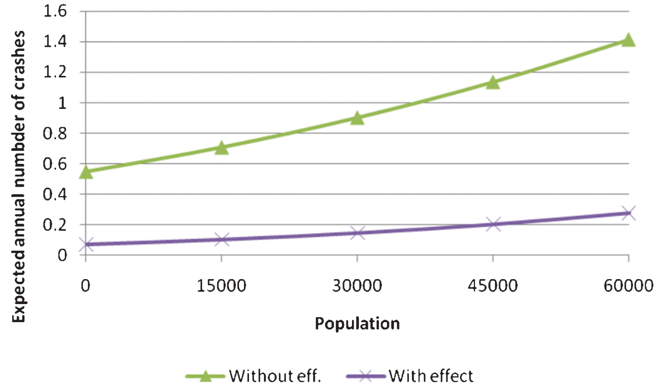

Figure 5.34 Effect of two left-turn parallel acceleration lanes on major roadway on expected annual number of PDO crashes with population increase.

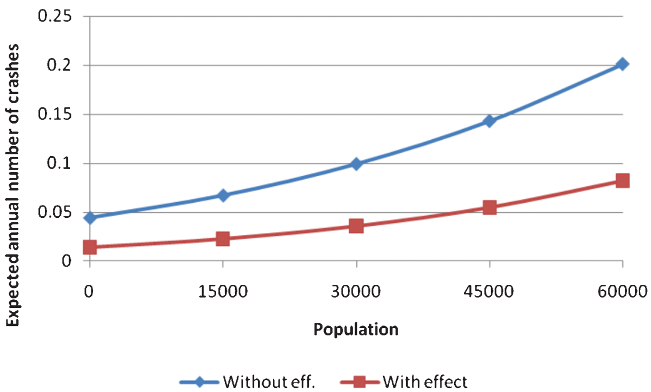

Figure 5.32 Effect of two left-turn parallel acceleration lanes on major roadway on expected annual number of KA crashes with population increase.

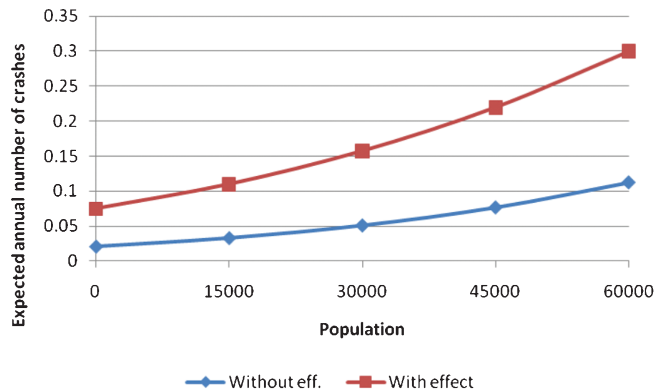

Figure 5.35 Effect of two left-turn bays on major roadway on expected annual number of KA crashes with population increase.

5.4.2 Graphs of Population and Intersection Effects

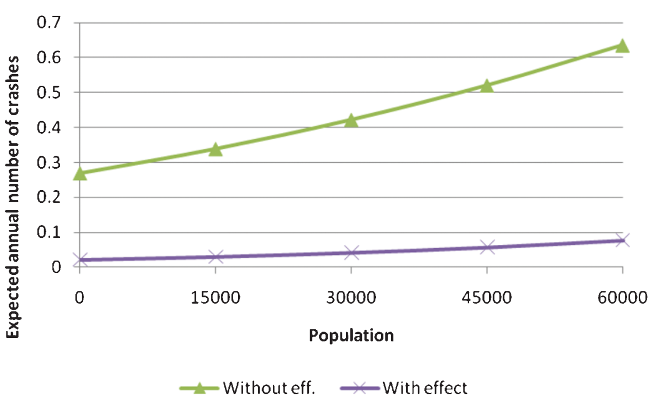

Figure 5.33 Effect of two left-turn parallel acceleration lanes on major roadway on expected annual number of BC crashes with population increase.

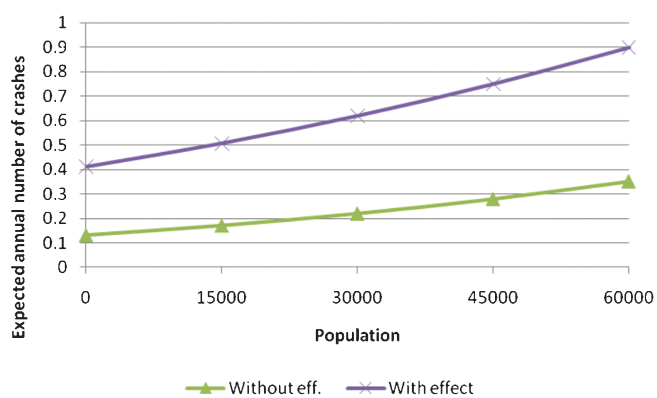

Figure 5.36 Effect of two left-turn bays on major roadway on expected annual number of BC crashes with population increase.

