EVALUATING CRASH CHARACTERISTICS AND SAFETY OUTCOMES AT ROUNDABOUTS: IMPLICATIONS FOR SAFER INTERSECTIONS

by

Rohit Chakraborty, B.S.

A thesis submitted to the Graduate Council of

Texas State University in partial fulfillment

of the requirements for the degree of

Master of Science

with a Major in Engineering

June 2025

Committee Members:

Dr. Subasish Das, Chair

Dr. Feng Hong

Dr. F. Benjamin Zhan

**COPYRIGHT**

by

Rohit Chakraborty

2025

**ACKNOWLEDGMENTS**

All praise and gratitude are due to Almighty God, the Most Gracious, the Most Merciful. My two-year journey at Texas State University has been a transformative learning experience, made possible by the guidance and encouragement of my mentor, Dr. Subasish Das. I am especially thankful to Dr. Das for his unwavering support and mentorship during my master’s degree program, which has shaped me into an independent researcher. His dedicated guidance in every aspect of this work stands as one of the most meaningful accomplishments of my life and will remain so always. I am also deeply grateful to Dr. Feng Hong and Dr. F. Benjamin Zhan for serving on my thesis committee. Their expertise and insightful feedback have greatly contributed to enhancing the quality of this work. My heartfelt thanks go to my peers, particularly Md Monzurul Islam for helping me in some tasks, and my friends for their constant encouragement and support throughout this journey. Most importantly, I am profoundly grateful to my family for their unconditional love, patience, and mental support, which sustained me through every challenge and kept me grounded during this academic pursuit. Last but not least, I would also like to thank myself for not giving up. To close, I am quoting a line from a poem that I have been following for the last decade and that has always kept me focused and inspired through difficult times:

“Miles to go before I sleep.”

— Robert Frost

TABLE OF CONTENTS

Page

[LIST OF TABLES vi](#_Toc201151808)

[LIST OF FIGURES vi](#_Toc201151809)

[LIST OF ABBREVIATIONS viii](#_Toc201151810)

[ABSTRACT ix](#_Toc201151811)

[1. INTRODUCTION 1](#_Toc201151812)

[1.1 Background 1](#_Toc201151813)

[1.2 Experimental Challenges 3](#_Toc201151814)

[1.3 Research Gap 4](#_Toc201151815)

[1.4 Objective of the Study 5](#_Toc201151816)

[1.5 Outline of the Study 6](#_Toc201151817)

[2. LITERATURE REVIEW 7](#_Toc201151818)

[2.1 Types of Roundabouts 7](#_Toc201151819)

[2.1.1 Single-Lane Roundabouts 8](#_Toc201151820)

[2.1.2 Multilane Roundabouts 9](#_Toc201151821)

[2.1.3 Turbo Roundabouts 10](#_Toc201151822)

[2.1.4 Dual Roundabout Interchange 11](#_Toc201151823)

[2.2 Crash Frequency and Severity at Roundabouts 13](#_Toc201151824)

[2.3 Driver Behavior at Roundabouts 15](#_Toc201151825)

[2.4 Roundabout Capacity and Operational Performance 17](#_Toc201151826)

[2.5 Connected and Automated Vehicles at Roundabouts 21](#_Toc201151827)

[2.6 Pedestrian and Cyclist Safety at Roundabouts 24](#_Toc201151828)

[2.7 Modeling Approaches and Assessment Techniques 27](#_Toc201151829)

[2.8 Applications of Cluster Correspondence Analysis in Crash Pattern Studies 29](#_Toc201151830)

[2.9 Policy and Implementation Implications 31](#_Toc201151831)

[3. STUDY DESIGN 40](#_Toc201151832)

[3.1 Data Preparation 41](#_Toc201151833)

[3.2 Exploratory Data Analysis 42](#_Toc201151834)

[3.3 Variable Importance Analysis 46](#_Toc201151835)

[3.4 Cluster Correspondence Analysis 48](#_Toc201151836)

[3.5 SHapley Additive exPlanation 50](#_Toc201151837)

[4. RESULTS AND DISCUSSION 51](#_Toc201151838)

[4.1 Cluster Correspondence Analysis 51](#_Toc201151839)

[4.1.1 Cluster 1 (C1) – Entry and Yield-Related Conflicts at Roundabouts 52](#_Toc201151840)

[4.1.2 Cluster 2 (C2)- Improper Maneuvers and Driver Misjudgment Crashes at Roundabouts 54](#_Toc201151841)

[4.1.3 Cluster 3 (C3)- Fixed Object and Environmental Hazard Crashes at Roundabouts 55](#_Toc201151842)

[4.1.4 Cluster 4 (C4)- Rear-End and Following-Distance Crashes in Circulating Roundabout Flow 57](#_Toc201151843)

[4.1.5 Cluster-Based Comparative Analysis 58](#_Toc201151844)

[4.2 SHAP Interpretation 62](#_Toc201151845)

[4.2.1 Cluster 1 63](#_Toc201151846)

[4.2.2 Cluster 2 66](#_Toc201151847)

[4.2.3 Cluster 3 69](#_Toc201151848)

[4.2.4 Cluster 4 72](#_Toc201151849)

[4.3 Exploration of KA Severity Crash Narratives 75](#_Toc201151850)

[4.4 Hot Spot Analysis 78](#_Toc201151851)

[5. CONCLUSIONS 81](#_Toc201151852)

[REFERENCES 86](#_Toc201151853)

# LIST OF TABLES

Page

[Table 2.1 Summary Table of Key Roundabout Studies 35](#_Toc201151869)

[Table 3.1 Percentage distribution of key attributes by injury severity 43](#_Toc201151870)

[Table 4.1 Centroids and size of the clusters 51](#_Toc201151871)

[Table 4.2 Cluster-based comparative analysis. 59](#_Toc201151872)

[Table 4.3 Summary of crash narratives 75](#_Toc201151873)

# LIST OF FIGURES

Page

[Figure 1.1 Fatalities at roundabouts in the U.S. by year 3](#_Toc201151879)

[Figure 2.1 Single lane roundabout layout 8](#_Toc201151880)

[Figure 2.2 Multilane roundabouts 9](#_Toc201151881)

[Figure 2.3 Turbo roundabout 11](#_Toc201151882)

[Figure 2.4 Dual Roundabout Interchanges 12](#_Toc201151883)

[Figure 3.1 Study Design 40](#_Toc201151884)

[Figure 3.2. Crash distribution by year 41](#_Toc201151885)

[Figure 3.3 List of considered variables 47](#_Toc201151886)

[Figure 3.4 Variable importance plot (XGBoost) 48](#_Toc201151887)

[Figure 3.5 Variable importance plot (Random Forest) 48](#_Toc201151888)

[Figure 4.1 Cluster biplot 52](#_Toc201151889)

[Figure 4.2 Entry and Yield-Related Conflicts at Roundabouts 54](#_Toc201151890)

[Figure 4.3 Improper Maneuvers and Driver Misjudgment Crashes at Roundabouts 55](#_Toc201151891)

[Figure 4.4 Fixed Object and Environmental Hazard Crashes at Roundabouts 57](#_Toc201151892)

[Figure 4.5 Rear-End and Following-Distance Crashes 58](#_Toc201151893)

[Figure 4.6 Cluster 1 SHAP plots for different severity levels 66](#_Toc201151894)

[Figure 4.7 Cluster 2 SHAP plots for different severity levels 69](#_Toc201151895)

[Figure 4.8 Cluster 3 SHAP plots for different severity levels 72](#_Toc201151896)

[Figure 4.9 Cluster 4 SHAP plots for different severity levels 75](#_Toc201151897)

[Figure 4.10 HotSpot analysis of crash locations 80](#_Toc201151898)

# LIST OF ABBREVIATIONS

**Abbreviation Description**

CCA Cluster Correspondence Analysis

SHAP SHapley Additive Explanations

FHWA Federal Highway Administration

SPFs Safety Performance Functions

CMF Crash Modification Factors

ADAS Advanced driver-assistance systems

HCM Highway Capacity Manual

CAV Connected and Automated Vehicle

SSAM Surrogate Safety Assessment Model

SUVs Sport utility vehicle

V2X Vehicle-to-Everything

V2I Vehicle-to-Infrastructure

# ABSTRACT

This study investigates crashes that occurred at roundabouts across Ohio from 2017 to 2021 to better understand the factors linked to crash risk and injury severity at these intersections. A total of 6,448 roundabout-related crashes were analyzed using a combination of Cluster Correspondence Analysis (CCA), SHapley Additive Explanations (SHAP), and spatial hotspot mapping. CCA was applied to group crashes by similar features, allowing the identification of distinct crash patterns, while SHAP was used to explain the influence of key variables such as vehicle type, crash type, pre-crash action, road and environmental conditions, and driver behavior on the severity of crash outcomes. Narrative summaries were reviewed to provide real-world context behind fatal and severe crashes, revealing that many of the most serious incidents involved drivers failing to yield, losing control, or striking fixed objects after entering the roundabout at high speed. The study also used spatial hotspot analysis to identify locations with higher concentrations of roundabout crashes, particularly in urban regions such as Cincinnati, Columbus, Toledo, and Cleveland. Results show that most roundabout crashes were property-damage-only, but severe crashes were more likely at night, in poor weather, and on approaches with higher speed limits. Younger and older drivers were found to be involved in different types of crash scenarios, indicating the need for age-specific driver education. Key factors influencing crash severity included failure to yield, improper maneuvers, poor visibility, and high-speed approaches. The findings suggest that while roundabouts are generally safer than traditional intersections, specific risks remain that require attention. Policy recommendations include improving entry and lane guidance, enhancing signage and lighting, and focusing driver education on common errors identified in the analysis.

# INTRODUCTION

**I.**

## Background

A roundabout is a particular type of at-grade intersection that is widely recognized as a safer alternative to traditional intersections, primarily due to its capacity to reduce conflict points and encourage lower vehicle speeds (Li et al., 2024; Maji and Ghosh, 2025; Wang and Cicchino, 2022). Across the United States, roundabouts have been shown to decrease fatalities compared to signalized intersections. Roundabouts have become increasingly important in the United States due to their ability to reduce crash severity, slow down vehicles, and lower conflicts at intersections compared to traditional intersections with traffic signals or stop signs. Even though roundabouts generally improve safety, crashes still happen at these locations, and ongoing research and safety improvements are needed. Studying roundabout safety is necessary because more roundabouts are being built, and traffic conditions continue to change. Roundabouts improve intersection safety mainly by reducing the points where crashes can occur, slowing vehicle speeds, and making decisions easier for drivers. Many studies show fewer serious crashes after roundabouts are built. However, crashes at roundabouts are different from crashes at regular intersections in terms of why they happen, the types of crashes, and who is involved. Because of these differences, carefully studying crashes at roundabouts helps identify specific safety problems and ways to fix them.

The need for continued research on roundabout safety is important because transportation systems keep changing. New vehicle technologies, changes in how drivers behave, and shifting demographics present new challenges. Technologies like driver-assistance systems, self-driving cars, and connected vehicles add new elements to roundabouts and may change how crashes happen. As these technologies become more common, ongoing research helps keep safety measures up to date. Analyzing roundabout crashes involves closely looking at crash records to find patterns and understand risk factors. Common methods include examining crash frequency and severity, looking into driver errors and environmental conditions, and studying intersection designs. Techniques such as regression analysis, spatial analysis, and machine learning are often used to find the main reasons for crashes at roundabouts. This type of research helps clearly understand why crashes happen and guides effective safety improvements.

Improving roundabout safety includes both physical changes and educational efforts. Physical changes might involve modifying the roundabout design by adjusting entry angles or lane setups, installing better signs and lights, or adding facilities for pedestrians. Education programs and campaigns to raise awareness among drivers, pedestrians, and cyclists are also important. These efforts work together to reduce both the number and severity of crashes. Therefore, researching roundabout safety, analyzing crashes, and creating effective safety measures remain important. As roundabouts become more common, thorough research and regular safety evaluations are needed. Understanding why crashes happen at roundabouts helps authorities make informed decisions that improve safety and make roundabouts safer for everyone.

Figure 1.1 shows that 46 fatalities occurred at 19 different states across the U.S. between 2005 to 2013, according to a Federal Highway Administration (FHWA) report (Steyn et al., 2015). Another recent study in Michigan showed despite the decrease in fatalities, roundabouts are prone to 58% more crashes compared to other conventional intersections (Savolainen et al., 2023). These incidents not only challenge the assumption that roundabouts are inherently safe but also highlight the need for a closer examination of specific crash characteristics at roundabouts. This study will investigate the crashes that occurred at roundabouts in Ohio between 2017 - 2021 to investigate the influencing factors related to such crashes. In Ohio, where roundabouts are increasingly implemented as a safety measure, understanding the nature and causes of these crashes is crucial to enhancing roundabout safety further and informing engineering, enforcement, and educational interventions.

A graph of crash in the u. s.

Description automatically generated

Figure 1.1 Fatalities at roundabouts in the U.S. by year

## Experimental Challenges

Researching roundabout crashes comes with several practical and experimental challenges. One major challenge is the availability and quality of data. Many crash databases do not specifically label crashes by roundabout location, making it difficult to separate roundabout crashes from those at other types of intersections. Sometimes, important details such as the exact entry or exit point, the direction of travel, or specific actions taken by drivers are missing from the records. This lack of detailed information can limit the depth of the analysis. Another challenge is the relatively low number of crashes at individual roundabouts compared to other intersections, since roundabouts are generally safer. This lower frequency can make it hard to identify patterns, especially for severe crashes. Small sample sizes also make it difficult to use some statistical methods or to draw strong conclusions.

There are also differences in roundabout design, traffic volumes, and surrounding environments, which can make it difficult to compare results across different locations. In addition, the introduction of new vehicle technologies and changes in road user behavior add more uncertainty, making it harder to isolate the causes of crashes. Furthermore, it can be difficult to measure the effect of safety improvements, since changes may take time to show up in the data and may be influenced by outside factors such as weather, road work, or changes in local traffic laws. These experimental challenges mean that researchers need to be careful in how they analyze data and interpret results when studying roundabout safety.

## Research Gap

Although many studies have analyzed roundabout safety using statistical and simulation-based approaches, important gaps still remain. A large portion of past research has focused on general crash trends, vehicle interactions, or geometric features of roundabouts, often relying on traditional regression models or aggregated data. These approaches sometimes overlook the complex interactions between multiple crash-related variables and do not fully capture the diversity of crash scenarios within roundabouts. One key gap is the limited application of unsupervised methods like CCA to understand roundabout crash patterns. Most earlier studies have used fixed-form models, which can make it difficult to detect naturally occurring groupings in the data. CCA allows for the identification of distinct crash clusters based on categorical variables, helping to uncover specific combinations of crash characteristics that are more common under certain roundabout conditions. In addition, while supervised models have been used to predict crash severity, few studies have combined them with explainable machine learning techniques such as SHAP. SHAP helps to explain the influence of each variable in a model’s prediction and can offer a clearer understanding of how different factors contribute to crash severity within each identified cluster. Moreover, although some spatial studies exist, roundabout-focused hotspot analysis is relatively limited in the literature. Most spatial work does not distinguish crashes at roundabouts from those at nearby intersections or corridors. A hotspot analysis, as used in this study, adds value by identifying high-risk locations where roundabout crashes are more likely to occur. This thesis addressed these gaps by applying CCA to classify crash patterns at roundabouts and using SHAP to examine the factors influencing severity within each cluster. In addition, hotspot analysis using ArcGIS helped to highlight areas with frequent roundabout crashes. This combined approach offers a deeper and more structured understanding of roundabout safety compared to earlier research.

## Objective of the Study

Although roundabouts are known to reduce severe crashes compared to traditional intersections, crashes still occur, and there is a need to better understand why these crashes happen and how they can be prevented. With the increasing use of roundabouts across Ohio, it is important to closely study the factors that contribute to crashes at these locations. This study aims to address gaps in knowledge about roundabout safety by answering the following research questions:

1. If roundabouts are generally considered the safest intersection design, what factors are contributing to different types of injuries when crashes occur?
2. What distinct clusters or patterns of crash characteristics can be identified within roundabout-related crashes, and how do these clusters relate to injury severity?
3. What specific design features or configurations of roundabouts are most closely linked to high-severity crashes?

To answer these research questions, the main objectives of this study are as follows:

1. To examine the patterns and main factors related to roundabout crashes, including when, where, and how crashes happen, and which types of vehicles and road users are most often involved.
2. To use clustering techniques to identify groups of crashes with similar features, and to analyze how injury severity varies between these groups.
3. To investigate how roundabout design elements, driver behavior, weather conditions, vehicle types, and the roundabout’s location can influence crash risk and severity.
4. To highlight unique safety challenges.
5. To recommend practical safety improvements for roundabouts, considering both roadway design and surrounding land use, based on the study’s findings.

## Outline of the Study

The Thesis consists of five chapters.

**Chapter One** provides an introduction to the study, highlighting the significance and the necessity of roundabout safety studies.

**Chapter Two** includes a comprehensive literature review of previous studies on roundabouts crashes and safety analysis.

**Chapter Three** highlights the study design of this research which also includes description of the analyzed data, exploratory analysis of the data, variable selection process, and a brief review of the methodological framework used for the roundabout study.

