

**USING FATAL CRASH DATA TO
ANALYZE NATIONWIDE TRENDS IN
PEDESTRIAN SAFETY AT BUS STOPS**

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ABSTRACT

The multimodal nature of public transit requires bus stops to be safely accessible to passengers who begin and end their trips as pedestrians. Prior studies have analyzed bus stop safety using crash data, but many of these studies assume that all crashes within a given distance of a bus stop are directly related to the stop itself. This is likely due to the limited availability of data that specifically identifies transit bus stop-related crashes, which this study confirmed through an examination of transit-related information in safety various safety datasets. This thesis begins to address this gap by analyzing fatal "transit bus stop-related" pedestrian crashes reported in the Fatality Analysis Reporting System (FARS) and comparing them with other nearby fatal pedestrian crashes. The data was preprocessed to include only fatal transit bus stop-related crashes and other fatal pedestrian crashes within a quarter- and half-mile radii. Then, a binary logit model and hierarchical clustering compared fatal transit bus stop-related crashes with other nearby fatal pedestrian crashes. Last, an inventory of bus stop infrastructure was manually compiled to assess fatal transit bus stop-related crashes. The binary logit model indicated that midblock stops, pedestrians on the roadside, and bus-involved crashes are strong indicators of fatal transit bus stop-related crashes. The cluster analysis revealed three fatal transit bus stop-related crash scenarios: (1) crossing to/from an intersection stop, (2) waiting on the roadside at a midblock stop, and (3) crossing to/from a midblock stop. The clustering of both transit bus stop-related and other nearby crashes showed that fatal crashes involving a pedestrian waiting at a midblock stop clustered separately from other nearby fatal crashes. Finally, the inventory revealed that bus stop infrastructure generally improved after the crash, but disparities exist between crossing- and waiting-related crash locations. This thesis reveals how fatal transit bus stop-related crashes compare to other nearby fatal crashes, helping identify countermeasures specific to transit stops. Crossing improvements may benefit both transit passengers and other pedestrians in the immediate areas. Relocating transit stops to signalized intersections and converting in-lane stops to curbside pull-out stops may enhance bus stop safety.

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CHAPTER 1

INTRODUCTION

The United States reported 7,522 pedestrian fatalities on American roads in 2022, which was a 41-year high (NHTSA, 2024). The number of pedestrian fatalities has rapidly grown in recent years, with 2022 marking an 83% increase in compared to 2009 (NHTSA, 2024). This is increasingly concerning, as the proportion of traffic fatalities involving pedestrians has been rising in recent years (NHTSA, 2024). This trend warrants action to protect pedestrians and reduce the overall loss of life associated with transportation in the United States.

Numerous prior studies have identified public transit as a strategy to improve the safety of road users. Dickens and Shaum (2018) found that travel by transit is ten times safer per mile than traveling by car. Additionally, Bia and Ferenchak (2022) found an overall reduction in vehicle speeds after the construction of a Bus Rapid Transit (BRT) route in Albuquerque, New Mexico. Building upon this finding, Ferenchak and Woods (2025) identified a notable 19.1% reduction in speeding-related crashes on the same BRT corridor. To realize these and other safety benefits, pedestrians must be able to safely access and egress from bus stops. Not only does safe access to transit impact pedestrian safety, but it also affects transit ridership. Pedestrians tend to avoid walking in areas that are perceived as unsafe (Ferenchak & Marshall, 2019; Kweon et al., 2021). Therefore, if the walking trip to a bus stop is perceived as unsafe, some transit riders may opt for alternative modes of transportation, potentially reducing transit ridership. Hence, addressing safe access to bus stops is a vital consideration for improving pedestrian safety and the overall success of transit systems.

First-mile and last-mile access for transit riders is a critical component of this problem, as many of these trips are made by walking (Goughnour et al., 2022; Pulugurtha & Vanapalli, 2008; Ulak et al., 2021). Bus stops are pedestrian generators (Goughnour et al., 2022; Ulak et al., 2021), and prior studies have consistently established a relationship between pedestrian crashes and transit service through measures such as transit ridership and proximity to bus stops and transit corridors (Anis et al., 2024; Goughnour et al.,

2022; Hess et al., 2004; Pulugurtha & Penkey, 2010; Pulugurtha & Vanapalli, 2008; Singh et al., 2022; Ulak et al., 2021; Yu, 2024). However, the pedestrian crash data that has been used in most prior studies does not explicitly state whether the pedestrian was going to, leaving from, or waiting at a transit stop at the time of the crash. Instead, many studies have used pedestrian crash data to infer this relationship based on the distance between all pedestrian crashes and bus stops (Anis et al., 2024; Hess et al., 2004; Pessaro et al., 2017; Pulugurtha & Penkey, 2010; Pulugurtha & Vanapalli, 2008; Salum et al., 2024; Singh et al., 2022; Ulak et al., 2021; Voorhes Transportation Center, 2012; Yu, 2024). This may introduce uncertainty into the analysis, potentially underreporting or possibly overreporting pedestrian involvement. The lack of detail in pedestrian crash data makes it particularly challenging to identify crash characteristics specifically associated with bus stops, rather than characteristics of crashes based solely on proximity to bus stops.