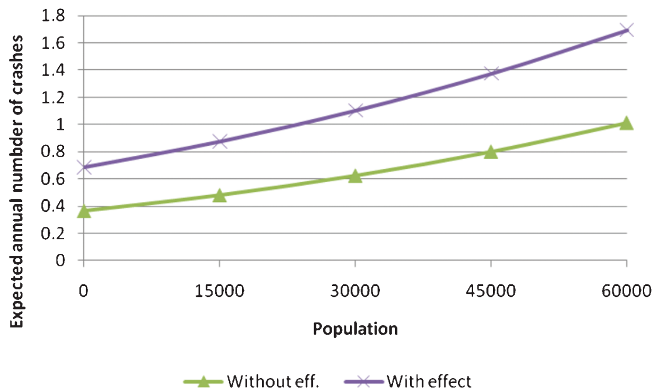

Figure 5.37 Effect of two left-turn bays on major roadway on expected annual number of PDO crashes with population increase.

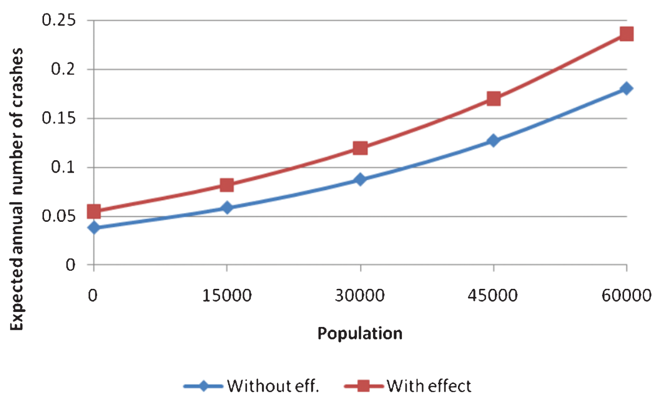

Figure 5.38 Effect of residential land uses in intersection area on expected annual number of KA crashes with population increase.

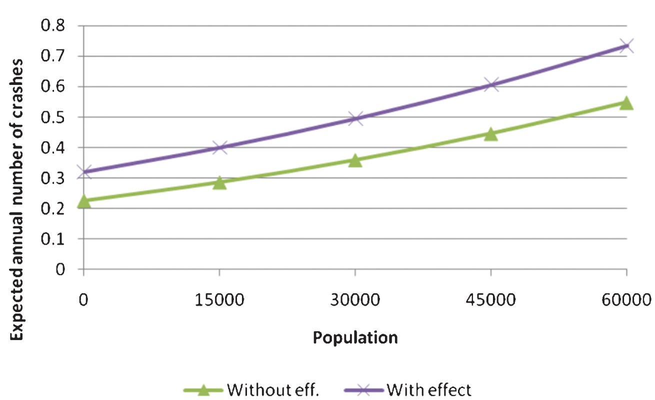

Figure 5.39 Effect of residential land uses in intersection area on expected annual number of BC crashes with population increase.

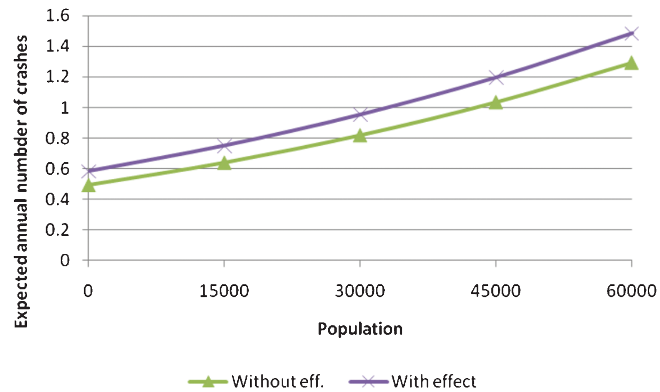

Figure 5.40 Effect of residential land uses in intersection area on expected annual number of PDO crashes with population increase.

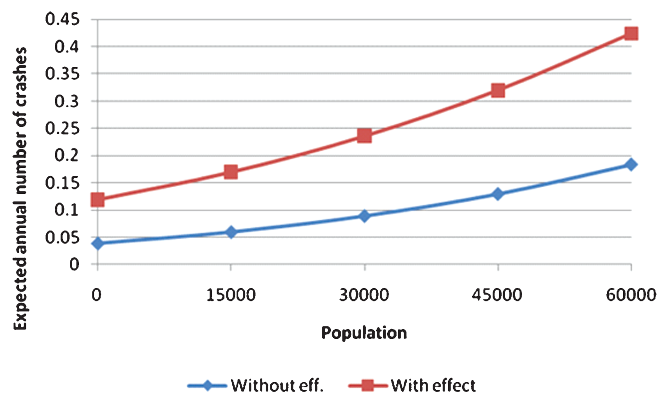

Figure 5.41 Effect of commercial land uses in intersection area on expected annual number of KA crashes with population increase.

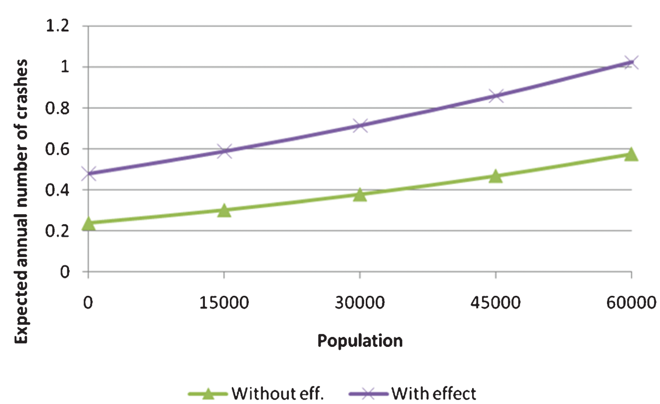

Figure 5.42 Effect of commercial land uses in intersection area on expected annual number of BC crashes with population increase.