**Chapter Four** describes the results from the CCA, SHAP, and hot spot analyses.

**Chapter Five** summarizes the key findings, highlighting the potential countermeasures based on the findings.

# LITERATURE REVIEW

**II.**

Roundabouts have been widely promoted for their safety and operational benefits. By eliminating perpendicular crossings and forcing lower speeds, modern roundabouts have dramatically reduced severe crashes compared to conventional intersections. For instance, converting intersections to roundabouts was reported to cut fatal and serious-injury crashes by roughly 78–82% (Novat et al., 2024). This safety record, along with smoother traffic flow and lower delays at moderate volumes, has led to rapid adoption of roundabouts in many countries. As of 2022, over 11,000 roundabouts were in operation across the United States and Canada (Jiang et al., 2024). However, the safety performance of roundabouts is not universally positive, especially in contexts with heterogeneous traffic or less disciplined driver behavior, some studies have found higher-than-expected crash frequencies (Maji and Ghosh, 2025). Researchers have accordingly examined roundabouts from multiple angles, including crash severity outcomes, driver behavior characteristics, capacity modeling, the impacts of emerging vehicle technologies, modeling methodologies, pedestrian and cyclist safety, and policy implications. This literature review synthesizes findings from recent studies on roundabouts, grouped by major thematic areas. All content is drawn from peer-reviewed papers and technical reports focused on roundabouts. Key studies are also summarized in a table at the end of the review.

## Types of Roundabouts

Modern roundabouts come in several configurations, each with distinct design characteristics suited to different traffic conditions. This section reviews some common types of roundabouts, describing their key design features along with typical advantages and drawbacks. The discussion draws on authoritative sources (e.g., FHWA guides, the Highway Capacity Manual) and recent studies to provide an academic yet accessible overview. Although this study does not investigate the design considerations of roundabouts, however the literature review includes some description related to the design specifications of different roundabout types.

### Single-Lane Roundabouts

Single-lane roundabouts are the simplest modern roundabout form. They have one entry lane per approach and a single circulating lane around a central island (NACTO, 2025). Inscribed circle diameters are often relatively small (on the order of 30–40 m, or ~100–130 feet), and they commonly include design elements like raised splitter islands for deflection and a traversable central **truck apron** to accommodate large vehicles while maintaining a compact footprint. Entering drivers must yield to any vehicle already circulating, and the geometry forces low speeds (typically 15–25 mph) through the intersection (WSDOT, 2025). These features promote safety and efficient operation for modest traffic volumes. Figure 2.1 shows the layout of a single lane roundabout.

A drawing of a crossroad

AI-generated content may be incorrect.

Figure 2.1 Single lane roundabout layout

### Multilane Roundabouts

Multilane roundabouts have two or more lanes entering and circulating, at least on some approaches, to accommodate higher traffic volumes than a single-lane roundabout can handle. A common form is the two-lane roundabout, featuring (at minimum) two entry lanes on the major approaches and a two-lane circulatory roadway (see Figure 2.2). These designs typically require a larger inscribed diameter (often ~45–55 m, or 150–180 feet for a two-lane roundabout) to fit the wider roadway and provide appropriate geometry. Drivers must choose the correct lane on approach (usually based on whether they intend to turn right, go through, or turn left/U-turn) and generally should not change lanes inside the circular roadway. Aside from the extra lanes, multilane roundabouts share the same basic design principles as single-lane roundabouts: yield-at-entry control, channelized approaches, and geometric curvature to induce lower speeds.

A circular intersection with a circular center

AI-generated content may be incorrect.

Figure 2.2 Multilane roundabouts

### Turbo Roundabouts

Turbo roundabouts are a specialized spiral multilane roundabout design developed to improve safety and operations over conventional two-lane roundabouts. Originating in the Netherlands in the late 1990s, the turbo roundabout concept uses raised lane dividers and spiral roadway markings to guide traffic into dedicated lanes for different movements, effectively preventing lane-changing within the circulatory roadway (FHWA, 2025). In a typical turbo roundabout, an approaching driver must choose the correct lane at entry (as with any multi-lane roundabout), but once in the roundabout, the spiral geometry and curbed lane separators will channel the vehicle along a fixed path to its exit. For instance, the outer lane may be directed to serve right-turn and through movements, while the inner lane spirals outward to serve through and left-turn movements, eliminating the need for weaving between lanes inside the circle. Turbo roundabouts often have a radial entry geometry (entries meet the circle at nearly a right angle) to slow vehicles and clearly separate the entry lanes. The raised lane dividers between lanes are typically mountable curbs: they are low enough that large trucks can ride over them if needed, but high enough to strongly discourage passenger cars from straying out of the lane. These design features distinguish turbo roundabouts from standard multi-lane roundabouts. A typical layout of a turbo roundabout is illustrated in Figure 2.3.

A map of a roundabout

AI-generated content may be incorrect.

Figure 2.3 Turbo roundabout

### Dual Roundabout Interchange

Dual roundabout interchanges, also known as double roundabout diamond interchanges (or colloquially “dumbbell” or “dog-bone” interchanges), are a form of grade-separated interchange that replaces the usual ramp terminal intersections with roundabouts. In a typical configuration, the off-ramps from a freeway (or major road) terminate at two roundabouts on the crossroad, one roundabout at each end of the interchange bridge. These roundabouts handle all turning movements to and from the ramps as well as cross-street through movements, without the need for traffic signals. The two roundabouts are usually spaced a short distance apart, often just at either end of the overpass or underpass structure. Traffic on the cross street can flow freely through one roundabout, then proceed directly to the next if going straight across the interchange. Left-turning ramp traffic enters a roundabout and effectively makes a U-turn via the roundabout to head onto the opposite ramp or road direction. This design is sometimes called a “raindrop” interchange (especially when the roundabouts are slightly tear-drop shaped with one side flared toward the ramps) (FHWA, 2010; Mohamed et al., 2020). The dual roundabout interchange has been adopted in parts of Europe and the U.K. for many years and is now gaining interest in the U.S. as an alternative to conventional diamond interchanges. Figure 2.4 illustrates a typical layout of a dual roundabout interchange.

A drawing of a road

AI-generated content may be incorrect.

Figure 2.4 Dual Roundabout Interchanges

## Crash Frequency and Severity at Roundabouts

Early research established that roundabouts tend to reduce crash severity even if total crash counts may not always drop. Numerous before-and-after evaluations showed significant declines in fatal and injury crashes after roundabout installation (Vinayaraj and Perumal, 2023). In the U.S., the Highway Safety Manual and FHWA have highlighted roundabouts as a proven safety countermeasure due to their life-saving potential (Novat et al., 2024). A recent U.S. study of 27 roundabout conversions in Michigan found that while the total number of crashes increased, the number of fatal and serious-injury crashes fell substantially (Savolainen et al., 2023). Vehicles are forced to slow and merge, which tends to replace high-speed right-angle crashes with lower-speed glancing blows. Crashes that do occur at roundabouts often relate to entry-circulating conflicts or loss of control within the circle. An analysis of 28 roundabouts in Belgium, for example, found that about 75% of crashes involved entering vehicles colliding with circulating traffic (Polders et al., 2015). Common minor collisions include sideswipes and rear-end crashes, especially at multi-lane roundabouts where lane-change confusion can occur. Multi-lane roundabouts can be prone to property-damage-only crashes if drivers are unsure of lane assignments, improper signs or pavement markings have been linked to higher minor crash rates (Maji and Ghosh, 2025). Geometric design factors also play a role in safety. A comprehensive crash modeling study in India identified several significant predictors of roundabout crashes, including larger central island diameters, wider entry and circulating lanes, higher approach speeds, and a greater number of approach lanes (Vinayaraj and Perumal, 2023). Simply put, roundabouts that allow higher vehicle speeds or more complex movements tend to see elevated crash frequencies, underscoring the importance of speed control and clear design. Roundabout safety outcomes can vary by region and traffic context. In countries with disciplined driving and good signage, roundabouts consistently show safety benefits (Maji and Ghosh, 2025). By contrast, in some developing countries, roundabouts have not delivered the same level of safety improvement. India’s national data in 2022 recorded over 11,000 crashes and 4,000 fatalities at roundabouts, reflecting that roundabout crashes can still be a serious concern in mixed-traffic environments (Maji and Ghosh, 2025). Contributing factors in such environments include a lack of lane discipline, poor yielding compliance, and inadequate traffic control. Researchers have pointed out that without proper design and implementation, roundabouts can even become “collision hot spots” rather than remedies (Vinayaraj and Perumal, 2023). This insight has driven recent efforts to develop Safety Performance Functions (SPFs) and Crash Modification Factors (CMFs) connected to roundabouts. For instance, a study developed SPFs for 21 urban roundabouts in India using five years of crash data (Vinayaraj and Perumal, 2023). Their models quantified how crash frequency rises with increasing two-wheeler traffic share, higher traffic volumes, and specific geometric features. Such models enable engineers to predict crashes at a proposed roundabout and adjust designs accordingly. Similarly, a U.S. study derived CMFs for mini-roundabouts: converting a two-way stop to a mini-roundabout was associated with ~39% reduction in multi-vehicle crashes, demonstrating a clear safety benefit (Avelar et al., 2023). These quantitative tools are increasingly important for evidence-based policy, allowing decision-makers to estimate the safety impact of installing roundabouts or modifying their design. The literature search strongly indicates that roundabouts improve overall safety by reducing severe injuries, though they may increase minor collisions in some cases. The magnitude of safety benefit depends on design details (entries, lanes, speeds), driver behavior, and context. Crashes that remain at roundabouts are often related to entry conflicts or driver confusion on multi-lane layouts. Addressing these issues through design (adequate deflection, signage, and lane markings) is a recurring recommendation to maximize roundabout safety performance (Maji and Ghosh, 2025).

## Driver Behavior at Roundabouts

Driver behavior is central to roundabout operations and safety, since roundabouts rely on yielding and gap acceptance rather than signal control. Numerous studies have observed how drivers adjust (or fail to adjust) when navigating roundabouts. One consistent finding is that roundabout geometry influences driver speeds and path choices. In a Michigan field study, drivers approached faster and braked later at roundabouts with larger radii or multiple lanes, whereas tighter single-lane roundabouts induced more cautious speeds (Savolainen et al., 2023). This suggested well-designed geometric curvature is critical for self-enforcing slow speeds. Once inside the roundabout, most drivers choose smooth paths, but some may cut across lanes if pavement markings are unclear. Proper channelization and lane markings can therefore reduce erratic maneuvers. Gap acceptance behavior, the judgment of when to enter, varies among drivers and by roundabout type. A study found that at multi-lane roundabouts, drivers tended to accept smaller gaps in circulating traffic compared to single-lane roundabouts (Savolainen et al., 2023). On three-legged (T-intersection) roundabouts, drivers also accepted shorter gaps on average than at four-legged ones, perhaps because traffic from one approach is absent (Savolainen et al., 2023). In general, drivers will “push” the yield requirement more aggressively in settings where they perceive lower risk or see others doing the same. A potential downside is that very short accepted gaps can lead to more entering-circulating conflicts and minor crashes. Some studies have measured critical gap times at roundabouts ranging roughly 2.5–5 seconds, depending on local driving culture and roundabout size (Khekare et al., 2022). When actual headways in the circle drop below these critical gaps during heavy traffic, entry queues grow quickly as drivers must wait for a larger gap (Long et al., 2023). Gap acceptance parameters are thus key inputs to roundabout capacity models (discussed further below) and are sometimes calibrated from local driver behavior observations. Yield compliance and priority understanding are another behavioral aspect. Ideally, entering vehicles yield to all circulating vehicles (and to pedestrians at crosswalks). However, real-world compliance is imperfect. Field observations in Michigan showed that yield compliance to circulating traffic was lowest at roundabouts located at freeway interchange ramps, where perhaps drivers are more aggressive or less accustomed to the roundabout (Savolainen et al., 2023). Yielding to pedestrians at crosswalks was also notably poor at certain sites, multi-lane roundabouts on high-speed roads had some of the lowest pedestrian yield rates (Savolainen et al., 2023). This indicates drivers often prioritize vehicle flow over pedestrian right-of-way unless the roundabout design strongly cues them (e.g. raised crosswalks or flashing beacons). The presence of slip lanes (free-right turn bypasses) further complicates yielding; drivers in slip lanes may ignore crosswalks due to the free-flow design (Novat et al., 2024). Overall, driver non-compliance, whether failing to yield or improper lane usage, contributes to many of the conflicts seen at roundabouts. Education and enforcement can help, but researchers stress that engineering for clarity is crucial (e.g. well-marked yield lines, “YIELD” signage, and geometric features that naturally slow drivers). Driver behavior at roundabouts is also influenced by familiarity and demographics. Studies in Europe have noted that older drivers tend to be more cautious, sometimes causing unusually long waiting times at entries (delaying traffic flow) but also potentially reducing crashes (Maji and Ghosh, 2025). In contrast, younger or aggressive drivers might force their way in, risking conflicts. In developing regions with non-lane-based traffic, drivers often treat roundabouts in a less regulated manner, e.g. forming multiple informal lanes and inching forward to merge wherever possible (Vinayaraj and Perumal, 2023). Such heterogeneity makes predicting driver behavior challenging. One 2024 study tackled this by calibrating microscopic car-following models specifically for roundabout maneuvers (Choi et al., 2024). By using naturalistic trajectory data, the researchers showed that accounting for the unique entry, circulation, and exit behaviors at roundabouts significantly improved the realism of driver behavior simulation. For example, the calibrated model captured instances of very short headways (under 1 second time-to-collision) during circulation, reflecting how some drivers closely “tailgate” through the roundabout. The implication is that standard models (developed for straight roads) might not represent roundabout driving well unless they include these behavioral nuances. Another emerging angle is how vehicle technology might alter driver behavior in roundabouts. Advanced driver-assistance systems (ADAS) like collision warnings or automatic braking could, in theory, improve yielding and gap choices. On the other hand, partial automation might distract drivers from paying attention during the roundabout approach, which is risky. A study found that drivers with certain advanced vehicle technologies and lower risk perception were more prone to distraction, though this study was not roundabout-specific (Schneider et al., 2024). More research is needed on how human drivers interact with partially automated systems at roundabouts, for instance, whether adaptive cruise control handles the speed reduction appropriately, and if drivers trust it. Driver behavior studies confirm that human factors are pivotal in roundabout performance. Good roundabout design should accommodate typical driver tendencies (e.g. provide adequate sight lines and deflection to induce slow entry speeds, use clear markings to guide lane choice). Education on how to navigate roundabouts (especially multi-lane ones) can also mitigate confusion. As one review noted, roundabouts function best in environments with a strong safety culture – when drivers respect yield rules and lane discipline, the roundabout operates smoothly and safely (Maji and Ghosh, 2025).