In light of this, the objective of this thesis is to analyze pedestrian crash data that explicitly identifies crashes related to bus stops. This approach may offer a more accurate evaluation of the connection between pedestrian crashes and bus stops, as it avoids the limitations of methods that depend solely on spatial proximity to bus stops. This thesis is guided by the following research questions:

1. What types of data are currently used to analyze pedestrian safety at bus stops, and what additional data sources are available to support further research?
2. What are the characteristics of fatal transit bus stop-related pedestrian crashes?
3. How do fatal transit bus stop-related pedestrian crashes compare to other nearby fatal pedestrian crashes?

In Chapter 2, a comprehensive review of the literature on pedestrian safety at bus stops in the United States is presented. In Chapter 3, a review of transit-related safety datasets is conducted. Additionally, in Chapter 3, transit-related data from the Fatality Analysis Reporting System (FARS) is introduced as the primary data source for the analysis. Next, Chapter 4 describes the three-part methodology used in the thesis, which analyzed characteristics of fatal transit bus stop-related pedestrian crashes and compared them to other fatal pedestrian crashes that occurred nearby. In Chapter 5, the results of

the three-part analysis were presented and discussed. Chapter 6 summarizes the major contributions of this thesis, as well as limitations and areas for future research. The overarching structure of this thesis is shown in **Figure 1-1**.

Last, it should be noted that some sections of this thesis (Chapter 2, Chapter 4, and Chapter 5) are currently under review at the Journal of Safety Research: Rewalt, A., Brakewood, C., and Cherry, C. “An Analysis of Pedestrian Safety at Bus Stops Using FARS Data”.

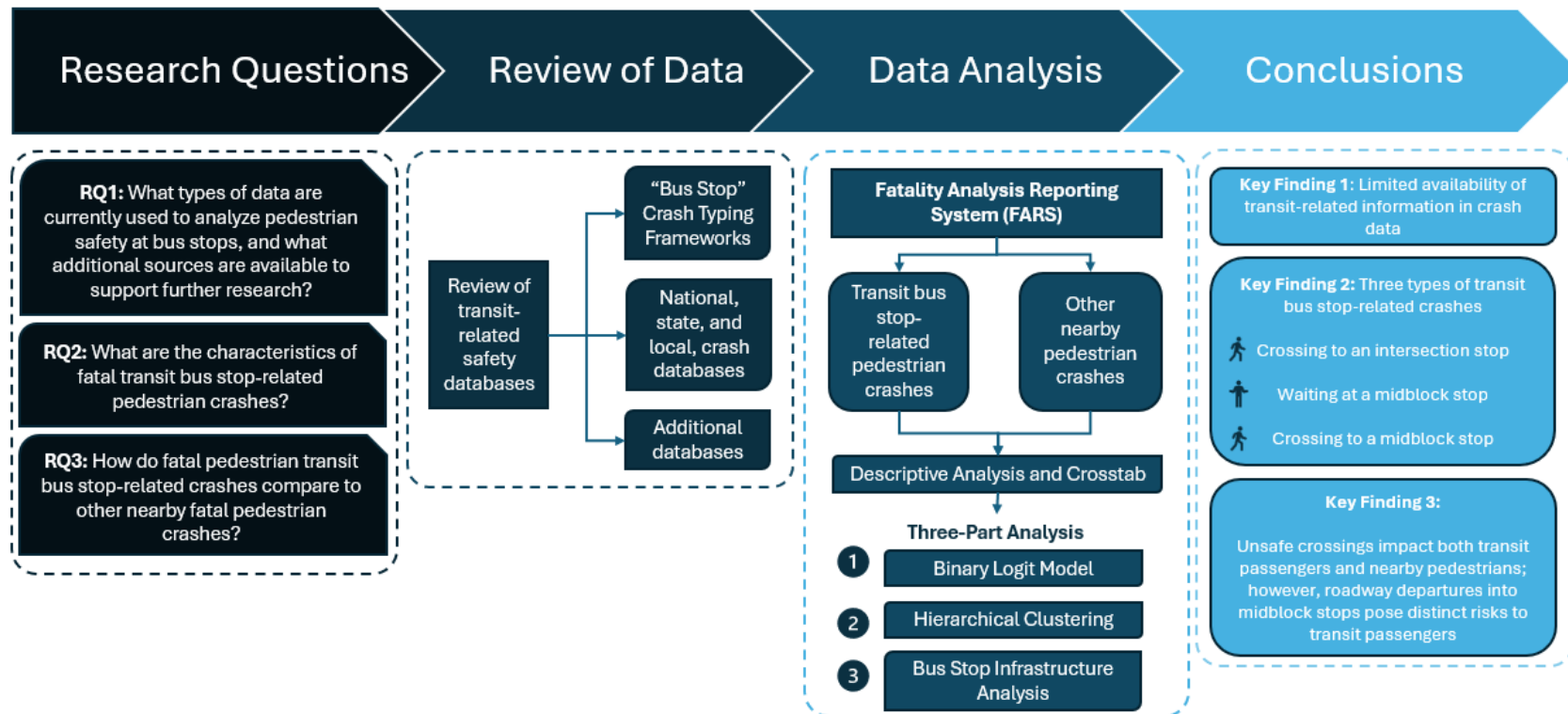


Figure 1-1 Thesis framework

CHAPTER 2

LITERATURE REVIEW

This chapter provides a review of literature from the United States over the past 20 years, including both academic research and studies by state DOTs and their partners, and it is summarized in **Table 2.1**. This review focuses on the data sources and methodological approaches used in prior studies. The limitations associated with these data sources and methods are then discussed. Next, a synthesis of key findings from the literature review is provided. Last, key gaps identified in the prior literature are presented.