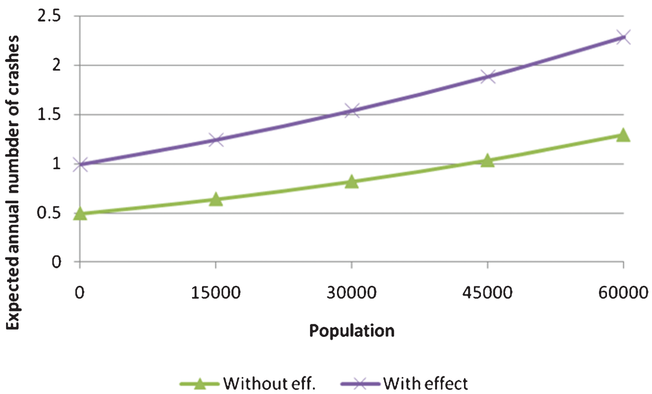

Figure 5.43 Effect of commercial land uses in intersection area on expected annual number of PDO crashes with population increase.

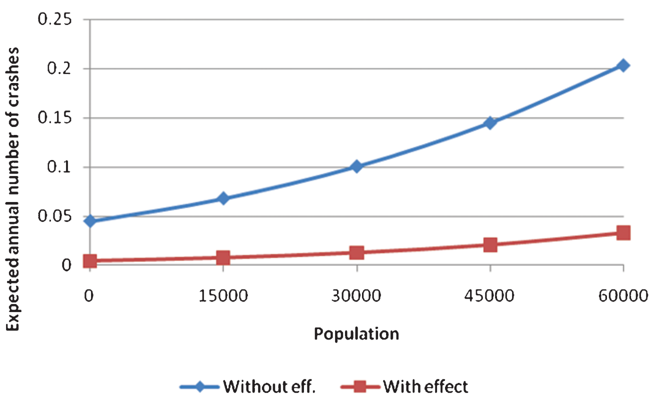

Figure 5.44 Effect of right-turn parallel acceleration lane (3-leg intersection) on major road on expected annual number of KA crashes.

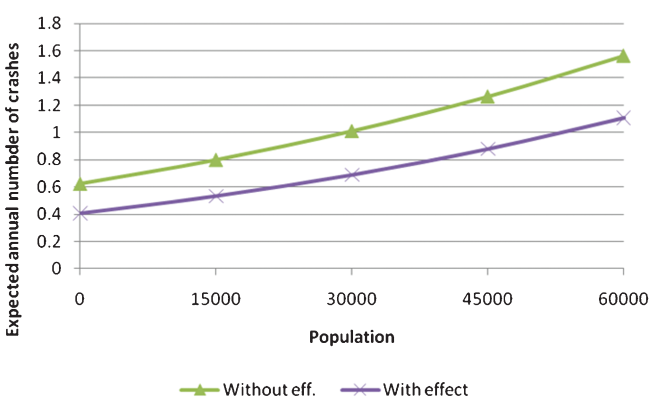

Figure 5.45 Effect of right-turn taper acceleration lane on major road on expected annual number of PDO crashes.

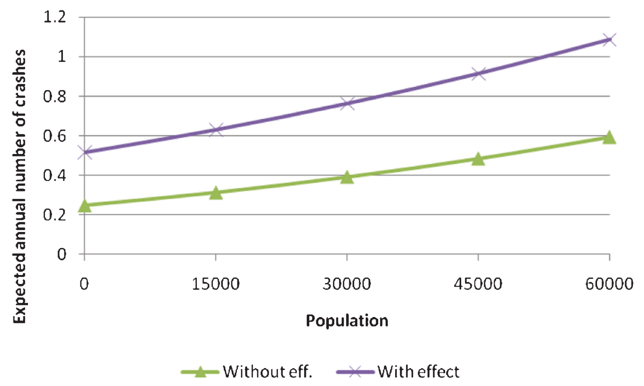

Figure 5.46 Effect of school or religious land uses on expected annual number of BC crashes with population increase.

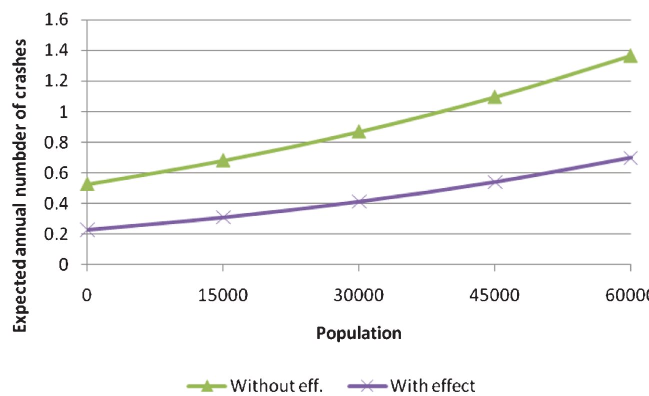

Figure 5.47 Effect of driveways in intersection area on expected annual number of PDO crashes with population increase.

