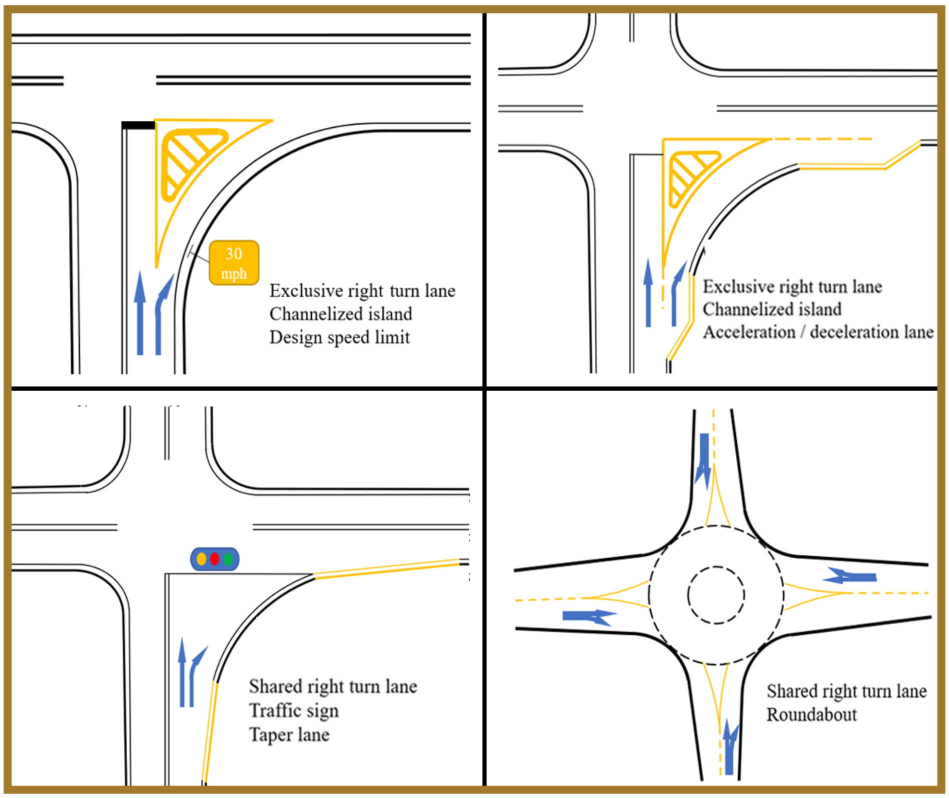
JOINT TRANSPORTATION RESEARCH PROGRAM
INDIANA DEPARTMENT OF TRANSPORTATION AND PURDUE UNIVERSITY

Performance of Right-Turn Lane Designs at Intersections



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16. Abstract

Right-turn lane (RTL) crashes are among the most key contributors to intersection crashes in the US. Based on their design, traffic volume, and location, different right-turn lanes have varying levels of crash risk. Therefore, engineers and researchers have been looking for alternative ways to improve the safety and operation of right-turn traffic. This study investigated the traffic safety performance of the RTL in Indiana based on multiple sources, including official crash reports, official databases, and field studies. To understand the RTL crashes' influencing factors, we introduced a random effect negative binomial model and log-linear model to estimate the impact of influencing factors on crash frequency and severity, and we adopted the robustness test to verify the reliability of estimations. In addition to the environmental factors, spatial and temporal factors, intersection, and RTL geometric factors, we propose the compound factors among the RTL geometrics and intersection characteristics to address the endogeneity issues, which is rarely addressed in accident-related research literature. Last, we developed a case study with the help of the Indiana Department of Transportation (INDOT). The empirical analyses indicated that RTL crash frequency and severity is mainly influenced by turn radius, traffic control, and other intersection-related factors such as right-turn type and speed limit, channelized type and AADT, and acceleration lane and AADT. The effects of these factors were different among counties and right-turn lane roadway types.

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EXECUTIVE SUMMARY

Introduction

Intersection-related crashes are one of the main contributors of total crashes. In 2014, intersection-related crashes contributed to 47% of all crashes and 28% of fatal crashes in the US, as reported by the National Highway Traffic Safety Administration (NHTSA, 2014). Within Indiana, intersection-related crashes contributed to 31% of total crashes and 24% of fatal crashes (INDOT, 2014). In addition, intersection-related crashes caused $120 billion in economic costs and $371 billion in comprehensive costs, accounting for 50% of all economic costs and 44% of all societal harm from motor vehicle crashes (Blincoe et al., 2015).

Although intersection-related crashes are generally decreasing, the decrease is modest. Different intersections, based on their design, traffic volume, and location, have varying levels of crash risk. Therefore, engineers and researchers have been looking for alternative ways to improve the safety and operation of intersections. Researchers commonly focus on examining the relationships of the intersections' geometry designs and the types of crashes, but a recent concern is safety impacts at intersections with right-turn lanes. Right-turn lanes provide space for deceleration and storage for right-turning vehicles. Since right-turn lanes separate turning movements from through traffic, they have been known to improve safety and operations at intersections. Depending on the traffic control methods and design elements used, right-turn lanes can be designed in different forms; however, each form has advantages and disadvantages. Constructing appropriate right-turn lanes will improve traffic safety, increase travel speed, reduce delay, and reduce congestion. Therefore, to figure out the design configurations that result in higher crash rates, there is a need to evaluate the safety and operation of right-turn lanes.

Findings

- The installment of the exclusive RTL can reduce the risk of crashes compared to the shared RTL; however, a high-speed limit increases the risk ratio. The compound factor of these two variables significantly contributes to right-turn related crashes. The exclusive RTL with a speed limit over 35 mph has 16% fewer crashes than the shared RTL with a speed limit over 35 mph. The exclusive RTL with a speed limit below or equal to 35 mph has 45% fewer crashes than the shared RTL with a speed limit below or equal to 35 mph.
- A high design speed limit increases the number of crashes, compared to a low design speed limit. The effects of the design speed limit are different for roadway class and county class.
- Exclusive RTLs reduce crashes, and the effects of the exclusive RTL depend on the AADT of roadway class and county class.
- A 1% increase in the RTL turn radius leads to a 0.22% increase in crash frequency. The effects of the RTL turn radius are different for roadway class and county class.
- RTLs having "yield/stop sign" have 0.785 times more crashes on average than RTLs having traffic signal control. RTLs having "nothing for control" have 0.647 times more crashes on average than RTLs having traffic signal control.
- When RTLs are on local roads and US roads, RTLs with signal control have fewer crashes; and RTLs with yield/stop signs have more crashes than RTLs with no traffic control. The effects of traffic control are different for RTLs on local and US roads.
- RTLs with signal control have fewer crashes. RTLs with yield/stop signs have more crashes than RTLs with no traffic control for roads in Marion County, Madison County, Tippecanoe County, Clark County, Harrison County, Vanderburgh County, Allen County, and La Porte County. However, the effect of traffic control is insignificant for roads in Hamilton County and Hancock County.
- The presence of bicycle lanes increases crash cost by 0.57% ($10,445), and a 1% increase in a RTL turn radius leads to a 0.14% increase in crash cost.
- The effects of bicycle lanes are different for the roadway classes and county classes.
- A 1% increase in RTLs turn radius increases crash frequency by 0.56% and increases crash cost by 0.21%.
- A 1% increase in a RTL turn radius leads to a 0.17% reduction of crash cost in Madison County, Tippecanoe County, Clark County, Harrison County, Vanderburgh County, Allen County, and La Porte County. A 1% increase in a RTL turn radius results in a 0.59%–0.28% increase in crash frequency for all counties.
- A 1% increase in a RTL turn radius increases crash cost by 1.78% on interstate roads and increases crash cost by 0.19% on the local/city road.
- The exclusive RTLs decrease crash cost by 0.07% ($4,229) compared to shared RTLs.
- The effect of the RTL type is different for county class and roadway class. Exclusive RTLs increase crash cost by 0.48% relative to shared RTLs in Marion County; however, they decrease crash cost by 0.12% in Madison County, Tippecanoe County, Clark County, Harrison County, Vanderburgh County, Allen County, and La Porte County. Exclusive RTLs decrease crash cost by 0.36% in Hamilton County and Hancock County. The exclusive RTLs increase crash cost by 2.69% on the interstate road, but they decrease crash cost by 0.74% on the US road, relative to the shared RTLs.
- The effects of traffic control at RTLs are different for roadway class and county class. Traffic signs decrease crash cost from 0.38%–1.64% for RTLs in different roadways. Traffic signals decrease crash cost from 0.82%–0.51% on different roadways. RTLs with traffic signals increase crash cost by 0.36%, and RTLs with traffic signs increase crash cost by 0.20%, relative to RTLs with nothing for control.

Implementation

There were six tasks for estimating the effects of influencing factors on right-turn lane safety performance.

Task 1 was conducting a literature review on previous research, determining the best practices of right-turn lanes (RTL) design to reduce crashes, and identifying methodology and data sources for analysis.

Task 2 was collecting and processing candidate intersections data. Data collection involved three parts:

1. The first part was collecting the population of RTLs, which were collected from the INDOT geodatabase for RTLs on major highways (US/SR/CR), US census road network for RTLs on ramps, and Google Maps for RTLs on local roads (Dr, Blvd, Rd, St, etc.).
2. The second part was collecting the dataset of intersection-related characteristic of RTLs. The dataset was manually collected from Google Maps for geometry, road name, location, and layout; Google Street View for traffic control and

the surrounding environment; and the INDOT traffic count database (AADT) for volume.

3. The third part was collecting the crash data obtained from the Automated Reporting Information Exchange System (ARIES). The data fusion method (a road name comparison-based method) for the multi-source datasets was employed in the data processing.

Task 3 was data cleaning. We re-corrected the measurement bias in the datasets and conducted the descriptive analysis for both crash frequency and crash severity. The correlation analysis was conducted for the explanatory variables, including RTL geometric factors, intersection characteristics, environmental-related factors, and location factors. To understand the traffic management background of different counties, we conducted a clustering method to divided ten counties into three groups according to population, percent of educated people, yearly household income, and number of individuals below the county poverty level. Finally, the preliminary data description showed that the RTLs at local roads had the highest number of crashes than any other types of roads (US, interstate, or state); and Marion had the highest crash frequency among the counties.

Task 4 was conducting statistical modeling for both the crash frequency and crash severity. We proposed several hypotheses, then selected the methodology for the crash frequency and severity, respectively. For the crash frequency model, we applied the negative binomial random effect model. For the crash severity analysis, we applied the log-linear model. To get detailed estimates, we estimated the crash on the overall level, estimated the RTL crashes on the county level (three types of grouped counties), and estimated the RTL crashes on the roadway class level (county road, local road, state road, interstate road, and US road). To ensure the reliability of the estimates, we conducted the robustness test for both models. The interpretations of the estimated results were based on the marginal effect and the elasticity estimates.

Task 5 was providing recommendations or safety improvements for the RTL geometric design. In this task, we combined the results from the crash frequency and severity analysis and provided the key geometric design factors in the overall RTLs, RTLs grouped by counties, and the RTLs in the roadway class. We also ranked recommendations for the RTLs geometric design by their effectiveness.

Task 6 was discussing and reaching conclusions for the analysis of the RTL geometric design improvements. We summarized the recommendation of the RTL geometric design based on the analysis of crash frequency and severity and concluded the study.

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1. INTRODUCTION

Intersection-related crashes are one of the main contributors of total crashes. In 2014, intersection-related crashes contributed to 47%–28% of all crashes and fatal crashes in the US, as reported by the National Highway Traffic Safety Administration (NHTSA). Within Indiana, they contributed to 30% of total crashes and 24% of fatal crashes (INDOT, 2014). In addition, the Federal Highway Administration (FHWA) estimated the annual economic and societal costs of intersection-related crashes were close to $120 billion (Blincoe et al., 2015).

Although intersection-related crashes are in general reducing annually, the decrease is modest. Different intersections based on their design, traffic volume and location have varying levels of crash risk. Therefore, engineers and researchers have been looking for alternative ways to improve the safety and operations at intersections. Researchers commonly focus on examining the relationships of the intersections' geometry designs and types of crashes. A recent concern is safety impacts at intersections with right-turn lanes. Right-turn lanes provide space for deceleration and storage for right-turning vehicles. Since they separate the turning movements from through traffic, they have been known to improve safety and operations at intersections. Depending on the traffic control methods and design elements used, right-turn lanes can be designed in different forms. However, each form has its own advantages and disadvantages. Constructing appropriate right-turn lanes will improve traffic safety, increase travel speed, reduce delay, and reduce congestion. Therefore, to figure out the design configurations that result in higher crash rates, there is a need to evaluate the safety and operations at right-turn lanes.

1.1 Background Information

Numerous districts have realized that large yield controlled, channelized right-turn lanes often have high crash rates. The problem appears to be that driver expectancy varies between the vehicles that yield, and those that follow. Also, the driver yielding must turn to check oncoming traffic almost 180 degrees behind them. Additionally, it has been discovered that right-turn lanes may actually be contributing to higher crash rates due to blocking visibility of approaching vehicles in the adjacent through lanes. Figure 1.1 and Figure 1.2 show these issues and highlight the design issues at SR-43 and US 40 respectively.

Figure 1.1 is an example located on SR-43 at the northbound I-65 off ramp, in Tippecanoe County. This intersection had 66 WB to NB right-turn rear-end crashes in a 3-year period (7/1/2012 to 6/30/2015).

Figure 1.2 is an example located at the eastern intersection of US-40 with SR-267/Quaker Blvd, in the Town of Plainfield. It includes an EB right-turn lane to SB SR-267/Quaker Blvd. There were 17 NB to EB right-turn rear-end crashes in a 3-year period from 2013–2015, and there were 10 EB to SB right-turn rear-end crashes in a 3-year period from 2013–2015.

Figure 1.1 The right-turn lane in the SR 43 and I 65 intersection.

Figure 1.2 The intersection of US-40 and SR-267.

There are various factors that influence on the decision on whether right-turn lanes should be used, and if yes, which right-turn lane design should designers follow. A systematic analysis of the safety issues related to right-turn lanes is critical to understand (1) current limitations; (2) identify factors that contribute to crashes at these intersections; and (3) provide recommendations for design. Currently, the INDOT does not have the guidelines for use of alternative turn-right lane designs. It is critical to have guidelines for designers so they can quickly narrow down options for consideration. These guidelines should be based on modeling tools that will used data from past crashes and diagnose high crash intersections and provide recommendations to improve safety.

The objectives of the research project are to (1) collect data from INDOT and conduct data analysis of the crashes at right-turn lanes; (2) identify factors that contribute to the crashes at right-turn lanes; (3) identify geometric design variables that correlate with right-turn crashes; and (4) provide recommendations to mitigate crashes and develop guidelines for use of alternative intersection designs, to improve safety. The guidelines are suggested based on the combination of performance measures obtained from the data at candidate intersections and analysis that will be conducted.

1.2 Study Benefits and Deliverables

By implementing this project, INDOT will gain the following significant benefits:

1. Future number of crashes and crash severity will be reduced.
2. Future intersection designs will be improved.

Deliverables of this project include the following:

1. *A list of right-turn lane design alternatives*. A list of right-turn lane design alternatives and key recommendations will be provided. The key factors help to select which right-turn lane should be used.
2. *Guidelines that will serve as a tool to utilize at high crash risk intersections*. Decision making at right-turn intersections with islands is complex. We will develop guidelines that facilitate the identification of high-risk intersections, guidelines for data collection and analysis and design guidelines to improve the safety. This guideline will facilitate the process of analyzing them internally and summarizing a set of alternatives that guide INDOT's decisions on selection of right-turn lane designs. INDOT engineers can use these guidelines at the design stage and construction stage for new intersections and possibly redesign existing intersections.

2. LITERATURE REVIEW

2.1 Common Layout and Traffic Controls of Right-Turn Lanes

Among common right-turn lane designs, there are four main layouts depending on whether there is designated right-turn lane, whether there is an island, and whether there is a dedicated downstream lane. We examine the four layouts and summarize the pros and cons in the following lists:

1. Designated right-turn lanes (Figure 2.1)

Pros

- Allows right-turn-on-red (unless prohibited), reducing right-turn queues.
- Removes turning vehicles from through vehicle lane for improved intersection operations.
- Lower turning speeds provides a safer pedestrian environment.

Cons

- All vehicles must stop on red, potentially increasing the right-turn queue.

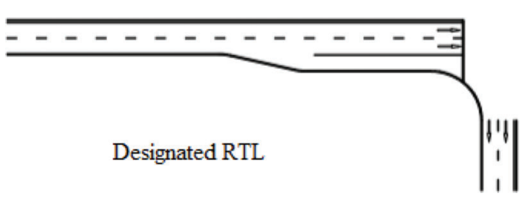


Figure 2.1 Designated right-turn lanes.

- The absence of an island eliminates its use for (1) placement of traffic control devices and (2) a pedestrian refuge.

2. Shared lane with island (Figure 2.2)

Pros

- Provision of islands permits its use for placement of traffic control devices or as a pedestrian refuge.
- Removes turning vehicle from head of queue.

Cons

- May encourage higher speeds.
- If signal support is located on the island, pedestrians will need to cross uncontrolled lane to reach pedestrian push button.
- Design may result in small island size.
- The through movement queue may obstruct the throat of the right-turn lane, reducing capacity of the intersection.

3. Exclusive right-turn lane with island (Figure 2.3)

Pros

- Provides relatively free movement for vehicles after yielding to pedestrians and opposing traffic, reducing right-turn queues.
- Removes turning vehicles from through vehicle lane for improved intersection operations.

Cons

- Higher turning speeds may present a hazard to pedestrians.
- Driver attention is split between looking back to merging traffic and looking forward to pedestrian crossing points that may be present in front of the vehicle.

4. Right-turn lane with island and dedicated downstream lane (Figure 2.4)

Pros

- Benefits motorized vehicles by lowering emissions and increasing capacity.

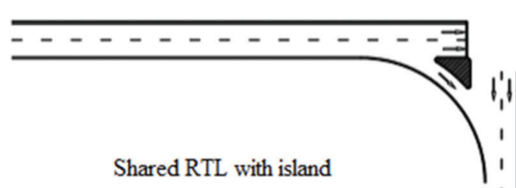


Figure 2.2 Shared lane with island.

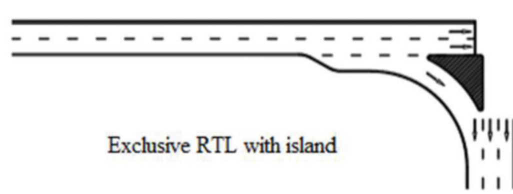


Figure 2.3 Exclusive right-turn lane with island.

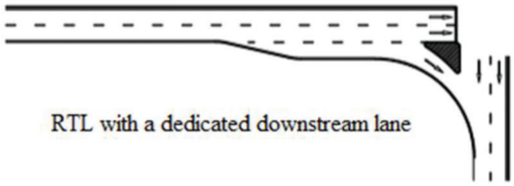


Figure 2.4 Right-turn lane with island and dedicated downstream lane.

- Provides free flow of turning vehicles, reducing right-turn queues.
- Eliminates need to look for merging vehicles (attention may be focused ahead of vehicle because driver is entering dedicated lane).
- Removes turning vehicles from through vehicle lane for improved intersection operations.

Cons

- High turning speeds are detrimental to pedestrian safety, so this design is not generally recommended in the urban environment.
- Vehicles are observed to frequently stop prior to entering the cross street even with an available dedicated lane, because drivers do not know they have a dedicated lane or how long it lasts.
- Dedicated downstream lane must be sufficient length for vehicles to merge.
- Access needs to be managed along dedicated downstream lane to ensure proper operation.

2.2 Right-Turn Lanes and Crashes Evaluations

There are two major type of crashes related to right-turn lanes, including right-angle crashes and rear-end crashes. The right-angle crashes happened when two vehicles collide perpendicular to each other. It mainly locates within intersection. The rear-end crashes happened when two vehicles traveling the same direction collide—with the front of the following vehicle colliding with the rear of the leading vehicle. It is more likely to occur at the beginning of right-turn lanes or upstream of intersection due to deceleration behaviors of right-turning vehicles. In the section, we mainly discuss the relationships between right-turn lanes and the two types of crashes.

Dixon et al. (1999) analyzed the crashes history at 17 signalized intersections with various right-turn treatments in Cobb County, Georgia, to identify the effects of those right-turn treatments on right-turn crashes. The use of a traffic island appears to reduce the number of right-angle crashes. The addition of an exclusive right-turn lane appears to correspond to elevated sideswipe crashes. The addition of an exclusive lane on the cross street for right-turning vehicles (i.e., an acceleration lane) does not appear to reduce the number of rear-end crashes when no additional control is implemented.

Ale (2012) measured the crash reductions due to right-turn lanes with intersections in Minnesota and concluded that right-turn lanes reduced right-turn movement related crash occurrences and conflicts by 85% and 80%, respectively. Right-turn lanes also reduced crash injury severity, hence, reducing the economic cost by 26%. Safety benefits, in dollars, realized with the use of right-turn lanes at driveways were 29% and 7% higher compared to those at intersections at low and high-speed conditions respectively for similar traffic conditions. Later, Ale et al. (2014) collected 5-year crash data on Minnesota's two-lane trunk highways and identified the safety benefits of right-turn lanes. The installation of right-turn lanes was found to reduce such RE crashes, on average, by 30% (not completely eliminate), reduce crash injury severity, and decrease the associated economic costs by 26%. According to the analysis of the South Australian crash data, Right-turn lanes at signalized intersections appear to reduce right-turn crashes as well as rear-end crashes (Kloeden et al., 2007).

McCoy et al. (1995) conducted field studies on rural two-lane highways and found a higher incidence of merging conflicts from vehicles entering the cross street from a channelized right-turn without an acceleration lane than those with an acceleration lane. Based on further accident analysis, it was concluded that channelized right-turn lanes do not provide the road user with any safety benefits. Tarawneh and McCoy (1996) conducted field investigations to study the effects of the geometrics of right-turn lanes on the turning performance of drivers at signalized intersections with channelized right-turn lanes. The investigation found that drivers turn right at speeds 5 to 8 km/h (4 to 5 mph) higher on intersection approaches with channelized right-turn lanes than they do on approaches without channelized right-turn lanes. In addition, it was observed that drivers are less likely to come to a complete stop before turning onto the cross street on approaches with channelized right-turns. Abdel-Aty and Nawathe (2006) showed that the presence of channelized right-turn lanes on the major road had no significant effect on total crashes but was linked to an increase in turning and sideswipe crashes and the presence of channelized right-turn lanes on the minor road was associated with a decrease in total crashes and an increase in rear-end crashes, after analyzing 1,562 signalized intersections from 6 counties in Florida. Fitzpatrick et al. (2016) implemented a study on relationships between crashes and characteristics of channelized right-turn lanes, with a special focus on driver age. They tested the differences in distributions of drivers for different right-turn treatment types, for with or without downstream departure lane, and for existing island or not. The results indicate the older Texas drivers are similarly involved in crashes for each type of right-turn treatment and presence of downstream departure lane is benefit to older drivers. In addition, the island may be serving as a surrogate for other characteristics of those approaches.

Hochstein et al. (2007) investigated the offset right-turn lane implementation at three two-way stop controlled rural expressway intersections that were effective in reducing the frequency of near-side right-angle collisions occurring.

2.3 Contributing Factors to Crashes

2.3.1 Modeling Approaches

The contributing factors for crashes have been investigated for few decades. Researchers also developed various methods, mainly based on statistical techniques, ranging from descriptive statistics, frequency analysis, chi-square based hypothesis testing, analysis of variance, and econometric models. Besides econometric models, all other methods identify the correlation relationship between crash frequency and contributing factors. The econometric models show a comprehensive understanding of influencing factors for crash frequency, as well as crash ratios and severity. In the section, we mainly summarize the current usage of control study methods and econometric models.

The three representative analysis approaches in control study methods are the before-after evaluation with yoked comparisons, before-after evaluation with a comparison group, and the Empirical Bayes method (Harwood et al., 2002). The first approach is a traditional one to evaluate traffic crash countermeasures and involves one-to-one intersection matching with and without certain countermeasures. The purpose of the matched or yoked comparison sites is to account for the effects of time trends. The second approach is a variation of the first approach and is intended to estimate the safety effectiveness of an improvement, or combination of improvements, while controlling for time-trend effects. This is achieved by careful selection of a suitable comparison group of intersections to match the improved intersections, so that the above-mentioned effects will be manifested equally in the treatment and the comparison groups. The last approach is the Empirical Bayes (EB) method. The distinctive features of the EB method are threefold. First, since there is a potential for selection bias in the choice of improvement sites, the EB method attempts to account for that bias, which neither the yoked comparisons nor the comparison group approach can. Second, the EB method attempts to account explicitly for changes from "before" to "after" in causal factors such as traffic volume. This is particularly important for intersections, since the expected number of accidents at an intersection is a nonlinear combination of the various conflicting flows, and it is often inappropriate to use a simple accident rate to account for the influence of changes in traffic volume. Third, in the comparison group approach, it is common to use only 2 to 3 years of "before" accident data for fear that older accident counts are no longer relevant; the EB method can correctly exploit the information in older accident counts, which is particularly important for intersection types that experience only a limited number of accidents per year.

Among the three control study methods, the EB approach should be considered the most desirable approach for observational before-after evaluation of safety improvements. The EB approach is the only evaluation approach with the potential to compensate for regression to the mean. Where the EB approach cannot be applied, the yoked comparison approaches should be considered as preferable to evaluation designs without comparison sites. The comparison group approach should generally be considered as preferable to the yoked comparison approach, because it incorporates a comparison group consisting of multiple sites. However, both the yoked comparison and comparison group approaches are likely to provide overly optimistic evaluation results.

Depending on the dependent variables, different econometric models are introduced. Considering the count nature of crash frequency that violates normal distribution, we always utilize the count data models (lognormal, Poisson, and negative binomial regression analyses) or generalized linear regression models instead of linear regression. Bauer and Harwood (2000) examined the performance of count data models for intersection crashes with explanatory variables of intersection geometric design, traffic control, and traffic volume variables. They also identified the applicability of models according to intersection design layouts. Generally, negative binomial regression models were developed to fit the accident data at rural, three- and four-leg, STOP-controlled intersections and urban, three-leg, STOP-controlled intersections. On the other hand, lognormal regression models were found more appropriate for modeling accidents at urban, four-leg, STOP-controlled and urban, four-leg, signalized intersections. The decision to use negative binomial or lognormal regression analysis was based on evaluation of the accident frequency distribution for the specific categories of intersections. Souleyrette et al. (2004) extended the generalized linear mixed model with covariance components that can address the correlated dependent variables while estimating crash frequencies and confirmed the outperformance of generalized linear models and its combination with covariance components. However, there are no extensive discussions on performance between the count data model and generalized linear mixed model, while modeling the crash frequencies.

Instead of crash frequencies, the crash ratio, or the probability of crashes at intersections are alternative dependent variables. For the crash probability specifications, the logistic regression is much popular. Lombardi et al. (2017) introduced the multivariate logistic regressions to investigate the impacts of ages on crash ratios. Ale et al. (2014) used the logistic regression for safety performance of right-turn lanes. Ale (2012) proposed binary logistic regression to model the probabilities of crashes caused by right-turning vehicles.

Except for crash frequencies or ratios, few studies explored the contributing factors for crash severity. Obviously, the crash severity can be ranked based on property damage, injury, and death. Ordered logit or probit model are frequently adopted for the variable, for example, Jin et al. (2010) modeled the right-angle crash severity with ordered probability model; and Anowar et al. (2014) analyzed intersection crash severity with ordered probit model. However, few studies also processed the crash severity without rank and specify with multinomial logistic regression model (Ale, 2012).

An alternative method to econometric models is classification tree (Miller et al., 2011). Based on the classification techniques in data mining, researchers can identify a bunch of variables that will lead to a certain type of crash, such as rear-end and right-angle. These classification trees gave average error rates of 12.21% (angle crashes) and 16.20% (rear-end crashes), which for all intersection classes were lower than the error rates that would have resulted from an educated guess.

2.3.2 Influencing Factors

Considering the compound effects on intersection crashes, we should have a comprehensive understanding of influencing factors, including drivers, facilities, environment, vehicles, and road. The analyses should not be limited to the impacts of right-turn lanes on right-turn related crashes. In the following section, we will summarize current findings on variables related to traffic and roadway characteristics, environment and intersection characteristics, and road users.

2.3.2.1 Variables related to traffic and roadway characteristics. In Bauer and Harwood (2000) study, the regression models of the relationships between accidents and intersection geometric design, traffic control, and traffic volume variables were found to explain between 16% and 39% of the variability in the accident data. However, most of that variability was explained by the traffic volume variables (major road and crossroad average daily traffic volumes). Geometric design variables accounted for only a small additional portion of the variability. In another study by Miller et al. (2011), traffic and roadway characteristics, including vehicle speed, alignment, traffic control, driver visibility obstruction, traffic volume, shoulder width, and surface condition, together with few environment-related variables, were major variables for classify various crashes.

Wang and Abdel-Aty (2007) studied 197 four-leg signalized intersections in Florida and discovered the significance of conflicting flows and geometric designs. The logarithm of the product of the conflicting through movements is consistently the most significant variable to explain right-angle crashes. The significance of this factor confirms the assumption that the frequency of collisions is related to the traffic flow to which the colliding vehicles belong and not to the sum of the entering flows for right-angle crashes. For geometric design features, the number of through lanes and angle of the intersections were identified as significant.

Schattler et al. (2016) discovered a set of variables having stronger relationship with right crashes: right-turn approach ADT, right-turn radius, and right-turn approach speed. Furthermore, the right-turn lane design was discussed based on seven test intersections. Approaches with right-turn angles less than 45 degree and head-turn angles greater than 140 degree were associated with significantly higher crash rates. Fitzpatrick et al. (2016) found that the older Texas drivers are similarly involved in right-turn related crashes under different levels of corner radii. Pernia et al. (2002) found that intersections with higher ADT, with more than four lanes, located either in urban or business areas would have more crashes than intersections with lower ADT, with four or less lanes, and located ether in rural or in other areas. Intersections with posted speed higher than 45 mph (72.41 km per hour) and paved shoulder would have fewer crashes than with posted speed lower or equal to 45 mph (72.41 km per hour) and with other types of shoulder. Intersections with median would have more crashes than without median except for rear-end crashes before signalization. In reference to the impacts of signalization on intersection crashes, based on average number of crashes estimated from the models, all crashes would increase except when low volume, angle crashes would decrease except for several cases on intersections with more of four lanes, left-turn crashes would decrease, rear-end crashes would increase except for several cases, and all other crashes would increase except for several cases of intersections with low volume.

Cooner et al. (2011) implemented a field study of 20 dual right-turn lanes in Texas urban areas and indicated that presence of channelization was a major contributing factor to high rear-end crash rates at dual right-turn lanes. The angle crashes at dual right-turn lanes can be caused by "trapped" through drivers on the curbside exclusive right-turn lane under unfriendly geometric conditions and inappropriately designed elements (e.g., small radii, confusing turning guidelines).

Abdel-Aty et al. (2006) investigated 1,335 intersections in six counties in Florida and concluded that expected crash frequency increased as the total number of lanes increased at all types of intersections and increase rate higher at four-legged two-way intersections than others. The dominant crash types were different at different intersection types, angle crashes at four-legged one-way intersections unlike rear-end crashes at other intersections. In addition, the crashes with higher severity were generally at four-legged two-way intersections and T-intersections.

Clarke and Tracy (1995) reported that 13% of all bicycle/motor vehicle crashes resulted when motorists were making a right-turn movement, and a majority of these crashes involved a straight-through bicyclist being struck by a right-turning motor vehicle. This is a little higher than another study reporting 5% of bicycle/motor vehicle crashes occurred when a motorist made a right-turn and 4% of bicycle/motor vehicle crashes occurred at an intersection controlled by a signal at which the motorist struck the bicyclist while making a right-turn-on-red. They also indicated that many bicyclists find changing lanes difficult or choose to ignore signage and pavement markings. Asgarzadeh et al. (2017) analyzed the bicycle related crashes in New York City and confirmed the crashes at non-orthogonal intersections are 1.37 times than those at orthogonal intersections. Crashes involved a truck or bus were twice as likely to result in a severe injury. In contrast, street width was not significantly associated with injury severity.

2.3.2.2 Variables related to environment and intersection characteristics. Choi (2010) found that crash occurrence while "turning right" at stop sign may be attributed to "false assumption of other's action." Preston and Storm (2003) worked on a sample of rural thru-stop controlled intersections with high crash frequency and identified the causality of the crashes, including increasing the conspicuity of traffic control devices by using bigger, brighter or additional signs and markings appears to lower the frequency of Ran the STOP crashes; rumble strips do not appear to be effective at reducing the frequency of Ran the STOP crashes (intersections with and without rumble strips had the same frequency of crashes); intersection sight distance does not appear to be related to the frequency of gap selection related crashes; and proximity to other controlled intersections may be related to crash frequency.

Wang and Abdel-Aty (2007) concluded that high design speed was associated with more right-angle crashes. Chin and Haque (2012) showed that red light cameras were effective in reducing the proneness of at-fault right-angle crash involvements of light and heavy vehicles and hence the vulnerability of motorcyclists in right-angle collisions and the probability of potential right-angle collisions was reduced when red light cameras were installed in any or both of the interacting approaches. Quddus et al. (2001) confirmed the importance of existence of surveillance camera, number of phases per cycle and high imposed approach speed in higher likelihood of motorcycle crashes, together with heavy approach traffic volumes, the presence of uncontrolled left-turn lane, and larger approach road width. On the other hand, a higher number of bus bays, the presence of an acceleration section or exclusive right-turn lane and the average cycle time and the adaptive signal control will decrease the likelihood of crashes.

Bui et al. (1990) implemented a before-after study on 217 intersection approaches in Australia and quantified the safety benefits of right-turn phase. Installation of partially controlled right-turn phases had no apparent safety benefits. From no control to fully controlled right-turn phase showed a 45% reduction in accidents, especially in right through crashes (right-turn with through vehicle from opposing lanes), however a 72% increase in rear-end and left-rear accidents. From partially controlled to fully control right-turn phase showed higher reductions in crashes, 65%, but lower increase in rear-end and left-rear crashes. Another recent study by Kloeden et al. (2007) measured the impacts of traffic control directly from Australian crash data and showed similar advantages of right-turn phase. Full control of right-turn movements at signalized intersections was a highly effective method of reducing right-turn crashes at such intersections but partial control of right-turn movements at signalized intersections (where the traffic signals control right-turns for only part of the time) appears to be ineffective in reducing right-turn crashes at such intersections. In addition, the right-turn arrows are most effective when also in operation during peak traffic periods and red-light cameras and in particular those that also measure vehicle speeds have the potential to reduce right-turn crashes at signalized. Wang and Abdel-Aty (2007) also confirmed that a flashing operation during the late-night and early-morning hours increases right-angle crashes. Moreover, the signal timing is also significant for intersection crashes, such as normalized all-red intervals at the entering roadway and the differences between the real values and the standard values for yellow and all-red intervals. In contrast, Souleyrette et al. (2004) worked on 228 intersections in Minneapolis but results did not support the commonly held hypothesis that an all-red clearance interval inherently improves traffic safety at signalized intersections.