## Roundabout Capacity and Operational Performance

While safety is a prime motivation for roundabouts, their traffic performance (capacity and delay) is another critical aspect. A roundabout’s capacity is typically defined as the maximum entry flow (vehicles per hour) an approach can handle, given the circulating traffic that conflicts with it. Roundabouts generally perform lower delays than signalized intersections under low-to-moderate traffic demand, because vehicles do not sit idle at red lights, and they can enter whenever gaps are available. However, as traffic volumes approach the roundabout’s capacity, delays and queues can grow rapidly. Researchers have long recognized that roundabouts are not a cure-all for congestion: for very heavy volumes or unbalanced flows, signalization might still be warranted (Al-Madani, 2022). A rule-of-thumb cited by FHWA is that a single-lane roundabout can comfortably handle intersection volumes up to roughly 20,000–25,000 vehicles per day; beyond that, multi-lane designs or alternative controls are needed (Long et al., 2023). Estimating roundabout capacity has been a major theme in the literature. Two broad modeling approaches exist: (1) Empirical regression models based on field data, such as the original British (UK TRL) formulas or the French and German models, and (2) Analytical gap-acceptance models, such as those adopted in the United States (Highway Capacity Manual (HCM)) and Australia (SIDRA software). Empirical models fit a curve to observed entry flow vs. circulating flow relationships, often yielding a simple equation for capacity. Gap-acceptance models, on the other hand, derive capacity from driver behavioral parameters (critical gap and follow-up headway) under certain assumptions. Studies have found that these models can produce quite different capacity estimates for the same roundabout. In a study, the researchers collected data from 13 saturated roundabouts in Bahrain and formulated new capacity models for dual-lane and triple-lane roundabouts (Al-Madani, 2022). The results showed that existing models (UK, SIDRA, etc.) differed substantially from each other and from the locally developed model, especially at high circulating flows. This underscores that driver population and local geometrics affect capacity, e.g. European drivers might merge differently than Middle Eastern drivers, leading to different regression curves. Their models highlighted important predictors like the number of entry lanes (positive effect on capacity), wider entries (positive up to a point), larger central islands (negative effect, likely by forcing slower speeds), and high exit flows (which can slightly reduce entry capacity on the same approach). Notably, the Bahrain study found a quadratic form fit best for two-lane entries (capacity initially rises then plateaus with increasing circulating flow), whereas an exponential form suited three-lane entries. In the United States, the HCM uses a gap-acceptance model for roundabouts. It assumes an exponential distribution of headways in the circulating stream and applies a fixed critical gap and follow-up time (adjusted for geometry). While convenient, this method may not hold in all conditions, especially in heterogeneous traffic with poor lane discipline. For example, in India’s mixed traffic, vehicles do not adhere to lanes, so the concept of a single “major stream” is blurred (Munshi and Patnaik, 2023). More recently, researchers have explored artificial intelligence and computer vision to enhance capacity analysis. A study developed a computer-vision-based system using aerial drone video to measure gap acceptance parameters at a multi-lane roundabout (Khekare et al., 2022). They proposed a one-step “gap-based” method to automatically detect accepted and rejected gaps and follow-up headways, using deep learning to track vehicles in video. The system computed the mean critical headway via maximum likelihood and compared results to traditional manual methods. It showed very close agreement with manually measured headways, but with far greater efficiency by processing a wider field of view. Another study used a hybrid AI algorithm, a Self-Adaptive Genetic Algorithm with simulated annealing, to fit a capacity model for Indian roundabouts (Munshi and Patnaik, 2023). Their AI-driven model achieved an excellent fit (R² ~0.95) to field data, outperforming a conventional regression model, and was deemed more suitable for field application under heterogeneous conditions. These advancements hint that future capacity models may rely less on hand-tuned formulas and more on machine learning trained on big datasets of roundabout traffic. In practice, when a roundabout nears its capacity, options to mitigate congestion include geometric modifications or metering. One common strategy is adding entry metering signals that briefly stop incoming vehicles to generate gaps in the circulating flow, thus allowing queued vehicles from other approaches to enter. This has been used in countries like Australia and the US on oversaturated multi-lane roundabouts. However, metering typically helps only within a narrow range of traffic conditions (peak periods) and if not well tuned, it can introduce delay without much benefit (Long et al., 2023). Another approach is full signalization of a roundabout (adding traffic lights on all entries). This essentially converts it into a circular signalized intersection. Studies (and practice in parts of Europe) have found that signalizing a busy roundabout can increase throughput, but it sacrifices some of the safety and environmental advantages, and incurs high cost (Long et al., 2023). Because of these trade-offs, researchers are exploring whether Connected and Automated Vehicles (CAVs) could boost roundabout capacity without physical changes (this is discussed more in the next section). The idea is that if vehicles can cooperatively adjust speeds and merge with minimal gaps, the roundabout can handle flow rates beyond what human reaction times allow. Simulation studies have indeed projected capacity gains with higher proportions of automated vehicles. For instance, one study adjusted the HCM capacity formula by introducing “automation adjustment factors” and found that 100% automated traffic could significantly raise entry capacities, especially for single-lane roundabouts (Campi et al., 2024). The benefit was less pronounced for multi-lane roundabouts, since even with automation there is more turbulence in multi-lane operations. Operational performance includes delay and queue length in addition to capacity. When volumes are below capacity, roundabouts often exhibit very low average delays (a few seconds) because most vehicles do not stop, they slow, find a gap, and proceed. A study measured improved Level of Service and reduced vehicle delay after intersections were converted to roundabouts in Michigan. They also documented fuel savings, attributing it to less idling time. At one site, emissions and fuel consumption dropped measurably post-conversion, highlighting roundabouts’ environmental benefits under free-flow conditions (Savolainen et al., 2023). However, as demand increases, delays are nonlinear: once an entry flow is at or above its capacity curve, queues accumulate and delay skyrockets. A study observed clear signs of capacity reduction and queuing at high demand levels, consistent with earlier findings that roundabout performance deteriorates sharply when oversaturated (Al-Madani, 2022). A modern innovation to address heavy flows is the turbo roundabout design (spiral lane configuration preventing lane changes). A case study from a rural intersection in California that was converted from a signal to a turbo roundabout showed promising results. The turbo roundabout reduced average queue lengths and also lowered conflict frequencies compared to the previous signal control, indicating both smoother and safer traffic (Shetty et al., 2025). Turbo roundabouts achieve higher capacity by guiding vehicles into dedicated lanes for each exit, reducing weaving conflicts. The literature suggested they are effective when traffic volumes are high but balanced among movements, though their performance can suffer if one direction dominates (Maji and Ghosh, 2025). Roundabouts generally improve operational efficiency in the right conditions, but careful capacity analysis is necessary to ensure a roundabout will function well. Current research continues to refine capacity models, taking into account local driver behavior and leveraging new data collection methods. The consensus is that geometric design and traffic composition heavily influence capacity, there is no universal capacity value; each site must be evaluated with appropriate models. For very high traffic volumes, either enhanced designs (e.g. multi-lane, turbo, metered roundabouts) or alternative control may be needed to prevent excessive delays.

## Connected and Automated Vehicles at Roundabouts

The rise of CAVs introduces new questions and opportunities for roundabout management. Roundabouts pose a notoriously complex scenario for autonomous driving; there are multiple moving agents, no traffic signals to dictate right-of-way, and heavy reliance on implicit communication (eye contact, yielding courtesy) among drivers. A study noted that roundabouts represent a highly interactive environment that challenges current AV decision-making algorithms (Jiang et al., 2024). An autonomous vehicle must detect and predict the intentions of approaching and circulating vehicles, select an appropriate gap to enter, and navigate the circular roadway all while adhering to right-of-way rules. Human drivers sometimes negotiate entry with subtle cues (e.g. inching forward to signal intent); programming an AV to handle this gracefully is nontrivial. Thus, early AV deployments have treated roundabouts as difficult scenarios, often proceeding overly cautiously or, conversely, hesitating too long and impeding traffic (Masi et al., 2022). To address these challenges, researchers have proposed various roundabout control strategies for CAVs. A study developed an optimal roundabout controller under a connected vehicle framework (Long et al., 2023). The controller uses trajectory optimization and a cooperative algorithm to sequence vehicles’ entry. In simulation, their system improved roundabout throughput by ~14% and reduced average delays by 66–94% compared to normal operation. Impressively, the algorithm computed control decisions in under 0.02 seconds, indicating feasibility for real-time use. The key idea is that connected vehicles approaching the roundabout can adjust their speeds to create just-enough gaps for each other, effectively “platooning” through the intersection without stopping. This eliminated much of the stop-and-go delay and can nearly double the entry capacity at high CAV penetration rates (Campi et al., 2024). Game theory and reservation-based algorithms have also been studied for managing AV passage at roundabouts (Long et al., 2023). In a reservation scheme, an AV would “reserve” a timeslot to enter the roundabout, and all vehicles would adjust accordingly to honor these slots. Such methods work well in simulations with either fully automated traffic or only a handful of vehicles, but they struggle to scale when many human-driven vehicles are present. The consensus from simulation research is that to truly unlock capacity gains, a high proportion of vehicles need to be cooperative and automated. For example, one study found negligible capacity improvement at 25% CAV penetration, but substantial gains once 75% or more of vehicles were automated (Campi et al., 2024). Furthermore, cooperative systems, where vehicles not only are automated but actively communicate and collaborate, appear far more effective than individual AVs acting alone (Campi et al., 2024). Another line of inquiry focuses on improving how a single autonomous vehicle behaves in a roundabout with mixed traffic. A study introduced a novel concept of “virtual occupancy intervals” to help an AV safely cross a multi-lane roundabout (Masi et al., 2022). Their method uses a high-definition map of the roundabout and creates virtual “instances” of other road users to predict future positions. In essence, the autonomous vehicle’s system projects ahead in time who will occupy what part of the roundabout and finds a safe gap for itself. Importantly, it accounts for uncertainties in other vehicles’ speeds and positions by widening the occupied intervals appropriately. The AV then only proceeds when it foresees a clear interval in all relevant conflict zones, ensuring no priority rules are broken. This demonstrates that predictive modeling and cautious gap selection can allow an AV to handle roundabouts even if other vehicles are human-driven (without any external coordination). However, one caveat is that the AV might be more conservative than human drivers, which is safe, but could reduce capacity if AVs always wait for larger gaps than a human would. Over time, if AVs become common, their uniform and predictable behavior could actually smooth traffic flow, but during a mixed period, some inefficiency is likely. Microscopic traffic simulations have been a vital tool to study CAV impacts at roundabouts. In a recent review, a study systematically reviewed simulation studies combining CAVs and roundabouts. They observed that many researchers integrate custom car-following models for AVs into simulators like VISSIM or AIMSUM to test scenarios. Common assumptions are that AVs can follow more closely (shorter headways) and react faster than humans, which tends to increase capacity. Communication (such as Vehicle-to-Everything (V2X)) allows vehicles to platoon or organize their merging order better. Path planning algorithms for roundabouts have also been explored, for example, guiding AVs into “virtual lanes” or specific trajectories that minimize conflict with others (Campi et al., 2024). Despite numerous simulations, the study point out a gap between simulation and reality: no large-scale field deployment has yet confirmed the predicted improvements. There are also reasonable doubts about human drivers’ interactions with CAVs, for instance, will human drivers yield more to AVs or try to take advantage of their caution? Some studies assumed human drivers behave the same regardless, which may not hold true. It appears that cooperative automation (where vehicles actively coordinate merging) is key to maximizing benefits; simple automation alone (each car doing its own automation) yields smaller gains.

## Pedestrian and Cyclist Safety at Roundabouts

One critique of roundabouts has been their mixed effects on vulnerable road users. The safety benefits of roundabouts are very clear for vehicle occupants, due to lower speeds and fewer head-on or right-angle collisions, but pedestrians and bicyclists sometimes fare worse at roundabouts compared to signalized intersections. Modern roundabouts require pedestrians to cross shorter distances (one direction of traffic at a time, using splitter island refuges), which is positive. However, pedestrians must judge gaps in traffic on their own, since vehicles rarely stop completely. This can be difficult for those with limited sight or mobility. Studies show that multi-lane roundabouts are especially challenging for pedestrians: even if one car yields, a second car in the adjacent lane might not, leading to multi-threat situations in the crosswalk. Furthermore, roundabouts that incorporate slip lanes (free right-turn bypass lanes) allow turning vehicles to bypass the circle at relatively higher speed. A study examined the impact of these slip lanes on pedestrian safety under both human-driven and autonomous vehicle scenarios (Novat et al., 2024). Using simulation calibrated with real trajectory data, they found that vehicles in slip lanes maintained significantly higher speeds than those in the normal approach lanes, which increased the risk at pedestrian crossing points. In fact, slip lanes altered merging behavior such that drivers focused on merging with traffic rather than looking for pedestrians, thus elevating conflict probability. This study quantified pedestrian “conflicts” (using surrogate safety measures) and found that introducing 75% autonomous vehicles to the mix reduced pedestrian conflict rates by about one-third. The AVs in the simulation were more likely to yield and maintained more consistent speeds, which improved safety for pedestrians. Nonetheless, the mere presence of slip lanes was still a net risk factor. An important outcome from this study was design guidance for slip lanes based on pedestrian volume. In areas with very low pedestrian traffic, a free-flow slip lane may be acceptable to minimize vehicle delay (since few pedestrians will be exposed). In medium pedestrian settings, they recommended using yield-controlled slip lanes, essentially treating the slip lane like a separate channelized turn with a yield sign at the crosswalk, to balance flow and safety. And in areas with high pedestrian volumes, the advice was to avoid slip lanes entirely, favoring a traditional roundabout entry which inherently reduces vehicle speed and conflict points. These suggestions align with other research, noting that roundabout design must also be focused on pedestrian safety, high-speed geometry should be avoided where pedestrians are expected, and visibility of crosswalks should be maximized. Early evidence suggests these enhancements can improve yielding compliance, mitigating the roundabout’s lack of a red-light stop for cars. Cyclists face a somewhat different set of challenges. At lower traffic volumes, confident cyclists often “take the lane” and circulate with vehicles through single-lane roundabouts without much trouble. But at busy or multi-lane roundabouts, mixing with faster vehicles can be perilous for cyclists. There is also the subjective safety (comfort) aspect, many cyclists do not feel safe sharing a roundabout with cars. A systematic review compiled findings from 49 studies on bicycle safety at roundabouts (Singleton et al., 2024). A recurring theme was that roundabouts with multiple lanes and higher speeds correlate with more cyclist crashes, especially involving motorists failing to yield to bicycles within the circle. Some European countries address this by providing separate cycle paths or grade-separated crossings for bikes. A study conducted an extensive survey of over 600 U.S. bicyclists to gauge their preferences for roundabout design (Singleton et al., 2024). The respondents overwhelmingly preferred roundabouts with cyclist-friendly features: smaller diameter (which implies lower speeds), single-lane entries/exits, low traffic volume, and critically, separated bicycle lanes or tracks. The survey included a discrete choice experiment with visual simulations of various roundabout designs. The most comfortable designs for cyclists were those that kept bikes out of the circulating stream, for example, a “protected roundabout” design where bike lanes diverge from the roadway and cross at dedicated bike crossings. Women and less confident riders (“interested but concerned” group) in particular had strong preferences for physical separation from traffic. Based on these findings, the authors recommend updating U.S. design guidelines to incorporate protected bicycle infrastructure at roundabouts, especially in communities aiming to encourage cycling. Alternatively, where space is limited, it might mean providing an off-road alternative path for cyclists who choose not to merge with traffic. It’s worth noting that roundabout entries tend to be safer for pedestrians than traditional intersections in one aspect: the crossing distance is shorter and one-way. A study noted that roundabouts reduce pedestrian crashes to some extent compared to two-way stop or signal control (Novat et al., 2024). However, the absence of a complete stop control means visually impaired pedestrians find roundabouts very difficult; they rely on audio cues of vehicles stopping, which rarely happen at a roundabout. This has led to research into pedestrian signals or beacons at roundabouts. A few modern roundabouts in the U.S. have been retrofitted with pedestrian hybrid beacons (flashing signals) at crosswalks to help those with disabilities. While not widespread, such treatments aim to make roundabouts more equitable for all users. Pedestrian and bicyclist safety at roundabouts requires special consideration. Design trade-offs often arise: for example, adding a slip lane can improve vehicle capacity but at a cost to pedestrian safety. The literature suggests the need to conduct more extensive research on roundabout design to make it safer for walkers, cyclists, and VRUs.

## Modeling Approaches and Assessment Techniques

Researchers employ a variety of modeling approaches to study roundabouts, reflecting the multifaceted nature of roundabout performance. Traditional methods include statistical crash modeling (for safety) and analytical capacity formulas (for operations), as discussed earlier. In recent years, there has been a trend toward integrated modeling, using simulation, conflict analysis, and empirical data together to get a fuller picture of roundabout behavior. One prominent technique in safety research is the use of surrogate safety measures and traffic conflict analysis. Because actual crash data can be sparse or unavailable (especially for new roundabouts or in proactive safety planning), many studies have looked at near-misses as indicators of safety. For example, a study developed a probabilistic framework to detect and quantify near-crash events in a roundabout from video trajectory data (Trullos et al., 2023). Their method defined a continuous measure of “criticality” based on two dimensions: proximity (distance between vehicles) and severity (speed differential). By analyzing real traffic video from a roundabout, they computed a criticality score for each interaction and could flag the most risky encounters. This kind of metric is valuable for assessing how design or traffic changes affect safety without waiting for actual crashes to occur. It also has relevance for automated driving development, helping identify scenarios that are challenging (high criticality) so that autonomous driving functions can be tested against them. Similarly, many studies use simulation software coupled with a conflict detection module (such as the FHWA’s Surrogate Safety Assessment Model (SSAM)). An example is the turbo roundabout study (Shetty et al., 2025), where researchers ran microsimulation models of both a signalized intersection and a turbo roundabout, then used SSAM to compare conflict frequencies and types. The turbo roundabout showed far fewer severe conflicts (e.g. no crossing conflicts at right angles, which a signalized intersection had). This aligns with known safety benefits and provides a microsimulation-based validation that the design is safer, even before years of crash data are collected. Microsimulation modeling in general is a cornerstone for roundabout analysis. Tools like VISSIM, AIMSUN, and SIDRA allow detailed replication of vehicle movements through roundabouts, including car-following, lane-changing, and gap acceptance processes. However, as noted, off-the-shelf models must often be calibrated to local conditions. A study showed that calibrating a microsimulation’s car-following model (in their case, the Krauss model) specifically for roundabout maneuver heterogeneity improved the accuracy of simulated speed and gap distributions (Choi et al., 2024). They validated their calibrated simulation by comparing the distribution of time-to-collision values from the simulation to those observed in real trajectory data, finding a close match. This kind of validation is crucial to build confidence in simulation-based findings. Another modeling challenge is representing unconventional roundabout designs (like turbo roundabouts or those with metering). Simulation packages are increasingly incorporating such features, but sometimes researchers develop custom code for particular algorithms (e.g. Long et al.’s CAV controller required a bespoke simulation environment to test). On the capacity side, modeling approaches include not just static formulas but also dynamic models. Roundabouts have been integrated into network traffic models and assignment simulations to see how they influence broader traffic patterns. Because roundabouts can act as bottlenecks if oversaturated, accurate modeling of their delay is important for network analysis. Some studies (Campi et al., 2024) have looked at macroscopic simulation combining driving simulators (for human behavior) with microscopic traffic flow models to better capture phenomena like reaction times and compliance. This hybrid approach is advanced and addresses the human-in-the-loop aspect that pure traffic flow models might miss. Data collection advancements underpin many of these modeling improvements. Ten or twenty years ago, studying roundabout conflicts or driver behavior relied on labor-intensive video reduction or in-person observation. Now, computer vision and vehicle trajectory datasets provide rich, precise data for modeling (Masi et al., 2022). Machine learning techniques are being used to identify patterns in this data, such as typical yielding behavior or conflict precursors. A study emphasized that combining naturalistic driving data with machine learning could produce more human-like driver models for AVs, essentially training an algorithm on how people actually behave in roundabouts. This would help autonomous systems to anticipate human moves more accurately (Jiang et al., 2024). Safety assessment is no longer just retrospective crash analysis; it includes proactive conflict modeling and simulation. Operational analysis is not just a simple capacity equation; it involves microsimulation with calibrated human factors and even network-level considerations. The overarching goal of these modeling efforts is to capture the real-world complexity of roundabouts, from human behavior to vehicle dynamics, so that engineers and planners can make informed decisions. Each approach has its strengths: empirical models distill real-world trends, simulation allows experimentation with scenarios, and analytical models offer clarity of cause-effect relationships.