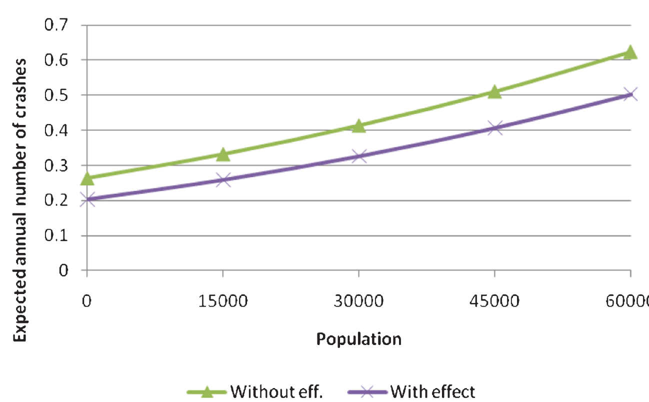

Figure 5.48 Effect of left-turn taper acceleration lane at 3-leg intersection on expected annual number of BC crashes with population increase.

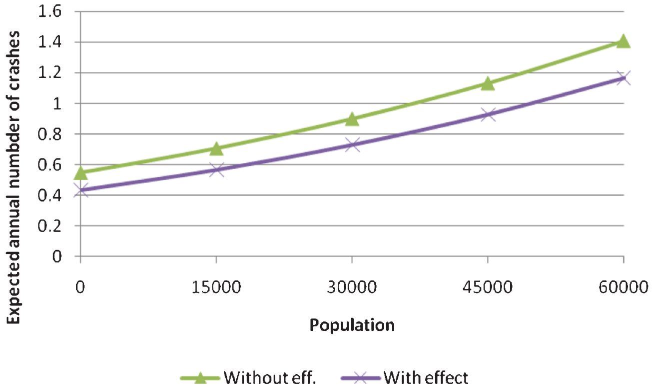

Figure 5.49 Effect of intersection angle (between 75° and 90°) on expected annual number of PDO crashes with population increase.

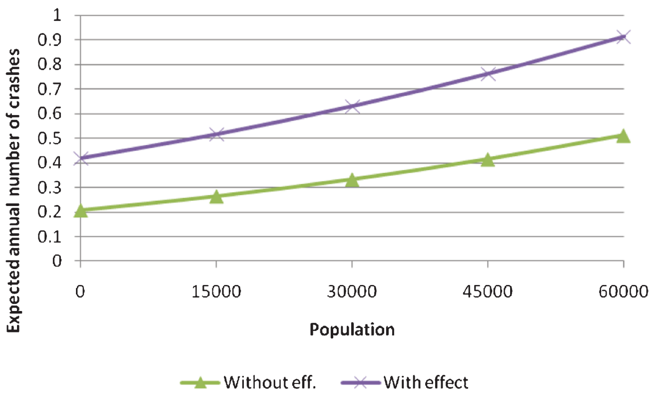

Figure 5.50 Effect of one right-turn bay on major road (one direction but not the other, as in a 3-leg intersection) on expected annual number of PDO crashes with population increase.

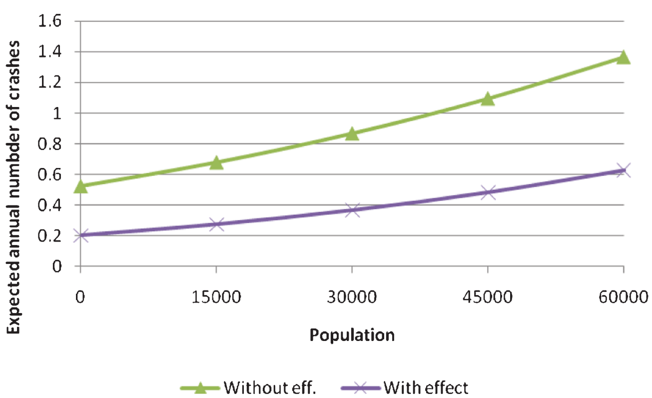

Figure 5.51 Effect of wide median (median at least 80 feet wide) on expected annual number of PDO crashes with population increase.

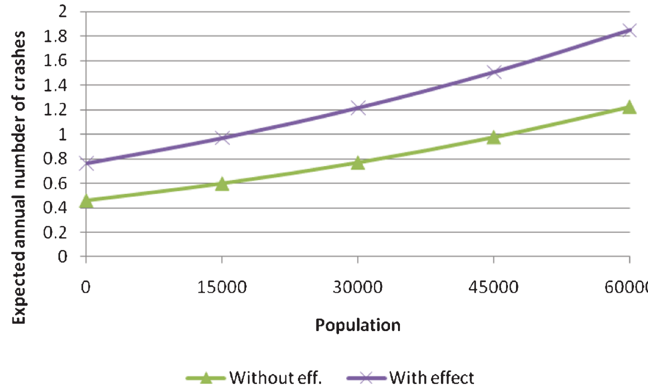

Figure 5.52 Effect of one right-turn bay on major road (one direction but not the other, as in a 3-leg intersection) on expected annual number of PDO crashes with population increase.

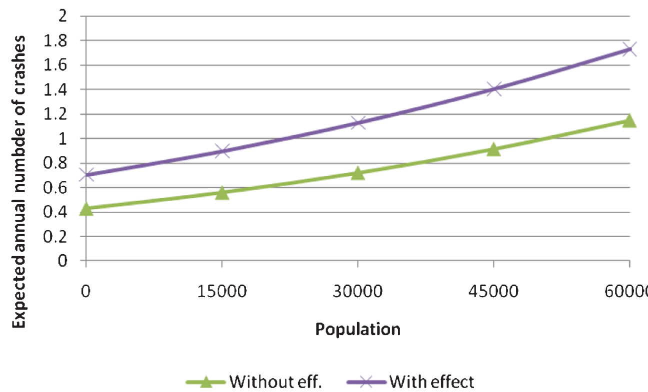

Figure 5.53 Effect of right-turn bays on major road (both directions, 4-leg intersection) on expected annual number of PDO crashes with population increase.