Preston and Storm (2003) also documented the light condition as one causality of the crashes, based on the facts that vehicles are running the STOP signs at intersections without street lights at twice the statewide average for all crashes. Mitra (2014) evaluated the impacts of sun glare on intersection crashes and mainly examined crashes along the east bound directions in the morning and those along the west during the evening glare window. Results indicate that odds of glare crash occurrence are higher in east and west bound compared to north and south bound directions. Adverse effect of glare is found to be greater in early spring, fall and in winter compared to summer months. There is some evidence that rear-end and angle crashes at signalized intersections are affected by sun glare.

2.3.2.3 Variables related to road users. The socioeconomic status of road users is attracting more attentions while analyzing intersection crashes, as the country is aging. Researchers have identified that the right-turn maneuver is more problematic for aging drivers compared with young or middle-aged drivers, presumably as a result of age-related diminished visual, cognitive, and physical capabilities. Lombardi et al. (2017) investigated the national fatal crash database and indicated that the aged drivers are more likely to be involved in fatal crashes. Choi (2010) found that drivers 54 and younger are generally involved in crashes at intersections controlled by traffic signals due to "distraction," "inattention," "illegal maneuver," or "too fast for conditions/aggressive driving." Similarly, Kloeden et al. (2007) concluded that both older and young drivers are at particular risk of being involved in a crash while turning right at a signalized intersection, based on South Australian crash data. Braitman et al. (2007) showed that drivers 80 years and older had fewer rear-end crashes than drivers ages 35–54 and 70–79, and both groups of older drivers had fewer ran-off-road crashes than drivers ages 35–54. Crashes where drivers failed to yield the right-of-way increased with age and occurred mostly at stop sign–controlled intersections, generally when drivers were turning left. The reasons for failure-to-yield crashes tended to vary by age. Compared with drivers ages 35–54 and 80 and older, drivers ages 70–79 made more evaluation errors—seeing another vehicle but misjudging whether there was adequate time to proceed. In contrast, drivers 80 and older predominantly failed to see or detect the other vehicle. Drivers ages 35–54 also tended to make search errors, but theirs were due more often to distraction. Preston and Storm (2003) indicated that drivers under 20 and over 85 are overrepresented in STOP and Pull Out crashes and drivers between the ages of 25 and 40 were overrepresented in Ran the STOP crashes at rural thru-stop controlled intersections.

In addition, Choi (2010) examined the impacts of gender on intersection crashes. The involvement of female drivers of all ages in the intersection-related crashes may be attributed to "distraction" or "inattention." On the other hand, male drivers of all ages are likely to be involved in such crashes due to "illegal maneuver," or "too fast for conditions/aggressive driving."

Aust et al. (2012) concluded that drivers who were performing a turning maneuver in these crashes faced perception difficulties and unexpected behavior from the primary conflict vehicle; on the other hand, drivers who were going straight had less perception difficulties but largely expect any turning drivers to yield, which led to either slow reaction or no reaction at all. Fitzpatrick et al. (2016) found that Texas drivers with different miles driven are similarly involved in right-turn related crashes.

The summary of the literature review for the right-turn lane geometric design can be seen in the Table 2.1.

2.3.3 Data Preparation

To have a comprehensive understanding of contributing factors, we should collect data from multiple sources covering roadway characteristics, crash records, road users, etc. In general, the data on intersection geometric is sponsored by state or national Department of Transportation (DOT) or collected from team member experiences, Google Earth/Maps, and Google Street View. The dataset includes number of legs, type of intersection traffic control, presence of street lighting; angle between approach and the cross street (whether skewed), corner radius, island dimension, turn lane type and characteristics, design speed, and neighboring significant intersection exist within 300 ft of the subject intersection on the approach leg. Another important database is the crash record or police report, which should collect directly from state or national transport authorities. Within the crash record or police report, we can obtain detail descriptions on crash time, location, reasons, environment, drivers, and vehicles. Few additional databases are also very interesting. The national household travel survey database presents the number of interviewed drivers and their average annual miles driven. US DOT, together with US census data provide number of drivers in spatial units of interest. State Traffic Count Database can estimate the most-to-update Annual Average Daily Traffic event at link level. All these databases yield insights into crash occurrence and causality.

Green and Agent (2003) developed a simple three step to combine multi-source database into a unified one. First, they utilized milepoint log database containing an inventory of the location of various landmarks including intersections for all state-maintained routes in Kentucky to identify candidate intersections, according to the objectives and expectations. Second, they determine intersection volumes from most up-to-date average annual daily traffic. Last, they combine crashes with intersections.

In addition, the *Manual of Transportation Engineering Studies* (Schroeder et al., 2010) provides an equation to estimate the sample size required to obtain a given accuracy to a specified confidence and margin of error shown below:

$$N = \left(\frac{SK}{E}\right)^2$$

where, N is sample size, S is the estimated standard deviation, K is the corresponding constant applicable to the level of confidence for the study, 1.96 if under a 95% confidence level, and E is the allowable error in the estimation of the sample mean.

2.4 Best Practices

Mitigating right-turn-lane related crashes has many countermeasures, including but not limited to right-turn lane geometry (e.g., channelization and dedicated lanes), intersection geometry (e.g., improve sight distance), traffic control (e.g., signal phasing), and bicycle/pedestrian protections. In the following sections, we will select few countermeasures from each of above four categories and summarize current guidelines on countermeasure implementation and safety impacts (both proven and promising).

2.4.1 Right-Turn Lane Geometry

Many states have posted their warrants for right-turn lanes. The North Dakota DOT (2014) considers the traffic control at intersections, turning volumes, and crashes. In general, the following conditions should be met for non-controlled approaches:

- a posted speed is greater than 50 mph (not controlled with traffic signal, stop sign, or yield sign),
- turning traffic volumes are above the critical volume, and
- all installations of right-turn lanes should implement engineering judgement.

Oregon DOT (2003) also takes volume, crash, and engineering judgement into account. In addition, they also consider few special cases, such as railroad crossings, passing lane, geometric/safety concerns, signalized intersections, and all additions should compile

TABLE 2.1
Literature review of the geometric design for intersection and right-turn lanes

Study	Sample Sizes	Intersections	Variables	Models
Bauer and Harwood (2000)	1,434 intersections	All types	Geometric designs, traffic controls, and traffic volumes	Regression
Miller et al. (2011)	72,218 crashes/ >6,000 intersections	All types	Environment-related variables, and traffic and roadway characteristics	Regression and crash estimation models
Wang and Abdel-Aty (2007)	197 intersections	Four-leg signalized intersections	Geometric designs, number of through lanes, and angle of the intersections	Regression
Schattler et al. (2016)	3,174 crashes at 10 intersection	Right-turn	Right-turn approach ADT, right-turn radius, and right-turn approach speeds	Regression, crash modification factors
Cooner et al. (2011)	20 intersections	Dual right-turn lanes	Geometric and signal designs	Collision diagrams, field conflict study, and comparison study
Abdel-Aty et al. (2006)	26,603 crashes at 1,335 intersections	Signalized intersections	Intersection geometries, number of lanes, angle of intersections	Regression
Asgarzadeh et al. (2017)	3,266 bicycle motor vehicle crashes	All types	AADT, design speed, geometric designs, road surfaces, road characters, time of day, vehicle types, and individual socio-demographic characteristics	Regression
Choi (2010)	2,188,969 crashes (787,236 intersection crashes)	All intersections and non-intersections	Turned with obstructed views, traffic control devices, external distractions, and atmospheric conditions	Descriptive statistics, relative ratio, generalized logit model, and configural frequency analysis
Preston and Storm (2003)	2,296 crashes at 1,604 intersections	All types	Signs, intersection sight distances, sight obstructions to signs, presence of other devices, proximity (distance) to other controlled intersections, daily traffic volumes	Descriptive analysis
Wang and Abdel-Aty (2007)	197 intersections	Four-leg signalized intersections	Geometric designs, number of through lanes, angle of the intersections, and traffic signals	Regression
Chin and Haque (2012)	8,613 two-vehicle right-angle crashes	All types	Number of lanes, traffic signals, vehicle types, and red-light cameras	Relative crash vulnerability
Quddus et al. (2001)	54 intersections	For-leg signalized intersections	Surveillance cameras, signal controls, design speed, traffic volumes, road characteristics, bus bays, and intersection designs	Regression
Bui et al. (1990)	129 intersection	Right-turn intersections	Type of intersections, number of right-turn lanes, divided/ undivided roads, number of opposing lanes, tram route/ non-tram routes, and signal controls	Descriptive analysis, and regression
Kloeden et al. (2007)	Fatality: 24 Casualty: 37,476 All report crashes: 203,184	Right-turn signalized intersections	Traffic flow, traffic phrasings, genders, drivers' ages, and vehicle types	Descriptive analysis
Mitra (2014)	67,491 crashes at 291 intersections	Signalized intersections	Sun glare	Descriptive analysis (Anova and frequency)

with access management spacing standards and conform to applicable local, regional, and state plans. Iowa DOT (2010) proposes few critical volume, for instance, 30 vehicles per hour for right-turn volume, 400 vehicles per hour for approach volume, and 20 vehicles per hour for approach truck traffic. In addition, at some intersections on four-lane expressways within 5 miles (8 kilometers) of some urban areas with a population of 20,000 or greater, drivers have used the granular shoulders as right-turn lanes. Right-turn lanes should be provided at all school locations regardless of turning and approach volumes. Other locations where right-turn lanes may be judged to be warranted by the project management team include main entrances for towns, shopping areas, housing developments, attraction locations such as recreational areas, and locations that would have special users such as truck traffic or campers. Special attention should be given to intersections serving locations that attract elderly drivers such as drug stores, grocery stores, retirement developments, medical facilities, nursing homes, etc. Intersections with paved side roads should also be considered for right-turn lanes. Washington State DOT (2017) identify the candidate intersections for right-turn lanes based on volumes and two-lane and multilane roadways with a posted speed of 45 mph or above. Michigan DOT (2008) does not provide details in guidelines besides few situations. A right-turn lane may be appropriate in situations where there are an unusually high number of rear-end collisions on a particular approach. Installation of a right-turn lane on one major road approach at a signalized intersection is expected to reduce total crashes. Arizona DOT (2019) simply proposes three concerns: (1) the combination of through traffic volume and turning traffic volume, (2) the posted roadway speed, and (3) the number of through lanes on the roadway. The Federal Highway Administration recommends the right-turn lanes for unsignalized intersections with a high frequency of rear-end crashes resulting from conflicts between (1) vehicles turning right and following vehicles and (2) vehicles turning right and through vehicles coming from the left on the cross street (FHWA, 2014a). Moreover, FHWA recommends longer right-turn lanes for unsignalized intersections that have an existing right-turn lane that is not long enough to store all right-turning vehicles and that is experiencing a high frequency of rear-end crashes resulting from the conflict between vehicles waiting to turn right and following vehicles (FHWA, 2014a).

Among all practices of right-turn lanes, Washington State DOT (2017) indicates an overall crash reduction. Michigan DOT (2008) presents the safety benefits that are 65% reductions in rear-end right-turn crashes and 20% reductions in others, sideswipe same direction crashes after installing right-turn lanes. FHWA concluded based on related research that added right-turn lanes are effective in improving safety at rural unsignalized intersections. Installation of a single right-turn lane on a rural major road approach would be expected to reduce total intersection crashes by 14%. Right-turn lane installation reduced crashes on individual approaches to four-legged rural unsignalized intersections by 27%. Installing a right-turn lane on one approach to a signalized intersection can reduce crashes by 4% and by 8% on two approaches. Lengthening of right-turn lanes may also reduce the potential for rear-end collisions between right-turning vehicles by providing longer entering taper and deceleration lengths. While there is no consensus on a quantitative estimate of the safety effectiveness of lengthening right-turn lanes, one study indicated that crashes could be reduced up to 15%. This effectiveness is likely to depend on the existing length of the right-turn lane, the proportion of time during which the storage capacity of the lane is exceeded, the volume and speed of traffic on the intersection approach, and the available sight distance to the rear of the right-turn queue. Potts et al. (2006), funded by National Cooperative Highway Research Program (NCHRP), discussed the relationship between lane width and crashes. A number of past studies have been conducted to determine the traffic safety effects of lane width, but results are varied. Despite the extensive research that has been conducted on the effect of lane width on motor vehicle safety, it is difficult to draw any definite conclusions about the relationship. Furthermore, researchers do agree that increasing the space between bicyclists and vehicles should result in increased bicycle safety. No studies have determined a quantitative relationship between lane width and bicycle safety, as well as between lane width and pedestrian safety. Harwood et al. (2002), funded by FHWA, compared hundreds of improved intersections with right-turn lanes with hundreds of intersections without right-turn lanes across eight states. Adding right-turn lanes are effective in improving safety at signalized and unsignalized intersections in both rural and urban areas. Installation of a single right-turn lane on a major-road approach would be expected to reduce total intersection accidents at rural unsignalized intersections by 14% and accidents at urban signalized intersections by 4%. Right-turn lane installation reduced accidents on individual approaches to four-leg intersections by 27% at rural unsignalized intersections and by 18% at urban signalized intersections. Only limited results were found for right-turn lane installation at three-leg intersections. Installation of right-turn lanes on both major-road approaches to a four-leg intersections would be expected to increase, but not quite double, the resulting effectiveness measures for total intersection accidents turn-lane improvements at rural intersections resulted in larger percentage reductions in accident frequency than comparable improvements at urban intersections. there is no indication that any type of turn-lane improvement is either more or less effective for different accident severity levels.

A variation of right-turn lane is the offset right-turn lane. It is adjacent to the through lane and give drivers on the minor approach (at the stop bar) an unobstructed view of through traffic in the near lanes, which allows for more effective use of gaps. There are two main types of offset right-turn lanes: the parallel-type and the tapered-type, shown in Figure 2.5.

The North Dakota DOT (2014) implemented engineering judgement for installation of offset right-turn lanes and proposes few examples of locations where offset right-turn lanes may be beneficial, including intersections where a crash trend (susceptible to correction by an offset right-turn lane) has been identified, intersections with large volumes of turning trucks, or intersections with sight distance issues. Iowa DOT (2010) stated that offset (tapered) right-turn lanes may be considered in areas where sightline difficulties may occur, such as: at the base of a long or steep decline (grade = 5% or larger) or at the crest of a hill. Michigan DOT (2008) just mentioned offset right-turn lanes as one countermeasure for certain crashes without detail guidelines on installation. Schurr and Foss (2012), funded by Nebraska Department of Roads, focused upon whether a standard or offset right-turn lanes is the optimal choice at a given location where a right-turn lane is warranted along the major roadway of a two-way stopped-controlled intersection. Results of driver behavior studies at existing locations of offset right-turns lanes indicate that drivers are not performing as expected at parallel-type offset right-turns lanes, rendering its presence useless. Tapered-type offset right-turns lanes appear to be much more intuitive to driver expectancy and appropriate for the three-dimensional characteristics of all vehicle types. FHWA (2014a) recommends the offset right-turn lanes at unsignalized intersections with a high frequency of crashes between vehicles on the minor road that are turning left, turning right, or proceeding straight through, and vehicles on the major road. No research has been conducted on offset right-turn lanes to determine their safety effectiveness. Safety effectiveness is likely to depend upon the traffic volumes of the conflicting turning and through movements and the amount of offset between the right-turn lanes at the intersection.

Another widely adopted variation of right-turn lanes is channelized right-turn lanes. Based on a survey, about 87% of state and local highway agencies are using channelized right-turn lanes (Potts et al., 2011). As a popular design, it has many guide books in the US, such as *A Policy on Geometric Design of Highways and Streets*, *Guide for the Planning, Design, and Operation of Pedestrian Facilities*, *Manual on Uniform Traffic Control Devices* (MUTCD), *Intersection Channelization Design Guide* (report 279 from NCHPR) and the *Traffic Engineering Handbook* from the Institute of Transportation Engineers. However, all of the above guidance generally discusses the purpose, considerations, and design elements of the channelized right-turn lanes without addressing justifications for use or the type of traffic control used. Based on the survey by Al-Kaisy and Roefaro (2012), using channelized right-turn lanes and type of traffic control heavily relies on engineering judgement by most state and local agencies, given limited guidance available. This is particularly true for selection of traffic control, as only 12% of state and 27% of local agencies reported the use of warrant studies in installing signal control at channelized right-turn lanes. In addition, an overwhelming perception by most state and local agencies about the safety benefits of signal control at channelized right-turn lanes. But have not been supported by studies or statistics.

One of the advantages of using curbed medians and intersection channelization is that it provides a better indication to motorists of the proper use of travel lanes at intersections. In general, the raised traffic islands are more effective than flush marked islands in reducing

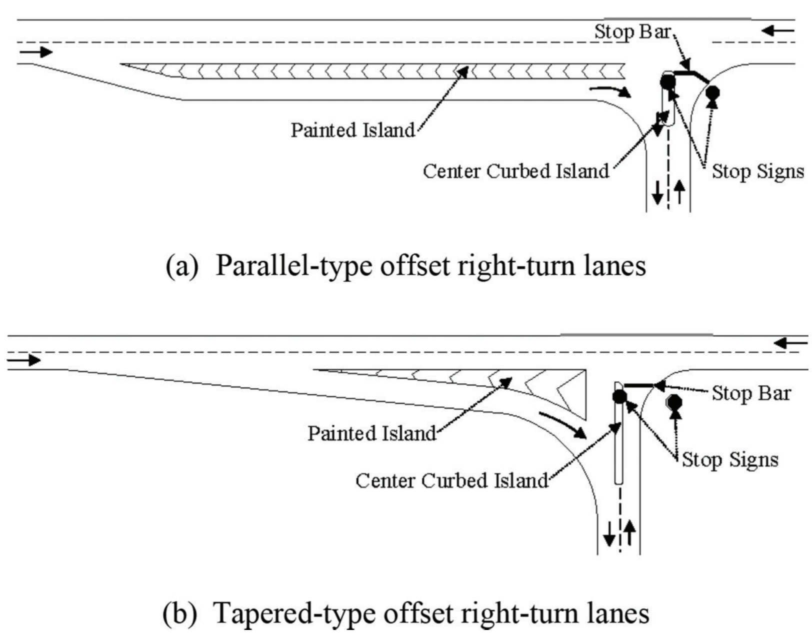


Figure 2.5 The offset right-turn lanes.

night crashes particularly in urban areas, little difference at rural intersections. The right-turn channelization affects the speed at which drivers make right-turns and the likelihood that they will stop before making a right-turn on red. Potts et al. (2006) reviewed current knowledge of safety effects of channelized right-turn. It is generally accepted that channelized right-turns improve safety for motor vehicles at intersections where they are used, but there is only limited quantitative data to demonstrate this. No studies have been found concerning pedestrian safety at channelized right-turns that have used crash data to document the pedestrian safety implications of channelized right-turns because motor vehicles entering the channelized right-turn roadway must weave across the path of bicycles traveling straight through the intersection, but no studied based upon crash history are available to support this presumption. However, this same type of conflict between through bicyclists and right-turn vehicles is present at conventional intersections as well. Potts et al. (2014) implemented both crash analysis and simulation and confirmed the advantages of channelized right-turn lanes for improving operations and safety at intersections. The annual crash predictions for channelized right-turn lanes and shared through/right-turn lanes were found to be similar, and 70%–80% lower than those for conventional right-turn lanes. However, to achieve these benefits they should have consistent design and traffic control and should be used at appropriate locations. The research provides design guidance for channelized right-turn lanes that addresses geometric elements such as crosswalk location, special crosswalk signing and marking, island type, radius of turning roadway, angle of intersection with cross street, acceleration and deceleration lanes, and traffic control.

The next variation of right-turn lanes is the improved channelized right-turn lanes with tighter turning radii to reduce turning speeds to approximately 17 to 18 mph, decrease pedestrian crossing distances and optimize the right-turning motorists' line of sight. This is also called right-turn slip lanes, as shown in Figure 2.6. The improved channelized right-turn lane design will place a sharper curve at the downstream end of the lane, which will force drivers to negotiate the lane more slowly; and by having the slip lane intersect the destination street at a larger angle, a driver will have better sight lines of approaching traffic on the destination street. Known implementations of this design include an intersection in Charlotte, NC, and several intersections in Florida and Texas (Brewer et al., 2014; Gemar et al., 2015). Nevada also includes the improved channelization in the state *Strategic Highway Safety Plan*. Schattler et al. (2016) examined the safety benefits of improved channelized right-turn lanes in Illinois and found that older-driver crash analysis revealed a 70% significant reduction in right-turn crashes at the subject approach and younger-driver crash analysis revealed significant reductions of 43% for intersection crashes, 63% for approach crashes, and 66% for right-turn-related crashes at the subject approach.

The last variation of right-turn lanes is the combination of right-turn lanes with deceleration lanes at upstream and acceleration lanes at downstream. Potts et al. (2014) listed the advantages of deceleration lanes before right-turns, including a means for safe deceleration outside the high-speed through lanes for right-turning traffic; a storage area for right-turning vehicles to assist in optimization of traffic signal phasing; and a means for separating right-turning vehicles from other traffic at stop-controlled intersection approaches. Their survey showed that 89% of the state highway agencies and 70% of the local agencies that use channelized right-turn lanes indicated that they have used deceleration lanes in advance of those channelized right-turn lanes for at least some locations. In addition, 77% of the state highway agencies and 43% of the local agencies that use channelized right-turns indicated that they have used acceleration lanes downstream of those channelized right-turns for at least some locations. One agency responded that acceleration lanes are generally used when the angle between turning roadway and intersecting roadway is less than 60 degrees. However, channelized right-turn lanes with acceleration lanes appear to be very difficult for pedestrians with vision impairment to cross. Therefore, the use of acceleration lanes at the downstream end of a channelized right-turn lane should generally be reserved for locations where no pedestrians or very few pedestrians are present.

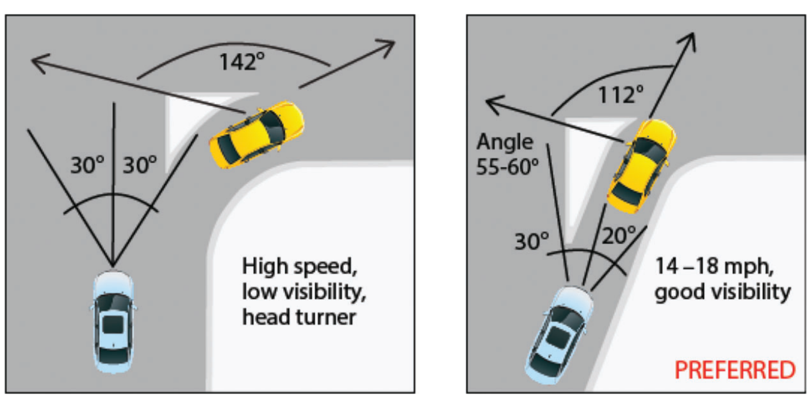


Figure 2.6 The standard and improved channelized right-turn lanes (FHWA, 2014c).

Typically, these would be locations without sidewalks or pedestrian crossings; at such locations, the reduction in vehicle delay resulting from addition of an acceleration lane becomes very desirable. FHWA (2014a) only recommends the acceleration lanes for unsignalized intersections that experience a high proportion of rear-end and/or sideswipe crashes related to the speed differential caused by vehicles making a right-turn maneuver onto the highway. By removing the slower right-turning vehicles from the through lanes, this strategy is expected to reduce rear-end and sideswipe crashes resulting from conflicts between vehicles making a right-turn maneuver onto the highway and through vehicles on the highway. Research has shown that right-turn acceleration lanes at intersections function effectively and do not create safety problems. However, no quantitative estimates of the safety effectiveness of right-turn acceleration lanes at intersections are available.

2.4.2 Intersections Geometry

In real world, it is impossible to build all intersections following the standard orthogonal layout. Those non-orthogonal intersections with a certain angle are called skewed intersections. However, there is some inconsistency among reference sources concerning the degree of skew that can be safely designed into an intersection. AASHTO green book recommend that factors to adjust intersection sight distances for skewness are suggested for use only when angles are less than 60 degrees. ITE and the *Traffic Engineering Handbook* provide a larger one with 75 degrees and define severe skew angles as 60 or less. Skewed intersections pose particular problems for aging drivers. many aging drivers experience a decline in head and neck mobility, which compares advancing age and may contribute to the slowing of psychomotor responses. Joint flexibility has been estimated to decline by approximately 25% in aging adults due to arthritis, calcification of cartilage and joint deterioration.

One countermeasure for right-turns at skewed intersections is the right-turn-on-red (RTOR) prohibit. Michigan DOT (2008) proposes a few conditions for RTOR prohibit, including (1) intersections have sight distance restrictions to the left that inhibit right-turns from that approach; (2) more than three RTOR crashes reported in a 12-month period for the particular approach; and (3) a signalized intersection with a railroad crossing (and pre-signal) in close proximity (less than 100 feet) shall have a "No Turn On Red," shown in Figure 2.7, if one of the following conditions exists: (1) insufficient clear storage distance for a design vehicle between the signalized intersection and the railroad crossing or (2) the highway-rail grade crossing does not have gates. Institute of Transportation Engineers also concluded that a significant proportion of drivers do not make a complete stop before executing an RTOR, and a significant portion of drivers do not yield to pedestrians (Schroeder et al., 2010). FHWA (2014a) adopts the RTOR prohibits at signalized intersections

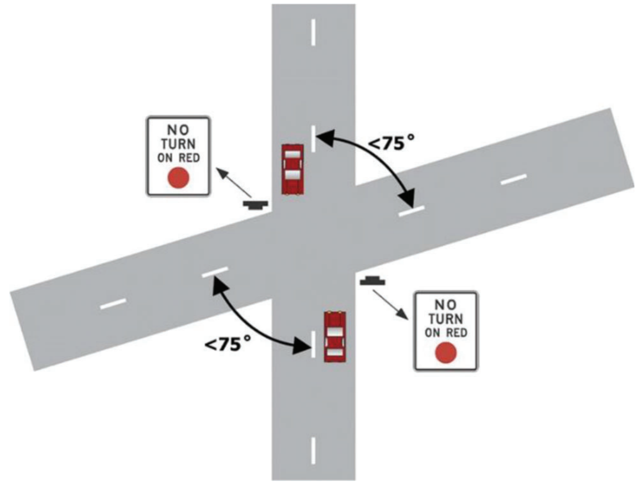


Figure 2.7 No-turn-on-red sign at skewed intersections (FHWA, 2014b).

with a high frequency of crashes related to turning maneuvers. The target of this strategy is right-turning vehicles that are involved in rear-end or angle crashes with cross-street vehicles approaching from the left or vehicles turning left from the opposing approach, and crashes involving pedestrians. One study in Florida concluded that prohibiting left turns at intersections (signalized and unsignalized) can reduce all crashes by 45% and left turn crashes by 90%. That same study determined that prohibiting right-turn-on-red can reduce right-angle crashes by 30% and rear-end crashes by 20%. Sometimes, the standard "No Turn On Red" sign was added with the supplementary "When Pedestrians Are Present" message. It was effective at several sites with low to moderate right-turn vehicle volumes. However, it was less effective when RTOR volumes were high. The supplemental message when added to the "No Turn On Red" sign with the circular red symbol reduced total pedestrian conflicts at one site and increased RTOR usage (as desired, from 5.7% to 17.4%), compared with full-RTOR prohibitions. It was recommended that the supplemental message be added to the *MUTCD* for the "No Turn On Red" sign with the circular red symbol, under low to moderate right-turn vehicle volumes and light or intermittent pedestrian volumes.

Except for signs, the split phasing at signalized skewed intersections is an alternative countermeasure. Split phasing allows opposing movements on the same roadway to proceed through the intersection at different times and is a way to address several geometric situations that pose safety problems for vehicles on opposite approaches. Split phasing targets crashes that occur related to opposing movements proceeding on the same phase through an intersection. Crash types related to this situation include angle, head-on left turn, rear-end-left turn, and other rear-ends. Though studies have not conclusively proven that implementation of split phases reduces fatalities and severe injuries at signalized intersections, the elimination of conflicts can logically be expected to reduce crashes. (Michigan DOT, 2008)

2.4.3 Traffic Control—All Red Interval

The purpose of an all-red clearance interval is to allow additional time for motorists already in the intersection to clear the intersection on the red indication before conflicting traffic movements are released. All-red may also be useful in mitigating amber dilemma zone problems, particularly at high-speed intersections. Generally, the duration of the all-red clearance interval is from 0.5 to 3.0 seconds.

Most studies have reported safety benefits from addition of the all-red clearance interval, but a handful of studies have produced mixed results. Many studies have examined the effects of the all-red clearance interval for several months to a year before-and-after the implementation. Over time, if drivers become familiar with the presence and length of the all-red interval, they might push the limits trying to make it through the signal. If this is the case, over a longer time period intersection crashes might return to pre implementation rates.

Based on the crash reductions published by Michigan DOT, all red intervals can reduce 10% of all types of crashes. Clearance intervals that are too short in duration can contribute to rear-end crashes related to drivers stopping abruptly and right-angle crashes resulting from signal violations. According to Texas A&M Transportation Institute, increasing all-red clearance interval can reduce crash by 20% and adding all-red interval can reduce crashes by 4%. A study conducted in Detroit, Michigan (Datta et al., 2000) showed that fewer crashes were observed at signals with the all-red clearance interval. In addition, there was a reduction in right-angle injury crashes at the treated intersections. It is important to note that all intersections studied in this before-and-after analysis were improved at the same time the all-red clearance interval was implemented. Therefore, results probably cannot be wholly attributed to implementation of the interval. A before-and-after crash analysis in Oakland County, Michigan (Schattler et al., 2003) was completed at the three intersections for 2 years before and 2 years after the signal retiming. At the time of publication of the study, intersection crashes were reduced at the three study intersections, but no follow-up research is published on final results. A study conducted in Indiana (Roper et al., 1990) took a different approach to evaluate the effectiveness of the all-red clearance interval. Rather than looking at only the short term before-and-after effect of implementation of the all-red clearance interval, this study examined 2 years before and 2 to 4 years after implementation of the all-red clearance interval. During the 1-year treatment period, the total crash rates, left turn crash rates, rear-end crash rates, right-turn crash rates, and right-angle crash rates decreased. This immediate decrease in crash rates was attributed to the implementation of the all-red clearance interval. Although crash rates decreased initially, for the 2 years following the treatment year, crash rates increased to rates similar to or higher than the initial rates during the before period. The study compared the intersection crash rates of 28 intersections with the all-red clearance interval versus 28 intersections without the all-red clearance interval. Each intersection was paired with an intersection based on entering Average Annual Daily Traffic (AADT), approach speed, and angle of intersection. This comparison showed no significant difference in intersection crash rates between intersections with and without the all-red clearance interval. The Indiana DOT is aware of the study conducted by Purdue University, which concludes that intersection delay outweighs the safety impacts of the all-red clearance interval. However, they have decided to continue using the all-red interval "in order to provide the safest roadway system possible."

2.4.4 Bicycle and Pedestrian Protections

Statistics gathered by the Oregon DOT (Dixon et al., 1999) showed that 19% of vehicle-pedestrian crashes occurred at intersections from drivers making right-turns. According to crash records information system by Texas Department of Transportation for the years 2007 to 2012, there was a recent upward trend in total number of crashes, including pedestrian-related incidents. Of the highway agencies that use channelized right-turn roadways, 23% of state highway agencies and 40% of local highway agencies indicated that they consider pedestrian issues in determining the radius and/or width of a channelized right-turn roadway. Of the highway agencies that use channelized right-turn roadways, approximately 23% of state highway agencies and 17% of local highway agencies have encountered pedestrian-related safety problems at channelized right-turn roadways.

According to FHWA (2014a), geometric or physical improvements that can be made to a signalized intersection with high frequencies of pedestrian and/or bicycle crashes and on routes serving schools or other generators of pedestrian and bicycle traffic. Possible countermeasures include continuous sidewalks, signed and marked crosswalks, sidewalk set-backs, median refuge areas, pedestrian overpasses, intersection lighting, physical barriers to restrict pedestrian crossing maneuvers at higher-risk locations, relocation of transit stops from the near side to the far side of the intersection, widening outside through lanes (or adding bike lanes), providing median refuge areas, providing independent crossing structures, upgrading storm drain grates with bicycle-safe designs, implementing lighting, and other traffic calming applications to reduce vehicle speeds or traffic volumes on intersection approaches. Although there are no proven safety benefits of these improvements, few studies presented some preliminary results. The presence of sidewalks on both sides of the street has proven to significantly reduce the "walking along roadway" pedestrian crash risk compared to locations where no sidewalks/walkways exist. Reductions of 50%–90% of these types of pedestrian crashes have occurred. The Federal Highway Administration (Zegeer et al., 2005) found that a raised median (or raised crossing island) was associated with a significantly lower pedestrian crash rate at multilane crossing locations, with both marked (46% reduction) and unmarked (39% reduction) crosswalks. In contrast, painted (not raised) medians and center two-way left-turn lanes did not offer significant safety benefits to pedestrians on multilane roads, compared to no median at all. In addition, the signalization is thought to be an effective countermeasure for pedestrian- and bicycle-related crashes. One study (Campbell, 2015) showed a 25% decrease in pedestrian-related crashes with the installation of pedestrian countdown signal heads.

The *Manual on Uniform Traffic Control Devices* (Agenda, 2017) and bicycle guide from the American Association of State Highway and Transportation Officials (Toole, 2010) recommend breaking bicycle lane markings ahead of the intersection and then marking the bicycle lane again at the intersection itself, to the left of the right-turn lane. This positions bicyclists traveling straight through the intersection away from any conflict with right-turning vehicles and allows a merge area for right-turning vehicles to get into right-turn lane.

Gemar et al. (2015) configured the intersections that may be problematic for pedestrians was a right-turn slip lane as it presents a crossing location outside of the physical area of the intersection. This separation facilitated larger curb radii and consequently, higher turning speeds. Typically, the crossing location along the turning roadway was essentially uncontrolled; therefore, it is important to produce guidelines for the proper design of right-turn slip lanes that take pedestrian safety into account.

For pedestrian crossing on channelized right-turn lanes with an adjacent pedestrian refuge island, the crosswalk should be located approximately one car length from the yield line for the intersection, which allow drivers on the approach leg to look for and yield to pedestrians before reaching the intersecting roadway and scanning for gaps in traffic. Since consistency in locating crosswalks is important and since current practice shows a clear preference for crosswalk locations near the center of a channelized right-turn lane, design guidance should recommend placing crosswalks near the center of the channelized right-turn lane for channelized right-turn lanes with yield control or no control at the entry to the cross street (Potts et al., 2014). Where the channelized right-turn lane has STOP sign control or traffic signal control, the crosswalk should be placed immediately downstream of the stop bar. If the channelized right-turn roadway intersects with the cross street at nearly a right angle, the stop bar and crosswalk can be placed at the downstream end of the channelized right-turn roadway. There has been little research that evaluates how the crosswalk location affects crossings by pedestrians with vision impairment, and more research would be desirable to provide more concrete recommendations.

Moreover, turning vehicles yield to pedestrians is recommended wherever engineering judgement indicates a clear potential for right-turning vehicles to come into conflict with crossing pedestrians. The "Turning Traffic Must Yield to Pedestrians" sign was effective in significantly reducing pedestrian-vehicle conflicts during right-turns. The sign was installed at six marked crosswalks in Nebraska, where right-turn vehicle-pedestrian conflict data were collected before and after its installation in an observational field study. For the six study crosswalks combined, a conflict occurred in 51% of the observations in the before period, but in only 38% of the observations during the after period. The reductions in pedestrian-vehicle conflicts across the observation sites ranged from 15%–30% and were statistically significant.