Scope of the Literature Review

The scope of this literature review is limited to studies from the past 20 years that examine pedestrian safety at bus stops within the United States. While many prior studies have explored the relationship between pedestrian safety and transit, numerous studies have focused specifically on pedestrian-bus crashes rather than safety concerns at bus stops (Kaplan & Prato, 2012; Ragland et al., 1994; Samerei et al., 2021; Strathman et al., 2010; Zhou et al., 2020). Although several international studies address pedestrian safety at bus stops, such research is more limited in the United States (Hazaymeh, 2009; Phillips et al., 2021; Tiboni & Rossetti, 2013; Truong & Somenahalli, 2011). As a result, this review focuses exclusively on studies within the United States.

Data Sources and Methodologies

A major finding from the literature review is that none of the prior studies have used pedestrian crash data that explicitly states that a crash was related to a bus stop. Instead, these studies often relied on assumptions to establish a relationship between pedestrian safety and bus stops. Throughout the literature, this relationship was established using three main approaches: (1) the location-based assumption, (2) analysis of crash narratives, and (3) obtaining field observations. The following section will discuss the use of these approaches and their limitations.

Table 2.1 Summary of academic literature regarding pedestrian safety at bus stops

Study	Authors	Location	Data	Approach	Methodology	Conclusion
Pedestrian Safety and Transit Corridors (2004)	Hess, Moudon, Matlick	King County, WA	Pedestrian crash data, roadway characteristics, bus stop locations, Automatic Passenger Counters (APC), and land use data	Location-based assumption (250 ft)	Binary logistic regression model	An increase of 10 bus users raises the odds of a pedestrian crash at a nearby highway or arterial by 1.17 times
Hazardous Bus Stops Identification: An Illustration Using GIS (2008)	Pulugurtha, Vanapalli	Las Vegas, NV	Pedestrian crash data, traffic volumes, bus stop locations, ridership, and street centerline data	Location-based assumption (100 ft)	Pedestrian crash/bus stop heat map; Collision frequency, collision rate	Field observations found over 95% of pedestrian trips within 100 ft of bus stops are transit-related; Collision rate better identifies hazardous bus stops
Assessing Use of Pedestrian Crash Data to Identify Unsafe Transit Service Segments for Safety Improvements (2010)	Pulugurtha, Penkey	Charlotte, NC	Street and transit network, traffic volumes, ridership, bus stop locations, pedestrian crash data, and land use data	Location-based assumption (transit corridors)	GIS analysis of road segments with versus without transit	Transit segments have 4.9 times more pedestrian crashes per mile and 2.7 times more per million vehicle miles traveled (MVMT)
Pedestrian Safety and Yielding Near Public Transit Stops (2012)	Craig, Morris, Houten, Mayou	Saint Paul, MN	Average Daily Traffic (ADT), roadway characteristics and field observations of yielding behavior	Field observations	Field observations at unsignalized marked crosswalks; Stepwise regression models	Crosswalks near bus stops showed worse yielding rates (34.6%) than those not located near bus stops (46.3%)
Pedestrian Safety at Bus Stops (2014)	Alan M. Voorhes Transportation Center, Rutgers, University	New Jersey	Pedestrian crash data, bus stop locations, census data on population and employment	Location-based assumption (100 m); crash narratives; field observations	GIS analysis to identify bus stops in high-crash locations; field observations conducted at the high-risk locations	High-crash locations were concentrated on arterials with commercial land uses. Bus passengers engaged in risky midblock crossings, and parallel path conflicts were common at intersections

Table 2.1 (continued) Summary of academic literature regarding pedestrian safety at bus stops

