Report

SPR 4218:
PERFORMANCE OF RIGHT-TURN LANE DESIGNS AT INTERSECTIONS

Task 1: **Studying Literature and best Practice**
Task 2: **Selecting the Candidate Intersections**
Task 3: **Data Gathering and Cleaning**

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1 INTRODUCTION

Intersection-related crashes are one of the main contributor to total crashes. In 2014, intersection-related crashes contributed to 47% and 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 33% of total crashes and 28% 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 $50 billion (FHWA 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. Researches 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 following. 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 and Figure 2 show these issues and highlight the design issues at SR-43 and US 40 respectively.

Figure 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. An Intersection on SR 43

Figure 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 2. An Intersection on US 40

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. A tool is needed to diagnose high crash intersections and provide recommendations to improve safety.

The objective of the proposed research project is 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 Scope of This Study

This study is divided into seven tasks. Task 1 primarily focuses on synthesis of existing body of knowledge and best practice about right-turn lane. Based on the findings in Task 1, a report will be submitted to INDOT. A presentation will be given in the SAC meeting and input will be obtained from the SAC on finalizing candidate intersections for the next tasks. Data will be obtained from INDOT for the candidate intersections and analysis and recommendations will be based on the modeling.

Task 1: Studying Literature and best Practice

The existing literature on intersections with free right-turn lanes and islands will be studied. Best practices will be gathered from other states, and local governments. The data requirements and design practices will be summarized in a document.

Task 2: Selecting the candidate intersections

The focus of this study is on all situations with existing right-turn lanes intersections. Based on the input from the SAC, candidate intersections will be selected so that a diversity of right-turn lane intersections can be considered in the analysis. Different right-turn lanes including right-turn lane with lane pavement marking, shared lane with island, channelized right-turn lane, right-turn lane with island and dedicated downstream lane will be considered. In addition, intersections at interstate ramps, local roadways and state road intersections. Medium to high volume intersections will be selected as candidate locations. The number of intersections will be decided based on discussions with the SAC.

Task 3: Data Gathering and Cleaning

The data will be obtained from INDOT for the candidate intersections. The data will be verified for any errors and clean to make sure there are no redundant information, no missing information and all intersections have variables that will be considered in the analysis. This include the right-turn lane length, width, turning radius, downstream lane width, corner radius, island dimensions when present, island size, acceleration lane etc. At the end of this task, the research team will deliver a clean dataset that will be used in the future tasks.

Task 4: Statistical Modeling and Analysis

We will utilize advanced statistical models to develop models that determine the factors that correlate with crashes at the right-turn lane intersections. In the models, the factors, which are generally considered by designers for the right-turn lane designs including the design variables of the right-turn lane, presence of an island, presence of a dedicated downstream lane, line of sight will be considered. Then, the set of variables which are related to the safety performance will be identified. The models will clearly show which variables – design, traffic flow, time of day, environmental variables impact the safety at the right-turn lanes.

Task 5: Recommendations for Intersection Safety and Design

Based on the developed quantitative safety effectiveness measures, guidelines for design improvements involving alternative right-turn lane designs will be developed. The project team will recommend the measures that should be taken from a design stand point and from traffic control perspective to reduce the crashes at right-turn lane intersections. These recommendations will be provided in a document that will be useful reference for INDOT engineers for design of new intersections or redesign of existing intersections

Task 6: Final Report

A final report will be developed that documents the data collection, data modeling and analysis of right-turn lane crashes. In addition, key recommendations to improve the intersection safety at right-turn lanes will be provided in the final report.

1.3 Study Benefits and Deliverables

INDOT will have significant benefits from this study by implementing this project:

(1) Reduction in crashes, and meeting driver expectancy.
(2) Future intersection designs will be improved.

Deliverables of this project include:

(1) *A list of right-turn lane design alternatives*. A list of right-turn lane design alternatives and key factors that correlated with crashes will be provided. The key factors help to select which right-turn lane should be used.

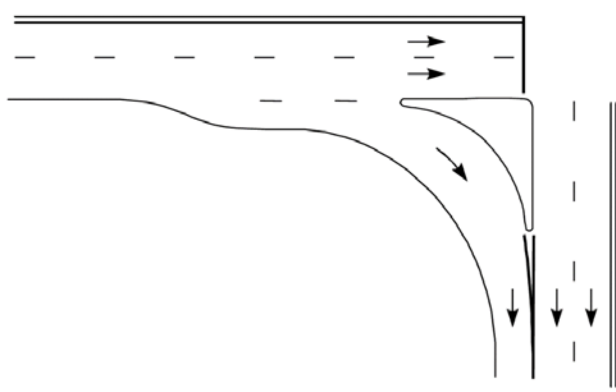
(2) *Guidelines that will serve as a tool to utilize at high crash intersections*. Decision making at right-turn intersections with islands is complex. We will develop guidelines that facilitate the identification of high risk intersections, guidelines for data collection and analysis and design guidelines 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. A hardcopy with a clear guidance is provided.

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 also examine the four layouts and summarize pros and cons as following (4):

- Designated right-turn lanes



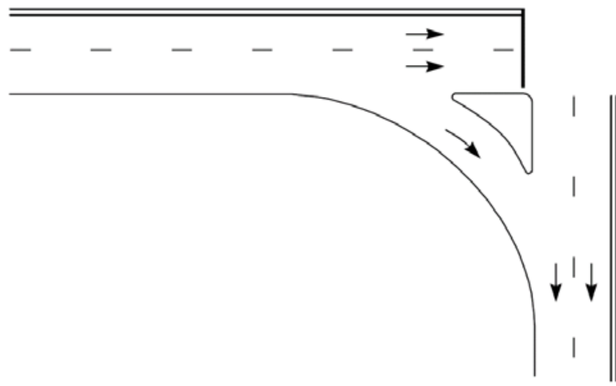
Pros:

- 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 provide a safer pedestrian environment.

Cons:

- All vehicles must stop on red, potentially increasing the right-turn queue.
- The absence of an island eliminates its use for:
  - Placement of traffic control devices, and
  - A pedestrian refuge.

- Shared lane with island



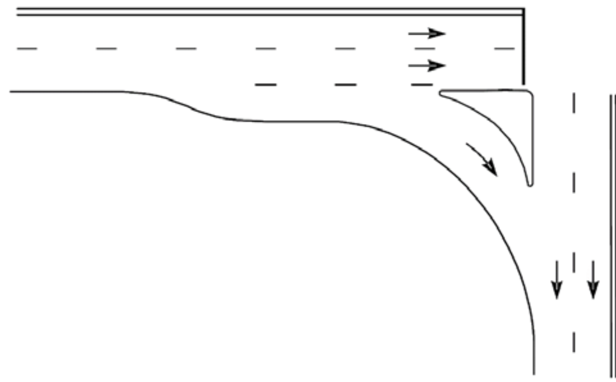
Pros:

- 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 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.

- Right-Turn Lane with Island



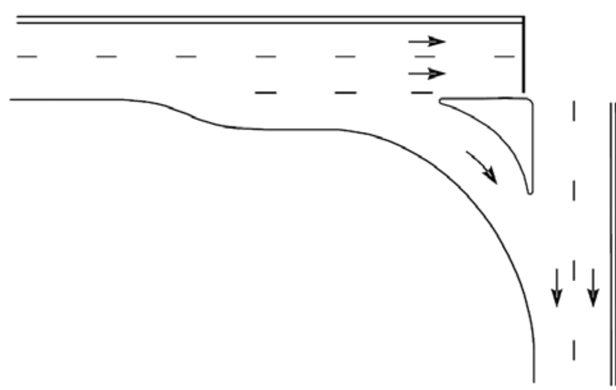
Pros:

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

Cons:

- o Higher turning speeds may present a hazard to pedestrians.
- o 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.

- Right-Turn Lane with Island and Dedicated Downstream Lane



Pros:

- o Benefits motorized vehicles by lowering emissions and increasing capacity.
- o Provides free flow of turning vehicles, reducing right-turn queues.
- o Eliminates need to look for merging vehicles (attention may be focused ahead of vehicle because driver is entering dedicated lane).
- o 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 Crash and Rear-End Crash. The right-angle crash happened when two vehicles collide perpendicular to each other. It mainly locates within intersection. The rear-end crash 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 crash 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 or disbenefits. 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 for Crashes

2.3.1 Modeling approaches

The contributing factors for crashes has been investigated for few decades. Researchers also developed various methods, mainly based on statistical techniques, ranging from descriptive statistics, configural frequency analysis, chi-square based hypothesis testing, analysis of variance, control study, to econometric models. Besides econometric models, all other methods are trying to identify the correlation relationship between crash frequency and contributing factors. The econometric models will 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 the evaluation of 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 two to three 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 probabilities 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 Bay, 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 crash) and 16.20% (rear-end crash), 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.

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 percent 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 on 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 guide lines).

Abdel-Aty et al. (2006) investigated 1,335 intersections in 6 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 crash at four-legged one-way intersections unlike rear-end crash at other intersections. In addition, the crashes with higher severity were generally at four-legged two-way intersections and T-intersections.

Clark 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.

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 higher speed limits were 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 limits 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.

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 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 over represented in STOP and Pull Out crashes and drivers between the ages of 25 and 40 were over represented 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.

Table 1. Summary of studies along with datasets, target intersections, influencing variables, and model uses

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, angle of the intersections, and traffic signals.	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
Pernia et al. (2002)	447 intersections	Signalized intersections	ADT, surrounding land uses, location types, number of lanes, posted speeds, and median and shoulder types.	Regression
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, speed limits, geometric designs, road surfaces, road characters, time of day, vehicle types,	Regression

Study	Sample sizes	Intersections	Variables	Models
			and individual socio-demographic characteristics.	
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
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, speed limits, 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)	24/37,476/203,184 fatal/casualty/all reported crashes	Right-turn signalized intersections	Traffic flow, traffic phrasings, genders, drivers' ages, and vehicle types.	Descriptive analysis

Study	Sample sizes	Intersections	Variables	Models
Mitra (2014)	67,491 crashes at 291 intersections	Signalized intersections	Sun glare	Descriptive analysis (Anova and frequency)

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/map, 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, speed limit, 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 (ITE, 2000) 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.

3 BEST PRACTICES

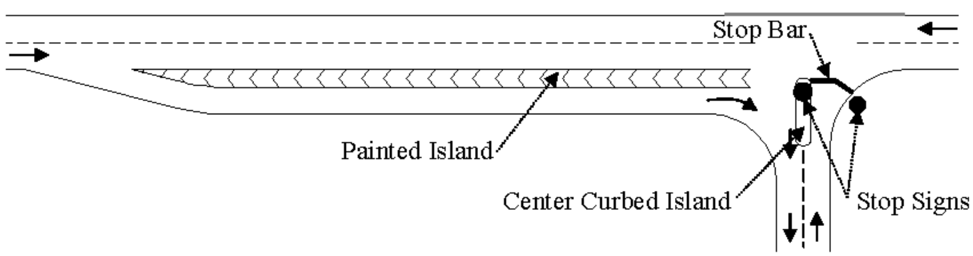
Mitigating right-turn-lane related crashes has many countermeasures, including but not limited to right-turn lanes (e.g. channelization and dedicated lanes), intersection geometry (e.g. improve sight distance), traffic control (e.g. signal phasing), and bicycle/pedestrian protections. In the following 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).