In the study by Hunter et al. (2000), the conflict zone, defined as the place where the paths of bicyclists and motorists crossed most often, was treated with blue pavement markings at ten intersections in Portland, Oregon. The treatment resulted in a safer riding environment and a heightened awareness on the part of both bicyclists and motorists. The city of Portland continues to use this treatment at six of the ten locations today. Harkey et al. (1998) examined the behaviors of bicyclists and motorists at a "combined" bicycle lane/right-turn lane used in Eugene, Oregon. the combined bicycle lane/right-turn lane to be an effective treatment that could be beneficial at locations where right-of-way constraints exist.

Lastly, we introduced the "Strategy to prevent accidents between straight going bicycles and right-turning lorries," a collaboration between the Danish National Police, the Danish Transport and Construction Authority and the Danish Road Directorate. In Denmark (Vejdirektoratet, n.d.b), approximately 25% of all cyclists involved in accidents between right-turning lorries and cyclists going straight ahead die from their injuries. The number of killed cyclists varies significantly from year to year. But seen over a longer period, cyclists in right-turn accidents involving lorries constitute 15%–20% of all cyclists killed in traffic. Two-thirds of the fatal right-turn accidents occur at signalized intersections.

In terms of the geometric design and the basic regulation type, there are generally three alternatives which are recommended in signalized intersections. Regarding right-turn lane and cycle track (possibly cycle lane), the following measures are considered:

1. Removal of reserve between carriageway and cycle track.
    a. On the last 30 m–50 m before the stop line, there should only be kerbed edges or a wide, raised edge line between the cycle track and the nearest lane (right-turn lane).
2. Advanced stop lines for bicycles and possible bike box, shown in Figure 2.8.

a. When there is a cycle track or lane right up to the intersection, an advanced stop line for bicycles will make cyclists visible in the natural field of vision of the right-turning drivers. This applies, however only to the situation where both parties after stopping for red light start to move simultaneously at a green light. A bike box is an additional area for bicycles in front of the vehicle stop line in the right-turn lane, where the area is clearly marked with for example blue paint with a white bicycle symbol.

3. "Pre-green" for cyclists.

   a. If it is not possible to retract the stop line for cars by 5 m, it is possible to combine a slightly shorter retraction of the stop line by giving a pre-green light for cyclists a few seconds before the cars. This gives drivers a chance to see the cyclists, who will also be able to pass through the intersection before the cars start to turn right.

Another solution is right-turn lane and truncated cycle track (possibly cycle lane), shown in Figure 2.9. It would be to interrupt the cycle track or lane 15–25 m before the stop line and let the cyclists continue in a right-turn lane together with the right-turning cars. This reduces the accident risk since cyclists and right-turning motorists are given the chance of weaving before the intersection, and the cyclists going straight ahead can position themselves on the left-hand side of the right-turning cars. This solution should only be used when the right-turn lane for car traffic is a designated right-turn lane that is not also used by traffic going straight ahead. This solution works well in safety terms—especially on sections with downhill grade towards the intersection—but it is done partly at the expense of the cyclists' perceived safety and mobility since they will need to weave with the motor vehicle traffic towards the intersection. If the bicycle traffic volume is large, it may also be difficult for right-turning drivers to weave into the flow of cyclists. The truncated cycle track can be combined with a cycle lane for the cyclist going straight ahead and turning left which is placed between the lane for cars going straight ahead and the right-turn lane. This cycle lane must be at least 1.50 m wide including edge. This solution is only applicable on roads with speeds of 50 km/h or less.

Separate phasing is a technical solution where each traffic flow is regulated by its own separate signals. In general, intersections with separate phasing/conflict-free signal control work well in road safety terms. The Danish Road Directorate has no documentation to the effect that significant safety differences should exist between the different solutions. However, separate signal control takes up some of the capacity, and in intersections with heavy traffic, this solution may result

Figure 2.8 Advance stop lines and add a bike box (Vejdirektoratet, n.d.a, n.d.c).

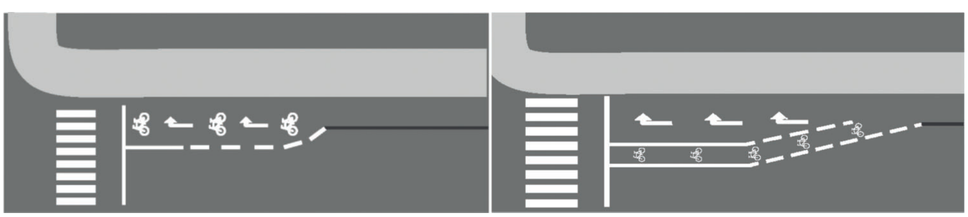


Figure 2.9 Two types of truncated cycle track (Vejdirektoratet, n.d.f, n.d.e).

Figure 2.10 Offset bicycle passage (Vejdirektoratet, n.d.d).

in long waiting times for both drivers and cyclists. Moreover, separate phasing (depending on how many flows that are controlled separately in the intersection) requires a lot of space, meaning that this solution cannot be established in all intersections.

The last countermeasure is the offset passage, shown in Figure 2.10. Cycle lanes have been led around the corners of the intersection, and cyclists' crossing of the intersecting road is slightly offset towards the right in relation to the original direction of travel. The design makes it possible to exempt cyclists from the signal control when driving into the intersection. The right-turning cyclists can thus bypass the signal control, and the cyclists going straight ahead will not be controlled by a signal until the stop lines right by the intersecting road.

3. DATA COLLECTION

In this study, we collect two main datasets which are right-turn lane charactersitics and crashes. The right-turn lane charactersitics data includes geometric design variables, traffic condition, and traffic management which are collected for right-turn lanes located on inter-state highways, state higways, ramps, and local roads. In addition, the crash data is also collected at the census and zip code levels. The data collection methods used in this study are illustrated in Figure 3.1.

3.1 Intersection Sampling

3.1.1 Candidate Counties and Intersection Inventory

We select 10 out of 92 counties in Indiana, considering their spatial locations and importance. The distributions of the 10 counties are shown in Figure 3.2. In addition, we summarize the subdivisions for each of the 10 counties, mainly using spatial units of ZCTA (Zip Code Tabulation Area) and the census tract, in Table 3.1.

3.1.1.1 Major highways (US/state). The geodatabase, shared by INDOT, contains all the US and state highways intersections. There is no information about intersections on inter-state and local highways in the dataset. In total, it presents 1,449 intersections across the whole Indiana state. Within the geodatabase, it provides turn-lane types (i.e., right-turn, left turn, both left and right, multiple right, multiple left, or multiple

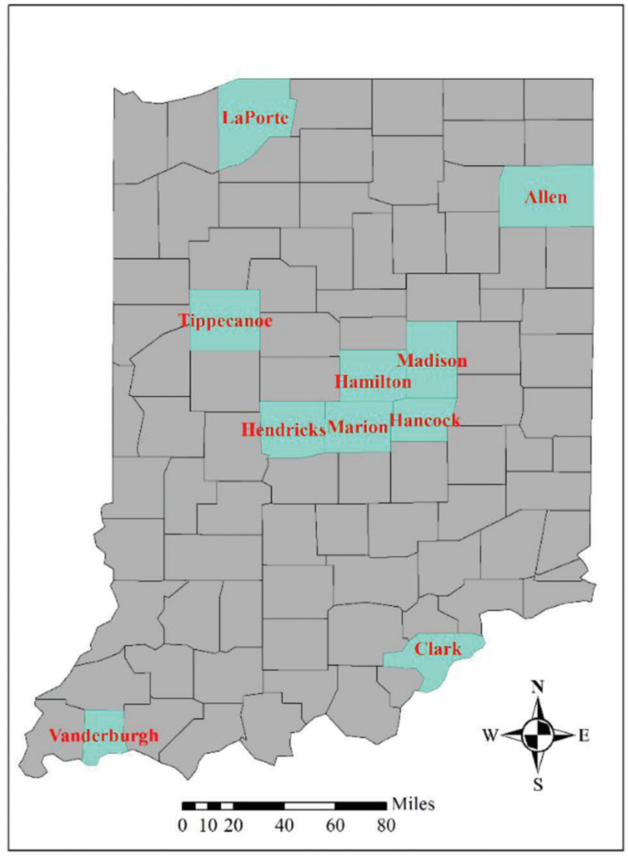


Figure 3.2 Spatial distribution of candidate counties.

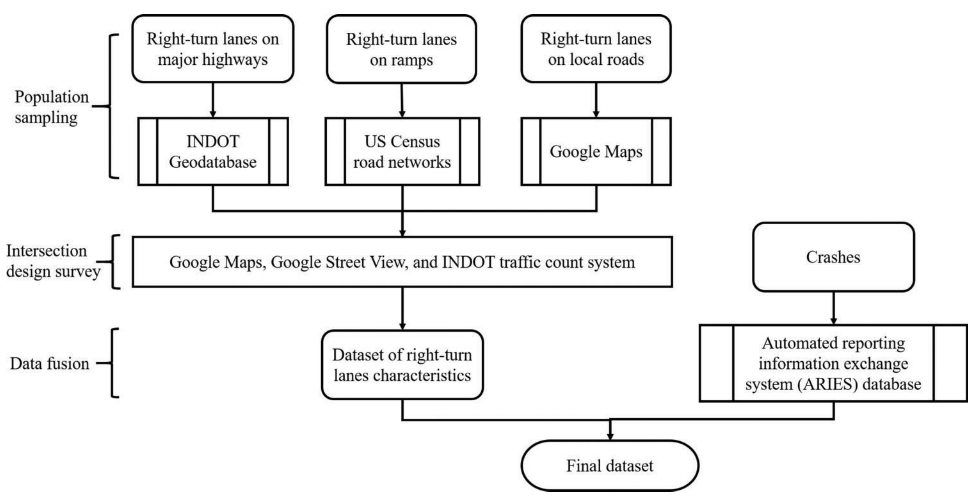


Figure 3.1 Data collection framework.

TABLE 3.1
List of candidate counties and corresponding subdivisions

Code	County Name	# of ZCTA	# of Census Tract
003	Allen	35	96
019	Clark	19	26
057	Hamilton	24	39
059	Hancock	18	10
063	Hendricks	24	21
091	La Porte	21	28
095	Madison	23	37
097	Marion	45	224
157	Tippecanoe	21	37
163	Vanderburgh	16	49
Total		*246*	*567*

both left and right) for each intersection, as well as location information, as shown in Figure 3.3.

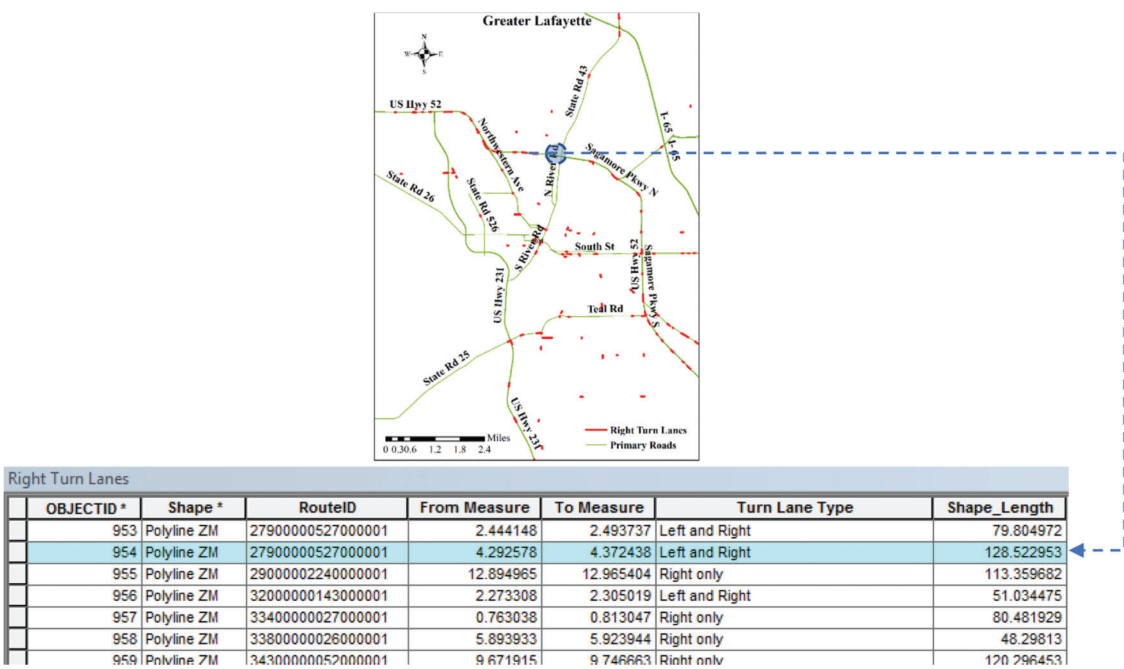
3.1.1.2 Interstate highways (entry/exit ramps). In general, almost all ramps are installed right-turn lanes while intersecting with regular highways. As such, we assume right-turn lanes are designed for all exit and entry ramps at the downstream and upstream, respectively. Therefore, if we have a full list of ramps, we can run a random sampling.

We use a new geodatabase from the US Census Bureau, called Tiger/Line. The geodatabase contains complete road networks for all counties in the US. For instance, the left plot in Figure 3.4 shows the completed road network in Tippecanoe County in Indiana. More importantly, the database provides a road type of each road segment, such as "I-interstate," "US-US highways," and "- undefined." In this geodatabase, the ramps are labeled as undefined road type. Therefore, we first filter out the links labeled as "I-interstate" highways and "undefined," as shown in the right plot of Figure 3.4. Then, spatial selection is run in ArcGIS to find undefined links, which intersect interstate highways. Finally, the outputs from spatial selection (i.e., undefined links intersecting interstate highways) are the sets of ramps in those 10 counties.

The ramps identified from the proposed method, however, may include a few errors. The errors happen when an overpass bridge is plotted as a separate link and is labeled as an "undefined" road type in the database. Under this circumstance, the overpass bridge link intersects the interstate highway link, and we will wrongly recognize the intersection as a ramp. However, this is not a common case.

3.1.1.3 Local roads (county/driveways). As per the *Access Management Manual*, right-turn deceleration lanes will be designed in the following circumstances: (1) the speed is over 45 mph and the right-turn volume is more than 50 vph; (2) the speed is less than or equal to 45 mph and the right-turn volume is more than 60 vph; or (3) because of other factors, such as crash records, heavy peak flow, large truck volumes, or limited sight distance. It is not common to have right-turn lanes at local (county) roads where have low speed and volume. However, a few roads are within the mentioned circumstances, so right-turn lanes need to be installed.

In this study, we utilize Google Maps for collecting needed data. Google Maps has advantages of up-to-date street view and detailed configurations at local levels. An example of a Google Maps local roads network is illustrated in Figure 3.5.



	OBJECTID *	Shape *	RouteID	From Measure	To Measure	Turn Lane Type	Shape_Length
	953	Polyline ZM	27900000527000001	2.444148	2.493737	Left and Right	79.804972
	954	Polyline ZM	27900000527000001	4.292578	4.372438	Left and Right	128.522953
	955	Polyline ZM	29000002240000001	12.894965	12.965404	Right only	113.359682
	956	Polyline ZM	32000000143000001	2.273308	2.305019	Left and Right	51.034475
	957	Polyline ZM	33400000027000001	0.763038	0.813047	Right only	80.481929
	958	Polyline ZM	33800000026000001	5.893933	5.923944	Right only	48.29813
	959	Polyline ZM	34300000052000001	9.671915	9.746663	Right only	120.296453

Figure 3.3 Information available in the shared INDOT geodatabase.

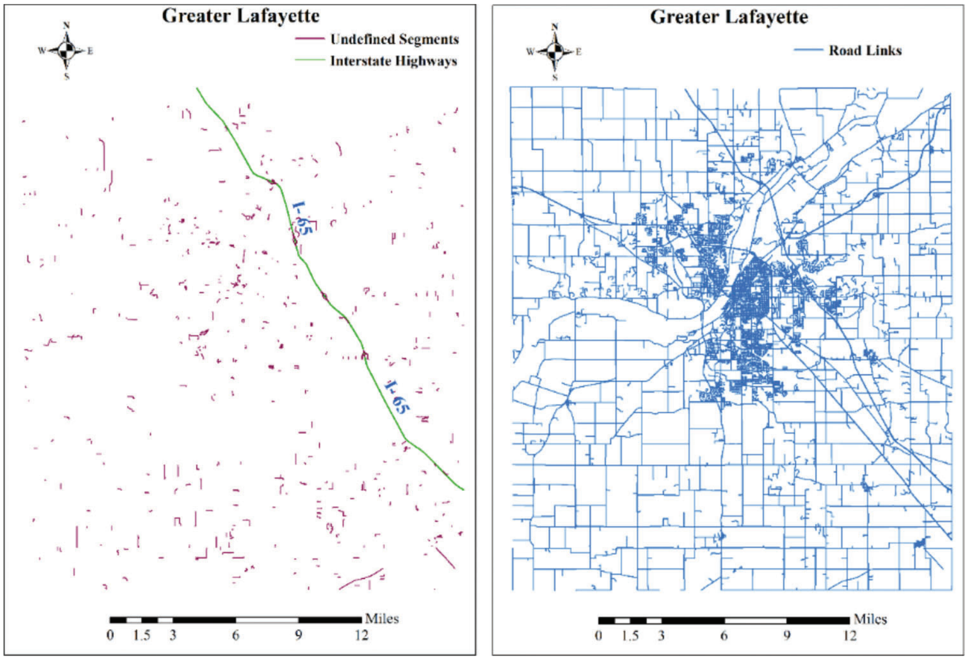


Figure 3.4 Illustration of data processing for ramp identification.

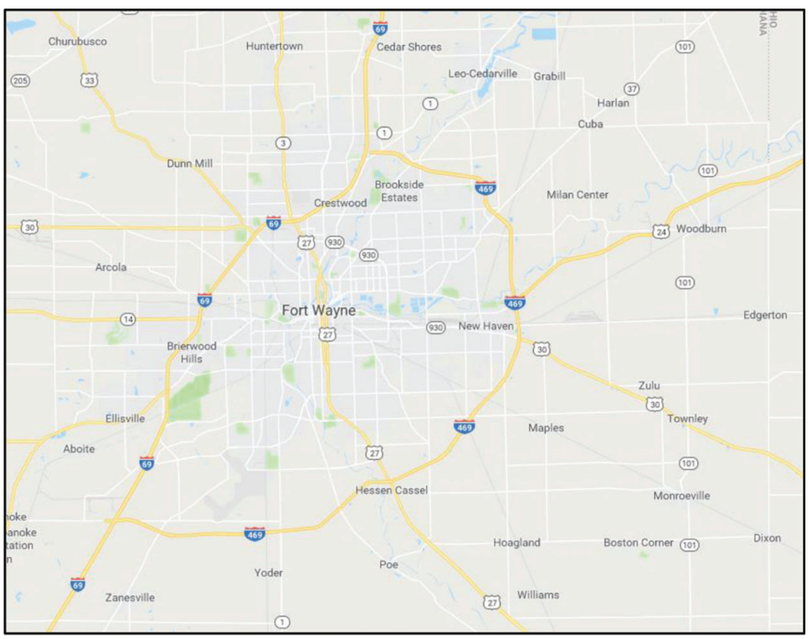


Figure 3.5 The Allen County road network (local roads are colored in white) (Google, n.d.m).

3.1.1.4 Right-turn lane intersections in each candidate county. The plots in Figure 3.6 show the distribution of right-turn lane intersections in each candidate county. Note that the plots only illustrate intersections with right-turn lanes on US/state highways and all exit and entry ramps (not include intersections with right-turn lanes on local roads).

3.1.2 Sampling Method

3.1.2.1 Major highways (US/state). Considering the future models will be estimated under different aggregation levels, such as county, ZCTA, and census tract, we run random sampling in the smallest spatial unit (i.e., census tract), then merge the sampled intersections

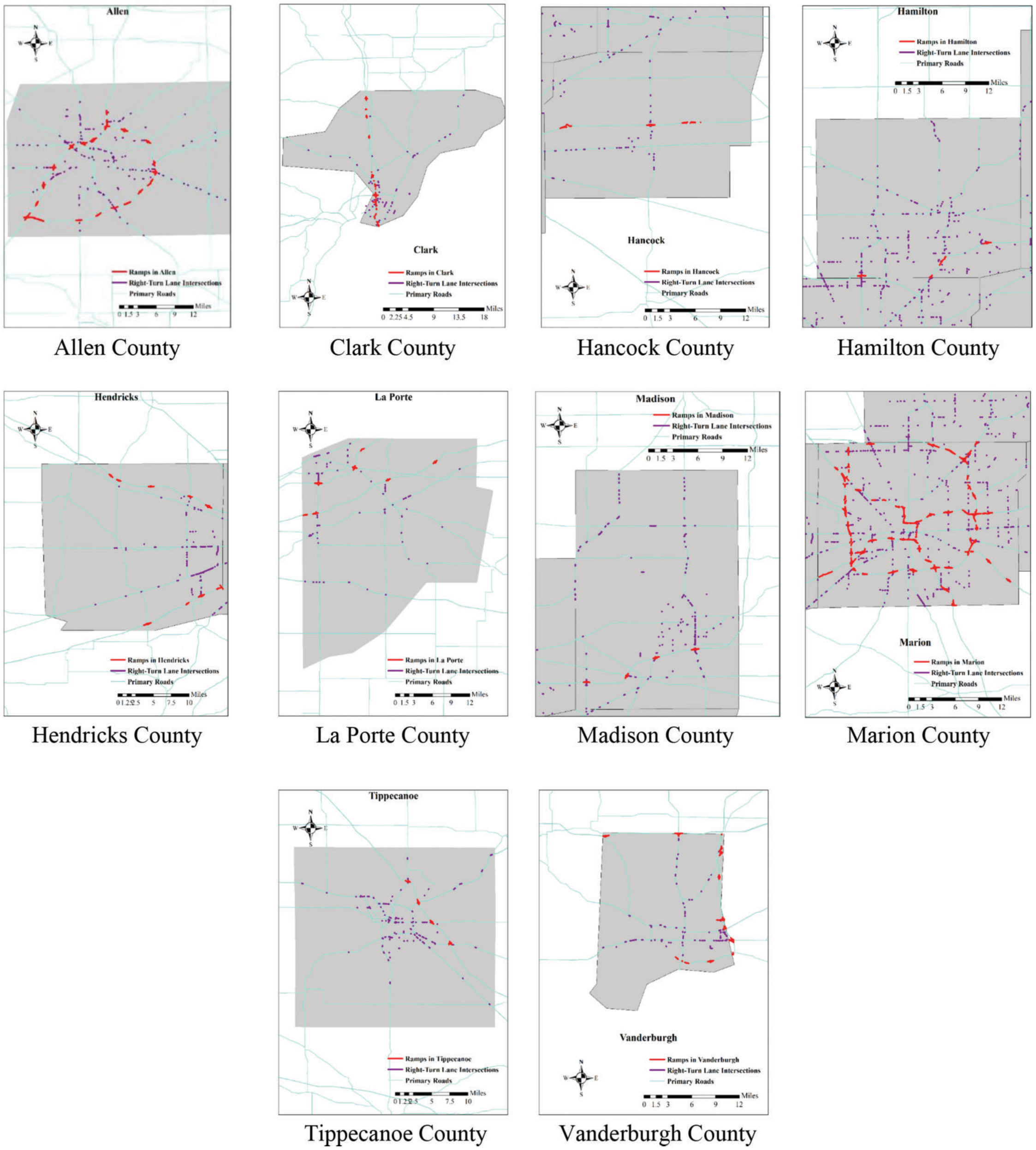


Figure 3.6 Right-turn lane intersections at 10 selected counties.

into a larger dataset for ZCTA and county based on spatial location. The following steps will be implemented:

1. We aggregate intersections at census tract levels and obtain the total numbers of intersections that are located in each of census tracts.
2. We conduct random sampling at a given ratio in each census tract and round the number to a nearest integer. For example, if one census tract has 3 intersections, we should randomly select 0.3 intersection given the sampling ratio of 10. The 0.3 will be rounded to 0, thus no intersections will be chosen in the census tract. However, for another case of 0.6 intersections, we will randomly select 1 intersection since we can round 0.6 to 1.
3. Based on spatial locations, we can identify the ZCTAs and counties of the sampled intersections.

The total numbers of all and sampled intersections (only considering three sampling ratio levels of 10%, 20%, and 30%) in each county are presented in Table 3.2. The full list of number of intersections in each census tract is separately shown in the attached worksheet.

3.1.2.2 Interstate highways (entry/exit ramps). The sampling method for ramps is slightly different from that of for major highways. This is mainly due to small numbers of ramps. If ramps are aggregated at census tract level, there are more likely to have less than 4 ramps in each census tract since there is only one interstate highway access for one or multiple census tracts. If we apply the previous method, we may not sample any ramp after rounding to nearest integers.

TABLE 3.2
Number of intersections under different sampling ratio

Code	County Name	# of Census	On Major Highways	10%	20%	30%
003	Allen	96	180	14	33	57
019	Clark	26	75	5	14	24
057	Hamilton	39	168	18	30	52
059	Hancock	10	50	4	9	15
063	Hendricks	21	97	8	19	29
091	La Porte	28	76	6	15	20
095	Madison	37	148	15	30	46
097	Marion	224	434	36	76	129
157	Tippecanoe	37	128	12	28	40
163	Vanderburgh	49	93	7	14	27
Total		*567*	*1,449*	*125*	*268*	*439*

TABLE 3.3
Number of ramps under different sampling ratios

Code	County name	Ramps (exit and entry)	10%	20%	30%
003	Allen	108	11	22	32
019	Clark	48	5	10	14
057	Hamilton	15	2	3	5
059	Hancock	13	1	3	4
063	Hendricks	26	3	5	8
091	La Porte	33	3	7	10
095	Madison	11	1	2	3
097	Marion	290	29	58	87
157	Tippecanoe	16	2	3	5
163	Vanderburgh	41	4	8	12
Total		*601*	*61*	*121*	*180*

Accordingly, we implement a random sampling with a given ratio at the county level other than at the census tract level (see Table 3.3). Then, the sampled ramps can be categorized to the ZCTA and census tract where they locate. This can enable us to obtain ramps at different levels, namely county, ZCTA, and census tracts.

3.1.2.3 Local roads (county/driveways). Identify right-turn lanes on local roads involve the screening of segments on Google Maps. To obtain random samples, the following procedures are needed.

1. For each county, five segments are selected. They should be distributed at Northwest, Northeast, Center, Southwest, and Southeast areas on the county map.
2. Each segment is about 2–5 miles in length.

As a result, the spatial distributions of segments in corresponding county are displayed in Figure 3.7. The list of segments including starting and ending points is displayed in Table 3.4.

3.2 Data Collection

3.2.1 Intersection Design and Traffic Characteristics

The intersection design and traffic characteristics include a set of measurements, for instance, intersection geolocation, name, and number of lanes of the road and the intersecting roads, right-turn lane layout, right-turn channelization, design speed, right-turn lane geometry, traffic control, traffic volume, and vulnerable traffic. All these measurements are manually surveyed through two data sources, namely Google Maps for designs and INDOT traffic count database system for traffic volume. The Table 3.5 summarizes all measurements, as well as the survey method. The summary of surveyed right-turn lanes is presented in Table 3.5, Table 3.6, and Figure 3.8.

3.2.2 Crash Data

The crash data is collected from the Automated Reporting Information Exchange System (ARIES), which records police crash reports. Considering the project needs, we request a 4-year crash dataset from 2013 to 2016. The dataset contains all crashes that happened in the 10 candidate counties, on both road intersections and road segments, summarized in Table 3.7. In the dataset, intersections are defined as a segment of "T-intersection," "Y-intersection," "four-way intersection," "five point or more," "traffic circle/roundabout," "railroad crossing," "interchange," and "ramp." Around 40% and 60% of crashes are at intersections and road segments, respectively. In our study, intersections are the locations of interests for design modifications in order to improve safety. As such, we only collect intersection-related crashes in which each data observation is recorded in detail. Besides, the combination of crash data and Google survey data has detailed characteristics which are summarized into categories at Table 3.8.

3.3 Data Fusion

Crashes are a vital factor to examine the safety performance. However, the crash dataset and surveyed dataset on sampled right-turn lanes which are collected from two different data sources (ARIES and Google Maps), do not have a common and unique ID for any intersection or right-turn lane. Therefore, the major

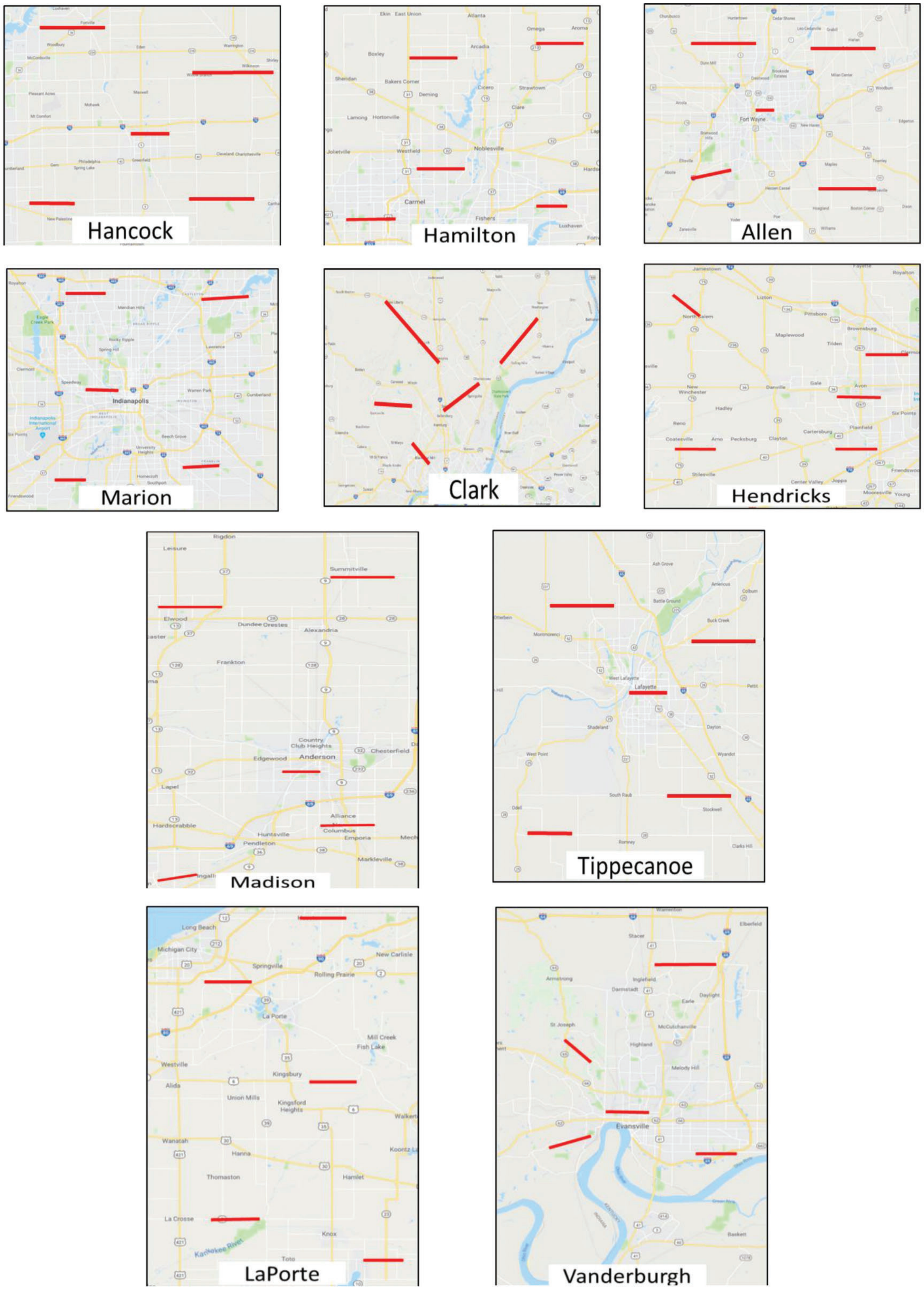


Figure 3.7 Spatial distributions of sampling segments in local roads.

TABLE 3.4
Detailed locations of local segments

Segment No.	From	To
Allen		
1	41.189673, -85.285574	41.195992, -85.143732
2	41.181026, -85.013025	41.183784, -84.873169
3	41.096354, -85.135515	41.097591, -85.092668
4	40.991980, -85.264449	41.002060, -85.192922
5	40.976317, -85.003051	40.978873, -84.881343
Clark		
6	38.565220, -85.867325	38.491955, -85.774419
7	38.541569, -85.543259	38.485684, -85.617034
8	38.452253, -85.672144	38.406420, -85.751808
9	38.346138, -85.816610	38.319024, -85.794455
10	38.418602, -85.915932	38.400585, -85.808280
Hamilton		
11	40.160100, -86.128010	40.161229, -86.052393
12	40.176435, -85.939694	40.177687, -85.865077
13	40.022070, -86.117353	40.021960, -86.042158
14	39.955602, -86.219722	39.956422, -86.149364
15	39.972166, -85.956989	39.973039, -85.893503
Hancock		
16	39.927721, -85.921062	39.929617, -85.820207
17	39.879768, -85.691446	39.880029, -85.575920
18	39.813738, -85.791234	39.814659, -85.726861
19	39.741407, -85.935710	39.742395, -85.879025
20	39.742676, -85.703417	39.742122, -85.607318
Hendricks		
21	39.893769, -86.688445	39.861952, -86.644343
22	39.806833, -86.396546	39.808047, -86.326642
23	39.747574, -86.433548	39.748401, -86.367009
24	39.674186, -86.438620	39.674713, -86.376822
25	39.674092, -86.687758	39.673825, -86.617431
La Porte		
26	41.752845, -86.677953	41.753163, -86.601749
27	41.665791, -86.849301	41.657374, -86.765422
28	41.518306, -86.668982	41.520389, -86.573551
29	41.317540, -86.834550	41.317111, -86.756285
30	41.259034, -86.567756	41.259000, -86.501831
Madison		
31	40.291375, -85.861445	40.292028, -85.786944
32	40.328405, -85.673050	40.328400, -85.588969
33	40.087416, -85.699173	40.087310, -85.677485
34	40.019155, -85.679330	40.018895, -85.614772
35	39.948705, -85.864964	39.958763, -85.814945
Marion		
36	39.910941, -86.263536	39.911992, -86.201824
37	39.904973, -86.041247	39.898255, -85.978247
38	39.780370, -86.231115	39.780951, -86.175337
39	39.662099, -86.303277	39.663034, -86.230956
40	39.680909, -86.079781	39.681502, -86.017726
Tippecanoe		
41	40.504908, -87.029007	40.504140, -86.916011
42	40.461194, -86.810158	40.465232, -86.708346
43	40.410054, -86.892865	40.410575, -86.851924
44	40.258510, -87.072467	40.258621, -87.006515
45	40.301707, -86.843101	40.301346, -86.731286
Vanderburgh		
46	38.123142, -87.553304	38.122567, -87.528756
47	38.049685, -87.638834	38.035070, -87.622150
48	37.984219, -87.600412	37.984758, -87.559900
49	37.952751, -87.659979	37.960397, -87.618952
50	37.948049, -87.511281	37.947979, -87.459869

objective of data fusion is to obtain the crashes at our manually surveyed intersections. Another big concern is the quality of intersection sampling. We should obtain a full list of crashes at all intersections with right-turn lanes, not limited to the surveyed intersections. Thus, the second objective of data fusion is to obtain the full list of intersections with right-turn lanes, as well as corresponding crashes.