Study	Authors	Location	Data	Approach	Methodology	Conclusion
Impact of Transit Stop Location on Pedestrian Safety (2017)	Pessaro, Catala, Wang, Spicer	Broward and Palm Beach County, FL	Pedestrian crashes, AADT, bus stop locations, boardings/alightings, crash narratives, stakeholder survey, road safety audits (RSAs)	Location-based assumption (100 ft); crash narratives; field observations	Bus stop ranking; site specific safety improvement recommendations	Most of the crashes involved a pedestrian crossing at an unmarked location or against the traffic signal
A Stop Safety Index to Address Pedestrian Safety Around Bus Stops (2021)	Ulak, Kocatepe, Yazici, Ozguven, Kumar	Palm Beach County, FL	Pedestrian crash data, bus stop locations (General Transit Feed Specification), bus frequency, ridership, population, employment, socio-demographics, facilities, and traffic indicators	Location-based assumption (decay function)	Spatial analysis of bus stops and pedestrian crashes using Cross K function; Stop Safety Index (SSI), using injury severity, pedestrian crashes, bus stop location, and a decay function	Bus stops and pedestrian crash locations have a significant spatio-statistical relationship; SSI ranks hazardous bus stops
Effect of Transit-Oriented Design on Pedestrian and Cyclist Safety Using Bivariate Spatial Models (2022)	Singh, Zhang, Cheng, Li, Clay	Los Angeles County, CA	Pedestrian, bicyclist, and vehicle-only crash data, socioeconomic, employment, land use, built environment, and transit-oriented development characteristics	Location-based assumption (0.5 mi)	Bivariate spatial analysis of pedestrian crashes near transit stops	More households, jobs, and transit stops correspond to more pedestrian crashes; more jobs, population, and express bus stops correspond to more bicyclist crashes
The Impact of Built Environments on Pedestrian Safety Around Bus Stops (2022)	Yu	Austin, TX	Pedestrian crash data, traffic volumes, bus stop, roadway, and land use characteristics	Location-based assumption (200 ft)	Analyzed pedestrian crashes using a negative binomial model; Controlled for variance with a variance inflation test; Excluded highly correlated variables	Crosswalks, sidewalks, and medians were linked to fewer pedestrian crashes near transit stops, while higher speed limits, big box stores, parking, nearside, and midblock stops were linked to more crashes

Table 2.1 (continued) Summary of academic literature regarding pedestrian safety at bus stops

Study	Authors	Location	Data	Approach	Methodology	Conclusion
Toolkit for the Assessment of Safety at Bus Stops (2023)	Salum, Kisabanzira, Alluri, Sando	Hillsborough, Jacksonville, Miami-Dade, FL	Bus stop characteristics (General Transit Feed Specification) and roadway characteristics inventory, land use, demographics, pedestrian crash data, AADT, ridership	Location-based assumption (100 ft)	Weighted bus stop safety score	The scoring methodology revealed that installing shelters and improving pedestrian facilities could improve the bus stops that performed the poorest.
Neighborhood Walking Environments Around Bus Stops: Report of Findings (2024)	Pilla, Yeager, Fitzpatrick, Steel, Grimes	Kansas City, MO	Inventory of sidewalks, crossings, bus stop amenities, aesthetics; observations of social conditions and perceived safety	Field observations	Audit of street characteristics near bus stops to evaluate conditions in disadvantaged zip codes.	Conditions varied across neighborhoods, with low-income areas facing worse conditions.
Pedestrian Safety and Traffic Operations Near Transit Stops (2024)	Singleton, Mandolakani, Subedi, Mekker	Utah	Video-based behavioral observation data at signalized intersections	Field observations	Aggregation of pedestrian and motorist behavior; bivariate analysis of traffic operations, crossing behavior, and turning vehicle conflicts with nearside/farside stops	While farside bus stops improve traffic operations, they negatively impact pedestrian safety
Safety Performance Functions by Random Parameters Negative Binomial-Lindley Model for Pedestrian Safety Near Bus Stops (2024)	Anis, Geedipally, Lord	Fort Worth, TX	Pedestrian crash data, bus stop data (locations, amenities, wheelchair accessibility), ridership, roadway inventory, AADT, land use characteristics	Location-based assumption (250 ft)	Sample of crash and zero crash bus stops; Random Parameters Negative Binomial-Lindley model	Signalized intersections and bus stop amenities reduced crash frequency. Non-signalized intersections and nearside stops increased crash frequency.

Location-based Assumption

The location-based assumption was the most widely used approach throughout the literature, with ten of the thirteen studies reviewed using this approach (Anis et al., 2024; Hess et al., 2004; Pessaro et al., 2017; Pulugurtha & Penkey, 2010; Pulugurtha & Vanapalli, 2008; Salum et al., 2024; Singh et al., 2022; Ulak et al., 2021; Voorhes Transportation Center, 2012; Yu, 2024). These studies obtained the locations of bus stops and defined a buffer radius around each bus stop. Using pedestrian crash data, any crash that occurred within the buffer zones of these bus stops was considered to be related to the bus stop in the analysis. An example of how this approach was typically used in the prior studies is shown in **Figure 2-1**. The relationship between pedestrian safety and bus stops was inferred solely based on the proximity of the bus stop to nearby crashes. This approach may have been used most frequently in the prior literature because of readily available data on pedestrian crashes, bus stop locations, roadway characteristics, ridership, and traffic volumes.