3.1 Right-Turn Lanes

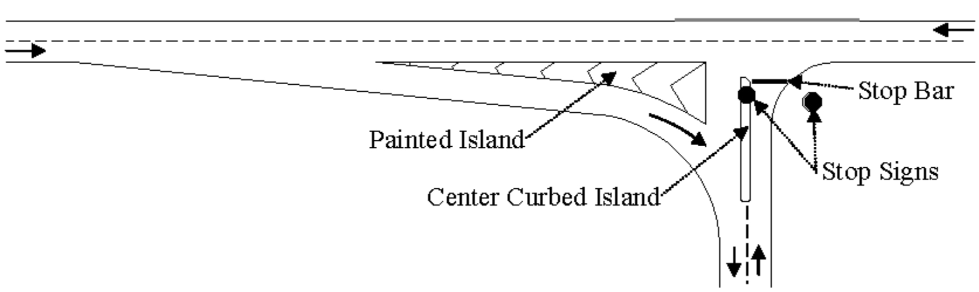
Many states have posted their warrants for right-turn lanes. The North Dakota DOT (2014) considers the traffic control at intersections, turning volumes, crashes. In general, the following conditions should be met: for non-controlled approaches, a posted speed is greater than 50 mph (not controlled with traffic signal, stop sign or yield sign), turning traffic volumes are above the critical volume, and there are two crashes in 3 years. More importantly, 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 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 (2018) simply proposes three concerns that (a) the combination of through traffic volume and turning traffic volume, (b) the posted roadway speed, and (c) the number of through lanes on the roadway. Federal Highway Administration (FHWA) (2014) 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; and for signalized intersections with a high frequency of rear-end collisions 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.. Moreover, FHWA (2014) recommends longer right-turn lanes for unsignalized intersections with an existing right-turn lane that is not long enough to store all right-turning vehicles and that are experiencing a high frequency of rear-end crashes resulting from the conflict between vehicles waiting to turn right and following vehicles.

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 non right-turn rear-end, sideswipe same direction crashes after installing right-turn lanes. FHWA concluded based on related researches 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 8 states. Added 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 percent and accidents at urban signalized intersections by 4 percent. Right-turn lane installation reduced accidents on individual approaches to four-leg intersections by 27 percent at rural unsignalized intersections and by 18 percent 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 3.



(a) Parallel-Type Offset Right-Turn Lanes



(b) Tapered-Type Offset Right-Turn Lanes

Figure 3. The offset right-turn lanes

The North Dakota DOT (2014) implements 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 countermeasures for certain crashes without detail guidelines in 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 (2014) 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, there are about 87% of state and local highway agencies are using channelized right-turn lanes. As one popular design, it also has many guidance in US, such as policy on geometric design of highways and streets and 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 Traffic Engineering Handbook from Institute of Transportation Engineers. However, all above guidance generally discuss 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 Roefar (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 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 percent 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 4. 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., 2016). Nevada also includes the improved channelization in the state 'Strategic Highway Safety Plan'. Shattler 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.

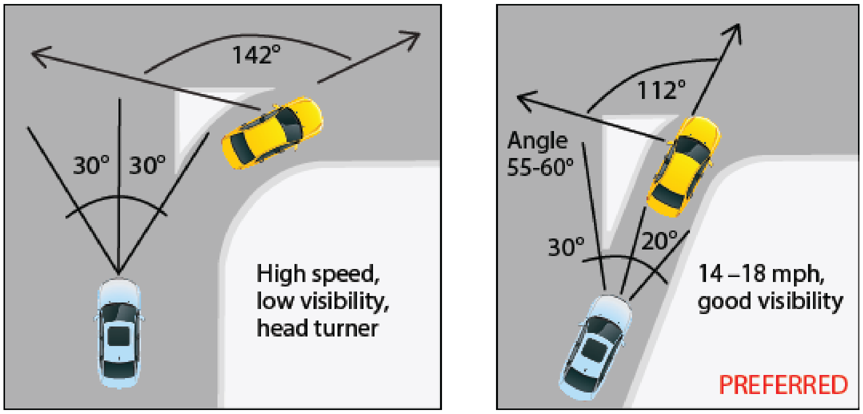


Figure 4. The standard and improved channelized right-turn lanes

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 percent of the state highway agencies and 70 percent 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 percent of the state highway agencies and 43 percent 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. 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 (2014) 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.

3.2 Skewed Intersections

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 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 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 5, if one of the following conditions exists: (3.1) Insufficient clear storage distance for a design vehicle between the signalized intersection and the railroad crossing, and (3.2) 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. FHWA (2014) adopts the RTOR prohibits at signalized intersections 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 percent to 17.4 percent), 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.

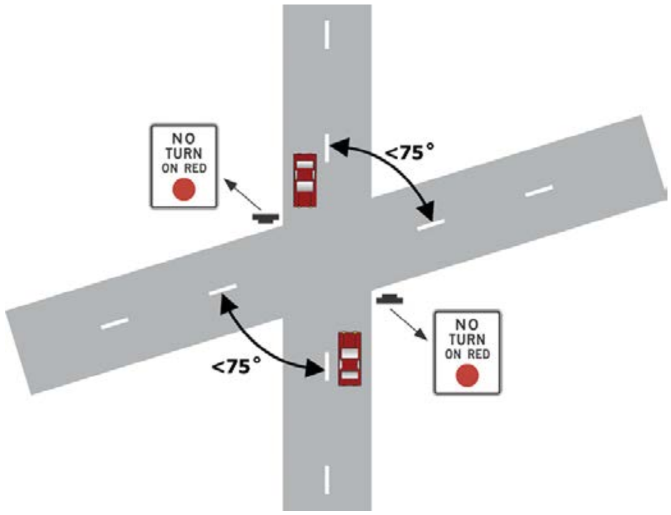


Figure 5. No Turn On Red Sign at skewed intersections

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)

3.3 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, the all red interval can reduce 10% of all types 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 (Schlattler et al., 2003) was completed at the three intersections for two years before and two 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 the 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 effects 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 one-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 two 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".

3.4 Bicycle and Pedestrian Protections

Statistics gathered by the Oregon DOT (Dixon et al., 1999) showed that 19 percent of vehicle-pedestrian crashes occurring at intersections arose 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 percent of state highway agencies and 40 percent 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 percent of state highway agencies and 17 percent of local highway agencies have encountered pedestrian-related safety problems at channelized right-turn roadways.

According to FHWA (2014), 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 to 90% of these types of pedestrian crashes have occurred. The Federal Highway Administration 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. A Danish study concluded that providing bicycle lanes can reduce bicycle crashes by 36%. In addition, the signalization is thought to be an effective countermeasure for pedestrian- and bicycle- related crashes. One study showed a 25% decrease in pedestrian-related crashes with the installation of pedestrian countdown signal heads. Another study indicated a 20% decrease in all types of crashes when pedestrian signals were installed. Yet another study determined that implementing a leading pedestrian interval may decrease pedestrian-related crashes by 5%.

The Manual on Uniform Traffic Control Devices and bicycle guide from American Association of State Highway and Transportation Officials 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., 2016 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 percent of the observations in the before period, but in only 38 percent of the observations during the after period. The reductions in pedestrian-vehicle conflicts across the observation sites ranged from 15 to 30 percent, 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 10 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 6 of the 10 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, 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:

- removal of reserve between carriageway and cycle track

On the last 30-50 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)

- advanced stop lines for bicycles and possible bike box, shown in Figure 6.

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.

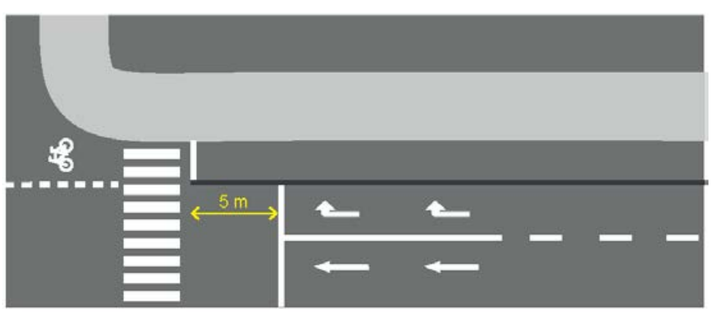


Figure 6. Advance stop lines (up) and add a bike box (down)

- “pre-green” for cyclists

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 7. 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 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 quite a lot of space, meaning that this solution cannot be established in all intersections.

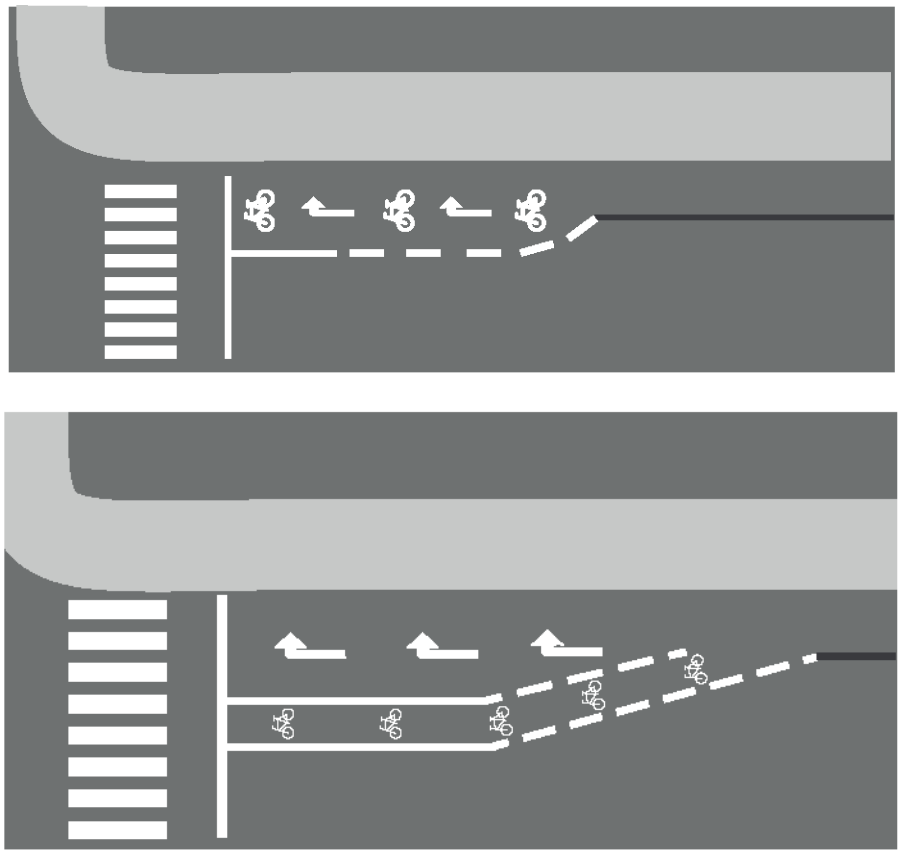


Figure 7. Truncated cycle track (up) and truncated cycle lane (down)

The last countermeasure is the offset passage, shown in Figure 8. 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.

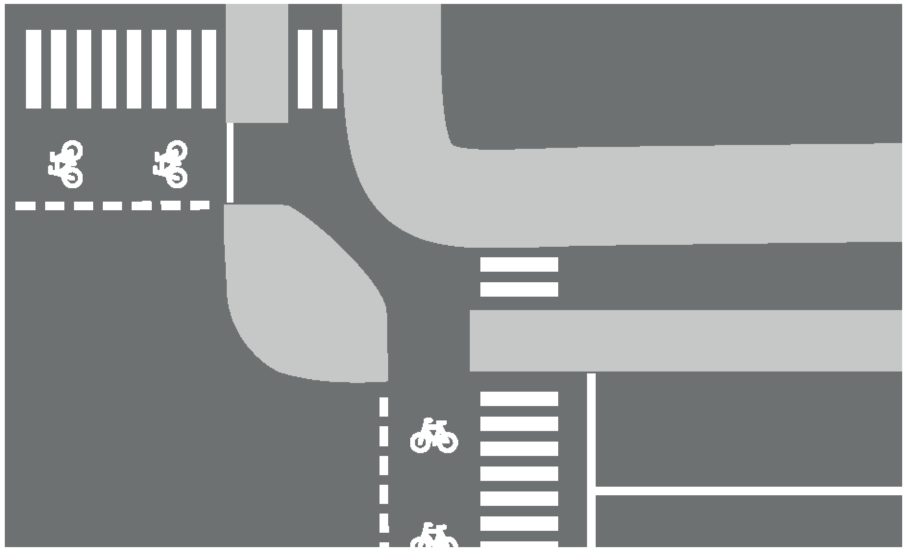


Figure 8. Offset bicycle passage

4 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 designs, traffic condition, and traffic management which are collected for right-turn lanes located on inter-state highways, state higways, ramps, and local roads. Equaly important, crash data is also collected. The data collection methods used in this study are illustrated in Figure 9.