The major objective can be achieved by finding a common identity across datasets and matching identities. The main identities that we use for both datasets are the roadway name and intersecting roadway name. The matching step yields a subset of crashes happened at the intersections with target right-turn lanes. The following string-matching method is proposed to complete data fusion:

1. Generate unique crash location ID by combining the road name and the intersecting road name. For example, a crash at the intersection of state road 1 (SR1) and north main street (NMAIN) will have a unique location ID of "SR1NMAN."
2. Similarly, generate unique location ID for surveyed intersections (road names from Google Maps).
3. Compute similarity ratio of two location IDs and do string matching

$$sr = \frac{2^{*} len(cs)}{len(s1) + len(s2)} \qquad \text{(Eq. 3.1)}$$

   where, *sr* is the similarity ratio; *len( )* returns the length of one string; cs is the common characters from the first occurrence of common characters; s1 is the string 1; and s2 is the string 2.
4. Match surveyed intersections with crashes if corresponding similarity ratio is greater than 0.85.

The second objective can be achieved by a proposed two-step method. First, we determine the road names for right-turn lanes in INDOT Geodatabase. Since the geodatabase only provides geolocation but not any road name information for right-turn lanes. Then we can repeat the matching process developed for the major objective, just replacing the surveyed intersections with all intersections in INDOT geodatabase.

In the first step of road name determinations, we can complete with the following procedures:

1. Get potential intersection points (black points in Figure 3.9) with road name information with road network shapefile from US census, which can be completed with the "intersection" tool in ArcGIS.
2. Compute the distance between every intersection point and its closest right-turn lane (the red line in Figure 3.9).
3. Filter out target intersection points with a threshold of 0.0005 (around 60 m).
4. Assign a unique intersection ID if distance between two intersection points are less than 100 m or if two intersection points have same name. Note that one physical intersection may have multiple intersection points in the road network shapefile, since one road may have multiple road names and two directions separated by median, shown in Figure 3.10.

TABLE 3.5
Survey on intersection design and traffic characteristics

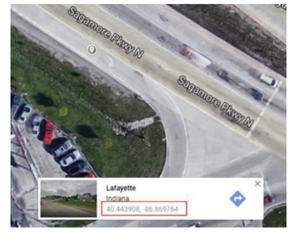
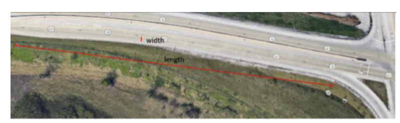
Measurement	Survey Method	Note
Geolocation	Any point locates on right-turn lane, identified on Google Maps, and presented with longitude and latitude	 (Google, n.d.h)
Road name Intersecting road name Number of lanes on the road Number of lanes on the intersecting road Skewness Number of legs	Manually measured from Google Maps	 (Google, n.d.i)
Number of right-turn lane Channelization type Turning radius Right-turn lane layout (deceleration/ acceleration)	Manually measured from Google Maps	 (Google, n.d.l)
Length of right-turn lane Width of right-turn lane	Manually measured from Google Maps	 (Google, n.d.e)
Length of acceleration lane Width of acceleration lane	Manually measured from Google Maps	 (Google, n.d.a)
Design speed on the road	Manually measured from Google Street View on Google Maps	 (Google, n.d.b)

TABLE 3.5
(Continued)

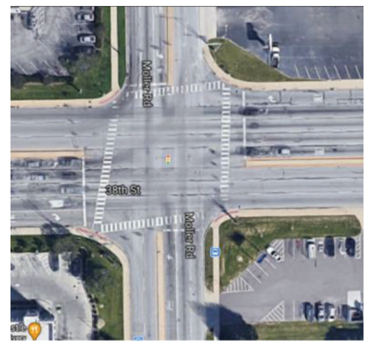
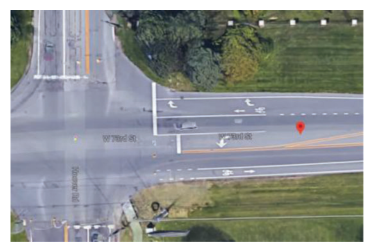
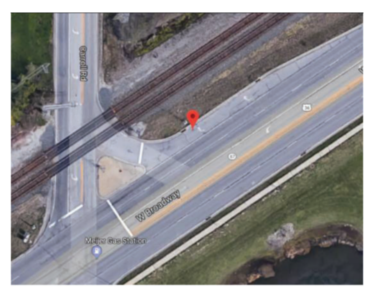
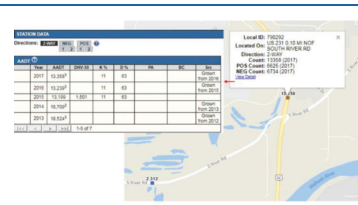
Measurement	Survey Method	Note
Traffic signal	Manually measured from Google Street View on Google Maps	 (Google, n.d.j)
Pedestrian crossing	Manually measured from Google Maps	 (Google, n.d.f)
Truncated bicycle lane	Manually measured from Google Maps	 (Google, n.d.k)
Railroad crossing	Manually measured from Google Maps	 (Google, n.d.g)
Traffic volume in both directions Traffic volume in the same direction Traffic volume in the opposite direction	Measured from INDOT traffic count database	 (Google, n.d.c)

TABLE 3.6
Number of surveyed intersections

		On Major Highways			Ramps			Local		Total	Surveyed
Code	County	Population	Sampled	Surveyed	Population	Sampled	Surveyed	Segments	Surveyed	Surveyed	Intersections
003	Allen	180	57	50	108	32	27	1	1	78	72
019	Clark	75	24	22	48	14	12	2	2	36	30
057	Hamilton	168	52	47	15	5	7	2	8	62	53
059	Hancock	50	15	15	13	4	5	2	6	26	21
063	Hendricks	97	29	30	26	8	11	3	14	55	49
091	La Porte	76	20	21	33	10	1	1	1	24	20
095	Madison	148	46	45	11	3	3	2	2	50	46
097	Marion	434	129	133	290	87	79	0	0	212	175
157	Tippecanoe	128	40	43	16	5	2	2	4	49	43
163	Vanderburgh	93	27	25	41	12	9	4	6	40	36
Total		*1,449*	*439*	*431*	*601*	*180*	*156*	*19*	*44*	*631*	*545*

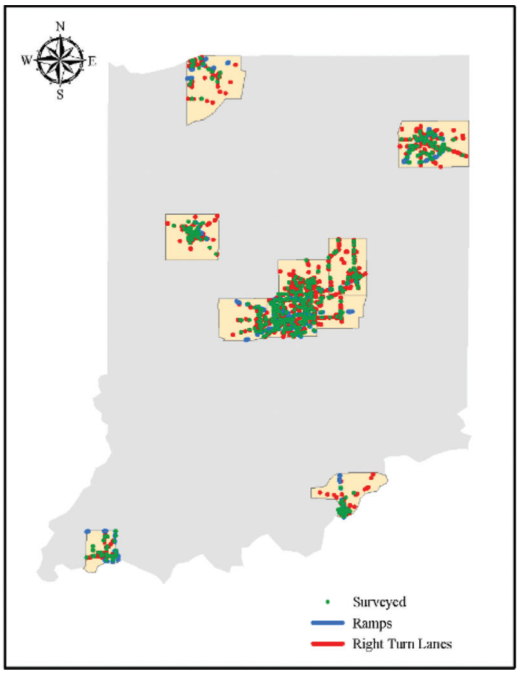


Figure 3.8 Spatial distribution of surveyed right-turn lanes.

Finally, we identify 1,319 intersections (with road names) for all 1,449 right-turn lanes in INDOT Geodatabase. The road name matching further yields a set of crashes on all intersections with right-turn lanes. The INDOT Geodatabase only presents the right-turn lanes on regular highways, for instance, US/state/county highways and urban streets, other than ramps of interstate highways. Regarding the full list of crashes on ramps, we assume the intersections connecting the interstate highways with regular highways must have special right-turn designs, such as channelization and right-turn lanes. Thus, we can just filter out crashes on ramps as the full list then compare with the set of crashes on sampled ramps. The crash frequency of every intersection (including sampled and not sampled) is shown in Figure 3.11.

TABLE 3.7
Crash frequency summary

Items	2013	2014	2015	2016	Total
All crashes	*74,760*	*79,400*	*86,815*	*91,930*	*332,905*
On segments	44,757	47,835	52,310	55,550	200,452
At intersections	29,955	31,531	34,467	36,338	132,291
% of intersection crashes	40.06%	39.71%	39.70%	39.53%	39.74%

Tables 3.9, 3.10, 3.11, and 3.12 show the crash frequency by year, locations, and crash types. Overall, we can conclude that the intersection with right-turn lanes have relatively more crashes than intersections without right-turn lanes. Since the 1,319 regular intersections with right-turn lanes, as well as 601 ramps, have around 24% of intersection crashes, but the number of intersections with right-turn lanes are far smaller than the total number of intersections. Because right-turn lanes are mainly built on large intersections with heavy flows and frequent turns. Table 3.9 also indicates that crashes are likely to distributed randomly and there are almost no significant high-risk or low-risk intersections, given the fact that 30% of intersections yield around 30% of crashes. Comparing the percentage in Table 3.10 and 3.11, we also observe several additional interesting points, including (1) both right-turn related and rear-end crashes are significant crash types on regular highways but only rear-end crashes are significant on ramps; (2) installing right-turn lanes can reduce right-turn related crashes; and (3) installing right-turn lanes can increase the rear-end crashes.

3.4 Selection Bias During Sampling

The selection bias is one popular bias during sampling, which results from the different crashes by values of variables between sampled and population dataset. The objective of this section is to validate whether our sampling during manual survey presents selection

TABLE 3.8
Attributes of crash records from ARIES

Classification	Attributes
Crash location and time	Date Time County Township City Locality Longitude and latitude
Crash descriptions	Number of dead Number of injured Number of deer Number of vehicles involved Number of trailers involved Direction Damage estimates Primary factor Collision manner
Roadway characteristics	Roadways name Roadway number Roadway ramp number Intersecting roadway name Intersecting roadway number Median type Junction type Road character (straight or not; at grade or not) Road surface type Number of legs Marking traffic island Exclusive shared right turn lane Number of lanes in RTL Direction of the RTL Length of the RTL Width of the RTL Acceleration/Deceleration lane Acceleration lane length Acceleration lane width Turning radius Skewness Pedestrian crossing at RTL Truncated bicycle lane Railroad crossing
Environment and surroundings	School zone Construction Light Leather Surface condition
Traffic characteristics	Traffic control Traffic control devices Rumble strips Volume both direction (major road) Volume POS (major road) Volume NEG (major road) Volume both direction (minor road) Volume POS (minor road) Volume NEG (minor road) Design speed
Drivers' characteristics	Aggressive driving Hit and run

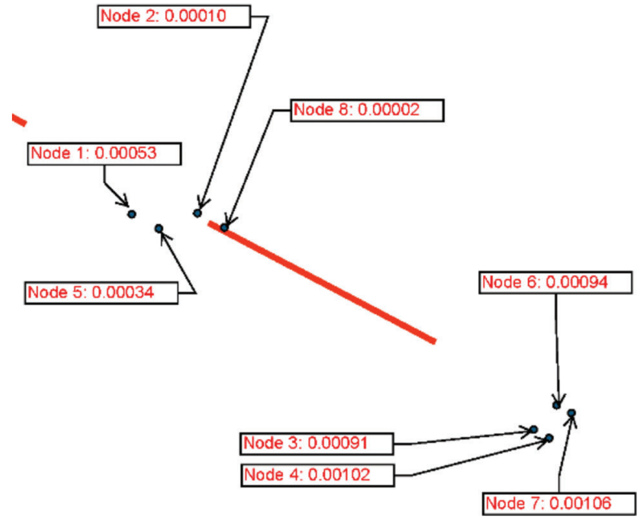


Figure 3.9 Illustration of road name determinations for right-turn lanes.

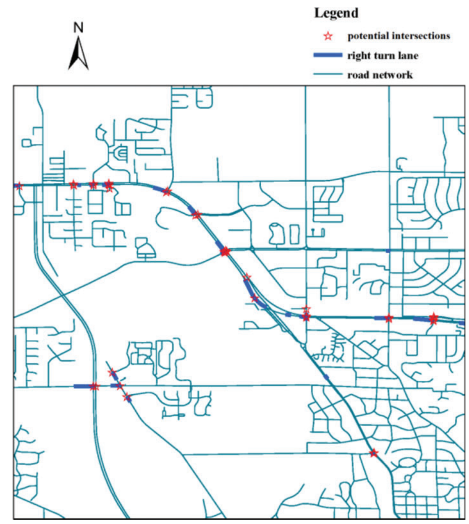
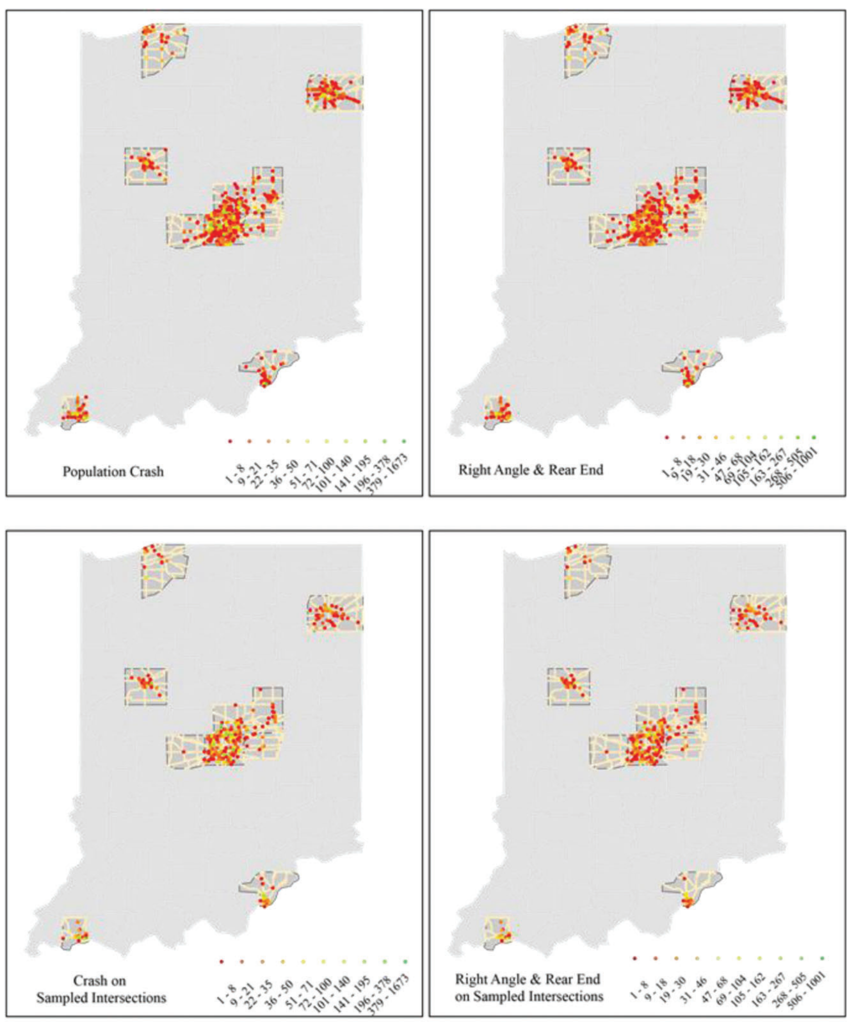
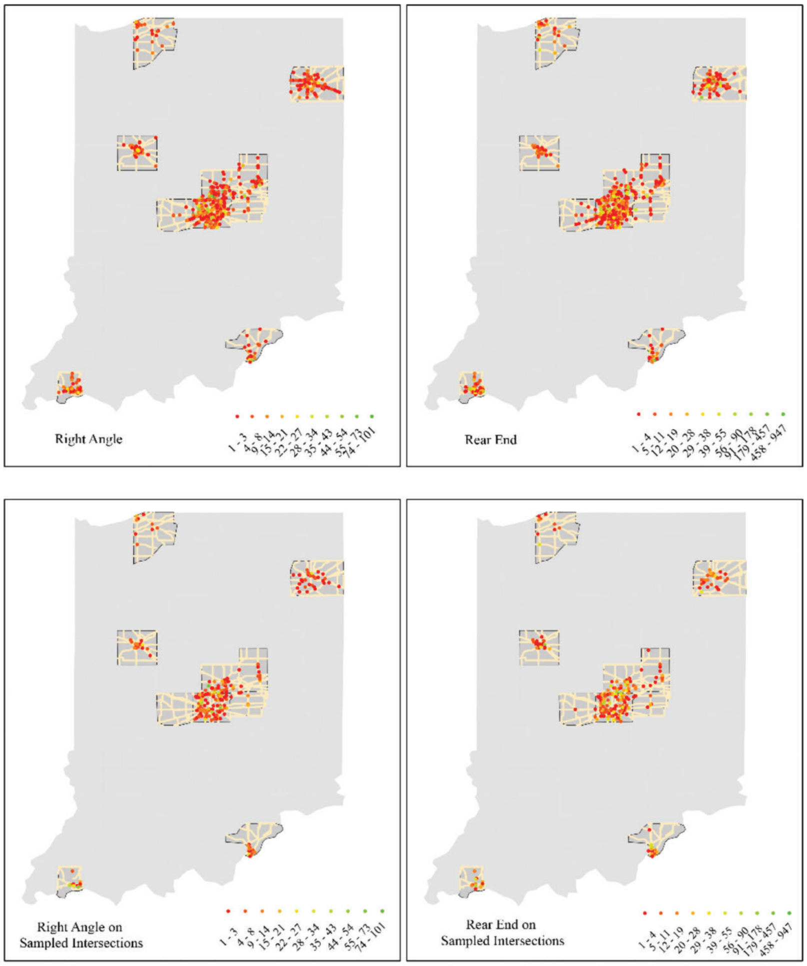


Figure 3.10 Illustration of multiple intersection points for physical intersection.



(a) Frequency of all types of crashes and two major types of crashes

Figure 3.11 Continued.



(b) Frequency of two major types of crashes

Figure 3.11 Crash frequency of all intersections and sampled intersections.

TABLE 3.9
Crash frequency by year and locations

Items	2013	2014	2015	2016	Total
All Crashes at Intersections in the 10 Counties					
Without right-turn lanes	22,504	23,820	26,244	27,718	100,286
With right-turn lanes	7,451	7,711	8,223	8,620	32,005
% of right-turn crashes	24.87%	24.45%	23.86%	23.72%	24.19%
All Crashes at Intersections with Right-Turn Lanes					
No. of crashes	7,451	7,711	8,223	8,620	32,005
On major highways	5,198	5,439	5,643	5,727	22,007
On ramps	2,253	2,272	2,580	2,893	9,998
All Crashes at 30% of Surveyed Intersections with Right-Turn Lanes					
No. of crashes	2,152	2,402	2,266	2,454	9,274
On major highways	1,885	2,152	2,008	2,180	8,225
On ramps	267	250	258	274	1,049
% of crashes at surveyed intersections	28.89%	31.15%	27.56%	28.47%	28.98%

TABLE 3.10
Frequency of right-turn related crashes

Items	2013	2014	2015	2016	Total	% of All Crashes
Right-Turn Related Crashes at All Intersections						
Crashes	8,651	9,291	9,470	10,170	37,582	28.41
Without right-turn lanes	7,089	7,601	7,816	8,402	30,908	30.82
Right-Turn Related Crashes at Intersections with Right-Turn Lanes						
Crashes	1,562	1,690	1,654	1,768	6,674	20.85
On major highways	1,341	1,478	1,457	1,516	5,792	26.31
On ramps	221	212	197	252	882	8.82
Right-Turn Related Crashes at 30% of Surveyed Intersections with Right-Turn Lanes						
Crashes	472	576	557	583	2,188	23.59
On major highways	445	556	524	552	2,077	25.25
On ramps	27	20	33	31	111	10.58

TABLE 3.11
Frequency of crashes by year

2013	2014	2015	2016	Total	% of All Crashes
8,651	9,291	9,470	10,170	37,582	28.41
7,089	7,601	7,816	8,402	30,908	30.82
1,562	1,690	1,654	1,768	6,674	20.85
1,341	1,478	1,457	1,516	5,792	26.31
221	212	197	252	882	8.82
472	576	557	583	2,188	23.59
445	556	524	552	2,077	25.25
27	20	33	31	111	10.58

TABLE 3.12
Frequency of rear-end crashes

Items	2013	2014	2015	2016	Total	% of All Crashes
Rear-End Crashes at All Intersections						
Crashes	10,430	10,766	11,739	12,704	45,639	34.50
Without right-turn lanes	7,073	7,417	8,137	8,928	31,555	31.46
Rear-End Crashes at Intersections with Right-Turn Lanes						
Crashes	3,357	3,349	3,602	3,776	14,084	44.01
On major highways	2,249	2,285	2,402	2,394	9,330	42.40
On ramps	1,108	1,064	1,200	1,382	4,754	47.55
Rear-End Crashes at 30% of Surveyed Intersections with Right-Turn Lanes						
Crashes	975	1,066	988	1,065	4,094	44.14
On major highways	845	939	866	933	3,583	43.56
On ramps	130	127	122	132	511	48.71

bias, as well as to identify what variables are biased if possible.

The chi-square method is proposed to compare the crash distribution between population and sampled datasets. The null hypothesis is that the two distributions in both datasets are statistically same at the confidence level of 95%. The main steps are as follows:

1. Group crash data by levels of one specific variable with a cross tabulation.
2. Compute the chi-square statistics and degree of freedom, then compare with critical values drawn from chi distribution.
3. Reject the null hypothesis if the computed statistic exceeds the critical one, which indicates the selection bias.

With the methods, we validate the selection bias in the dataset of crashes on regular highways, and in the dataset of crashes on ramps. This also indicates that we cannot remove selection bias even focusing on a certain type of crashes. Overall, two key variables show the significant selection bias, which are number of injuries and number of deaths. The two variables are very important for safety performance measurement, thus should be addressed appropriately in our modeling structure. The three other variables also demonstrate selection bias but only if we model crashes separately on regular highways or ramps, including manner of collision, number of involved vehicles, and number of involved deer. Several variables, for instance, season, light condition, weather, aggressive driving, school zone, and road surface condition, presents selection bias. The remaining variables are without any selection bias, including location/locality, year, and road design characteristics. The test results are summarized in Table 3.13. Furthermore, we also identify the selection bias in the dataset of both right-turn related and rear-end crashes, in the dataset of right-turn related crashes, and in the dataset of rear-end crashes. The corresponding test results are shown in Table 3.14. We can observe almost same set of variables with selection bias.

3.5 Crash Severity Measurement

The severity of each crash is measured in terms of the total monetary costs associated with the crashes. According to *Crash Cost for Highway Safety Analysis* (FHWA Safety Program), the crash cost calculation includes fatality cost, injury cost, property-damage-only (PDO) cost, economic crash unit cost, and quality-adjusted life years (loss of life quality costs) (Harmon, 2018). Besides, we calculate the cost adjusted per year for the state of Indiana using consumer price index (CPI) and national and state per capita income (PCI). The national KABCO person-injury unit cost is regarded as the base year calculation and the corresponding transferred value in each year can be seen in Table 3.15.

Where the cost of a fatality is K, and the cost of an injury is the average of A, B, and C injury levels. The property damage only (PDO) is the average value within the range of the damage estimate variable in the dataset.

3.6 Statistics Over Crashes

The statistics of crashes simply reveals the crash distributions by right-turn lane and intersection designs, mainly based on the crashes on intersections with right-turn lanes. Additionally, we also examine the safety performance of right-turn lanes by comparing the crash distribution between intersections with and without right-turn lanes. The comparison is also based on the proposed chi-square based method for selection bias test. From the comparison results shown in Table 3.16, we can conclude that (1) there are almost no differences in crash severity when all crash types are considered; (2) there are reduced death and injuries in the two major crash types (i.e., right-turn related and rear-end) if installing right-turn lanes on regular intersections and ramps; and (3) there are increased injuries in right-turn related crashes in the presence of right-turn lanes on regular US/state/county highways and urban streets.

TABLE 3.13
Variables with selection bias in the dataset with all crash types

Variables	Rear-End Crashes	On Ramps	On Major Highways
Injured/Death	More injured less death	More injured/–	Less injured and death
Trailers/Vehicles	–	–	Less involved trailers/–
Deer	–	Less with deer	–
Rumble strips/Aggressive driving	–	Less with rumble strips/Less with aggressive driving	–
Damage	–	More with losses	–
School zone	Less with school zone	–	More with school zone
Hit and run	More hit and run	–	Less hit and run
Light	More in dawn and daylight	More in dawn/Dusk	More in dawn and daylight
Road surface condition	–	More on dry, snow, and icy surface	–
Seasons	More in winter	Less in winter	–
Weather	–	–	More in clear, raining, and foggy days
Road character/Road surface	–/–	More on straight/More on concrete	–/–

TABLE 3.14
Variables with selection bias in the dataset with two major crash types

Variables	Rear-End Crashes	On Ramps	On Major Highways
Dataset with Both Right-Turn Related and Rear-End Crashes			
Injured/Death	More injured less death	–	Less injured and death
Trailers	More without trailers	More with trailers	More without trailers
Deer	More without deer	More with deer	–
Vehicles	More with multiple vehicles involved	–	More with multiple vehicles involved
Rumble strips/ Aggressive driving	–	More without rumble strips/With aggressive driving	–
Damage	–	More with lower or higher losses	More with moderate or higher losses
Manner of collision	–	More with right-turns	–
School zone	More with school zone	More without school zone	More with school zone
Hit and run	More hit and run	–	Less hit and run
Light	More in dark	More in dark and dawn/Dusk	–
Road surface condition	–	More on dry and snow surface	–
Seasons/Year	More in summer, fall, winter/–	More in summer/In 2013 to 2015	More in fall, winter/–
Weather	More in clear and raining days	More in cloudy and foggy days	More in clear and raining days
Road character/ Road surface	–	More on straight/Level and straight/ Hillcrest/Concrete	–/More on concrete
Dataset with Only Right-Turn Related Crashes			
Injured/Death	More crashes with injuries, but less with death	–	–
Trailers	More crashes without trailers	More crashes with trailers	More crashes without trailers
Deer	More without deer	–	–
Vehicles	–	More 2-vehicle crashes	–
Rumble strips/ Aggressive driving	–/–	More with rumble strips/Less with aggressive driving	–/–
Road surface/ Road character	More on concrete/Curve-level and straight-hillcrest	–/Curve-grade and straight-hillcrest	More on concrete
Year/Location	More in 2014 to 2016/–	More in 2015/Rural areas	More in 2014 to 2016/–
School zone/ Construction zone	Less with school zones/More without construction zone		
Hit and run	More hit and run		
Light	More in dark, dawn, dusk		
Road surface condition	More in dry and snow		
Seasons	More in summer and fall		
Weather	More in raining, blowing, clear days	More in cloudy, blowing days	More in clear, blowing days
Dataset with Only Rear-End Crashes			
Variables	Rear-end crashes	On Ramps	On major highways
Injured/Death	More crashes with injuries, but less with death	–	–
Trailers	More crashes without trailers	–	–
Deer	More with deer	–	–
Vehicles	More one-vehicle crashes	–	More 1-vehicle crashes
Rumble strips/ Aggressive driving	–	More without rumble strips/More with aggressive driving	More with rumble strips
Damage	More with lower or higher losses	–	More with moderate losses
Location	More in urban areas	–	–
School zone	More with school zones	Less with school zones	More with school zones
Hit and run	More without hit and run	More hit and run	More without hit and run
Light	More in dark	More in dark and dawn/Dusk	More in dark and dawn/Dusk
Road surface condition	More on wet and water surface	More on dry and snow surface	–
Seasons/Year	More in summer, fall, and winter/–	More in summer/In 2013, 2014	More in fall and winter/–
Weather	More in cloudy, foggy, and raining days	More in cloudy, foggy, and snow	More in clear, raining and snow
Road character/ Road surface	–/–	More on level, straight, hillcrest, concrete	–/More on concrete

TABLE 3.15
Crash cost calculation and transferred monetary value (Harmon, 2018)

National KABCO Person-Injury Unit Costs (2010 dollars)			
Severity	**Economic Person: Injury Unit Costs ($)**	**QALY Person: Injury Unit Costs ($)**	**Comprehensive Person: Injury Unit Costs ($)**
K	1,398,916	7,747,082	9,145,998
A	84,507	363,324	447,832
B	32,105	97,974	130,079
C	21,749	49,926	71,675
O	5,717	2,563	8,280

Indiana KABCO Person-Injury Unit Costs (2010 dollars)				
Severity	**2013 ($)**	**2014 ($)**	**2015 ($)**	**2016 ($)**
K	1,317,805.72	1,320,902.61	1,314,494.71	1,436,616.32
A	79,607.22	79,794.30	79,407.20	81,347.63
B	30,243.53	30,314.60	30,167.54	30,904.73
C	20,487.98	20,536.12	20,436.50	20,935.89
O	5,385.52	5,398.18	5,317.99	5,503.27

TABLE 3.16
Crash distribution between intersections with and without right-turn lanes

Severity	Right-Turn Related	Rear-End
Both Regular Intersections and Ramps		
Death	0.01% more crashes without death 0.01% more crashes with 1 death 0.01% less crashes with 3 death	0.03% more crashes without death 0.01% more crashes with 1 death, 0.01% more crashes with 2 death
Injuries	0.26% more crashes without injuries 1% less crashes with 1 injury 0.64% more crashes with 2 injuries 0.1% more crashes with 3 injuries 0.05% more crashes with more than 5 injuries	—
Deer	0.02% less crashes without deer 0.02% more crashes with 1 deer 0.01% less crashes with more than 5 deer	0.03% less crashes without deer 0.01% more crashes with 1 deer 0.01% less crashes with 2 deer 0.02% more crashes with more than 5 deer
Regular Intersections		
Death	0.04% more crashes without death 0.02% more crashes with 1 death	0.01% more crashes without death 0.03% more crashes with 1 death 0.01% more crashes with 2 death
Injuries	0.30% less crashes without injuries 0.7% less crashes with 1 injury 0.77% more crashes with 2 injuries 0.24% more crashes with 3 injuries 0.01% less crashes with 4 injuries 0.06% more crashes with more than 5 injuries	—
Deer	0.06% more crashes without deer 0.08% less crashes with 1 deer 0.01% more crashes with 2 deer 0.01% less crashes with more than 5 deer	0.04% less crashes without deer 0.02% more crashes with 1 deer

3.6.1 Crash Frequency by Location

There are around 9,274 crashes and were found at 355 unique intersections. As such, the average crashes per intersection is around 26 crashes. Figure 3.12 presents crashes at intersection by frequencies from smallest to largest.

Table 3.17 shows a list of top 5 most-frequent-crash intersections. The intersection of Georgetown road and 38th street is found to have the largest number of crashes (213 crashes) over 4 years from 2013 to 2016. This intersection is located at Marion County in Indianapolis area.

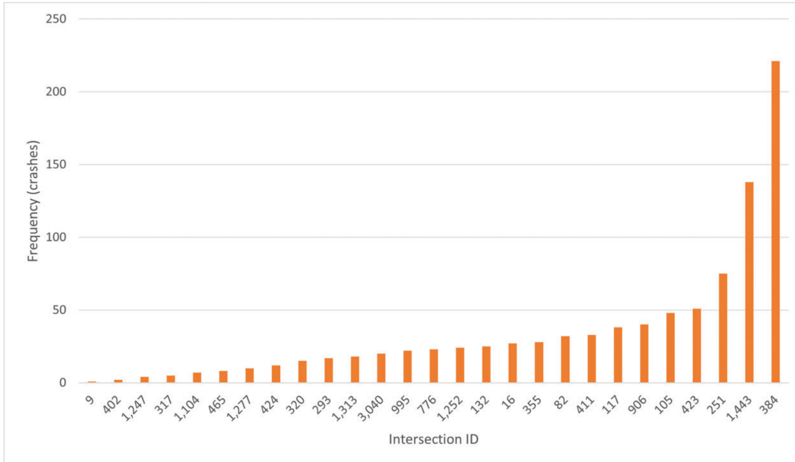


Figure 3.12 Crash frequency by intersection.

TABLE 3.17
The most frequent crash intersections are in the Indianapolis metro area

Roadway	Intersection	County	City	Frequency (crashes)
South	N Creasy Ln	Tippecanoe	Lafayette	155
E Virginia	N Burkhardt Rd	Vanderburgh	Evansville	156
E 116th St	Keystone Pkwy	Hamilton	Carmel	162
W 146th St	Spring Mill Rd	Hamilton	Carmel	175
Georgetown	38th St	Marion	Indianapolis	213

3.6.2 Crash Frequency by Time of Day

There are 6,896 crashes at daytime and 2,379 crashes at night time (daytime: 6:00 am–18:00 pm; night time: 18:00 pm–6:00 am the second day). Besides, the crash frequency in Marion is much higher than other counties. The possible reasons are that the day traffic volume is much higher than it is at night; Indianapolis, the capital of Indiana, is in Marion County and has higher traffic volume than other counties. Statistical analyses of the crash frequency in different locations with the time of day include the following:

- The highest crash frequency by roadway class: Local/city Road: 7,078 (76% in total crashes).
- The highest crash frequency by time and roadway class: Local/city Road (day: 5,288, night: 1,790). It is shown at Figure 3.13.
- The highest crash frequency at the county level: Marion (4,828).
- The highest crash frequency by time and county: Marion (day: 3,505, night: 1,323). See Figure 3.14.

3.6.3 Crash Severity by Time of Day

The overall crash cost at local/city road is higher than other roadway class at both day and night. However, the state road has the highest cost per crash at daytime ($29,559) and US road has the highest cost per crash at nighttime ($25,113). The crash cost in roadway

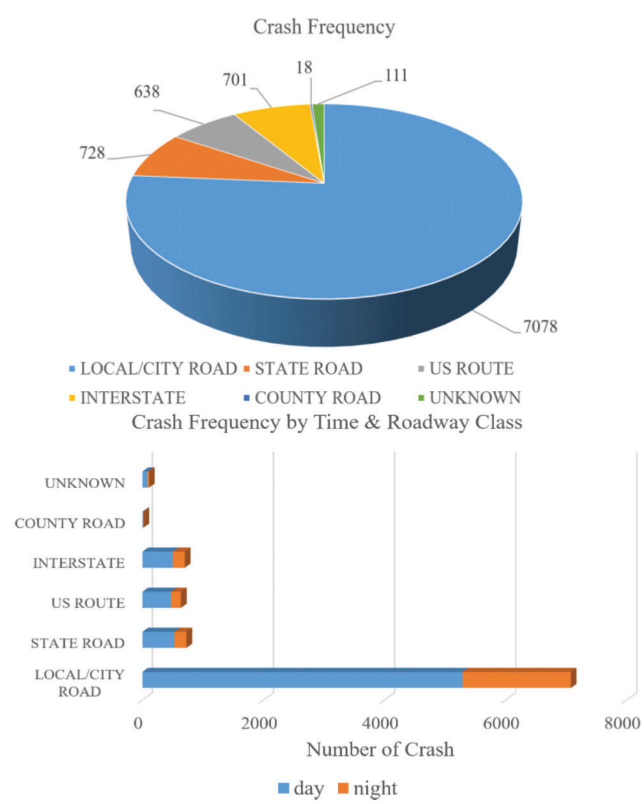


Figure 3.13 Crash frequency at roadway class level by time of day.

class level by time of day can be seen in Table 3.18 and Figure 3.15. The overall crash cost in Marion is highest among all other counties at both day and night (see Figure 3.16). Besides, Clark has the highest cost per crash at both daytime ($37,313) and nighttime ($24,084); There are over 38% of crashes associated with intersection designs as presented in Table 3.19.