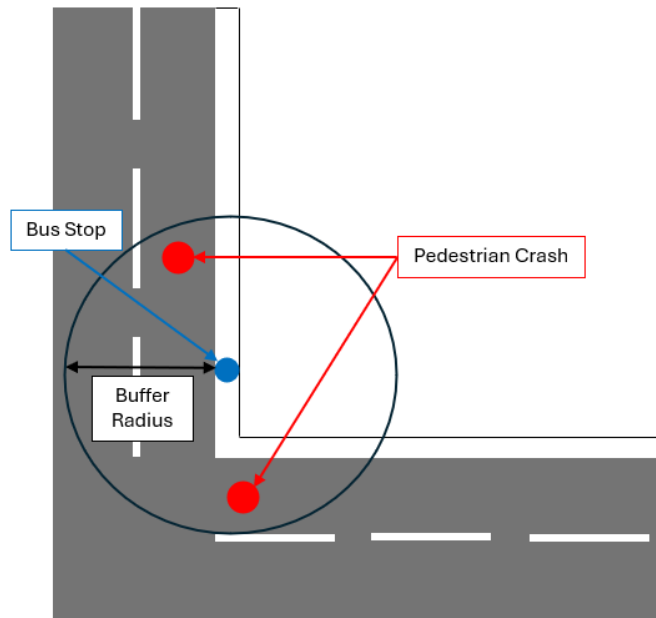


Figure 2-1 Example of location-based assumption used in prior studies

The location-based assumption introduces uncertainty in the extent of pedestrian involvement in the analysis. It may overreport pedestrian involvement, given that some crashes within the buffer zones may not have been related to the bus stop. Conversely, crashes may be underreported, as some relevant crashes may have occurred outside the buffer zone. Moreover, the size of the buffer zones varies throughout the literature, with some studies using a buffer as small as 100 feet, and others as large as a half mile (see **Table 2.1**). The sensitivity of the buffer zone is also commonly referenced as a limitation throughout the studies (Hess et al., 2004; Pessaro et al., 2017; Pulugurtha & Penkey, 2010; Pulugurtha & Vanapalli, 2008; Voorhes Transportation Center, 2012). Last, many of these studies are conducted locally, where bus stop density is high. As a result, crashes may be duplicated (i.e., the buffer zones of bus stops overlap, therefore the crash falls within the buffer zones of multiple bus stops). Duplication makes it challenging to determine which bus stop takes on the attributes of the crash, which is another limitation of this assumption.

Crash Narratives

Another approach used in existing literature involves analyzing the officer narrative from the crash report to determine whether the crash report indicates that a bus stop was a contributing factor (Pessaro et al., 2017; Voorhes Transportation Center, 2012). This approach is commonly used with the location-based assumption by reviewing the crash reports for all pedestrian crashes within a given distance of a bus stop. However, this approach is time-consuming, as an analyst must review each individual crash narrative. It may also be subjective in that it is the reviewer's discretion to decide whether a crash was related to a bus stop. Moreover, involving multiple reviewers may lead to inconsistencies in this interpretation. The extent of detail provided by the officer in the narrative can also impact the accuracy.

Field Observations

The third approach involves conducting field observations to document pedestrian and motorist behavior near transit stops, as well as to assess the surrounding environmental

and infrastructure conditions (Craig et al., 2019; Pessaro et al., 2017; Pilla et al., 2024; Singleton et al., 2024; Voorhes Transportation Center, 2012). This approach is occasionally used in combination with the location-based assumption and the analysis of crash narratives. However, this type of data collection is typically conducted on a local scale, which may limit its generalizability to nationwide trends. Collecting field observations is time-consuming, as it requires analysts to conduct site visits or review extensive video data.

Synthesis of Key Findings

Despite the limitations in available data sources and methods, prior studies have established a relationship between pedestrian safety and transit. Specifically, prior literature has associated increased risks with (1) bus stop locations, (2) ridership levels, (3) pedestrian and motorist behavior, and (4) stop spacing. In some of the prior studies, these factors were used as metrics for prioritizing higher-risk bus stops. The key findings from these studies are synthesized in the following sections.

Bus Stops and Pedestrian Crash Locations

Many studies aimed to explore the relationship between pedestrian crashes and their proximity to bus stops. Hess et al. (2004) established a relationship between bus boardings/alightings and pedestrian crash locations on urban arterials. Ulak et al. (2021) used the Global Cross K function method to establish a significant spatial correlation between bus stops and pedestrian crash locations. Similarly, Singh et al. (2022) identified a positive relationship between pedestrian crash frequency and bus stop density.

Anis et al. (2024) and Yu (2024) both used negative binomial models to assess the factors that increase pedestrian crash frequency near bus stops. Anis et al. (2024) found that increased traffic volume and ridership, and the absence of pedestrian facilities (refuge medians, crosswalks, and street lighting) increased crash frequency near bus stops, while signalized intersections, farside stops, and mixed land uses decreased crash frequency. A positive relationship between crash frequency and large parking supplies, big box stores, and gas stations was identified by Yu (2024). Both studies found that

increased sidewalk coverage was associated with decreased crash frequency near bus stops (Anis et al., 2024; Yu, 2024).

Many studies used pedestrian crashes near bus stops as criteria in the ranking methodology to prioritize bus stops of higher risk (Anis et al., 2024; Pessaro et al., 2017; Pulugurtha & Vanapalli, 2008; Salum et al., 2024; Ulak et al., 2021; Voorhes Transportation Center, 2012). For example, using a ranking methodology, one study found that pedestrian crashes were concentrated near bus stops along arterial roadways and in commercial areas. These bus stops were then further examined to identify potential causes of the relatively higher pedestrian crash frequency (Voorhes Transportation Center, 2012).