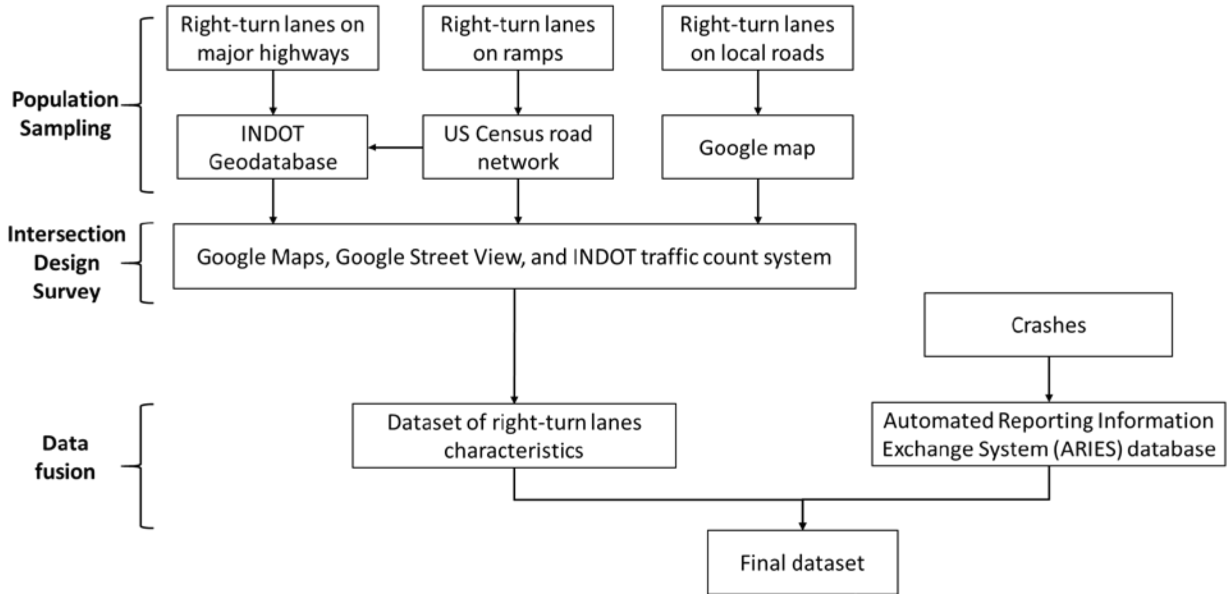


Figure 9. Data collection framework

4.1 Intersection Sampling

4.1.1 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 10. 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 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 both left and right) for each intersection, as well as location information, as shown in Figure 11.

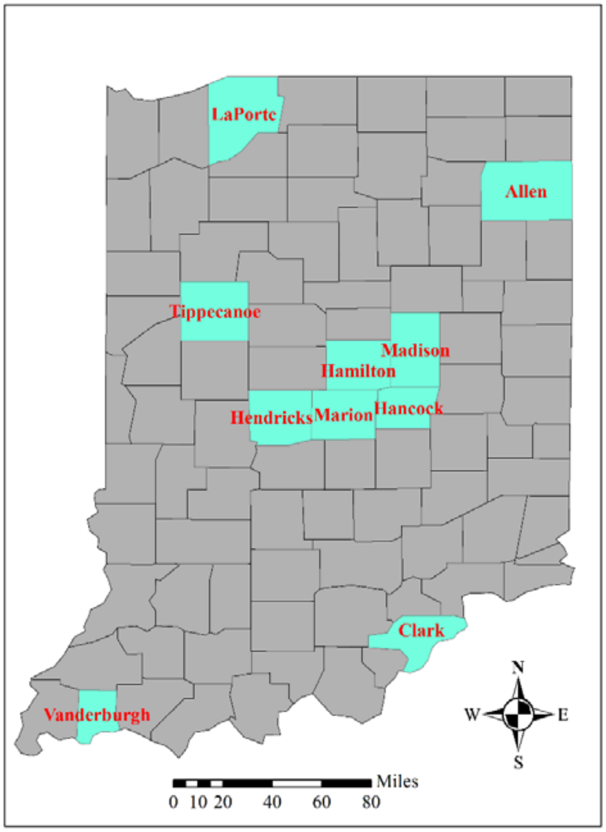
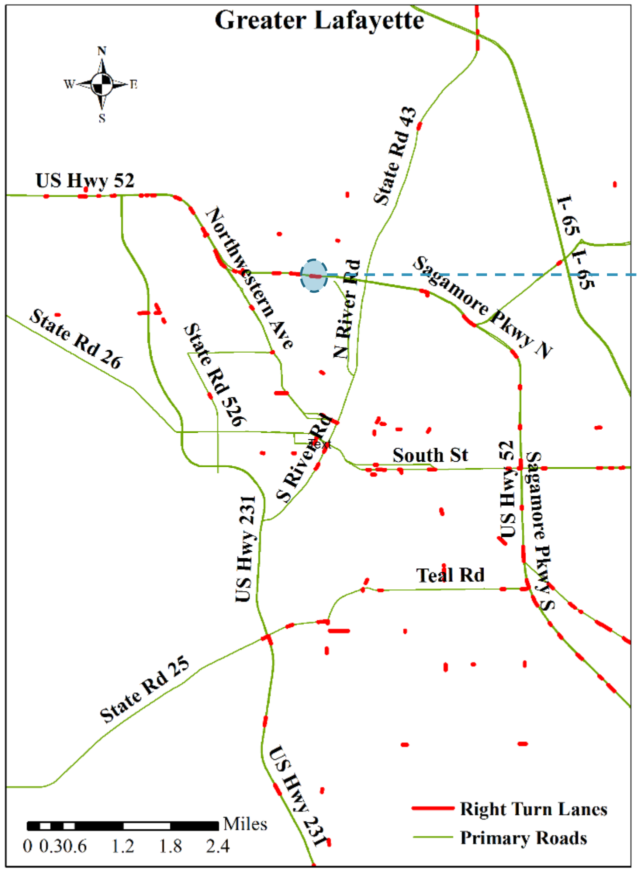


Figure 10. Spatial distribution of candidate counties

Table 2. 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**



Right Turn Lanes

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 11. The information in the shared INDOT geodatabase

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 12 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 12. 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.

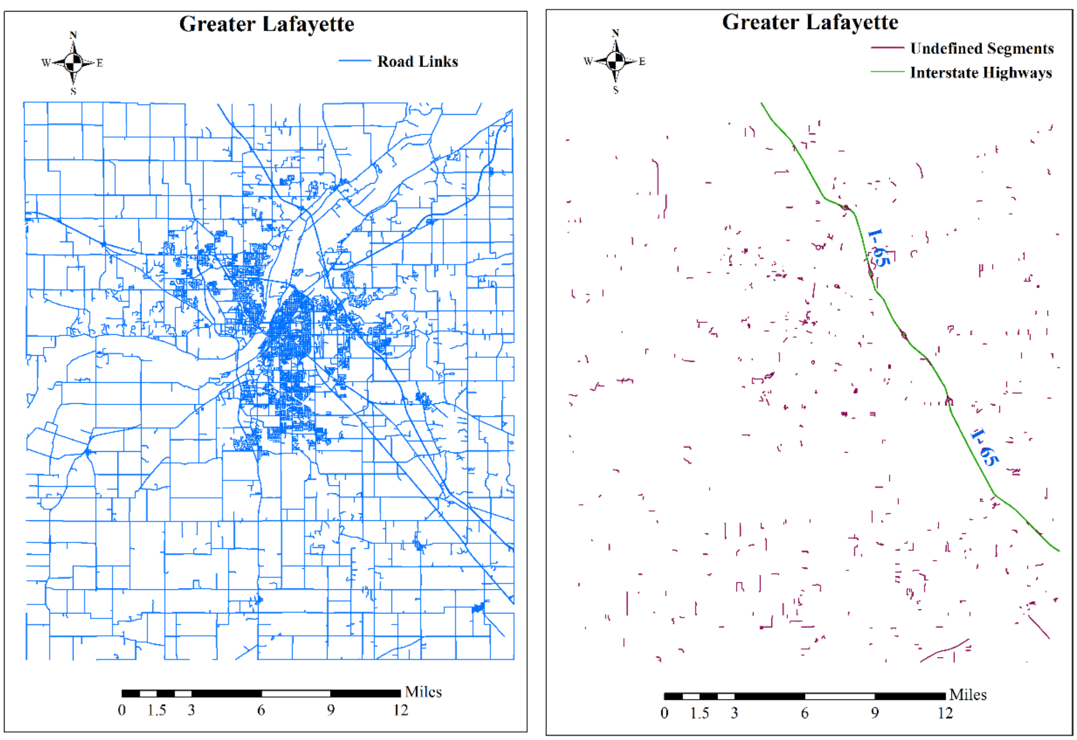


Figure 12. Illustration of data processing for ramp identification

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 45mph and the right-turn volume is more than 50 vph; (2) the speed is less than or equal to 45mph 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 map for collecting needed data. Google map has advantages of up-to-date street view and detailed configurations at local levels. An example of a Google map local roads network is illustrated in Figure 13.