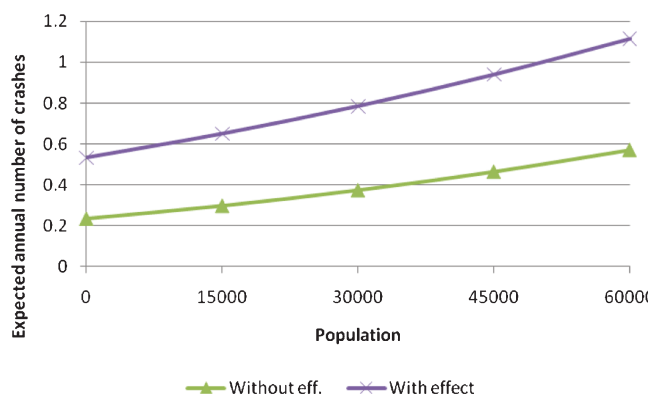

Figure 5.54 Effect of INDOT jurisdiction over minor roadway on expected annual number of BC crashes with population increase.

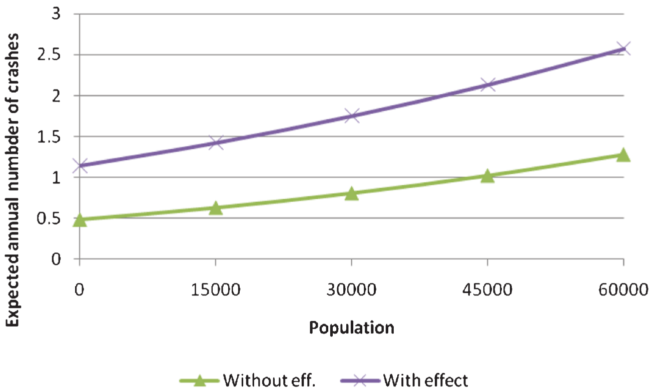

Figure 5.55 Effect of INDOT jurisdiction over minor roadway on expected annual number of PDO crashes with population increase.

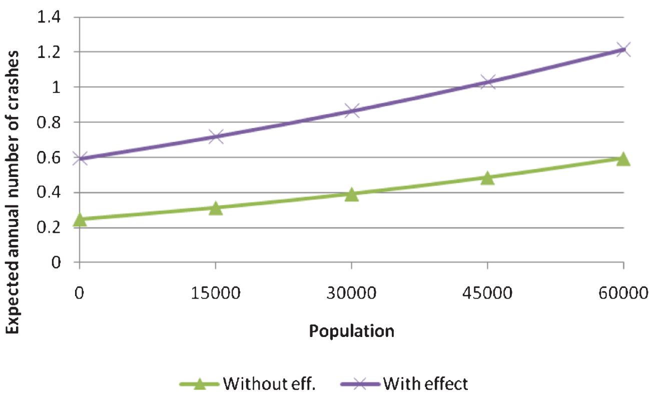

Figure 5.56 Effect of Railroad Crossing on major road on expected annual number of BC crashes with population increase.

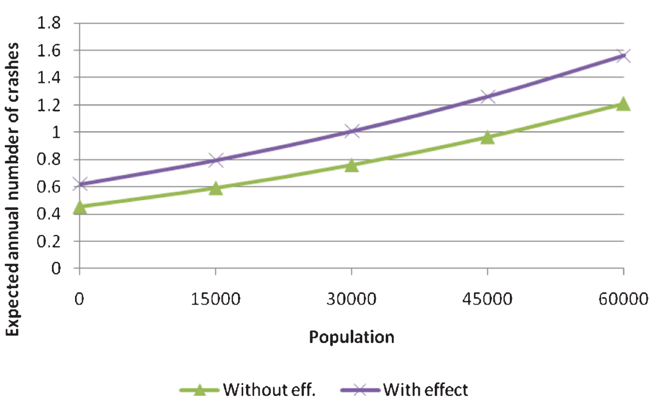

Figure 5.57 Effect of intersection recognizability deficiency (at 1.2 times AASHTO stopping sight distance) on expected annual number of PDO crashes with population increase.

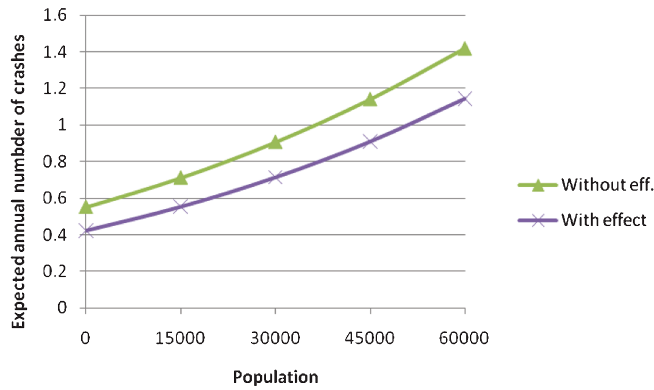

Figure 5.58 Effect of one curve on major roadway near (or at) Intersection on expected annual number of PDO crashes with population increase.

