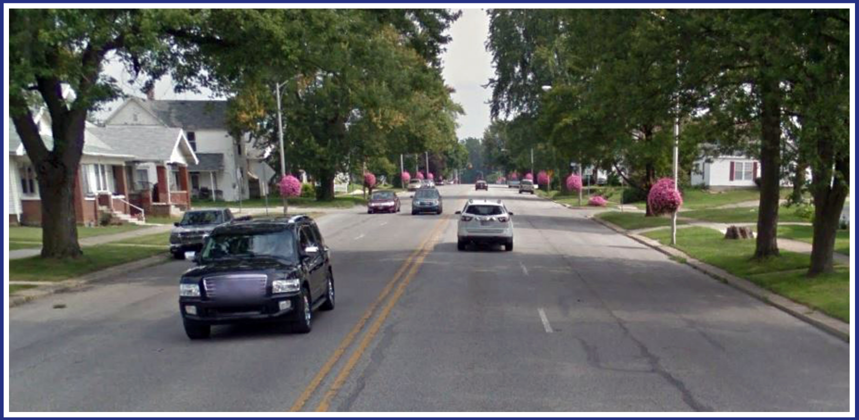
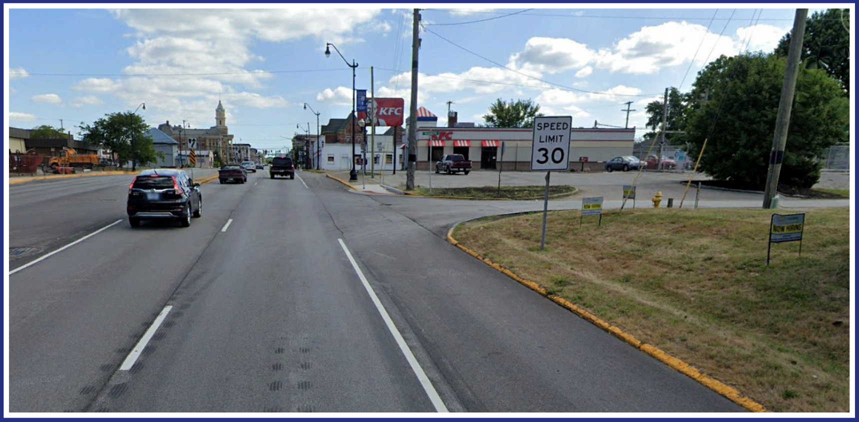
JOINT TRANSPORTATION
RESEARCH PROGRAM
INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

Speed Management in Small Cities and Towns—Guidelines for Indiana





Andrew P. Tarko, Thomas Hall, Cristhian Lizarazo, Fernando España-Monedero

SPR-4217 • Report Number: FHWA/IN/JTRP-2020/10 • DOI: 10.5703/1288284317122

RECOMMENDED CITATION

Tarko, A. P., Hall, T., Lizarazo, C., & España-Monedero, F. (2020). *Speed management in small cities and towns—Guidelines for Indiana* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2020/10). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317122

AUTHORS

Andrew P. Tarko, PhD
Professor of Civil Engineering and Director of Center for Road Safety
Lyles School of Civil Engineering
(765) 494-5027
tarko@purdue.edu
Corresponding Author

Thomas Hall, Post-Doctoral Research Assistant
Cristhian Lizarazo, Graduate Research Assistant
Fernando España-Monedero, Visiting Graduate Assistant
Lyles School of Civil Engineering
Purdue University

ACKNOWLEDGEMENTS

This research was made possible because of the contributions of many people. The authors would like to thank Mr. Luis Laracuente, Mr. Alan Holderread, Dr. Shuo Li, and Mr. Dirk Schmidt from the Indiana Department of Transportation (INDOT) and Mr. Rick Drumm from the FHWA Indiana Division for their help and support throughout the project. Dr. Mario Romero and Mr. Jose Thomaz of the Purdue University Center for Road Safety (CRS) aided in various data processing tasks throughout the project. CRS research assistants Fahad Alqahtani and Raul Pineda Mendez contributed to the statistical modeling and review of past studies, respectively. Thank you to Mr. Howell Li and Dr. Darcy Bullock of the Joint Transportation Research Program for their help in obtaining the speed data for arterial roads that was employed in this research. Multiple undergraduate and graduate students graciously assisted during the data extraction phase of the research.

JOINT TRANSPORTATION RESEARCH PROGRAM

The Joint Transportation Research Program serves as a vehicle for INDOT collaboration with higher education institutions and industry in Indiana to facilitate innovation that results in continuous improvement in the planning, design, construction, operation, management and economic efficiency of the Indiana transportation infrastructure. https://engineering.purdue.edu/JTRP/index_html

Published reports of the Joint Transportation Research Program are available at http://docs.lib.purdue.edu/jtrp/.

NOTICE

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA/IN/JTRP-2020/10	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle Speed Management in Small Cities and Towns–Guidelines for Indiana	**5. Report Date** March 2020
	6. Performing Organization Code
7. Author(s) Andrew P. Tarko, Thomas Hall, Cristhian Lizarazo, and Fernando España-Monedero	**8. Performing Organization Report No.** FHWA/IN/JTRP-2020/10
9. Performing Organization Name and Address Joint Transportation Research Program (SPR) Hall for Discovery and Learning Research (DLR), Suite 204 207 S. Martin Jischke Drive West Lafayette, IN 47907	**10. Work Unit No.**
	11. Contract or Grant No. SPR-4217
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204	**13. Type of Report and Period Covered** Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

Many small cities and towns in rural states such as Indiana are crossed by arterial highways. The local traffic on these roads, particularly vulnerable road users, face the excessive risk of injury and death. This danger is amplified with local land development, driveways, and on-street parking in town centers. This report presents an Indiana study of the speeding problem on arterial roads passing through small communities. Past research on various countermeasures suitable for the studied conditions were identified and the connection between speed reduction and safety improvements was investigated in a sample of Indiana small towns. Promising speed-reduction measures include speed feedback signs and converging chevrons with speed limit legends marked on the pavement. Point-to-point enforcement is a modern and highly effective alternative that may be applicable on highways passing small towns if the through traffic prevails with limited interruptions. This report provides a method of evaluating the benefits of speed reduction in the studied conditions where the risk of severe injury and fatality is excessive to road users while the frequency of crashes is low. The method includes the proactive estimation of the economic benefit. The results indicate that both the local and through traffic on highways passing a small town benefit considerably from speed reduction even after accounting for the loss of time. An Excel spreadsheet developed in the study facilitates the calculations.

17. Key Words small towns, high-speed through traffic, speed reduction, proactive safety management	**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 62 including appendices	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EXECUTIVE SUMMARY

Introduction

There is a strong need in Indiana to study the speeding problem, particularly on arterial roads passing through small communities. Across Indiana, more than 400 small cities and towns (<15,000 population) are crossed by arterial highways that serve a diverse composition of road users. Pedestrians and bicyclists, a large majority of which are residents of these local communities, face the highest risk of injury and death; however, they are not the only group exposed to speed-related hazards in small towns and cities. The considerable speed difference between vehicles traveling through communities and local vehicles merging, egressing, or crossing the high-speed traffic poses a potentially serious safety threat to all vehicle occupants. This danger is amplified by the presence of driveways, pedestrian traffic, land development near the road, the presence of on-street parking, and other factors.

Multiple tried measures of reducing speeds on arterial roads passing through small communities were discussed and the promising countermeasures and their combinations identified. To make the implementation of the countermeasures effective, the tool for estimating the safety benefit of using these measures is included in the outcomes of this study.

Findings

Various speed-reduction countermeasures to improve safety conditions in small towns were investigated. Among the most promising measures were speed feedback signs and converging chevrons with speed limit legends marked on the pavement. Point-to-point enforcement is a promising and potentially highly effective measure of reducing speeds of traffic passing through small communities without interruptions.

The potential implications of this study are two-fold. (1) This report provides a useful method to evaluate the benefits of speed reduction when applied on arterial highways crossing small communities. (2) This study also identifies several practical countermeasures for speed reduction that can help reduce crash severity, particularly among vulnerable road users. The framework adopted in this study can help justify the case for speed reduction in small communities that have a low numbers of crashes but a high probability of severe outcome, thus helping guide decision makers who face the dilemma of choosing between mobility and safety.

Implementation

The research results of this study are readily applicable. The overview of the speed reduction measures and the four-step method for their justification are included in the report to facilitate implementation of the project's results. An excel-based spreadsheet was developed to conveniently execute the four-step method. An implementation phase should include the INDOT engineering practice and preferences when considering the proposed in this study measures and tools.

CONTENTS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

1.1 Background

Arterial highways carry a significant portion of the nation's traffic, annually accounting for nearly 35% of the rural vehicle miles traveled (VMT) (FHWA, 2019). In addition to facilitating the long-distance, high-speed travel of through traffic and trucks, arterial highways provide a frequently-used link for local road users in the small cities and towns through which they pass. Across Indiana, more than 400 small cities and towns (<15,000 population) are crossed by arterial highways that serve a diverse composition of road users.

The main streets in the centers of some small communities experience pedestrian traffic, bicycle riding, and children crossing to schools and other activities. The relatively short distance between the entry and the center of these communities provides a short transition zone for drivers to slow down to a safe speed. These conditions combine to create potentially hazardous conditions for residents of these towns.

Vehicle speed, one of the strongest factors influencing traffic safety, is particularly important for the safety of vulnerable road users such as pedestrians (see Figure 1.1) and bicyclists. Severe injuries or fatalities occur when a pedestrian or bicyclist is struck at higher speeds. Figure 1.1 shows that the risk of severe injury jumps from 30% to 75% with an increase in the impact speed from 25 mph to 40 mph (Tefft, 2013).

Pedestrians (and bicyclists) face the highest risk of injury and death but they are not the only group exposed to speed-related hazards in the urban centers of small towns and cities. The mix of high-speed through vehicles and low-speed local vehicles leads to a considerable speed differential that poses potentially serious safety issues to vehicle occupants. This danger is amplified with the high density of driveways and land development, presence of on-street parking, and sight-distance obscured by buildings, parked cars, trees, etc.

The INDOT Greenfield District conducted a speed study in the transition zones between the rural and in-town speed limits of nearly 100 small cities and towns. Many of these communities have speed limit transitions from the 55-mph rural speed limit through the 45-mph speed limit to the 35-mph speed limit. The INDOT study was aimed to check whether adjusting these transition zones to the built environment and adding warning signs was needed. The study has confirmed the need for adjustments and other more effective speed-reduction measures.

There is a strong need in Indiana to study the speeding problem, particularly on arterial roads passing through small communities. Multiple past attempts and solutions of speeding in general conditions must be re-evaluated for this particular case and the best countermeasures and their combinations identified. A manual for using these speed reduction measures and predicting their safety benefits should be among the outcomes of the study.

1.2 Scope of Work and Research Objectives

The scope of work includes arterial U.S and state highways passing through small Indiana cities and towns, defined as those with population less than 15,000. Particular attention is devoted to communities in the lower end of this range that tend to have the highest speeds due to a shorter transition from the rural edges to the urban center. Both two-lane and multilane arterials are considered in the study.

To address the safety risk associated with state highway vehicle speeds entering and passing through small urban centers, this project will look at answering the following questions:

- What are the roadway, land use, and environmental conditions influencing the speed and safety of road users passing through small urban and residential centers? Moreover, what is the appropriate speed through such communities? Motorists may drive an urban roadway at 35 mph and feel that this speed is appropriate for the roadway and surrounding environment, without factoring in the consequences shown in Figure 1.1. The currently posted speed limits may not be the best choice if pedestrians, bicyclists, and other local users are present.
- What are effective methods to manage vehicle speeds on arterials passing through small communities? Any new solutions must account for the Indiana Design Vehicle and snow removal operations. Solutions could be multifaceted and include signage (including ITS), minor cross-sectional changes, gateway treatments, markings, and other solutions such as police enforcement.
- Finally, what is the recommended implementation of the identified measures, and how can their safety benefits be quantified? The lower overall number of crashes in small communities means that the adopted measures should be scalable to help facilitate their systemic implementation and reduce costs. Minor treatments could include signage, markings, and speed display. Moderate treatments could include limited changes in the cross-section combined with signage. Major treatments could include gateways, changes in horizontal alignment and cross-section, signage, and markings. The produced results should serve as the basis for developing language on recommendations and limitations to be added to the *Indiana Design Manual.*

1.3 Report Organization

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

- Chapter 2 Review of Past Studies
- Chapter 3 Data
- Chapter 4 Methodology
- Chapter 5 Safety and Speed
- Chapter 6 Benefits of Speed Reduction
- Chapter 7 Indiana Speed Limit Modifications
- Chapter 8 Summary and Conclusions
- Appendices, including *Manual of Estimating the Speed Reduction Benefits on Arterial Roads in Small Indiana Communities*

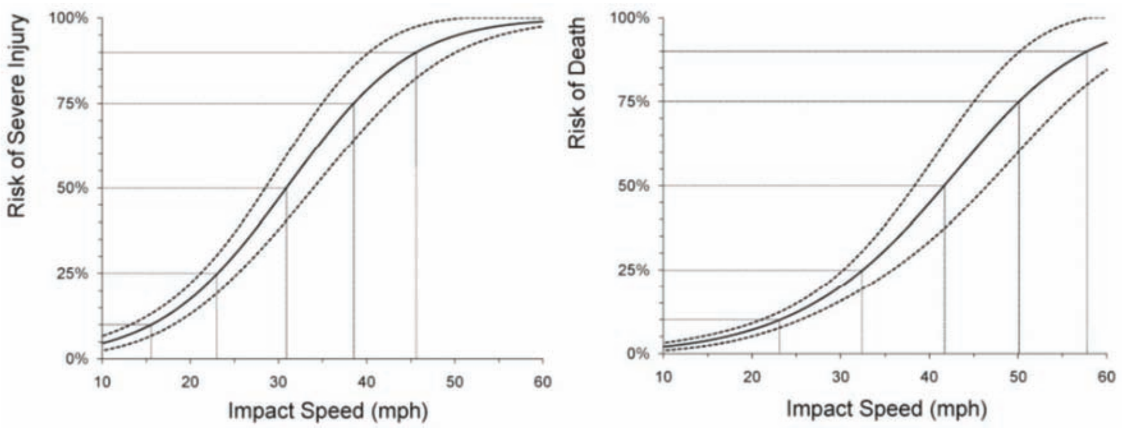


Figure 1.1 Impact speed and a pedestrian's risk of severe injury or death (Tefft, 2013).

CHAPTER 2. REVIEW OF PAST STUDIES

2.1 Background

The disruptive conditions introduced by high-speed arterial roads passing through small communities is a relatively unexplored research area. A study by Shrestha and Liu (2018) focusing on Canadian highways suggests that sections of arterial roads passing through small urban communities typically have roadway and traffic characteristics different than the sections located in rural areas. The short length of the urban environment fail to increase driver risk perception, and drivers tend to keep the high speed adopted from the rural highway sections. These conditions pose a high-risk to the local population, particularly vulnerable road users such as pedestrians and bicyclists.

Traditional safety management strategies focus on detecting high-crash zones and often do not identify the potential for improvement on arterials in small communities due to the typically low crash frequencies. An adequate characterization of the relationship between speed and safety in small communities can provide a basis for decision-makers to estimate the benefits when installing speed reduction measures. The first section of this chapter provides an extensive discussion of the complex relationship between speed and safety. The second section discusses potential countermeasures, including traditional and state-of-the-art speed management techniques, provided to better guide decision-makers in their objective of improving safety via a reduction in the speed adopted by drivers.

2.2 Relation Between Speed and Safety

The relation between speed and the frequency and severity of motorized vehicle crashes has been a topic of extensive discussion, considering the benefits of higher speed limits for mobility and the consequent reduction in travel time. Studies focusing on this relation can be categorized into before-and-after studies and cross-sectional studies, the former of which better controls for the heterogeneity of multiple indicators. Cross-sectional studies control heterogeneity by including in the model covariates influencing the crash frequency.

Literature in before-and-after studies are generally associated with the power model, (Elvik, 2009; Elvik, 2013; Harkey et al., 2008). These models emphasize the benefits of providing a lower speed limit towards improving safety. Multiple authors have attempted to provide a mathematical relationship between speed and safety with varying results. Elvik (2009) summarized the relationship as follows (Equation 2.1):

$$Accidents_{after} = Accidents_{before} * \left(\frac{Speed_{after}}{Speed_{before}}\right)^{Exponent} \quad \text{(Eq. 2.1)}$$

Elvik (2013) further explored a relation considering the initial speed, estimating chained accident modification factors to evaluate the influence of speed on crashes. The researcher found that the power function outperforms the chained exponential model when analyzing fatal crashes, while opposing results were found for injury and property damage only crashes.

As compared to the before-and-after studies, consensus among cross-sectional studies has not been reached. The diversity of findings in the relation between speed and safety (crash frequency) for cross-sectional studies is attributable to the difficulties in eliminating the effects from heterogenous factors across environments (Elvik, 2004; Hauer, 2009). Crashes are events caused by diverse factors with complex interactions in terms of drivers, vehicle design, geometry, and the environment. This issue was first observed by Lave (1985), who developed linear regression models for different types of highways. In this case, 10 of the 12 estimated models showed a negative relationship between speed and safety.

Justification of the negative association between speed and safety can be explained in relation to the superior design standards on roads with higher speed limits (Garber & Gadiraju, 1989). Other authors explain the negative relation in terms of heavy congested flows that result in low mean speed values, but high accident rates (Golob et al., 2004). High speed roads might also be safer due to the lower variability in the speed limit. Finally, risk compensation can support these findings, as drivers may exercise greater caution with the higher speeds.

Contrarily, studies better controlling for heterogeneity have identified a positive association between speed and safety (Taylor et al., 2002). Observing a positive relationship, additional factors in cross-sectional studies including geometric design and traffic should be similar on all sections. Other researchers even argue that speed metrics explain little about crash occurrence, and other factors are at play in crash occurrence. According to these researchers, speeds are instead associated with crash severity and may be fundamental to specific types of crashes such as rear-end and rollover crashes (Kockelman et al., 2007). Still other authors argue that there is a relation between the speed variability and higher crash occurrences (Garber & Gadiraju, 1989; Imprialou, 2016; Kweon & Kockelman, 2005; Lave, 1985).

Aggregation problems are regarded as one of the issues affecting the relationship between speed and safety. Some researchers propose a condition-based structure of datasets that groups crashes occurring under similar traffic and geometric scenarios, assuming them as spatially and temporally independent.

The connection between speed and the frequency of crashes between vehicles and vulnerable road users (VRUs) has been explored less extensively. Past studies have primarily focused on the probability of being seriously or fatally injured in terms of the speed at collision or related approximations (Gårder, 2004; Tefft, 2013). The kinematic energy dissipated in the collision increases with speed, thus leading to higher crash severity outcomes.

The change in severity with respect to collision speed is more dramatic for VRU crashes. Kröyer et al. (2014) found that small changes in impact speed result in a steep increase in the probability of being injured or killed. After correcting for exogeneous conditions, Tefft (2013) found that the probability of severe injury increases from 10% to 90% as the impact speed increases from 24.1 mph to 54.6 mph. Similar results were found in the study by Kröyer et al. (2014).

Utilizing the knowledge of the frequency and severity models explained in the literature, this study aims to implement a method to evaluate the potential benefits of reducing driver speeds on arterial roads passing through small Indiana communities. Speed reduction may yield tangible benefits for the safety of all road users. Speed reduction implemented jointly with traffic calming solutions can provide a safer environment for vulnerable road users and low-speed local vehicles utilizing arterial roads on a regular basis.

2.3 Speed Management Strategies

A wide variety of speed management strategies have been implemented in the U.S and overseas. Considering the diversity of countermeasures identified in the literature, a distinction is made among traditional and non-traditional countermeasures in the following sections. Speed change effects are investigated in terms of mean speed change and 85th percentile speed change.

2.3.1 Traditional Speed Management Strategies

One of the most widely-applied speed management strategies involves reducing the posted speed limits. A study by Heydari et al. (2014) supports a significant reduction of operating speeds via speed limit reduction measures. However, the authors also show that the speed limit reduction had no significant effect on excessive speeding behavior which carries great risk to vulnerable road users (pedestrians and bicyclists). Additional results found that night conditions and lane width had an increasing effect on speeding while the presence of roadside parking has a decreasing effect on speeding.

In a comparable study, Islam et al. (2014) looked at six residential communities in the city of Edmonton, Canada. Countermeasures included reducing posted speed limits from 50 km/h to 40 km/h (30 mph to 25 mph). Using a before-and-after approach, the researchers found a significant 4.88 km/h (3 mph) reduction in the mean free-flow speed. The reduction was even greater for heavy vehicles.

Alternative speed management strategies that effectively reduce excessive speeding behavior include physical devices for calming traffic along major roads through small rural communities in Iowa (Hallmark et al., 2008). Another study made by Katz (2007) found that peripheral transverse pavement markings reduced the average operating speed on rural highways and interstate highways by up to 24% (Katz, 2007). This can be explained by the narrow appearance of the roadway.