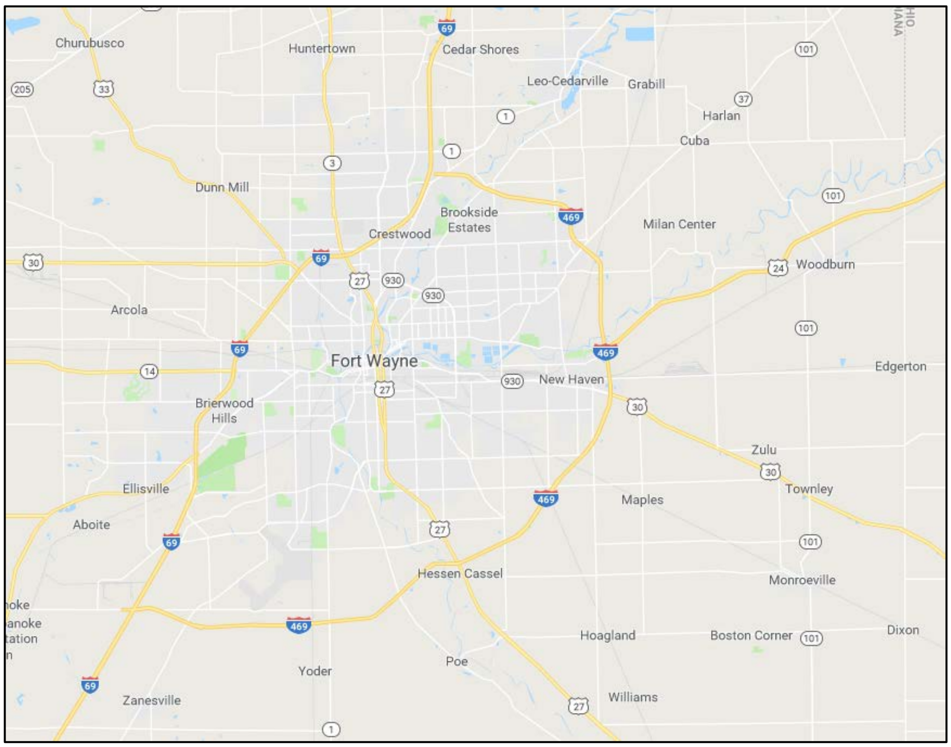
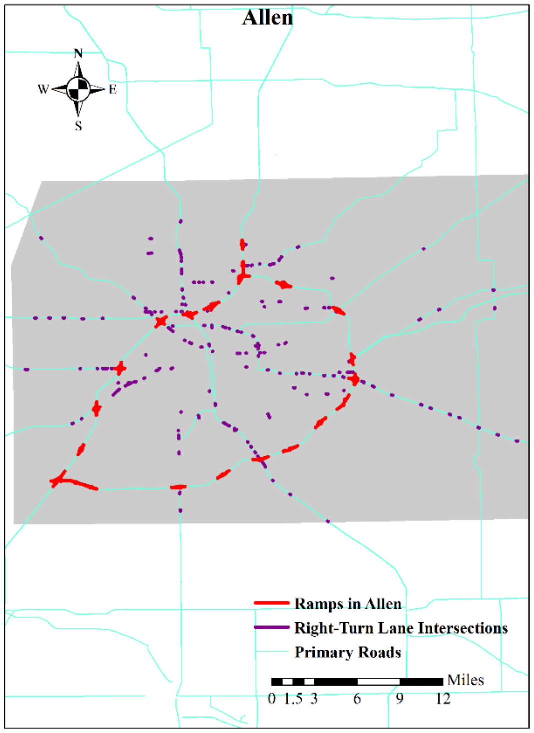
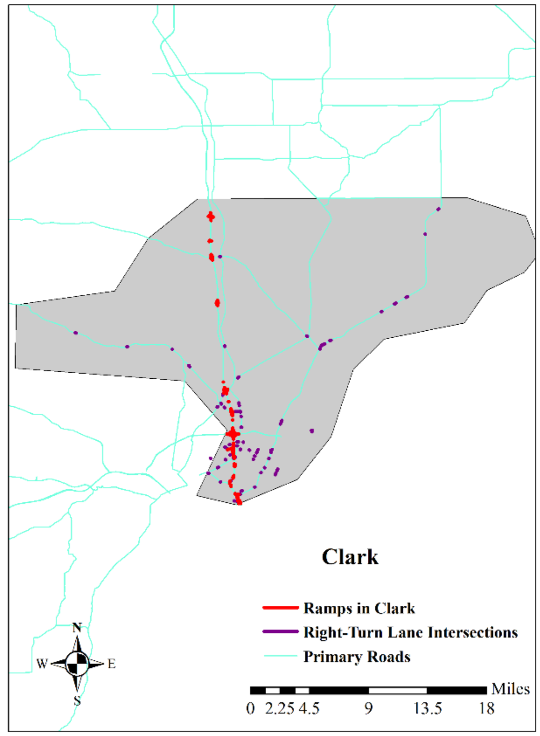


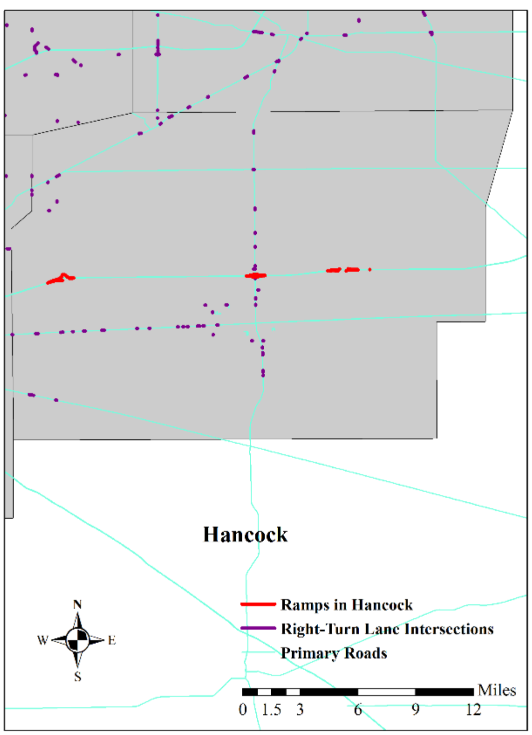
Figure 13. The Allen County road network (local roads are colored in white).

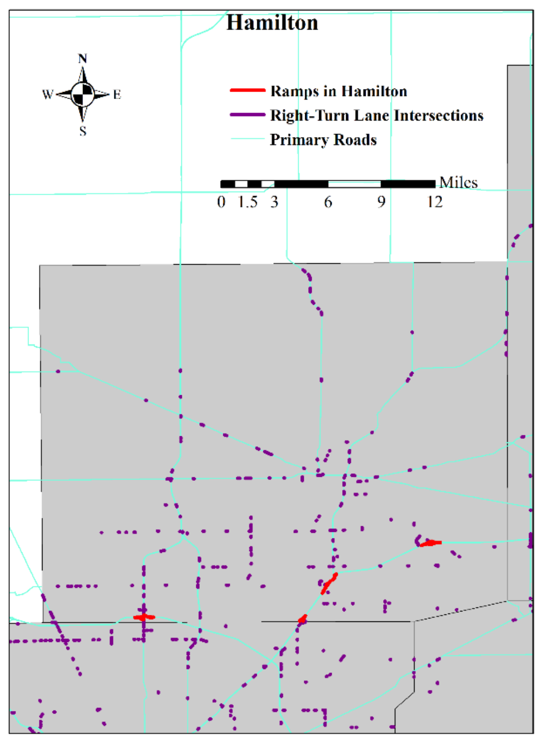
Right-turn Lane Intersections in Each Candidate County

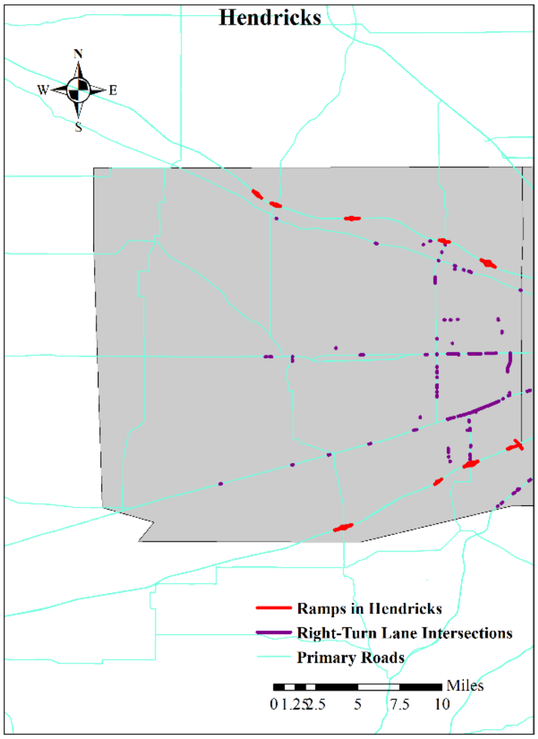
The following plots show the distribution of right-turn lane intersections in each candidate county. Note that the plots only illustrate intersections with right-turn lanes on US/state highways and all exit and entry ramps (not include intersections with right-turn lanes on local roads).

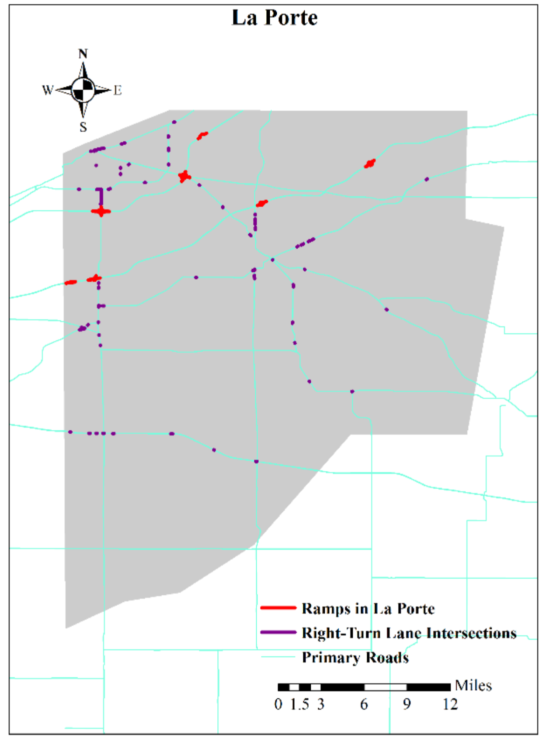

Allen
N
W
E
S
Ramps in Allen
Right-Turn Lane Intersections
Primary Roads
Miles
0 1.5 3 6 9 12

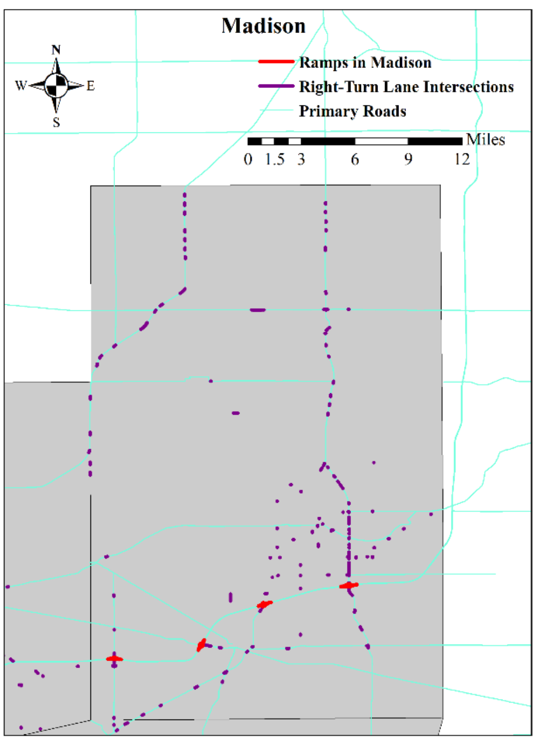

Clark
N
W
E
S
Ramps in Clark
Right-Turn Lane Intersections
Primary Roads
Miles
0 2.25 4.5 9 13.5 18

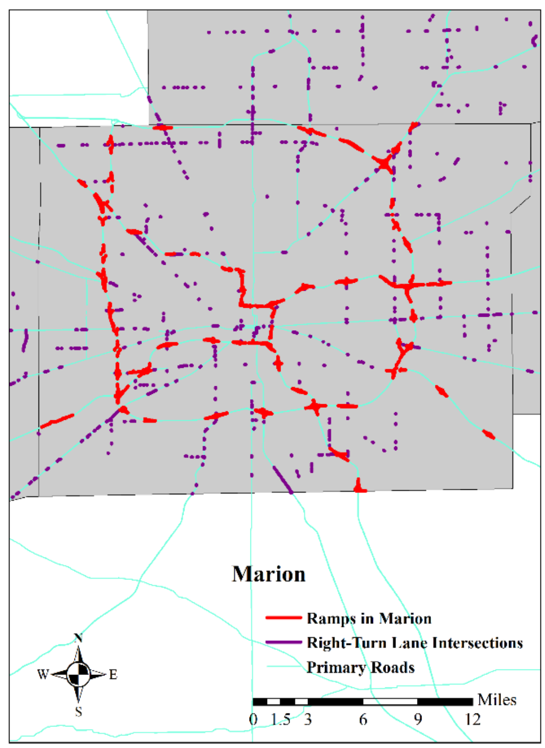

Hancock
N
W
E
S
Ramps in Hancock
Right-Turn Lane Intersections
Primary Roads
Miles
0 1.5 3 6 9 12