## Applications of Cluster Correspondence Analysis in Traffic Safety Studies

Cluster Correspondence Analysis (CCA) and Multiple Correspondence Analysis (MCA) have been used in traffic safety studies previously. The authors and their colleagues have extensively applied CCA in past studies to uncover patterns in crash data. In the domain of motorcycle safety, for example, a study applied a correspondence analysis approach to seven years of motorcycle crash records from Louisiana and identified multiple clusters of contributing factors (Das et al., 2022a). Several other studies have also investigated motorcycle crashes using CCA (Dzinyela et al., 2025). Das et al. (2023) also investigated moped and seated motor scooter involved fatal crashes using CCA to find out the significant factors influencing the injury severities. In another study, the authors used MCA to examine factors linked to fatal and severe pedestrian crashes under dark, no-streetlight conditions in Louisiana (Hossain et al., 2023). They analyzed 722 cases to identify high-risk patterns involving driver, pedestrian, and roadway characteristics. The clusters revealed distinct crash scenarios, such as impaired riders crashing at night on unlit roads, collisions on rural two-lane highways with no access control, and rear-end crashes involving traffic violations in mixed localities. CCA has similarly been used to study pedestrian-related crashes. A study analyzed 2,201 pedestrian-involved hit-and-run crashes and uncovered six distinct clusters of crash characteristics (Rahman et al., 2024). The two largest clusters (accounting for about 66% of cases) involved crashes on city streets at night and in the afternoon, whereas smaller clusters captured more severe patterns on higher-speed roadways. Roadside barrier-related crashes have also been examined by the authors using CCA. Chakraborty et al. (2024) investigated over 63,000 crashes involving roadside or median barriers in Texas, identifying six clusters of associated factors. This analysis revealed that high-speed barrier crashes were frequently linked to dry road conditions and clear weather, while crashes on lower-speed roads were often associated with driver distraction and lack of traffic control devices. In another study, Das et al. (2022b) used CCA to explore traffic crashes attributed to sun glare, which led to six meaningful clusters of crash patterns. Each cluster corresponded to a unique scenario under sun glare conditions, including, for example, intersection crashes in mixed residential–commercial areas, single-vehicle crashes on residential two-lane roads, and curve-related crashes in open rural localities. Beyond actual crashes, the authors have extended pattern-mining techniques to near-crash events. Kong et al. (2022) examined naturalistic driving data to identify recurring circumstances in near-crash incidents, situations where a collision was narrowly avoided. Their pattern mining (through association rules) revealed notable differences between near-crashes with driver distraction and those without distraction, highlighting how secondary tasks (like cellphone use) often precipitated near-miss events. Several of these studies additionally leveraged explainable machine-learning tools to enrich the interpretation of results. In one pedestrian crash analysis. Chakraborty et al. (2025) investigated child bicyclists’ crashes and identified six clusters. Later, the authors explained the clusters using SHapley Additive exPlanations (SHAP) to highlight the important features that are leading to child bicyclists’ crashes.

## Policy and Implementation Implications

The accumulated research on roundabouts carries several policy-relevant implications. First and foremost, the safety evidence supports policies that promote roundabout installation in place of conventional intersections, particularly where severe crashes are a problem. Many transportation agencies have indeed adopted such policies: for example, FHWA encourages consideration of roundabouts as a safety improvement and documents their crash reductions and benefit-cost ratios. A FHWA study on mini-roundabouts found benefit-cost ratios around 2.9 when considering safety benefits alone, and much higher (up to 13.4) if operational benefits are included (Avelar et al., 2023). These economic analyses give policymakers confidence that investing in roundabouts can yield high returns in terms of lives saved and injuries prevented. The Michigan Department of Transportation’s 2023 update on roundabout performance likewise concluded that roundabout conversions generally reduced serious crash rates and improved traffic flow (Savolainen et al., 2023). That report even developed guidelines on where roundabouts are most warranted (e.g. intersections with high angle-crash histories or excessive delay), helping inform project selection. However, research also urges caution that roundabouts must be implemented correctly to achieve their potential. A poorly designed or misapplied roundabout could fail to yield safety benefits or even make matters worse. Thus, design policy and standards play a critical role. A study documented cases of multi-lane roundabouts in the U.S. that had confusing or insufficient lane markings, leading to driver errors and higher crash frequencies (Johnson, 2019). Once those roundabouts were re-marked and signed properly, crashes (especially property-damage-only crashes) dropped. This highlights that design standards need to stress clarity: policies might require, for instance, that any multi-lane roundabout include diagrammatic guide signs, lane-use arrow markings on approaches, and possibly lane designation signage to minimize confusion. Several studies also suggested updating design guides to incorporate safety performance insights (Maji and Ghosh, 2025; Vinayaraj and Perumal, 2023). For example, if research shows that very large roundabouts tend to encourage speeding and result in more crashes, guidelines could set an upper limit on inscribed diameter for urban installations or require additional calming measures for large-radius roundabouts. As discussed, pedestrians and bicyclists have unique needs at roundabouts. Policymakers and design guideline committees are increasingly aware of this. A study recommended to incorporate protected bike lanes in U.S. roundabout designs is a call-to-action for bodies like AASHTO and state DOTs to modify their standard plans (Singleton et al., 2024). Already, some U.S. cities (e.g. in Colorado and Massachusetts) have constructed roundabouts with set-back cycle tracks or multi-use paths to separate cyclists, often citing European designs as inspiration. If design policies evolve to mandate or at least encourage such features in areas with high cycling demand, it could address one of the main criticisms of roundabouts. Based on the future recommendations, policies may need to adapt to technological integration. If connected vehicle infrastructure (like Vehicle-to-Infrastructure (V2I) communication) is to be leveraged at roundabouts, transport agencies might consider deploying roadside units at complex roundabouts to assist in CAV coordination. A review implied that standardization of communication protocols and algorithms will be important; thus, governmental bodies might spearhead pilot programs to test connected roundabout systems (Campi et al., 2024). Roundabouts are generally a sound policy choice for safer and efficient intersections, but they must be planned and designed with careful attention to detail. Policymakers should view roundabouts not as a simple off-the-shelf solution, but as a part of a safe systems approach that requires context-specific adaptation. Therefore, there is a need to explore the roundabout safety more comprehensively. Table 2.1 summarizes the summary of some studies that have been reviewed in this literature.

Table 2.1 Summary Table of Key Roundabout Studies

|  |  |  |  |
| --- | --- | --- | --- |
| **Study (Author, Year)** | **Location** | **Methodology** | **Key Findings** |
| (Maji and Ghosh, 2025) | Global (Systematic Review) | Systematic literature review of 85 studies | Roundabouts generally improved safety, but research gaps noted especially in developing countries. Highlighted the role of design, driver behavior, and data collection methods in roundabout safety. Emphasized proper signage/markings to reduce driver confusion. |
| (Savolainen et al., 2023) | Michigan, USA | Field data analysis (before-after, Empirical Bayes, cross-sectional) | Converting intersections to roundabouts increased total crashes but significantly reduced fatal/injury crashes. Geometry affected speeds (tighter designs slowed drivers). Developed SPFs by lanes/legs and found roundabouts yield net safety and environmental benefits. |
| (Avelar et al., 2023) | WA/MI/MD, USA | Before-after study with comparison sites; Bayesian analysis | Installation of mini-roundabouts at stop-controlled intersections led to ~31–42% fewer crashes (various types). Found a 39% reduction in multi-vehicle crashes (statistically significant). Benefit–cost ratios ~2.9 solely for safety (higher when including operational gains), supporting mini-roundabouts as cost-effective safety measures. |
| (Vinayaraj and Perumal, 2023) | India (21 urban roundabouts) | Crash data modeling (5-year crash history); Negative binomial SPFs and CMFs | Developed SPFs for roundabouts in heterogeneous, non-lane-based traffic. Identified key risk factors: high two-wheeler share, larger central islands, more lanes, higher speed limits, etc. Provided CMFs for various geometric parameters and suggested updates to design guidelines to incorporate these safety considerations. |
| (Novat et al., 2024) | Simulation (USA scenario) | Simulation with calibrated trajectory data; Surrogate safety (conflict) analysis | Studied slip lanes and AV presence on pedestrian safety at roundabouts. Slip lanes increased vehicle speeds and pedestrian conflict risk. With 75% AVs, pedestrian conflicts dropped ~35%, indicating AVs improve yielding. Recommended: use free-flow slip lanes only in low-ped areas, yield-controlled slips in medium-ped areas, and no slip lanes in high-ped areas. Emphasized adjusting slip lane geometry and crosswalk placement to enhance safety. |
| (Long et al., 2023) | Simulation (CAV scenario) | Developed and simulated CAV roundabout controller; performance comparison | Proposed a cooperative roundabout control algorithm for connected automated vehicles. Improved throughput by ~14% and cut delays by 66–94% versus conventional operation. Demonstrated real-time feasibility (control decisions <0.02s). Highlighted that CAV technology can overcome roundabout capacity limits without physical signals, provided high market penetration of CAVs. |
| (Campi et al., 2024) | Global (Review & Simulations) | Literature review of CAV-roundabout studies; analysis of simulation approaches | Summarized research on CAVs in roundabouts. Concluded that cooperative CAV strategies (platooning, communication) could greatly increase capacity and safety, especially at high CAV penetration. Noted a gap between simulation results and real-world uncertainty. Emphasized integrating microscopic traffic simulation with driving simulators to study human-CAV interactions. |
| (Khekare et al., 2022) | Cincinnati, USA (case study) | Computer vision and deep learning on UAV video; one-step gap acceptance analysis | Used drone video and AI to automatically measure roundabout capacity parameters (critical and follow-up headways) at a multi-lane roundabout. Achieved accurate detection of accepted/rejected gaps, matching manual methods. Demonstrated a tech-driven approach to evaluate roundabout capacity more efficiently, supporting the use of AI and computer vision in traffic data collection. |
| (Al-Madani, 2022) | Bahrain | Empirical capacity study (field measurements at 13 roundabouts); statistical modeling | Developed new entry capacity models for multi-lane roundabouts. Found quadratic capacity-flow relationship for two-lane entries and exponential for three-lane entries. Significant predictors included circulating flow, exiting flow, number of entry/circulating lanes, and geometric widths. The local model differed markedly from UK, French, and SIDRA models, indicating regional driver behavior effects. Highlighted large differences between international models and need for local calibration. |
| (Munshi and Patnaik, 2023) | India | Capacity modeling under heterogeneous traffic; Compared regression vs. AI (genetic algorithm) models | Developed two models for roundabout entry capacity in non-lane-based conditions: a weighted regression and a SASEGASA genetic algorithm model. The AI-based model had very high fit (R² ~0.95) and was deemed the best for predicting capacity. Concluded that AI techniques can better capture complex interactions in heterogeneous traffic and recommended using such models in practice. |
| (Singleton et al., 2024) | USA (nationwide survey) | Systematic lit review on bicycle safety; Online stated-preference survey of 613 cyclists | Investigated bicyclist comfort and preference at roundabouts. Cyclists preferred designs with smaller central islands, single-lane approaches, lower traffic speeds/volumes, and especially separated bike lanes/tracks. Women and cautious cyclists had a strong preference for protected cycling infrastructure. Recommended U.S. design guidelines adopt “protected roundabout” designs (with separated cycle paths) to improve cyclist safety and comfort, thereby encouraging cycling. |
| (Trullos et al., 2023) | Brunswick & Berlin, Germany | Video-based trajectory analysis; Developed criticality metric (proximity vs. delta-V); Probabilistic near-crash detection | Proposed a two-dimensional risk metric to identify near-crashes at a roundabout from trajectory data. Combined distance and speed difference to quantify event severity. Applied to real roundabout data to detect and rank critical interactions. Showed correlation between the new metric and expert risk judgments, and demonstrated its use in gathering meaningful safety data (near-misses) for Vision Zero goals. Highlighted the value of surrogate safety measures for understanding and improving roundabout safety, as well as for testing automated driving systems in challenging scenarios. |

# STUDY DESIGN

**III.**

This section includes the explanation of the results from the analyses conducted in this study. Figure 3.1 shows the overall analytical framework used in this study to examine roundabout crashes. The process begins with clustering, where CCA is used to group crashes with similar characteristics into clusters. These clusters represent different patterns or types of crashes observed in the data. After clustering, the next step is interpretation, where the SHAP method is applied to each cluster. SHAP helps explain which factors, such as vehicle type, driver behavior, or environmental conditions, have the greatest influence on crash severity within each cluster. Furthermore, to investigate the crash narratives in the considered data, this study also conducted some crash narrative analysis focusing on the fatal or severe injury crashes. In parallel to these steps, spatial analysis is performed using hotspot analysis. This spatial analysis identified locations where roundabout crashes are more concentrated, helping to pinpoint areas that may require additional safety attention. Together, these three components, clustering, interpretation, and spatial analysis, provided a comprehensive approach for understanding roundabout crash patterns, key risk factors, and their geographic distribution.

A diagram of a process

AI-generated content may be incorrect.

Figure 3.1 Study Design

## Data Preparation

This study considered Ohio crash data for analyzing Roundabout safety. Figure 3.2 displays an interactive map (can be found here: <https://roundabout-crashes.vercel.app/>) of 6,448 roundabout-related crashes in Ohio from 2017 to 2021. Each marker represents a crash location for fatal/severe crashes (KA), moderate/minor injury crashes (BC), and property damage only (O). The markers are clustered for visualization efficiency, with cluster size reflecting the number of crashes in that area. A summary box provides the yearly distribution of crash severity. The yearly distribution is showing an increasing tendency in fatalities at roundabout crashes throughout the years. This visualization highlights both the spatial concentration and temporal trends of roundabout crashes across the state.

A map with a map of the state

AI-generated content may be incorrect.

Figure 3.2. Crash distribution by year

## Exploratory Data Analysis

Table 3.1 provides a detailed breakdown of roundabout crashes across different severity levels, revealing key insights into the influence of environmental, road, demographic, and behavioral factors on crash outcomes. The exploratory data analysis of roundabout crashes across different severity levels fatal/severe (KA), moderate/minor injury (BC), and property damage only (O), revealed some important and intuitive distinctions that go beyond surface-level summaries. Although property damage crashes form the majority, the patterns emerging from the small but critical KA group highlight the seriousness of specific crash contexts. One striking observation is the relationship between crash type and severity. Fixed object crashes make up more than half (51.5%) of fatal and severe (KA) crashes, while they account for only about 16.4% of property damage crashes. This pattern suggests that loss of control and run-off-road (ROR) incident, often associated with high impact, are far more likely to lead to serious injury or death. This is further reinforced by the contributing factor breakdown, where violations and RORs together account for over 40% of KA crashes. In contrast, angle crashes, common in roundabouts due to merging or yielding failures, are more likely to result in property damage, with nearly half of O-level crashes involving this type, but only 12.1% in the KA group. Lighting conditions and environmental factors also play a key role. While a majority of crashes across all severity levels happen in daylight, the share of crashes occurring in low-light conditions, particularly dark but lighted roadways, jumps significantly in KA crashes (40.9%) compared to only 19.5% for property damage cases. This suggests that even when lighting infrastructure is present, visibility challenges at night may still hinder proper judgment or reaction. Poor weather like rain or cloud cover also appears more frequently in severe crashes, and notably, nearly 17% of KA crashes occur under wet road conditions, compared to about 10% in property damage cases. Pre-crash actions also shed light on risk profiles. Nearly one-third of KA crashes involved drivers who were “Negotiating a Curve,” a rate much higher than that in injury or damage-only crashes. This suggests that handling the curvature of roundabouts can be challenging, especially under stress or poor visibility, and may result in severe outcomes if a vehicle leaves its path. On the other hand, “Straight Ahead” movement was the most common action across all severity levels, including KA, but its relative impact on severity seems to depend heavily on accompanying factors like following distance or driver attentiveness.