In relation to small towns, an important characteristic includes creating appropriate high-speed to low-speed transition zones informing drivers of the need to reduce speed in order to compensate for high-risk conditions (Bagdade et al., 2012; Krammes & Sheldahl, 2009; World Health Organization, 2008). Hallmark et al. tested seven different low-cost speed management treatments in five rural communities in Iowa (Hallmark et al., 2007, 2008). Based on the study results by these authors, some of the most effective countermeasures applied in transition zones include transverse pavement markings and speed feedback signs. A complete evaluation of the countermeasures implemented in the study is shown in Table 2.1.

Studies in other states were conducted on measuring the effectiveness of optical speed bars and pedestrian-related countermeasures. When installing optical speed bars in Virginia, small speed reductions of 1 to 2.3 mph were observed in sections with posted speed limits of 55 mph outside of town and 45 mph inside of town (Arnold & Lantz, 2007). Kamyab et al. (2003) evaluated the effectiveness of two speed management treatments in Minnesota with high pedestrian traffic. Removable pedestrian islands and pedestrian crossing devices were installed on CSAH Route 4 at

TABLE 2.1
Past Research Study Locations and Speed Treatment Types

Community	State	Road	Treatment	Mean Speed Change	85th Percentile Speed Change
Hazleton	IA	C-57/Hayes Street	Transverse bars	-1.6	-1
Jesup	IA	220th street/SH 939	Colored entrance	-1.5	-2
Ossian	IA	W-42	Colored entrance	-2.3	-2
Quasqueton	IA	W-40	Transverse bars	-2.3	-2
St. Charles	IA	R-35	Raised curbing	-2.2	-3.3
		SH 251	Raised curbing	-0.3	-1
		SH 251	LED speed limit sign	-0.6	-0.1
Rowley	IA	D-47	Speed feedback sign	-7.6	-9
		D-47	LED speed limit sign	-5.9	-7
Union	IA	D-65	TPM with speed feedback sign	-5.2	-4
		S-62/SH 215	TPM with speed feedback sign	-7	-4.4
			Lane narrowing using painted center island and edge line marking	-1.8	-1
		SH-215	TPM	-1.9	-2
Roland	IA	E-18 (both edges of town)	Converging chevrons with "25 mph" pavement legend	-3	-4
		E-18/R-77	Lane narrowing and 25 mph pavement legend	1	0.3
		E-18/R-77	"25 mph" pavement legend	-3	-4
Gilbert	IA	E-23 (center of community)	Speed table	-4	-4
Slater	IA	R-38/SH 210	Lane narrowing with center island using tubular markers channelizing markers	-3	-3
		R-38 (near north city limit)	Speed feedback sign	-5.4	-7
		SH 210/R-38	SLOW pavement legend	2.4 to -3	1 to -2
Dexter	IA	F-65 (both edges of town)	"35 mph" pavement legend with red background	-7.4	-9
Zuni	VA	US-460	Optical Speed bars	-3	N.A.
Twin Lakes	MN	CSAH-4	Removable pedestrian islands	-5	-7
Bemidji Lake	MN	CSAH-20	Dynamic variable message sign	0	0
Andale	KS	247th St. West	"35 mph" pavement legend	-1.9	-2.0
Bentley	KS	151st St. West	"30 mph" pavement legend	2.1	3.0
Branson West	MO	Missouri 13	"50 mph" pavement legend	-2.5	N.A.
Brooklyn	WI	Wisconsin 92	"25 mph" pavement legend	-4.7	-5.0

Twin Lakes, MN. The road had a posted speed limit of 30 mph inside of city limits and 55 mph outside of city limits with a transition speed limit of 40 mph. The researchers found a 3.5 to 5 mph reduction in mean speed and a 4 to 7 mph reduction in 85th-percentile speed. Table 2.1 summarizes the results of previous studies in terms of the reduction in the mean and 85th-percentile speeds.

The NCHRP Report 737, *Design Guidance for High-speed to Low-speed Transition Zones for Rural Highways*, evaluated the effectiveness of several speed management treatments in reducing operating speeds through transition zones passing communities (Gilmore et al., 2013). Three treatments and their combinations, roundabouts, transverse pavement markings, and welcome signs at community entrances, were tested in 12 different towns located in Kansas, Nebraska, Iowa, and Virginia (Table 2.2). Adequate control locations were considered.

The evaluation criterion used in the NCHRP study differs from past research in the sense that relative speed reduction (%) was utilized as an effectiveness measure when comparing it with the posted speed limit reduction in a control zone. Results showed that all treatments achieved high relative speed reduction (%). Roundabout relative speed reduction was 73% (Winnebago, NE) to 93% (Blair, NE) with a posted speed limit reduction of 30 mph and 15 mph, respectively. Transverse pavement markings achieved 60% (Roland, IA) of speed reduction in the most conservative scenario and 110% (Rossville, KS) of speed reduction in the most optimistic scenario, with a posted speed limit reduction of 30 mph and 20 mph, respectively. As for non-treatment, it achieved a relative

TABLE 2.2
NCHRP Report 737—Study Locations and Speed Treatment Types

Community	State	Road	Treatment
Rossville	KS	US 24 (WB)	TPM
		US 24 (WB)	None
McLouth	KS	SR 92 (WB)	Welcome sign
		SR 92 (EB)	Welcome sign
Silver Lake	KS	US 24 (EB)	TPM (welcome sign)
Fredonia	KS	K 47/US 400 (WB)	Roundabout (rumble strips)
Burden	KS	US 160 (EB)	Welcome sign
		US 160 (WB)	Welcome sign
Rock	KS	US 77 (NB)	None
		US 77 (SB)	None
Meriden	KS	Rt 4 (SB)	TPM
		Rt 4 (NB)	TPM
Blair	NE	US 30/Rt 144 (EB)	Roundabout (welcome sign)
		US 75 (SB)	None
Winnebago	NE	US 77 (NB)	Roundabout
		US 77 (SB)	None
Roland	IA	Rt 77 (NB)	TPM (Welcome sign)
McCallsburg	IA	Co ED E18 (WB)	None
Amherst	VA	US 60 (EB)	Roundabout
		US 60 (WB)	None

speed reduction of 27% (Blair, NE) in the most conservative scenario and 270% in the most optimistic scenario (McCallsburg, IA). It is concluded that the treatment sites had a non-significant, small reduction in mean speeds as compared to the control sites. When applying welcome signs, a reduction in up to 3 mph was observed.

The Federal Highway Administration (FHWA) summarizes more than 50 measures in a "Desktop Reference" of speed management countermeasures (FHWA, 2014). Countermeasures are included for a variety of urban and rural road types and safety focus areas (pedestrian, intersection, roadway departure, and others). Some of the greatest speed reductions are found with speed tables, chicanes, converging chevron pavement markings, and speed feedback signs, although not all countermeasures are suitable for arterials given the considerable traffic volume and heavy vehicle presence. A number of the most promising speed reduction measures suitable for arterials in small communities are included in the *Manual of Estimating the Speed Reduction Benefits on Arterial Roads in Small Indiana Communities.*

2.3.2 Non-Traditional Speed Management Strategies

Some researchers have investigated the effectiveness of non-traditional speed management treatments. Point-to-point speed enforcement, as compared to the traditional static speed feedback sign, was found to reduce the mean speed by 9.8 km/h (6.1 mph) and the 85th-percentile speed by 14.1 km/h (8.8 mph) for light vehicles traveling in a motorway section in Naples, Italy (Montella et al., 2015).

Results from a driving simulator study with drivers from Beijing, China found that audio warnings could significantly reduce drivers' operating speed before entering an urban area (Yan et al., 2016). They also found that the lit speed limit sign had a minimal effect on improving the drivers' speed control performance. The study by Makwasha and Turner (2013) evaluated the use of rural-urban gateway treatments. The results showed that gateways, particularly pinch point gateways, were effective in lowering crashes in rural-urban transition zones in New Zealand.

CHAPTER 3. DATA

The analysis presented in this report evaluates U.S and state arterial highways passing through the occupied areas of small Indiana cities and towns (<15,000 population), with a particular focus on the communities falling within the lower end of this range that tend to have the highest vehicle speeds. A random selection of segments was utilized from across the study area to evaluate the influence of multiple factors on the adopted driver speed and safety-related measures including crash frequency and severity. A total of 396 segments crossing 226 small towns are represented in the data sample. ArcGIS tools were employed in organizing and processing the data.

3.1 Traffic Data

Annual average daily traffic (AADT), the proportion of AADT comprised by trucks, road classification, speed limit, and road geometrics (number of lanes, lane width, shoulder width, and median width) was obtained from the Federal Highway Administration's Highway Performance Monitoring System (HPMS) and supplemented with road element data from the Purdue Center for Road Safety (CRS).

INRIX data was used to extract the speed of drivers traveling on the studied segments. The INRIX data consists of minute-by-minute speed observations for U.S, state, and some local roads across Indiana. The average speed of all recorded observations from May 2015–March 2017 was used for the studied segments. Dispersion measures were considered in the analysis as well as the standard deviation and interquartile ranges of speed. To maintain consistency, the research team adopted the definition of the segments provided by INRIX for both the speed and safety analysis.

INRIX data is massive in its scale. The quality of the speed measurements are reported in terms of confidence scores. The confidence score is a data quality metric with three possible levels.

- 30–Indicates high confidence based on real-time data for a particular segment.
- 20–Indicates medium confidence based on real-time data across multiple segments and/or based on a combination of expected and real-time data.
- 10–Indicates lower confidence based primarily on historical data.

Only speed observations that attained the highest level of confidence were used in the speed and safety analyses.

3.2 Road and Land Use Data

Relevant information characterizing the road features and infrastructure of the segments and adjacent land use was extracted in this study. The locations and types of all businesses across the state of Indiana were obtained from 2011 commercial business data available through Purdue CRS. Moreover, data on land development was derived from the National Land Cover Database (NLCD) 2011 available from the United States Geological Survey (USGS). The mean value of impervious (paved) surfaces of the adjacent areas (within a three-block buffer of the analyzed segments) were considered as a proxy for urban and commercial development.

Extensive extraction of road and roadside features was conducted to characterize the factors influencing the adopted speed of drivers as well as the road safety conditions. Extracted data included the number of unsignalized and signalized intersections (three-leg and four-leg), all-way stop-controlled intersections, and four types of driveways including school, commercial, major residential (3 or more residences), and minor residential (1–2 residences). Furthermore, the proportion of segment with on-street parking and the presence of pedestrian facilities (number of midblock crosswalks per mile and the proportion of segment with sidewalk) were extracted. Midblock crosswalks consisted of crosswalks in-between intersections, typically located in the vicinity of schools and including pedestrian or school crossing signage along with white pavement markings. Sidewalks were assessed at varying distances from the traveled way, including no clearance, 1 to 5 feet away, 6 to 10 feet away, and more than 10 feet away. Descriptive statistics for the 396 segments included in the analysis are shown in Table 3.1.

3.3 Crash Data

Crashes were obtained from the Automated Reporting Information Exchange System (ARIES), a database of police-reported crashes occurring on Indiana roads. Crashes occurring along the study segments or at intersections located along the segments were included in the sample. Two safety scenarios corresponding to two types of crashes were of particular interest. (1) Crashes involving both motorized and vulnerable road users including pedestrians and bicyclists (labeled VRU), and (2) crashes involving only motorized road users (labeled MRUs). Both the types of crashes could involve local or out-of-town drivers. Crashes from 2013–2017 were utilized for MRUs, while the VRU crash data was expanded to the years 2008–2017 to account for the much lower sample mean of the latter. The longer period for VRU crashes leads to more efficient parameter estimates in the statistical models.

A total of 361 VRU crashes were observed on the 396 segments from 2008–2017. The individual injury of the highest level incurred during a crash defined the severity of the crash. Of the 361 injury crashes occurring during the study period, 74.52% involved pedestrians and 25.48% involved bicyclists. The VRU crashes were evaluated across the following two severity levels: (1) minor injury, which includes crashes categorized as possible injury (C) and evident injury (B), and (2) major injury/fatal, which includes disabling injury (A) and fatal (K) crashes (NSC, 2016). Minor injury and Major injury/fatal crashes constituted 70.36% and 29.64% of the crash sample, respectively. Table 3.2 provides the summary statistics for the explanatory variables across the observed VRU crashes.

A total of 18,225 MRU crashes were observed in the period of analysis, 2013–2017. MRU crashes were categorized into the following three severity levels: (1) Property Damage Only (PDO) crashes; (2) minor injury, including possible injury (C) and evident injury (B), and (3) major injury/fatal, including disabling injury (A) and fatal (K) crashes. In this sample, 84.34% of the crashes are categorized as PDO, 9.95% as minor injury, and the remaining 5.71% as major injury/fatality. Table 3.3 provides the summary statistics for the explanatory variables across the observed MRU crashes.

TABLE 3.1
Summary Statistics for 396 Arterial Highway Segments

Variable	Mean	Standard Deviation	Min	Max
Vulnerable road user crashes involving minor injury (2008–2017)	0.64	1.33	0.00	10.00
Vulnerable road user crashes involving major injury or fatality (2008–2017)	0.27	0.60	0.00	5.00
Motorized road user crashes involving property damage only (2013–2017)	38.82	49.54	0.00	359.00
Motorized road user crashes involving minor injury (2013–2017)	4.58	5.58	0.00	38.00
Motorized road user crashes involving major injury or fatality (2013–2017)	2.63	3.40	0.00	27.00
Speed on interrupted road (mph)	37.43	7.98	18.33	60.32
Speed on uninterrupted road (mph)	46.12	8.15	31.65	63.08
Speed on interrupted or uninterrupted road (mph)	40.66	9.07	18.33	63.08
Speed limit on interrupted road (mph)	42.41	7.67	30.00	60.00
Speed limit on uninterrupted road (mph)	45.88	8.48	30.71	60.00
Speed limit on interrupted or uninterrupted road (mph)	43.70	8.15	30.00	60.00
Percent paved surfaces within three blocks (1,200 feet) of the road	17.55	11.51	2.91	65.75
AADT	8,648.94	6,041.31	473.00	33,099.00
Log of AADT	8.83	0.72	6.16	10.41
Proportion of AADT comprised of trucks	0.12	0.07	0.02	0.47
Segment length (feet)	5,169.78	1,265.85	514.60	7,970.83
Log of segment length in feet	8.50	0.38	6.24	8.98
Unsignalized intersections per mile	5.94	4.23	0.00	19.78
Unsignalized four-leg intersections per mile	2.15	2.32	0.00	13.86
Unsignalized three-leg intersections per mile	3.79	3.26	0.00	16.88
Signalized intersections per mile	0.80	1.18	0.00	9.04
Signalized four-leg intersections per mile	0.69	1.08	0.00	9.04
Signalized three-leg intersections per mile	0.11	0.39	0.00	3.75
All-way stop-controlled intersections per mile	0.14	0.56	0.00	6.58
Commercial (business) driveways per mile	7.68	7.52	0.00	49.72
School driveways per mile	0.12	0.62	0.00	6.58
Minor residential driveways (1–2 residences) per mile	10.82	9.77	0.00	44.32
Major residential driveways (3 or more residences) per mile	0.50	1.14	0.00	11.87
Proportion of segment with sidewalk	0.19	0.28	0.00	1.00
Proportion of segment with no clearance between sidewalk and traveled way	0.06	0.14	0.00	0.99
Proportion of segment with on-street parking	0.03	0.08	0.00	0.99
Businesses within three blocks (1,200 feet) of the road per mile	26.28	34.22	0.00	315.19
IRI	111.71	45.69	32.04	400.00
Average change in deflection angle (degrees/mile)	44.16	46.50	0.00	370.71
Lane width (feet)	11.89	0.45	8.56	13.00
Shoulder width (feet)	4.18	3.50	0.00	13.26
Midblock crosswalks per mile	0.03	0.20	0.00	1.85
City/town population	3,453.63	2,808.22	83.00	11,210.00
Log of city/town population	7.75	0.98	4.42	9.32

Indicator Variables (1 if condition is true, 0 otherwise)	Percent of Observations
Interrupted road	62.88
Uninterrupted road	37.12
U.S highway	40.15
State highway	59.85
Multilane undivided highway	12.37
Multilane divided highway	14.39
Multilane (undivided or divided) highway	26.77
Low development on both sides of road (less than 25% of area developed within 1,200 feet)	43.69
Segment has curb and sidewalk	38.13
Segment has curb but no sidewalk	14.65

TABLE 3.2
Summary Statistics for 361 Vulnerable Road User Crashes

Variable	Mean	Standard Deviation	Min	Max
Speed limit (mph)	40.63	7.52	30.16	60
Proportion of AADT comprised of trucks	0.10	0.05	0.02	0.36
Midblock crosswalks per mile	0.04	0.23	0	1.83
Indicator Variables (1 if condition is true, 0 otherwise)	Percent of Observations			
Primary cause of crash related to unsafe speed	0.83			
Primary cause of crash related to pedestrian action	35.73			
Primary cause of crash related to vehicle's failure to yield	22.16			
Primary cause of crash related to distracted driving	5.82			
Aggressive driver involved in crash	2.49			
No curb present	26.59			
Low development on both sides of road	11.91			
Multilane (undivided or divided) highway	32.69			
Crash occurred on weekend (Saturday or Sunday)	21.33			
Crash occurred in daylight conditions	68.70			
Crash occurred on dark, lighted road	15.79			
Crash occurred on dark, unlighted road	10.25			
Crash occurred in clear weather conditions	70.91			
Crash occurred in rainy weather conditions	9.14			
Crash occurred in snowy weather conditions	0.83			
Crash occurred on a dry road surface	83.38			
Crash occurred on a wet road surface	13.02			
Crash occurred on a wintery (snowy, slushy, or icy) road surface	2.77			
Crash occurred at signalized intersection	20.50			
Crash occurred at stop-controlled intersection	10.80			
Crash occurred on straight road	92.52			
Crash occurred on curve	3.60			
Crash occurred in school zone	6.93			
Bicyclist involved in crash	25.48			
Younger driver (21 years and younger) involved in crash	14.13			
Older driver (65 years and older) involved in crash	17.45			
Younger pedestrian/bicyclist (21 years and younger) involved in crash	35.18			
Older pedestrian/bicyclist (65 years and older) involved in crash	13.02			

TABLE 3.3
Summary Statistics for 18,225 Motorized Road User Crashes

Variable	Mean	Standard Deviation	Min	Max
Speed limit (mph)	41.83	7.52	30	60
Indicator variables (1 if condition is true, 0 otherwise)	Percent of Observations			
Primary cause of crash related to unsafe speed	5.67			
Primary cause of crash related to vehicle's failure to yield	19.54			
Primary cause of crash related to distracted driving	5.00			
Aggressive driver involved in crash	2.52			
No curb present	33.73			
Low development on both sides of road	20.84			
Multilane (undivided or divided) highway	38.81			
Crash occurred on weekend (Saturday or Sunday)	22.33			
Crash occurred in daylight conditions	75.57			
Crash occurred on dark, lighted road	12.21			
Crash occurred on dark, unlighted road	7.58			
Crash occurred in clear weather conditions	63.04			
Crash occurred in rainy weather conditions	8.70			
Crash occurred in snowy weather conditions	3.94			
Crash occurred on a dry road surface	75.75			
Crash occurred on a wet road surface	14.39			
Crash occurred on a wintery (snowy, slushy, or icy) road surface	9.16			
Crash occurred at signalized intersection	23.32			
Crash occurred at stop-controlled intersection	9.19			
Crash occurred on straight road	89.37			
Crash occurred on curve	6.22			
Crash occurred in school zone	3.07			
Rear-end crash	55.02			
Head-on crash	3.77			
Right-angle crash	13.34			
Motorcycle involved in crash	1.09			
Passenger car involved in crash	66.73			
Van involved in crash	6.30			
Pickup truck involved in crash	20.27			
Sport utility vehicle involved in crash	15.96			
Semi-trailer involved in crash	3.96			
Younger driver (21 years and younger) involved in crash	22.45			
Older driver (65 years and older) involved in crash	18.90			

CHAPTER 4. METHODOLOGY

Chapter 2 discussed the complex relationship between speed and safety (crashes). The complexity to unveil this relationship increases in cross-sectional studies, since heterogeneity must be better controlled as compared to before-and-after methods. As a potential solution in studies not finding a clear relationship, severity models have proven to better characterize the speed/safety relationship, thus leading to better estimation of the potential benefits of speed limit reduction. Advantages of severity models include the non-aggregation of crashes into segments as well as the inclusion of crash-specific variables that better characterize the relationship between speed and safety.

This study explores the relationship between speed and safety by first introducing a crash frequency model that includes speed limit as one of the covariates. As many variables as possible from Table 3.1 are tested in the model to ensure that heterogeneity from the cross-sectional nature of the study is controlled. Then, a severity model is introduced (using variables from Table 3.2 and Table 3.3) to better capture the potential benefits of speed limit reduction. Crash modification factors are derived based on the severity model.