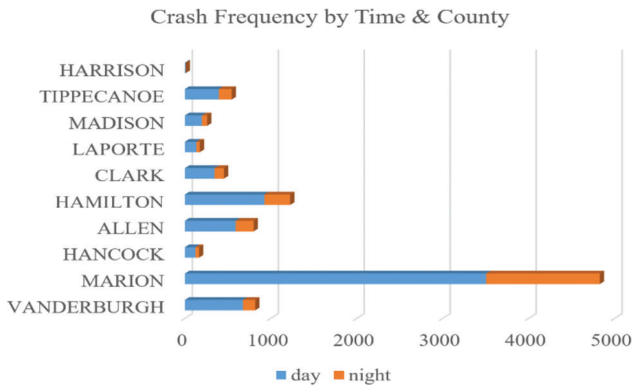


Figure 3.14 Crash frequency at the county level by time of day.

3.6.4 Crash Frequency by Geometric Design Factors

Significant performance metrics are found at different right-turn traffic control at traffic light intersections. Right-turn-on-red signal intersections crated a large number of crashes (about 60%), while full stop or no-turn-on-red signal intersections only generated very few crashes (about 3%) (see Figure 3.17). About 70% of crashes were happened at four-way intersections as can been seen at Figure 3.18.

3.6.5 Crash Frequency by Right-Turn Lane Types

More than 80% of crashes are found to happen at exclusive right-turn lanes. In which, over 60% crashes happened at urban-road intersections, while only a few crashes happened at interstate- and rural-road intersections (see Figure 3.19). The highest numbers of injuries and dead are found at exclusive right-turns lanes (see Figure 3.20).

In straight/level shared right-turn and exclusive right-turn lanes, there were a majority of crashes as can be seen in Table 3.20. For the manner of collision, right-angle and rear-end crashes have been found as the most frequent crashes as shown in Table 3.21.

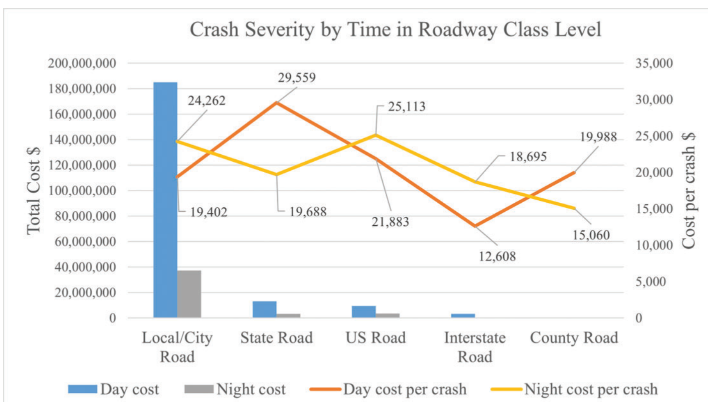


Figure 3.15 Crash severity at roadway class level by time of day.

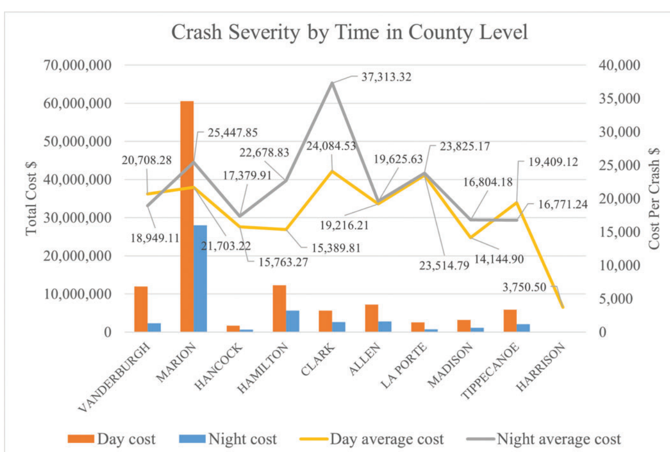


Figure 3.16 Crash severity at the county level by time of day.

TABLE 3.18
Crash cost at roadway class level by time

Roadway Class	Day Cost	Day Cost per Crash	Night Cost	Night Cost per Crash
Local/City road	185,036,716	19,402	37,364,929	24,262
State road	13,094,658	29,559	3,307,618	19,688
US road	9,431,864	21,883	3,541,037	25,113
Interstate road	3,202,565	12,608	175,324	18,695
County road	279,832	19,988	75,301	15,060

TABLE 3.19
Top main factors contribute to crashes

Main Factor	Crash Frequencies	Crashes (%)
Unsafe speed	152	1.65
Ran off road right	168	1.82
Unsafe backing	174	1.88
Speed too fast for weather conditions	251	2.72
Driver distracted–explain in narrative	253	2.74
Improper turning	267	2.89
Unsafe lane movement	304	3.29
Improper lane usage	305	3.30
Other (driver)–explain in narrative	422	4.57
Disregard signal/reg sign	917	9.92
Failure to yield right of way	2,317	25.08
Following too closely	3,198	34.61

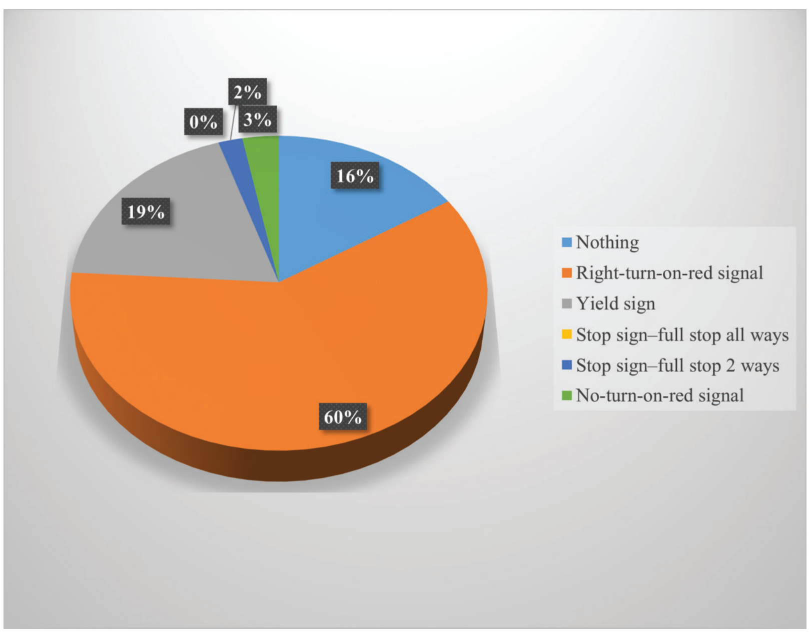


Figure 3.17 Crash share by traffic control types.

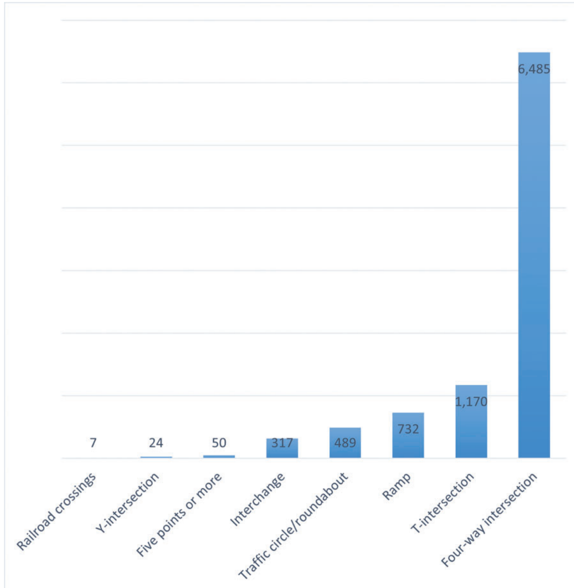


Figure 3.18 Crash frequency at roadway junction type.

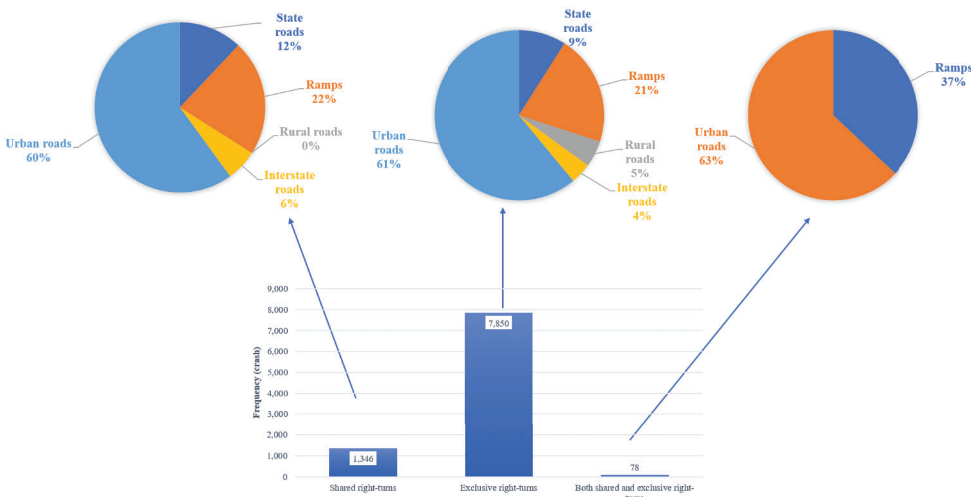


Figure 3.19 Crashes and spatial distributions.

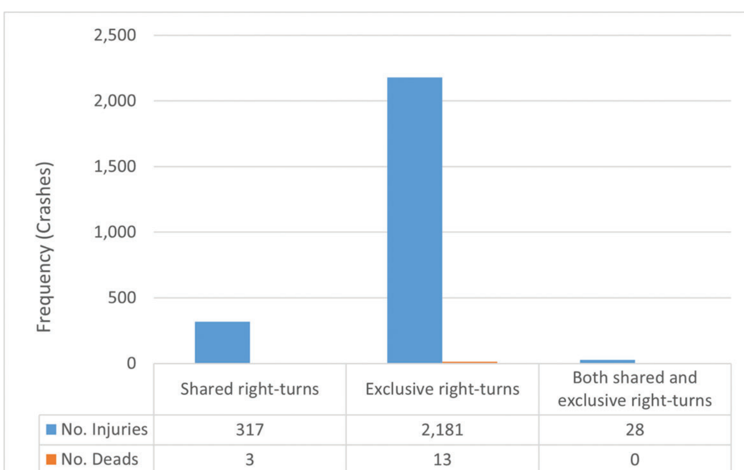


Figure 3.20 Crash severity at right-turn lane types.

TABLE 3.20
Crashes by alignment types and right-turn lane types

Road Characters	Shared Right-Turns	Exclusive Right-Turns	Both Shared and Exclusive Right-Turns
Curve/Hillcrest	7	46	–
Straight/Hillcrest	32	152	1
Curve/Grade	45	248	2
Curve/Level	79	477	–
Straight/Grade	98	621	5
Straight/Level	1,084	6,281	70

TABLE 3.21
Manner of collision by right-turn lane types

Manner of Collision	Shared Right-Turns	Exclusive Right-Turns	Both Shared and Exclusive RTLs
Collision with deer	2	4	–
Collision with object in road	1	6	–
Rear to rear	1	7	–
Non-collision	3	24	–
Opposite direction sideswipe	14	83	–
Left/Right-turn	15	122	–
Right-turn	20	146	5
Other–explain in narrative	17	152	1
Backing crashes	32	154	2
Head on between two motor vehicles	41	252	2
Ran off road	34	255	1
Left turn	117	688	8
Same direction sideswipe	145	893	17
Right angle	289	1,568	23
Rear end	613	3,462	19

4. METHODOLOGY AND ESTIMATION

4.1 Variables Dataset Preparation

4.1.1 Traffic Volume Modification

In order to eliminate the crashes due to the effect of the traffic volume, we adopted the safety performance function (SPF) from the federal *Highway Safety Manual* (Part, 2009) and modified the traffic volume. The new variable that we created is called "volume balanced." The SPF is as below:

$$N_{bimv} = \exp\left(a + b \times In\left(AADT_{maj}\right) + c \times In\left(AADT_{min}\right)\right)$$

where,

$AADT_{maj}$ is the average daily traffic volume (vehicle/day) for major road (both directions of travel combined);

$AADT_{maj}$ is the average daily traffic volume (vehicles/day) for minor road (both directions of travel combined); and

a, b, c are the regression coefficients, which are different according to intersection joint types and crash types (i.e., fatality, injury, or PDO).

4.1.2 Homogeneity of Counties

A hierarchical agglomerative clustering procedure (Lukasová, 1979) was applied to group counties and infer the homogeneity of counties based on the sociodemographic population, the percentage of people having at least high school level education, and the yearly household income. Thus, the generated new variable "cluster," explores the effect of the socioeconomic management on crash frequency. The agglomerative strategy is a "bottom-up" approach, where each observation starts in its cluster, and pairs of clusters are merged as one. Then, they move up the hierarchy, as shown in Figure 4.1. The second derivative distance ("elbow") is conducted to measure the efficiency of the hierarchy algorithm. Finally, three clusters were obtained based on the hierarchical agglomerative clustering procedure. The cluster 0 (county: Marion) represents the county that has the highest population, the lowest percentage of the educated population, and lowest yearly household income. Cluster 1 (counties: Hamilton and Hancock) represents counties that have the middle population, the highest percentage of the educated population, and the highest yearly household income. Cluster 2 (counties: Madison, Tippecanoe, Clark, Harrison, Vanderburgh, Allen, and La Porte) represents counties that have the lowest population, the middle percentage of the educated population, and the middle yearly household income.

4.1.3 Methodology Description

The right-turn lane performance estimation has two specific measurements: crash frequency and crash

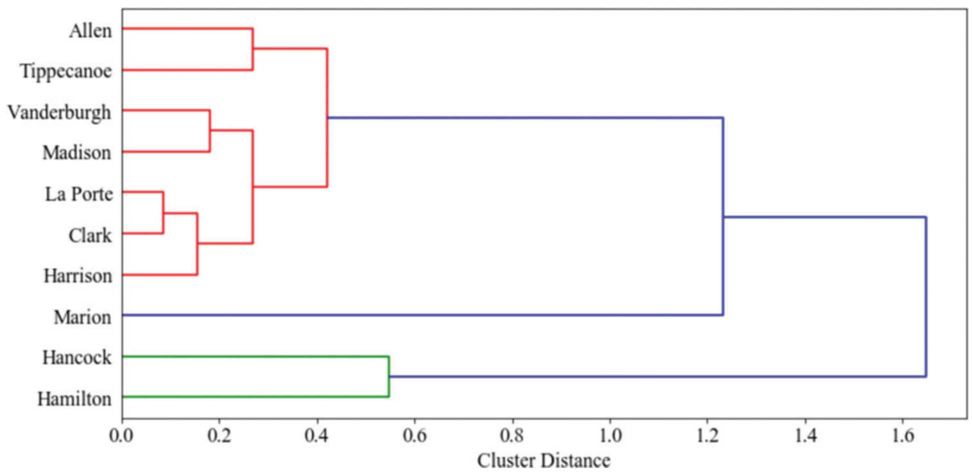


Figure 4.1 Hierarchical clustering for counties.

severity. We define three scenarios for each of the measurements: (1) the performance is estimated via the all crashes; (2) the performance is estimated on the crashes at right-turn lanes at the county level; and (3) the performance is estimated on the crashes at right-turn lanes in roadway class level. A set of variables are used to test the effects on the crash frequency and crash severity of the right-turn lane, which includes right-turn lane geometric design variables, intersection characteristics, spatial and temporal factors, and environmental factors. The description of the influencing factors can be seen in the following section.

4.1.4 Variable Descriptions

Summary statistics of explanatory variables and their correlation matrix can be seen in Table 4.1, Table 4.2, and Figure 4.2.

4.2 Hypothesis for Crash Frequency and Crash Severity

4.2.1 Hypotheses for Crash Frequency

Based on the study interests, we mainly focus on the effects of the right-turn lane geometric design variables on the crash frequency. As a consequence, we propose six hypotheses as below:

1. The presence of solid traffic island at RTL significantly decreases crash frequency compared with the RTL having no traffic island or RTL having marking traffic island.
2. RTLs in the poor visibility in wet surface conditions increases crash frequency.
3. The presence of roundabout/traffic circle in the intersection reduces crash frequency than other intersection types.
4. RTL with large turn radius decreases the crash frequency.
5. Intersection with high traffic volume increases crash frequency than Intersection with low traffic volume.
6. Exclusive RTL decreases crash frequency compared with shared RTL.

4.2.2 Hypotheses for Crash Severity

Correspondingly, we propose the following six hypotheses on crash severity, which are measured by the crash cost in the right-turn lane:

1. The presence of solid traffic island at RTL significantly decreases crash cost relative to the RTL having no traffic island or RTL having marking traffic island.
2. RTLs in the poor visibility in wet surface conditions increases crash cost.
3. The presence of roundabout/traffic circle in the intersection reduces crash cost than other intersection types.
4. RTL with large turn radius decreases the crash cost.
5. Exclusive RTL decreases crash cost compared with shared RTL.
6. RTL having a design speed above 35 mph increases the crash cost.

4.3 Methodology

4.3.1 Crash Frequency Model Specifications

4.3.1.1 Basic model selection. Previous studies (Lord & Mannering, 2010) suggested that most of the crash data are extremely over-dispersed. Thus, directly assuming it follows the Poisson distribution may not be realistic. Poisson model (Null hypothesis: the true dispersion is close to 1).

Since the crash data may have over-dispersion (see Table 4.3), we tested the data via different general assumptions: gamma, Weibull, negative binomial (NB), and generalized-gamma. The benchmark model is selected from five methods. Besides, we adopt the Akaike information criterion (AIC) and Bayesian information criterion (BIC) as model selection criteria (Vrieze, 2012). Based on the estimation results in Table 4.4 and Table 4.5, the NB model is selected as the benchmark model as it has the lowest AIC and BIC values. To capture the potential spatial-correlated heterogeneity, we furtherly propose the random effect of explanatory variables (RENB) on the benchmark model and test if there is a nested spatial correlation among intersections (also ramps or interchange) within the

TABLE 4.1
Description of explanatory variables

Explanatory Variables	Abbreviation	Unit	Min/Max	Avg/Sd or Dist
Intersection Characteristics				
Design speed, 1 if design speed is above 35 mph, 0 if not otherwise[a]	Spl > 35/Spl ≤ 35	n/a	0/1	64.12/36.88
Intersection AADT	AADT	vpd	3165/109908	35002/16936
Environmental Factors				
Visibility condition, 1 if the visibility is good, 0 if not otherwise	visgo/vispo	n/a	0/1	82.31/18.69
Surface condition, 1 if roadway surface is wet, 0 if not otherwise	suwe/sudr	n/a	0/1	45.42/55.58
Spatial Factors				
Cluster 1, 1 if the county is in cluster 1, 0 if not otherwise	clu1/clu0	n/a	0/1	38.27/61.73
Cluster 2, 1 if the county is in cluster 2, 0 if not otherwise	clu2/clu0	n/a	0/1	23.24/76.76
Locality, 1 if urban area, 0 if not otherwise	loub/lora	n/a	0/1	95.06/5.94
Temporal Factors				
Time, 1 if nighttime, 0 if not otherwise[b]	night/day	n/a	0/1	40.68/60.32
RTL Geometric Factors				
RTL type, 1 if exclusive RTL, 0 if not otherwise	exRTL/shaRTL	n/a	0/1	84.11/16.89
Acceleration lane, 1 if RTL associates acceleration lane, 0 if not otherwise	accye/accno	n/a	0/1	2.08/98.92
RTL channelized type, 1 if the channelized type is traffic island, 0 if not otherwise	chtraf/chno/mark	n/a	0/1	16.56/84.44
Traffic signal control, 1 if yes, 0 if not otherwise	trafsg/trafno	n/a	0/1	68.87/31.13
Traffic sign control, 1 if yes, 0 if not otherwise	trafsn/trafno	n/a	0/1	31.28/68.72
Length	len	inch	45.22/1340	340.36/206.5
Width	wid	inch	8.29/38.39	13.13/2.96
Turn radius	tur	inch	12.56/740	80.09/77.73

[a]Studies (Ye et al., 2001) mentioned that the design speed below 35 mph in Indiana is regarded as "low speed," And the approach design speed of school zone and work zone is usually below 35 mph (Gambatese et al., 2013; Mountain et al., 2005).

[b]Day: 6:00am–18:00pm; night: 18:00 pm–6:00 am (the next day). Avg/sd is the mean value and standard deviation of continuous variables. Dist is the percentage value for indicator variables.

TABLE 4.2
The correlation matrix of the explanatory variables

	Spl > 35	AADT	Visgo	Suwe	Clu1	Clu2	Loub	Night	ExRTL	Accye	Chtraf	Trafsg	Trafsn	Len	Wid	Tur
Spl > 35	1.00	0.14	0.02	0.05	0.12	0.10	0.15	0.01	0.08	0.05	0.06	0.05	0.05	0.05	0.03	0.01
AADT	0.14	1.00	0.02	0.01	0.16	0.23	0.14	0.04	0.12	0.23	0.14	0.01	0.01	-0.03	0.04	0.25
Visgo	0.02	0.02	1.00	0.06	0.04	0.02	0.05	0.11	0.03	0.02	0.00	0.01	0.04	0.02	0.00	0.03
Suwe	0.05	0.01	0.06	1.00	0.02	0.01	0.05	0.10	0.00	0.03	0.02	0.06	0.02	0.02	0.02	0.03
Clu1	0.12	0.16	0.04	0.02	1.00	0.46	0.04	0.01	0.00	0.06	0.13	0.14	0.04	0.02	0.06	0.13
Clu2	0.10	0.23	0.02	0.01	0.46	1.00	0.23	0.01	0.09	0.06	0.08	0.15	0.00	0.01	0.12	0.05
Loub	0.15	0.14	0.05	0.05	0.04	0.23	1.00	0.03	0.01	0.20	0.11	0.18	0.16	0.10	0.02	0.23
Night	0.01	0.04	0.11	0.10	0.01	0.01	0.03	1.00	0.00	0.00	0.00	0.02	0.02	0.02	0.01	0.02
ExRTL	0.08	0.12	0.03	0.00	0.00	0.09	0.01	0.00	1.00	0.06	0.01	0.04	0.04	0.05	0.02	0.07
Accye	0.05	0.23	0.02	0.03	0.06	0.06	0.20	0.00	0.06	1.00	0.21	0.10	0.06	0.02	0.06	0.05
Chtraf	0.06	0.14	0.00	0.02	0.13	0.08	0.11	0.00	0.01	0.21	1.00	0.30	0.37	0.08	0.27	0.20
Trafsg	0.05	0.01	0.01	0.06	0.14	0.15	0.18	0.02	0.04	0.10	0.30	1.00	0.64	0.04	0.13	0.20
Trafsn	0.05	0.01	0.04	0.02	0.04	0.00	0.16	0.02	0.04	0.06	0.37	0.64	1.00	0.06	0.19	0.23
Len	0.05	-0.03	0.02	0.02	0.02	0.01	0.10	0.02	0.05	0.02	0.08	0.04	0.06	1.00	0.01	0.18
Wid	0.03	0.04	0.00	0.02	0.06	0.12	0.02	0.01	0.02	0.06	0.27	0.13	0.19	0.01	1.00	-0.05
Tur	0.01	0.25	0.03	0.03	0.13	0.05	0.23	0.02	0.07	0.05	0.20	0.20	0.23	0.18	-0.05	1.00

Note:
The correlation between continuous variables and continuous variables is measured by Pearson correlation measurement.
The correlation between indicator variables and indicator variables is measured by Cramér's V measurement.
The correlation between continuous variables and indicator variables is measured by ANOVA partial eta squared measurement.

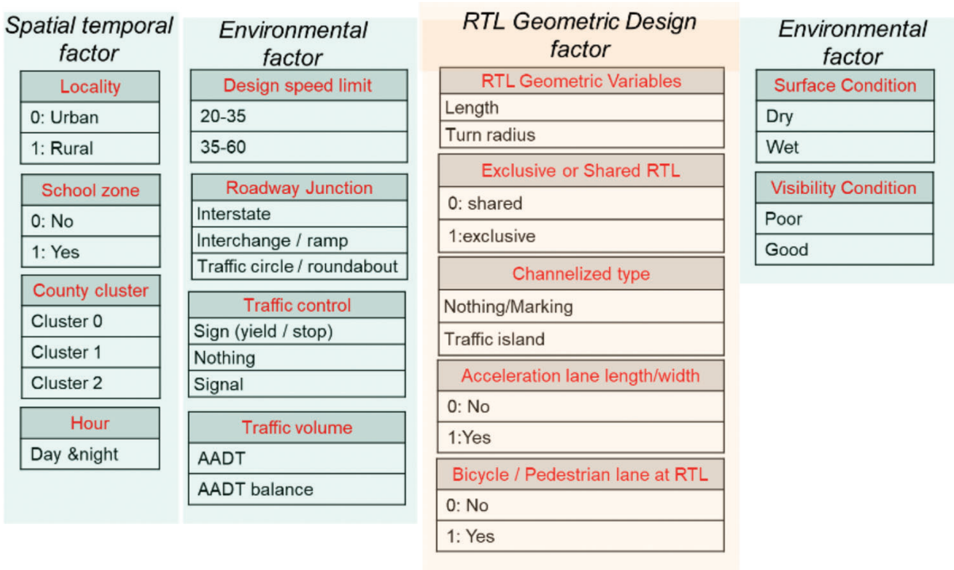


Figure 4.2 Summary of the variable dataset.

TABLE 4.3
The over-dispersion test

Dispersion	z-score	p-value
3.7723	5.8707	2.17E-09

TABLE 4.4
Likelihood ratio test: (basic model: Poisson model)

Alternative Model	Chisq	Df	Critical Value
NB	2,591.424	1	3.841459
Weibull	2,271.198	1	3.841459
Gamma	2,281.536	1	3.841459
Generalized-gamma	2,489.756	2	5.991465

TABLE 4.5
Model comparison

Model	AIC	BIC
Gamma	9,121.988	9,321.419
Wei bull	9,132.326	9,331.757
NB	8,814.1	9,019.229
Generalized-gamma	8,915.767	9,120.896
Poisson	11,401.524	11,595.257

county. The null hypothesis states that no significant variations between crashes in a specific intersection/ramp within the county (the nested term is the location ID and the county ID). Then, a robustness test is applied to confirm the stability of estimates. Finally, the insights are obtained based on the comparison of the two models.

4.3.1.2 Model specification. Previous studies pointed out that the standard errors of regression coefficients are underestimated if the spatial-correlated effects are ignored (Chen & Tarko, 2014). The crash data in our study were collected from a set of intersections or ramps over 4 years. Intuitively, there might exist unobserved spatial-related factors that affect crash frequency. Nevertheless, the fixed NB model assumes no spatial-correlated effects over time in our case. The random-effects negative binomial (RENB) model, therefore, was selected as the comparison. The fixed NB assumes that crash observation y_i is independent over time (Chen & Tarko, 2014).

$$E(y_i) = \gamma_i = exp(\beta X_i + \varepsilon_i) \qquad \text{(Eq. 4.1)}$$

where X_i is the vector of explanatory variables for intersection i, and β is a vector of estimated coefficients. The exp(ε_i) is a gamma-distributed error term with mean one and variance α, and γ_i is the expected number of crashes for intersection i. The mean-variance relationship is as follows:

$$Var(y_i) = E(y_i)[1 + \alpha E(y_i)] \qquad \text{(Eq. 4.2)}$$

The NB reduces to a Poisson distribution if α=1. Otherwise, data is over-dispersed or under-dispersed. On the other hand, the spatial-correlated RENB model essentially layers a random spatial effect (u_i) on the parent NB by assuming that the over-dispersion parameter is randomly distributed across groups (Chen & Tarko, 2014). The variance-to-mean ratio of being unconstrained as constant across locations is the key advantage of this approach (Lord & Mannering, 2010). The RENB assumes that $\frac{1}{1+a_i}$ follows the beta distribution of Beta(r,s), where a_i is the dispersion variable. The estimation of the β vector can be conducted through the standard maximum likelihood procedures.

The structure of the RENB model is as follows:

$$E(y_i) = exp(\beta X_i + u_i + \varepsilon_i) \quad \text{(Eq. 4.3)}$$

Instead of using a linearizing link function to transform the expectation of the response variable γ_i to its linear predictor, we applied a logarithmic function to extract the relationship between crash frequency and the continuous factors. The non-linear logarithmic function provides a general assumption that suits the statistical inferences and eliminates the heteroscedasticity for the variances of regression residuals. Therefore, the linear predictors X_i in Equation 4.4 are adopted to the indicator variables, and the nonlinear predictors are rearranged as $\log(X_i)$. For example, RTL length, RTL width, RTL turn radius, intersection AADT.

The model goodness of fit was conducted by the McFadden pseudo-R-squared, which is expressed as:

$$R^2 = 1 - \frac{LL(\beta)}{LL(C)} \quad \text{(Eq. 4.4)}$$

where $LL(\beta)$ represents the log-likelihood of the full model and $LL(C)$ represents the log-likelihood of the restricted model (constant only model).

4.3.2 Crash Severity Model Specification

4.3.2.1 Basic model selection. The dependent variable of the crash severity model is crash cost, which is a continuous variable. To estimate the effects of influencing factors, we start from the linear model. Besides, we adopt the logarithm transformation for the explanatory variables to better fit the statistic inference and eliminate the heteroscedasticity for the variances of regression residuals. As a consequence, the linear model and the log-linear model are two base models. The model selection can be found in Table 4.6, where the linear model outperforms the log-linear model. The formula of the linear model can be seen as below. Furthermore, to capture the spatial correlation among crashes in difference right-turn lane within the same counties, we again propose the random effect to the base model.

$$In(y_i) = \beta_j x_{i,j} + \varepsilon \quad \text{(Eq. 4.5)}$$

where,

y_i is the crash cost of the right-turn lane i;

β_j is the coefficient of the influencing factor j;

$x_{i,j}$ is the j_{th} influencing factor in the j_{th} right-turn lane; and

ε is the error term.

In the log-linear model, the explanatory variables are expressed as $\text{In}(x_{i,j})$.

The comparison of the base model:

TABLE 4.6
Crash severity model selection

Model Comparison	Adj. R2
Linear	0.132
Log-linear	0.111

4.3.2.2 Model specification. From the comparison, the log-linear model better fits the data. Therefore, the random effect is adopted to the log-linear model. The expression is as follows:

$$In(y_i) = \beta_i In(x_{i,j}) + \mu Z + \varepsilon \quad \text{(Eq. 4.6)}$$

where,

y_i, β_i, and ε are the same as aforementioned log-linear function; and

Z is the design matrix for random effects, and μ is a vector of the random effects.

5. ECONOMETRIC MODEL B FOR CRASH FREQUENCY

5.1 Model Robustness Testing

A robustness test for the RTL geometric factors and compound effects in the overall model is presented in Table 5.1 (for RENB and NB). The effects of RTL geometric factors and compound effects have been computed in each specification. The first three regressions examine the specification with only RTL geometric factors and compound factors. In all specifications, we use different combinations of environmental-related controls and spatial-temporal controls (B1, B2, and B3 are controlled from one in three; C1, C2, and C3 are controlled from two in three; D is the full model with all variables). Based on the results of the robustness test, the effects of both "len" and "wid" are nonsignificant in any specification, which confirms the consistent estimates of "len" and "wid." Besides, the robustness test suggests that the effect of cluster 1 is not significantly different from cluster 0. Thus, the final model takes both cluster 0 and cluster 1 into one group as the reference level. Furthermore, the effects of compound factors, such as channelized type with traffic volume (AADT) and the right-turn type with design speed, are not significant under any specifications in the NB model. It means those compound factors are not sufficiently significant in the NB model even the NB (D) full model suggests that the effects of these compound factors are significant at 0.1 level. Thus, we will not consider it into the final NB model. However, these compound effects are significant in the RENB model.