Hamilton
N
W
E
S
Ramps in Hamilton
Right-Turn Lane Intersections
Primary Roads
Miles
0 1.5 3 6 9 12


Hendricks
N
W
E
S
Ramps in Hendricks
Right-Turn Lane Intersections
Primary Roads
Miles
0 1.252.5 5 7.5 10


La Porte
N
W
E
S
Ramps in La Porte
Right-Turn Lane Intersections
Primary Roads
Miles
0 1.5 3 6 9 12


Madison
N
W
E
S
Ramps in Madison
Right-Turn Lane Intersections
Primary Roads
Miles
0 1.5 3 6 9 12


Marion
Ramps in Marion
Right-Turn Lane Intersections
Primary Roads
N
W
E
S
Miles
0 1.5 3 6 9 12

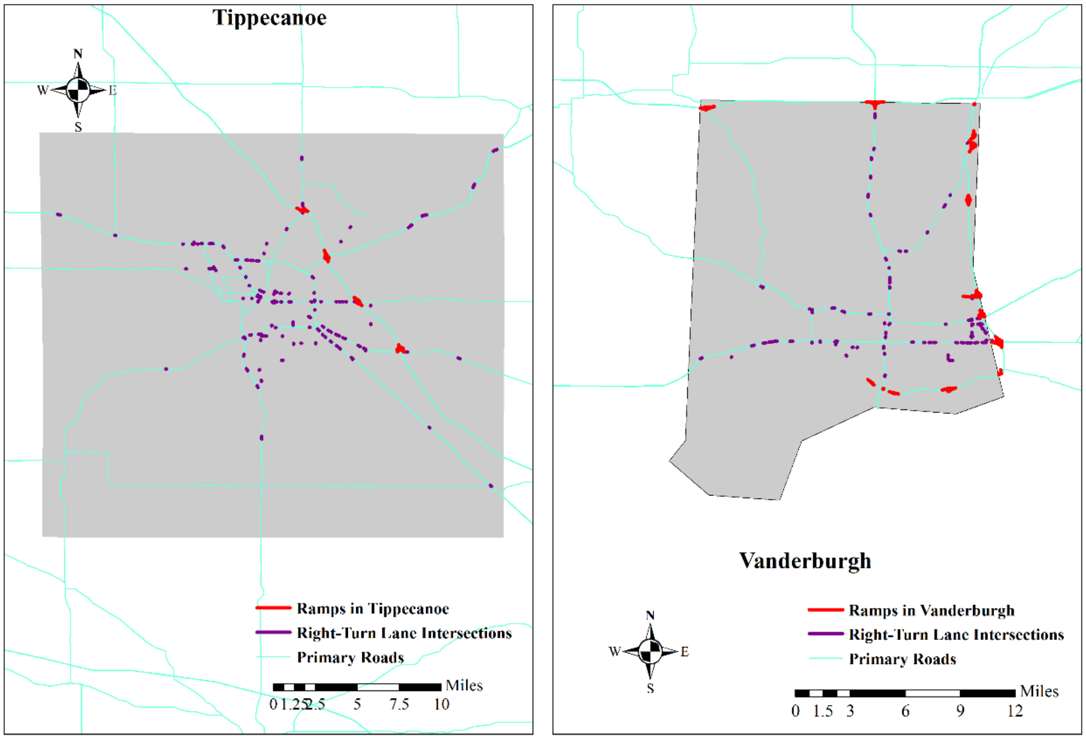


Figure 14. Right-turn lane intersections at 10 selected counties

4.1.2 Sampling Method

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 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 2. The full list of number of intersections in each census tract is separately shown in the attached worksheet.

Table 3. 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**	**1449**	**125**	**268**	**439**

<u>Interstate Highways (Entry/Exit Ramps)</u>

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.

Accordingly, we implement a random sampling with a given ratio at the county level other than at the census tract level. 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.

Table 4. Number of ramps under different sampling ratios

Code	County name	Ramps (exit and entry)	10%	20%	30%
003	Allen	108	11	22	32

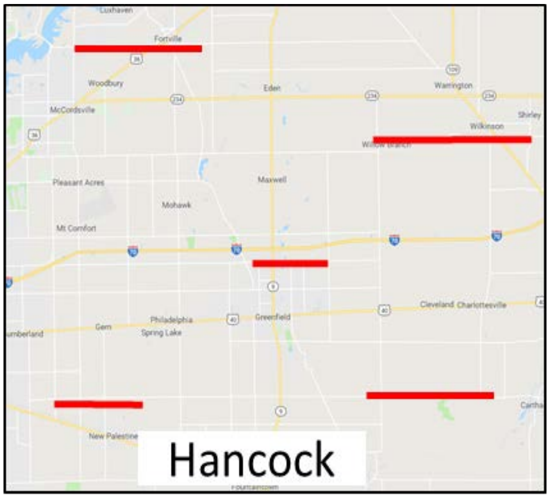
019	Clark	48	5	10	14
057	Hamilton	15	2	3	5
059	Hancock	13	1	3	4
063	Hendricks	26	3	5	8
091	La Porte	33	3	7	10
095	Madison	11	1	2	3
097	Marion	290	29	58	87
157	Tippecanoe	16	2	3	5
163	Vanderburgh	41	4	8	12
Total		**601**	**61**	**121**	**180**

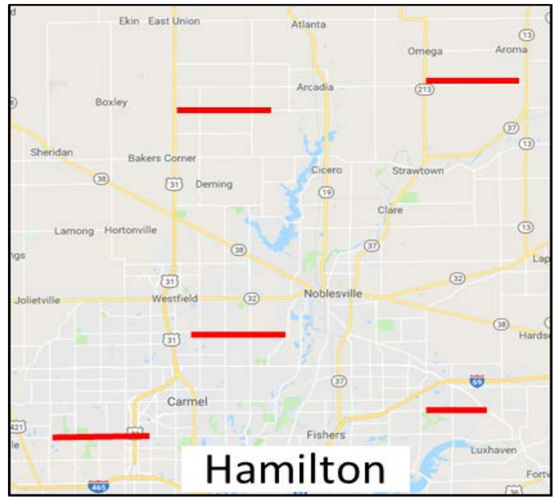
<u>Local Roads (County/Driveways)</u>

Identify right-turn lanes on local roads involve the screening of segments on Google maps. To obtain random samples, the following procedures are needed:

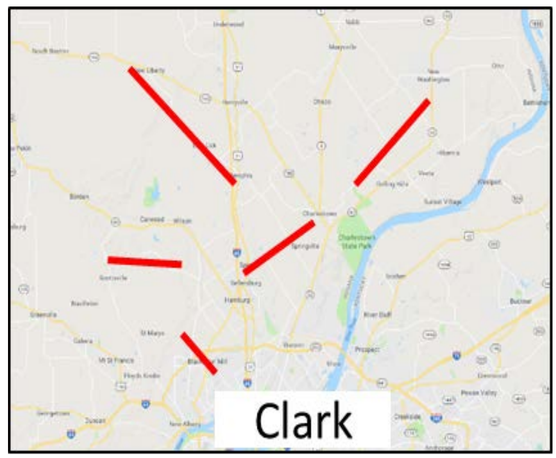
1) For each county, five segments are selected. They should be distributed at Northwest, Northeast, Center, Southwest, and Southeast areas on the county map.
2) Each segment is about 2-5 miles in length.

As a result, the spatial distributions of segments in corresponding county are displayed in Figure 15. The list of segments including starting and ending points is displayed in Table 4.

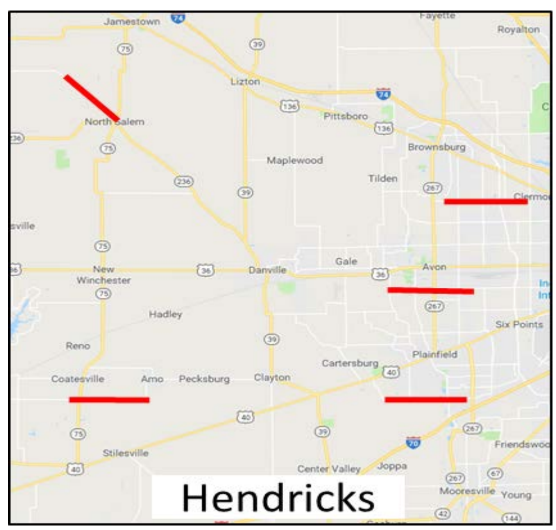

Hancock


Hamilton


Allen


Clark


Marion


Hendricks

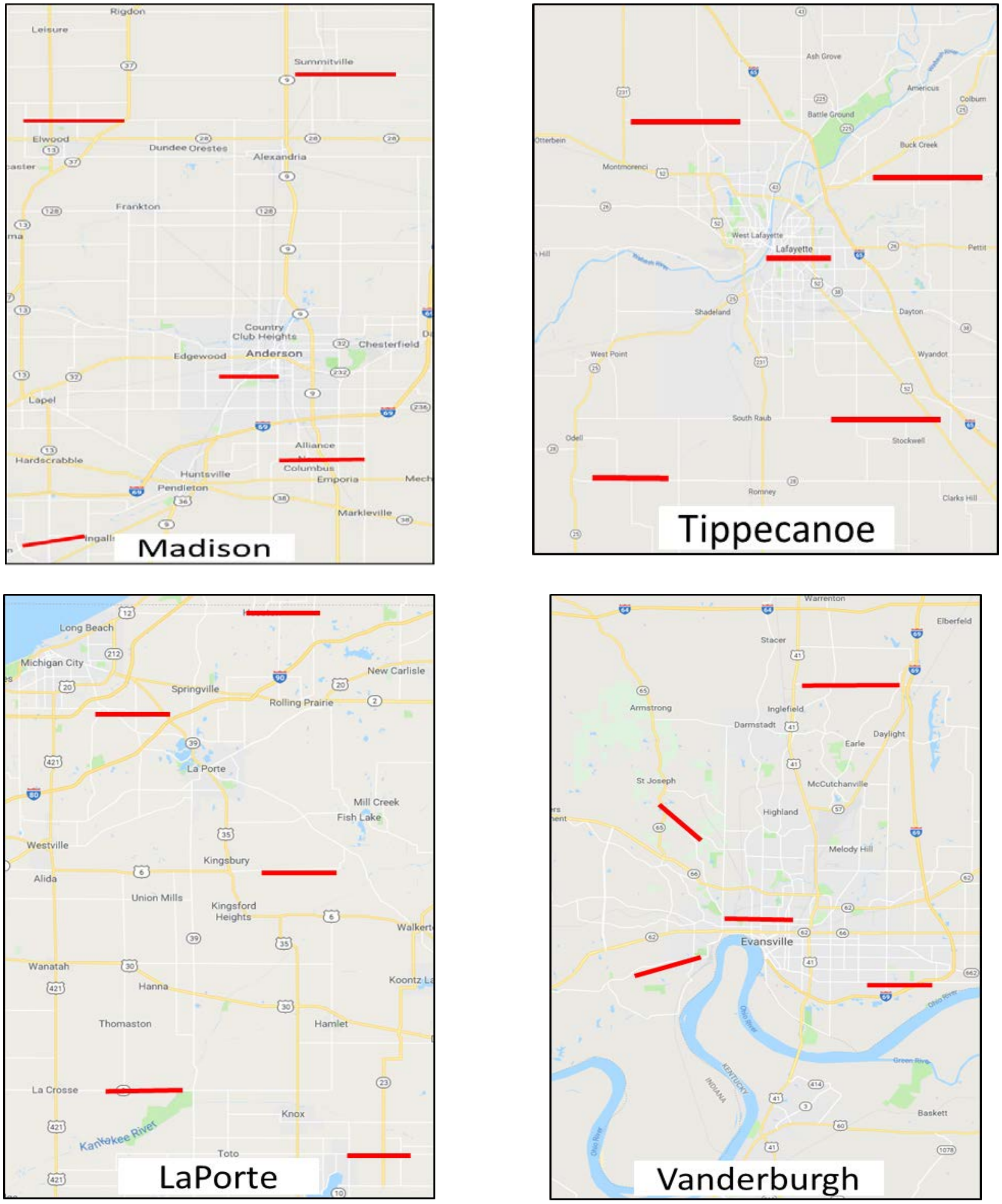


Figure 15. Spatial distributions of sampling segments in local roads

Table 5. 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

Segment No	From	To
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
Laporte		
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

Segment No	From	To
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

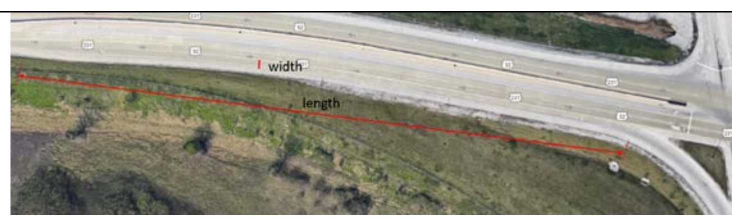
4.2 Data Collection Tools

4.2.1 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, speed limit, 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 5 summarizes all measurements, as well as the survey method. The summary of surveyed right-turn lanes are presented in Table 6 and Figure 15.