In summary, the prior literature has often relied on the location-based assumption; however, as mentioned previously, this approach is limited since it assumes that all crashes were related to the bus stops.

Ridership Levels and Pedestrian Crashes Near Bus Stops

Several studies established a link between ridership levels and pedestrian crashes. Hess et al. (2004) found that an increase of 10 transit riders increases the odds of a pedestrian crash on a nearby arterial or state highway by a factor of 1.17. Similarly, Pulugurtha and Penkey (2010) analyzed pedestrian crashes on transit corridors and found that 30.1% of center lane miles on transit corridors experienced more than 5 pedestrian crashes per 1,000 transit riders. Last, Anis et al. (2024) used transit passenger boarding and alighting data as a proxy for pedestrian volumes near bus stops and found that increased boarding and alighting activity was associated with higher crash frequency. Recognizing the potential association between ridership and pedestrian crashes near bus stops, other studies used ridership levels as a measure to prioritize bus stops of higher risk (Pulugurtha & Vanapalli, 2008; Salum et al., 2024). In summary, this relationship has been commonly noted in prior research; therefore, bus stops with higher ridership levels may be a strong consideration to prioritize bus stop safety.

Pedestrian and Motorist Behavior Near Bus Stops

Prior research consistently shows that both pedestrian and motorist behavior near bus stops influences pedestrian safety. Many studies specifically highlight pedestrian crossing behavior as a key area of focus. One study used crash narratives to identify crashes involving bus passengers and concluded that bus passengers are more likely to engage in risky midblock crossings (Voorhes Transportation Center, 2012). Another recent study used video data to observe pedestrian and motorist behavior near bus stops at intersections and concluded that transit riders were slightly more likely to cross midblock near farside stops (Singleton et al., 2024). Additionally, Pessaro et al. (2017) found that pedestrians near bus stops frequently crossed at unmarked locations or crossed against the traffic signal. Subsequently, both Craig et al. (2019) and Singleton et al. (2024) observed poor motorist yielding behavior near bus stops. The pedestrians' tendency to engage in risky crossing behaviors and the motorists' reduced awareness near bus stops raises a particularly significant area of concern for pedestrian safety at bus stops.

Stop Spacing and Pedestrian Safety

Stop spacing is an important consideration for both transit operational efficiency and pedestrian safety. However, there are conflicting findings from prior research on pedestrian safety at nearside and farside bus stops. Singleton et al. (2024) found that there were more severe outcomes for pedestrians crossing at farside stops due to worsened motorist yielding behavior at these locations. Other studies identified increased crash risks at nearside stops, likely due to the visual screen created by the bus in between crossing pedestrians and oncoming vehicular traffic (Voorhes Transportation Center, 2012). Additionally, Anis et al. (2024) established a reduced crash risk near bus stops at signalized intersections. This discrepancy may suggest that the crash risk at bus stops located at intersections are context-dependent and may be challenging to generalize due to various interacting factors like intersection design, pedestrian and motorist behavior, and signalization. Last, the relationship between crossings near midblock bus stops has been thoroughly documented in prior literature, with this action increasing the crash risk for pedestrians (Pessaro et al., 2017; Pulugurtha & Vanapalli, 2008; Voorhes

Transportation Center, 2012). Given these findings, midblock bus stops are a particularly important focus area for pedestrian safety, and high-visibility crossings should be provided at these vulnerable locations.

Research Gap and Framework for a Transit Passenger's Journey

This literature review first considered the data sources and methodologies used in prior research on pedestrian safety at bus stops and concluded that most studies utilized pedestrian crash data and employed a location-based assumption by linking crashes to bus stops using a buffer radius. Then, focusing on the key findings from the literature, many studies have established risks associated with (1) bus stop locations, (2) ridership levels, (3) pedestrian and motorist behavior, and (4) stop spacing. Based on this review, prior research has not used pedestrian crash data that explicitly identifies transit bus stop-related crashes. Instead, prior studies have depended on assumptions to infer the relationship between pedestrian safety and bus stops, which could introduce uncertainty into the analysis. The absence of such studies may stem from a lack of crash data that includes trip purpose information, particularly for trips to and from transit. Therefore, the data and methodologies used in previous studies may not fully consider the risks associated with a transit passenger's trip to and from a bus stop, as well as the time spent waiting at the bus stop itself. This thesis begins to address this gap in the research.

Conceptually, transit passengers can face various safety-related risks during their journey. These risks can perhaps be more clearly identified by considering the various stages of a transit passenger's complete journey (see **Figure 2-2**). Although additional risks are associated with boarding, alighting, and traveling on transit (stages that are shaded in black in **Figure 2-2**), this thesis focuses specifically on the walking and waiting portions of the trip (stages that are shaded in blue in **Figure 2-2**), which is when they are a pedestrian.