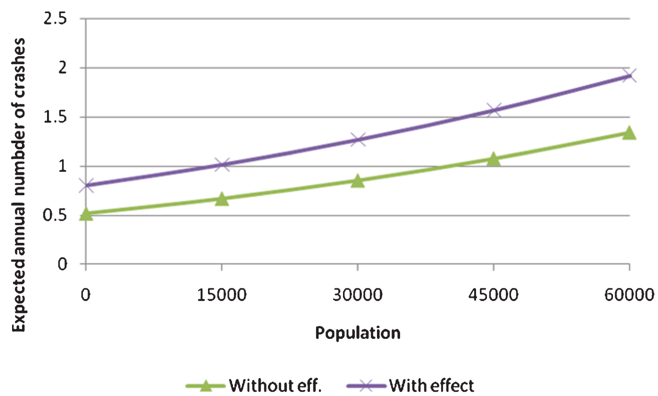

Figure 5.59 Effect of two curves on major roadway near Intersection on expected annual number of PDO crashes with population increase.

5.5 Crash Reduction Factors

Tables 5.2 through 5.4 show the calculated crash reduction factors for all identified countermeasures, along with some other possible effects. Table 5.2 shows the crash reduction factors for fatal and incapacitating injury crashes (KA); Table 5.3 shows the crash reduction factors for minor injury and possible injury crashes

TABLE 5.2
KA Crash Reduction Factors

Possible countermeasure	
Add left-turn acceleration lanes at a four-leg intersection	68.3%
Add right-turn acceleration lane at a three-leg intersection	90.1%

TABLE 5.3
BC Crash Reduction Factors

Possible countermeasure	
Add left-turn acceleration lanes at a four-leg intersection	91.8%
Add left-turn acceleration taper at a three-leg intersection	22.9%
Remove railroad crossing from major road	58.0%

NOTE: Only three intersections in sample.

TABLE 5.4
PDO Crash Reduction Factors

Possible countermeasure	
Add left-turn acceleration lanes at a four-leg intersection	86.3%
Reduce speed limit from 60 MPH to 55 MPH*	24.5%
Increase intersection angle to make it at least 75 degrees	20.5%
Widen median to make it at least 80 feet wide	61.2%
Make the intersection recognizable from the distance 1.2 times stopping sight distance or longer	26.6%
Add right-turn acceleration tapers at either a three-leg or a four-leg intersection	34.2%

*As explained earlier, an endogeneity issue may be present regarding the association of the increased speed limit on the improvement on safety with respect to PDO crashes.

(BC); and Table 5.4 shows the crash reduction factors for property damage only (PDO) crashes. In all cases, the crash reduction factors were estimated for the effect of having the measure in place (1) versus not having the measure in place (0), as well as the effect of having the measure in place versus the sample mean.

A positive value indicates that the measure reduces crashes and therefore improves safety; a negative value indicates that the measure results in an increased number of crashes and therefore has a negative impact on safety.

Note that acceleration lanes, angles between 75 and 90 degrees, medians at least 80 feet wide, right-turn taper acceleration lanes, and increased recognizability of intersections, all contribute to increased intersection safety. The countermeasures that have the strongest effect are the acceleration lanes, with left-turn and right-turn acceleration lanes both showing a very strong improvement in safety.

5.6 The Effect of U-Turns

To assess the effect of U-turns on safety, data from 72 two-way stop-controlled intersections in the state of Michigan were collected. The Michigan dataset is very similar to the Indiana data. The differences are contained in:

- The speed limit: In the Indiana dataset the speed limits vary from intersection to intersection and, in some cases (in some non-freeway roads) within the same intersection, whereas in Michigan they are 55 miles per hour; and
- The information derived from the INDOT Video Log: such as signage and recognizability, which is not available for Michigan.

Given that there was no information on the Michigan intersections with respect to crashes before the location of U-turns, a before-and-after study was not possible. Such a study would clearly illustrate the true effect of U-turns on the studied intersections. Therefore, the methodology employed was as follows: (a) identify the effect of U-turns and other factors on safety in Michigan intersections, (b) test whether the model parameters are transferable between the Michigan and Indiana datasets, and (c) draw inferences with respect to the model estimation results for both states.

The same modeling scheme followed in Indiana was applied in the Michigan dataset, and multivariate (trivariate) ordered probit models were developed for the same injury severity levels as in Indiana. Surprisingly, the model estimation results illustrated that U-turns do not improve safety; on the contrary, they were found to be associated with increases in the BC crash category and were statistically insignificant in the KA and PDO crash categories). Although this, at first, may appear to be a counter-intuitive result, it can be explained. First of all, U-turns are typically located at signalized intersections to improve their operation; therefore, it would be expected that U-turns are located at unsignalized intersections in Michigan with the same objective (i.e., to improve the intersection's operation. Secondly, if the U-turns are located at intersections in Michigan with the objective to improve safety, this would imply that these intersections had some safety issues, which translates into higher numbers and severity levels of crashes, which, in Statistics, is referred to as endogeneity). Therefore, in that case, the U-turns do not represent a safety counter-measure, but rather indicate the presence of a safety problem at the intersections, which in turn is clearly depicted in the model estimation results in the Michigan models.