4.1 Crash Frequency Model

Traffic crash frequency modeling across road elements has typically employed count models such as Poisson and negative binomial regression to estimate the impact of road features on crashes (Washington et al., 2010). The negative binomial model is usually selected as the more appropriate modeling alternative due to the presence of overdispersion in the crash data (variance greater than the mean). Some researchers have indicated the risk of erroneous parameter estimates in count models estimated under the presence of a low sample mean (Lord, 2006; Lord & Mannering, 2010). Most recently, the suitability of negative binomial models when applied to roads with a low crash sample mean was investigated by Hall and Tarko (2019) for rural local intersections in Indiana. The researchers detected no obvious prediction biases for the estimated models, even finding the negative binomial model to slightly outperform an ordered probit model alternative.

This study employs the bivariate and multivariate versions of the negative binomial model (Gueorguieva, 2001). The bivariate model estimates the frequency of minor injury *and major injury/fatality* crashes involving VRUs across road segments. The multivariate (tri-variate) derivation includes estimation of a frequency model for MRUs for the *Property Damage Only* (*PDO*), *minor injury, and major injury/fatality* levels. Advantages of joint modeling across multiple crash severities include more efficient parameter estimates and additional information regarding the correlation between different severity outcomes. The AADT, road features, land use, and surrounding environmental characteristics of the segments are used to predict the number of crashes.

Summarizing the model form for the multivariate case (MRU crashes), consider a tri-variate response vector for segment i as $y_i = (y_{i1}{}^T, y_{i2}{}^T, y_{i3}{}^T)$ representing each crash severity outcome. We assume that $y_{i1j}, j = 1, \ldots, N_{i1}$ are conditionally independent given b_{i1} with negative binomial density represented in its exponential family form (Equation 4.1):

$$f_1(k, r, p) = \binom{k+r-1}{k} \exp[k\ ln(p) + r\ ln(1-p)] \quad \text{(Eq. 4.1)}$$

y_{i2j} and y_{i3j} also meet the same conditions. Moreover, y_{i1}, y_{i2}, and y_{i3} are conditionally independent given $b_i = \left(b_{i1}^T, b_{i2}^T, b_{i3}^T\right)^T$ with responses from different subjects being independent. Let the conditional means of y_{i1j}, y_{i2j}, and y_{i3j} be μ_{i1j}, μ_{i2j}, and μ_{i3j}, respectively. The link functions are represented as follows (Equation 4.2):

$$\ln\left(\mu_{i1j}\right) = x_{i1j}^T \beta_1 + b_{i1} \quad \text{(Eq. 4.2)}$$

$$\ln\left(\mu_{i2j}\right) = x_{i2j}^T \beta_2 + b_{i2}$$

$$\ln\left(\mu_{i3j}\right) = x_{i3j}^T \beta_1 + b_{i3}$$

Where $\beta_1 \beta_2$, and β_3 are the parameter vectors for each of the severities. The correlation across multiple outcomes is included by assuming b_{i1}, b_{i2}, and b_{i3} are independent and identically distributed with multivariate normal joint distribution represented by Equation 4.3:

$$b_i = \begin{pmatrix} b_{i1} \\ b_{i2} \\ b_{i3} \end{pmatrix} \sim MVN(0, \Sigma)\ being\ \Sigma$$

$$= \begin{bmatrix} \sigma_1^2 & \rho\sigma_1\sigma_2 & \rho\sigma_1\sigma_3 \\ \rho\sigma_2\sigma_1 & \sigma_2^2 & \rho\sigma_2\sigma_2 \\ \rho\sigma_3\sigma_1 & \rho\sigma_3\sigma_2 & \sigma_3^2 \end{bmatrix} \quad \text{(Eq. 4.3)}$$

The appropriateness of the multivariate form is indicated by a value of ρ significantly different than 0, which indicates correlation between the *PDO, minor injury* and *major injury/fatality* levels. Furthermore, the multivariate form accounts for the varying impacts of variables at the different severity levels by allowing for different parameter estimates between the severity levels.

The SAS statistical software was used to estimate the model parameters using the GLIMMIX procedure. A similar bivariate negative binomial model was estimated for the *minor injury* and *major injury/fatality* crash types for VRU crashes. The estimated models for MRU and VRU crashes are provided in the next chapter.

4.2 Crash Severity Model

Multinomial Logistic regression is applied in estimating the crash severity models for VRU and MRU crashes (Al-Ghamdi, 2002; Tefft, 2013). Based on the crash attributes, the discrete model is able to estimate the probability of a specific category being in severity level *i*. Estimable discrete outcome models are calculated by assuming a distribution of the error term of the utility functions (Ben-Akiva & Bierlaire, 1999). The standard multinomial logit formulation evaluates the probabilities in order to define the severity of the analyzed crash (Equation 4.4):

$$P(i) = \frac{\exp(\beta_i + \beta_{i1} X_1 + \ldots + \beta_{ik} X_k)}{\sum_{j=1}^{J} \exp(\beta_j + \beta_{j1} X_1 + \ldots + \beta_{jk} X_k)} \quad \text{(Eq. 4.4)}$$

Where $P(i)$ denotes the probability of the crash being in severity i, X is the object's attributes, and β_i are the model parameters for category i. Since this model includes crash-specific characteristics in addition to segment-based characteristics, it is expected to produce superior estimation of the effect between changes in speed limit and safety.

Crash Modification Factors for speed limit reduction using logistic regression can be derived using Equation 4.5. In this expression, CMF_i represents the crash modification factor for severity level i, $\beta_{SL,i}$ is the parameter estimate for the speed limit for crash severity i obtained from the logistic regression, sl_b is the speed limit in the before period, and sl_a is the speed limit in the after period.

$$CMF_i = \exp\left[\beta_{SL,i}(sl_a - sl_b)\right] \quad \text{(Eq. 4.5)}$$

Chapter 5 presents the logistic regression models underlying the CMFs, while Chapter 6 discusses the usage of the CMFs for evaluating the safety benefit of speed reduction on VRU and MRU crashes.

4.3 Modeling Split of Safety Benefits

Estimating the benefit for local road users attained when reducing the speed is facilitated via modeling the proportion of the safety benefit (represented here as the economic benefit, or cost of crashes saved) involving local road users. A local road user is defined as a person involved in the crash whose residence is located in the same zip code as where the crash occurred; consequently, all other road users involved in the crash are considered to be non-local (out-of-town). Considering the nature of the dependent variable, a proportion that is bounded between the values [0, 1], beta regression is applied to estimate the proportion of the safety benefit involving local road users.

Beta regression proposes a beta-distributed variable using a parametrization of the beta law that is indexed by the mean and dispersion parameters (Ferrari & Cribari-Neto, 2004). In this case, let p and q be the parameters of a beta-distributed variable. Let $\mu = p/(p+q)$, $\phi = p+q$, and $q = (1-\mu)\phi$. Hence:

$$E(y) = \mu \qquad \text{(Eq. 4.6)}$$

and

$$var(y) = \frac{V(\mu)}{1+\phi} \qquad \text{(Eq. 4.7)}$$

Where $V(\mu) = \mu(1-\mu)$. The density of the dependent variable y can be rewritten as:

$$f(y;\mu,\phi) = \frac{\Gamma(\phi)}{\Gamma(\mu\phi)\Gamma((1-\mu)\phi)} y^{\mu\phi-1}$$

$$(1-y)^{(1-\mu)\phi-1}, 0 < y < 1 \qquad \text{(Eq. 4.8)}$$

With $0 < \mu < 1$ and $\phi > 0$. Let $y_1, \ldots, y_n$ be independent, where each y_t ($t=1,\ldots, n$) y_t follows the density in Equation 4.8. The model is obtained by assuming the mean of y_t can be written as follows (Equation 4.9):

$$g(\mu_t) = \sum_{i=1}^{k} x_{ti}\beta_i = \eta_t \qquad \text{(Eq. 4.9)}$$

Where $\beta = (\beta_1, \ldots, \beta_k)^T$ is a vector of unknown regression parameters and $x_{t1}, \ldots, x_{tk}$ are observations on k covariates. There are multiple choices for the link function $g(.)$; these include the logit specification $g(\mu) = \log\left\{\frac{\mu}{1-\mu}\right\}$ and the probit function $g(\mu) = \phi^{-1}(\mu)$, where $\phi(.)$ is the cumulative distribution function of a standard normal random variable.

In the current study, the beta regression models were estimated in the R software using the 'betareg' package (Zeileis et al., 2019).

CHAPTER 5. SAFETY AND SPEED

In this chapter, the results of the safety and speed analyses for arterials in small communities are presented, including the estimated crash frequency and severity models and insights into the speed limit and the adopted speed of drivers.

5.1 Crash Frequency Models

Table 5.1 and Table 5.2 present the results of the multivariate crash frequency models estimated for vulnerable road user (VRU) crashes and motorized road user (MRU) crashes, respectively. A bivariate model considering two severity levels (minor injury and major injury/fatality) was estimated for VRU crashes. Moreover, a tri-variate model for three severity levels (PDO, minor injury, and major injury/fatality) was estimated for MRU crashes. These models represent the relationship between a specific crash type/severity and a road's traffic, speed limit, road features, and surrounding land use. An explanation of these features is included after the tables.

Road features that tend to increase the number of VRU and MRU crashes occurring at different severity levels include increasing exposure (traffic volume and segment length), commercial driveways, a higher density of businesses surrounding the road, and a greater percentage of paved surfaces (proxy for greater land use activities and pedestrian exposure) surrounding the road.

Increasing density of unsignalized four-leg intersections increase the frequency of VRU major injury/fatality crashes, while the proportion of a segment with a sidewalk close to the road was associated with a greater number of VRU minor injury crashes. Roads with a curb and sidewalk tend to have an increased number of VRU major injury/fatal crashes, albeit to a lesser extent than roads with a curb and no sidewalk. The sidewalk variables likely represent exposure measures for vulnerable road user activity occurring close to the road. Curvy road alignments and deteriorating pavement condition (the latter represented by increasing IRI) tend to increase MRU crashes.

The effect of speed limit on crashes was found to vary depending on the type of crash and level of severity. In fact, the effect of speed limit on crashes was found to be limited at low crash severity levels. In general, as crashes become more severe, increasing speed limit becomes more influential in increasing the number of VRU and MRU crashes. Multilane highways were also found to have mixed impacts on the number of VRU and MRU crashes. At low severity levels (minor injury for VRUs and PDO and minor injury for MRUs), multilane highways (undivided and/or divided) decreased crashes. However, multilane undivided highways were found to increase the frequency of major injury/fatal crashes for MRUs, perhaps attributable to the high speeds associated with this road type. The density of signalized intersections (per mile) was associated with a higher number of MRU PDO crashes but a lower number of MRU major injury/fatality crashes. Although there is an increased amount of activity and interactions between vehicles at

TABLE 5.1
Bivariate Negative Binomial Model of Vulnerable Road User Crashes on Arterial Highway Segments Passing Through Small Communities

Variable	Parameter Estimate	Standard Error	z-statistic	p-value
Dependent variable: Minor injury crashes				
Intercept	-15.6257	2.6641	-5.87	0.00
Speed limit (mph)	-0.0067	0.0138	-0.49	0.63
Log of AADT	0.8038	0.1873	4.29	0.00
Log of segment length in feet	0.8974	0.2752	3.26	0.00
Commercial (business) driveways per mile	0.0221	0.0109	2.01	0.04
Multilane (undivided or divided) highway indicator (1 if true, 0 otherwise)	-0.5688	0.2333	-2.44	0.02
Percent paved surfaces within three blocks (1,200 feet) of the road	0.0194	0.0106	1.83	0.07
Low development on both sides of road (1 if true, 0 otherwise)	-0.9286	0.2729	-3.40	0.00
Businesses within three blocks (1,200 feet) of the road per mile	0.0043	0.0026	1.65	0.10
Proportion of segment with no clearance between sidewalk and traveled way	0.7934	0.4489	1.77	0.08
Overdispersion parameter	0.3981	0.1480	2.69	0.01
Dependent variable: Major injury or fatality crashes				
Intercept	-16.5779	3.6428	-4.55	0.00
Speed limit (mph)	0.0088	0.0174	0.50	0.61
Log of AADT	0.5199	0.1962	2.65	0.01
Log of segment length in feet	1.0815	0.3901	2.77	0.01
Unsignalized four-leg intersections per mile	0.0434	0.0411	1.06	0.29
Percent paved surfaces within three blocks (1,200 feet) of the road	0.0298	0.0113	2.63	0.01
Low development on both sides of road (1 if true, 0 otherwise)	-0.6289	0.3373	-1.86	0.06
Segment has curb and sidewalk (1 if true, 0 otherwise)	0.5928	0.2930	2.02	0.04
Segment has curb but no sidewalk (1 if true, 0 otherwise)	0.7760	0.3053	2.54	0.01
Overdispersion parameter	0.0883	0.2012	0.44	0.66
Number of observations	396	—	—	—
λ	1.5289	0.6537	2.34	0.02
Log likelihood	-564.9704	—	—	—

signalized intersections (perhaps contributing to the higher number of PDO crashes), the lower number of severe crashes may be due to lower speed driving in the proximity of signalized intersections.

Arterials with low levels of development on both sides of the road (represented as <25% of the area developed within three blocks of the road) tend to have a lower number of crashes. Finally, increases in the density of all-way stop-controlled intersections tend to reduce MRU major injury/fatality crashes.

Based on the model results shown in Table 5.1 and Table 5.2, crash prediction equations, or safety performance functions (SPFs), can be derived to predict the expected annual crash frequencies under current roadway conditions. These SPFs are shown in Table 5.3.

In order to facilitate their usability and ease calculations, simplified forms of the SPFs shown above are presented in the document *Manual of Estimating the Speed Reduction Benefits on Arterial Roads in Small Indiana Communities*. The reduced SPFs in this manual exclude the inputs most difficult to obtain and less critical for accuracy while adequately estimating the average number of annual crashes expected to occur on roads under current conditions.

5.2 Crash Severity Models

Logistic regression is applied in estimating the crash severity models for VRU and MRU crashes. The results from the logistic regression applied for VRU crashes are shown in Table 5.4, while the results for MRU crashes are presented in Table 5.5. The VRU model estimates the probability of a crash being categorized as a *major injury/fatal* crash, while the MRU model provides a multinomial representation considering the crash categories as *minor injury* and *major injury/fatal*.

Multiple variables were included in each model to better represent the relationship between speed and safety. These variables consider the impact of road features as well as crash-specific information. After evaluating the influence of traffic, geometric, infrastructure, land use, and crash-specific characteristics in the severity models, the VRU model shows an increasing trend in the probability of a *major injury/fatal* crash as speed limit increases, as well as an increasing trend in the probability of *minor injury* and *major injury/fatal* for MRU crashes.

Including crash-specific information (for example, the environmental characteristics when the crash occurred

TABLE 5.2

Multivariate Negative Binomial Model of Motorized Road User Crashes on Arterial Highway Segments Passing Through Small Communities

Variable	**Parameter Estimate**	**Standard Error**	**z-statistic**	**p-value**
Dependent variable: PDO crashes				
Intercept	-13.3909	1.2100	-11.07	0.00
Speed limit (mph)	-0.0067	0.0068	-0.99	0.32
Log of AADT	0.7602	0.0745	10.20	0.00
Log of segment length in feet	1.1199	0.1264	8.86	0.00
Signalized intersections per mile	0.0661	0.0389	1.70	0.09
Commercial (business) driveways per mile	0.0113	0.0061	1.86	0.06
Multilane divided highway indicator (1 if true, 0 otherwise)	-0.3442	0.1278	-2.69	0.01
Percent paved surfaces within three blocks (1,200 feet) of the road	0.0177	0.0059	2.99	0.00
Low development on both sides of road (1 if true, 0 otherwise)	-0.3259	0.1011	-3.22	0.00
Businesses within three blocks (1,200 feet) of the road per mile	0.0027	0.0016	1.66	0.10
IRI	0.0031	0.0009	3.27	0.00
Average change in deflection angle (degrees/mile)	0.0008	0.0009	0.89	0.38
Variance	2.5678	0.6134	—	—
Dependent variable: Minor injury crashes				
Intercept	-13.4671	1.2198	-11.04	0.00
Speed limit (mph)	0.0023	0.0066	0.35	0.72
Log of AADT	0.8699	0.0776	11.21	0.00
Log of segment length in feet	0.7313	0.1262	5.80	0.00
Commercial (business) driveways per mile	0.0091	0.0056	1.62	0.11
Multilane divided highway indicator (1 if true, 0 otherwise)	-0.2308	0.1250	-1.85	0.06
Percent paved surfaces within three blocks (1,200 feet) of the road	0.0234	0.0054	4.33	0.00
Low development on both sides of road (1 if true, 0 otherwise)	-0.1132	0.1058	-1.07	0.28
Businesses within three blocks (1,200 feet) of the road per mile	0.0018	0.0014	1.35	0.18
IRI	0.0015	0.0009	1.59	0.11
Average change in deflection angle (degrees/mile)	0.0009	0.0009	1.07	0.28
Variance	1.3920	0.1568	—	—
Dependent variable: Major injury or fatality crashes				
Intercept	-13.7075	1.6418	-8.35	0.00
Speed limit (mph)	0.0189	0.0075	2.52	0.01
Log of AADT	0.6251	0.0911	6.86	0.00
Log of segment length in feet	0.8493	0.1751	4.85	0.00
Signalized intersections per mile	-0.0438	0.0523	-0.84	0.40
All-way stop-controlled intersections per mile	-0.1729	0.1487	-1.16	0.24
Multilane undivided highway indicator (1 if true, 0 otherwise)	0.5008	0.1134	4.42	0.00
Percent paved surfaces within three blocks (1,200 feet) of the road	0.0190	0.0060	3.14	0.00
Businesses within three blocks (1,200 feet) of the road per mile	0.0042	0.0018	2.29	0.02
IRI	0.0030	0.0011	2.63	0.01
Average change in deflection angle (degrees/mile)	0.0011	0.0011	1.04	0.30
Variance	1.1951	0.1618	—	—
Number of observations	396	—	—	—
Correlation (PDO, minor)	0.4764	0.0394	—	—
Correlation (PDO, major)	0.4983	0.0383	—	—
Correlation (minor, major)	0.3807	0.0435	—	—
Scale	0.1859	0.0542	—	—
-2 Res Log Pseudo-Likelihood	2975.0700	—	—	—

TABLE 5.3
Safety Performance Functions for Arterial Highways Passing Through Small Communities

Crash Severity	**Vulnerable Road User Crashes**
Minor	$Annual\ crashes = 1.636 * 10^{-8} * \exp(-0.007 * SL + 0.804 * lnAADT + 0.897 * \ln(5{,}280 * Length) + 0.022 * \frac{Comm}{Length} - 0.569 * M + 0.019 * PP - 0.929 * Low + 0.004 * \frac{B}{Length} + 0.793 * Sidewalk)$
Major/Fatal	$Annual\ crashes = 6.314 * 10^{-9} * \exp(0.009 * SL + 0.520 * lnAADT + 1.082 * \ln(5{,}280 * Length) + 0.043 * \frac{UFL}{Length} + 0.030 * PP - 0.629 * Low + 0.593 * CS + 0.776 * CNS)$
Crash Severity	Motorized Road User Crashes
PDO	$Annual\ crashes = 3.058 * 10^{-7} * \exp(-0.007 * SL + 0.760 * lnAADT + 1.120 * \ln(5{,}280 * Length) + 0.066 * \frac{S}{Length} + 0.011 * \frac{Comm}{Length} - 0.344 * MD + 0.018 * PP - 0.326 * Low + 0.003 * \frac{B}{Length} + 0.003 * IRI + 0.0008 * DA)$
Minor	$Annual\ crashes = 2.834 * 10^{-7} * \exp(0.002 * SL + 0.870 * lnAADT + 0.731 * \ln(5{,}280 * Length) + 0.009 * \frac{Comm}{Length} - 0.231 * MD + 0.023 * PP - 0.113 * Low + 0.002 * \frac{B}{Length} + 0.002 * IRI + 0.0009 * DA)$
Major/Fatal	$Annual\ crashes = 2.228 * 10^{-7} * \exp(0.019 * SL + 0.625 * lnAADT + 0.849 * \ln(5{,}280 * Length) - 0.044 * \frac{S}{Length} - 0.173 * \frac{AWS}{Length} + 0.501 * MU + 0.019 * PP + 0.004 * \frac{B}{Length} + 0.003 * IRI + 0.001 * DA)$

where: SL = Speed limit (mph),
$InAADT$ = Natural log of annual average daily traffic in vehicles per day (vpd),
$Length$ = Segment length (miles),
UFL = Number of unsignalized four-leg intersections,
S = Number of signalized intersections,
AWS = Number of all-way stop-controlled intersections,
$Comm$ = Number of commercial (business) driveways,
MD = Multilane divided highway indicator (1 if true, 0 otherwise),
MU = Multilane undivided highway indicator (1 if true, 0 otherwise),
M = Multilane (undivided or divided) highway indicator (1 if true, 0 otherwise),
PP = Percent paved surfaces within three blocks (1,200 feet) of the road,
B = Number of businesses within three blocks (1,200 feet) of the road,
Low = Low development on both sides of road (1 if true, 0 otherwise),
$Sidewalk$ = Proportion of segment with no clearance between sidewalk and traveled way,
CS = Segment has curb and sidewalk (1 if true, 0 otherwise),
CNS = Segment has curb but no sidewalk (1 if true, 0 otherwise),
IRI = International Roughness Index, and
DA = Average change in deflection angle (degrees/mile).

or the attributes of the involved users) is particularly important to better understand the impact of speed limit on crashes. Therefore, crash modification factors (CMFs) were estimated based on the logistic regression models considering the impact of both road- and crash-specific information. These CMFs are presented in Figure 5.1 for different levels of speed limit reduction. CMFs are computed for *major injury/fatal* VRU crashes and for *minor injury* and *major injury/fatal* crashes involving MRUs using Equation 4.5 and the corresponding parameter estimate for speed limit estimated from the logistic regression models. For *minor injury* VRU crashes and for *PDO* MRU crashes, the impact of speed limit reduction on crashes was evaluated using CMFs based on the work of Elvik (2013); these CMFs were used as a reference to adjust the CMFs for the other crash types/severities.