Table 3.1 Percentage distribution of key attributes by injury severity

|  |  |  |  |
| --- | --- | --- | --- |
| **Variables** | **KA** | **BC** | **O** |
| N=66 | N=929 | N=5453 |
| **Young driver indicator (Yng)** | | | |
| No (N) | 48 (72.7%) | 611 (65.8%) | 3525 (64.6%) |
| Yes (Y) | 18 (27.3%) | 318 (34.2%) | 1928 (35.4%) |
| **Crash type (Typ)** | | | |
| Angle | 8 (12.1%) | 330 (35.5%) | 2594 (47.6%) |
| Animal | 0 (0.00%) | 1 (0.11%) | 68 (1.25%) |
| Fixed Object | 34 (51.5%) | 188 (20.2%) | 892 (16.4%) |
| Rear End | 6 (9.09%) | 226 (24.3%) | 1065 (19.5%) |
| Turning | 5 (7.58%) | 100 (10.8%) | 592 (10.9%) |
| Vulnerable road user (VRUs) | 9 (13.6%) | 41 (4.41%) | 7 (0.13%) |
| Other | 4 (6.06%) | 43 (4.63%) | 235 (4.31%) |
| **Facility type (Fcl)** | | | |
| Two Way Roadway | 29 (43.9%) | 427 (46.0%) | 2476 (45.4%) |
| One Way Roadway | 3 (4.55%) | 46 (4.95%) | 355 (6.51%) |
| Other | 34 (51.5%) | 456 (49.1%) | 2622 (48.1%) |
| **Lighting condition (Lgh)** | | | |
| Daylight | 32 (48.5%) | 650 (70.0%) | 3879 (71.1%) |
| Dark - Lighted Roadway | 27 (40.9%) | 199 (21.4%) | 1064 (19.5%) |
| Dark - Roadway Not Lighted | 4 (6.06%) | 35 (3.77%) | 151 (2.77%) |
| Dawn/Dusk | 3 (4.55%) | 45 (4.84%) | 359 (6.58%) |
| **Number of lanes (Ln)** | | | |
| Two | 39 (59.1%) | 561 (60.4%) | 3392 (62.2%) |
| Four | 24 (36.4%) | 315 (33.9%) | 1837 (33.7%) |
| Five and above | 3 (4.55%) | 53 (5.71%) | 224 (4.11%) |
| **Road condition (Cnd)** | | | |
| Dry | 52 (78.8%) | 731 (78.7%) | 4079 (74.8%) |
| Wet | 11 (16.7%) | 172 (18.5%) | 1058 (19.4%) |
| Ice | 2 (3.03%) | 22 (2.37%) | 250 (4.58%) |
| Other | 1 (1.52%) | 4 (0.43%) | 66 (1.21%) |
| **Road contour (Cnt)** | | | |
| Curve Grade | 6 (9.09%) | 54 (5.81%) | 305 (5.59%) |
| Curve Level | 30 (45.5%) | 390 (42.0%) | 2678 (49.1%) |
| Straight Grade | 4 (6.06%) | 56 (6.03%) | 250 (4.58%) |
| Straight Level | 26 (39.4%) | 424 (45.6%) | 2204 (40.4%) |
| Other / Unknown | 0 (0.00%) | 5 (0.54%) | 16 (0.29%) |
| **Contributing factor (Cnf)** | | | |
| Fail to yield | 8 (12.1%) | 253 (27.2%) | 1732 (31.8%) |
| Following (Flwng) close | 7 (10.6%) | 207 (22.3%) | 1021 (18.7%) |
| Improper Action | 17 (25.8%) | 255 (27.4%) | 1696 (31.1%) |
| Run-off-road (ROR) | 9 (13.6%) | 88 (9.47%) | 326 (5.98%) |
| Violation | 18 (27.3%) | 51 (5.49%) | 180 (3.30%) |
| Other | 7 (10.6%) | 75 (8.07%) | 498 (9.13%) |
| **Posted speed limit (PSL)** | | | |
| 0-25mph | 20 (30.3%) | 355 (38.2%) | 2256 (41.4%) |
| 30-40mph | 24 (36.4%) | 372 (40.0%) | 2194 (40.2%) |
| 45 and above | 22 (33.3%) | 202 (21.7%) | 1003 (18.4%) |
| **Unit type (Unt)** | | | |
| Vulnerable road users (VRUs) | 23 (34.8%) | 59 (6.35%) | 26 (0.48%) |
| Bus/Truck | 7 (10.6%) | 109 (11.7%) | 674 (12.4%) |
| Car | 24 (36.4%) | 473 (50.9%) | 2883 (52.9%) |
| Sport utility vehicles (SUVs) | 10 (15.2%) | 258 (27.8%) | 1490 (27.3%) |
| Other | 2 (3.03%) | 30 (3.23%) | 380 (6.97%) |
| **Pre-crash action (Act)** | | | |
| Backing/Parked | 0 (0.00%) | 2 (0.22%) | 109 (2.00%) |
| Changing lanes/Overtaking | 0 (0.00%) | 51 (5.49%) | 412 (7.56%) |
| Entering/Leaving | 4 (6.06%) | 105 (11.3%) | 803 (14.7%) |
| Negotiating A Curve | 20 (30.3%) | 129 (13.9%) | 832 (15.3%) |
| Slowing or Stopped in Traffic | 0 (0.00%) | 33 (3.55%) | 154 (2.82%) |
| Straight Ahead | 32 (48.5%) | 460 (49.5%) | 2358 (43.2%) |
| Turning | 4 (6.06%) | 115 (12.4%) | 607 (11.1%) |
| Other Non-Motorists | 4 (6.06%) | 7 (0.75%) | 3 (0.06%) |
| Other/Unknown | 2 (3.03%) | 27 (2.91%) | 175 (3.21%) |
| **Traffic control device (Tcd)** | | | |
| Roundabout | 51 (77.3%) | 609 (65.6%) | 3321 (60.9%) |
| Flasher | 0 (0.00%) | 0 (0.00%) | 1 (0.02%) |
| No Control | 6 (9.09%) | 149 (16.0%) | 974 (17.9%) |
| Signal | 1 (1.52%) | 14 (1.51%) | 52 (0.95%) |
| Stop Sign | 1 (1.52%) | 14 (1.51%) | 61 (1.12%) |
| Yield Sign | 7 (10.6%) | 143 (15.4%) | 1044 (19.1%) |
| **Weather condition (Wth)** | | | |
| Clear | 47 (71.2%) | 591 (63.6%) | 3206 (58.8%) |
| Cloudy | 10 (15.2%) | 208 (22.4%) | 1327 (24.3%) |
| Rain | 6 (9.09%) | 101 (10.9%) | 577 (10.6%) |
| Other | 3 (4.55%) | 29 (3.12%) | 343 (6.29%) |

## Variable Importance Analysis

To identify the most influential variables contributing to crash severity at roundabouts, a systematic variable selection process was conducted, as illustrated in Figure 3.3. The dataset initially consisted of 6,448 roundabout-related crashes in Ohio between 2017 and 2021, with 21 categorical variables describing vehicle characteristics, roadway conditions, environmental factors, and driver behavior. To ensure meaningful and unbiased analysis, variables with more than 85% skewed distribution (i.e., dominated by a single category) were removed. This preprocessing step resulted in a refined set of 18 variables, including severity. These variables were then subjected to a Variable Importance Analysis using two machine learning algorithms, XGBoost and Random Forest, both of which are known for their robustness in handling high-dimensional and categorical data.

The XGBoost model identified the top predictors of crash severity to include unit type, crash type, pre-crash action, contributing factor, functional class, and environmental features such as weather and lighting conditions. Similarly, the Random Forest model highlighted crash type, unit type, contributing factor, and roadway departure as the most important variables, along with several contextual attributes like gender, road condition, and number of lanes. Based on the consensus across both models, a final set of 14 variables was selected for CCA. These included vehicle type, crash type, contributing factor, pre-crash action, and roadway and environmental conditions (e.g., weather, lighting, road contour, posted speed limit, number of lanes, and facility type). The variable “Severity” was retained as a reference outcome to support interpretability and discussion of CCA-based crash patterns. This data-driven approach ensured that only relevant and non-redundant variables were used in the clustering analysis, leading to more reliable pattern detection and interpretation in the context of roundabout crashes. These variable importance plot are generated using XGBoost (Chen et al., 2024), and Random Forest (Breiman et al., 2024) in R. These highlight the relative contribution of various factors to roundabout crash severity. The variable importance analysis assists in identifying the importance of variables.

A screenshot of a computer

AI-generated content may be incorrect.

Figure 3.3 List of considered variables

The variable importance analysis assists in identifying the importance score of variables. The plots in Figure 3.4 and Figure 3.5 show the variable importance analysis using XGBoost and Random Forest models respectively. Both models selected and highlighted the importance score of each variable on crash severity.

A graph of a number of gray bars

AI-generated content may be incorrect.

*Note: Severity is the dependent variable, while all other variables are independent predictors contributing to the model*

Figure 3.4 Variable importance plot (XGBoost)

A graph with blue and white bars

AI-generated content may be incorrect.

Figure 3.5 Variable importance plot (Random Forest)

## Cluster Correspondence Analysis

CCA is a widely recognized technique for analyzing categorical datasets by uncovering associations among categorical variables (Sourial et al., 2010). Its main goal is to organize observations into distinct and interpretable groups based on selected variables. CCA achieves this by simultaneously determining cluster memberships and assigning scaling scores to variable categories to enhance differences across clusters. Initially introduced by Velden et al. (2017), CCA integrates correspondence analysis with K-means clustering. This integration allows the method to compute both the group assignments and the optimal scaling coordinates for categorical variables, thus maximizing the variance between clusters. The method operates by examining the cross-tabulation of cluster assignments and categorical variable levels. It outputs both the membership of each observation and the spatial representation (coordinates) of each category in a lower-dimensional space. One of CC’s key advantages lies in its ability to visually communicate results using biplots, which aid in the interpretation of cluster structures and category contributions.

The procedure begins by transforming a standard data matrix , consisting of observations and categorical variables, into a super indicator matrix through one-hot encoding. This generates , where each is an ​ binary matrix corresponding to the J-th categorical variable with categories. The complete matrix has rows and columns. A cluster membership matrix ​ is also defined, indicating which cluster each observation belongs to.

To assess the relationship between variables and clusters, a contingency matrix is constructed. Correspondence analysis is applied to to derive scaling scores for both clusters and variable categories. This process ensures that clusters are differentiated based on the distributional patterns of the categorical data. The iterative algorithm initiates with a random assignment of observations to clusters, creating an initial ​ and corresponding matrix . After computing the quantification matrix using correspondence analysis, object scores are calculated as is calculated. K-means clustering is then applied to , and the membership matrix ​ is updated iteratively until it converges (Velden et al., 2017). Upon convergence, the resulting matrices and category quantification matrix are scaled using a constant **,** producing scaled outputs and for graphical display in biplots.

## SHapley Additive exPlanation

SHAP was applied in this study to investigate the influence of specific crash-related features on severity outcomes at roundabouts. SHAP is a model interpretation tool that explains how each input variable contributes to a prediction. Based on Shapley values from cooperative game theory, SHAP values fairly distribute the difference between the predicted value and the baseline (average prediction) across all input features. Each SHAP value reflects the individual contribution of a variable to the final prediction. A positive SHAP value suggests that a feature increases the likelihood of a more severe crash, whereas a negative value indicates a reduced likelihood. The greater the absolute SHAP value, the more influential the feature is on the model’s decision. For a given model , the SHAP value for a feature is computed as (Lundberg and Lee, 2017),

|  |
| --- |
|  |

where:

* is the full set of features,
* is a subset of features excluding ,
* is the model’s prediction using only the features in ,
* is the prediction when is added.

# RESULTS AND DISCUSSIONS

**IV.**

This section includes a detailed explanation of the results found from the analyses. This section starts with a description of the cluster selection process and explains the clusters. Further, this section includes SHAP interpretation, a discussion on the analysis of crash narratives, and hot spot analysis. Detailed descriptions are provided below.

## Cluster Correspondence Analysis

This section includes a description of the findings from this study. Table 4.1 provides a summary of the centroids, variability, and sizes of the clusters identified from the roundabout crash data using CCA. The centroids (Dim 1 and Dim 2) indicate the central positions of each cluster in the data space, while the within-cluster sum of squares reflects the degree of variability among crashes within each cluster. The size column indicates the number of crashes assigned to each cluster, with Cluster 1 containing the most crashes (2,453) and Cluster 4 the fewest (1,298). The table illustrates how crashes were grouped based on shared features and the relative internal consistency of each cluster.

Table 4.1 Centroids and size of the clusters

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Cluster** | **Roundabout crashes** | | | |
| **Dim 1** | **Dim 2** | **Within cluster sum of squares** | **Size** |
| Cluster 1 | -0.0096 | -0.0053 | 0.0424 | 2453 |
| Cluster 2 | -0.0026 | 0.0036 | 0.0327 | 1396 |
| Cluster 3 | 0.0048 | 0.0165 | 0.0396 | 1301 |
| Cluster 4 | 0.0161 | -0.0103 | 0.0408 | 1298 |

*Note: Dim: dimension or axis*

Figure 4.1 presents a biplot generated through correspondence analysis, displaying clusters of roundabout crashes based on shared characteristics. Each cluster (C1 to C4) represents a group of crashes with similar patterns, plotted along two dimensions (Dim 1 and Dim 2). Teal-colored ovals mark the centroids of each cluster. The biplot also shows associations between crash severity and key categorical variables, with circles, squares, and triangles representing different variable categories. The proximity of these variables to specific clusters reflects their associations; for instance, “Slowing or Stopped in Traffic” and “Rear End” are closely linked to C4, while “Yield Sign” and “Entering/Leaving” are more associated with C1. This visual representation helps identify distinct crash patterns and the factors influencing each cluster.

A graph with black dots

AI-generated content may be incorrect.

Figure 4.1 Cluster biplot

### Cluster 1 (C1) – Entry and Yield-Related Conflicts at Roundabouts

Cluster 1 in Figure 4.2, accounts for 38% of all roundabout crashes in the dataset and primarily highlights crashes related to improper entries and yielding behavior. The most prominent factors in this cluster are “Fail to Yield”, “Entering/Leaving”, and “Angle”-type crashes, all of which are closely tied to the roundabout’s unique structure that requires drivers to yield before entering and maintain awareness of circulating traffic. In this cluster, crashes are often triggered by vehicles entering the roundabout without properly yielding to circulating traffic. These types of crashes were identified as one of the common crashes at roundabouts in previous studies (Mandavilli et al., 2009; Polders et al., 2015). Yet, these remain a common type of crashes at such intersections. These crashes typically result in angle collisions, which are common when vehicles merge at improper times or misjudge the speed or gap of other road users already in the roundabout. The strong presence of the “Yield Sign” traffic control variable in this cluster supports this interpretation, indicating that even when yield signs are present, some drivers either fail to notice them or choose not to follow the right-of-way rule. Additionally, this cluster includes a large number of crashes during turning movements or changing lanes/overtaking within the roundabout. Previous studies have identified lane changing maneuver as a significant contributor to crashes at roundabouts (Hu and Cicchino, 2019). These maneuvers, though relatively minor in open intersections, become complicated at roundabouts due to the continuous flow of traffic and the need for precise judgment in timing and positioning. Drivers misjudging these movements can easily collide with other vehicles, particularly if they are trying to exit the roundabout from the wrong lane or switch lanes within the circle. From a contributing factor perspective, “Fail to Yield” stands out as the most dominant reason for crashes, which logically aligns with roundabout design expectations, where yielding to traffic already inside is essential. In contrast, crash types like “Rear End” and “Fixed Object” are negatively associated with this cluster, suggesting that such crash types occur less frequently when compared to the more interaction-based angle collisions found here.

A graph with red and black text

AI-generated content may be incorrect.

Figure 4.2 Entry and Yield-Related Conflicts at Roundabouts

### Cluster 2 (C2)- Improper Maneuvers and Driver Misjudgment Crashes at Roundabouts

Cluster 2 in Figure 4.3 includes 21.7% of all roundabout crashes and is largely shaped by driver behavior such as “Improper Action”. The cluster also includes “Angle”-type crashes, and “Negotiating a Curve”, suggesting that these crashes may be associated with confusion or sudden movement while adjusting to the roundabout’s curvature. This is particularly the case in wet conditions, where stopping distance increases, and minor misjudgments can lead to collisions. The inclusion of “Wet” roadway conditions supports this interpretation, as even a slight loss of traction may turn a following-distance mistake into a crash. The presence of “Five and above” and “Four” lane roads in this cluster may also contribute, as multi-lane roundabouts require greater awareness of both lane positioning and the behavior of vehicles in adjacent lanes, adding to the complexity. Previous studies also indicated factors like driver errors or confusion while navigating through roundabouts can significantly impact crashes at roundabouts (Ashqar et al., 2024; Maji and Ghosh, 2025). Interestingly, crash causes like “Fail to Yield,” “Yield Sign,” and “Entering/Leaving” are negatively associated with this cluster, meaning such factors are less relevant here. This indicates that these crashes are less about right-of-way violations and more about errors made while already inside the roundabout or during steady traffic movement. The environment appears routine, with few indicators of risky maneuvers, supporting the idea that these crashes occur during normal driving rather than due to erratic or illegal actions.

A screenshot of a graph

AI-generated content may be incorrect.

Figure 4.3 Improper Maneuvers and Driver Misjudgment Crashes at Roundabouts

### Cluster 3 (C3)- Fixed Object and Environmental Hazard Crashes at Roundabouts

Cluster 3 is highlighted in Figure 4.4 It represents 20.2% of the total roundabout crashes, is primarily characterized by crashes involving vehicles striking fixed objects, especially under conditions of poor visibility or environmental hazards. The most prominent variable in this cluster is “Fixed Object” crash type, strongly linked with ROR, suggesting that drivers are either losing control of their vehicles or misjudging the roundabout’s curvature and geometry, causing them to veer off the intended path. The environmental conditions in this cluster further support this pattern. Crashes occurring during “Dark – Lighted Roadway” and “Dark – Not Lighted Roadway” conditions point toward limited visibility, which can affect a driver’s ability to judge entry and exit points, lane positions, or the location of medians, signs, or other infrastructure within the roundabout. Such situations are worsened when combined with ice, animal presence, or other unexpected hazards on the road. These environmental risks can disrupt a driver’s attention and reaction time, making it difficult to maintain control on a circular path. ROR or single vehicle crashes have been a common type of crash that most frequently occur at roundabouts (Burdett et al., 2017; Mandavilli et al., 2009; Polders et al., 2015). Another notable feature of this cluster is the involvement of backing or parked vehicle actions, which are generally unusual at roundabouts. This may indicate confusion or misbehavior, such as illegal maneuvers or incorrect vehicle positioning, especially in larger roundabouts or at roundabout-adjacent areas like splitter islands or exits. The presence of “Violation” as a contributing factor also supports this idea. This cluster also includes crashes involving vulnerable road users (VRUs), such as pedestrians or cyclists, which can be especially dangerous in poorly lit or high-speed environments. The presence of PSL of 45 mph and above aligns with this risk, as higher speeds reduce the reaction window for both drivers and VRUs and increase the severity of crashes when they occur. On the other hand, the cluster is negatively associated with “Angle” and “Rear-End” crashes, as well as traditional roundabout dynamics like “Entering/Leaving” and “Yield Sign” interactions. This implies that the crashes in this group are less about driver interaction and more about environmental conditions, visibility, and individual driver errors.