Table 6. Survey on intersection design and traffic characteristics

Measurement	Survey method	Note
Geolocation	Any point locates on right-turn lane, identified on Google Map and presented with longitude and latitude	

Road Name	Manually measured from Google Maps	
Intersecting Road Name		
Number of lanes on the road		
Number of lanes on the intersecting road		
Skewness		
Number of legs		
Number of right-turn lane	Manually measured from Google Maps	
Channelization type		
Turning radius		
Right-turn lane layout (deceleration/ acceleration)		
Length of right-turn lane	Manually measured from Google Maps	
Width of right-turn lane		
Length of acceleration lane		

Width of acceleration lane		
Speed limit on the road	Manually measured from Google Street View on Google Maps	
Traffic signal	Manually measured from Google Street View on Google Maps	

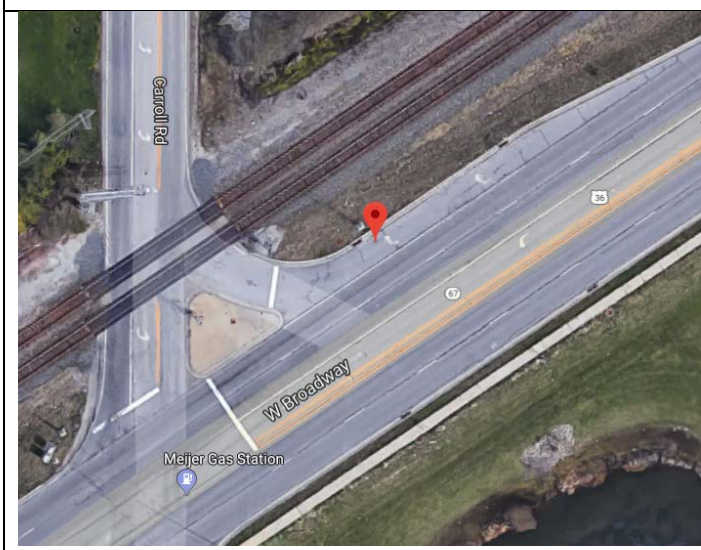
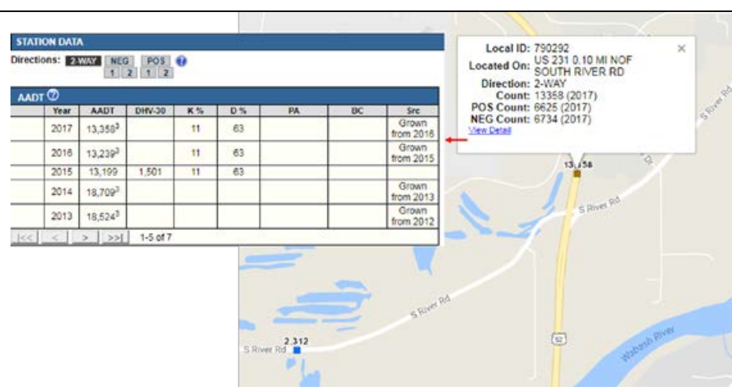
<table>
<tr><td>Pedestrian crossing</td><td rowspan="3">Manually measured from Google Maps</td><td></td></tr>
<tr><td>Truncated bicycle lane</td><td></td></tr>
<tr><td>Railroad crossing</td><td></td></tr>
<tr><td>Traffic volume in both directions</td><td rowspan="3">Measured from INDOT traffic count database</td><td rowspan="3"></td></tr>
<tr><td>Traffic volume in the same direction</td></tr>
<tr><td>Traffic volume in the opposite direction</td></tr>
</table>

Table 7. Number of surveyed intersections

Code	County	On major highways			Ramps			Local		Total	Surveyed
		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		**1449**	**439**	**431**	**601**	**180**	**156**	**19**	**44**	**631**	**545**

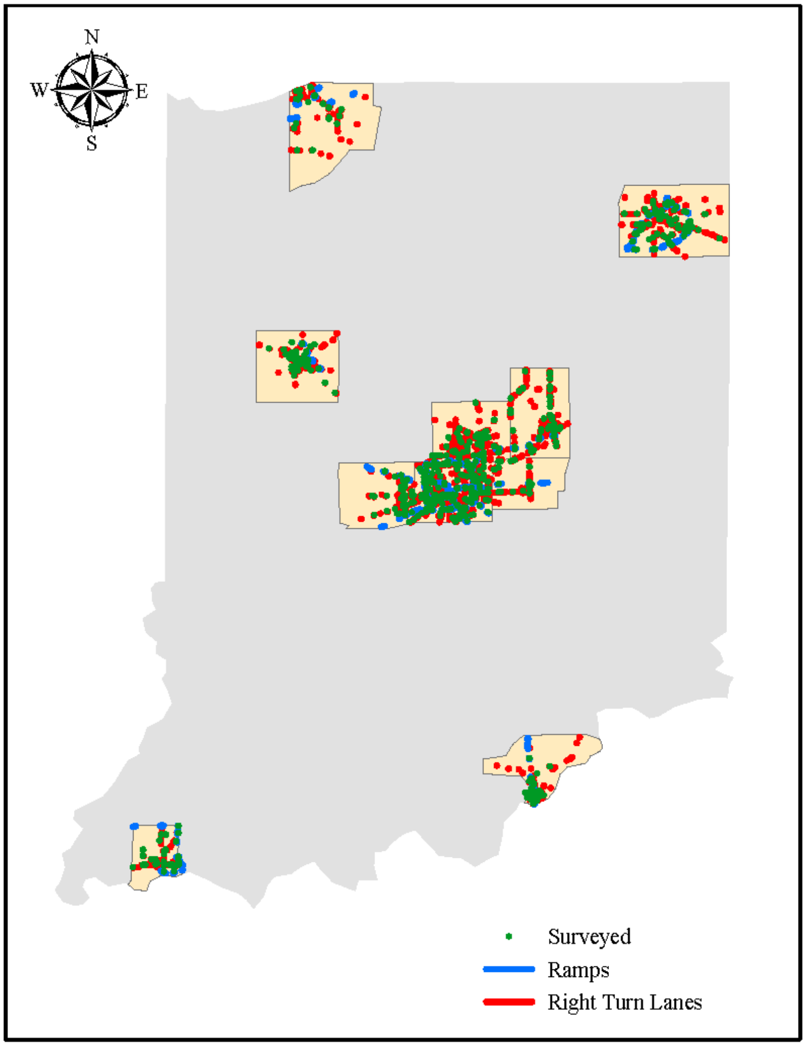


Figure 16. Spatial distribution of surveyed right-turn lanes

4.2.2 Crash Data

The crash data is collected from the Automated Reporting Information Exchange System (ARIES), where records police crash reports. Considering the project needs, we request a 4-year crash dataset from 2013 to 2016. The dataset contains all crashes happened in the 10 candidate counties, on both road intersections and road segments, summarized in Table 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 description.

Table 8. Crash frequency by year and location

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%

4.3 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 objective of data fusion is to obtain the crashes at our manually surveyed intersections. Another big concern is the quality of intersection samplings. 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 the 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. A string matching method is proposed to complete data fusion as follows:

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;

$$sr = \frac{2 * len(cs)}{len(s1) + len(s2)} \tag{1}$$

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 Geodatabse, since the geodatabase only provides geolocation but no 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 16) 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 16);
3) Filter out target intersection points with a threshold of 0.0005 (around 60m);
4) Assign a unique intersection id if distance between two intersection points are less than 100m 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 17.]