5.3 Driver Speed Adopted for Different Speed Limit Ranges

Table 5.6 shows the average speed of drivers adopted across different ranges of the speed limit for the 396 arterial segments evaluated in this study. The average speed is shown separately for all segments, interrupted

TABLE 5.4
Logistic Regression Model for the Severity of Vulnerable Road Users Only Crashes

Variable	Parameter Estimate	Standard Error	z-statistic	p-value
Major injury or fatality outcome				
Intercept	-2.3540	0.7374	-3.19	0.00
Speed limit (mph)	0.0189	0.0161	1.17	0.24
Proportion of AADT comprised of trucks	4.6292	2.2404	2.07	0.04
Older driver (65 years and older) involved in crash (1 if true, 0 otherwise)	-0.9479	0.3752	-2.53	0.01
Crash occurred in clear weather conditions (1 if true, 0 otherwise)	0.3225	0.2786	1.16	0.25
Crash occurred in school zone (1 if true, 0 otherwise)	-1.1851	0.6481	-1.83	0.07
Primary cause of crash related to pedestrian action (1 if true, 0 otherwise)	0.7155	0.2458	2.91	0.00
Crash occurred at signalized intersection (1 if true, 0 otherwise)	-0.3625	0.3140	-1.15	0.25
Number of observations	361			
Log likelihood	-204.4860			

TABLE 5.5
Logistic Regression Model for the Severity of Motorized Road User Crashes

Variable	Parameter Estimate	Standard Error	z-statistic	p-value
Minor injury outcome				
Intercept	-3.2023	0.1629	-19.66	0.00
Speed limit (mph)	0.0130	0.0038	3.38	0.00
Primary cause of crash related to unsafe speed (1 if true, 0 otherwise)	0.1487	0.1109	1.34	0.18
Older driver (65 years and older) involved in crash (1 if true, 0 otherwise)	0.1318	0.0627	2.10	0.04
Aggressive driver involved in crash (1 if true, 0 otherwise)	0.4331	0.1406	3.08	0.00
Crash occurred on curve (1 if true, 0 otherwise)	0.4229	0.0941	4.49	0.00
Right angle crash (1 if true, 0 otherwise)	0.8403	0.0633	13.27	0.00
Head-on crash (1 if true, 0 otherwise)	1.1729	0.1009	11.62	0.00
Crash occurred on a dry road surface (1 if true, 0 otherwise)	0.1576	0.0632	2.50	0.01
Crash occurred on dark, unlighted road (1 if true, 0 otherwise)	0.2474	0.0898	2.76	0.01
Low development on both sides of road (1 if true, 0 otherwise)	0.1420	0.0660	2.15	0.03
Multilane (undivided or divided) highway (1 if true, 0 otherwise)	0.1817	0.0549	3.31	0.00
Major injury or fatality outcome				
Intercept	-4.4984	0.2332	-19.29	0.00
Speed limit (mph)	0.0174	0.0057	3.06	0.00
Primary cause of crash related to unsafe speed (1 if true, 0 otherwise)	0.2730	0.1393	1.96	0.05
Older driver (65 years and older) involved in crash (1 if true, 0 otherwise)	0.1556	0.0814	1.91	0.06
Aggressive driver involved in crash (1 if true, 0 otherwise)	0.6731	0.1619	4.16	0.00
Crash occurred on curve (1 if true, 0 otherwise)	0.8067	0.1046	7.71	0.00
Right angle crash (1 if true, 0 otherwise)	1.0123	0.0795	12.73	0.00
Head-on crash (1 if true, 0 otherwise)	1.3142	0.1220	10.78	0.00
Crash occurred on a dry road surface (1 if true, 0 otherwise)	0.4139	0.0867	4.77	0.00
Crash occurred on dark, unlighted road (1 if true, 0 otherwise)	0.5431	0.1022	5.31	0.00
Crash occurred in school zone (1 if true, 0 otherwise)	-0.3898	0.2382	-1.64	0.10
Low development on both sides of road (1 if true, 0 otherwise)	0.3920	0.0812	4.83	0.00
Multilane (undivided or divided) highway (1 if true, 0 otherwise)	0.3538	0.0717	4.93	0.00
No curb present (1 if true, 0 otherwise)	0.1485	0.0801	1.85	0.06
Number of observations	18,225	—	—	—
Log likelihood	-9,388.6025	—	—	—

segments (those with signalized intersections, all-way stop-controlled intersections, railroad crossings, etc.), and uninterrupted segments. These results are provided for the entire sample, as well as for segments crossing communities of population 5,000 and under and 2,000 and under.

Drivers on uninterrupted road segments tend to travel faster in comparison to the speed limit across the lower speed limit ranges. As expected, the results show that there are considerable differences in the average speed of drivers on uninterrupted versus interrupted road segments. For the same speed limit, drivers on

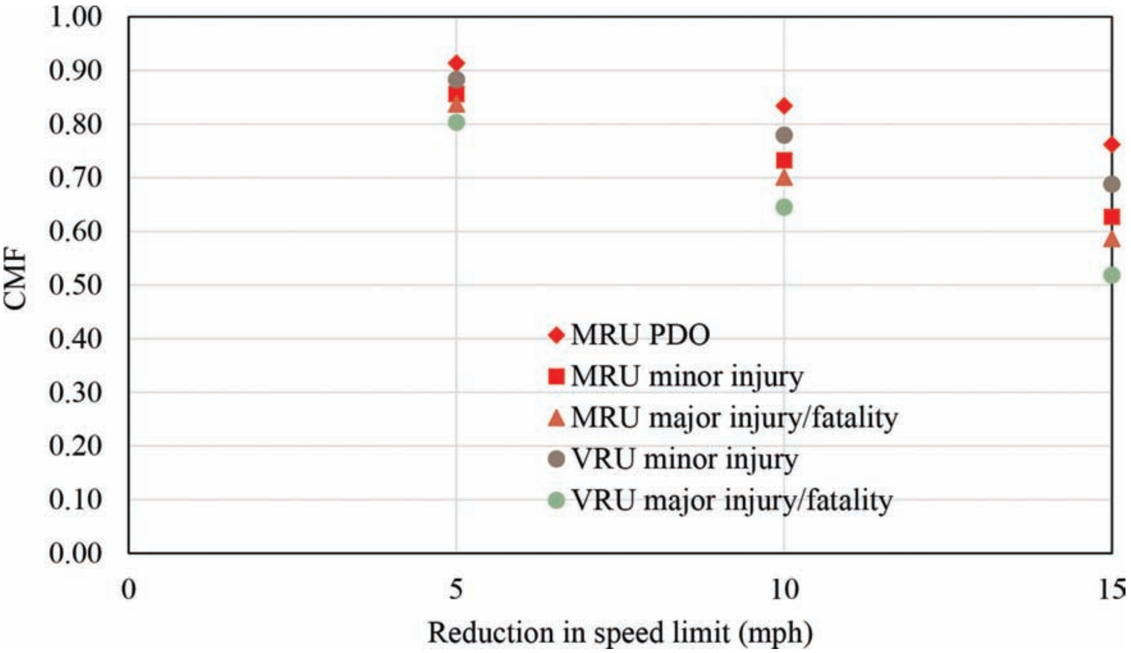


Figure 5.1 Crash modification factors by crash type and severity for different levels of speed limit reduction.

TABLE 5.6
Average Speeds (mph) for Different Speed Limits

Speed Limit (mph)	Entire Sample			Cities/Towns with Population Under 5,000			Cities/Towns with Population Under 2,000		
	All Segments	Uninterrupted Segments	Interrupted Segments	All Segments	Uninterrupted Segments	Interrupted Segments	All Segments	Uninterrupted Segments	Interrupted Segments
30	30.5	34.8	29.4	30.9	34.5	29.8	31.5	34.7	30.3
35	36.3	39.3	34.3	37.2	39.6	34.7	38.1	39.5	36.1
40	39.2	43.1	36.9	39.7	43.3	37.5	40.3	43.6	38.2
45	40.9	44.8	39.3	40.7	44.5	38.6	41.8	44.4	40.3
50	46.9	50.4	44.2	47.2	50.5	44.1	48.5	52.1	44.9
55	50.2	54.0	47.4	51.2	53.9	48.5	50.3	56.4	47.5
60	60.5	61.1	55.4	60.5	61.1	50.5	60.7	61.5	50.5
Average	40.7	46.1	37.4	41.4	46.5	37.5	42.6	47.1	38.8

uninterrupted road segments travel between 8 and 9 mph faster on average.

In smaller towns where there is a shorter distance to transition between rural and urban conditions, the average speed was observed to be slightly higher. This difference is most pronounced for communities with population of 2,000 and under, where average speeds in relation to the entire sample tend to be around 1-mph faster on uninterrupted roads and around 1.3-mph faster on interrupted roads.

CHAPTER 6. BENEFITS OF SPEED REDUCTION

6.1 Evaluating the Benefits of Speed Reduction

In the previous chapter, the relationship between a road's speed limit and its safety (crashes) was deduced. To evaluate the safety-related impact of reducing driver speed, a connection between a road's speed limit and the average speed of vehicles traveling on the segment must be established. Therefore, a regression model predicting the average segment speed based upon the speed limit and other road features was developed (see Table 6.1). It was found that the relationship depends on the presence of interruptions (for instance, signalized intersections, all-way stop-controlled intersections, railroad crossings, etc.) along the road. The results from the regression model were used to connect the speed limit on uninterrupted and interrupted roads to the average speed of users, as obtained from the INRIX speed data over the period from May 2015 to March 2017. Reductions in the average speed were associated with corresponding reductions in speed limit by dividing the average speed reduction by the model regression parameter for speed limit on uninterrupted and interrupted roads. Then, the CMFs were again computed using the procedure discussed in section 5.2. Table 6.2 provides a summary of the CMFs for VRU and MRU crashes, in 1-mph increments, that reflect the

TABLE 6.1
Regression Model of Average Speed for Arterial Highway Segments Passing Through Small Communities

Variable	Parameter Estimate	Standard Error	t-statistic	p-value
Intercept	20.9602	3.9982	5.24	0.00
Speed limit on interrupted road (mph)	0.4554	0.0333	13.67	0.00
Speed limit on uninterrupted road (mph)	0.5385	0.0333	16.16	0.00
Signalized intersections per mile	-0.8645	0.2348	-3.68	0.00
All-way stop-controlled intersections per mile	-1.3537	0.3532	-3.83	0.00
U.S highway indicator (1 if true, 0 otherwise)	0.9067	0.4400	2.06	0.04
Multilane divided highway indicator (1 if true, 0 otherwise)	4.2726	0.6553	6.52	0.00
Multilane undivided highway indicator (1 if true, 0 otherwise)	1.6678	0.6101	2.73	0.01
Proportion of segment with sidewalk	-2.2535	0.9608	-2.35	0.02
Proportion of segment with on-street parking	-6.2046	2.5830	-2.40	0.02
Businesses within three blocks (1,200 feet) of the road per mile	-0.0480	0.0079	-6.10	0.00
Average change in deflection angle (degrees/mile)	-0.0094	0.0042	-2.22	0.03
Lane width (feet)	0.1537	0.2725	0.56	0.57
Shoulder width (feet)	0.2136	0.0646	3.31	0.00
Log of city/town population	-0.3068	0.2084	-1.47	0.14
Number of observations	396			
R-squared	0.8406			
Adjusted r-squared	0.8347			
Root MSE	3.6871			

reduction of average speed on uninterrupted and interrupted road segments.

Equation 6.1 is used to determine the expected crash reduction (R_{ji}) for crash type j and severity i resulting from a reduction in average speed along a road segment.

$$R_{ji} = B_{ji} \cdot (1 - CMF_{ji}) \qquad \text{(Eq. 6.1)}$$

where: B_{ji} = SPF-predicted crashes of type j at severity level i before reducing the speed,

CMF_{ji} = Crash modification factor representing the effect of reducing speed on an uninterrupted or interrupted road for crash type j and severity level i.

The safety benefit corresponding to a reduction in crashes is evaluated based on the average unit crash cost for each crash type and severity. Table 6.3 provides the average unit crash cost values (adjusted to 2019 dollars) applicable to highways passing through small Indiana communities. These costs were obtained by averaging the individual costs of observed VRU and MRU crashes over the analysis period, based on National Safety Council estimates (NSC, 2016). Equation 6.2 is used to predict the safety benefit (S_{ji}) for crash type j at severity level i:

$$S_{ji} = R_{ji} \cdot C_{ji} \qquad \text{(Eq. 6.2)}$$

where R_{ji} is the expected reduction of crashes type j at severity level i and C_{ji} is the average cost of crash type j at severity level i.

The product in Equation 6.2 is calculated for each crash type/severity on uninterrupted and interrupted roads, with the resulting values summed to find the total annual benefit.

The entire procedure for determining the current safety level and for predicting the benefits of speed reduction are presented in the *Manual of Estimating the Speed Reduction Benefits on Arterial Roads in Small Indiana Communities*.

6.2 Local and Out-of-town Safety Benefits

The effect of speed changes on the local population may be assessed by splitting the benefits into those for the local and non-local (out-of-town) population. To this end, the proportion of the safety benefit for local road users is estimated using the Beta regression methodology described in Chapter 4. Since the safety benefit split between local and out-of-town road users depends on the crash type (VRU or MRU), separate models were estimated for each crash type. Only road segments that experienced crashes during the analysis period (hence facilitating computation of a benefits proportion) are included in each sample. The model results using maximum likelihood estimation are shown in Table 6.4 and Table 6.5 for VRU and MRU crashes, respectively.

Multiple covariates were tested in these models, with the most influential variables being the population of the city/town through which the road segment passes and its AADT. In general, for both VRU and MRU crashes, increases in the city/town population tend to increase the proportion of the benefit for local users. On the contrary, increases in the AADT reduce the benefit proportion for local users for both crash types. Additional significant variables in the MRU crash model include the number of unsignalized intersections per mile and the number of commercial driveways per mile.

A Probit link function provides the best model fit. Hence, the relation between the expectation and the covariates is characterized by the following expressions (Equations 6.3 and 6.4):

TABLE 6.2
Crash Modification Factors for an Average Speed Reduction

	Uninterrupted Road					Interrupted Road				
	Vulnerable Road Users Involved		Motorized Road Users Only			Vulnerable Road Users Involved		Motorized Road Users Only		
Speed Reduction (mph)	**Minor Injury Crashes**	**Major Injury or Fatality Crashes**	**Property Damage Only**	**Minor Injury Crashes**	**Major Injury or Fatality Crashes**	**Minor Injury Crashes**	**Major Injury or Fatality Crashes**	**Property Damage Only**	**Minor Injury Crashes**	**Major Injury or Fatality Crashes**
1	0.95	0.92	0.97	0.94	0.94	0.95	0.91	0.96	0.93	0.92
2	0.91	0.85	0.93	0.89	0.88	0.90	0.82	0.92	0.87	0.86
3	0.87	0.78	0.90	0.84	0.82	0.85	0.75	0.89	0.81	0.79
4	0.83	0.72	0.87	0.79	0.77	0.80	0.68	0.85	0.76	0.73
5	0.79	0.67	0.84	0.75	0.72	0.76	0.62	0.82	0.71	0.68
6	0.76	0.61	0.82	0.71	0.67	0.72	0.56	0.79	0.66	0.63
7	0.72	0.57	0.79	0.67	0.63	0.68	0.51	0.76	0.62	0.58
8	0.69	0.52	0.76	0.63	0.59	0.65	0.46	0.73	0.58	0.54
9	0.66	0.48	0.74	0.59	0.55	0.61	0.42	0.70	0.54	0.50
10	0.63	0.44	0.71	0.56	0.52	0.58	0.38	0.67	0.50	0.46

TABLE 6.3
Average Unit Crash Costs for Different Crash Types and Severities on Arterial Highways Passing Through Small Communities (2019 dollars)

Crash Type/Severity	Value
VRU minor injury	299,400
VRU major injury or fatality	2,072,220
MRU property damage only	39,960
MRU minor injury	363,410
MRU major injury or fatality	1,689,270

VRU crashes:

$$P_{LocalVRU} = g(\mu) = \phi^{-1}(\mu) = \phi^{-1}$$

$$(1.062 + 0.312 * lnPop - 0.374 * lnAADT) \quad \text{(Eq. 6.3)}$$

MRU crashes:

$$P_{(LocalMRU)} = g(\mu) = \phi^{-1}(\mu) = \phi^{-1}$$

$$(-0.492 + 0.249 * lnPop - 0.216 * lnAADT + 0.019 * Unsig/Length + 0.008 * Comm/Length) \quad \text{(Eq. 6.4)}$$

where: $P_{LocalVRU}$ and $P_{LocalMRU}$ is the proportion of the safety benefit for local users
for VRU and MRU crashes, respectively,
$lnPop$ = Natural log of the city/town population,
$lnAADT$ = Natural log of annual average daily traffic in vehicles per day (vpd),
$Length$ = Segment length (miles),
$Unsig$ = Number of unsignalized intersections,
$Comm$ = Number of commercial (business) driveways.

An approximation of the standard normal distribution can be obtained using a logit link specified as follows (Equations 6.5 and 6.6):

$$P_{LocalVRU} = \frac{1}{1 + \exp\left[-1.7 * \begin{pmatrix} 1.062 + 0.312 \\ * lnPop - 0.374 * lnAADT \end{pmatrix}\right]} \quad \text{(Eq. 6.5)}$$

$$P_{LocalMRU} = \frac{1}{1 + \exp\left[-1.7 * \begin{pmatrix} -0.492 + 0.249 * lnPop - 0.216 * lnAADT \\ +0.019 * \dfrac{Unsig}{Length} + 0.008 * \dfrac{Comm}{Length} \end{pmatrix}\right]} \quad \text{(Eq. 6.6)}$$

The proportion of the safety benefit for out-of-town users (P_{OutVRU} and $\mathrm{P_{OutMRU}}$) is equal to 1 – proportion of the safety benefit for local users.

TABLE 6.4
VRU Beta Regression Model of the Proportion of the Safety Benefit for Local Road Users on Arterial Highway Segments (mean model with probit link function)

Variable	Parameter Estimate	Standard Error	z-value	p-value
Intercept	1.0622	1.0042	1.06	0.29
Log of city/town population	0.3122	0.0828	3.77	0.00
Log of AADT	-0.3737	0.1177	-3.18	0.00
Phi coefficient	0.1558	0.0131	11.93	0.00
Number of observations	164	—	—	—
Pseudo r-squared	0.0982	—	—	—

TABLE 6.5
MRU Beta Regression Model of the Proportion of the Safety Benefit for Local Road Users on Arterial Highway Segments (mean model with probit link function)

Variable	Parameter Estimate	Standard Error	z-value	p-value
Intercept	-0.4922	0.5559	-0.89	0.38
Log of city/town population	0.2491	0.0443	5.63	0.00
Log of AADT	-0.2155	0.0636	-3.39	0.00
Unsignalized intersections per mile	0.0187	0.0110	1.70	0.09
Commercial (business) driveways per mile	0.0084	0.0062	1.35	0.18
Phi coefficient	0.9077	0.0534	16.99	0.00
Number of observations	387	—	—	—
Pseudo r-squared	0.0733	—	—	—

TABLE 6.6
Potential Safety Benefits of Reducing Average Speed Across 202 Arterial Highway Segments

Policy	VRU		MRU		
	Minor Injury	Major Injury/ Fatality	PDO	Minor Injury	Major Injury/ Fatality
2-mph speed reduction					
Annual expected crashes (current conditions)	6.619	3.661	1085.614	153.852	106.713
Annual expected crashes (after speed reduction)	5.984	3.047	1003.183	135.130	92.688
Annual crashes saved by speed reduction	0.635	0.614	82.431	18.722	14.025
Benefit of speed reduction (2019 dollars)	$190,310	$1,271,300	$3,293,940	$6,803,920	$23,691,130
By types of users involved:					
Benefit for local users	*$99,490*	*$660,740*	*$1,091,530*	*$2,204,470*	*$7,572,730*
Benefit for out-of-town users	*$90,820*	*$610,560*	*$2,202,410*	*$4,599,450*	*$16,118,400*
5-mph speed reduction					
Annual expected crashes (current conditions)	6.619	3.661	1085.614	153.852	106.713
Annual expected crashes (after speed reduction)	5.109	2.345	899.040	111.792	74.395
Annual crashes saved by speed reduction	1.510	1.316	186.574	42.060	32.318
Benefit of speed reduction (2019 dollars)	$452,030	$2,725,720	$7,455,500	$15,285,190	$54,592,930
By types of users involved:					
Benefit for local users	*$236,160*	*$1,417,650*	*$2,470,950*	*$4,952,660*	*$17,449,900*
Benefit for out-of-town users	*$215,870*	*$1,308,070*	*$4,984,550*	*$10,332,530*	*$37,143,030*

6.3 Systemwide Benefits of Speed Reduction

Considering the entire data sample, there are 202 segments (108 uninterrupted and 94 interrupted) which have average speeds exceeding 40 mph. An analysis of benefits for these higher speed segments was assessed under the following two scenarios: (1) a 2-mph reduction in average speed from the segment's current average speed, and (2) a 5-mph reduction in average speed. A step-by-step example of the speed reduction benefits for one of these segments is presented in the *Manual of Estimating the Speed Reduction Benefits on Arterial Roads in Small Indiana Communities*.