The transferability of the model parameters between Indiana and Michigan data was tested using likelihood ratio tests *(34)*. The tests clearly showed that the model parameters are not transferable. This result means that no inferences should be drawn as to whether the effect of the U-turns in Michigan intersections can be assumed to be similar to Indiana intersections. To further validate this result, and since the correlation between the injury categories in the trivariate ordered probit model for the Michigan intersections was not as highly significant as in the Indiana intersections model, univariate ordered probit models were additionally estimated, and the transferability of the parameters between the two datasets (Michigan and Indiana) was evaluated. The test results illustrated once more that the model parameters cannot be assumed to be transferable between the Michigan and Indiana datasets.

Appendix B presents the representative model estimation results and likelihood ratio tests for the evaluation of the parameters transferability between the Michigan and Indiana models.

There are several reasons as to why the transferability test was inconclusive and the model parameters were not transferable between the Michigan and Indiana datasets. First, there was missing information in the Michigan dataset, as discussed earlier in this section, and omitted variables typically result in biased parameter estimates. Second, perhaps there are different ways that data are collected in the two states, which may result in variable-specific inconsistencies. Finally, the Michigan dataset is much smaller compared to the Indiana dataset, which may magnify potential irregularities in the data, and which in turn may result in biased parameter estimates.

6. RECOMMENDATIONS

In this chapter, recommendations are offers on how to improve safety at high-speed rural divided highway intersections. These recommendations are based both on the modeling results discussed previously, as well as on the literature review. These recommendations are with respect to improving safety for construction of new high-speed divided highways and for existing intersections with higher crash potential.

6.1 Recommendations for New Constructions

The recommendations for new construction are as follows:

- **Design the intersection angle at 75 degrees minimally**. The conducted Indiana research indicates that 20% of crashes can be saved by following this recommendation.
- **Consider J-turns at intersections** with considerable left-turn volumes from the major road and weak crossing volume from the minor road. **U-turns** may be a good choice where all the turning volumes and crossings from the minor road are weak.
- **Design left-turn bays and right-turn bays at intersections** along the major roadway**,** to allow turning traffic to decelerate away from the through traffic before turning. NCHRP Report 500 *(6)* and other sources have documented the clear safety benefits of having deceleration lanes for turning movements, and it is considered to be a "proven" countermeasure by NCHRP Report 500 *(6)*.
- **Design the median at 80 feet wide minimally in the intersection area**. It was shown in this research that there are fewer crashes at intersections with medians at least 80 feet wide than at intersections with narrower medians. The wider medians allow more opportunities to make a two-stage crossing by giving ample space in the median to store larger vehicles.
- **If the median must be significantly narrower than 80 feet wide** at an intersection because of right-of-way constraints, especially if the median must be no more than 25 or 30 feet wide, **intersections might be limited to 3 legs if possible.** Three-leg intersections do not have a crossing conflict involving the minor road; they only have potential turning conflicts. The results of this research have demonstrated improved safety at three-leg intersections than at four-leg intersections. Since all minor road traffic is required to turn onto the major road at a three-leg intersection, the median can store vehicles turning left without needing to be as wide as a median that must store a crossing vehicle.
- **Consider left-turn acceleration lanes in the median** to assist drivers turning left from the minor roadway in entering the major roadway. This solution is particularly recommended where the median is narrow.
- **Avoid locating intersections on horizontal curves** on the major roadway. Several studies have documented that intersections near horizontal curves do experience more crashes than intersections on tangent segments. The results from this study confirm those previous results.
- **Avoid locating intersections close to an existing at-grade railway crossing.** The possible negative effect was shown in this research. Although this result should be confirmed with a large study, it is prudent to follow this recommendation if it does not involve considerable extra costs.

6.2 Recommendations for Improving Safety at Existing Intersections

Recommendations for improving safety at existing intersections are as follows:

- **Convert direct left turns and crossing maneuvers into indirect maneuvers** by closing off or restricting the movements that can be made at the median and adding U-turns in the median. With the minor road through and turning movements prohibited across the highway, and redirected to other routes, usually a U-turn, the number of conflicts in the median is reduced, and a two-stage left-turn or crossing is facilitated.
- **Adding parallel acceleration lanes** in the median. The research results from this research and other studies show some safety benefits resulting from the use of a left-turn median acceleration lane. This result is due to vehicles turning left onto the major road being able to more easily enter the highway, without necessarily having to find a gap in the far-side traffic where the bulk of angle crashes occur. However, the median acceleration lanes will not solve a crash problem involving crossing traffic if the median is not wide enough, nor will it remedy a crash problem involving near-side traffic.
- **Add larger signage to make the intersection more conspicuous.** The results of this research and several other studies have shown some safety benefits from making intersections more conspicuous, possibly with larger signage.
- **Add lighting.** If the majority of crashes at an intersection occur at night, the addition of lighting at night can greatly reduce the probability of crashes. NCHRP Report 500 *(6)* lists it as a "proven" countermeasure.
- **Build grade separations only where absolutely necessary.** Grade separations are costly to build and are associated with higher user costs since travelers will have to take indirect routes to turn between the major road and the minor road unless there is a one-quadrant ramp or an interchange that allows such movements. Grade separations should be considered only where: (a) a planning study indicates a need (e.g., where warranted by higher traffic volumes or where freeway conversion is proposed for the major roadway); (b) topographic or other considerations preclude the use of other treatments (e.g., grade separations are often justified where there is an at-grade railroad crossing in the intersection area); or (c) all other countermeasures have been tried and have failed to improve intersection safety.