A screenshot of a computer

AI-generated content may be incorrect.

Figure 4.4 Fixed Object and Environmental Hazard Crashes at Roundabouts

### Cluster 4 (C4)- Rear-End and Following-Distance Crashes in Circulating Roundabout Flow

Cluster 4 in Figure 4.5 represents 20.1% of all roundabout crashes and is strongly associated with rear-end collisions caused by close following distances, particularly during routine or slowed traffic flow within the roundabout. The most influential variables in this cluster are “Rear End” crash type and “Following Too Closely” as a contributing factor, clearly pointing to situations where vehicles collide because drivers are not maintaining sufficient space from the vehicle ahead. Previous studies identified that this type of crash is common in roundabouts, where stop-and-go movement is frequent (Burdett et al., 2016; Saccomanno et al., 2008). Vehicles may slow down unexpectedly when entering or yielding, or during lane changes while exiting. If a driver is distracted or assumes traffic will keep flowing without interruption, they may fail to react in time. This pattern is emphasized by the variable “Slowing or Stopped in Traffic,” which suggests that a significant number of these crashes occur when vehicles are reducing speed or are momentarily halted, situations that require constant attention from the driver behind. This cluster also shows a strong presence of “Straight Ahead” movement, meaning the involved vehicles were moving directly through the roundabout, likely in the circulating lane. Since roundabouts require curved navigation, the “straight ahead” label likely reflects a lack of major maneuvers like turning or entering, reinforcing the idea that these crashes happen in the most routine parts of travel, where attentiveness might decrease. Cluster 4 captures a pattern of low-complexity but high-frequency crashes driven by inattentiveness or aggressive following during slowdowns in roundabout traffic.

A graph with text on it

AI-generated content may be incorrect.

Figure 4.5 Rear-End and Following-Distance Crashes

### Cluster-Based Comparative Analysis

A cluster-based comparative analysis has also been done in this study. Table 4.2 presents a detailed look at how different crash, roadway, driver, and environmental characteristics are distributed across the four clusters identified in the study. Several patterns stand out, revealing how certain types of crashes tend to concentrate in specific conditions or involve particular behaviors. One of the clearest patterns is the strong link between failure to yield and Cluster 1, where over 70% of crashes are caused by drivers not giving the right of way, and nearly all are angle-type crashes. This points to a persistent challenge at roundabout entry points, with most incidents happening in daylight and on dry roads, suggesting that clear conditions do not necessarily lead to safer driving. Cluster 2 revealed a very different scenario, with a much higher share of improper actions and multi-lane maneuvers, such as changing lanes or negotiating curves. Notably, nearly 15% of crashes here are with fixed objects, a much larger share than in other clusters, implying that drivers may be struggling with roundabout navigation or are distracted. The lighting and weather profile for Cluster 2 is also notable, with more crashes in low light, wet, or icy conditions compared to Cluster 1. Cluster 3 stands out for its severity. Nearly 4% of crashes here result in fatalities or serious injuries, much higher than other clusters. This group is heavily dominated by ROR and fixed-object collisions, often at night or in poor weather, and frequently on higher-speed approaches. There’s a noticeable presence of VRUs, which points to the potential for severe outcomes when a driver loses control under challenging conditions. Cluster 4, by contrast, is almost entirely composed of rear-end crashes (over 96%), with “following too close” as the top contributing factor. These typically happen when vehicles are traveling straight ahead or are stopped/slowed in traffic, and the vast majority occur in daylight and on dry pavement. The presence of both young and older drivers, along with a high share of two-lane roads, suggested that following distance and driver attention remain issues even in simple conditions. Other interesting points emerged when comparing environmental and geometric features. For instance, icy roads are much more common in Clusters 2 and 3, connecting severe crashes to winter weather. Four-lane and multi-lane setups also appear more frequently in Clusters 2 and 4, where improper maneuvers and rear-ends are dominant. Clusters with higher posted speed limits, especially Cluster 3, are also linked with more severe and unusual crashes, pointing to the importance of speed management at roundabout approaches.

Table 4.2 Cluster-based comparative analysis.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Variable Name** | **Cluster 1** | **Cluster 2** | **Cluster 3** | **Cluster 4** |
| N=2453 | N=1396 | N=1301 | N=1298 |
| **Severity (Sev):** | | | | |
| KA | 0.08% | 0.64% | 3.69% | 0.54% |
| BC | 11.10% | 14.90% | 17.70% | 16.90% |
| O | 88.80% | 84.50% | 78.60% | 82.60% |
| **Yound driver indicator (Yng)** | | | | |
| N | 59.60% | 70.00% | 74.60% | 59.80% |
| Y | 40.40% | 30.00% | 25.40% | 40.20% |
| **Crash type (Typ)** | | | | |
| Angle | 76.00% | 70.30% | 3.61% | 2.93% |
| Animal | 0.00% | 0.29% | 4.92% | 0.08% |
| Fixed Object | 0.00% | 14.80% | 69.60% | 0.08% |
| Rear End | 0.37% | 1.93% | 0.46% | 96.70% |
| Turning | 23.20% | 8.24% | 0.77% | 0.23% |
| VRUs | 0.41% | 1.72% | 1.77% | 0.00% |
| Other | 0.00% | 2.65% | 18.80% | 0.00% |
| **Facility type (Fcl)** | | | | |
| Two Way Roadway | 47.40% | 43.30% | 41.40% | 48.20% |
| One Way Roadway | 4.73% | 4.08% | 5.23% | 12.60% |
| Other | 47.90% | 52.60% | 53.30% | 39.20% |
| **Lighting condition (Lgh)** | | | | |
| Daylight | 83.40% | 66.30% | 40.00% | 82.30% |
| Dark - Lighted Roadway | 11.50% | 23.90% | 41.80% | 10.20% |
| Dark - Roadway Not Lighted | 0.69% | 2.44% | 9.22% | 1.46% |
| Dawn/Dusk | 4.40% | 7.45% | 8.92% | 6.09% |
| **Number of lanes (Ln)** | | | | |
| Two | 58.50% | 51.40% | 74.20% | 67.30% |
| Four | 39.10% | 41.30% | 21.10% | 28.00% |
| Five and above | 2.32% | 7.23% | 4.69% | 4.70% |
| **Road condition (Cnd)** | | | | |
| Dry | 85.90% | 71.60% | 59.40% | 75.70% |
| Wet | 13.20% | 23.50% | 25.70% | 19.60% |
| Ice | 0.41% | 3.80% | 12.40% | 3.85% |
| Other | 0.49% | 1.15% | 2.46% | 0.85% |
| **Road contour (Cnt)** | | | | |
| Curve Grade | 6.81% | 5.37% | 6.00% | 3.47% |
| Curve Level | 62.80% | 45.00% | 37.80% | 33.70% |
| Straight Grade | 2.69% | 4.30% | 7.30% | 6.86% |
| Straight Level | 27.50% | 45.10% | 48.30% | 55.50% |
| Other / Unknown | 0.20% | 0.29% | 0.54% | 0.39% |
| **Contributing factor (Cnf)** | | | | |
| Fail to yield | 70.50% | 16.40% | 0.77% | 1.93% |
| Following (Flwng) close | 0.57% | 1.07% | 0.69% | 92.20% |
| Improper Action | 27.40% | 54.60% | 38.00% | 3.08% |
| Run-off-Road (ROR) | 0.00% | 3.30% | 29.00% | 0.00% |
| Violation | 0.08% | 4.80% | 13.80% | 0.00% |
| Other | 1.51% | 19.80% | 17.70% | 2.77% |
| **Posted speed limit (PSL)** | | | | |
| 0-25mph | 40.40% | 45.10% | 39.70% | 38.10% |
| 30-40mph | 47.40% | 36.00% | 27.50% | 43.80% |
| 45 and above | 12.20% | 19.00% | 32.70% | 18.20% |
| **Unit type (Unt)** | | | | |
| Vulnerable road users (VRUs) | 0.08% | 1.43% | 6.00% | 0.62% |
| Bus/Truck | 11.50% | 13.90% | 10.70% | 13.50% |
| Car | 52.10% | 51.60% | 52.30% | 53.90% |
| Sport utility vehicles (SUVs) | 34.40% | 21.90% | 18.30% | 28.60% |
| Other | 1.96% | 11.10% | 12.70% | 3.39% |
| **Pre crash action (Act)** | | | | |
| Backing/Parked | 0.00% | 0.07% | 8.46% | 0.00% |
| Changing lanes/Overtaking | 15.20% | 5.87% | 0.23% | 0.39% |
| Entering/Leaving | 32.30% | 5.37% | 2.00% | 1.39% |
| Negotiating A Curve | 5.06% | 28.90% | 30.90% | 4.01% |
| Slowing or Stopped in Traffic | 0.57% | 1.00% | 0.85% | 11.40% |
| Straight Ahead | 25.20% | 43.90% | 45.50% | 79.20% |
| Turning | 21.40% | 9.74% | 2.69% | 2.39% |
| Other Non-Motorists | 0.00% | 0.00% | 1.08% | 0.00% |
| Other/Unknown | 0.33% | 5.16% | 8.30% | 1.23% |
| **Traffic control device (Tcd)** | | | | |
| Roundabout | 51.10% | 64.00% | 76.80% | 64.30% |
| Flasher | 0.00% | 0.00% | 0.08% | 0.00% |
| No Control | 15.90% | 24.50% | 16.80% | 13.70% |
| Signal | 0.65% | 1.65% | 0.54% | 1.62% |
| Stop Sign | 0.86% | 1.00% | 0.92% | 2.23% |
| Yield Sign | 31.50% | 8.81% | 4.84% | 18.10% |
| **Weather condition (Wth)** | | | | |
| Clear | 65.60% | 57.30% | 51.60% | 58.90% |
| Cloudy | 26.70% | 23.20% | 19.00% | 24.70% |
| Rain | 6.48% | 13.30% | 14.70% | 11.50% |
| Other | 1.30% | 6.23% | 14.80% | 4.93% |

## SHAP Interpretation

The SHAP plots in this section help explain which factors are most important in predicting crash severity at roundabouts. Each dot in the plot represents a case. The position of the dot along the horizontal axis shows how much that factor influenced the model’s prediction for crash severity, either increasing or decreasing the chance of a severe crash. Dots farther to the right mean that the factor pushed the prediction toward the target severity. Dots on the left mean the factor helped lower the severity prediction. The color of the dots shows the value of the factor, for example, yellow means the factor was present (or high), and black means the factor was absent (or low). By looking at the spread and color of the dots, it can be understood how different features influence crash outcomes.

### Cluster 1

The SHAP analysis in Figure 4.6(a) revealed that in fatal and severe roundabout crashes within Cluster 1, which represents entry and yield-related crashes, cloudy weather stands out as a major factor. Poor weather conditions like overcast skies can reduce visibility, making it harder for drivers to judge the speed and position of circulating vehicles. This becomes particularly dangerous at roundabouts, where drivers need to make quick decisions while yielding and merging into traffic. Another contributing factor, curved roadway segments on a grade, showed high feature importance. Roundabouts naturally involve curves, but when these curves are combined with elevation changes, drivers may have difficulty controlling their vehicles while entering or exiting, especially if speeds are not sufficiently reduced. SUVs are also associated with increased severity in this cluster. These vehicles are larger and heavier than regular passenger cars, and crashes involving SUVs at roundabouts often result in more damage or serious injury, especially during side-impact (angle) crashes. Additionally, drivers who are not categorized as young, likely middle-aged or older, are more involved in these severe crashes. This may reflect slower reaction times or difficulty judging gaps in traffic, particularly in more complex driving situations like yielding at a roundabout. Another important factor is the presence of yield signs and drivers going straight through the roundabout. These patterns suggest that many severe crashes in this cluster result from drivers failing to yield or misjudging the flow of traffic as they attempt to continue straight without fully understanding the right-of-way. Multi-lane roundabouts (with two, four, or more lanes) also play a role in crash severity, as navigating them requires lane discipline and careful observation, which not all drivers follow consistently.

In injury crashes that are not fatal but still cause harm, failure to yield stands out as one of the most important factors (see Figure 4.6(b)). Many drivers at roundabouts do not wait for a clear gap in traffic before entering. This mistake often causes collisions, especially when other vehicles are already in the roundabout. Although these crashes are less severe than fatal ones, they still result in injuries due to the impact. Interestingly, crashes also occur often in dry and clear conditions. While these may seem like safe weather conditions, drivers may feel more confident and fail to slow down or pay full attention. This overconfidence leads to errors in judgment during merging or exiting. The geometry of the road, such as two-lane roads and straight-level designs, also appears in the plot. These suggest that crashes can happen even on regular, flat segments of the roundabout when drivers are not cautious. Buses and trucks are also involved in injury crashes. These large vehicles can be difficult to maneuver inside roundabouts, and smaller vehicles may get caught in unsafe positions around them. However, the absence of such longer vehicles can also lead to higher BC crashes. It may be because in the presence of such vehicles, the other drivers may drive more cautiously, which can improve safety. The speed limits shown in the plot (25–40 mph) are typical for many roadways with roundabouts. Still, if drivers do not adjust their speed appropriately or do not yield, even moderate speeds can lead to injuries.

In crashes that only cause vehicle damage, dry road conditions showed up as the top feature (see Figure 4.6(c)). In the absence of wet roads, the vehicles may veer off the roundabout, however, in dry condition with cautious driving, the ROR incidents may reduce and reduce the likelihood of crashes. Buses and trucks are once again present in this group. Due to their size, they can easily cause fender-benders if they turn too sharply or occupy more space than expected. Failure to yield continues to be a problem even in low-severity crashes. Although the impact may not lead to injuries, it still results in damage when drivers enter without checking for oncoming traffic. Non-young drivers are again common in these cases, which might reflect cautious but sometimes incorrect decision-making at roundabouts. Speed limits in the 30–40 mph range appear often in these crashes. This indicated that such speed limits can decrease the no injury crashes as these can lead to injury crashes. Features like straight or curved level roads and two-way roadway types also contribute to these crashes.

|  |  |
| --- | --- |
| (a) Cluster 1 (KA) | (b) Cluster 1 (BC) |
| (c) Cluster 1 (O) | |

Figure 4.6 Cluster 1 SHAP plots for different severity levels

### Cluster 2

This cluster includes crashes that mainly happen because of driver mistakes or confusion inside the roundabout. These crashes often involve improper actions like incorrect turns, lane changes, or difficulty negotiating the circular roadway. In fatal and severe crashes for Cluster 2 (see Figure 4.7(a)), the SHAP plot shows that failure to yield is again the most influential factor. This aligns with the nature of roundabouts, where proper yielding is essential. If a driver enters the roundabout without waiting for a safe gap in traffic, a serious crash can occur, especially if other vehicles are already circulating. Cloudy weather also appears near the top, suggesting that limited visibility or dull lighting makes it harder for drivers to correctly judge the speed and position of other vehicles in the roundabout. Daylight conditions seem to increase severity, meaning fatalities can also occur in daylight conditions. Turning maneuvers and SUV involvement are also important. Turning within the roundabout can be risky if done abruptly or without proper signaling. SUVs, due to their size, can cause more harm in angle-type crashes, especially during turning or merging. Two-lane roads and two-way roadway facilities also appear in this plot, showing that navigating multiple lanes and traffic directions can increase complexity and crash severity when drivers are not fully attentive. Speed limits under 25 mph and the presence of “No Control” (i.e., absence of proper traffic control devices) may lead to confusion, causing drivers to misjudge or act suddenly. Improper actions, such as making wrong turns or switching lanes without checking, further add to the problem, especially on curved-level segments of roundabouts where quick adjustments are harder to make safely.

For injury crashes in Cluster 2 (see Figure 4.7(b)), the SHAP plot highlights that crashes happening on “Other” facility types, likely meaning roads that don’t fit usual categories, are more likely to lead to injuries. These may be locations with unusual design or layout near roundabouts. Driving while negotiating a curve is another key factor. This shows that injuries can happen when drivers lose focus or control while trying to follow the circular shape of the roundabout. Drivers who are not young (middle-aged or older) also contribute more to these injuries, possibly due to slower responses during sudden changes in traffic flow. Injuries also appear to involve vulnerable road users (VRUs), such as bicyclists or pedestrians. Although rare in roundabouts, when they are present, the risk of injury is higher. Crashes involving cloudy weather and curved road geometry suggest that environmental and design conditions make it harder for drivers to respond in time, leading to crashes that result in minor or moderate injuries. Multi-lane roundabouts, especially those with five or more lanes, are more difficult to navigate, and crashes here tend to involve higher impact due to traffic complexity. Even in low-speed zones (under 25 mph), minor injuries can still happen if drivers act without caution.