Table 6.6 shows the crashes of different types/severities expected to occur each year, under the current conditions of the 202 road segments. Moreover, the table shows the expected crashes and safety benefit for the 2-mph and 5-mph speed reduction scenarios.

In total, the 2-mph and 5-mph speed reductions were found to result in annual benefits of $35,250,600 and $80,511,370, respectively, across the 202 evaluated segments. The components of these benefits for local road users are $11,628,960 and $26,527,320 for the 2-mph and 5-mph speed reduction scenarios, respectively.

6.4 Reduction in Benefits

One of the main components reducing the benefits of speed reduction is the monetary value of lost time by motorists due to the lower speeds. The impact of this factor can be evaluated using Equation 6.7. below. A typical value of $15/person-hour (adjusted to 2019 dollars) for all-purpose local travel is adopted in the current study (USDOT, 2016). The annualized value of lost time for individual road segments is calculated as follows:

$$Value\ of\ lost\ time = \left(\frac{1}{s_2} - \frac{1}{s_1}\right) * Length * AADT * 365 * O * C \qquad \text{(Eq. 6.7)}$$

where: s_1 = Average speed on segment before implementing speed control measure (mph),

s_2 = Average speed on segment after implementing speed control measure (mph),

$AADT$ = Annual average daily traffic in vehicles per day (vpd),

$Length$ = Segment length (miles),

O = Average vehicle occupancy (assumed 1.67 persons/veh, NHTSA, 2018),

C = Monetary value of motorists' time (assumed $15/person-hour).

Using the above equation for each of the 202 arterial segments, the reduction in benefits resulting from 2-mph and 5-mph speed reductions are equal to $16,246,940 and $43,550,220, respectively.

In addition to the value of lost time, another factor that may modify the benefits of speed reduction measures are changes in the vehicle operating costs (VOC). VOC may either increase or decrease depending on the vehicle type and initial speed of the vehicle (Sinha & Labi, 2011). Considering medium-sized autos and a flat grade, speed reduction at lower initial speeds (at or below 35 mph) increases the VOC, while speed reduction at higher initial speeds decreases the VOC. Overall, in comparison to the lost time, the changes in benefits due to changing VOC are small, and hence they are not considered in this analysis.

The cost of installing and maintaining a speed control measure (including the material, equipment, and labor costs) are also outside the analysis scope. Apart from major roadway modifications such as geometrical changes, the cost of speed reduction measures identified in this research tend to be low. Nonetheless, before selecting a speed reduction measure, a complete evaluation of economic feasibility should also consider the installation and maintenance costs.

CHAPTER 7. INDIANA SPEED LIMIT MODIFICATIONS

7.1 Background

This chapter describes a before-and-after study of modifications made to the speed limit transition zones by the Indiana Department of Transportation (INDOT) in 2017. A total of 17 small cities and towns from across the INDOT Greenfield District are represented in the sample. Both U.S and state roads pass through the analyzed towns. Table 7.1 provides general information regarding these towns.

7.2 Data

The INRIX speed data for Indiana (2015–2018), discussed previously in the Data section, was used in this study. Directional INRIX segments covering different town zones were evaluated. These included the transition zone, one per side of each town; the town zone, one or more segments inside the town; and the control zone (where speed limits remained unchanged), one per side of the town in order to validate the effectiveness of the changes. Coordinates of the actual posted speed limits and after changes were collected for the 17 towns using Google Earth and from work order forms graciously provided by the INDOT Greenfield district. This data was necessary to identify the different zones across each town.

Different time periods were considered in order to evaluate possible differences of driver's speed depending on the time of day on weekdays and weekends. For weekdays, two-time periods were examined: morning (9 AM to 12 PM) and afternoon (4 PM to 6 PM). The morning time was selected in order to avoid the morning rush-hour period, when driver behavior may be affected by external factors (work, school, errands, etc.). The afternoon time attempts to evaluate different driver behavior by overlapping the afternoon rush hour. For weekends, a wider 9 AM to 5 PM time period was chosen for two reasons. First, the rush hour is typically less pronounced on weekends, so the period may be continuous. Second, there are fewer days from which to select from on the weekend.

Although there are no restrictions on the minimum number of observations required, segments should have as much observations as possible in order to avoid randomness and error in the results. To ensure a sufficient number of observations, a criterion for the minimum number of days of data was established. For weekdays, at least 10 days of speed data was used for the before-and-after periods, while for weekends, a

TABLE 7.1
Indiana Towns considered in the before-and-after study

Town	County	Roadway	Directions	Population
Elwood	Madison	SR 13	NB/SB	8,614
Daleville	Madison	SR 32	EB/WB	1,647
Morristown	Shelby	US 52	EB/WB	1,218
Windfall	Tipton	SR 213	NB/SB	708
Oakford	Howard	SR 26	EB/WB	—
Russiaville	Howard	SR 26	EB/WB	1,094
Gwynneville	Shelby	US 52	EB/WB	211
Galveston	Cass	US 35	NB/SB	1,311
Lapel	Madison	SR 13	NB/SB	2,068
Fountaintown	Shelby	US 52	EB/WB	2,508
Tipton	Tipton	SR 19	NB/SB	5,106
Fortville	Hancock	US 36	EB/WB	3,929
Wilkinson	Hancock	SR 109	NB/SB	449
Edgewood	Madison	SR 32	EB/WB	1,913
Cicero	Hamilton	SR 19	NB/SB	4,812
Shelbyville	Shelby	SR 9	NB/SB	19,191
Sheridan	Hamilton	SR 38	EB/WB	2,665

period of 4 days of speed data was used. A 5-day period before-and-after the day changes were implemented was excluded from the sample.

Environmental conditions were another factor considered when selecting days for the study. Since poor weather conditions may impact driver behavior, only the days with good weather conditions were selected. To do so, data from the *National Oceanic and Atmospheric Administration* (NOAA) was collected across all study counties. The specific criteria defining good weather conditions was precipitation ≤0.05 inches and non-snowy conditions.

An average of 462 speed observations per segment have been used for the study. Further information is presented in Appendix B.

7.3 Speed Changes

Across each town transition zone, changes in the existing signage and/or the installation of new signage were implemented. However, these changes were not always the same, and they may be classified into different categories to facilitate better comparison of results. Most changes have similar characteristics, since speed limits in transition zones were removed. Table 7.2 summarizes the changes introduced for each town, while Table 7.3 shows the range of the mean speed change observed across different zones (transition, town, and control) for the different categories of speed limit changes. Table 7.3 is a simplification for this chapter, showing only the most representative segments (based on the number of observations and statistical significance). Columns without a reduction listed (—) means that the segments covering these towns were located solely within the transition zone or insufficient data was available. Appendix B contains further information for all segments considered in the analysis.

Even though mean speed may be reduced in the transition zones, it is still important to check the zone inside the town, where vulnerable road users are more susceptible to being injured by a crash. Therefore, the change in mean speed is evaluated within this zone in order to confirm that the speed limit changes achieved their goal. Moreover, the control zone shows the results from segments located near the studied town, but away from the influence of the speed limit changes. A lack of considerable change in the mean speed across the control zone suggests that any changes observed in the transition and towns zones are due to the modified speed limit and not other external factors.

The first change (classified here as type 1A) consisted of extending the rural speed limit into the transition zone while also adding advance speed limit signage. Mean speeds tended to remain similar within the transition zones, with maximum reductions of 2.2 mph for the weekday afternoon period in Morristown and 6.3-mph for the weekend period in Windfall. However, in the latter case of Windfall, the mean speed increased for other periods in the town. Interestingly, mean speeds in the town zones tended to decrease. The weekend period appears to have the greatest speed reduction, with a maximum 2.6-mph mean speed reduction observed in Morristown.

Changes in Lapel (type 1B) reduced mean speed in the transition zone across all periods, with a maximum of 3.5 mph observed during the weekend period. Town zones in Lapel also saw a general reduction in mean speeds, albeit to a lesser extent than for the transition zone.

For those towns in which the town speed limit was extended into the transition zone while also adding advance speed limit signage (type 2A), in most cases, the mean speed was successfully reduced in both the transition and town zones. On average, the magnitude of this reduction was about 1 mph. Maximum mean speed reductions included 5.36 mph in the transition zone of Edgewood and 5.5 mph in the town zone of Tipton.

TABLE 7.2
Categories of Speed Limit Changes Across Studied Towns

Town	Roadway	Directions	Change	Date of Change	Transition Before	Transition After
Type 1A. Rural Speed Limit Extended into Transition Zone + Add Advance Speed Limit Signage						
Elwood	SR 13	NB/SB	Extension of 55 mph zone to 30 mph zone (Adv. 30)	8/15/17	55 40 30	55 30
Daleville	SR 32	EB/WB	Extension of 50 mph zone to 35 mph zone (Adv. 35)	8/15/17	50 45 35	50 35
Morristown	US 52	EB/WB	Extension of 55 mph zone to 30 mph zone (Adv. 30/ Adv. 40)	9/26/17	55 45 30	55 30
Windfall	SR 213	NB/SB	Extension of 55 mph zone to 30 mph zone (Adv. 30)	8/24/17	55 45 30	55 30
Oakford	SR 26	EB/WB	Extension of 55 mph zone to 35 mph zone (Adv. 35)	11/2/17	55 45 35	55 35
Russiaville	SR 26	EB/WB	Extension of 55 mph zone to 30 mph zone (Adv. 30)	11/2/17	55 40 30	55 30
Gwynneville	US 52	EB/WB	Extension of 55 mph zone to 35 mph zone (Adv. 35)	9/26/17	55 45 35	55 35
Galveston	US 35	NB	Extension of 55 mph zone to 35 mph zone (Adv. 35)	11/15/17	55 45 35	55 35
Type 1B. Rural Speed Limit Extended into Transition Zone						
Lapel	SR 13	NB/SB	Extension of 55 mph zone to 40 mph zone	8/3/17	55 50 40	55 40
Type 2A. Town Speed Limit Extended into Transition Zone + Add Advance Speed Limit Signage						
Fountaintown	US 52	EB/WB	Extension of 35 mph zone to 55 mph zone (Adv. 35)	10/12/17	55 45 35	55 35
Tipton	SR 19	NB/SB	Extension of 35 mph zone to 55 mph zone (Adv. 35)	8/24/17	55 45 35	55 35
Fortville	US 36	EB/WB	Extension of 40 mph zone to 55 mph zone (Adv. 40)	9/18/17	55 50 40/55 50 45 40	55 40
Wilkinson	SR 109	NB/SB	Extension of 30 mph zone to 55 mph zone (Adv. 30)	9/18/17	55 40 30	55 30
Edgewood	SR 32	EB/WB	Extension of 40 mph zone to 55 mph zone (Adv. 40)	8/15/17	55 50 40	55 40
Type 2B. Town Speed Limit Extended into Transition Zone						
Cicero	SR 19	NB/SB	Extension of 30 mph zone to 55 mph zone	8/13/17	55 40 30	55 30
Galveston	US 35	SB	Extension of 35 mph zone to 55 mph zone	11/15/17	35 45 55	35 55
Type 3. Rural Speed Limit and Town Speed Limit Extended in Transition Zone + Add Advance Speed Limit Signage						
Shelbyville	SR 9	NB/SB	Extension of 55 mph zone and extension of 30 mph zone (Adv. 30)	8/30/17	55 45 35 30	55 30
Type 4. No changes in Speed Limit Zone + Add Advance Speed Limit Signage						
Sheridan	SR 38	EB	Adv. 30 entering EB	8/14/17	—	—

TABLE 7.3

Range of Mean Speed Change (mph) in Different Zones for Speed Limit Changes

	Transition Zone			Town Zone			Control Zone		
Type 1A. Rural Speed Limit Extended into Transition Zone + Add Advance Speed Limit Signage									
Town	**9 AM to 12 PM**	**4 PM to 6 PM**	**Weekend**	**9 AM to 12 PM**	**4 PM to 6 PM**	**Weekend**	**9 AM to 12 PM**	**4 PM to 6 PM**	**Weekend**
Elwood	-1.76 to 2	-1.4 to -0.8	1.2	-1.52 to 0	-1 to 1.3	-2.1 to -0.1	-0.7 to 0.79	-0.9 to -0.1	-1 to 1.9
Daleville	-0.6 to 2.5	-1.5 to -1.1	-4.4 to -2	-0.28 to 0.43	-2 to -0.1	-2.1 to -0.8	0.24 to 0.42	-1.1 to 0	-1.1
Morristown	-1.1 to -0.7	-2.2 to -0.2	-1.6 to -1.1	-1.11 to -0.82	-0.4 to 0.7	-2.6 to 0.1	0.28 to 0.48	-1.2 to 2.2	-0.3 to 2.2
Windfall	0.3 to 0.45	0 to 0.9	-6.3 to -0.3	-0.25 to 0.79	-2.2 to -1.4	-1.4 to 1	-0.14 to 0	-2.9 to 0	0.3
Oakford	0.5 to 1.8	-0.7 to 1	0.8 to 1.2	—	—	—	0.23 to 0.43	-0.5 to 0	-0.4 to 0.5
Russiaville	-0.33 to 2.33	0.5 to 1.3	-0.5 to 1.5	—	—	—	-0.94 to 0.79	-1.9 to -0.2	-0.2 to 1.1
Gwynneville	-0.25 to 0.65	-0.4 to 1.7	-1.5 to 0.8	—	—	—	0.28 to 0.48	-2 to 2.2	-1 to 2.2
Galveston	-0.47 to -0.18	-0.9 to -0.4	0.7	—	—	—	-1.97 to 0.23	-3 to -1	-2.5 to 2.6
Type 1B. Rural Speed Limit Extended into Transition Zone									
Town	**9 AM to 12 PM**	**4 PM to 6 PM**	**Weekend**	**9 AM to 12 PM**	**4 PM to 6 PM**	**Weekend**	**9 AM to 12 PM**	**4 PM to 6 PM**	**Weekend**
Lapel	-1.12 to 0.6	-3 to -1.4	-3.5 to -1.1	-0.66 to 0.12	-2.6 to 0.7	-2.1 to 1.6	-0.21 to -0.14	-0.1 to 0.8	-2.1 to 1.6
Type 2A. Town Speed Limit Extended into Transition Zone + Add Advance Speed Limit Signage									
Town	**9 AM to 12 PM**	**4 PM to 6 PM**	**Weekend**	**9 AM to 12 PM**	**4 PM to 6 PM**	**Weekend**	**9 AM to 12 PM**	**4 PM to 6 PM**	**Weekend**
Fountaintown	-0.36 to 0.18	-0.6 to 0.6	-2.3 to 0.1	-0.26	-0.5 to 1.6	-1.4 to 0.4	0.27 to 0.45	0.3	-2 to 2.3
Tipton	-1 to -0.3	-1.7 to -0.7	0.3	-1.57 to -0.27	-1.2 to -0.7	-5.5 to 2	-1.23 to -0.21	-0.8 to 1.5	-0.9 to 0.9
Fortville	-1.57 to -1.1	-1.4 to 0	-1.6 to -0.7	-1.12 to 0.59	-1.3 to -0.7	-1.8 to 0.2	-0.96 to -0.03	-1.3 to 0.6	-1.3 to -0.1
Wilkinson	-1.59 to -1.04	-1.4 to -1.1	-2	-2.1 to -1.11	-1	0.6	-0.92 to 0.96	-1.4 to 0.3	-0.4 to 0.3
Edgewood	-5.36 to -0.73	-0.9 to -0.5	-0.3	—	—	—	-1.96 to -1.65	-1.2 to 1.4	-0.6 to 2
Type 2B. Town Speed Limit Extended into Transition Zone									
Town	**9 AM to 12 PM**	**4 PM to 6 PM**	**Weekend**	**9 AM to 12 PM**	**4 PM to 6 PM**	**Weekend**	**9 AM to 12 PM**	**4 PM to 6 PM**	**Weekend**
Cicero	-3.17 to -1.14	-0.1 to 0.1	-1.9 to 4.6	-2.4 to 0.44	-0.3 to 0.3	-0.65	-4.41 to 0.83	0.2 to 1.4	0.5
Galveston	-0.47 to -0.18	-0.9 to -0.4	-0.1	—	—	—	-1.97 to 0.23	-3 to -1	-2.5 to 2.6
Type 3. Rural Speed Limit and Town Speed Limit Extended in Transition Zone + Add Advance Speed Limit Signage									
Town	**9 AM to 12 PM**	**4 PM to 6 PM**	**Weekend**	**9 AM to 12 PM**	**4 PM to 6 PM**	**Weekend**	**9 AM to 12 PM**	**4 PM to 6 PM**	**Weekend**
Shelbyville	-1.57 to 0.77	0.1 to 0.4	-6.6 to 0.4	-2.75 to 0.32	-1.3 to 0.6	—	-0.45 to 0.54	-0.3 to 1.2	-0.1 to 0.9
Type 4. No changes in Speed Limit Zone + Add Advance Speed Limit Signage									
Town	**9 AM to 12 PM**	**4 PM to 6 PM**	**Weekend**	**9 AM to 12 PM**	**4 PM to 6 PM**	**Weekend**	**9 AM to 12 PM**	**4 PM to 6 PM**	**Weekend**
Sheridan	10.35	0.42	—	—	—	—	-0.44	0.5	-0.5

In Cicero and Galveston, the town speed limit was extended into the transition zone, but no advance signage was added (type 2B). Mean speeds in transition and town zones were reduced for most cases, with maximums of 3.17 mph (transition zone) and 2.4 mph (town zone) occurring in Cicero during the weekday morning period.

In Shelbyville, for the type 3 speed limit changes that consisted of extending both the rural and town speed limits within the transition zone, results were rather mixed during the weekday morning and afternoon periods. The largest decrease (up to 6.6 mph) in the mean speed across the transition zone was observed during the weekend period in Shelbyville. Moving to the town zone, mean speeds generally decreased during the two weekday periods. Insufficient data was available in the town zone for the weekend period.

Finally, for Sheridan (type 4, no changes in the posted speed limit, but advance speed limit signage added), the mean speed in the transition zone increased by 10.35 mph during the weekday morning period. However, this may be primarily attributable to the low number of speed observations available for this segment. The mean speed remained similar during the weekday afternoon period. Insufficient speed observations were available for evaluating the weekend period across the transition zone and for all time periods in the town zone.

7.4 Discussion

Most changes introduced by INDOT consisted of removing transition speed limits and extending either the rural speed limit into the transition zone (type 1A/type 1B) or the town speed limit into the transition zone (type 2A/type 2B). The "A" and "B" for the different types represent whether advance speed limit signage was added or not. In general, the type 2 changes seem to have been more effective in reducing mean speeds in comparison to the type 1 changes. By extending the low speed limit zone before entering the town, drivers have a greater distance to start slowing down to maintain a proper speed through the town. Results have shown that the reduction of mean speed is maintained through town for most cases. However, the magnitude of this reduction tends to be low (on average, around 1 mph across the transition and town zones).

CHAPTER 8. SUMMARY AND CONCLUSIONS

Arterial highways provide benefits in terms of mobility and economic development in the small cities and towns through which they pass, accommodating a mixture of road users that includes long-distance travelers as well as local road users. Urbanization and residential development in the areas adjacent to arterial highways increases local traffic and promotes pedestrian and bicycle activities that increase exposure for vulnerable road users (VRUs). Potentially hazardous conditions are faced by local residents considering the high speed of drivers passing along these arterials, which can lead to severe crash outcomes in the case of occurrence. This problem is further emphasized since traditional safety management frameworks that focus on identifying high-crash zones may not identify the potential for improvement in small communities due to the typically low frequency of crashes.

The Indiana Department of Transportation (INDOT) recently conducted a project aimed at managing speed and improving safety for road users on arterial highway corridors passing through small cities and towns. The project evaluated the before-and-after speed of drivers based on modifications made to the speed limit transition zones by the Indiana Department of Transportation (INDOT) in the Greenfield district in 2017. The primary changes introduced by INDOT included removing transition speed limits and extending either the rural speed limit into the transition zone (type 1A/type 1B) or the town speed limit into the transition zone (type 2A/type 2B). Based on the findings of this study, the type 2 changes seem to have been more effective in reducing speed, although the magnitude of reduction is rather low (approximately 1 mph). By extending the low-speed limit zone before entering the town, drivers have a greater distance to start slowing down to maintain a proper speed through the town.