6.3 Recommendations for Pilot Studies in Indiana

Out of the number of potential countermeasures that could potentially be implemented, the systems based on advanced detection of vehicles and warning the drivers about potentially dangerous gaps on the major road seems to be quite promising from a safety and cost effectiveness point of view. For example, the Cooperative Intersection Collision Avoidance

Systems-Stop Sign Assist has been thoroughly tested and calibrated, but it still awaits field studies to estimate and eventually confirm its safety benefit. A pilot study of this or a similar system in Indiana is recommended.

Other suggestions for pilot studies include safety countermeasures that are considered to be proven but still require research to better identify design conditions of their use and also estimation of the crash reduction factors to promote them as safety countermeasures at existing intersections. They include:

- Median acceleration lanes;
- Indirect left turns (such as U-turns and J-turn); and
- Enhanced intersection approach signage.

A promising solution that deserves pilot studies is roundabouts. The NCHRP Report 613 *(28)* report encourages using roundabouts to reduce speed and safety at existing and new intersections. It also admits that multilane roundabouts exhibit lower safety performance then single-lane roundabouts due to additional potential of conflict between vehicles exiting the roundabout and other remaining on the circulatory roadway. The case studies by Ritchie and Lenters *(29)* indicated that modern roundabouts on roadways with high-speed approaches may be effective in improving safety. The authors also warned that a roundabout will not always result in a safe intersection if its design is inadequate. They emphasized design conditions important for safety performance of roundabouts on high-speed roads.

7. CONCLUSION

The Indiana Five Percent Reports over the past several years identified a safety problem concerning at-grade intersections on high-speed divided highways. Hence, a research project was proposed to identify which factors tend to increase the frequency and severity of crashes at these intersections and then identify countermeasures that could be used to improve safety.

The safety recommendations of this research were based on both a literature review 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 as 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 crossing 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 were all factors found to decrease the likelihood of crashes at 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 aid with this 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 in Indiana.

7.1 Directions for Future Research

Although the modeling that was done in Indiana was based on many intersections, the bulk of the findings were due to factors that all increased the likelihood of crashes at the different severity levels. Very few of the intersections studied had any of the countermeasures implemented as suggested in other studies. For instance, only 46 of the 557 intersections studied had median acceleration lanes, and the majority of these intersections were located on the same highway corridor of the same INDOT district. Even fewer intersections had a median width greater than 80 feet. Only three intersections had at-grade railroad crossings on the major road; whereas, only one intersection had a partial J-turn installed, without the U-turns that would have permitted all movements *(14)*, and it was replaced with a grade-separation in 2006.

The only way to identify whether all of these potential countermeasures are truly effective is to apply reasonable research findings in practice. For example, the various countermeasures contained herein could be installed in new intersections, and their effectiveness then evaluated further with a before-and-after study.

Future research could further involve the analysis of intersections in other states that have implemented some of these countermeasures extensively. For example, research could be conducted on intersections in Michigan to quantify the effects of median U-turns with respect to improving intersection safety. That undertaking would require exhaustive data collection that would include information about the same intersection before the location of the U-turn and after. Similarly, research could be done with intersections in Ohio to quantify the effects of offset left-turn lanes or their enhanced signage practices.

Additionally, it is recommended that the suggested countermeasures be implemented in Indiana, potentially as a pilot study. A before-and-after study could then be conducted to prove their benefits in improving safety. For instance, more median acceleration lanes, U-turns, or J-turns could be built in Indiana, or enhanced signage and warning devices (such as the Cooperative Intersection Collision Avoidance Systems-Stop Sign Assist) could be installed at selected locations to show that they are truly effective. A test of any new countermeasure should determine whether the results in Indiana agree or disagree with other studies that have been conducted to date, or if the experience in Indiana is similar to or different from the experience in other jurisdictions. In all cases, a before-and-after study should be conducted. Particular emphasis on any pilot studies conducted should focus on which intersections would benefit the most from the different types of countermeasures available. NCHRP Report 650 *(23)* is an excellent resource in this regard; however, other research studies could serve as a guide.

Additional before-and-after studies of the safety effect of overhead flashers are needed. Although intended to increase recognizability at intersections, the results from this study agree with prior research that the presence of overhead flashers at intersections has not been consistently effective in reducing crashes. Instead, flashing lights could be installed on the advance signage *(8)* and could possibly flash only when approaching vehicles are present on the minor road approaches as described in NCHRP Report 500 *(6)* and NCHRP Report 650 *(23)*. If these alternative flashers are implemented in Indiana, research should be done to determine their effectiveness compared with intersections that have traditional overhead flashers and intersections with no flashers.

Finally, it is recommended to continue monitoring other research studies to determine when, or if, other promising countermeasures may be suitable for implementation (e.g., the Intersection Decision Support System) and to monitor other jurisdictions' experiences with various other countermeasures that have been proposed in an attempt to improve safety conditions.

APPENDIX A

http://docs.lib.purdue.edu/cgi/viewcontent.cgi?filename=3&article=1842&context=jtrp&type=additional

APPENDIX B

http://docs.lib.purdue.edu/cgi/viewcontent.cgi?filename=4&article=1842&context=jtrp&type=additional

APPENDIX C

http://docs.lib.purdue.edu/cgi/viewcontent.cgi?filename=5&article=1842&context=jtrp&type=additional

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