Table 5.2 presents the final estimations for RENB and NB models. The RENB model has more significant variables (such as "design speed") than the NB model, which confirms that RENB can capture more variance and better fit the data than the NB model. Besides, variables in the RENB model have a higher significant level than they are in the NB model. For example, the effect of "ExRTL : Spl > 35" is at 0.05 significance level in the RENB model but at 0.1 significance level in the NB model. Furthermore, the RENB model outperforms due to a higher Log-likelihood value. The result of the bootstrapping test for the nested random effect term indicates that the crashes variability is significant

TABLE 5.1
Robustness test of the RTL geometric factors

	Overall RENB Model									
Explanatory Variables	**A1**	**A2**	**A3**	**B1**	**B2**	**B3**	**C1**	**C2**	**C3**	**D**
Log (len)	0.010	0.063	0.035	0.035	0.044	0.038	0.047	0.037	0.038	0.043
Log (wid)		0.027	-0.068	-0.065	-0.066	-0.065	-0.063	-0.064	-0.059	-0.059
Log (tur)		0.275***	0.347***	0.290***	0.305***	0.316***	0.280***	0.269***	0.251***	0.231***
ExRTL			-0.717***	-0.598***	-0.681***	-0.670***	-0.668***	-0.641***	-0.561***	-0.605***
Accye			7.493†	6.338†	8.261*	7.341†	8.105*	6.149*	7.043†	6.836†
Chtraf			3.857*	3.495†	4.151†	4.385†	4.650*	4.296†	3.880†	4.618*
Trafsn			0.255**	0.299**	0.288**	0.252**	0.284**	0.308***	0.340***	0.345***
Trafsg			0.184	0.245*	0.242*	0.169	0.226**	0.222*	0.301**	0.278†
Spl > 35			0.490**	0.313*	0.507**	0.411**	0.431**	0.248†	0.344*	0.279*
Log (AADT)			0.296***	0.310***	0.274**	0.334***	0.313***	0.354***	0.300***	0.339***
Visgo				1.192***				1.066***	1.190***	0.345***
Suwe				-0.336**				-0.396***	-0.333**	0.278*
Clu1					0.039		0.032		0.087	0.074
Clu2					-0.158†		-0.160†		-0.162*	-0.165*
Loub					0.516**		0.510**		0.455**	0.492**
Night						-0.653***	-0.653***	-0.638***		-0.639***
ExRT : Spl > 35			0.292	0.252†	0.292†	0.323*	0.323*	0.308*	0.244*	0.300*
Accye : Log (AADT)			-0.645*	-0.543†	-0.697*	-0.632†	-0.685*	-0.527†	-0.592†	-0.574*
Chtraf : Log (AADT)			-0.303*	-0.283†	-0.326†	-0.350†	-0.370	-0.351†	-0.313*	-0.376*
Visgo : Suwe				-0.789***				-0.766***	-0.794***	-0.771***
Log-likelihood	-4825.7	-4809.1	-4716.5	-4344.3	-4710.2	-4618.3	-4612	-4232.9	-4337.6	-4225.8
McFadden pseudo R^2	0.008	0.012	0.031	0.107	0.032	0.051	0.052	0.130	0.109	0.132
Over-dispersion parameter	1.34	1.36	1.56	2.52	1.55	1.75	1.75	3.17	2.51	3.18
Observations	2173	2173	2173	2173	2173	2173	2173	2173	2173	2173
	Overall NB Model									
	A1	**A2**	**A3**	**B1**	**B2**	**B3**	**C1**	**C2**	**C3**	**D**
Log (len)	-0.0001	0.048†	0.045	0.03	0.051.	0.042	0.048	0.029	0.02	0.029
Log (wid)		0.041	-0.025	0.001	-0.019	-0.024	-0.018	-0.001	0.008	0.007
Log (tur)		0.228***	0.269***	0.257***	0.239***	0.259***	0.230***	0.251***	0.225***	0.219***
ExRTL			-0.445***	-0.328***	-0.435***	-0.431***	-0.420***	-0.334***	-0.308***	-0.317***
Accye			7.844*	6.825*	9.170*	7.771*	9.012*	6.807*	8.0459*	8.037*
Chtraf			2.390	1.847	3.134*	2.729.	3.414*	2.22	2.618†	2.967*
Trafsn			0.232***	0.226***	0.289***	0.236***	0.289***	0.265***	0.331***	0.333***
Trafsg			0.190*	0.238**	0.255**	0.185*	0.247**	0.227**	0.306***	0.295***
Spl > 35			0.169	0.118	0.213	0.134	0.175	0.077	0.166	0.124
Log (AADT)			0.286***	0.303***	0.297***	0.321***	0.330***	0.338***	0.325***	0.357***
Visgo				1.190***				1.052***	1.189***	1.052***
Suwe				-0.292*				-0.341**	-0.291	-0.340**
Clu 1					0.017		0.019		0.075	0.071
Clu 2					-0.195***		-0.183***		-0.190**	-0.185***
Loub					0.467***		0.45***		0.402***	0.419***
Night						-0.664***	-0.661***	-0.617***		-0.616***
ExRTL : Spl > 35			0.256*	0.191†	0.267*	0.269*	0.281*	0.220*	0.196	0.227†
Accye : Log (AADT)			-0.688*	-0.600*	-0.785*	-0.682*	-0.773*	-0.600*	-0.690*	-0.690**
Chtraf : Log (AADT)			-0.182	-0.141	-0.243†	-0.211	-0.267*	-0.173	-0.204*	-0.233†
Visgo : Suwe				-0.811***				-0.781***	-0.815***	-0.786***
Log-likelihood	-4865.94	-4844.63	-4764.64	-4413.75	-4752	-4667.17	-4655.18	-4317.82	-4398.6	-4302.04
McFadden pseudo R^2	0.000	0.004	0.021	0.093	0.023	0.041	0.043	0.113	0.096	0.116
Over-dispersion parameter	1.2019	1.2264	1.3297	1.9438	1.3464	1.4733	1.4936	2.2424	1.9811	2.2944
Observations	217	2173	2173	2173	2173	2173	2173	2173	2173	2173

Note
†$p < 0.1$
*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

TABLE 5.2
The estimations of overall final models

	RENB		NB	
Explanatory Variables	**Coefficient**	**Standard Deviation**	**Coefficient**	**Standard Deviation**
Constant	-2.650***	0.804	-2.744***	0.508
RTL Geometric Factors				
Log (tur)	0.220***	0.051	0.211***	0.032
ExRTL	-0.590***	0.128	-0.296 ***	0.085
Accye	6.103*	3.066	7.137*	2.84
Chtraf	3.991*	2.023	2.599*	1.225
Trasn	0.353***	0.092	0.338***	0.059
Trasg	0.265*	0.11	0.289***	0.071
Intersection Characteristics				
Spl > 35	0.295*	0.144	0.139	0.099
Log (AADT)[a]	0.343***	0.08	0.362***	0.05
Environmental-Related Factors				
Visgo[b]	1.063***	0.073	1.052***	0.074
Suwe	-0.394***	0.115	-0.342**	0.116
Spatial Factors				
Clu2	-0.160*	0.08	-0.180***	0.049
Loub	0.475**	0.155	0.407***	0.111
Temporal Factors				
Night	-0.639***	0.042	-0.616***	0.043
Compound Effects				
ExRTL : Spl > 35	0.287*	0.145	0.212†	0.11
Chtraf : Log (AADT)	-0.367*	0.184	-0.228†	0.117
Visgo : Suwe	-0.770***	0.123	-0.784***	0.125
Accye : Log (AADT)	-0.579*	0.291	-0.697**	0.263
Bootstrapping	1.6778e-10***		–	
Observations	2137		2137	
Over-dispersion parameter	3.17		2.293	
Log-likelihood[c]	-4,226.5(-4865.9)		-4,302.617(-4865.9)	
McFadden pseudo R^2	0.131		0.116	

Note:
[a]Log (AADT) is equal to Log (intersection AADT).
[b]Light 1 : Surface 1 is equal to Light condition 1 : Surface condition 1.
[c]The log-likelihood of constant only model is in the parentheses.
†$p < 0.1$
*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

across different intersections within the county. All influencing factors are acceptable when the significant level is below 0.05, as suggested in previous studies (Venkataraman et al., 2013).

5.2 Marginal Effect and Elasticity Estimation

The average marginal effects and elasticities of explanatory variables in the overall model of both RENB and NB models are presented in Table 5.3. The marginal effects describe the changes in the conditional mean of the crashes in response to a unit change in the explanatory variables. Meanwhile, the elasticity measures the percentage changes of the crash frequency in response to a unit percentage change in the continuous explanatory variables. Therefore, the elasticity is adopted to interpret the effects of continuous variables, and the marginal effects are more appropriate to measure the effects of nominal variables. In particular, the coefficients of the continuous explanatory variables in the logarithm function directly estimate the elasticity. The final overall model is presented in Table 5.3.

TABLE 5.3
Average marginal effect and elasticity

	RENB	NB
RTL Geometric Factors		
Log (tur)[a]	0.220	0.211
ExRTL	-0.691	-0.750
Accye	25.763	25.039
Chtraf	13.012	18.653
Trafsn	0.785	0.749
Trafsg	0.647	0.717
Intersection Characteristics		
Spl > 35	0.426	0.310
Log (AADT)[a]	0.343	0.362
Environmental-Related Factors		
Visgo	1.783	1.801
Suwe	-0.779	-0.770
Spatial Factors		
Clu 2	-0.626	-0.413
Loub	0.549	0.778
Temporal Factors		
Night	-1.321	-1.344
Compound Effects		
ExRTL : Spl > 35	0.362	0.479
Chtraf : Log (AADT)	-0.432	-0.520
Visgo : Suwe	-1.636	-1.665
Accye : Log (AADT)	-1.692	-1.588

[a]Elasticity measurement is estimated for continuous variables (turn radius, AADT). Marginal effect is estimated for nominal variables.

5.3 Interpretation

5.3.1 Overall Level

5.3.1.1 Intersection characteristics. The "design speed" and the "AADT" have significant impacts on the crash frequency in the overall model. Besides, these two variables have component effects associated with the right-turn lane geometric design variables. The interpretation of these two variables and their component effects is presented in the section of "right-turn lane geometric deign variables and component effect."

5.3.1.2 Right-turn lane geometric design variables and component effect. The parameter of the logarithm of the RTL turn radius to be 0.220 in the RENB model indicates that the RTLs with a large turn radius has more crashes than RTLs with a small turn radius. Besides, the elasticity estimation (Table 5.1) suggests a 1% increase in the RTL turn radius leads to 0.22% more crashes, which is similar to the findings in previous studies (Rifaat et al., 2011). The corner radius affects drivers' judgments on the speed they choose for the right turning; it also affects the pedestrians in dealing with the speed of the turning vehicles. A large turn radius not only increases the pedestrian and vehicle crossing time but also increases the vehicle's turning speed. Therefore, it potentially leads to a worse situation in right turning. However, as studies (Fitzpatrick et al., 2006) mentioned, a large radius also contributes to reducing the rear-end conflicts due to a smaller-speed differential of the vehicle following.

For traffic control estimations, the RTLs having yield/stop sign or RTLs with no traffic control tend to be more dangerous than RTLs having signal control. Marginal effects for the traffic control in Table 5.1 show that the RTLs having yield/stop sign has 0.785 more crashes on average relative to signal control, and the RTLs with no traffic control have 0.647 more crashes on average relative to signal control. Intuitively, signal control can separate different entities, thus reduces conflicts. As mentioned by studies (Al-Kaisy & Roefaro, 2012), the installment of signal control in channelized RTLs can even get more safety benefits in reducing the rear-end collisions.

There are three significant compound effects between RTL geometric factors and intersection characteristics.

1. First, the reference level for the compound factor of "ExRTL : Spl > 35" is the shared RTL with the design speed below or equal to 35 mph. The risk ratio for an exclusive RTL with the design speed over 35 mph to the shared RTL with the design speed over 35 mph is 0.74, which suggests the exclusive RTL with the high design speed has 16% fewer risk of crashes than the shared RTL with the high design speed. Furthermore, exclusive RTLs with the design speed below or equal to 35 mph has 45% fewer risk of crashes than shared RTLs with the design speed below or equal to 35 mph. The compound effect implies that exclusive RTLs reduce the risk of crashes. As mentioned by Gao et al. (2019), the exclusive RTL reduces the risk of crashes between the through and right-turn traffic flow because of separating space for the through movement and the right-turn traffic flow. The marginal effect of the compound effect between RTL types and design speed shows in Table 5.1. For exclusive RTLs estimation, the design speed over 35 mph has 0.788 more crashes on average than the design speed below or equal to 35 mph. In addition, shared RTLs with design speed over 35 mph are found to has 0.426 more crashes on average relative to shared RTLs with design speed below or equal to 35 mph keeping other conditions equal.
2. Second, the reference level for the "Accye : Log (AADT)" is the effect of the combination of RTLs without an acceleration lane and intersection AADT. The risk ratio for RTL with acceleration lane is less than the risk ratio for the RTL without acceleration lane when AADT is above 37,120 vpd, which means RTL acceleration lane having fewer crashes than without acceleration lane under that condition. However, the effect of the RTLs with acceleration lane is different depending on the volume of intersection AADT. For example, the risk ratio for the RTL with acceleration lane to the RTL without acceleration lane is 0.57 when intersection AADT is 100,000 vpd, which means RTL with acceleration lane has 43% fewer risk of crashes than the RTL without acceleration lane when AADT is 100,000. Besides, as indicated by elasticity in Table 5.1, a 1% increase in intersection AADT leads to 0.343% more crashes on average.

3. Third, the reference level of "Chtraf : Log (AADT)" is the effect of the combination of the traffic channelized type of RTL and the intersection AADT. The risk ratio for the presence of traffic island is less than the channelized type of nothing or making when the intersection AADT is above 52,821 vpd. In addition, the effects of the compound factor are different along with the change of AADT. For example, the risk ratio for the presence of traffic island is 0.79 when intersection AADT is 100,000 vpd, which means traffic island has 21% fewer crashes than channelized type to be nothing or marking when AADT is 100,000 vpd. This finding supplements with Dixon et al. (2000), where the use of a traffic island appears to reduce the number of right-angle crashes. The traffic island serves as refuge points for pedestrians and provides suitable locations to place traffic control devices (Al-Kaisy & Roefaro, 2012). Besides, studies (Harwood et al., 2002) found the installation of a raised median island reduced the pedestrian accident rate by 11.5%.

5.3.1.3 Environmental variables. Visibility condition affects the driver's vision, and surface condition measures the friction of the road. The estimates of "Visgo : Suwe" suggest a significant compound effect between the visibility condition and road surface condition on crash frequency. The reference level of the environmental compound factor is the poor visibility with the dry road surface. The risk ratio for the RTLs in the good visibility with the wet road surface to the poor visibility with the wet road surface to be 1.34 indicates RTLs in good visibility with wet road surface has 34% more crashes than RTLs in the poor visibility and wet road surface. And the good visibility with the wet road surface is found to significantly increase crashes by an average of 0.147 relative to the poor visibility with the wet road surface as estimated by the marginal effect. The RTLs in the good visibility and wet road surface has 69% more crashes than RTLs in the good visibility and dry road surface. Besides, the poor visibility and the wet road surface has 77% fewer crashes than the good visibility and dry road surface. RTLs in the poor visibility and wet road surface have 0.779 fewer crashes comparing to RTLs in the poor visibility and dry road surface as estimated in marginal effect. The insights infer that RTLs in the poor visibility and wet road surface seems to be the safest situation among the four kinds of environmental conditions, which is in contrast to Atalar and Thomas (2019). In Atalar and Thomas's study, crashes decrease during the daytime or at night in the presence of light. However, as Mannering and Bhat (2014) mentioned, other factors will impact the estimation results, such as drivers tend to avoid the bad weather (e.g., snow and sand storm) and would be more careful when the visibility condition is not good. Therefore, the observed traffic flow will be much less than it is on normal days and lead to the reduction of risk exposure. Empirically, the estimation would be biased when the unobserved factors come to the picture.

5.3.1.4 Spatial and temporal variables. The RTL location is the primary consideration for the spatial effects. The parameter estimates for the county cluster 2 (including Madison, Tippecanoe, Clark, Harrison, Vanderburgh, Allen, and La Porte) of -0.160 indicates fewer crashes in cluster 2 compared with the reference level of cluster 0 and cluster 1. The underlying reason is the counties with fewer populations have fewer crashes due to low traffic flow. Besides, the estimation for "Loub" of 0.475 implies RTLs in the urban area have more crashes than RTLs in the rural area. Marginal effects in Table 5.1 show that RTLs in the urban area has 0.549 more crashes on average relative to RTLs in rural area due to the complicated traffic conditions, which is in contrast with the findings presented by Ouni and Belloumi (2019). However, Ouni and Belloumi also supported that the hot zones in the Urban area have more crashes. In terms of temporal factors, the negative marginal effect of "Night" indicates RTLs in the nighttime having 1.321 fewer crashes on average than the RTLs in the daytime. This insight is consistent with Shaheed et al. (2013). But it is in contrast to Kumar and Toshniwal (2017), where they suggested the crashes mostly occur at night.

5.3.1.4.1 Sites with High Crashes. We ranked the high risk intersections based on the crash frequency using the tools of intersection safety performance function (SPF). SPFs for multiple-vehicle intersection-related collisions are applied below (Part, 2009):

$$N_{bimv} = \exp(a + b \times In\left(AADT_{maj}\right) + c \times In\left(AADT_{min}\right) \quad \text{(Eq. 4.7)}$$

where,

$AADT_{maj}$=average daily traffic volume (vehicles/day) for major road (both directions of travel combined);

$AADT_{min}$=average daily traffic volume (vehicles/day) for minor road (both directions of travel combined); and

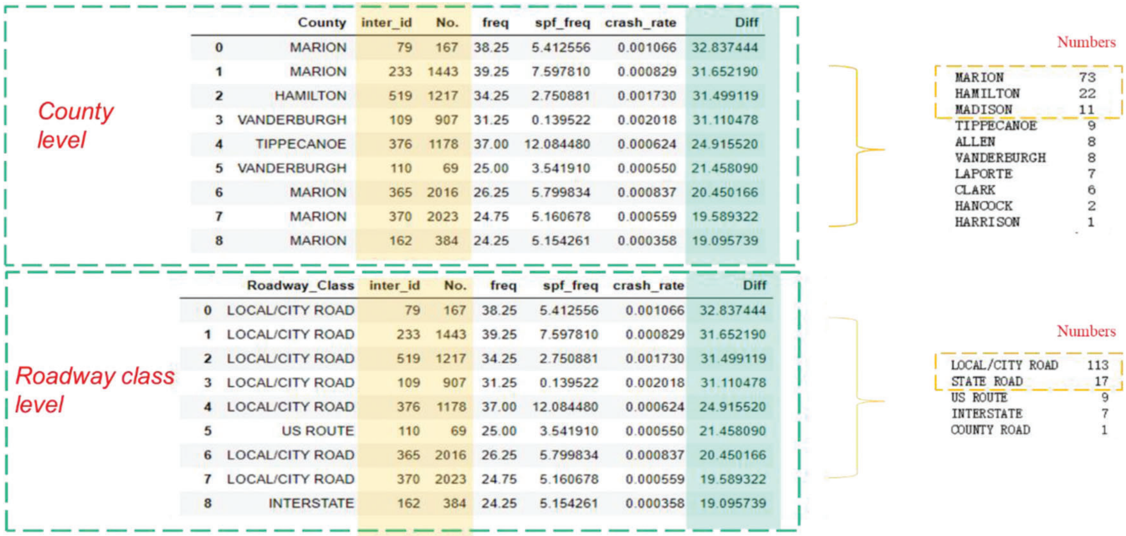
a, b, c=regression coefficients.

Based on the SPF, we rank the intersections by roadway class and county. The rank result is in Figure 5.1.

5.3.2 County Level

As described in the section 4.1.2, there are three classes of counties. Class A is Marion County; class B is Hamilton County and Hancock County; class C is Madison County, Tippecanoe County, Clark County, Harrison County, Vanderburgh County, Allen County, and La Porte County.

5.3.2.1 County class A. Among all variables, AADT, hour, light condition and turn radius have high contribution on crash frequency. Besides, the significant right-turn lane geometric design variables are traffic control and the channelized type of the right-turn lane. The estimation result can be seen in Table 5.4. RTLs



	County	inter_id	No.	freq	spf_freq	crash_rate	Diff
0	MARION	79	167	38.25	5.412556	0.001066	32.837444
1	MARION	233	1443	39.25	7.597810	0.000829	31.652190
2	HAMILTON	519	1217	34.25	2.750881	0.001730	31.499119
3	VANDERBURGH	109	907	31.25	0.139522	0.002018	31.110478
4	TIPPECANOE	376	1178	37.00	12.084480	0.000624	24.915520
5	VANDERBURGH	110	69	25.00	3.541910	0.000550	21.458090
6	MARION	365	2016	26.25	5.799834	0.000837	20.450166
7	MARION	370	2023	24.75	5.160678	0.000559	19.589322
8	MARION	162	384	24.25	5.154261	0.000358	19.095739

	Roadway_Class	inter_id	No.	freq	spf_freq	crash_rate	Diff
0	LOCAL/CITY ROAD	79	167	38.25	5.412556	0.001066	32.837444
1	LOCAL/CITY ROAD	233	1443	39.25	7.597810	0.000829	31.652190
2	LOCAL/CITY ROAD	519	1217	34.25	2.750881	0.001730	31.499119
3	LOCAL/CITY ROAD	109	907	31.25	0.139522	0.002018	31.110478
4	LOCAL/CITY ROAD	376	1178	37.00	12.084480	0.000624	24.915520
5	US ROUTE	110	69	25.00	3.541910	0.000550	21.458090
6	LOCAL/CITY ROAD	365	2016	26.25	5.799834	0.000837	20.450166
7	LOCAL/CITY ROAD	370	2023	24.75	5.160678	0.000559	19.589322
8	INTERSTATE	162	384	24.25	5.154261	0.000358	19.095739

Figure 5.1 High risk sites based on the crash frequency.

TABLE 5.4
Estimation result for counties in class A

	Estimate	Std. Error	Pr(>|z|)
Junction type (intersection)	0.56	0.22	*
Design speed 1	0.50	0.11	***
Locality (urban)	0.99	0.20	***
Hour night	-0.86	0.08	***
Visibility condition (lighted)	1.15	0.14	***
Surface condition WET	-0.64	0.23	**
Visibility condition (lighted) : Surface condition WET	-0.56	0.24	*
Log (turn radius)	0.59	0.08	***
RTL type 1	-0.42	0.15	**
Log (AADT)	0.17	0.14	*
Traffic control (signal)	-0.45	0.18	*
Traffic control (yield/stop)	0.38	0.20	*
Channelized type (traffic island)	8.98	2.82	**
Log (AADT) : Channelized type (traffic island)	-0.87	0.27	**

Note:
*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

having signal control at intersection have 0.67 times risk relative to RTLs with no traffic control; RTLs having yield/stop sign have 1.46 times more risk than RTLs with no traffic control. The channelized type of traffic island has fewer crashes than nothing/marking when AADT is higher than 30,389 veh/day.

5.3.2.2 County class B. Among all variables, AADT, hour and surface condition have high contribution on crash frequency. Besides, the significant right-turn lane geometric design variables are the channelized type and the exclusive and shared right-turn lane. The estimation result can be seen in Table 5.5. The channelized type of traffic island has 0.53 times risk relative to nothing/marking. Exclusive RTL have fewer crashes than shared RTL when AADT is higher than 25,491 veh/day.

5.3.2.3 County class C. Among all variables, AADT and turning radius have high contribution on crash frequency. Besides, the significant right-turn lane geometric design variables are the exclusive and shared right-turn lane and traffic control. The estimation result can be seen in Table 5.6. The effects of roundabout/traffic circle are non-significant; Exclusive RTL has fewer crashes than shared RTL when AADT is higher than 11,520 veh/day.

5.3.2.4 County level estimates conclusion

1. RTL with large turn radius increases crashes.
2. RTL with high design speed has more crashes than low design speed.

3. Exclusive RTL reduce crashes and the effects depend on the AADT and county type.
4. The presence of pedestrian crosswalk at RTL increases crashes while the effects are different for county types.
5. Signal control has fewer crashes and yield/stop sign has more crashes than no traffic control for counties in cluster 0 and cluster 2. However, the effect of traffic control is insignificant for counties in cluster 1.
6. The channelized type of traffic island has less crashes than nothing/ marking and the effects depend on the AADT and county type.
7. Intersections with high traffic volume have more crashes than intersection with low traffic volume.

5.3.3 Roadway Class Level

The estimation for the right-turn lane performance is based on the roadway class level: city/local road, US road, interstate road, and state road. The detail interpretation can be found in the following sections.

5.3.3.1 City/local road. Among all variables, hour, light condition, design speed and turn radius have high contribution to the crash frequency. The significant right-turn lane geometric design variables are exclusive and shared right-turn lane and channelized type of right-turn lane. The estimation result can be seen in Table 5.7. Exclusive RTL has fewer crashes than shared RTL when AADT is higher than 6,447 veh/day; RTL with traffic island has fewer crashes than the channelized type of nothing/marking when AADT is higher than 35,672 veh/day. Besides, the junction type of roundabout/traffic circle has 2.61 times more risk than interchange/ramp.

5.3.3.2 State road. Among all variables, right-turn lane turning radius and surface condition has high contribution to crash frequency. The estimation result can be seen in Table 5.8. One unit increases in turn radius results in the incidence rate ratio increase by a factor of 1.75; RTL with high design speed has 2.24 times more risk than RTL with low design speed.

5.3.3.3 US road. Among all variables, surface, hour, signal, and turn radius have high contribution to crash frequency. The estimation result can be seen in Table 5.9. Exclusive RTL has fewer crashes than shared RTL when AADT is higher than 23,035 veh/day.

5.3.3.4 Interstate road. Among all variables, design speed, exclusive RTL, and the component effects between traffic island and Log (AADT) have high contribution to crash frequency. The significant right-turn lane geometric design variables are exclusive

TABLE 5.5
Estimation result for counties in class B

	Estimate	Std. Error	Pr(>|z|)
Design speed 1	0.54	0.16	***
Hour night	-0.83	0.13	***
Visibility condition (lighted)	0.81	0.17	***
Surface condition (wet)	-1.07	0.12	***
Pedestrian crosswalk at RTL 1	0.40	0.22	*
Log (turn radius)	0.49	0.14	***
RTL type 1	9.03	4.05	*
Log (AADT)	1.52	0.38	***
Channelized type (traffic island)	-0.64	0.48	†
RTL Type1 : Log (AADT)	-0.89	0.40	*

Note:
†$p < 0.1$
*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

TABLE 5.6
Estimation result for counties in class C

	Estimate	Std. Error	Pr(>|z|)
Junction type (intersection)	0.75	0.23	***
Junction type (traffic circle/roundabout)	1.01	0.72	Insignificant
Design speed 1	0.39	0.10	***
Locality (urban)	2.16	0.84	**
Hour night	-0.71	0.06	***
Visibility condition (lighted)	1.20	0.10	***
Surface condition (wet)	-1.19	0.07	***
Pedestrian crosswalk at RTL 1	0.20	0.12	†
Log (turn radius)	0.28	0.08	***
RTL type 1	5.05	2.64	*
Log (AADT)	1.02	0.24	***
Traffic control (signal)	-0.41	0.17	*
Traffic control (yield/stop)	0.14	0.20	Insignificant
RTL type 1 : Log (AADT)	-0.54	0.25	*

Note:
†$p < 0.1$
*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

TABLE 5.7
Estimation result for right-turn lanes in city/local roads

	Estimate	Std. Error	Pr(>|z|)
Junction type (intersection)	0.96	0.22	***
Junction type (traffic circle/roundabout)	0.88	0.39	*
Design speed 1	0.44	0.07	***
Locality (urban)	1.50	0.48	**
Hour night	-0.81	0.05	***
Cluster 1	-0.07	0.18	Insignificant
Cluster 2	-0.37	0.12	**
Visibility condition (lighted)	1.46	0.10	***
Surface condition (wet)	-0.29	0.15	*
Visibility condition (lighted) : Surface condition (wet)	-0.96	0.16	***
Pedestrian crosswalk at RTL 1	0.21	0.10	*
Log (turn radius)	0.36	0.07	***
RTL type 1	3.07	1.84	*
Log (AADT)	0.79	0.18	***
Traffic control (signal)	-0.38	0.13	**
Traffic control (yield/stop)	0.16	0.16	Insignificant
Channelized type (traffic island)	5.87	2.70	*
Exclusive RTL 1 : Log (AADT)	-0.35	0.18	*
Log (AADT) : Channelized type (traffic island)	-0.56	0.26	*

Note:
†$p < 0.1$
*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

TABLE 5.8
Estimation result for right-turn lanes in state roads

	Estimate	Std. Error	Pr(>|z|)
Design speed 1	0.81	0.21	***
Hour night	-0.65	0.15	***
Visibility condition (lighted)	0.59	0.21	**
Surface condition (wet)	-1.00	0.15	***
Log (turn radius)	0.56	0.18	**

Note:
**$p < 0.01$
***$p < 0.001$

and shared RTL and the component effect between channelized type of right-turn lane and AADT. The estimation result can be seen in Table 5.10. Exclusive RTL has fewer crashes than shared RTL when the AADT is higher than 41,212 veh/day. The presence of traffic island has fewer crashes than the channelized type of nothing/marking when the AADT is higher than 18,919 veh/day.

5.3.3.5 Roadway class level estimates conclusion

1. The presence of roundabout/traffic circle increases crashes for RTL in local road.
2. RTL with high design speed increases crashes, and the effects are different on road classes.
3. Pedestrian crosswalk at RTL increases crashes for RTL in local road.

TABLE 5.9
Estimation result for right-turn lanes in US roads

	Estimate	Std. Error	Pr(>|z|)
Junction type (intersection)	1.44	0.78	*
Design speed 1	0.38	0.19	*
Hour night	-0.69	0.18	***
Visibility condition (lighted)	1.14	0.22	***
Surface condition (wet)	-1.32	0.19	***
Log (turn radius)	0.36	0.13	**
RTL type 1	13.46	4.91	**
Log (AADT)	1.78	0.42	***
Traffic control (signal)	-0.79	0.27	**
Traffic control (yield/stop)	1.33	0.31	***
RTL type 1 : Log (AADT)	-1.34	0.47	**

Note:
*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

4. RTL with large turn radius has more crashes than small turn radius, and the effects are different on road classes.
5. Exclusive RTL reduce crashes and the effects depends on the AADT and road class.
6. Signal control has fewer crashes and yield/stop has more crashes than RTLs with no traffic control in local road and US road. The effects of traffic control are different for RTL in local and US road.
7. RTL with traffic island decreases crashes than nothing/marking for RTL in local and interstate road.
8. Intersection traffic volume increase crashes.

TABLE 5.10
Estimation result for right-turn lanes in interstate roads

	Estimate	Std. Error	Pr(>|z|)
Junction type intersection	3.63	0.77	***
Design speed 1	0.34	0.12	**
Locality (urban)	1.00	0.38	**
Hour night	-0.96	0.13	***
Cluster 1	1.20	0.95	Insignificant
Cluster 2	-1.58	0.27	***
Visibility condition lighted	1.07	0.18	***
Surface condition (wet)	-1.43	0.13	***
Log (turn radius)	1.07	0.11	***
RTL type 1	8.82	3.36	**
Log (AADT)	1.38	0.28	***
Channelized type (traffic island)	16.84	9.28	*
RTL type 1 : Log (AADT)	-0.83	0.32	**
Log (AADT) : Channelized type (traffic island)	-1.71	0.91	*

Note:
*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

6. ECONOMETRIC MODEL B FOR CRASH SEVERITY

6.1 Model Robustness Testing

A robustness test for the RTL geometric factors and compound effects in the overall severity log-linear model is presented in Table 6.1. The effects of RTL geometric factors and compound effects have been computed in each specification. The first three regressions examine the specification with only RTL geometric factors and compound factors. In all specifications, we use different combinations of environmental-related controls and spatial-temporal controls (B1, B2, and B3 are controlled from one in three; C1, C2, and C3 are controlled from two in three; D is the full model with all variables). Based on the results of the robustness test, the effects of both "len" is nonsignificant in any specification, which confirms the consistent estimates of "len." Besides, the robustness test suggests that the effect of cluster is nonsignificant. The geometric design variable "Accye" and the intersection characteristics variable "Spl > 35" are nonsignificant in any specification. Furthermore, the effects of compound factors, such as channelized type with intersection traffic volume (AADT) and the right-turn type with design speed, are not significant under any specifications. Thus, we won't consider it into the final Log-linear model.

6.2 Marginal Effect and Elasticity Estimation

The average marginal effects and elasticities of explanatory variables in the overall model of log-linear models is presented in Table 6.1. The marginal effect describes the changes in the conditional mean of the crashes in response to a unit change in the explanatory variables. Meanwhile, the elasticity measures the percentage changes of the crash frequency in response to a unit percentage change in the continuous explanatory variables. Therefore, the elasticity is adopted to interpret the effects of continuous variables, and the marginal effects are more appropriate to measure the effects of nominal variables. In particular, the coefficients of the continuous explanatory variables in the logarithm function directly estimate the elasticity. The final overall model is presented in Table 6.2.

6.3 Interpretation

6.3.1 Overall Level

6.3.1.1 Intersection characteristics. There are two significant intersection characteristics factors: the presence of intersection junction type and the design speed. The effect of the presence of roundabout/traffic circle is insignificant compared with the RTLs in interchange/ramp and the presence of intersection junction has more crash cost than RTLs in interchange/ramp (0.36% of crash cost or $12,260) (see Figure 6.1). Besides, right-turn lane with a design speed exceed 35 mph increase 0.21% of crash cost ($12,423).

6.3.1.2 Right-turn lane geometric design variables. The significant right-turn lane geometric design variables are the presence of bicycle lane, right-turn lane turn radius, right-turn lane width, the presence of traffic island, and the right-turn lane type (exclusive RTL or shared RTL). Among all right-turn lane geometric design variables, the presence of bicycle lane and right-turn lane turn radius have the most significant contributions to crash cost (see Figure 6.2). The presence of bicycle lane is worse than no bicycle lane in the RTL, where the crash cost of the presence of the bicycle lane is 0.57% ($10,445) more than no bicycle lane. Increasing the RTL turn radius will make the situation even worse,

TABLE 6.1
Robustness test of the RTL geometric factors in overall log-linear model

	Log-Linear									
Explanatory Variables	**A1**	**A2**	**A3**	**B1**	**B2**	**B3**	**C1**	**C2**	**C3**	**D**
Log (len)	0.046	0.131†	0.118	0.111	0.092	0.125	0.101	0.120†	0.080	0.0898
Log (wid)		-0.339†	-0.334†	-0.402†	-0.202†	-0.336†	-0.207*	-0.402†	-0.291†	-0.299†
Log (tur)		-0.189**	-0.195**	-0.231***	-0.199**	-0.196**	-0.200**	-0.232***	-0.219**	-0.220**
ExRTL			-0.212	-0.289†	-0.226*	-0.245†	-0.257†	-0.331†	-0.290*	-0.330*
Accye			11.894	9.264	11.379	11.365	10.877	8.555	8.855	8.164
Chtraf			2.846	2.954	2.571	3.109	2.834	3.245	2.803	3.090
Trafsn			0.166	0.244*	0.160	0.171	0.165	0.251*	0.254*	0.262*
Trafsg			0.022	0.113	0.009	0.023	0.010	0.113	0.112	0.113
Spl > 35			0.043	0.028	0.052	0.014	0.023	-0.007	0.049	0.015
Bicla (bicycle lane)			-7.006*	-7.105*	-7.110*	-7.012*	-6.205*	-6.983*	-6.173*	-6.423*
Log (AADT)			0.041	0.069	0.026	0.057	0.042	0.087	0.058	0.075
Intsec (intersection)				0.312†	0.317†	0.298†	0.279†	0.343*	0.356*	0.352*
Rouab (round about)				0.223	0.254	0.221	0.259	0.231	0.297	0.294
Visgo				1.058***				1.021***	1.059***	1.022***
Suwe				-0.491**				-0.510**	-0.499**	-0.519**
Clu1					0.141		0.136		0.208†	0.201†
Clu2					0.170		0.163		0.154	0.145
Loub					-0.198		0.294		-0.126	-0.106
Night						-0.274***	-0.270***	-0.638***		-0.325***
ExRTL : Spl > 35			0.099†	0.194†	0.091†	0.137†	0.128†	0.241†	0.184†	0.229†
Bicla : Log (AADT)			0.756*	0.724*	0.718*	0.694*	0.692*	0.772*	0.721*	0.753*
Chtraf : Log (AADT)			-0.28	-0.293	-0.251	-0.308	-0.279	-0.323	-0.276	-0.305
Visgo : Suwe				-0.680***				-0.695***	-0.671***	-0.687***
Adj R-squared	0	0.005	0.005	0.117	0.005	0.011	0.010	0.124	0.127	0.134
Observations	2173	2173	2173	2173	2173	2173	2173	2173	2173	2173

$^{\dagger}p < 0.1$
$^{*}p < 0.05$
$^{**}p < 0.01$
$^{***}p < 0.001$

where a 1% increase in RTL turn radius leads to 0.14% more crash cost. The bicycle lane is implemented in the intersections with high bicycle flow, and the high across traffic flow (bicycle flow) or faster speed make the risk exposure worse. Besides, from the statistical analysis, increasing the RTL width will be beneficial to save crash cost, where a 1% increase in RTL width leads to 0.38% less crash cost. This is because the lane width provides safe space for movement and ease of turning, which helps to avoid the rear-end collision. Exclusive RTLs provide space for the turning movement. Thus, it improves safety performance. The presence of exclusive RTLs is beneficial to save 0.07% of crash cost ($4,229) relative to shared RTLs (see Figure 6.3). Furthermore, the presence of traffic island is beneficial to save the crash cost by 0.15% ($7,799) (see Figure 6.4).