The safety benefits achieved via speed reduction seem to be considerable. The estimation of benefits focused on the following two crash types: (1) vulnerable road user (VRU) crashes, and (2) motorized road users (MRU) crashes. Safety performance functions and crash modification factors obtained via crash severity models were estimated to quantify the benefits achieved by reducing the speed. These benefits were subdivided into those of the local and non-local (out-of-town) users. Example studies show the considerable benefits that may be obtained by reducing speed along the road segments.

The adopted speed of drivers is an important consideration when determining the benefits of speed reduction measures. Different measures were investigated that may help improve safety conditions across these small towns. Among the most promising ones include speed feedback signs, road diets, and narrowing countermeasures such as chokers and bulb-outs. Point-to-point enforcement is an interesting alternative that has been found to be highly impactful elsewhere and can help reduce speed in the small communities free of interruptions.

The implications of this study are two-fold. The report and associated manual present a useful method to evaluate the benefits of speed reduction for different types of vulnerable and motorized road users when applied on arterial highways crossing small communities. Moreover, the study identified several practical speed reduction measures and assessed their implementation potential for arterials in small communities, thus helping to facilitate the reduction in severe crashes. The framework adopted in this study can help justify the case for speed reduction in small communities with lower numbers of crashes but a high probability of severe outcome, helping to better guide decision makers when facing the dilemma of mobility versus safety.

REFERENCES

Al-Ghamdi, A. S. (2002). Using logistic regression to estimate the influence of accident factors on accident severity. *Accident Analysis & Prevention*, *34*(6), 729–741.

Arnold, E. D., & Lantz, K. E., Jr. (2007). *Evaluation of best practices in traffic operations and safety: Phase I: Flashing LED stop sign and optical speed bars* (Report No. FHWA/VTRC 07-R34). Virginia Transportation Research Council. https://rosap.ntl.bts.gov/view/dot/19846

Bagdade, J., Nabors, D., McGee, H., Miller, R., & Retting, R. (2012). *Speed management: A manual for local rural road owners*. Federal Highway Administration. https://safety.fhwa.dot.gov/local_rural/training/fhwasa010413spmgmt/

Ben-Akiva, M., & Bierlaire, M. (1999). Discrete choice methods and their applications to short term travel decisions. In *Handbook of Transportation Science* (pp. 5–33). Springer.

Elvik, R., Christensen, P., & Amundsen, A. H. (2004, December). *Speed and road accidents. An evaluation of the Power Model* (TØI report 740/2004). Institute of Transport Economics. https://lib.ugent.be/fulltxt/RUG01/001/813/795/RUG01-001813795_2012_0001_AC.pdf

Elvik, R. (2009, October). *The Power Model of the relationship between speed and road safety: Update and new analyses* (Report No. 1034/2009). Norwegian Institute of Transportation Economics. https://www.toi.no/getfile.php?mmfileid=13206

Elvik, R. (2013, November). Risk of road accident associated with the use of drugs: A systematic review and meta-analysis of evidence from epidemiological studies. *Accident Analysis & Prevention*, 60, 254–267. https://doi.org/10.1016/j.aap.2012.06.017

FHWA. (2014, July). *Engineering speed management countermeasures: A Desktop reference of potential effectiveness in reducing speed*. United States Department of Transportation Federal Highway Administration. https://safety.fhwa.dot.gov/speedmgt/ref_mats/eng_count/2014/reducing_speed.cfm

FHWA. (2019). *Highway statistics 2017*. United States Department of Transportation Federal Highway Administration.

Ferrari, S., & Cribari-Neto, F. (2004). Beta regression for modelling rates and proportions. *Journal of Applied Statistics*, *31*(7), 799–815.

Garber, N. J., & Gadiraju, R. (1989). Factors affecting speed variance and its influence on accidents. *Transportation Research Record*, *1213*, 64–71.

Gårder, P. E. (2004). The impact of speed and other variables on pedestrian safety in Maine. *Accident Analysis & Prevention*, *36*(4), 533–542.

Gilmore, D., Bauer, K., Torbic, D., Kinzel, C., & Frazier, R. (2013). Treatment effects and design guidance for high– to low-speed transition zones for rural highways. *Transportation Research Record*. https://doi.org/10.3141/2348-06

Golob, T. F., Recker, W. W., & Alvarez, V. M. (2004). Freeway safety as a function of traffic flow. *Accident Analysis & Prevention*, *36*, 933–946.

Gueorguieva, R. (2001). A multivariate generalized linear mixed model for joint modelling of clustered outcomes in the exponential family. *Statistical Modelling*, *1*(3), 177–193.

Hall, T., & Tarko, A. P. (2019). Adequacy of negative binomial models for managing safety on rural local roads. *Accident Analysis & Prevention*, *128*, 148–158.

Hallmark, S. L., Peterson, E., Fitzsimmons, E. J., Hawkins, N. R., Resler, J., & Welch, T. (2007). *Evaluation of gateway and low-cost traffic-calming treatments for major routes in small rural communities*. https://lib.dr.iastate.edu/intrans_reports/30/

Hallmark, S. L., Hawkins, N., Fitzsimmons, E., Resler, J., Plazak, D., Welch, T., & Petersen, E. (2008). Use of physical devices for calming traffic along major roads through small rural communities in Iowa. *Transportation Research Record*, *2078*(1), 100–107.

Harkey, D. L., Srinivasan, R., Baek, J., Council, F. M., Eccles, K., Lefler, N., Gross, F., Persaud, B., Lyon, C., Hauer, E., & Bonneson, J. A. (2008). *Accident modification factors for traffic engineering and ITS improvements: Appendix F* (NCHRP report 617). Transportation Research Board. http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_617appendixF.pdf

Hauer, E. (2009). Speed and safety. *Transportation Research Record*, *2103*(1), 10–17. https://doi.org/10.3141/2103-02

Heydari, S., Miranda-Moreno, L. F., & Liping, F. (2014). Speed limit reduction in urban areas: A before–after study using Bayesian generalized mixed linear models. *Accident Analysis & Prevention*, *73*, 252–261.

Imprialou, M. I. M., Quddus, M., & Pitfield, D. E. (2016). Predicting the safety impact of a speed limit increase using condition-based multivariate Poisson lognormal regression. *Transportation Planning and Technology*, *39*(1), 3–23.

Islam, M. T., El-Basyouny, K., & Ibrahim, S. E. (2014). The impact of lowered residential speed limits on vehicle speed behavior. *Safety Science*, *62*, 483–494.

Kamyab, A., Andrle, S., Kroeger, D., & Heyer, D. S. (2003). Methods to reduce traffic speed in high-pedestrian rural areas. *Transportation Research Record*, *1828*(1), 31–37.

Katz, B. J. (2007). *Peripheral transverse pavement markings for speed control*. Virginia Polytechnic Institute and State University. http://hdl.handle.net/10919/27759

Kockelman Kara, M., & Ma, J. (2007). Freeway speeds and speed variations preceding crashes, within and across lanes. *Journal of the Transportation Research Forum*, *46*(1), 43–61. https://doi.org/10.22004/ag.econ.206875

Krammes, R., & Sheldahl, E. (2009, February). *Traffic calming on main roads through rural communities* (Publication No. FHWA-HRT-08-067). United States Department of Transportation Federal Highway Administration.

Kröyer, H. R. G., Jonsson, T., & Várhelyi, A. (2014). Relative fatality risk curve to describe the effect of change in the impact speed on fatality risk of pedestrians struck by a motor vehicle. *Accident Analysis & Prevention*, *62*, 143–152.

Kweon, Y.-J., & Kockelman, K. M. (2005). Safety effects of speed limit changes: Use of panel models, including speed, use, and design variables. *Transportation Research Record*, *1908*(1), 148–158.

Lave, C. A. (1985, December). Speeding, coordination, and the 55 mph limit. *American Economic Review*, *75*(5), 1159–1164.

Lord, D. (2006). Modeling motor vehicle crashes using Poisson-gamma models: Examining the effects of low sample mean values and small sample size on the estimation of the fixed dispersion parameter. *Accident Analysis & Prevention*, *38*(4), 751–766.

Lord, D., & Mannering, F. (2010). The statistical analysis of crash-frequency data: A review and assessment of methodological alternatives. *Transportation Research Part A: Policy and Practice*, *44*(5), 291–305.

Makwasha, T., & Turner, B. (2013). Evaluating the use of rural-urban gateway treatments in New Zealand. *Journal of the Australasian College of Road Safety*, *24*(4), 14.

Montella, A., Punzo, V., Chiaradonna, S., Mauriello, F., & Montanino, M. (2015, April). Point-to-point speed enforcement systems: Speed limits design criteria and analysis of drivers' compliance. *Transportation Research Part C: Emerging Technologies*, *53*, 1–18. https://doi.org/10.1016/j.trc.2015.01.025

NSC. (2016). *Estimating the costs of unintentional injuries,* 2014. National Safety Council. https://cdn.ymaws.com/www.safestates.org/resource/resmgr/evaluation_resources_webpage/estimating-the-costs-of-unin.pdf

NHTSA. (2018). *National household travel survey*. National Highway Traffic Safety Administration.

Office of Management and Budget. (2010, June 28). Federal register, part IV: 2010 Standards for delineating metropolitan and micropolitan statistical areas. *Federal Register*, *76*(123), 37245–37252.

Shrestha, S., & Liu, A. (2018). Traffic safety studies for highway sections through small urban communities in Saskatchewan. In *TAC 2018: Innovation and Technology: Evolving Transportation–2018 Conference and Exhibition of the Transportation Association of Canada*. https://www.tac-atc.ca/sites/default/files/conf_papers/shresthas_-_traffic_safety_studies_.pdf

Sinha, K. C., & Labi, S. (2011). *Transportation decision making: Principles of project evaluation and programming*. John Wiley & Sons.

Taylor, M. C., Baruya, A., & Kennedy, J. V. (2002). *The relationship between speed and accidents on rural single-carriageway roads* (Report TRL511). TRL.

Tefft, B. C. (2013). Impact speed and a pedestrian's risk of severe injury or death. *Accident Analysis & Prevention*, *50*, 871–878.

USDOT. (2016). *The value of travel time savings: Departmental guidance for conducting economic evaluations revision 2* (2016 Update). United States Department of Transportation. https://www.transportation.gov/sites/dot.gov/files/docs/Revised%20Departmental%20Guidance%20on%20Valuation%20of%20Travel%20Time%20in%20Economic%20Analysis%20-%20September%202016.pdf

Washington, S. P., Karlaftis, M. G., & Mannering, F. (2010). *Statistical and econometric methods for transportation data analysis*. Chapman and Hall/CRC.

World Health Organization. (2008, February 5). *Speed management: A road safety manual for decision-makers and practitioners*. https://apps.who.int/iris/rest/bitstreams/52184/retrieve

Yan, X., Wang, J., & Wu, J. (2016). Effect of in-vehicle audio warning system on driver's speed control performance in transition zones from rural areas to urban areas. *International Journal of Environmental Research and Public Health*, *13*(7). https://doi.org/10.3390/ijerph13070634

Zeileis, A., Cribari-Neto, F., Gruen, B., Kosmidis, I., Simas, A. B., & Rocha, A. V. (2020, February 3). *Package 'betareg'*. https://cran.r-project.org/web/packages/betareg/betareg.pdf

APPENDICES

Appendix A: Estimated Models for Safety Performance Functions

Appendix B: Summary of Results for Before-and-After Speed Limit Study

Appendix C: Manual of Estimating the Speed Reduction Benefits on Arterial Roads in Small Indiana Communities

APPENDIX A. ESTIMATED MODELS FOR SAFETY PERFORMANCE FUNCTIONS

Table A.1 Bivariate Negative Binomial Model of Vulnerable Road User Crashes on Arterial Highway Segments Passing Through Small Communities: Condensed Form for SPFs

Variable	Parameter Estimate	Standard Error	z-statistic	p-value
Dependent variable: Minor injury crashes				
Intercept	-16.4143	2.7703	-5.93	0.00
Speed limit (mph)	-0.0108	0.0142	-0.76	0.45
Log of AADT	0.8448	0.1838	4.60	0.00
Log of segment length in feet	0.8941	0.2838	3.15	0.00
Commercial (business) driveways per mile	0.0189	0.0111	1.70	0.09
Multilane (undivided or divided) highway indicator (1 if true, 0 otherwise)	-0.4929	0.2360	-2.09	0.04
Percent paved surfaces within three blocks (1,200 feet) of the road exceeds 15% (1 if true, 0 otherwise)	1.0672	0.2335	4.57	0.00
Businesses within three blocks (1,200 feet) of the road per mile	0.0087	0.0022	4.01	0.00
Overdispersion parameter	0.4891	0.1542	3.17	0.00
Dependent variable: Major injury or fatality crashes				
Intercept	-17.1993	3.7276	-4.61	0.00
Speed limit (mph)	0.0054	0.0178	0.31	0.76
Log of AADT	0.5924	0.1800	3.29	0.00
Log of segment length in feet	1.0679	0.4117	2.59	0.01
Percent paved surfaces within three blocks (1,200 feet) of the road exceeds 15% (1 if true, 0 otherwise)	0.8740	0.2841	3.08	0.00
Businesses within three blocks (1,200 feet) of the road per mile	0.0058	0.0027	2.16	0.03
Segment has curb and sidewalk (1 if true, 0 otherwise)	0.5991	0.3016	1.99	0.05
Segment has curb but no sidewalk (1 if true, 0 otherwise)	0.8274	0.3092	2.68	0.01
Overdispersion parameter	0.1644	0.2190	0.75	0.45
Number of observations	396			
λ	1.5615	0.6400	2.44	0.02
Log likelihood	-570.7482			

Table A.2 Multivariate Negative Binomial Model of Motorized Road User Crashes on Arterial Highway Segments Passing Through Small Communities: Condensed Form for SPFs

Variable	Parameter Estimate	Standard Error	z-statistic	p-value
Dependent variable: PDO crashes				
Intercept	-11.8278	1.1289	-10.48	0.00
Speed limit (mph)	-0.0129	0.0066	-1.95	0.05
Log of AADT	0.8056	0.0706	11.41	0.00
Log of segment length in feet	0.9490	0.1200	7.91	0.00
Commercial (business) driveways per mile	0.0142	0.0058	2.44	0.01
Multilane divided highway indicator (1 if true, 0 otherwise)	-0.3530	0.1249	-2.83	0.00
Percent paved surfaces within three blocks (1200 feet) of the road exceeds 15% (1 if true, 0 otherwise)	0.5401	0.0962	5.62	0.00
Businesses within three blocks (1200 feet) of the road per mile	0.0062	0.0014	4.49	0.00
Variance	2.6035	0.5831		
Dependent variable: Minor injury crashes				
Intercept	-12.6234	1.2005	-10.52	0.00
Speed limit (mph)	-0.0033	0.0067	-0.50	0.62
Log of AADT	0.9472	0.0760	12.46	0.00
Log of segment length in feet	0.6169	0.1258	4.90	0.00
Commercial (business) driveways per mile	0.0110	0.0056	1.97	0.05
Multilane divided highway indicator (1 if true, 0 otherwise)	-0.2442	0.1253	-1.95	0.05
Percent paved surfaces within three blocks (1200 feet) of the road exceeds 15% (1 if true, 0 otherwise)	0.3430	0.0980	3.50	0.00
Businesses within three blocks (1200 feet) of the road per mile	0.0051	0.0012	4.21	0.00
Variance	1.4649	0.1569		

Variable	Parameter Estimate	Standard Error	z-statistic	p-value

Dependent variable: Major injury or fatality crashes				
Intercept	-12.4403	1.5841	-7.85	0.00
Speed limit (mph)	0.0115	0.0075	1.54	0.12
Log of AADT	0.6650	0.0862	7.72	0.00
Log of segment length in feet	0.7553	0.1718	4.40	0.00
Multilane undivided highway indicator (1 if true, 0 otherwise)	0.5099	0.1122	4.54	0.00
Percent paved surfaces within three blocks (1,200 feet) of the road exceeds 15% (1 if true, 0 otherwise)	0.2517	0.1235	2.04	0.04
Businesses within three blocks (1,200 feet) of the road per mile	0.0061	0.0015	4.13	0.00
Variance	1.2663	0.1625		
Number of observations	396			
Correlation (PDO, minor)	0.5166	0.0373		
Correlation (PDO, major)	0.5372	0.0361		
Correlation (minor, major)	0.4175	0.0419		
Scale	0.1868	0.0508		
-2 Res Log Pseudo-Likelihood	2877.3800			

APPENDIX B. SUMMARY OF RESULTS FOR BEFORE-AND-AFTER SPEED LIMIT STUDY

Table B.3 Summary of Before-and-After Results for Speed Limit Changes During Weekday Morning Period (9 AM to 12 PM)

Town	Zone Type	Direction	Length (miles)	Observations Before	Mean Speed Before (mph)	Std Deviation Before	Observations After	Mean Speed After (mph)	Std Deviation After	Mean Speed Difference (mph)	T-test Value	Degree of Freedom	P-value
Sheridan	Transition	EB	0.74	13	18.5	6.58	53	28.8	2.43	10.35	-5.58	12.82	0.0001
	Control	EB	0.50	651	57.4	1.53	744	57.0	1.51	-0.44	5.42	1363.00	0.0000
Galveston	Control	NB	0.57	417	50.7	5.78	229	50.9	1.80	0.23	-0.76	544.46	0.2252
	Transition	NB	0.62	408	32.6	3.04	217	32.2	2.76	-0.47	1.97	478.75	0.0249
Galveston	Transition	SB	0.62	546	36.1	3.89	251	35.9	4.15	-0.18	0.58	459.09	0.2814
	Control	SB	0.57	549	50.1	6.86	256	48.1	2.32	-1.97	6.03	752.80	0.0000
Wilkinson	Control	NB	0.67	1018	56.3	2.17	736	55.4	4.14	-0.93	5.59	1026.63	0.0000
Wilkinson	Transition	NB	0.53	1073	46.1	2.99	800	44.1	3.97	-1.98	11.86	1426.56	0.0000
Wilkinson	Town	NB	0.40	988	36.7	4.31	719	34.6	4.81	-2.10	9.32	1441.66	0.0000
Wilkinson	Transition	NB	0.50	1068	43.5	2.82	793	42.4	3.72	-1.04	6.58	1421.31	0.0000
Wilkinson	Control	NB	0.59	622	56.9	2.56	660	57.9	2.73	0.96	-6.48	1279.99	0.0000
Wilkinson	Control	SB	0.59	822	56.3	4.35	939	56.7	2.22	0.33	-1.96	1184.76	0.0253
Wilkinson	Transition	SB	0.50	810	40.0	2.70	787	38.4	2.67	-1.59	11.79	1594.48	0.0000
Wilkinson	Town	SB	0.40	1120	35.3	2.90	1090	34.2	3.37	-1.10	8.25	2141.11	0.0000
Wilkinson	Transition	SB	0.53	969	45.9	3.96	985	45.1	2.28	-0.84	5.75	1540.83	0.0000
Wilkinson	Control	SB	0.67	1026	54.8	4.46	1080	53.9	2.30	-0.92	5.89	1518.01	0.0000
Shelbyville	Control	NB	0.56	538	58.2	2.20	545	58.7	2.55	0.54	-3.71	1060.96	0.0001
Shelbyville	Transition	NB	0.70	431	39.9	5.49	445	38.3	5.39	-1.57	4.28	871.76	0.0000
Shelbyville	Town	NB	0.56	334	27.6	7.16	311	24.9	3.44	-2.74	6.26	486.81	0.0000
Shelbyville	Town	SB	0.15	900	33.1	6.51	793	33.4	7.80	0.32	-0.92	1548.73	0.1786
Shelbyville	Transition	SB	0.70	390	39.2	6.93	325	40.0	8.50	0.77	-1.31	622.78	0.0958
Shelbyville	Control	SB	0.56	459	59.2	3.08	517	58.7	1.91	-0.45	2.72	747.03	0.0033
Cicero	Control	NB	0.52	160	54.0	5.58	181	49.6	3.31	-4.41	8.72	251.42	0.0000
Cicero	Transition	NB	0.50	114	43.0	2.25	144	39.8	1.26	-3.17	13.45	167.88	0.0000
Cicero	Town	NB	0.59	154	29.7	1.88	223	27.3	4.05	-2.40	7.72	334.68	0.0000
Cicero	Town	SB	0.52	328	29.9	2.77	569	30.4	2.75	0.44	-2.32	677.65	0.0104
Cicero	Transition	SB	0.50	384	44.7	3.88	619	43.6	2.79	-1.14	5.00	627.74	0.0000
Cicero	Control	SB	0.52	396	52.7	3.59	685	53.5	3.30	0.83	-3.78	768.50	0.0001

Table B.4 Summary of Before-and-After Results for Speed Limit Changes During Weekday Afternoon Period (4 PM to 6 PM)