During the first and last stages of a typical trip, a transit passenger typically walks up to a quarter mile to and from a bus stop (Goughnour et al., 2022). Then, as transit passengers wait at the bus stop, they are exposed to passing vehicular traffic, which may influence their risk of being involved in a crash (Yu, 2024). They may also experience

greater exposure to buses compared to other pedestrians. Additionally, the environment in which a pedestrian waits, particularly whether the bus stop includes amenities, may influence crash risk. Because transit routes may serve higher-speed arterials, the risks may be exacerbated in these environments (Hess et al., 2004; Pulugurtha & Vanapalli, 2008; Yu, 2024).

Moreover, transit passengers must cross the road at least once during a complete transit trip (see dashed line in **Figure 2-2**, which shows the crossing happening on the return trip). Crossing risk may increase when buses are stopped at the bus stop, as they can obstruct the line of sight between motorists and pedestrians (Nabors et al., 2008). Additionally, during the walking stage, pedestrians may engage in risky crossing behavior due to the urgency to reach the bus stop before the bus departs.

To begin to address this gap and to analyze factors influencing pedestrian safety at bus stops focusing on the walking, waiting, and crossing stages of a typical transit passenger's journey. The next chapter presents a comprehensive search of safety databases that report transit-related details, upon which the transit bus stop-related pedestrian crashes in the Fatality Analysis Reporting System (FARS) were identified for further analysis.

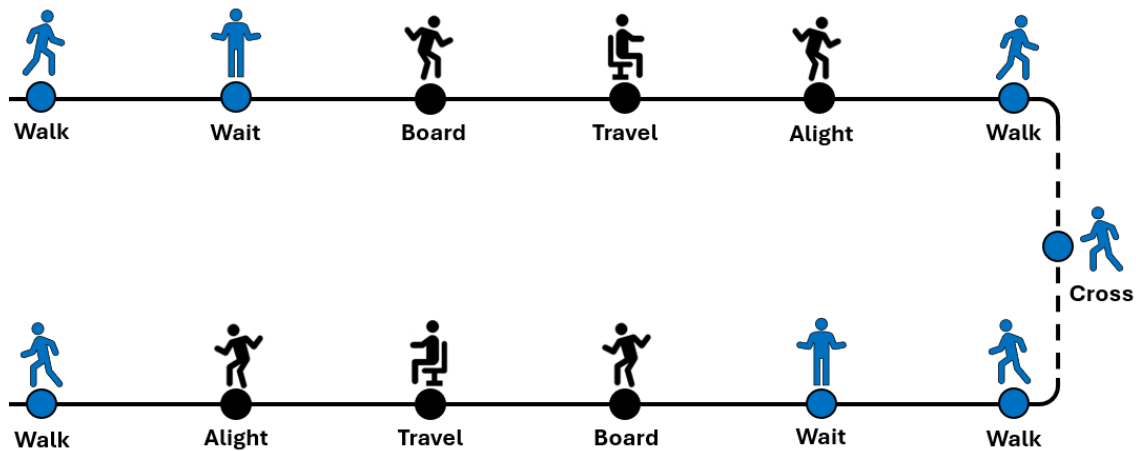


Figure 2-2 Stages of a transit trip

Adapted from Yendra et al. (2024)

CHAPTER 3

REVIEW OF DATA

The following chapter includes a review of transit-related safety databases, from which the primary data source for this thesis, the transit bus stop-related pedestrian crashes reported in the Fatality Analysis Reporting System (FARS), was selected. Given that the prior literature has not used data that explicitly states that a crash was a factor in a crash, this suggests that there may be a lack of transit-related safety information reported in the data. Therefore, the objective of the review of databases was to identify those applicable to research on pedestrian safety at bus stops. First, crash typing frameworks were reviewed to determine whether any included crash types related to bus stops. Then, crash databases across various geographic scales, including national, state, and local, were then evaluated to assess whether these frameworks are used in reporting. Finally, additional safety databases not primarily focused on crash data were examined for relevant transit-related information.

Transit-Related Crash Typing Frameworks

Crash data is commonly used in traffic safety analysis, offering valuable insights into crash trends and supporting infrastructure and policy decisions. Crash data reporting generally follows a standardized format to ensure consistency and comparability across agencies (local, state, and national). The Pedestrian and Bicyclist Crash Analysis Tool (PBCAT) and Model Minimum Uniform Crash Criteria (MMUCC) are two reporting frameworks commonly used in crash data that contain transit-related information.

Pedestrian and Bicyclist Crash Analysis Tool (PBCAT)

First, the PBCAT framework was introduced in 1999 to support agencies in categorizing vulnerable road user crashes. An updated version was released in 2006 (PBCAT 2.0), including a “*bus-related*” (#340) pedestrian crash group (Harkey et al., 2006). A crash is categorized as bus-related when “*the pedestrian was struck while crossing/walking to a bus or bus stop or while waiting at a bus stop*”. Within this crash group, there are two crash types: (1) “*commercial bus-related*” (#341) and (2) “*school bus-related*” (#342)

(Harkey et al., 2006). The separate categorization of commercial and school bus-related crashes is particularly beneficial because it supports targeted countermeasures to address the unique characteristics of each crash type. While PBCAT does not specify which types of bus services are classified as commercial bus-related, it is presumed that transit services are included within this scope. This may also include services like charter buses, shuttle services, or tourist buses, making it challenging to draw independent conclusions about transit-related crashes without the ability to isolate these crashes from the others that are included by definition. Additionally, commercial bus-related crashes depend on the presence of the bus, excluding crashes that occur at a bus stop when the bus is not present. This definition may lead to underreporting of crashes and overlooks potentially bus-related crashes that are unrelated to the presence of a bus.