6.3.1.2.1 Environmental variables. The environmental factors (visibility condition and surface condition) have the highest effects on crash cost among all factors (see Figure 6.5). Good visibility in wet road surface condition at RTLs is worse than poor visibility in dry road surface condition at RTLs by introducing 0.17% ($5,453) more crash cost. The possible reason is that drivers avoid the bad driving environment. The good visibility condition at right-turn lanes leads to 0.75% ($19,235) more crash cost relative to poor visibility condition at right-turn lanes. The wet surface condition at right-turn lanes is beneficial to save 1.10% of crash cost ($46,863) relative to dry surface condition at right-turn lanes.

6.3.1.2.2 Spatial and temporal variables. Right-turn lanes at nighttime is better than RTLs at daytime by saving 0.33% of crash cost ($14,410).

Conclusion: the ranking of the contribution of right-turn lane geometric design variables on crash severity at overall level can be seen in Table 6.3.

6.3.2 County Level

As described in the section 4.1.2, there are three classes of counties. Class A is Marion County; class B is Hamilton County and Hancock County; class C is Madison County, Tippecanoe County, Clark County, Harrison County, Vanderburgh County, Allen County, and La Porte County.

6.3.2.1 County class A. The estimation result of the crash severity at county class A is shown in Table 6.4. The most significant right-turn lane geometric design variables for counties in class A is the presence of bicycle lane and exclusive or shared right-turn lane. The presence of bicycle lane results in 0.23% ($10,487) more crash cost and the presence of pedestrian lane leads to

TABLE 6.2
The estimations of overall final severity model and marginal effect

	Coefficient	Standard Deviation	Marginal Effect
RTL Geometric Factors			
Log (tur)	-0.142*	0.065	-0.002
Log (wid)	-0.375†	0.204	-0.029
ExRTL	-0.370*	0.175	-0.069
Bicla (bicycle lane)	-6.98*	3.436	0.566
Chtraf	0.154†	0.109	0.154
Trafsn	0.19†	0.098	0.191
Trafsg	0.043	0.119	0.042
Intersection Characteristics			
Intsec (intersection)	0.356*	0.156	0.356
Rouab (round about)	0.294	0.254	0.294
Spl > 35	-0.119	0.192	0.043
Log (AADT)	0.035	0.077	0.001
Environmental-Related Factors			
Visgo	1.038***	0.119	0.751
Suwe	-0.572***	0.172	-1.096
Temporal Factors			
Night	-0.331***	0.074	-0.331
Compound Effects			
ExRTL : Spl > 35	0.394†	0.214	–
Visgo : Suwe	-0.642***	0.189	–
Bicla : Log (AADT)	0.782*	0.359	–
Adj R-squared	0.134	–	–
Observations	2173	–	–

Note: Elasticity measurement is estimated for continuous variables (turn radius, width, AADT). Marginal effect is estimated for nominal variables.
†$p < 0.1$
*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

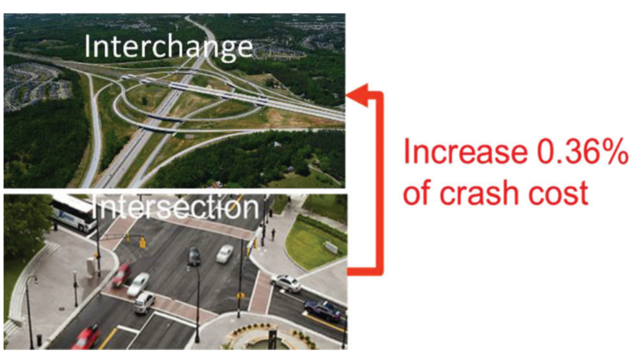


Figure 6.1 Effects of the intersection junction type (NACTO, 2017; Raleigh, 2010).

Figure 6.2 Effects of the presence of a bicycle lane (Fucoloro, 2014; Miyerov, 2021).

0.06% ($2,611) more crash cost. However, the exclusive RTLs are worse than the shared RTLs with more crash cost (0.48% ($14,077)). This might because the exclusive RTLs are usually installed in the high turning traffic intersections and the high turning traffic tends to increase the crash risk. Another possible reason could be non-appropriate design.

For the intersection characteristics, we find the presence of roundabout/traffic circle is better than intersection by saving 0.65% of crash cost ($36,037).

For environmental and temporal factors, RTLs at nighttime is beneficial to save 0.59% ($35,288) crash cost relative to RTLs at daytime. Good visibility condition at RTLs is worse than the poor visibility condition at RTLs with 0.89% ($20,170) more crash cost relative to the poor visibility condition at RTLs. The wet surface condition at RTLs is beneficial to save 1.16% of crash cost ($42,072) relative to the dry surface condition at RTLs.

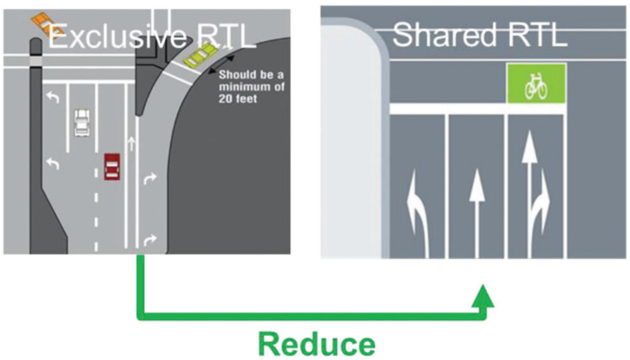


Figure 6.3 Effects of the RTL type (FHWA, 2016; WKNZTA, n.d.)

Figure 6.4 Effects of the channelized type of RTLs (Cutrufo, 2015; ePermitTest, 2020).

6.3.2.2 County class B. The estimation result of the crash severity at county class B is shown in Table 6.5. The most significant right-turn lane geometric design variables for counties in class B is the presence of bicycle lane and RTL width. A 1% increase in RTL turn radius is beneficial to save 0.17% of crash cost. And the presence of bicycle lane is worse than no bicycle lane with a 1% ($64,247) of crash cost. Besides, a 1% increase in RTL width is beneficial to save 0.76% of crash cost. Exclusive RTLs is beneficial to save 0.12% of crash cost ($8,945) relative to shared RTLs. RTLs having traffic signal control is worse than RTLs having traffic sign with 0.36% ($21,117) of crash cost and RTLs having traffic sign is worse than RTLs with no traffic control with 0.20% of crash cost ($11,731). That is because RTLs having traffic control (signal or traffic sign) usually have higher turning movement.

For environmental factors, we find good visibility condition at RTLs is worse than poor visibility condition at RTLs with 0.74% of crash cost ($17,074). Besides, wet surface condition at RTLs is beneficial to save 1.15% of crash cost ($51,715) relative to dry surface condition at RTLs.

For spatial and temporal factors, RTLs at urban have more crash cost (2.63% ($48,299)) relative to

TABLE 6.3
Ranked importance of crash severity in the overall model

Importance Ranking
1. Roadway junction
2. Presence of bicycle lane
3. RTL type
4. RTL turn radius
5. RTL width
6. Presence of traffic island

Figure 6.5 Good visibility vs. bad visibility (ADOT, n.d.; Berg & Alaniz, 2018; Khanna, 2020; NOAA, n.d.).

TABLE 6.4
Severity estimation result for counties in class A

	Coefficient	Standard Deviation	Marginal Effect
RTL Geometric Factors			
ExRTL	23.639***	6.186	0.476
Bicla (bicycle lane)	24.646**	8.41	0.228
Perdla (pedestrian lane)	-6.42	3.913	0.06
Intersection Characteristics			
Rouab (round about)	-0.653**	0.245	-0.653
Log (AADT)*	2.311***	0.687	0.001
Environmental-Related Factors			
Visgo	0.888***	0.2	0.888
Suwe	-1.164***	0.166	-1.164
Temporal Factors			
Night	-0.594***	0.171	-0.594
Compound Effects			
ExRTL : Log (AADT)	-2.441***	0.656	–
Bicla : Log (AADT)	-2.574**	0.897	–
Perdla : Log (AADT)	0.683†	0.411	–
Adj R-squared	0.193	–	–
Observations	349	–	–

Note:
$^{\dagger}p < 0.1$
$*p < 0.05$
$**p < 0.01$
$***p < 0.001$

RTLs at rural area. In addition, RTLs at nighttime is beneficial to save crash cost ($23,644) relative to RTLs at daytime.

6.3.2.3 County class C. The estimation result of the crash severity at county class C is shown in Table 6.6. The most significant RTL geometric design variables for counties in class C is the RTL type (exclusive RTLs or shared RTLs). For counties in class C, the exclusive RTLs in these counties is better than shared RTLs by saving 0.36% of total crash cost ($26,330). Besides, the presence of intersection junction is worse than the presence of interchange /ramp with more crash cost ($15,870). For environmental factors, the wet surface condition at RTLs is better than dry surface condition at RTLs by saving 1.10% of total crash cost ($43,646). Good visibility condition at RTLs is worse than the poor visibility condition at RTLs with 0.74% of total crash cost ($23,334). Furthermore, we find RTLs at nighttime is beneficial to save 0.29% of total crash cost ($20,729) relative to RTLs at daytime for RTLs in county class C.

6.3.2.4 Conclusion for county level estimation

- The environmental factors (visibility condition and surface condition) have the *highest effects* on crash cost among all factors (see Figure 6.6).
- Exclusive RTLs and the presence of bicycle lane are the most important factors among all geometric factors (see Figure 6.7).
- RTL width is a significant factor for county class C, where a 1% increase in RTL width at county class **B** is beneficial to save 0.76% of crash cost.

Conclusion: the ranking of the contribution of right-turn lane geometric design variables on crash severity at the county level can be seen in Table 6.7.

6.3.3 Roadway Class Level

The estimation for the right-turn lane performance in terms of crash severity is based on the roadway class level: city/local road, US road, interstate road, and state road. The detail interpretation can be found in the following sections.

6.3.3.1 City/local road. The estimation result of the crash severity at city/local road is shown in Table 6.8. The most significant RTL geometric design variables for RTLs in city/local road is the traffic control. RTLs with signal control is better than RTLs with no traffic control by saving 0.82% of crash cost ($61,399) and RTLs with traffic sign control is better than RTLs with no traffic control by saving 0.54% of crash cost ($40, 433). For the intersection characteristics, the presence of

TABLE 6.5
Severity estimation result for counties in class B

	Coefficient	Standard Deviation	Marginal Effect
RTL Geometric Factors			
Log (tur)	-0.174*	0.087	-0.002
Log (wid)	-0.761*	0.302	-0.029
ExRTL	-0.85**	0.289	-0.069
Bicla (bicycle lane)	0.991***	0.216	0.566
Trafsn	0.198	0.191	0.191
Trafsg	0.355*	0.161	0.042
Intersection Characteristics			
Spl > 35	-0.477	0.311	0.043
Environmental-Related Factors			
Visgo	0.995***	0.166	0.751
Suwe	-0.685**	0.239	-1.096
Spatial Factors			
Loub	2.632**	0.827	-0.331
Temporal Factors			
Night	-0.301**	0.1	-0.331
Compound Effects			
ExRTL : Spl > 35	0.93**	0.341	–
Visgo : Suwe	-0.561*	0.261	–
Adj R-squared	0.148	–	–
Observations	1,132	–	–

Note:
*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

intersection junction is worse than RTLs in interchange/ramp with 0.29% more crash cost, and the presence of roundabout/traffic circle is beneficial to save 1.40% of crash cost ($5,432) relative to RTLs in interchange/ramp. Because the roundabout/traffic circle helps to slow down the speed.

6.3.3.2 State road. The estimation result of the crash severity at state road is shown in Table 6.9. For the effects of environmental factors in state road, good visibility at RTLs is worse than poor visibility at RTLs by introducing 1.04% ($15,582) of crash cost. Besides, wet surface condition is better than the dry surface condition at RTLs by saving 1.14% of crash cost ($55,760).

For the effects of spatial and temporal factors in the state road, RTLs at nighttime is better than RTLs at daytime by saving 0.66% of crash cost ($37,407) and RTLs at school zone are worse than RTLs at non-school zone by introducing 1.13% ($78,006) more crash cost. In above two conditions, either more traffic flow presents in daytime or more pedestrians cross the intersections.

6.3.3.3 US road. The estimation result of the crash severity at state road is shown in Table 6.10. The most significant right-turn lane geometric design variable for RTLs in US road is the RTLs type (exclusive RTLs or shared RTLs) and RTLs width. Exclusive RTLs is beneficial to save 0.74% of crash cost ($38,496) relative to the shared RTLs. A 1% increase in RTLs width leads to 0.22% reduction of crash cost. Besides, the presence of pedestrian lane is worse than no pedestrian by introducing 0.78% ($49,808) of crash cost.

For the effects of the environmental variables, good visibility condition at RTLs is worse than the poor visibility condition at RTLs by introducing 0.80% of crash cost ($24,328). And wet surface condition 0.73% of crash cost ($37,157) relative to the dry surface condition at RTLs.

6.3.3.4 Interstate road. The estimation result of the crash severity at interstate road is shown in Table 6.11. The most significant right-turn lane geometric design variables for RTLs in interstate road is the RTL turn radius and design speed. A 1% increases in RTL turn radius leads to 1.78% increase in crash cost. This because high speed of movement aggravates collision. RTL with a design speed above 35 mph is worse than RTL with a design speed below 35 mph by 3.95% of

TABLE 6.6
Severity estimation result for counties in class C

	Coefficient	Standard Deviation	Marginal Effect
RTL Geometric Factors			
ExRTL	-0.359*	0.165	-0.359
Intersection Characteristics			
Intsec (intersection)	0.552**	0.210	0.552
Environmental-Related Factors			
Visgo	1.167***	0.218	0.737
Suwe	-0.285†	0.327	-1.099
Temporal Factors			
Night	-0.282*	0.136	-0.282
Compound Effects			
Visgo : Suwe	-0.995**	0.358	–
Adj R-squared	0.124	–	–
Observations	692	–	–

Note:
†$p < 0.1$
*$p < 0.05$
**$p < 0.01$
***$p < 0.001$

Figure 6.6 Effects of visibility (ADOT, n.d.; Berg & Alaniz, 2018; Khanna, 2020; NOAA, n.d.).

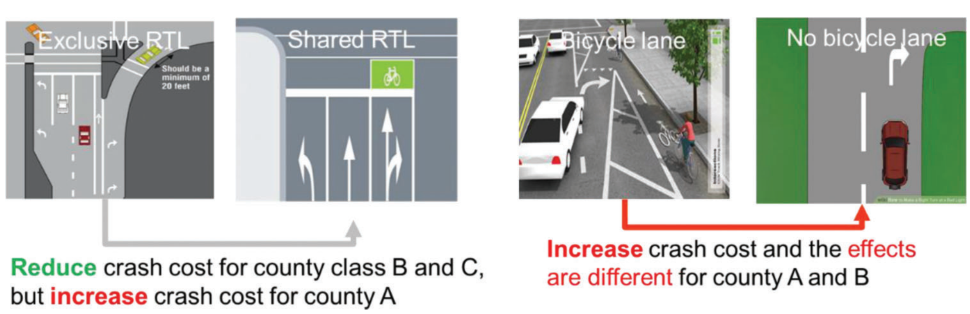


Figure 6.7 Effects of the RTL type and the presence of the bicycle lane (FHWA, 2016; Fucoloro, 2014; Miyerov, 2021; WKNZTA, n.d.).

crash cost ($94,567) relative to the RTL with a design speed below 35 mph. Besides, we find the exclusive RTLs are worse than the shared RTLs by introducing 2.69% ($58,125) of crash cost.

RTL types (exclusive RTLs and shared RTLs) either introduce crash cost or reduce crash cost. Exclusive RTLs provide space for turning movement and reduce the crash risk due to the speed-difference. However, the unappropriated design of the exclusive RTLs may increase crashes. For example, in the location of (39.91049465, -86.26956807), (40.493456, -86.86872). The design speed is 40 mph at both RTLs, and there is *no* acceleration lanes in the RTLs. The turn radius: 200 inch, 400 inch (the average turn radius is 67 inches when the design speed is 40 mph). In such cases, there is a large speed difference between the right-turn vehicle and the through movement due to the lack of accelerate lane or inappropriate design, thus leading to rear-end collision (see Figure 6.8).

For the effects of the environmental factors, good visibility condition is worse than poor visibility condition at RTLs by introducing 1.04% of crash cost ($12,795), and wet surface condition is better than the dry surface condition at RTLs by saving 1.77% of crash cost ($40,287).

For the spatial and temporal factors, RTLs at urban area are worse than RTLs at rural area by introducing 2.75% of crash cost. RTLs at nighttime is better than RTLs at daytime by saving 0.69% of crash cost ($18,228).

TABLE 6.7
Ranked importance of crash severity at the county level

Importance Ranking
1. RTL type
2. Presence of bicycle lane
3. Presence of pedestrian lane
4. Roadway junction
5. RTL turn radius
6. Traffic control

TABLE 6.8
Estimation result for right-turn lanes crash severity in city/local roads

City/Local Road	**Coefficient**	**Standard Deviation**	**Marginal Effect**
RTL Geometric Factors			
Log (tur)*	-0.194*	0.077	-0.004
Log (wid)*	-0.677**	0.237	0.055
ExRTL	-0.346†	0.189	0.019
Bicla (bicycle lane)	-8.679*	3.664	0.608
Chtraf	0.207†	0.124	0.207
Trafsn	0.382*	0.162	0.382
Trafsg	0.512***	0.128	0.512
Intersection Characteristics			
Intsec (intersection)	0.578*	0.226	0.578
Rouab (round about)	0.807*	0.322	0.807
Spl > 35	-0.3	0.233	0.146
Log (AADT)*	0.045	0.102	0.001
Environmental-Related Factors			
Visgo	1.014***	0.14	0.734
Suwe	-0.633**	0.201	-1.146
Temporal Factors			
Night	-0.355***	0.083	-0.355
Compound Effects			–
ExRTL : Spl > 35	0.514*	0.251	–
Visgo : Suwe	-0.618**	0.22	–
Bicla : Log (AADT)	0.959**	0.381	–
Adj R-squared	0.142	–	–
Observations	1,648	–	–

Note:
†p < 0.1
*p < 0.05
**p < 0.01
***p < 0.001

TABLE 6.9
Estimation result for right-turn lanes crash severity in state roads

State Road	Coefficient	Standard Deviation	Marginal Effect
RTL Geometric Factors			
Log (tur)	-0.392	0.26	-0.008
Trafsn	-0.535	0.339	-0.535
Trafsg	-0.815*	0.345	-0.815
Intersection Characteristics			
Intsec (intersection)	0.291	0.873	0.291
Rouab (round about)	-1.398	1.041	-1.398
Environmental-Related Factors			
Visgo	1.037***	0.277	1.037
Suwe	-1.138***	0.22	-1.138
Spatial Factors			
School zone	1.132[†]	0.691	1.132
Temporal Factors			
Night	-0.655**	0.229	-0.655
Adj R-squared	0.142	–	–
Observations	1,648	–	–

Note:
*p < 0.05
**p < 0.01
***p < 0.001

TABLE 6.10
Estimation result for right-turn lanes crash severity in US roads

US Road	Coefficient	Standard Deviation	Marginal Effect
RTL Geometric Factors			
Log (wid)	1.878*	0.923	0.137
ExRTL	-0.736*	0.37	-0.736
Perdla (pedestrian lane)	9.702	7.231	-0.778
Intersection Characteristics			
Log (AADT)*	-0.218	0.349	0.001
Environmental-Related Factors			
Visgo	0.803*	0.319	0.803
Suwe	-0.729**	0.276	-0.729
Compound Effects			
Perdla : Log (AADT)	-1.088	0.756	–
Adj R-squared	0.065	–	–
Observations	190	–	–

Note:
*p < 0.05
**p < 0.01

TABLE 6.11
Estimation result for right-turn lanes crash severity in interstate roads

Interstate Road	Coefficient	Standard Deviation	Marginal Effect
RTL Geometric Factors			
Log (tur)	1.778*	0.729	0.008
ExRTL	2.692†	1.496	2.692
Intersection Characteristics			
Spl > 35	3.946*	1.766	3.946
Log (AADT)	-1.227	0.884	0.001
Environmental-Related Factors			
Visgo	1.609***	0.462	1.035
Suwe	-0.763	0.681	-1.767
Spatial Factors			
Lourb	2.745†	1.471	2.745
Temporal Factors			
Night	-0.691*	0.332	-0.691
Compound Effects			
Visgo : Suwe	-1.317†	0.763	–
Adj R-squared	0.286	–	–
Observations	101	–	–

Note:
$^{\dagger}p < 0.1$
$*p < 0.05$
$**p < 0.01$
$***p < 0.001$

Figure 6.8 Acceleration lane design (Google, n.d.n; Google, n.d.o)

6.3.3.5 Conclusion for roadway class level estimation

- The environmental factors (visibility condition and surface condition) and the temporal factor (daytime/nighttime) have the highest effects on crash cost among all factors (see Figure 6.9).
- Traffic control in RTLs, RTL type, and the presence of bicycle lane are the most important factors among all geometric factors (see Figure 6.10).
- The presence of bicycle lane at RTLs also increases crash cost.

Conclusion: the ranking of the contribution of right-turn lane geometric design variables on crash severity at the roadway class level can be seen in Table 6.12.

Figure 6.9 Effects of temporal and environmental roadway factors on crash cost severity (ADOT, n.d.; Berg & Alaniz, 2018; Khanna, 2020; NOAA, n.d.).

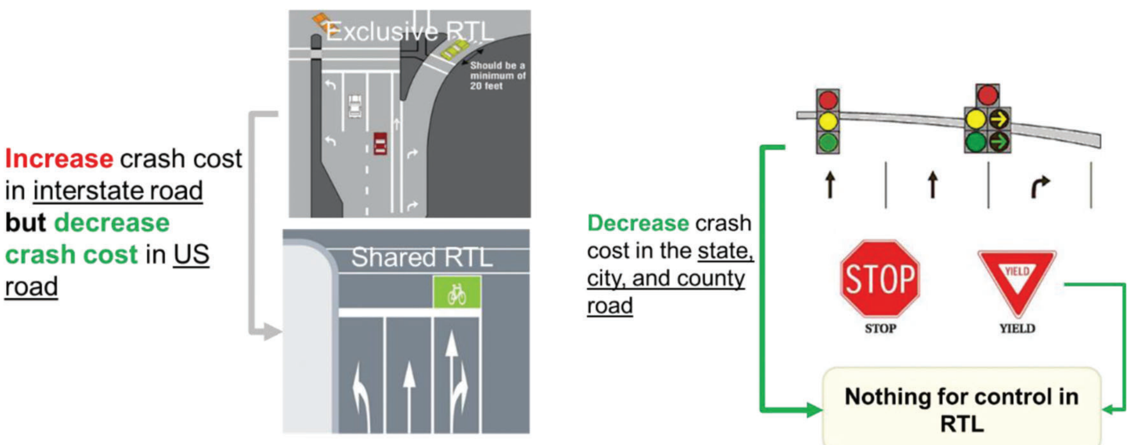


Figure 6.10 Effects of the RTL type and traffic control (roadway) on crash cost (FHWA, 2016; PNG All, 2020; Road Warrior, 2013; WKNZTA, n.d.).

TABLE 6.12
Ranked importance of crash severity at the roadway class level

Importance Ranking
1. Traffic control
2. RTL type
3. Presence of bicycle lane
4. RTL turn radius
5. Design speed
6. RTL width

7. MODELING CRASH FREQUENCY AND SEVERITY

7.1 Key Geometric Design Factors

7.1.1 Overall Level Intersection Characteristics

7.1.1.1 Design speed. Design speed above 35 mph has significant effects on both crash frequency and crash cost.

RTL with a design speed above 35 is worse than RTL with design speed below (equal to) 35 mph by introducing 1.56 times crashes and 0.21% more crash cost (see Figure 7.1).

7.1.1.2 Intersection junction type. The presence of an intersection junction has significant effect on crash frequency and crash cost relative to interchange/ramp. The presence of roundabout/traffic circle has significant effect on crash cost relative to interchange/ramp but no difference in crash frequency.

An intersection junction has 1.97 times the crash frequency risk and a 0.36% increase of crash cost relative to interchange/ramp. Roundabout/traffic circle is worse than interchange/traffic circle by introducing 0.29% more crash cost (see Figure 7.2).

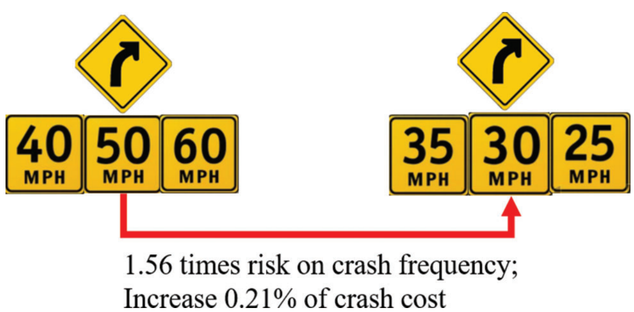


Figure 7.1 The effects of the design speed (overall) on frequency and severity (Wikipedia Commons, n.d.).

7.1.1.3 Right-turn lane geometric design variables

7.1.1.3.1 RTL turn radius and RTL type. RTLs turn radius and RTL type have the most significant effects on crash frequency and crash cost. A 1% increase in RTLs turn radius increases 0.56% of crash frequency and increases 0.21% of crash cost (see Figure 7.3). The exclusive RTLs with a design speed above 35 mph have 16% fewer crashes than the shared RTLs with a design speed above 35 mph. The exclusive RTLs with a design speed below 35 mph is better than the shared RTLs with a design speed below 35 mph by saving 0.07% of crash cost (see Figure 7.4).

7.1.1.3.2 RTL channelized type and the presence of bicycle lane. The channelized type of traffic island has significant effect on both crash frequency and crash cost. The effect of the traffic island at RTL is different depending on the AADT of the intersection (e.g., RTLs with traffic island has 21% fewer crashes when AADT is 100,000). RTLs with traffic island increase 0.15% of

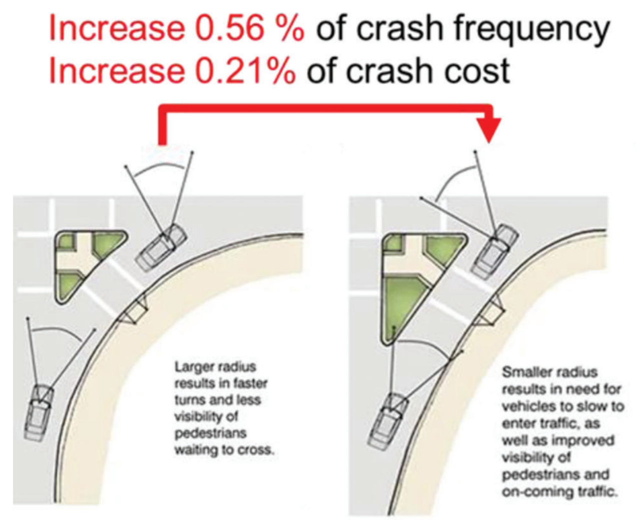


Figure 7.3 Effects of the RTL turn radius (overall) on frequency and severity (sfbetterstreets, n.d.)

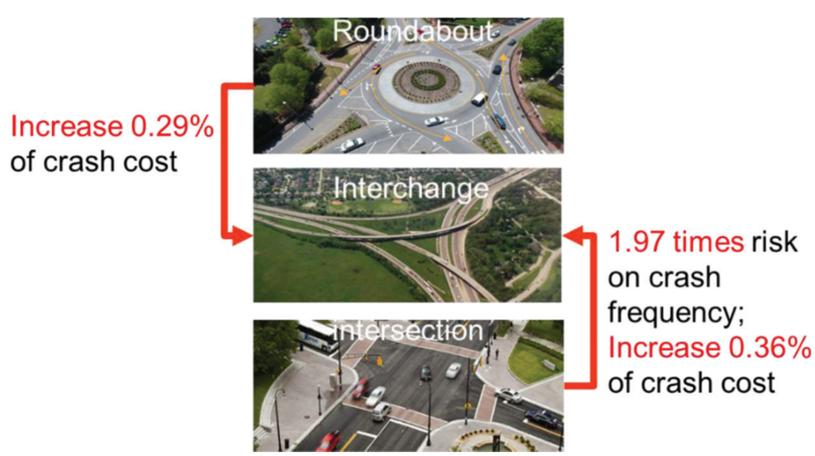


Figure 7.2 Effects of the intersection junction type (overall) on frequency and severity (NACTO, 2017; NCDOT, n.d.; Raleigh, 2010).

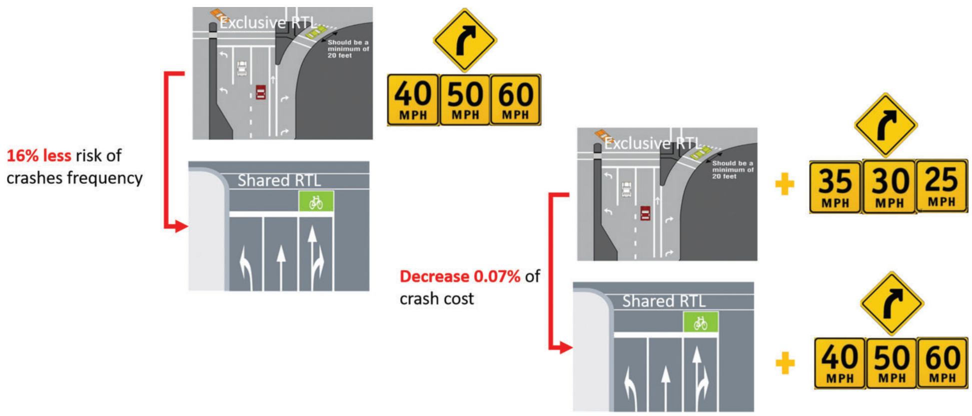


Figure 7.4 Effects of RTL types (overall) on frequency and severity (FHWA, 2016; Wikipedia Commons, n.d.; WKNZTA, n.d.).

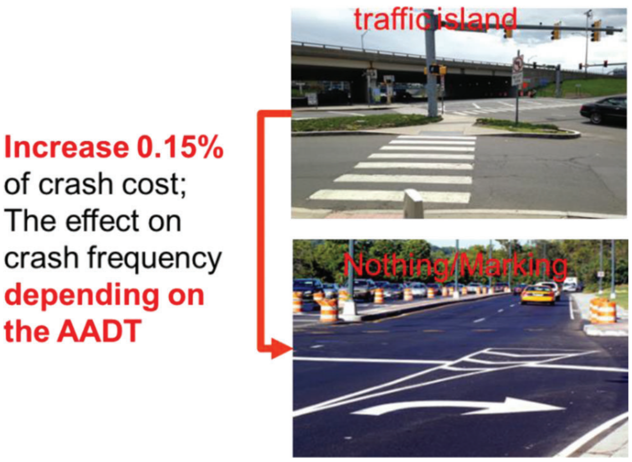


Figure 7.5 Effects of RTL channelized type (overall) on frequency and severity (Cutrufo, 2015; ePermitTest, 2020).

crash cost (see Figure 7.5). The presence of bicycle lane increases 0.57% of crash cost; and the sign control have 1.23 times risk on crash frequency more than no traffic control.

Conclusion: the ranking of the contribution of right-turn lane geometric design variables on both crash frequency and crash severity at overall level can be seen in Table 7.1.

7.1.2 County Level Intersection Characteristics

7.1.2.1 Design speed. Design speed above 35 mph has significant effects on crash frequency. RTL with a design speed above 35 has 1.5~1.7 times risk on crash frequency (see Figure 7.6).

7.1.2.2 Intersection junction type. The presence of intersection junction has significant effect on crash frequency and crash cost. The presence of roundabout/traffic circle is better than RTLs at intersection junction by reducing 0.57 times crashes and saving 0.65% of crash cost on county class A. The presence of intersection junction is worse than the presence of interchange /ramp by introducing 2.12 times more crashes and 0.55% more crash cost on county class C (see Figure 7.7).

TABLE 7.1
Ranked importance for both crash frequency and crash severity at the overall level

Importance Ranking
1. RTL turn radius
2. RTL type
3. Channelized type
4. Design speed
5. Intersection junction type

Figure 7.6 Effects of the design speed (county) on frequency and severity (Wikipedia Commons, n.d.).

7.1.2.3 Right-turn lane geometric design variables

7.1.2.3.1 RTL types and RTL turn radius. RTL type and RTLs turn radius has the most significant effects on crash frequency and crash cost. Exclusive RTLs are worse than shared RTLs by introducing 1.53 times crashes and 0.48% of crash cost on county class A, but exclusive RTLs are better than shared RTLs by reducing 0.89 times crashes and saving 0.12% of crash cost on county class B and reducing 0.8 times crashes

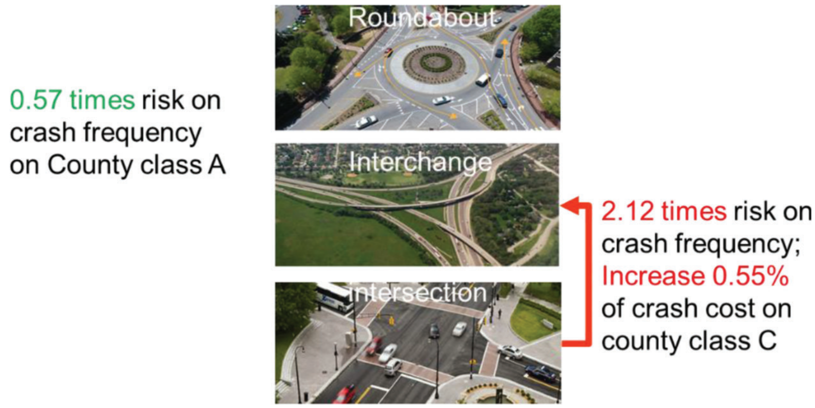


Figure 7.7 Effects of the intersection junction type (county) on frequency and severity (NACTO, 2017; NCDOT, n.d.; Raleigh, 2010).

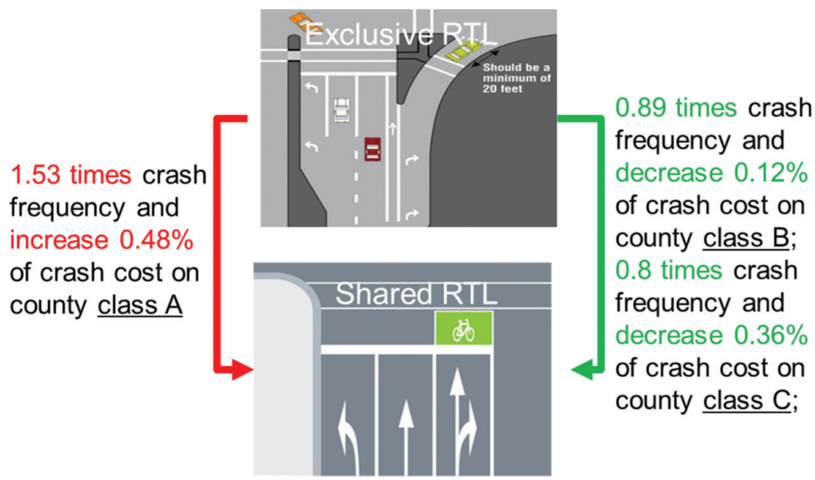


Figure 7.8 Effects of the RTL type (county) on frequency and severity (FHWA, 2016; WKNZTA, n.d.).