Town	Zone Type	Direction	Length (miles)	Observations Before	Mean Speed Before (mph)	Std Deviation Before	Observations After	Mean Speed After (mph)	Std Deviation After	Mean Speed Difference (mph)	T-test Value	Degree of Freedom	P-value
Sheridan	Transition	EB	0.74	24	35.0	4.27	36	35.4	2.85	0.4	-0.42	36.57	0.3387
	Control	EB	0.50	699	57.2	2.13	663	57.7	2.05	0.5	-4.84	1359.56	0.0000
Galveston	Control	NB	0.57	389	53.5	3.72	216	52.5	4.17	-1.0	2.92	404.09	0.0018
	Transition	NB	0.62	361	32.3	4.68	214	31.3	2.49	-0.9	3.09	567.11	0.0010
Galveston	Transition	SB	0.62	444	34.7	4.11	313	34.3	3.98	-0.4	1.24	685.47	0.1085
	Control	SB	0.57	449	52.9	3.02	324	49.9	5.43	-3.0	8.98	466.19	0.0000
Wilkinson	Control	NB	0.67	761	55.6	2.62	885	54.1	5.78	-1.4	6.67	1272.18	0.0000
Wilkinson	Transition	NB	0.53	856	46.2	3.28	914	45.0	4.52	-1.2	6.39	1665.23	0.0000
Wilkinson	Town	NB	0.40	792	35.5	3.62	889	34.4	3.43	-1.1	6.13	1632.74	0.0000
Wilkinson	Transition	NB	0.50	830	44.2	2.27	943	42.8	3.90	-1.4	9.46	1545.23	0.0000
Wilkinson	Control	NB	0.59	631	57.5	3.24	694	57.7	1.86	0.3	-1.87	982.51	0.0306
Wilkinson	Control	SB	0.59	693	56.7	1.83	789	56.4	3.84	-0.2	1.52	1158.99	0.0643
Wilkinson	Transition	SB	0.50	662	40.1	2.79	839	39.0	3.66	-1.1	6.52	1497.16	0.0000
Wilkinson	Town	SB	0.40	871	34.6	2.40	1018	33.6	3.17	-1.0	7.41	1860.29	0.0000
Wilkinson	Transition	SB	0.53	770	45.8	2.32	897	44.6	6.33	-1.2	5.08	1165.05	0.0000
Wilkinson	Control	SB	0.67	818	54.6	2.65	916	54.5	3.11	-0.1	0.64	1727.99	0.2619
Shelbyville	Control	NB	0.56	430	58.0	3.57	607	57.7	2.65	-0.3	1.26	748.17	0.1037
Shelbyville	Transition	NB	0.70	286	38.4	3.86	363	38.8	3.80	0.4	-1.36	607.61	0.0879
Shelbyville	Town	NB	0.56	269	24.3	3.79	323	23.0	4.26	-1.3	3.91	587.45	0.0001
Shelbyville	Town	SB	0.15	862	29.9	6.06	849	30.5	8.19	0.6	-1.85	1562.55	0.0323
Shelbyville	Transition	SB	0.70	479	42.2	7.28	456	42.3	5.19	0.1	-0.19	865.32	0.4233
Shelbyville	Control	SB	0.56	515	58.9	3.51	491	60.1	2.47	1.2	-6.31	924.92	0.0000
Cicero	Control	NB	0.52	263	51.1	2.65	364	52.5	2.79	1.4	-6.21	581.54	0.0000
Cicero	Transition	NB	0.50	140	39.7	6.74	227	39.8	5.49	0.1	-0.12	250.36	0.4515
Cicero	Town	NB	0.59	219	28.0	3.40	401	28.3	2.64	0.3	-0.96	363.30	0.1676
Cicero	Town	SB	0.52	209	29.4	3.02	250	29.0	3.99	-0.3	1.06	452.65	0.1456
Cicero	Transition	SB	0.50	254	43.3	3.21	338	43.1	3.73	-0.1	0.50	579.59	0.3092
Cicero	Control	SB	0.52	324	52.5	2.86	419	52.6	2.72	0.2	-0.79	677.05	0.2156

Table B.5 Summary of Before-and-After Results for Speed Limit Changes During Weekend Period (9 AM to 5 PM)

Town	Zone Type	Direction	Length (miles)	Observations Before	Mean Speed Before (mph)	Std Deviation Before	Observations After	Mean Speed After (mph)	Std Deviation After	Mean Speed Difference (mph)	T-test Value	Degree of Freedom	P-Value
Sheridan	Transition	EB	0.74	0	—	—	26	45.5	4.59	—	—	—	—
	Control	EB	0.50	293	57.6	2.16	364	57.1	1.76	-0.5	3.14	558.99	0.0009
Galveston	Control	NB	0.57	288	54.6	2.51	265	52.1	4.33	-2.5	8.26	416.11	0.0000
	Transition	NB	0.62	269	32.8	3.46	234	33.4	4.62	0.7	-1.77	427.03	0.0386
Galveston	Transition	SB	0.62	236	33.5	3.32	242	33.4	7.50	-0.1	0.16	333.90	0.4348
	Control	SB	0.57	248	45.8	11.50	308	48.4	8.05	2.6	-2.99	426.78	0.0015
Wilkinson	Control	NB	0.67	494	56.6	2.01	345	56.2	3.50	-0.4	1.69	502.59	0.0460
Wilkinson	Transition	NB	0.53	522	46.7	3.96	374	45.8	2.97	-1.0	4.11	892.07	0.0000
Wilkinson	Town	NB	0.40	476	38.1	3.41	349	35.8	3.02	-2.2	9.98	794.32	0.0000
Wilkinson	Transition	NB	0.50	548	44.5	3.32	425	42.7	2.25	-1.8	10.07	954.59	0.0000
Wilkinson	Control	NB	0.59	362	57.3	1.53	366	57.5	3.30	0.2	-0.86	516.79	0.1962
Wilkinson	Control	SB	0.59	500	58.0	1.57	550	57.5	1.99	-0.5	4.86	1028.54	0.0000
Wilkinson	Transition	SB	0.50	366	40.5	6.21	491	38.5	2.98	-2.0	5.82	490.26	0.0000
Wilkinson	Town	SB	0.40	575	35.6	5.03	686	35.4	2.59	-0.2	0.84	823.70	0.2010
Wilkinson	Transition	SB	0.53	440	45.9	2.63	595	46.5	3.31	0.6	-3.10	1027.52	0.0010
Wilkinson	Control	SB	0.67	486	54.7	1.76	650	55.0	2.42	0.3	-2.51	1133.31	0.0061
Shelbyville	Control	NB	0.56	134	58.9	2.21	432	58.8	2.57	-0.1	0.42	254.30	0.3392
Shelbyville	Transition	NB	0.70	50	45.3	3.94	336	38.7	5.03	-6.6	10.65	74.94	0.0000
Shelbyville	Town	NB	0.56	59	24.4	5.63	345	26.9	3.66	2.4	-3.20	66.63	0.0011
Shelbyville	Town	SB	0.15	411	31.9	5.68	566	31.3	9.55	-0.6	1.29	941.36	0.0991
Shelbyville	Transition	SB	0.70	194	44.0	3.58	469	44.4	3.91	0.4	-1.39	391.70	0.0833
Shelbyville	Control	SB	0.56	224	59.5	2.09	530	60.4	3.86	0.9	-4.22	708.51	0.0000
Cicero	Control	NB	0.52	80	53.3	3.29	196	53.8	4.15	0.5	-0.98	183.53	0.1654
Cicero	Transition	NB	0.50	57	41.8	2.60	136	46.4	3.56	4.6	-10.07	142.33	0.0000
Cicero	Town	NB	0.59	76	29.7	1.14	194	29.1	3.00	-0.6	2.37	267.83	0.0093
Cicero	Town	SB	0.52	122	29.3	2.48	160	28.5	3.01	-0.7	2.28	278.26	0.0116
Cicero	Transition	SB	0.50	107	44.5	2.40	138	42.7	2.55	-1.9	5.89	233.95	0.0000
Cicero	Control	SB	0.52	155	52.3	1.58	204	52.6	1.98	0.3	-1.76	356.30	0.0397

APPENDIX C. MANUAL OF ESTIMATING THE SPEED REDUCTION BENEFITS ON ARTERIAL ROADS IN SMALL INDIANA COMMUNITIES

The manual of selecting and justifying speed reduction measures on arterial highways passing through small Indiana communities is organized in three parts:

1. First, speed reduction measures for reducing driver speeds are proposed.
2. Then, a four-step procedure for predicting the safety benefits produced by the applied speed reduction measures is described.
3. Finally, example calculations are presented to demonstrate the four-step procedure.

C.1 Speed Reduction Measures

Promising speed reduction measures are briefly introduced in this part of the manual.

Figure C.1 shows promising speed control measures that are suitable for arterial highways passing through small cities and towns. These measures include a posted speed limit reduction as the primary means and additional measures that reinforce the posted speed limit. The speed reinforcement measures are grouped in four categories: (1) signage, (2) pavement markings, (3) enforcement, and (4) geometry. Particular consideration was given to the measures derived from the current study as well as those implemented in Midwestern states with similar conditions to Indiana. Promising measures from other regions, including overseas countries, are also included. The speed reductions expected after implementation of these measures are provided together with examples and the sources of information.

Speed feedback sign (Hallmark et al., 2013, 2007; Knapp & Giese, 2001) (Photo-Bagdade et al., 2012).

Speed limit with radar-activated LED lights (Hallmark et al., 2013).

Transverse speed bars (Hallmark et al., 2013).

Colored entrance treatment (Hallmark et al., 2007).

Speed limit pavement marking sign (Chitturi et al., 2017).

Road diet—reduce lanes from 4 to 3 (Corkle et al., 2001; FHWA, 2014; Knapp & Giese, 2001).

Chevrons prompting a speed limit (Corkle et al., 2001; Hallmark et al., 2007).

Rumble strips at high-speed intersections (FHWA, 2014; Ray et al., 2008).

Choker/bulb-out (Ewing, 1999; FHWA, 2014) (Photo-City of Alexandria, VA).

Figure C.1 Examples of promising speed control measures suitable for arterial highways passing through small communities.

Descriptions about the implementation of the speed reduction measures are provided below.

C.1.1 Speed feedback signs

Speed feedback signs provide an effective means of reinforcing the speed limit and slowing driver speeds, especially at transition zones (community entrances, beginning of school zones, or areas with considerable vulnerable road user presence) (Bagdade et al., 2012). These solar-powered signs use radar or loop detectors to measure the speed of approaching vehicles, which is relayed to speeding drivers via a changing "YOUR SPEED" sign display (Hallmark et al., 2013). A mean speed reduction of 3 mph applies for arterials in small communities.

C.1.2 Speed limit signs with radar-activated LED lights

Speed limit signs with radar-activated LED lights are a viable alternative tested for lower-volume roads (less than 2,500 vehicles per days). The LED lights are located along the edges of the sign and are solar-powered, flashing continuously as speeding drivers approach (Hallmark et al., 2013). A mean speed reduction of 3 mph applies.

C.1.3 Transverse speed bars

Transverse speed bars, a gateway treatment, are thermoplastic pavement markings consisting of three horizontally-placed bars that repeat at an interval (10–12 feet) for approximately 100 feet (Hallmark et al., 2013). Sometimes, the distance between consecutive bars is decreased and the bars are made thinner as vehicles progress across the treatment, thus giving drivers the illusion that they are moving faster than they actually are. Although the treatment has been found to have a marginal effectiveness in reducing the mean speed of drivers (~1 mph), it has shown the most promising results in reducing the proportion of vehicles surpassing the posted speed limit.

C.1.4 Colored entrance treatments and speed limit pavement marking signs

Colored entrance treatments (Hallmark et al., 2013) and speed limit pavement marking signs (Chitturi et al., 2017) are pavement markings indicating a reduced speed limit. These treatments have been studied for low- and medium- volume roads and have been found to reduce mean speeds by 1–2 mph. Colored entrance treatments use two rectangles with red thermoplastic pavement coloring containing white speed limit lettering to alert drivers and reinforce a new speed limit zone entering a town (Hallmark et al., 2013). The treatment is sometimes accompanied by triangular “dragon’s teeth” markings for around 100 feet upstream from the treatment. On the other hand, speed limit pavement markings utilize paint, thermoplastic materials, or tape to mark on the pavement a symbolized, elongated version of an actual speed limit sign (Chitturi et al., 2017).

C.1.5 Road diets

Road diets are an effective speed reduction measure (3-mph mean speed reduction) that involve the “reallocation” of space on undivided roadways with medium- to high-volumes (FHWA, 2014). Typically, four through lanes are converted to two through lanes, a center two-way left-turn lane, and biking lanes and/or parking. The reduced number of lanes for through-passing drivers coupled with the additional activities surrounding the road may increase driver risk perception and encourage them to drive slower while passing through the town.

C.1.6 Converging chevrons

Converging chevron arrows that prompt a reduced speed limit have been found effective in reducing driver speeds on the edges of and within communities (Corkle et al., 2001; Hallmark et al., 2007). The chevrons are installed over a distance of approximately 200 feet. For some installations, the spacing between markings is reduced and the width of the chevrons are made narrower to give drivers the appearance that they are moving faster than they actually are (Corkle et al., 2001). Although the effect on the mean speed is low (~2 mph), converging chevrons have been found to be particularly impactful in reducing speeds for fast-moving drivers (85th-percentile speed and the highest recorded speeds) (Corkle et al., 2001; Hallmark et al., 2007). To maintain their effectiveness, converging chevrons must be painted regularly as the markings tend to wear off over time.

C.1.7 Rumble strips at high-speed intersections

In communities where there are major intersections on the edges of the town, transverse rumble strips assist in alerting and slowing drivers (~1 mph reduction in 85th-percentile speed) who are approaching an intersection (Ray et al., 2008). To reduce the noise-related impact as vehicles pass across them, transverse rumble strips are most appropriate for spots located away from residential developments.

C.1.8 Choker/bulb-out

Chokers and bulb-outs extend the curb to narrow the roadway at midblock and intersection locations, respectively, resulting in a 4-mph reduction in the 85th-percentile speed (Ewing, 1999). These countermeasures are appropriate for reducing driver speeds within the town.

C.1.9 Other measures

Reductions in the lane width and shoulder width (evaluated in the current study) reduce the mean speed of drivers by 0.15 mph and 0.21 mph, respectively, for every 1-foot reduction in width. These treatments may be appropriate during roadway realignments or in projects that focus on reallocating the space available for motorists passing through the community.

Another measure evaluated in this study consists of adding advance speed limit signage (Reduced Speed Limit Ahead signs) and extending the town speed limit zone through the transition zone to the rural speed limit zone. A mean speed reduction of 1 mph applies to this measure.

A more promising measure for long road segments than multiple spot speed-reduction treatments is point-to-point speed limit enforcement (Montella et al., 2015). Vehicles are automatically identified at both ends of the segment with enforced speed. A driver is penalized if the average travel speed along the segment exceeds the speed limit. The measure has shown promising results, with an approximately 6-mph reduction in the mean speed observed. The measure may be a viable alternative to local speed enforcement on arterial roads crossing small towns if major traffic interruptions are not present. Otherwise, the spots with major interruptions must be excluded from the section controlled with this measure by installing additional vehicle identifiers upstream and downstream of the traffic interruption spots.

Although the calculations in this manual do not support its inclusion as a speed reduction measure, roundabouts are sometimes built on arterials to facilitate the high-speed to low-speed transition between rural and urban areas. Studies have found the 85th-percentile speed to be significantly lower (~20 mph) in the vicinity of the roundabout (FHWA, 2014; Ritchie & Lenters, 2005).

C.2 Estimating the Safety Benefits of Speed Reduction

The following section discusses a four-step method which may be used to evaluate the safety-related impact of the measures for speed reduction. The method presented in this section can be implemented with a companion speed management spreadsheet. The user inputs the road segment features and local conditions around the segment to compute the safety benefits of the proposed speed reduction measures. The four steps are as follows:

Step 1: Predict the annual crash frequency in current conditions for each crash type and severity.
Step 2: Select the speed-control measure(s) and calculate the speed reduction.
Step 3: Predict the crash reduction for each crash type and severity.
Step 4: Calculate the safety benefit, which is the cost of crashes saved annually. The safety benefit can be split into benefits for the local and non-local (out-of-town) population.

Each of these steps is discussed in further detail below.

Step 1: Predict the annual crash frequency in current conditions for each crash type and severity.

The expected annual frequencies of crashes are determined using safety performance functions (SPFs) for vulnerable road user (VRU) and motorized road user (MRU) crashes (summarized in Table C.6). These equations require inputs such as AADT, segment length, number of commercial driveways, and binary values (1 or 0) that represent the presence of certain features (yes or no, respectively). The models underlying these SPFs are shown in Appendix A.

To ease the calculations, the SPFs in Table C.6 are a simplified form of the prediction models shown in Chapter 5 of the research report. Inputs difficult to obtain but less important for accuracy were eliminated and the equations re-calibrated. These reduced SPFs well estimate the average number of annual crashes on roads under current conditions represented with the input values. They may be less accurate for predicting on roads for future conditions represented with changed input values. Nevertheless, the effect of speed reduction on crashes is properly accounted for in Step 3.

Table C.6 Safety Performance Functions for Arterial Highways Passing Through Small Communities: Simplified Form

Crash Severity	**Vulnerable Road User Crashes**
Minor	$Annual\ crashes = 7.436 * 10^{-9} * \exp(-0.011 * SL + 0.845 * lnAADT + 0.894 * \ln(5280 * Length) + 0.019 * \frac{Comm}{Length} - 0.493 * M + 1.067 * P + 0.009 * Busy)$
Major/Fatal	$Annual\ crashes = 3.392 * 10^{-9} * \exp(0.005 * SL + 0.592 * lnAADT + 1.068 * \ln(5280 * Length) + 0.874 * P + 0.006 * Busy + 0.599 * CS + 0.827 * CNS)$
Crash Severity	**Motorized Road User Crashes**
PDO	$Annual\ crashes = 1.460 * 10^{-6} * \exp(-0.013 * SL + 0.806 * lnAADT + 0.949 * \ln(5280 * Length) + 0.014 * \frac{Comm}{Length} - 0.353 * MD + 0.540 * P + 0.006 * Busy)$
Minor	$Annual\ crashes = 6.588 * 10^{-7} * \exp(-0.003 * SL + 0.947 * lnAADT + 0.617 * \ln(5280 * Length) + 0.011 * \frac{Comm}{Length} - 0.244 * MD + 0.343 * P + 0.005 * Busy)$
Major/Fatal	$Annual\ crashes = 7.912 * 10^{-7} * \exp(0.012 * SL + 0.665 * lnAADT + 0.755 * \ln(5280 * Length) + 0.510 * MU + 0.252 * P + 0.006 * Busy)$

where: SL = Speed limit (mph),

$lnAADT$ = Natural log of annual average daily traffic in vehicles per day (vpd),

$Length$ = Segment length (miles),

$Comm$ = Number of commercial (business) driveways,

MD = Multilane divided highway indicator (1 if true, 0 otherwise),

MU = Multilane undivided highway indicator (1 if true, 0 otherwise),

M = Multilane (undivided or divided) highway indicator (1 if true, 0 otherwise),
P = Considerable paved area surrounding the road (1 if true, 0 otherwise),
$Busy$ = Business intensity surrounding road,
CS = Segment has curb and sidewalk (1 if true, 0 otherwise),
CNS = Segment has curb but no sidewalk (1 if true, 0 otherwise).

Highway segments not classified as multilane (divided and/or undivided) are considered to be two-lane undivided.

A considerable paved area surrounding the road is indicated if more than 15% of the land area within three blocks (1,200 feet) of the road is paved. The presence of considerable paved surfaces represents a proxy for greater land use and pedestrian activities.

The business intensity surrounding the road ($Busy$) is split into three categories based on percentiles of the business density within three blocks (1,200 feet) of the road. Low represents the lower one-third (0 to 8.183 businesses/mile), Medium the middle one-third (8.184 to 24.553 businesses/mile), and High the upper one-third (24.554 businesses/mile and greater). Within each category, the following average values of the business density are used in the SPFs above: Low (3.815 businesses/mile), Medium (15.796 businesses/mile), and High (59.465 businesses/mile). These values are automatically input in the speed management spreadsheet by entering “1” (Low), “2” (Medium), or “3” (High).

Step 2: Select the speed-control measure(s) and calculate the speed reduction.

This step involves selecting a suitable speed reduction measure(s) and calculating the overall speed reduction using Equation C.1. If multiple measures are implemented together, then the total speed effect equals the effect of the posted speed limit change (if applicable) plus the strongest effect among all the measures applied to reinforce the speed limit. Although this calculation does not support the application of multiple speed limit reinforcement measures, the use of multiple measures is encouraged to increase the prospect of achieving the desired speed reduction.

$$\textit{Overall Speed Reduction} = \textit{Effect of Speed Limit Reduction} + \textit{Strongest Effect Among Speed Limit Reinforcing Measures} \quad \text{(Eq. C.1)}$$

The mean speed reduction associated with the posted speed limit reductions and with the speed limit reinforcement measures are shown in Table C.7 and Table C.8, respectively.