In the property damage group for Cluster 2 (see Figure 4.7(c)), the SHAP plot shows that VRUs have the highest impact on crash prediction. However, these cases likely resulted in minor contact rather than injury, perhaps involving close calls or low-speed bumps with cyclists or pedestrians. Dry road conditions are also common here, while these are generally safer, they can encourage higher speeds or careless maneuvers, leading to small-scale collisions. Crash types like “Fixed Object” or “Angle” also contributed. This means that some crashes occur when drivers hit signs, curbs, or barriers inside or near the roundabout. These types of crashes are common when drivers misjudge the curve or speed, especially in multi-lane roundabouts. SUVs and buses/trucks are again involved. Their size and turning space make them more likely to brush against curbs or other vehicles, causing damage without injury. Speed limits under 25 mph also appear here, showing that even low-speed areas don’t fully eliminate the risk of minor crashes, especially when vehicles are packed closely in traffic. Pre-crash actions like “Negotiating a Curve” and “Turning” are clearly relevant. These actions, when done without proper lane positioning or signaling, often lead to minor crashes. Weather conditions such as rain and clear skies both show up, which suggests that crashes happen across different weather types, pointing more toward driver behavior than just environmental causes. Improper actions are once again highlighted, reinforcing that driver misjudgment or lack of attention is a recurring cause of property damage crashes at roundabouts.

|  |  |
| --- | --- |
| (a) Cluster 2 (KA) | (b) Cluster 2 (BC) |
| (c) Cluster 2 (O) | |

Figure 4.7 Cluster 2 SHAP plots for different severity levels

### Cluster 3

This cluster includes crashes where vehicles struck fixed objects or went off the road, often under poor visibility or environmental conditions. In fatal and severe crashes for Cluster 3 (see Figure 4.8(a)), VRUs such as pedestrians or bicyclists were the most significant factor. Although VRUs are not always common in roundabouts, especially at night or in poor weather, the chances of severe outcomes are much higher due to the lack of protection. These crashes are often more deadly when visibility is low, and speeds are not properly reduced. Clear weather also appears high on the list, which may seem unexpected. However, clear conditions can sometimes lead drivers to feel more confident and drive faster, especially if road conditions appear safe. Violations such as speeding or illegal maneuvers are also key contributors, showing that poor driving decisions in roundabouts can quickly become dangerous. Low speed zones like 0–25 mph show up here, but their presence alongside severe crashes may suggest that crashes happened during entry or exit rather than within the circulating flow, likely when drivers misjudged the geometry or lane alignment. Wet road conditions, improper actions, and negotiating a curve also rank high. These findings highlight that the circular shape of roundabouts can become difficult to handle if the surface is wet or if the driver is not fully focused. Middle-aged or older drivers (Yng\_N), rain, and low lighting conditions further increase severity. In particular, dark but lighted roadways indicate that artificial lighting might not be enough to prevent severe crashes if drivers are unfamiliar with the roundabout or make errors while navigating. Curved-level roads and fixed object crashes are also shown, confirming that these incidents involve loss of control and collisions with roundabout features like signs, poles, or curbs.

Injury crashes in Cluster 3 are also shaped by a mix of environmental and behavioral factors (see Figure 4.8(b)). The most important factor is listed as “Other” contributing factors, suggesting that these crashes often result from varied driver errors or distractions that don’t fall into neat categories. Dry road conditions and clear weather appear again, possibly reflecting overconfidence or faster driving in otherwise safe environments. Improper actions, such as sudden turning, lane shifting, or failure to yield properly, are also influential in these injury cases. These are common inside roundabouts, especially when traffic volume is moderate and drivers misjudge gaps or misread signage. Crashes that occurred during straight-ahead travel also appear in the SHAP results, suggesting that even when drivers are not making complex maneuvers, distraction or inattention can still result in crashes. Drivers who are not young are again more commonly linked to these crashes. They may struggle with quick steering adjustments or interpreting lane markings at night. Interestingly, backing or parked actions appear, which is uncommon in roundabouts and may reflect confused or illegal behavior, such as reversing after a missed exit. Lighting conditions, whether it is daylight or dark, but with lighting, are both present, showing that crashes occur across all visibility settings. VRUs and weather conditions like wet roads or “Other” weather types (such as fog) also appear in this group, reinforcing the pattern that injuries often result from a combination of poor visibility and driver misjudgment. The influence of low speed limits and road curvature again confirms the role of roundabout geometry in these incidents.

In Cluster 3’s property damage cases (see Figure 4.8(c)), VRUs once again appear at the top. These may involve near misses, or very low-speed impacts where no injury occurred. In such cases, the driver might have braked late or swerved, resulting in hitting something else instead of the VRU. Weather conditions described as “Other” or “Unknown” are high on the list. This reflects that unusual or unclear environmental conditions, like fog, strong winds, or glare, may have played a role, increasing the chance of driver confusion. Poor lighting at dawn or dusk also contributes. These are times of day when visibility is low but headlights may not yet be in full use, creating difficulty in identifying roundabout entry or exit paths. Backing or parked actions show up again, which could suggest hesitation or confusion near splitter islands or roundabout exits. Several factors such as straight-ahead travel, animal crashes, and dry or icy conditions appear, showing a mix of routine and unusual circumstances. While these crashes did not lead to injuries, they show how a wide range of factors can still result in minor impacts at roundabouts. Other influences include less common vehicle types, unusual facility types, and the typical roundabout geometry (curved-level road). In these crashes, low speeds likely helped reduce the impact to vehicle damage only.

|  |  |
| --- | --- |
| (a) Cluster 3 (KA) | (b) Cluster 3 (BC) |
| (c) Cluster 3 (O) | |

Figure 4.8 Cluster 3 SHAP plots for different severity levels

### Cluster 4

For fatal and severe crashes in this cluster. Buses and trucks (Unt\_Bus/Truck) are significant contributors (see Figure 4.9(a)). These large vehicles require more space to stop and navigate, and in cases where following distances are too short or movement is misjudged, the impact can be more serious. Middle-aged or older drivers (Yng\_N) are also linked to more severe crashes, possibly due to slower reaction times during unexpected slowdowns or congestion inside the roundabout. Speed limits in the 30–40 mph range and higher (PSL\_45 and above) appear in the plot, showing that when drivers approach the roundabout at moderate to high speeds without reducing speed enough, it can lead to more severe outcomes, especially in multi-lane conditions. Geometry also matters, straight-level and curve-level road contours appear in this cluster, indicating that even in less complex roadway shapes, driver inattentiveness or misjudgment can lead to serious crashes. Rain and dark conditions (with lighting) further raise crash severity. Even when lighting is provided, rainy or low-light environments make it harder to see slowing traffic ahead. Finally, two-lane and four-lane configurations show up, confirming that more lanes create greater chances for error or reduced space for evasive maneuvers inside the roundabout.

For injury crashes, SHAP plots show that crashes involving “Other” vehicles (Unt\_Other) are important (see Figure 4.9(b)). These may include work or utility vehicles that operate differently from standard cars. These vehicles may cause unexpected stops or maneuvers inside the roundabout, confusing other drivers. Like in other clusters, non-young drivers (Yng\_N) are associated with injury crashes, reflecting slower reactions to sudden changes in traffic flow. One-way roadways and rear-end crashes (Typ\_Rear End) dominate this group. Rear-end collisions are very common in roundabouts, especially when vehicles stop suddenly due to congestion or yield delays. Speed limits at both ends, 0–25 mph and 45+ mph, are linked to injury crashes. This shows that both low-speed and high-speed environments can be risky if drivers misjudge distances or fail to stop in time. Weather also plays a role, ice, cloudy weather, and clear conditions are all present, showing that injury crashes occur under various environmental settings. It is not just bad weather, but also careless driving in good weather, that contributes to these outcomes. Road types like straight-level segments, other facility types, and routine movements like driving straight ahead are all present, confirming that these crashes happen during normal driving conditions when drivers become inattentive.

In property damage-only crashes, the most important factor is the action “Straight Ahead” (see Figure 4.9(c)). These crashes happen when drivers are simply circulating through the roundabout without turning or changing lanes, but still crash due to following too closely, braking late, or not expecting the vehicle ahead to slow down. This confirms that even routine roundabout travel can lead to minor crashes when attention lapses. Older drivers (Yng\_N) are again associated with these crashes, possibly due to hesitating, braking late, or reacting slowly. Two-way roadways, low-speed zones (PSL 0–25 mph), and roundabout traffic control signs appear frequently, suggesting that even with well-designed road features, crashes still occur when driving behavior is not careful. The presence of yield signs (Tcd\_Yield Sign) indicates that drivers may still be misjudging or not respecting the need to give way to circulating vehicles. Environmental conditions like wet roads, ice, dawn/dusk lighting, and moderate to high-speed limits (PSL 45 and above) are also linked to these crashes. While these crashes don’t result in injuries, they highlight how risky behavior, especially following too closely (Cnf\_Flwng close), can easily result in minor collisions at roundabouts.

|  |  |
| --- | --- |
| (a) Cluster 4 (KA) | (b) Cluster 4 (BC) |
| (c) Cluster 4 (O) | |

Figure 4.9 Cluster 4 SHAP plots for different severity levels

## Exploration of KA Severity Crash Narratives

To investigate the fatal or severe injury in more details, the review of crash narratives for fatal or severe injury crashes at Ohio roundabouts have been explored. The narrative analysis shows that these crashes often involve loss of control, high speeds, or drivers entering the roundabout without yielding. Many of the serious crashes happened when a driver either did not slow down enough for the roundabout or tried to enter without checking for traffic already in the circle. In several cases, vehicles left the roadway entirely, sometimes rolling over or striking fixed objects like light poles or trees, which often leads to more serious injuries. There are also examples of severe crashes when one vehicle entered the roundabout and was hit from the side or head-on by another vehicle, usually because someone failed to yield. In a few cases, stolen vehicles or very fast driving was mentioned, which increases the risk of losing control and getting hurt. A key takeaway from these narratives is that while roundabouts are designed to slow traffic, high speeds, poor decisions at entry, and not paying attention to other vehicles still lead to some of the most serious crashes. ROR and fixed-object collisions, in particular, stand out as especially dangerous in roundabout environments. Another pattern is that not all severe crashes fit a single type; some happen as rear-ends, while others involve sideswipes or direct hits to the front or side. Sometimes, unexpected stopping or confusion inside the roundabout also plays a part. Table 4.3 illustrates a summary of some of the crash narratives that have been explored in this study.

Table 4.3 Summary of crash narratives

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Damage Description** | **Crash Severity** | **Crash Type** | **Fault/Contributing Factor** | **Crash Narrative Summary** |
| Not Specified | KA | Other/Unknown | Unspecified/Unknown | Unit #1 was traveling east on Dutch Road when it failed to negotiate the roundabout and collided with Unit #2. Both drivers sustained serious injuries. |
| Rear End | KA | Other/Unknown | Unspecified/Unknown | Driver of unit 01 stated he was traveling through the roundabout when unit 02 stopped unexpectedly, causing a rear-end collision. Unit 02's driver was seriously injured. |
| Side | KA | Other/Unknown | Unspecified/Unknown | Witness Hughes stated he was southbound on the inside lane when Unit 2 entered from the east, resulting in a side impact that caused major injury. |
| Side | KA | Other/Unknown | Failed To Yield | Unit 2 was inside the roundabout at the intersection when Unit 1 entered without yielding, striking Unit 2 in the passenger side and causing severe injury. |
| Not Specified | KA | ROR/Rollover | Unspecified/Unknown | Unit #1 was westbound on SR-0261 when it struck the curb at the roundabout, lost control, and rolled over. Serious injuries were reported. |
| Side | KA | Fixed Object | Failed To Yield | Unit #1 was traveling east on State Route 29. Unit #2 failed to yield and entered the roundabout, causing Unit #1 to veer off and hit a light pole. |
| Not Specified | KA | Other/Unknown | Speeding | Unit 01 was reported as a stolen vehicle and was traveling at a high speed when it failed to negotiate the roundabout, left the roadway, and struck multiple signs. Serious injuries resulted. |
| Front End | KA | Other/Unknown | Unspecified/Unknown | Unit # 1 exited turnpike off ramp heading westbound, failed to maintain control entering the roundabout, and struck Unit #2 head-on. Injuries were severe. |
| Front End | KA | Fixed Object | Unspecified/Unknown | Unit 1 was traveling south in the 200 block of North Main Street when it lost control, crossed the center island, and hit a tree in the roundabout. The driver sustained major injuries. |
| Not Specified | KA | Other/Unknown | Unspecified/Unknown | Unit #1 and unit #2 were traveling eastbound on Kossuth. Unit #2 attempted to enter the roundabout, was struck by Unit #1, and both units spun out. One driver was transported with serious injuries. |

## Hot Spot Analysis

The hotspot analysis shown in the Figure 4.10 identifies areas across Ohio where roundabout-related crashes were statistically more concentrated (hot spots) or less concentrated (cold spots). The analysis was conducted using the Getis-Ord Gi\* statistic, which helps find clusters of high or low crash occurrences that are unlikely to have occurred by chance. Several previous studies have used Getis-Ord Gi\* to identify hot spots and cold spots (Jana and Sar, 2016; Peeters et al., 2015; Rossi and Becker, 2019). Each round dot on the map represents a roundabout crash location from 2017 to 2021. The different colors show how statistically significant those clusters are. Red and orange dots indicate hot spots, where crashes occurred more frequently than in other areas. These are locations where roundabout crashes are more concentrated and may reflect consistent safety problems. The shades of red reflect confidence levels, darker red means a higher confidence (up to 99%) that the clustering is meaningful. Similarly, blue dots indicate cold spots, or areas where crashes occurred less frequently than expected, also measured at different confidence levels. From the map, several regions stand out as hot spots, especially around Cincinnati, Columbus, Toledo, and Cleveland. These urban areas have a higher density of roundabouts and higher traffic volumes, which may explain why crashes are more common there. The presence of high-confidence hot spots in these cities suggests that there may be location-specific design issues, high traffic exposure, or behavioral trends among drivers that lead to repeated crash patterns. In contrast, some small pockets of cold spots, particularly in the central and southeastern parts of the state, show areas where roundabout crashes are less frequent. These may be rural or lower-traffic regions. The areas marked as “Not Significant” in gray represent locations where crash counts do not show strong clustering, meaning the crashes there may be more random or isolated. The results support the idea that while roundabouts generally improve safety, crash risks remain higher in specific cities and traffic environments.

A map of the united states

AI-generated content may be incorrect.

Figure 4.10 HotSpot analysis of crash locations

# CONCLUSIONS

**V**

This thesis provided a comprehensive examination of crashes occurring at roundabouts in Ohio, utilizing an integrated approach that combines CCA, SHAP-based model interpretation, and spatial hotspot mapping. The analysis of 6,448 crash records from 2017 to 2021 revealed important patterns about how, when, and why roundabout crashes happen, and offers guidance for improving intersection safety in real-world settings. A central finding from this work is that while roundabouts overall continue to reduce the likelihood of fatal and serious injuries compared to traditional intersections, crashes still occur and often follow distinct patterns. Many crashes result from drivers failing to yield, making improper maneuvers inside the roundabout, or misjudging distances in multi-lane environments. The study also showed that low-visibility conditions and high-speed approaches can lead to severe ROR or fixed-object collisions, and that rear-end crashes frequently happen when drivers follow too closely in circulating traffic. Importantly, most crashes at roundabouts in Ohio are of low severity, with property damage only, but the small share of serious outcomes is tied to very specific circumstances such as nighttime, bad weather, or high-speed environments. The data highlighted that both younger and older drivers face unique challenges at roundabouts, suggesting the need for education that addresses a broad range of driver experience and ability.

To supplement the structured data analysis, a focused review of fatal and severe injury crash narratives was conducted. The narratives provided deeper insights into how these crashes unfold. Many of the serious crashes involved drivers failing to yield, entering the roundabout at high speeds, or losing control and striking fixed objects. Some drivers rolled over after leaving the roadway or crashed head-on during confused or aggressive maneuvers. Several narratives also mentioned poor decision-making under pressure, such as sudden entry without checking for circulating vehicles or overcorrecting on curves. Cases involving vulnerable road users, high-speed pursuits, and stolen vehicles were also noted, revealing that even rare but extreme behaviors can lead to critical outcomes. These accounts helped confirm and enrich the patterns identified through CCA and SHAP by highlighting real-world scenarios behind the data and reinforcing the need for specific countermeasures that address both behavioral and environmental risks.

This research stands out for several reasons. By using CCA, the study moves beyond simple before-and-after comparisons and basic regression models, providing a clearer picture of the complex interactions between driver behavior, road design, vehicle type, and environmental factors. The addition of SHAP analysis brings interpretability to machine learning predictions, revealing the exact contribution of each factor to crash severity in a way that is accessible for practitioners and policymakers. The spatial hotspot analysis also adds a practical layer, helping to pinpoint not only where roundabout crashes happen most frequently, but also offering clues about the types of interventions likely to be most effective in those settings. In doing so, the research directly addressed major gaps in existing literature by identifying previously overlooked crash patterns and combining advanced analytical techniques for a more complete understanding of roundabout safety. All the core aims of this study have been met. The work provided new evidence about the nature of roundabout crashes, explains how various factors combine to affect crash outcomes, and demonstrates how advanced analysis methods can support data-driven decision making. By drawing on recent and location-specific data, the findings are grounded in real-world practice. The research also illustrated how integrating spatial, statistical, and explainable machine learning approaches can yield a richer understanding than relying on any single method.