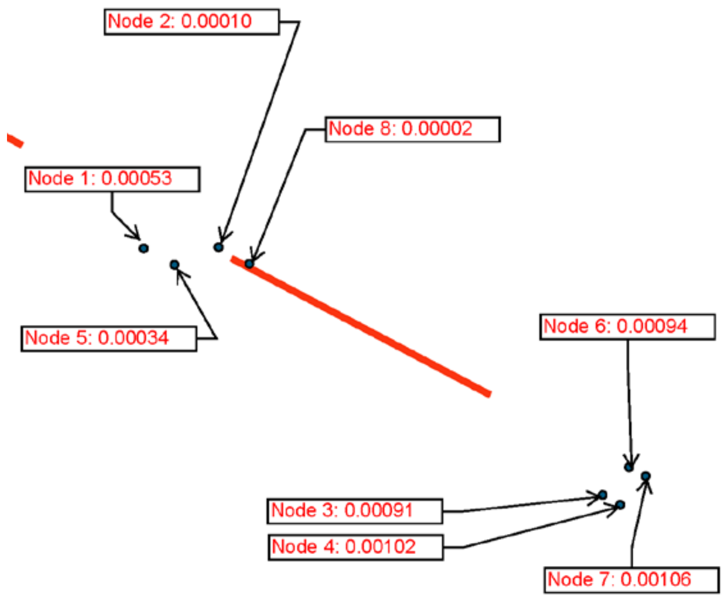


Figure 17. Illustration of road name determinations for right-turn lanes

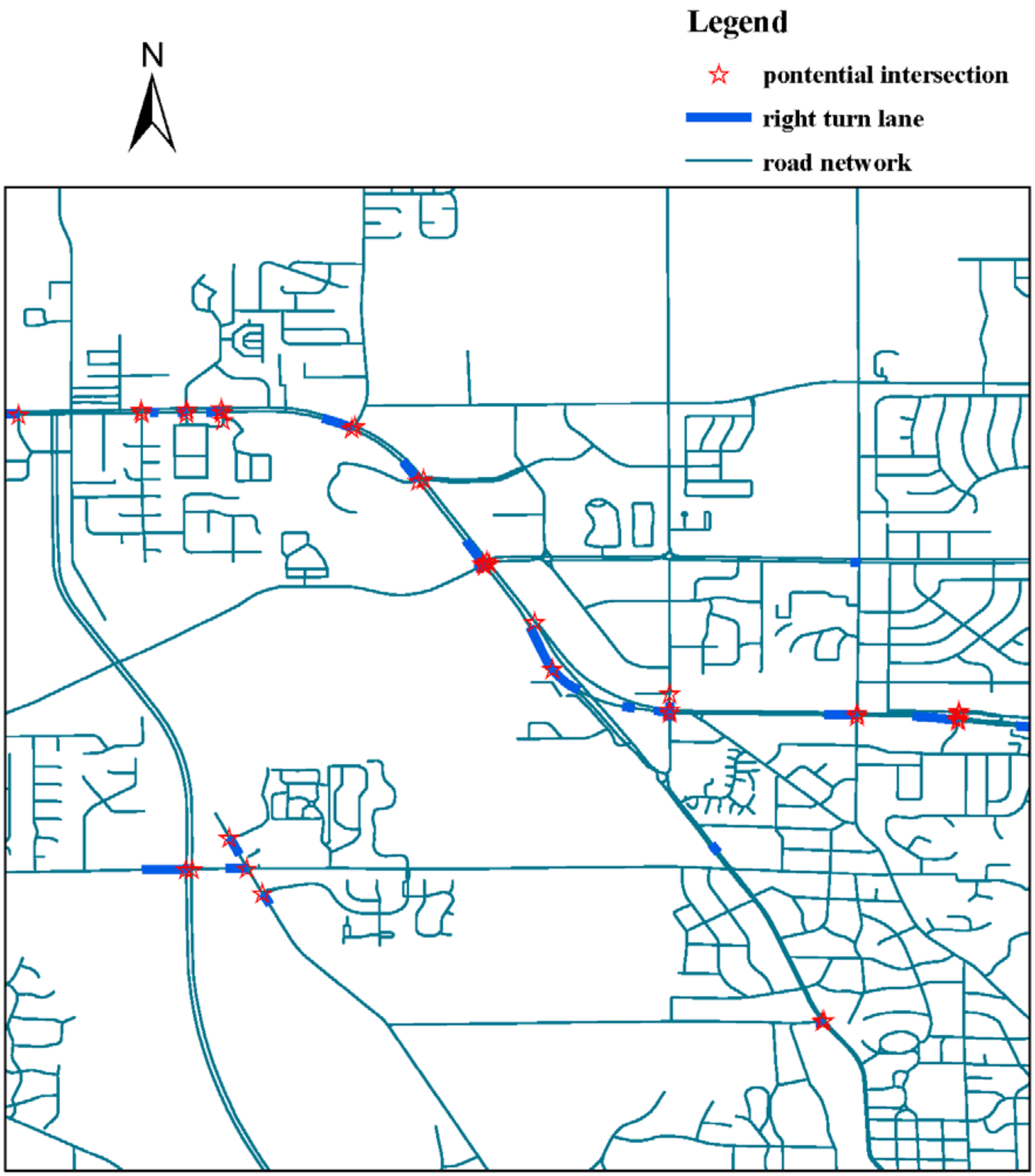
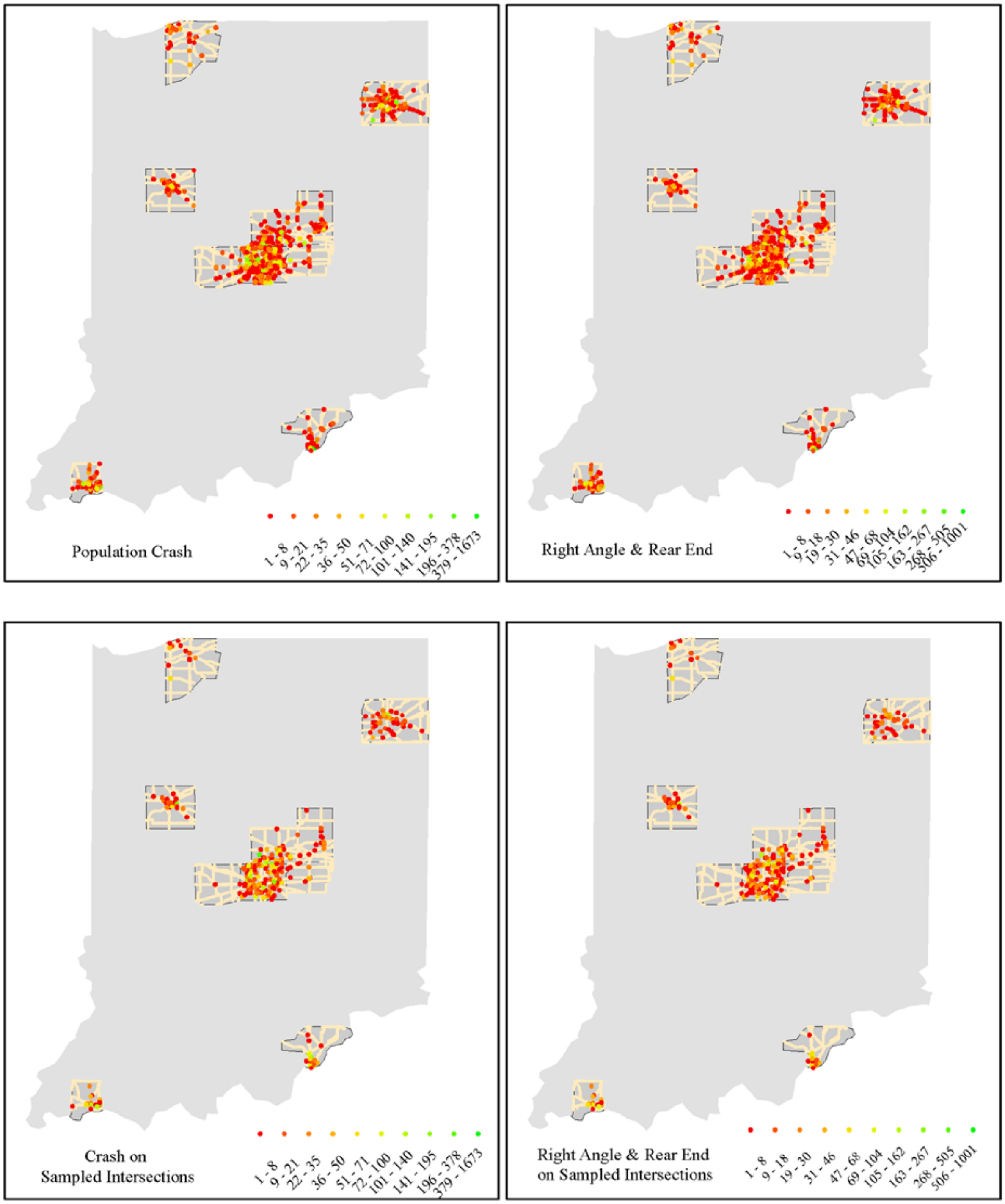
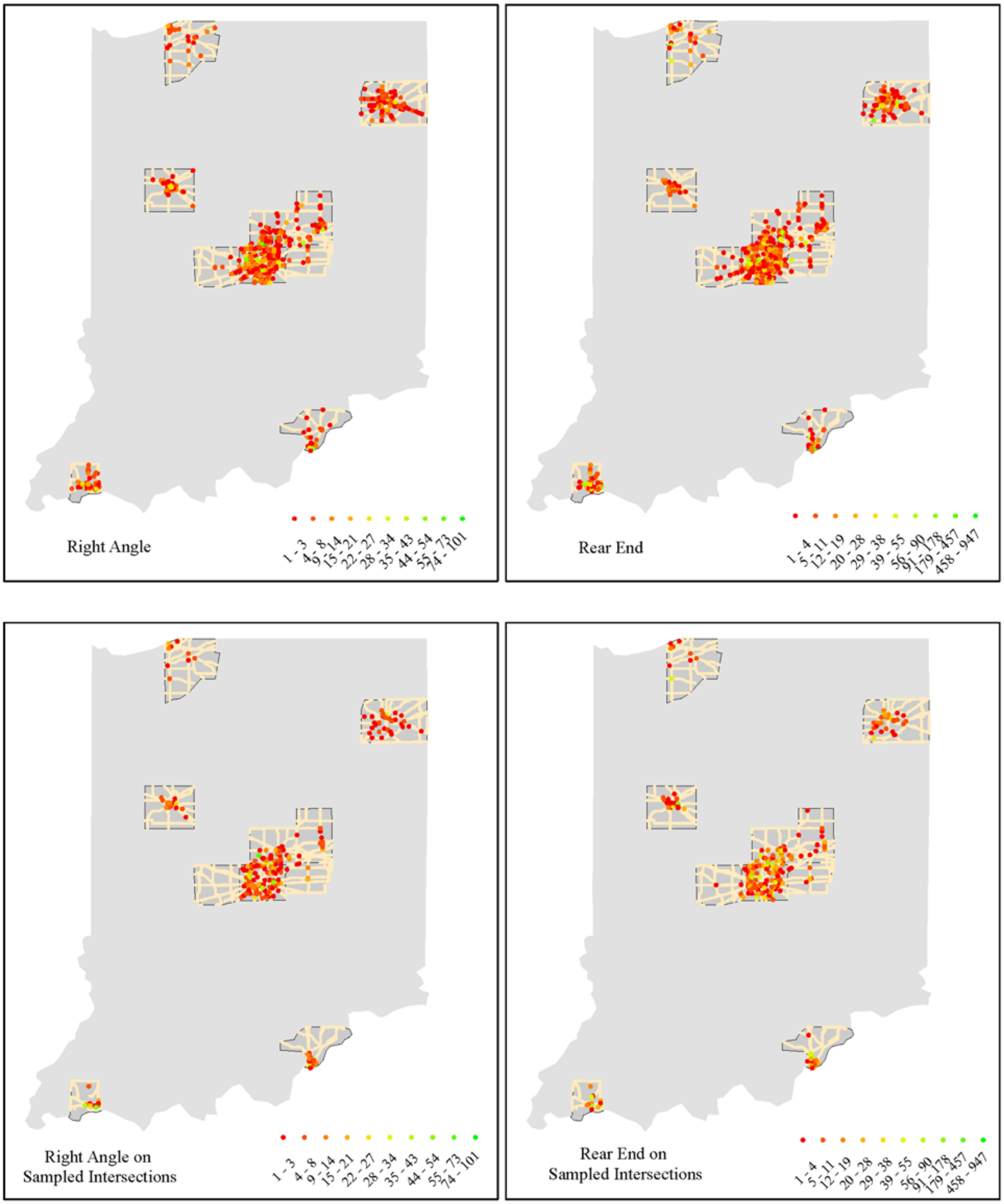


Figure 18. Illustration of multiple intersection points for one unique physical intersection

Finally, we identify 1319 intersections (with road names) for all 1449 right-turn lanes in INDOT Geodatabase. The road name matching further yields a set of crashes on all intersections with right-turn lanes. The INODT 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 18.



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



(b) frequency by two major types of crashes

Figure 19. Crash frequency of all and sampled intersections

Table 9, 10, and 11 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 1319 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. The conclusion make sense considering the fact that right-turn lane mainly installs on large intersections with heavy flows and frequent turns. Table 9 also indicates that crashes are likely to distribute 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 10 and 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 crash is 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.

Table 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 crash	24.87%	24.45%	23.86%	23.72%	24.19%
All crashes at Intersections with right-turn lanes					
Crash	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 sampled 30% of intersections with right-turn lanes					
Crash	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 10. Frequency of right-turn related crashes

Items	2013	2014	2015	2016	Total	% of all crashes
Right-turn related crashes at all intersections						
Crash	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						
Crash	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 surveyed 30% of intersections with right-turn lanes						
Crash	472	576	557	583	2188	23.59%
On major highways	445	556	524	552	2077	25.25%
On ramps	27	20	33	31	111	10.58%

Table 11. Frequency of rear end crashes

Items	2013	2014	2015	2016	Total	% of all crashes
Rear end crashes at all intersections						
Crash	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						
Crash	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 surveyed 30% intersections with right-turn lanes						
Crash	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%

The combination of crash data and Google survey data has detailed characteristics which are summarized into categories in Table 11.