Table C.7 Mean Speed Reduction with Reducing Speed Limits

Traffic	Posted Speed Limit Reduction (mph)	Mean Speed Reduction (mph)
Uninterrupted	5	2.7
	10	5.4
	15	8.1
	20	10.8
Interrupted	5	2.3
	10	4.6
	15	6.8
	20	9.1

Table C.8 Speed Limit Reinforcement Measures Suitable for Arterial Highways in Small Communities

Category	Speed Limit Reinforcement	Mean Speed Reduction (mph)	Source
Signage	Speed feedback sign	3	Hallmark et al., 2007, 2013; Sandberg et al., 2006
	Speed limit sign with radar-activated LED lights	3	Hallmark et al., 2013
	Town speed limit extended into transition zone + Add advance speed limit signage	1	Current study
Pavement Markings	Transverse speed bars	1	Hallmark et al., 2013
	Colored entrance treatment	1	Hallmark et al., 2013
	Speed limit pavement marking sign	2	Chitturi et al., 2017

Category	Speed Limit Reinforcement	Mean Speed Reduction (mph)	Source
	Road diet (restripe road to reduce lanes from 4 to 3)	3	Corkle et al., 2001; Knapp & Giese, 2001; FHWA, 2014
	Converging chevrons prompting a speed limit	2	Corkle et al., 2001; Hallmark et al., 2007
	Rumble strips (high-speed intersection)	1[a]	Ray et al., 2008; FHWA, 2014
Enforcement	Point-to-point speed enforcement	6	Montella et al., 2015
Geometry	Reduce lane width by 1 foot	0.15[b]	Current study
	Reduce shoulder width by 1 foot	0.21[b]	Current study
	Choker/bulb-out	4[a]	Ewing, 1999; FHWA, 2014

[a] Indicates that the speed change listed is for the 85th-percentile speed;

[b] Multiply the value by the width reduction expressed in feet.

The speed limit reinforcement measures in Table C.8 present the mean speed reductions expected at and near the spot where the measure was applied. Therefore, to maintain a consistent speed reduction along a road segment, the measure may need to be repeated at sufficient frequency.

Step 3: Predict the crash reduction for each crash type and severity.

The crash modification factors (CMFs) for speed reduction for the different crash types and severities are presented in Table C.9. CMFs are presented for average speed reductions on uninterrupted and interrupted roads. Interruptions may include signalized intersections, all-way stop-controlled intersections, major railroad crossings, etc. The estimation of these CMFs is described in the research report.

After predicting the annual number of crashes for current conditions, identifying the speed reduction measure(s), and finding the corresponding CMFs for speed reduction, the expected crash reductions (R) for each crash type/severity are found using Equation C.2:

$$R = B \cdot (1 - CMF) \qquad \text{(Eq. C.2)}$$

where: B = Number of VRU or MRU crashes calculated with an SPF selected from

Table C.6 for certain severity (PDO, minor injury, or major/fatal injury), before reducing the speed,

CMF = crash modification factor representing the effect of reducing speed selected from Table C.9 for the corresponding crash type, traffic type, and injury severity.

Table C.9 Crash Modification Factors Representing the Speed Reduction Safety Effects

	Uninterrupted Road					Interrupted Road				
	VRU[a] Crashes			MRU[b] Crashes		VRU Crashes			MRU Crashes	
Speed Reduction (mph)	Minor Injury	Major Injury or Fatality	PDO[c]	Minor Injury	Major Injury or Fatality	Minor Injury	Major Injury or Fatality	PDO	Minor Injury	Major Injury or Fatality
1	0.95	0.92	0.97	0.94	0.94	0.95	0.91	0.96	0.93	0.92
2	0.91	0.85	0.93	0.89	0.88	0.90	0.82	0.92	0.87	0.86
3	0.87	0.78	0.90	0.84	0.82	0.85	0.75	0.89	0.81	0.79
4	0.83	0.72	0.87	0.79	0.77	0.80	0.68	0.85	0.76	0.73
5	0.79	0.67	0.84	0.75	0.72	0.76	0.62	0.82	0.71	0.68
6	0.76	0.61	0.82	0.71	0.67	0.72	0.56	0.79	0.66	0.63
7	0.72	0.57	0.79	0.67	0.63	0.68	0.51	0.76	0.62	0.58
8	0.69	0.52	0.76	0.63	0.59	0.65	0.46	0.73	0.58	0.54
9	0.66	0.48	0.74	0.59	0.55	0.61	0.42	0.70	0.54	0.50
10	0.63	0.44	0.71	0.56	0.52	0.58	0.38	0.67	0.50	0.46

[a] VRU = Vulnerable Road Users,

[b] MRU = Motorized Road Users,

[c] PDO = Property Damage Only

Step 4: Calculate the safety benefit, which is the cost of crashes saved annually.

The safety benefit (S) is the product of the crash reduction R predicted in Step 3 and the corresponding average unit crash cost (C) taken from Table C.10 (see Equation C.3):

$$S = R \cdot C \qquad \text{(Eq. C.3)}$$

This product is calculated for each type of traffic and crash type/severity. The obtained benefits are summed up to obtain the total annual benefit.

Table C.10 Average Unit Crash Costs for Different Crash Types and Severities on Arterial Highways Passing Through Small Communities (2019 dollars)

Crash Type/Severity	**Value**
VRU minor injury	299,400
VRU major injury or fatality	2,072,220
MRU property damage only	39,960
MRU minor injury	363,410
MRU major injury or fatality	1,689,270

The benefits obtained in Step 4 can be further split into the benefits for the local and non-local (out-of-town) population. Equations C.4 and C.5 are used for calculating the proportion of the safety benefit for local users for VRU and MRU crashes, respectively. The models underlying the equations are presented in Chapter 6.

VRU crashes:

$$P_{Local\ VRU} = \frac{1}{1+\exp[-1.7*(1.062+0.312*lnPop-0.374*lnAADT)]} \qquad \text{(Eq. C.4)}$$

MRU crashes:

$$P_{Local\ MRU} =$$

$$\frac{1}{1+\exp\left[-1.7*\left(-0.492+0.249*lnPop \quad .216*lnAADT+0.019*\frac{Unsig}{Length}+0.008*\frac{Comm}{Length}\right)\right]} \qquad \text{(Eq. C.5)}$$

where: $P_{Local\ VRU}$ and $P_{Local\ MRU}$ is the proportion of the safety benefit for local users for VRU and MRU crashes, respectively,

$lnPop$ = Natural log of the city/town population,

$lnAADT$ = Natural log of annual average daily traffic in vehicles per day (vpd),

$Length$ = Segment length (miles),

$Unsig$ = Number of unsignalized intersections,

$Comm$ = Number of commercial (business) driveways.

The proportion of the safety benefit for out-of-town users is equal to 1 – proportion of the safety benefit for local users.

The proportions are multiplied by the safety benefit at each crash severity level to obtain the benefit for local and out-of-town users at that severity level.

C.3 Example Calculation of the Speed Reduction Benefit

To demonstrate the safety benefit calculations, segments with the average speed exceeding 40 mph are analyzed. The example is the 0.825-mile long segment of undivided two-lane US 224 entering the town of Decatur, Indiana. The characteristics of this uninterrupted segment are summarized in Table C.11. The objective is to determine the safety benefits of a 5-mph reduction in average speed.

Table C.11 Characteristics of Example Road Segment in Decatur, Indiana

Feature	**Value**
Average speed (mph)	43.7
Speed limit (mph)	45
AADT (vpd)	6,850
Segment length (miles)	0.825
Number of unsignalized intersections	3
Number of commercial (business) driveways	2
Considerable paved area surrounding road? (yes/no)	Yes
Business intensity surrounding road (low/medium/high)	Low
Segment has curb and sidewalk? (yes/no)	No
Segment has curb but no sidewalk? (yes/no)	No
Town population (2016)	9,524

Note: The values calculated in the following example may vary slightly due to rounding.

Step 1: Predict the annual crash frequency in current conditions for each crash type and severity.

Using the SPFs in Table C.6, the expected annual crash frequencies under current conditions are calculated. The equations and input values used in these equations are presented below. In these equations, the 1 stands for *yes* and 0 for *no* in binary indicators. A “Low” business intensity of 3.815 businesses/mile (within three blocks of the road) is adopted:

VRU minor injury

$$\begin{aligned}&\mathit{Annual\ crashes}\\&= 7.436 * 10^{-9} * \exp(-0.011 * SL + 0.845 * lnAADT + 0.894 * \ln(5280 * Length)\\&+ 0.019 * \frac{Comm}{Length} - 0.493 * M + 1.067 * P + 0.009 * Busy)\end{aligned}$$

$$\begin{aligned}&\mathit{Annual\ crashes}\\&= 7.436 * 10^{-9} * \exp(-0.011 * (45) + 0.845 * \ln(6850) + 0.894 * \ln(4356)\\&+ 0.019 * \left(\frac{2}{0.825}\right) - 0.493 * (0) + 1.067 * (1) + 0.009 * (3.815))\\&= \mathbf{0.045\ crashes/year}\end{aligned}$$

VRU major injury/fatality

$$\begin{aligned}&\mathit{Annual\ crashes}\\&= 3.392 * 10^{-9} * \exp(0.005 * SL + 0.592 * lnAADT + 1.068 * \ln(5280 * Length)\\&+ 0.874 * P + 0.006 * Busy + 0.599 * CS + 0.827 * CNS)\end{aligned}$$

$$\begin{aligned}&\mathit{Annual\ crashes}\\&= 3.392 * 10^{-9} * \exp(0.005 * (45) + 0.592 * \ln(6850) + 1.068 * \ln(4356) + 0.874\\&* (1) + 0.006 * (3.815) + 0.599 * (0) + 0.827 * (0)) = \mathbf{0.015\ crashes/year}\end{aligned}$$

MRU PDO

$$\begin{aligned}&\mathit{Annual\ crashes}\\&= 1.460 * 10^{-6} * \exp(-0.013 * SL + 0.806 * lnAADT + 0.949 * \ln(5280 * Length)\\&+ 0.014 * \frac{Comm}{Length} - 0.353 * MD + 0.540 * P + 0.006 * Busy)\end{aligned}$$

$$\begin{aligned}&\mathit{Annual\ crashes}\\&= 1.460 * 10^{-6} * \exp(-0.013 * (45) + 0.806 * \ln(6850) + 0.949 * \ln(4356)\\&+ 0.014 * \left(\frac{2}{0.825}\right) - 0.353 * (0) + 0.540 * (1) + 0.006 * (3.815))\\&= \mathbf{5.183\ crashes/year}\end{aligned}$$

MRU minor injury

$$Annual\ crashes = 6.588 * 10^{-7} * \exp(-0.003 * SL + 0.947 * lnAADT + 0.617 * \ln(5280 * Length) + 0.011 * \frac{Comm}{Length} - 0.244 * MD + 0.343 * P + 0.005 * Busy)$$

$$Annual\ crashes = 6.588 * 10^{-7} * \exp(-0.003 * (45) + 0.947 * \ln(6850) + 0.617 * \ln(4356) + 0.011 * \left(\frac{2}{0.825}\right) - 0.244 * (0) + 0.343 * (1) + 0.005 * (3.815)) = \mathbf{0.641\ crashes/year}$$

MRU major injury/fatality

$$Annual\ crashes = 7.912 * 10^{-7} * \exp(0.012 * SL + 0.665 * lnAADT + 0.755 * \ln(5280 * Length) + 0.510 * MU + 0.252 * P + 0.006 * Busy)$$

$$Annual\ crashes = 7.912 * 10^{-7} * \exp(0.012 * (45) + 0.665 * \ln(6850) + 0.755 * \ln(4356) + 0.510 * (0) + 0.252 * (1) + 0.006 * (3.815)) = \mathbf{0.355\ crashes/year}$$

Step 2: Select the speed-control measure(s) and calculate the speed reduction.

The measure for a posted speed limit reduction of 10 mph in uninterrupted traffic conditions is selected from

Table C.7. For simplicity, the corresponding reduction in the average speed achieved via this measure is assumed as 5 mph.

Step 3: Predict the crash reduction for each crash type and severity.

From Table C.9, the relevant CMFs for a 5-mph reduction in the average speed on an uninterrupted road are as follows:

VRU minor injury: **0.79**

VRU major injury/fatality: **0.67**

MRU PDO: **0.84**

MRU minor injury: **0.75**

MRU major injury/fatality: **0.72**

The expected crash reduction (R) for each crash type/severity are calculated with Equation C.2:

VRU minor injury

$R = B \cdot (1 - CMF) = 0.045\ \frac{\text{crashes}}{\text{year}} \cdot (1 - 0.79) = \mathbf{0.0094}\ \frac{\textbf{crashes}}{\textbf{year}}$

VRU major injury/fatality:

$R = 0.015\ \frac{\text{crashes}}{\text{year}} \cdot (1 - 0.67) = \mathbf{0.0049} \frac{\boldsymbol{crashes}}{\boldsymbol{year}}$

MRU PDO

$R = 5.183\ \frac{\text{crashes}}{\text{year}} \cdot (1 - 0.84) = \mathbf{0.829}\ \frac{\textbf{crashes}}{\textbf{year}}$

MRU minor injury

$R = 0.641 \frac{\text{crashes}}{\text{year}} \cdot (1 - 0.75) = \mathbf{0.160}\ \frac{\textbf{crashes}}{\textbf{year}}$

MRU major injury/fatality:

$R = 0.355 \frac{\text{crashes}}{\text{year}} \cdot (1 - 0.72) = \mathbf{0.099}\ \frac{\textbf{crashes}}{\textbf{year}}$

Step 4: Calculate the safety benefit, which is the cost of crashes saved annually.

Using Equation C.3, the expected crash reduction calculated in step 3 is multiplied by the corresponding crash cost from Table C.10 to obtain the safety benefit (S) for each crash type/severity. The results are summarized in Table C.12:

VRU minor injury

$S = R \cdot C = 0.0094 * \$299{,}400 = \$\mathbf{2,800}$

VRU major injury/fatality:

$S = 0.0049 * \$2{,}072{,}220 = \$\mathbf{10,230}$ **MRU PDO**

$S = 0.829 * \$39{,}960 = \$\mathbf{33,140}$

MRU minor injury:

$S = 0.160 * \$363{,}410 = \$\mathbf{58,210}$

MRU major injury/fatality

$S = 0.099 * \$1{,}689{,}270 = \$\mathbf{167,990}$

Hence, the total benefit of the 5-mph reduction in average speed on the example segment is $\$2{,}800 + \$10{,}230 + \$33{,}140 + \$58{,}210 + \$167{,}990 = \$\mathbf{272,370.}$

The proportion of the benefit for local road users is computed using Equations C.4 and C.5 for VRU and MRU crashes, respectively:

VRU crashes

$$P_{Local\,VRU} = \frac{1}{1 + \exp[-1.7 * (1.062 + 0.312 * lnPop - 0.374 * lnAADT)]}$$

$$= \frac{1}{1 + \exp[-1.7 * (1.062 + 0.312 * \ln{(9524)} - 0.374 * \ln{(6850)})]} = \mathbf{0.741}$$

Therefore, the proportion for out-of-town users ($P_{Out\,VRU}$) is $1 - 0.741 = \mathbf{0.259}$.

MRU crashes

$$P_{Local\,MRU} = \frac{1}{1 + \exp\left[-1.7\left(-0.492 + 0.249 * lnPop - 0.216 * lnAADT + 0.019 * \frac{Unsig}{Length} + 0.008 * \frac{Comm}{Length}\right)\right]}$$

$$= \frac{1}{1 + \exp\left[-1.7\left(-0.492 + 0.249 * \ln(9524) - 0.216 * \ln(6850) + 0.019 * \left(\frac{3}{0.825}\right) + 0.008 * \left(\frac{2}{0.825}\right)\right)\right]}$$

$$= \mathbf{0.486}$$

Therefore, the proportion for out-of-town users ($P_{Out\,MRU}$) is $1 - 0.487 = \mathbf{0.514}$.

Multiplying the proportions by the safety benefits for VRU minor injury crashes, for instance, yields benefits of $0.741(\$2{,}800) = \$\mathbf{2,070}$ and $0.259(\$2{,}800) = \$\mathbf{730}$, for local and out-of-town users, respectively. The complete breakdown of benefits for local and out-of-town users are shown in Table C.12.

Table C.12 Potential Safety Benefits of Reducing Average Speed by 5 mph for Example Segment

Policy	VRU			MRU	
	Minor Injury	Major Injury/ Fatality	PDO	Minor Injury	Major Injury/ Fatality
Annual expected crashes (current conditions)	0.045	0.015	5.183	0.641	0.355
Annual expected crashes (after 5-mph speed reduction)	0.035	0.010	4.353	0.481	0.256
Annual crashes saved by 5-mph speed reduction	0.0094	0.0049	0.829	0.160	0.099
Benefit of 5-mph speed reduction (2019 dollars)	$2,800	$10,230	$33,140	$58,210	$167,990
By types of users involved:					
Benefit for local users	$2,070	$7,580	$16,100	$28,280	$81,610
Benefit for out-of-town users	$730	$2,650	$17,040	$29,930	$86,380

Reduction in Benefits

Reduction in benefits consists of the value of lost time. In the case of the example segment considered above, a 5-mph reduction in average speed results in the following value of lost time:

$$Value\ of\ lost\ time = \left(\frac{1}{s_2} - \frac{1}{s_1}\right) * Length * AADT * 365 * O * C$$

$$Value\ of\ lost\ time = \left(\frac{1}{38.7} - \frac{1}{43.7}\right) * 0.825 * 6850 * 365 * 1.67 * 15 = \$152{,}760/year$$

APPENDICES REFERENCES

Bagdade, J., Nabors, D., McGee, H., Miller, R., & Retting, R. (2012, November). *Speed management: A manual for local rural road owners* (Report No. FHWA-SA-12-027). U.S. Department of Transportation Federal Highway Administration. https://safety.fhwa.dot.gov/local_rural/training/fhwasa010413spmgmt/

Chitturi, M. V., Alsghan, I., Santiago, K. R., & Noyce, D. A. (2017). Field evaluation of elongated pavement marking signs. *Transportation Research Record: Journal of the Transportation Research Board*, *2624*(1), 28–37. https://doi.org/10.3141/2624-04

Corkle, J. Giese, J. L., & Marti, M. M. (2001, October). *Investigating the effectiveness of traffic calming strategies on driver behavior, traffic flow, and speed* (Report No. MN/RC –2002-02). Minnesota Local Road Research Board (LRRB), Minnesota Department of Transportation. https://www.lrrb.org/pdf/200202.pdf

Ewing, R. (1999, August). Traffic calming: State of the practice. *Institute of Transportation Engineers*.

FHWA. (2014, July). *Engineering speed management countermeasures: A Desktop reference of potential effectiveness in reducing speed.* United States Department of Transportation. Federal Highway Administration. https://safety.fhwa.dot.gov/speedmgt/ref_mats/eng_count/2014/reducing_speed.cfm

Hallmark, S. L., Knickerbocker, S., & Hawkins, N. (2013, April). *Evaluation of low cost traffic calming for rural communities: Phase II* (IHRB Project TR-630). Center for Transportation Research and Education. https://rosap.ntl.bts.gov/view/dot/26102

Hallmark, S. L., Peterson, E., Fitzsimmons, E. J., Hawkins, N. R., Resler, J., & Welch, T. (2007). *Evaluation of gateway and low-cost traffic-calming treatments for major routes in small rural communities* (CTRE Project 06-185). Retrieved from https://lib.dr.iastate.edu/intrans_reports/30/

Knapp, K., & Giese, K. (2001, April). *Guidelines for the conversion of urban four-lane undivided roadways to three-lane two-way left-turn lane facilities* (CTRE Management Project 99-54). Center for Transportation Research and Education. https://rosap.ntl.bts.gov/view/dot/14499

Montella, A., Punzo, V., Chiaradonna, S., Mauriello, F., & Montanino, M. (2015). Point-to-point speed enforcement systems: Speed limits design criteria and analysis of drivers' compliance. *Transportation Research Part C: Emerging Technologies*, *53*, 1–18. https://doi.org/10.1016/j.trc.2015.01.025

Ray, B., Kittelson, W., Knudsen, J., Nevers, B., Ryus, P., Sylvester, K., Potts, I., Harwood, D., Gilmore, D., Torbic, D., Hanscom, F., McGill, J., & Stewart, D. (2008). *Guidelines for selection of speed reduction treatments at high-speed intersections* (NCHRP report 613). https://nacto.org/docs/usdg/nchrp613_ray.pdf

Ritchie, S., & Lenters, M. (2005, May 10). *High speed approaches at roundabouts report*. Roundabouts & Traffic Engineering. http://onlinepubs.trb.org/Onlinepubs/circulars/ec083/12_Ritchiepaper.pdf

Sandberg, W., Schoenecker, T., Sebastian, K., & Soler, D. (2006). Long-term effectiveness of dynamic speed monitoring displays (DISMAYED) for speed management at speed limit transitions. In *2006 ITE Annual Meeting and Exhibit Compendium of Technical Papers Institute of Transportation Engineers (ITE)*. https://trid.trb.org/view/793577

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

About This Report

An open access version of this publication is available online. See the URL in the citation below.

Tarko, A. P., Hall, T., Lizarazo, C., & España-Monedero, F. (2020). *Speed management in small cities and towns—Guidelines for Indiana* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2020/10). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317122