In relation to the research questions and objectives, this study successfully addressed the intended goals. The analysis identified the main factors contributing to different types of injuries at roundabouts, grouped crashes based on similar patterns using CCA, and explored how these patterns connect to injury severity. The influence of driver behavior, vehicle type, environmental conditions, and spatial concentration of crashes across Ohio was also examined. Regarding design features, the study found that crashes occur more frequently at multi-lane roundabouts compared to single-lane roundabouts, suggesting that roundabout configuration and complexity play an important role in crash risk. Although the study did not include detailed geometric measurements for every roundabout, the available data clearly showed that multi-lane designs are associated with a greater number of crashes and certain types of driver errors, such as improper lane changes and confusion inside the roundabout.

Based on the findings, several practical policy implications emerge. Improving entry design and yield controls should be a priority, with engineering measures such as tighter entry curvature, splitter islands, and highly visible yield signage likely to reduce the frequency of entry-related crashes. Multi-lane roundabouts would benefit from better lane-use guidance, including overhead signs, pavement markings, and clear diagrams that help drivers select and stay in the correct lane. Upgrading lighting and visibility at roundabouts, especially in suburban and rural areas, can directly address the problem of severe night-time or poor weather crashes. Advisory speed plaques and speed feedback signs should be considered at roundabout entries to encourage slower, safer approaches, while enforcement of following distance and speed, where feasible, may also help reduce rear-end collisions. Public education efforts should target both young and older drivers to address the specific types of errors most commonly seen among these groups. Where clusters of crashes have been identified in urban areas, local agencies should prioritize safety audits and rapid improvements at those sites.

Despite the strengths of this study, several important limitations should be recognized. First, the analysis relied on administrative crash reports, which do not always provide the full story behind each crash. For example, it is often difficult to tell exactly what happened in complex situations, such as whether a crash in a multi-lane roundabout was caused by a risky lane change, a missed yield, or confusion about which lane to use. The lack of detailed trajectory data, in-vehicle video, or precise movement records means that many subtle or near-miss events could not be observed, and some crash patterns may be grouped together even if their causes were different. The study was also limited by the absence of detailed geometric data for each roundabout, such as entry and exit angles, lane widths, or sight distance. This made it challenging to pinpoint how specific design features influence crash risk or severity, especially for questions about how roundabout layout and visibility might lead to more frequent or more severe crashes. Without this level of detail, the study could only broadly compare multi-lane and single-lane roundabouts, rather than identify which design elements are most critical for safety. Another limitation is that the analysis could not account for driver distractions, vehicle speeds at the time of the crash, or real-time traffic volumes, all of which are factors that likely influence crash risk but are rarely captured in standard reports. This limits the ability to fully understand the influence of driver behavior or exposure on crash outcomes.

Looking ahead, several directions for future work are clear. More detailed studies using naturalistic driving data or roadside video can help clarify the human factors and vehicle interactions underlying roundabout crashes, especially in multi-lane and complex settings. Testing specific interventions, such as enhanced signage, lighting, or lane guidance, at crash-prone roundabouts and evaluating their real-world impacts would provide direct evidence for the recommendations proposed here. Incorporating vehicle-to-vehicle interaction modeling, as well as linking crash data with maintenance records or weather sensors, could further enrich future analyses and improve the predictive power of safety models. Finally, as new vehicle technologies and connected infrastructure become more common, ongoing monitoring and research will be needed to ensure that roundabout designs and policies continue to deliver real safety benefits for all users. This thesis advances both the science and practice of roundabout safety analysis by providing a detailed, subtle, and practical understanding of crash patterns, risk factors, and potential interventions. This approach demonstrates how applying CCA to identify groups of crashes with similar characteristics, using SHAP to explain which factors most affect crash severity, and conducting spatial analysis to locate high-risk roundabout sites together allows for a more complete and practical understanding of roundabout safety issues.

# REFERENCES

Al-Madani, H.M.N., 2022. Multilane Roundabout Capacity: Methodology Formation and Model Formulation. International Journal of Intelligent Transportation Systems Research 20, pp 223-237. https://doi.org/10.1007/s13177-021-00286-x

Ashqar, H.I., Alhadidi, T.I., Elhenawy, M., Jaradat, S., 2024. Factors affecting crash severity in Roundabouts: A comprehensive analysis in the Jordanian context. Transportation Engineering 17, 100261. https://doi.org/10.1016/j.treng.2024.100261

Avelar, R., Park, E.S., Kutela, B., Texas A&M Transportation Institute, Federal Highway Administration, 2023. Developing Crash Modification Factors for Mini-Roundabouts.

Breiman, L., Cutler, A., Liaw, A., Wiener, M., 2024. randomForest: Breiman and Cutlers Random Forests for Classification and Regression.

Burdett, B., Alsghan, I., Chiu, L.-H., Bill, A.R., Noyce, D.A., 2016. Analysis of Rear-End Collisions at Roundabout Approaches. Transportation Research Record: Journal of the Transportation Research Board pp 29-38. https://doi.org/10.3141/2585-04

Burdett, B., Bill, A.R., Noyce, D.A., 2017. Evaluation of Roundabout-Related Single-Vehicle Crashes. Transportation Research Record: Journal of the Transportation Research Board pp 17-26. https://doi.org/10.3141/2637-03

Campi, E., Mastinu, G., Previati, G., Studer, L., Uccello, L., 2024. Roundabouts: Traffic Simulations of Connected and Automated Vehicles—A State of the Art. IEEE Transactions on Intelligent Transportation Systems 25, pp 3305-3325. https://doi.org/10.1109/TITS.2023.3325000

Chakraborty, R., Das, S., Mimi, M.S., Kutela, B., 2024. Investigating Factor Associations in Barrier Crashes through Cluster Correspondence Analysis. Transportation Research Record 03611981241297976. https://doi.org/10.1177/03611981241297976

Chakraborty, R., Mills, D., Das, S., 2025. Children on wheels: Identifying crash determinants using cluster correspondence analysis. Accident Analysis & Prevention 216, 108025. https://doi.org/10.1016/j.aap.2025.108025

Chen, T., He, T., Benesty, M., Khotilovich, V., Tang, Y., Cho, H., Chen, K., Mitchell, R., Cano, I., Zhou, T., Li, M., Xie, J., Lin, M., Geng, Y., Li, Y., Yuan, J., 2024. xgboost: Extreme Gradient Boosting.

Choi, J., Joo, Y.-J., Kim, D.-K., 2024. Effects of heterogeneity in driving manoeuvres on calibrating car-following models at a roundabout. Transportmetrica B: Transport Dynamics 12, 2386537. https://doi.org/10.1080/21680566.2024.2386537

Das, S., Hossain, M.M., Ashifur Rahman, M., Kong, X., Sun, X., Al Mamun, G. m., 2023. Understanding patterns of moped and seated motor scooter (50 cc or less) involved fatal crashes using cluster correspondence analysis. Transportmetrica A: Transport Science 19, 2029613. https://doi.org/10.1080/23249935.2022.2029613

Das, S., Mousavi, S.M., Shirinzad, M., 2022a. Pattern recognition in speeding related motorcycle crashes. Journal of Transportation Safety & Security 14, pp 1121-1138. https://doi.org/10.1080/19439962.2021.1877228

Das, S., Sun, X., Dadashova, B., Rahman, M.A., Sun, M., 2022b. Identifying Patterns of Key Factors in Sun Glare-Related Traffic Crashes. Transportation Research Record: Journal of the Transportation Research Board 2676, pp 165-175. https://doi.org/10.1177/03611981211037891

Dzinyela, R., Dadashova, B., Westfall, G., Das, S., Silvestri-Dobrovolny, C., Adanu, E.K., Lord, D., 2025. Analysis of motorcyclists crash severity using cluster correspondence and hierarchical binary logit models. Multimodal Transportation 4, 100197. https://doi.org/10.1016/j.multra.2025.100197

FHWA, 2025. Turbo Roundabouts: Support Safety, Efficiency, and Increased Capacity.

FHWA, 2010. Chapter 9 - Alternative Intersections/Interchanges: Informational Report (AIIR), April 2010 - FHWA-HRT-09-060 [WWW Document]. URL https://www.fhwa.dot.gov/publications/research/safety/09060/009.cfm (accessed 6.18.25).

Hossain, A., Sun, X., Thapa, R., Hossain, Md.M., Das, S., 2023. Exploring association of contributing factors to pedestrian fatal and severe injury crashes under dark-no-streetlight condition. IATSS Research 47, 214–224. https://doi.org/10.1016/j.iatssr.2023.03.002

Hu, W., Cicchino, J.B., 2019. Long-term crash trends at single- and double-lane roundabouts in Washington State. Journal of Safety Research 70, 207–212. https://doi.org/10.1016/j.jsr.2019.07.005

Jana, M., Sar, N., 2016. Modeling of hotspot detection using cluster outlier analysis and Getis-Ord Gi\* statistic of educational development in upper-primary level, India. Model. Earth Syst. Environ. 2, 60. https://doi.org/10.1007/s40808-016-0122-x

Jiang, H., Shen, Q., Li, A., Yin, C., 2024. A Review of Traffic Behaviour and Intelligent Driving at Roundabouts Based on a Microscopic Perspective. Transportation Safety and Environment 6, tdad031. https://doi.org/10.1093/tse/tdad031

Johnson, M.T., 2019. Safety Impacts of Signing and Pavement Markings on Property-Damage-Only Crashes at Multi-Lane Roundabouts. Transportation Research Record: Journal of the Transportation Research Board. https://doi.org/10.1177/0361198118823738

Khekare, P., Bonthu, S., Hunt, V., Helmicki, A., Lee, K., 2022. A Case Study on Multilane Roundabout Capacity Evaluation Using Computer Vision and Deep Learning. Journal of Computing in Civil Engineering 36, 05022001. https://doi.org/10.1061/(ASCE)CP.1943-5487.0001007

Kong, X., Das, S., Zhang, Y., Wu, L., Wallis, J., 2022. In-Depth Understanding of Near-Crash Events Through Pattern Recognition. Transportation Research Record: Journal of the Transportation Research Board 2676, pp 775-785. https://doi.org/10.1177/03611981221097395

Li, L., Zhang, Z., Xu, Z.-G., Yang, W.-C., Lu, Q.-C., 2024. The role of traffic conflicts in roundabout safety evaluation: A review. Accident Analysis & Prevention 196, 107430. https://doi.org/10.1016/j.aap.2023.107430

Long, K., Hu, J., Gao, Z., Ma, C., Yang, X., 2023. Optimal Controller for a Roundabout with Cooperative Optimization. Journal of Transportation Engineering, Part A: Systems 149, 04022118. https://doi.org/10.1061/JTEPBS.0000780

Lundberg, S., Lee, S.-I., 2017. A Unified Approach to Interpreting Model Predictions. https://doi.org/10.48550/arXiv.1705.07874

Maji, A., Ghosh, I., 2025. A systematic review on roundabout safety incorporating the safety assessment methodologies, data collection techniques, and driver behavior. Safety Science 181, 106661. https://doi.org/10.1016/j.ssci.2024.106661

Mandavilli, S., McCartt ,Anne T., and Retting, R.A., 2009. Crash Patterns and Potential Engineering Countermeasures at Maryland Roundabouts. Traffic Injury Prevention 10, 44–50. https://doi.org/10.1080/15389580802485938

Masi, S., Xu, P., Bonnifait, P., 2022. Roundabout Crossing With Interval Occupancy and Virtual Instances of Road Users. IEEE Transactions on Intelligent Transportation Systems 23, pp 4212-4224. https://doi.org/10.1109/TITS.2020.3042870

Mohamed, A.I.Z., Ci, Y., Tan, Y., 2020. Safety Performance Evaluation of the New Mega Elliptical Roundabout Interchanges Using the Surrogate Safety Assessment Model. Journal of Transportation Engineering, Part A: Systems 146, 04020137. https://doi.org/10.1061/JTEPBS.0000463

Munshi, A.K., Patnaik, A.K., 2023. Selecting a Suitable Model for Roundabout Entrance Capacity Estimation: A Case Study. Romanian Journal of Transport Infrastructure 12, 17p. https://doi.org/10.2478/rjti-2023-0013

NACTO, 2025. Roundabouts and Circular Intersections. NACTO. URL https://nacto.org/publication/urban-bikeway-design-guide/designing-safe-intersections/unsignalized-intersections/roundabouts-and-circular-intersections/ (accessed 6.18.25).

Novat, N.K., Kwigizile, V., Oh, J.-S., 2024. Impact of Slip Lanes on Pedestrian Safety at Roundabouts Considering Autonomous Vehicles. Transportation Research Record: Journal of the Transportation Research Board. https://doi.org/10.1177/03611981241275562

Peeters, A., Zude, M., Käthner, J., Ünlü, M., Kanber, R., Hetzroni, A., Gebbers, R., Ben-Gal, A., 2015. Getis–Ord’s hot- and cold-spot statistics as a basis for multivariate spatial clustering of orchard tree data. Computers and Electronics in Agriculture 111, 140–150. https://doi.org/10.1016/j.compag.2014.12.011

Polders, E., Daniels, S., Casters, W., Brijs, T., 2015. Identifying Crash Patterns on Roundabouts. Traffic Injury Prevention 16, pp 202-207. https://doi.org/10.1080/15389588.2014.927576

Rahman, M.A., Das, S., Hossain, A., Codjoe, J., Mitran, E., Sun, X., 2024. Exploring Attribute Associations in Pedestrian-Involved Hit-and-Run Crashes through Cluster Correspondence Analysis. Transportation Research Record 03611981241242751. https://doi.org/10.1177/03611981241242751

Rossi, F., and Becker, G., 2019. Creating forest management units with Hot Spot Analysis (Getis-Ord Gi\*) over a forest affected by mixed-severity fires. Australian Forestry 82, 166–175. https://doi.org/10.1080/00049158.2019.1678714

Saccomanno, F.F., Cunto, F., Guido, G., Vitale, A., 2008. Comparing Safety at Signalized Intersections and Roundabouts Using Simulated Rear-End Conflicts. Transportation Research Record 2078, 90–95. https://doi.org/10.3141/2078-12

Savolainen, P.T., Gates, T.J., Gupta, N., Megat-Johari, M.-U., Cai, Q., Imosemi, S., Ceifetz, A., McArthur, A., Hagel, E.C., Smaglik, E.J., 2023. Evaluating the Performance and Safety Effectiveness of Roundabouts – An Update (No. SPR-1725).

Schneider, E.M., D’Ambrosio, L.A., Lee, C., Coughlin, J.F., 2024. Impacts of Advanced Vehicle Technologies and Risk Attitudes on Distracted Driving Behaviors. Transportation Research Record: Journal of the Transportation Research Board 2678, pp 622-634. https://doi.org/10.1177/03611981241242079

Shetty, V., Sauciur, M., Pande, A., Mineta Transportation Institute, State of California, California Department of Transportation, Department of Transportation, 2025. Investigating the Conversion of a Signalized Intersection to a Turbo Roundabout (Digital/other). https://doi.org/10.31979/mti.2025.2233

Singleton, P., Poudel, N., Utah State University, L., Mountain-Plains Consortium, Office of the Assistant Secretary for Research and Technology, 2024. Investigating Bicyclist Safety Perceptions and Behaviors at Roundabouts.

Sourial, N., Wolfson, C., Zhu, B., Quail, J., Fletcher, J., Karunananthan, S., Bandeen-Roche, K., Béland, F., Bergman, H., 2010. Correspondence analysis is a useful tool to uncover the relationships among categorical variables. Journal of Clinical Epidemiology 63, 638–646. https://doi.org/10.1016/j.jclinepi.2009.08.008

Steyn, H.J., Griffin, A., Lee, A.R., 2015. A Review of Fatal and Severe Injury Crashes at Roundabouts.

Trullos, J., Zhang, M., Junghans, M., Gimm, K., 2023. Criticality dimension-based probabilistic framework to detect near crashes in a roundabout. European Transport Research Review 15, 35. https://doi.org/10.1186/s12544-023-00602-4

van de Velden, M., D’Enza, A.I., Palumbo, F., 2017. Cluster Correspondence Analysis. Psychometrika 82, 158–185. https://doi.org/10.1007/s11336-016-9514-0

Van De Velden, M., D’Enza, A.I., Palumbo, F., 2017. Cluster Correspondence Analysis. Psychometrika 82, 158–185. https://doi.org/10.1007/s11336-016-9514-0

Vinayaraj, V.S., Perumal, V., 2023. Developing Safety Performance Functions and Crash Modification Factors for Urban Roundabouts in Heterogeneous Non-Lane-Based Traffic Conditions. Transportation Research Record: Journal of the Transportation Research Board 2677, pp 644-661. https://doi.org/10.1177/03611981231157727

Wang, J., Cicchino, J.B., 2022. Safety effects of roundabout conversions in Carmel, Indiana, the Roundabout City. Journal of Safety Research 82, pp 159-165. https://doi.org/10.1016/j.jsr.2022.05.007

WSDOT, 2025. Roundabouts | WSDOT [WWW Document]. URL https://wsdot.wa.gov/travel/traffic-safety-methods/roundabouts (accessed 6.18.25).