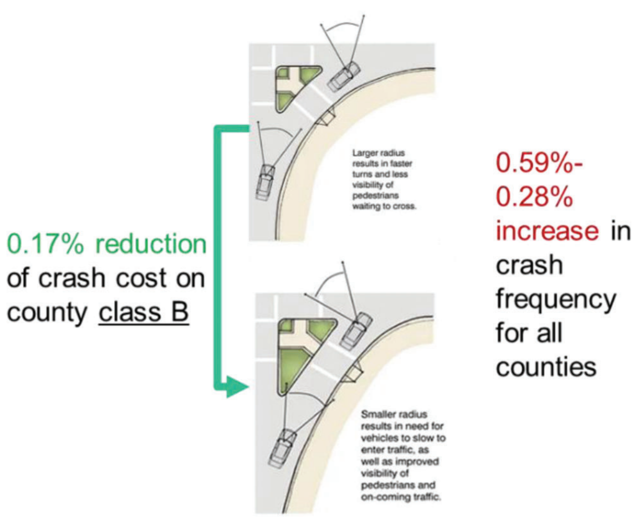


Figure 7.9 Effects of RTL turn radius (county) on frequency and severity (sfbetterstreets, n.d.).

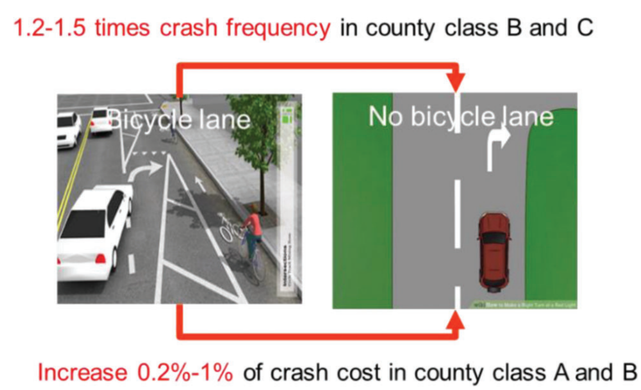


Figure 7.10 Effects of the bicycle lane at RTL (county) on frequency and severity (Fucoloro, 2014; Miyerov, 2021).

and saving 0.36% of crash cost on county class C (see Figure 7.8). A 1% increase in RTL turn radius leads to 0.17% reduction of crash cost on county class B, 1% increase in RTL turn radius 0.59%–0.28% increase in crash frequency for all counties (see Figure 7.9).

7.1.2.3.2 Bicycle lane and pedestrian lane. The presence of bicycle lane and pedestrian lane is worse than no bicycle lane in county class A and B by introducing 0.2%–1% of crash cost. The presence of bicycle lane and pedestrian lane is worse than no bicycle lane in

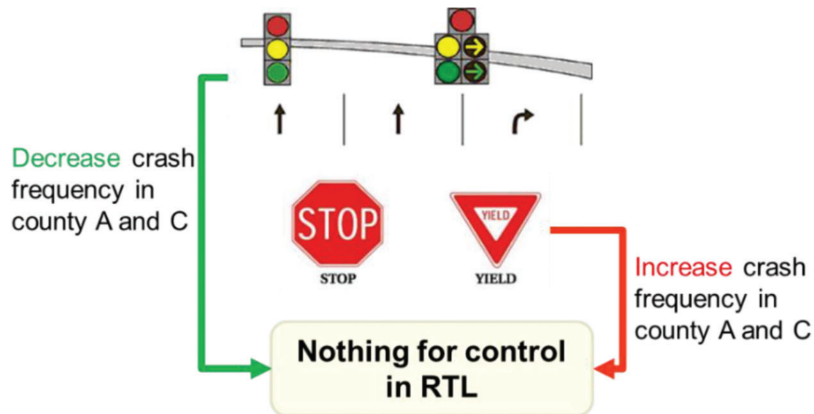


Figure 7.11 Effects of the traffic control (county) on frequency and severity (PNG All, 2020; Road Warrior, 2013).

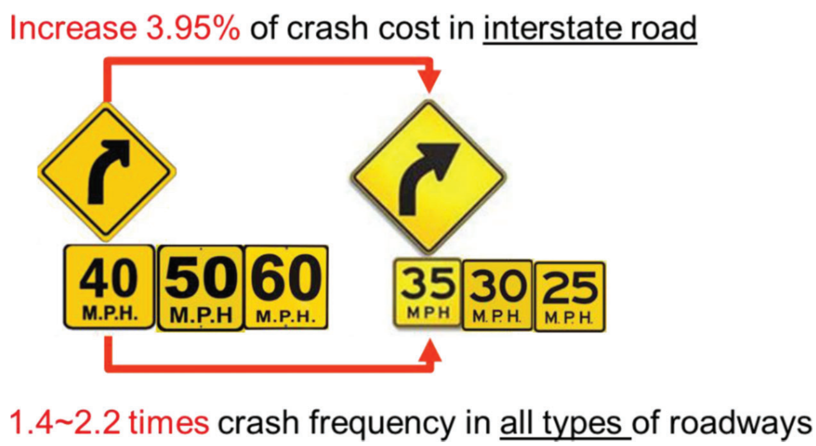


Figure 7.12 Effects of the design speed (roadway) on frequency and severity (Wikipedia Commons, n.d.).

county class B and C by introducing 1.2–1.5 times more crashes (see Figure 7.10).

7.1.2.3.3 Traffic control. RTLs having traffic signal control are better than RTLs having no traffic control by reducing the crash frequency for county class A and C (see Figure 7.11). However, RTLs having traffic sign control are better than RTLs having no traffic control for county class A and C by reducing crashes. RTLs having traffic signal are worse than RTLs with no traffic control by introducing 0.36% of crash cost and RTLs having traffic sign are worse than RTLs with no traffic control by introducing 0.20% of crash cost. Conclusion—the ranking of the contribution of right-turn lane geometric design variables on both crash frequency and crash severity at the county level can be seen in Table 7.2.

7.1.3 Roadway Class Level Intersection Characteristics

7.1.3.1 Design speed. Design speed above 35 mph has significant effects on both crash frequency and crash cost. RTL with a design speed above 35 mph is worse than the RTL with a design speed below (equal to) 35 mph by introducing 3.95% of crash cost in RTLs in the interstate road and increasing 1.4~2.2 times more crashes in RTLs in different roadways (see Figure 7.12).

TABLE 7.2
Ranked importance of both crash frequency and crash severity at the county level

Importance Ranking
1. RTL type
2. RTL turn radius
3. Presence of bicycle lane
4. Design speed
5. Traffic control

7.1.3.2 Intersection junction type. The presence of intersection junction has significant effect on crash frequency and crash cost. The presence of intersection junction is worse than interchange/ramp in state road by introducing 0.29% of crash cost and the presence of roundabout/traffic circle is better than interchange/ramp in state road by saving 1.40% of crash cost. The presence of intersection junction has 2.61–4.22 times more crashes than the presence of interchange/ramp and the presence of roundabout/traffic circle has 2.4 times more crashes than the presence of interchange/ramp in local/city road (see Figure 7.13).

7.1.3.3 Right-turn lane geometric design variables

7.1.3.3.1 RTLs turn radius and traffic control of RTLs. RTLs turn radius and traffic control of RTLs have the most significant effects on crash frequency and crash cost. The installment of traffic sign is better than RTLs with no traffic control system by saving 0.38%~1.64% of crash cost in different roadways. The installment of traffic signal is better than RTLs with no traffic control system by saving 0.82%~0.51% of crash cost in different roadways. The installment of traffic sign is worse than no traffic control system by introducing 1.17~3.78 times crashes and the installment of traffic signal is better than no traffic control system by reducing 0.45~0.68 times crashes in different roadways (see Figure 7.14). A 1% increase in RTLs turn radius leads to 0.38%~1.07% increase of crash risk in different roadways and increases 1.78% of crash cost in the interstate road and 0.19% of crash cost in the local/city road (see Figure 7.15).

7.1.3.3.2 RTL type. Exclusive RTLs are better than shared RTLs by reducing crashes in different roadways, However, the exclusive RTLs have 2.69% more crash cost than the shared RTLs in the interstate road but are better than shared RTLs by saving 0.74% of crash cost in the US road.

Conclusion: the ranking of the contribution of right-turn lane geometric design variables on both crash frequency and crash severity at roadway class level can be seen in Table 7.3.

TABLE 7.3
Ranked importance of both crash frequency and crash severity at the roadway class level

Importance Ranking
1. RTL turn radius
2. Traffic control
3. Design speed
4. Exclusive and shared RTL
5. Intersection junction type

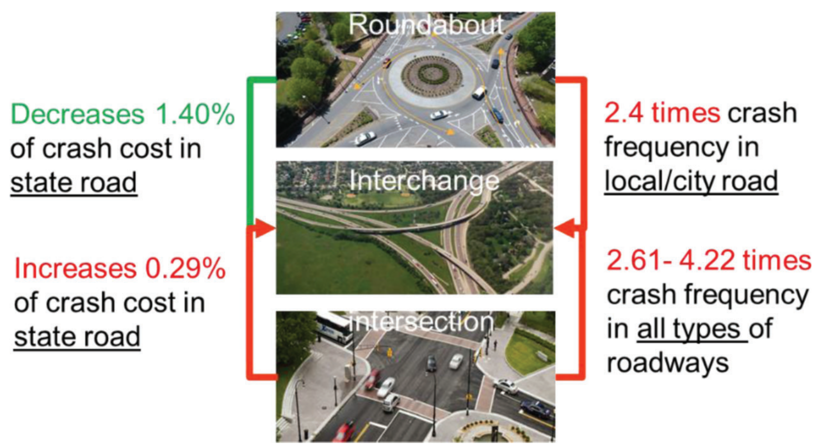


Figure 7.13 Effects of intersection junction (roadway) on frequency and severity (NACTO, 2017; NCDOT, n.d.; Raleigh, 2010).

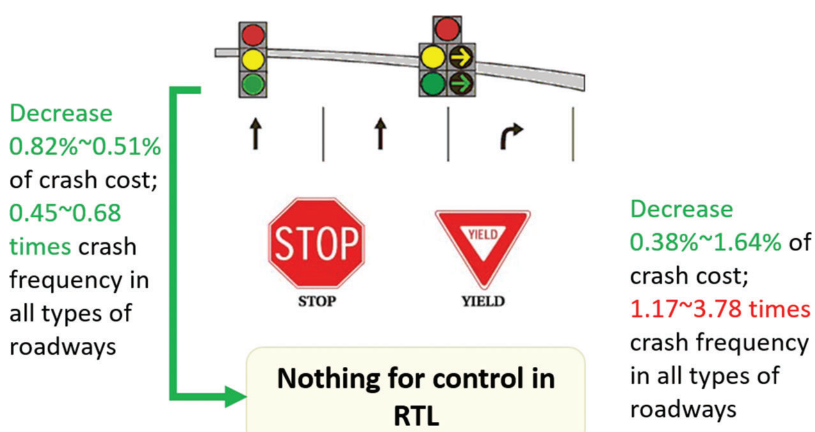


Figure 7.14 Effects of the traffic control (roadway) on frequency and severity (PNG All, 2020; Road Warrior, 2013).

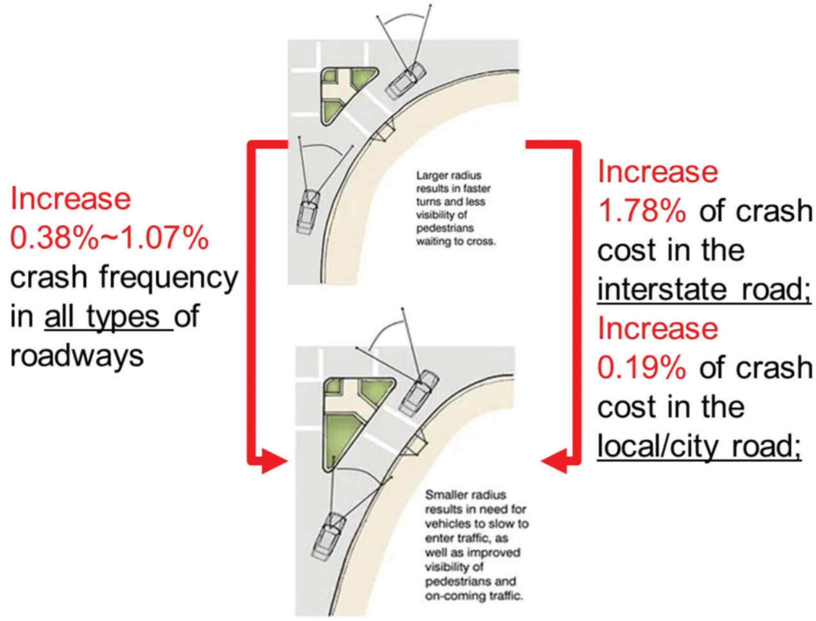


Figure 7.15 Effects of the RTL turn radius (roadway) on frequency and severity (sfbetterstreets, n.d.).

TABLE 7.4
Ranked importance of intersection characteristics and RTL geometric design factors for both crash frequency and severity

Importance Ranking
1. RTL turn radius
2. Exclusive and shared RTL
3. Design speed
4. Traffic control
5. Intersection junction type
6. Presence of bicycle lane
7. RTL channelized type

7.2 Recommendations for Right-Turn Lane Geometric Design

7.2.1 Key Factors Ranking

From the statistical analysis and modeling, based on the statistical analysis, we rank the importance of the intersection characteristics and RTL geometric design factors based on their effects on both crash frequency and severity.

8. DISCUSSIONS AND CONCLUSIONS

8.1 Summary of Recommendations

8.1.1 The Recommendation for Crash Frequency

Based on the statistical analysis and modeling for the crash frequency, we find the environmental factors (visibility condition, road surface condition, and the temporal factors) have the most significant effects on number of crashes among all factors (geometric design factors, intersection factors, temporal and spatial factors). In the estimates, the good visibility condition has more crashes than the poor visibility and the dry surface condition of RTLs increases the risk exposure comparing to the wet surface condition of RTLs. Besides, RTLs at daytime has more crashes than RTLs at nighttime. This seems to contradict our expectations, since good environmental conditions (good visibility and surface condition) usually improves the driving vision. The reason behind that could be that drivers tend to avoid the bad weather (e.g., snow and sandstorm) and would be more careful when the visibility condition is not good. Therefore, the observed traffic flow will be much less than on normal days and leads to the reduction of risk exposure.

For the intersection characteristics and geometric design factors, *the most significant factors affecting crash frequency are the designed design speed, RTL type (and acceleration lane design), RTL turn radius, traffic channelized type, and traffic control.* Other factors like the intersection junction, the presence of bicycle lane/pedestrian lane, channelized type, the installment of acceleration lane, and RTL width also impact the number of crashes.

8.1.1.1 The effect of the geometric design compound factors. *First, there is a significant effect between designed design speed and the RTL type on the crash frequency.* In the overall level, the installment of the exclusive RTL can reduce the risk of crashes compared to the shared RTL. However, the high design speed increases number of crashes. The compound factor of these two variables significantly contribute to right-turn related crashes: the exclusive RTL with design speed over 35 mph have 16% fewer crashes than the shared RTL with design speed over 35 mph. In the case when the design speed is below or equal to 35 mph, the exclusive RTL with design speed below or equal to 35 mph has 45% fewer crashes than the shared RTL with design speed below or equal to 35 mph.

Second, the installment of acceleration lane and traffic island in RTLs can either increase or decrease crashes depending on the number of intersection AADT. The risk ratio for RTL with acceleration lane is less than the risk ratio for the RTL without acceleration lane when AADT is above 37,120 vpd, which means RTL acceleration lane having fewer crashes than without acceleration lane under that condition. However, the effect of the RTLs with acceleration lane is different depending on the volume of intersection AADT. For example, the risk ratio for the RTL with acceleration lane to the RTL without acceleration lane is 0.57 when intersection AADT is 100,000 vpd, which means RTL with acceleration lane has 43% fewer risk of crashes than the RTL without acceleration lane when AADT is 100,000. Besides, a 1% increase in intersection AADT leads to 0.343% increase in the crash frequency on average.

Third, the risk ratio for the presence of traffic island is less than the channelized type of nothing or making when the intersection AADT is above 52,821 vpd. In addition, the effects of the compound factor are different along with the change of AADT. For example, the risk ratio for the presence of traffic island is 0.79 when intersection AADT is 100,000 vpd, which means traffic island has 21% fewer crashes than channelized type to be nothing or marking when AADT is 100,000 vpd. The traffic island serves as a refuge point for pedestrians and provides suitable locations to place traffic control devices.

1. RTLs in the urban area have 0.549 more crashes on average relative to RTLs in the rural area, and counties with a high population have more crashes.
2. RTLs at daytime has 1.321 more crashes on average than RTLs at nighttime.
3. The high design speed is worse than the low design speed by introducing number of crashes, and the effects of the designed design speed are different among roadway class and county class.
4. Exclusive RTLs reduce crashes and the effects of the exclusive RTL depends on the AADT of roadway class and county class.

8.1.1.2 The effect of the RTL turn radius. *The RTL turn radius has positive effects on number of crashes.* Overall, we observe that a 1% increase in the RTL turn radius is worse than no increase in the RTL turn radius by increasing 0.22% more crashes. The effects of the RTL turn radius are different among roadway class and county class.

1. The interstate road RTLs turn radius has the highest effects on crash frequency among all roadway classes (local/city, interstate, state, and US), where a 1% increase in the RTLs turn radius leads to 1.07% more crashes.
2. The effects of RTLs turn radius on crash frequency are heterogenous in different counties. RTL turn radius has the highest effects on the crash frequency when RTLs are located in Marion County, where a 1% increases in the RTLs turn radius results in 0.59% more crashes when RTLs are located in Marion County.

8.1.1.3 The effect of the traffic control. *The traffic control is also an important factor that affects the crash frequency.* In the overall level, RTLs having "yield/stop" traffic sign and RTLs with no traffic control have 0.785 and 0.647 more crashes on average than RTLs having traffic signal control.

1. RTLs having signal control have fewer crashes and RTLs having yield/stop sign control have more crashes than

RTLs with no traffic control for RTLs on local roads and US roads. The effects of traffic control are different for RTLs on local and US roads.
2. RTLs with signal control have fewer crashes, and yield/stop signs have more crashes than RTLs with no traffic control for roads in Marion County, Madison County, Tippecanoe County, Clark County, Harrison County, Vanderburgh County, Allen County, and La Porte County. However, the effect of traffic control is insignificant for roads in Hamilton County and Hancock County.

The recommendations for reducing number of crashes from the RTL geometry design type and design speed aspects are as follows. It is more appropriate to have an exclusive RTL rather than a shared RTL when the intersection traffic volume is high. Besides, it is better to install exclusive RTLs no matter the design speed is below or above 35 mph. However, the benefit-cost estimates should depend on the life cycle utilization in the particular area. In addition, the exclusive RTLs provide space for turning movement and reduce the crash risk due to the speed-difference. To improve the RTL safety, the appropriate design of the exclusive RTLs should consider many aspects. The countermeasure for exclusive RTLs should combine the RTL turn radius, the deceleration or acceleration lane, and the design speed in the adjacent lanes. The inappropriate design of RTL types leads to rear-end collisions. For the design speed setting, although the high design speed increases crashes, it is also beneficial to the intersection capacity. For the traffic control variables, the RTLs at city/local roadway and US road are recommended to have traffic signal control but not traffic sign control. Because the traffic signal control reduces number of crashes. However, the traffic sign control is worse than no traffic control by increasing crashes. Therefore, the trade-off between intersection capacity and safety (crashes) should be considered for a specific intersection.

8.1.2 The Recommendation for Crash Severity

Based on the statistical analysis and modeling for the crash severity, we find the environmental factors (visibility condition, temporal factors, and road surface condition) has the most significant effects on the crash cost among all factors (geometric design factors, intersection factors, temporal and spatial factors). Based on the modeling, good visibility condition has more crash cost comparing to the poor visibility and the dry surface condition is worse than the wet surface condition by introducing more crash cost. Besides, RTLs at daytime is worse than RTLs at nigh time by introducing more crash cost.

For the intersection characteristics and geometric design factors, *the most significant factors affecting crash cost are the presence of the bicycle lane, RTL type, RTL turn radius, and traffic control.* Other factors like the intersection junction, RTL width, and channelized type also impact crash cost.

8.1.2.1 The effect of the presence of bicycle lane. The presence of bicycle lane has significant effects on the crash cost. In the overall level, the presence of bicycle lane is worse than no bicycle lane by introducing 0.57% ($10,445) of crash cost and a 1% increase in RTL turn radius leads to 0.14% increase of crash cost.

1. The presence of a bicycle lane is worse than no bicycle lane by introducing more crash cost. The effects of the presence of the bicycle lane are different among the roadway class and county class, which ranges from 0.23% to 1% of crash cost. In particular, the presence of bicycle lane in the local/city road have 0.61% more crash cost. This is because the conflict between bicycle and right-turn vehicle increases.
2. The presence of bicycle lane has the highest effect on crash cost when the RTLs are located in Madison County, Tippecanoe County, Clark County, Harrison County, Vanderburgh County, Allen County, and La Porte County, where the presence of bicycle lane is worse than no bicycle lane by introducing $64,247 crash cost on average.

8.1.2.2 The effect of the RTL turn radius. Increasing RTL turn radius is worse to have more crash cost. In the overall, a 1% increase in RTLs turn radius has a 0.56% increase of crash frequency and a 0.21% increase of crash cost.

1. A 1% increase in RTL turn radius increases 1.78% of crash cost in the interstate road and 0.19% of crash cost in the local/city road.
2. A 1% increase in RTL turn radius leads to 0.17% reduction of crash cost on Madison County, Tippecanoe County, Clark County, Harrison County, Vanderburgh County, Allen County, and La Porte County, a 1% increase in RTL turn radius 0.59%–0.28% increase in crash frequency for all counties.

8.1.2.3 The effect of the RTL type. RTL type is an important factor affecting crash cost.

1. In the overall level, the exclusive RTLs are better than shared RTLs by saving 0.07% of crash cost ($4,229).
2. The exclusive RTLs have more crash cost (2.69%) in the interstate road. But the exclusive RTLs are better than the shared RTLs in the US road by saving 0.74% of crash cost.
3. The effect of the RTL type is different among county class and roadway class. Exclusive RTLs are worse than the shared RTLs on Marion County by introducing 0.48% of crash cost, but exclusive RTLs are better than shared RTLs on Madison County, Tippecanoe County, Clark County, Harrison County, Vanderburgh County, Allen County, and La Porte County by saving 0.12% of crash cost, and the exclusive RTLs are better than the shared RTLs on Hamilton County and Hancock County by saving 0.36% of crash cost.

8.1.2.4 The effect of the traffic control. Traffic control is a crucial factor affecting crash cost. In the overall level, RTLs having traffic sign is worse than RTLs with no traffic control by introducing 0.19% of crash cost. This might because few traffic flows in the no traffic control intersections. Besides, there is no significantly different effects between RTLs with traffic signal control and RTLs with no traffic control system.

1. RTLs with traffic sign are better than RTLs with no traffic control system by saving 0.38%~1.64% of crash cost for RTLs in different roadways. RTLs with traffic signal are better than RTLs with no traffic control system by saving 0.82%~0.51% of crash cost in different roadways. RTLs having traffic signal are worse than RTLs with no traffic control by introducing 0.36% of crash cost and RTLs having traffic sign are worse than RTLs with no traffic control by introducing 0.20% of crash cost.
2. The effects of RTLs with traffic control are positively related to crash cost compared with the effects of RTLs with no traffic control in Madison County, Tippecanoe County, Clark County, Harrison County, Vanderburgh County, Allen County, and La Porte County.

The recommendations for reducing crash cost from the RTL geometry design type and design speed aspects are as follows. To mitigate the negative effects of the implementation of bicycle lane, other countermeasures should also be considered. For example, the traffic control system, the turn radius of RTLs, and the design speed. The RTL turn radius should be carefully designed. The larger RTL turn radius increases capacity and smoothens the turning movements at intersections. On the other hand, the larger RTL turn radius also increase turning speed due to the fluent turning movement. In addition, the turn radius of RTLs is supposed to increase when RTLs are located at the local/city road and state road. However, the turn radius of RTL is recommended to be reduced when RTLs are located at the US and interstate road. Besides, the installment of RTL types should associate the design of acceleration/deceleration lane, turn radius, and design speed. In general, the implementation of exclusive RTL helps to reduce crash cost. For example, the RTLs in the US road are recommended to install the exclusive RTLs. Whereas the installment of exclusive RTL in the interstate road may increase crash cost otherwise. The application of the traffic control system in RTLs should consider the intersection traffic flow. In high traffic flow intersections (e.g., intersection in the interstate road and state road), it is recommended the RTL to be equipped with traffic signal control system or traffic sign control. However, RTLs in the local/city road are recommended to keep no traffic control management.

8.2 Concluding Remarks

Right-turn lane (RTL) crashes are one of the most important contributors to intersection crashes in the US. This study investigates the traffic safety performance of the RTL crashes in Indiana based on multiple data sources, including official crash reports, AERIS data, Google Maps data and, official database, and field study. To understand the influencing factors for the RTL crashes, we introduce a random effect negative binomial model to specify the spatial-correlated effects among crashes and log-linear model to estimate the effects of the influencing factors on crash severity. We then adopt the robustness test to verify the reliability of estimations. In addition to the environmental factors, spatial and temporal factors, intersection factors, and RTL geometric factors, we propose the compound factors between the RTL geometrics and intersection characteristics to address the endogeneity issues, which is barely discussed in the literature. The empirical analyses indicate that the random effect negative binomial model outperforms the fixed effect ones and the log-linear model fits the data better than the linear model. In addition to the environmental, spatial, and temporal factors, the results suggest that RTL crash frequency is mainly influenced by RTL type, turn radius, traffic control, and compound factors: RTL types and design speed, channelized type and AADT, acceleration lane and AADT. The crash severity is mainly affected by the presence of bicycle lane, RTL turn radius, the RTL type, and the traffic control. More importantly, we evaluate the effects of geometric design factor and propose the recommendations to reduce the crash frequency and crash severity based on the analysis (see Table 8.1).

This study quantifies the effects of the influencing factors on the RTL crash frequency and crash severity. The following are several improvements in the study:

1. Data preparation is the first improvement in this research. In the previous studies, the analysis is mainly based on one or two-dimensional aspects for RTLs safety studies, either the geometric characteristics or human factors (and others) due to the RTL-related geometric characteristics to be seldom obtained from existed data sources. To achieve a comprehensive understanding of the influencing factors on the RTLs crash frequency, we first proposed a data collection framework based on the population of different types of RTLs. A string similarity fusion method for the multi-source datasets was then employed to merge diverse data sources, which facilitates the efficiency of data processing and avoid the selection bias for the sampled RTLs. Furthermore, a clustering method was applied to capture the homogeneity of counties from the aspects of population, yearly household income, and the percentage of the educated population. The created spatial variable (county clusters) helps to obtain a more interpretable format for the underlying effects of each county.
2. The modeling methodology is also advanced to systematically understand the RTL crash frequency and severity. In addition to investigating the hazardous factors of RTL geometric design, environmental factors, spatial-temporal factors, we develop compound effects between RTL geometric design and intersection characteristics, which is among the first step to deal with the downward estimation for the "selectivity bias/endogeneity" issue in the model estimation. On the other hand, the model comparison suggests that the RENB model outperforms the fixed one because of capturing the spatial-correlated effects. The robustness test confirms the reliability of our estimations. The key insights in this study are as follows:

   a. A 1% increase in the RTL turn radius leads to 0.22% increase in the crash frequency.

TABLE 8.1
Countermeasures and recommendations

Geometric Design	Category	RTL Location	Level of Significance	Countermeasures	Detailed Countermeasure	Benefits and Additional Considerations
Intersection						
Roadway junction	Intersection/ roundabout or traffic circle/ interchange or ramp	County road/city or local road/state road/US road/ interstate road	B	The interchange or ramp and roundabout are recommended in most of the roadway junctions.	If the RTLs are in the county road, and city/ local road, then the roundabout/traffic circle is recommended to be installed. If the RTLs are in the state road, the interchange/ ramp are recommended to be implemented.	The installment of interchange or ramp and roundabout is better than the intersection by saving 0.356% of crash cost on average. The installment of the roundabout/ traffic circle is better than intersection junction by reducing 0.08% crashes when RTLs are in the city/local road. The installment of the interchange/ ramp is better than intersection by reducing 1.44% and 3.6% of number of crashes relative to intersection when RTLs are in the US road and interstate road.
Right-Turn Lane						
Turn radius		County road/city or local road/state road/US road/ interstate road	A	The RTL turn radius is recommended to reduce when RTLs are in the city or local road and interstate road.		1% increases in turn radius leads to 0.002% more crash cost and 0.22% more crashes on average. 1% increase in RTL turn radius results in 0.19% more crash cost and 0.36% more crashes when RTLs are in the city/local road. 1% increase in RTL turn radius results in 0.008% more crash cost and 1.07% more crashes when RTLs are in the interstate road.
Width		County road/city or local road/state road/US road/ interstate road	B	The influence of RTL width is insignificant in most of the cases. The road width is recommended to increase when the RTLs are in the city/local road and US road.		1% increase in RTL width leads to 0.38% less crash cost on average. 1% increase in RTL width results in 0.68% less crash cost when RTLs are in the city/local road. 1% increase in RTL width results in 0.14% more crash cost when RTLs are in the US road.

TABLE 8.1
(Continued)

Geometric Design	Category	RTL Location	Level of Significance	Countermeasures	Detailed Countermeasure	Benefits and Additional Considerations
Channelized type	Solid traffic island/ marking traffic island/no traffic island	County road/city or local road/state road/US road/ interstate road	A	Whether the traffic island should be installed or not depending on the intersection AADT.	If the intersection AADT is above 52,821 vpd, then the traffic island is recommended to be installed. If the intersection AADT is above 35,672 vpd in the city/local road, then the traffic island is recommended to be installed in the RTL. If the intersection AADT is above 18,919 vpd in the interstate road, then the traffic island is recommended to be installed in the RTL.	RTLs with the channelized type as traffic island has 21% fewer crashes than RTLs with channelized type to be nothing or marking when AADT is 100,000 vpd on average. However, the presence of traffic island increases 0.15% of crash cost on average. If the AADT is higher than 35,672 vpd, then RTL with traffic island has fewer crashes than the RTLs with channelized type of nothing/ marking when RTLs are located in the city/local road. If the AADT is higher than 18,919 vpd, RTLs with traffic island has fewer crashes than the RTLs with channelized type of nothing/ marking when RTLs are located in the interstate road.
Traffic control	Traffic signal control/traffic sign control/ no control system	County road/city or local road/state road/US road/ interstate road	A	The installment of the traffic signal control is superior in the state road and US road.	If RTLs are in the state road, the traffic signal is recommended to be installed. If RTLs are in the city/local road, the traffic signal and traffic sign control are recommended to be installed.	RTLs with signal control are better than RTLs with no traffic control by saving 0.82% of crash cost and RTLs with traffic sign control are better than RTLs with no traffic control by saving 0.54% of crash cost. If RTLs are in the US road, then the presence of the traffic signal control is better than RTLs with no traffic control by reducing 0.79% of crashes. If RTLs are in the city/local road, then the presence of traffic signal control system is better than no traffic control system by saving 0.38% of crashes.
Bicycle lane	Yes/No	County road/city or local road/state road/US road/ interstate road	B	Bicycles are not recommended in the city/local road. The presence of the bicycle lane is insignificant in most of the cases.		The presence of bicycle lane increases 0.57% of crash cost on average. If the RTLs are in the city/local road, then the presence of bicycle lane is worse than no bicycle lane by introducing 0.61% of crash cost.

TABLE 8.1
(Continued)

Geometric Design	Category	RTL Location	Level of Significance	Countermeasures	Detailed Countermeasure	Benefits and Additional Considerations
RTL types	Shared RTL/ exclusive RTL	County road/city or local road/state road/US road/ interstate road	A	It is recommended to install the exclusive RTLs.	If the design speed is above 35 mph, then the exclusive RTLs are recommended to be installed. If the RTLs are in the US road, state road, and interstate road, then the exclusive RTLs are recommended to be installed.	The presence of exclusive RTLs is better than the shared RTLs by saving 0.07% of crash cost on average. If the RTLs are in the state road, then the presence of the exclusive RTLs is better than the shared RTLs by saving 0.74% of crash cost. If the RTLs are in the interstate road, then the presence of the exclusive RTLs is better than the shared RTLs by saving 2.69% of crash cost. If the design speed is above 35 mph, then the exclusive RTL with the high design speed has 16% fewer risk of crashes than the shared RTLs with high design speed.
Acceleration/deceleration lane	Yes/No	County road/city or local road/state road/US road/ interstate road	B	If the intersection AADT is above 37,120 vpd, then the acceleration lane is recommended to be installed. The presence of the acceleration lane is insignificant in most of the cases.		RTL with acceleration lane is better than RTL without acceleration lane when AADT is above 37,120 vpd.
Design speed	Above 35 mph, below (equal to) 35 mph	County road/city or local road/state road/US road/ interstate road	A	RTLs are recommended to set the design speed below 35 mph in most of cases.	If RTLs are on the city/ local road and interstate road, then the RTL design speed is recommended to below 35 mph.	RTLs with a design speed below (equal to) 35 mph are better than RTLs with a design speed above 35 mph by saving 0.04% of crash cost and 0.43% of crashes on average. If RTL are in the city/local road, then RTLs with a design speed below (equal to) 35 mph are better than RTLs with a design speed above 35 mph by saving 0.15% of crash cost and 0.44% of crashes. If RTLs are in the state road, US road, and interstate road, then RTLs with a design speed below (equal to) 35 mph are better than RTLs with a design speed above 35 mph by reducing 0.81%, 0.38% and 0.34% of crashes.

Note: The priority in level of significance is: A > B. For example, the effect of RTL turn radius is considered more significant than the effect of roadway junction.

b. RTLs having "yield/stop sign" and RTLs with no traffic control have 0.785 and 0.647 more crashes on average than RTLs having traffic signal control.
c. The installment of the exclusive RTL is beneficial to reduce number of crashes compared to the shared RTL. However, the high design speed has more crashes than low design speed. The compound factor of these two variables significantly contribute to right-turn related crashes: the exclusive RTL with design speed over 35 mph have 16% fewer crashes than the shared RTL with design speed over 35 mph; for the design speed is below or equal to 35 mph, the exclusive RTL with design speed below or equal to 35 mph has 45% fewer crashes than the shared RTL with design speed below or equal to 35 mph.
d. The installment of acceleration lane and traffic island in RTLs can either increase or decrease crashes depending on the intersection AADT.
e. RTLs in the urban area have 0.549 more crashes on average relative to RTLs in the rural area, and counties with a high population have more crashes.
f. RTLs at daytime has 1.321 more crashes on average than RTLs at nighttime.

Due to data limitations, one potential drawback of this study is the "risk compensation" issue. The estimation of environmental-related factors could be biased because drivers may compensate for the adverse environmental conditions by changing their behavior to an acceptable level of risk. The lack of accurate data to describe the trade-off between their expectations and the actual choice may result in biased estimation. In this study, RTLs in poor visibility have fewer crashes than RTLs in good visibility might because drivers avoid driving in the poor visibility condition. The future direction for the RTL safety study should focus on (1) dealing with the "risk compensation" issue based on additional survey or other data sources and (2) the advanced methods are also encouraged for gaining more precise parameter estimation. In the future, these explorations will help to reach a better understanding of RTL safety problems and provide more precise geometric design countermeasure suggestions.

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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.

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