Table 12. 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

Classification	Attributes
	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 Surrounding Built	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)
	Speed limit
Drivers' Characteristics	Aggressive driving
	Hit and run

4.4 Selection Bias during Sampling

The selection bias is one popular bias during sampling, which results from the different crash 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 bias, as well as to identify what variables are biased if possible.

The chi-square based method is proposed to compare the crash distribution between population and sampled datasets. The null hypothesis is that the two distributions in the 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 all crashes, 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 death. 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 12. 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 13. We can observe almost same set of variables with selection bias.

Table 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 14. Variables with selection bias in the dataset with two major crash types

(a) dataset with both right-turn related and rear end crashes

Variables	Rear end crashes	On ramps	On major highways
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

(b) dataset with only right-turn related crashes

Variables	**Right angle crashes**	**On ramps**	**On major highways**
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

(c) 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 1-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

4.5 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 14, we can conclude that 1) there are almost no difference in crash severity if we consider all crash types; 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; but 3) there are increased injuries in right-turn related crashes if installing right-turn lanes on regular US/state/county highways and urban streets.

Table 15. Crash distribution between intersections with and without right-turn lanes

Severity	Right tune 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

All 9,275 crashes were found to happen at 355 unique intersections. As such, the average crashes per intersection is around 26 crashes. Figure 20 presents crashes at intersection by frequencies from smallest to largest.

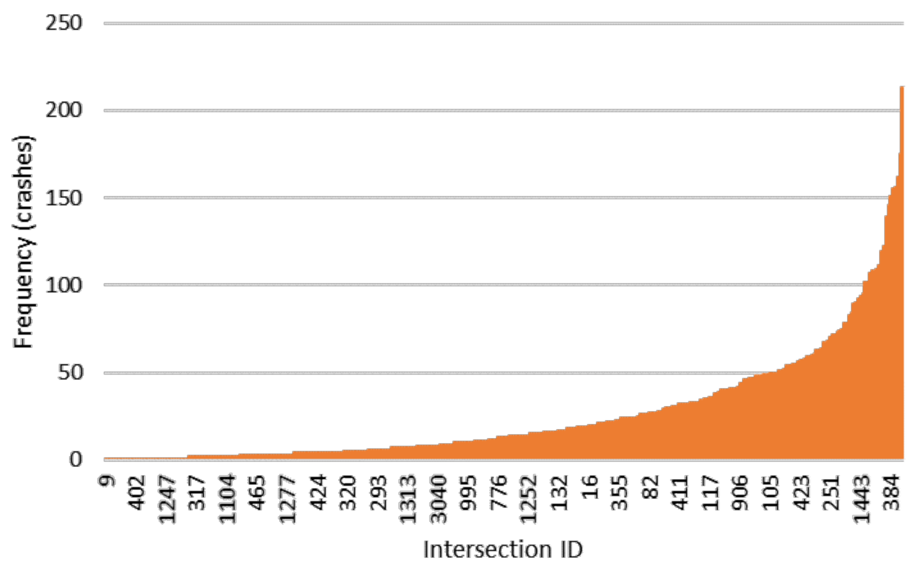


Figure 20. Crash frequencies by intersection.

Table 15 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.

Table 16. Top five most-frequent-crash intersections

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

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.

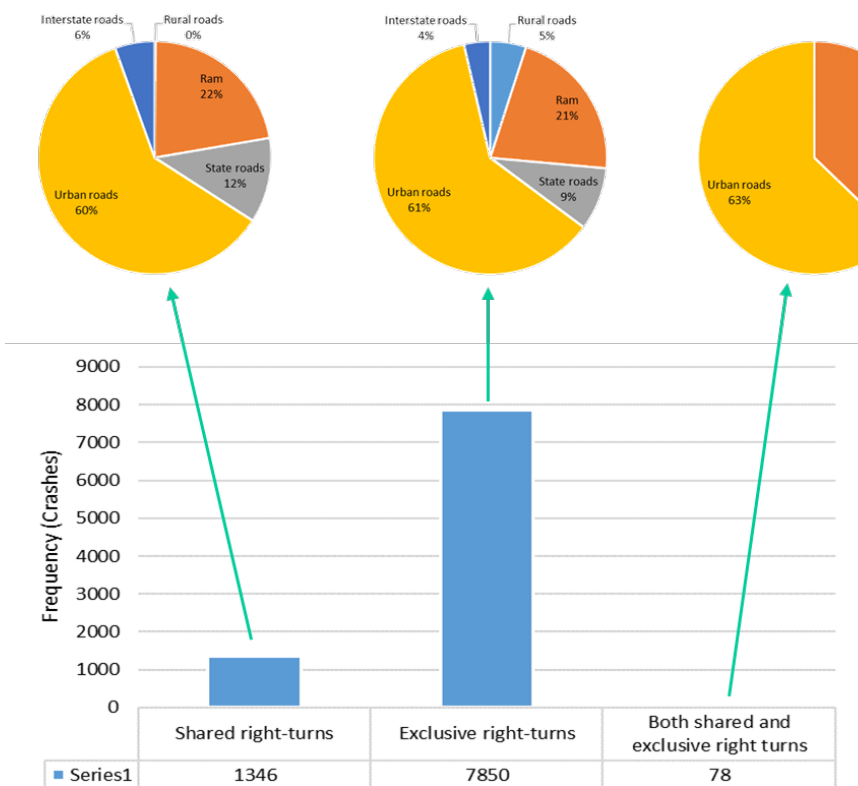


Figure 21. Crashes and spatial distributions

The highest numbers of injuries and dead are found at exclusive right-turns lanes.

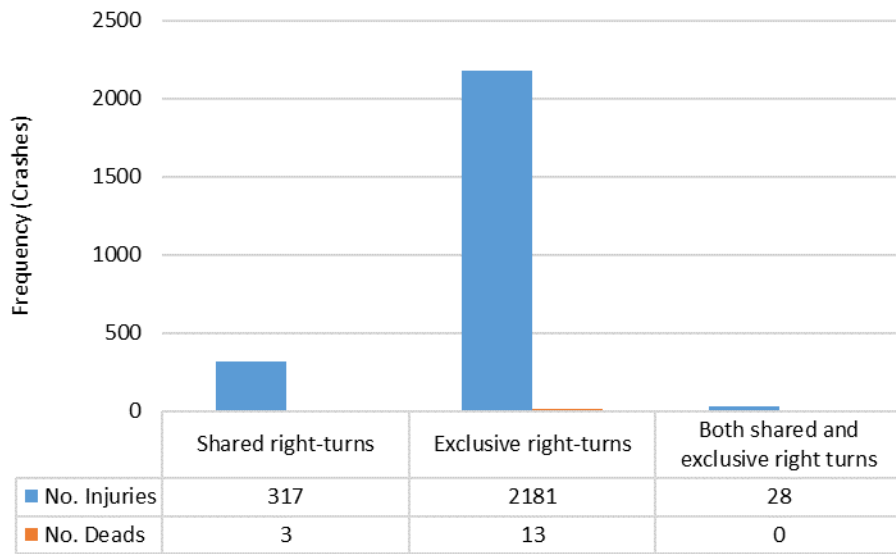


Figure 22. Crash severity at right-turn lane types.

In straight/level shared right-turn and exclusive right-turn lanes, there were a majority of crashes as can be seen in Table 16.

Table 17. 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	1084	6281	70

For the manner of collision, right-angle and rear-end crashes have been found as the most frequent crashes as shown in Table 17.

Table 18. Manner of collision by right-turn lane types

Manner of collision	Shared right-turns	Exclusive right-turns	Both shared and exclusive right-turns
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 crash	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	1568	23
Rear end	613	3462	19

Interestingly, significant performance were 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%).

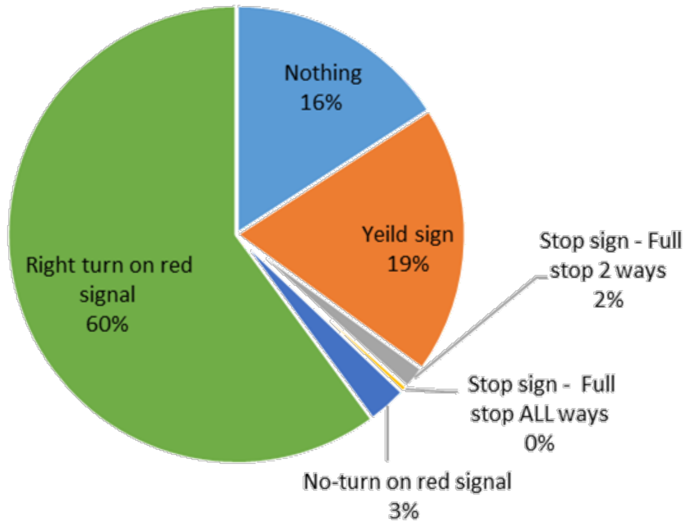


Figure 23. Crash share by traffic control types

About 70% of crashes were happened at four-way intersections as can been seen at Figure 24.

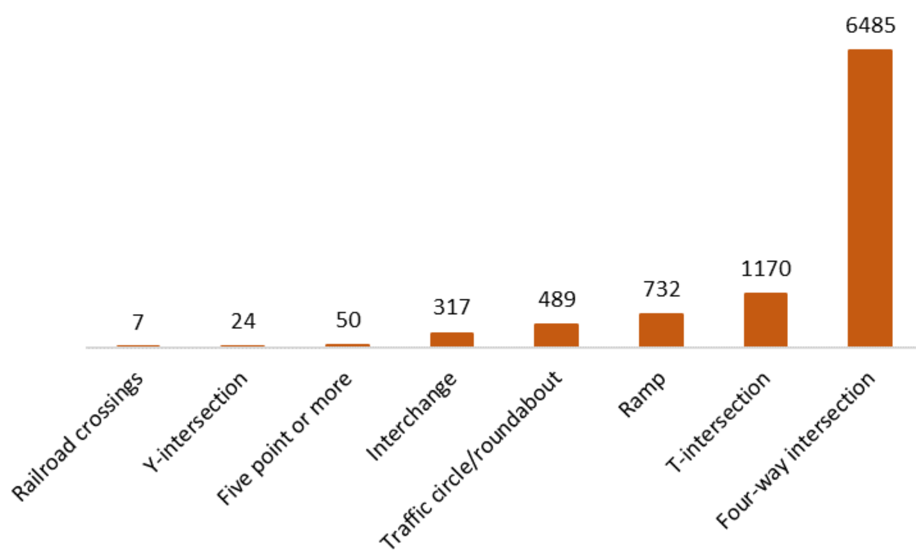


Figure 24. Crash frequency at roadway junction type

There are over 38% of crashes associated with intersection designs as presented in Table 18.

Table 19. Top main factors contribute to crashes

Main factor	Crash frequencies	Crash %
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	2317	25.08%
Following too closely	3198	34.61%

5 METHODOLOGY AND ESTIMATION

5.1 Modeling Crash Frequency and Severity

A combined model incorporates both crash frequency and severity.

5.2 Estimation Results

Present results here: ….

5.2.1 Intersection geometric design variables

Design variables of the right-turn lane: right-turn lane with lane pavement marking, shared lane with island, channelized right-turn lane, right-turn lane with island and dedicated downstream lane, line of sight

5.2.2 Traffic control

Traffic flow, traffic control

5.2.3 Environmental variables

Time of day, weather

5.2.4 Recommendations for right-turn lane design

A list of right-turn lane design alternatives and key factors that correlated with crashes

A set of alternatives that guide INDOT's decisions on selection of right-turn lane designs

6 DISCUSSIONS AND CONCLUSIONS

6.1 Discussions

6.2 Concluding remarks

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