The most recent version of PBCAT, updated in 2021 (PBCAT 3.0), addresses the aforementioned concerns by redefining “*commercial bus-related*” and expanding on the existing definition to create a hierarchical structure specific to “*transit-related*” crashes (Hamilton, 2021). First, “*transit*” is used instead of “*commercial*” to analyze crash risks associated with transit stops exclusively. Transit-related crash types were created to specify the action of both the non-motorist and motorist at the time of the crash, highlighting three main scenarios: [1] “*obstructed view*”, [2] “*bus pullover*”, and [3] “*other*”. This reclassification addresses some pedestrian safety challenges at transit stops and facilitates targeted countermeasures. For example, if “*bus pullover*” crashes are found to be problematic, installing pedestrian detection warning systems on transit buses to alert drivers may improve pedestrian safety around bus stops. On the other hand, frequent or severe “*obstructed view*” crashes may suggest a need for improved visibility of bus stops or nearby crossing facilities.

Model Minimum Uniform Crash Criteria (MMUCC)

Beginning in 2017, MMUCC (5th edition) adopted the crash factor “*related to a bus stop*”, which includes many activities leading to a crash associated with a bus stop (e.g. vehicles maneuvering around a bus waiting at the bus stop, pedestrians walking to/from the bus stop, and pedestrians crossing lanes of traffic to access the bus stop) (NHTSA,

2017). This definition is maintained in the most recent version of the framework, released in 2024 (6th edition) (NHTSA, 2025). While the MMUCC framework is more widely used for crash reporting by agencies compared to PBCAT, the "*related to a bus stop*" data element does not differentiate between school and transit bus stop crashes, which is a significant limitation of this framework.

National, State and Local Databases

Many national, state, and local agencies have used these frameworks in their crash data. Additionally, some agencies have reported transit-related information outside the scope of these frameworks. The following sections are a discussion of these datasets that were identified by reviewing publicly available raw data, data dictionaries, and crash dashboards for transit-related data fields. This discussion is limited to fifteen datasets; additional datasets may exist but may not be publicly available or were not identified during this search.

National Databases

The review of nationwide databases revealed three main sources that report transit-related information: the Fatality Analysis Reporting System (FARS), the Crash Reporting Sampling System (CRSS), and the National Transit Database (NTD). Each of these databases is managed by federal agencies and includes several years of data, though they differ in scope and sample size. The following provides an overview of their characteristics and how each contributes to the understanding of pedestrian safety at bus stops.

FARS is a national crash database maintained by NHTSA (NHTSA, 2022c) . Beginning in 1975, FARS has documented a yearly population of police-reported fatal motor vehicle crashes in the United States. To be reported in FARS, a crash must involve a motor vehicle traveling on a trafficway and result in the death of at least one road user within 30 days of the crash (NHTSA, 2022c). Fatal crash information is collected from multiple state sources (including police crash reports, crash report supplements, vehicle registration files, driver records, roadway classification files, death certificates,

toxicology reports, and emergency medical service reports) and standardized into over 170 FARS data elements.

In 2014, FARS adopted a version of the PBCAT 2.0 framework for reporting transit-related crashes (NHTSA, 2016). FARS modified the definition specified in PBCAT 2.0 from "*commercial bus-related*" to "*transit bus stop-related*" to narrow the scope to transit stops. The definition clarifies that this crash type applies to all pedestrians, regardless of the pedestrians' intent to ride the bus. It also specifies that the crash type includes all vehicle types and is not limited to pedestrian-bus crashes. FARS has reported 196 pedestrians involved in fatal transit bus stop-related crashes over the nine years of data available. Additionally, in 2020, FARS implemented the MMUCC framework to include the "*related to a bus stop*" crash factor in the data reporting process (NHTSA, 2022a). There have been 122 fatal crashes that were related to a bus stop since the adoption in 2020.

CRSS, also maintained by NHTSA, is a nationally representative sample of motor vehicle crashes in the United States (NHTSA, 2022b). The database was introduced in 2016 as an expansion of its predecessor, the National Automotive Sampling System General Estimates System (NASS GES). CRSS samples police-reported motor vehicle crashes that occur in 60 predefined locations in the United States. These locations are chosen to reflect the geography, population, travel behavior, and crash characteristics of the United States. Additionally, the survey is designed to sample crashes of greater relative importance (e.g. fatal crashes and pedestrian-involved crashes). Trained coders translate the crash reports into 120 CRSS data elements and each crash is assigned a case weight which is representative of the annual estimate of crashes. CRSS documents the same transit-related information that is included in FARS. The adapted definition from PBCAT 2.0 has been documented in CRSS since 2016 and has reported 83 pedestrians involved in transit bus stop-related crashes. The definition from MMUCC was implemented in 2020 and has reported 151 crashes that were related to a bus stop.

NTD, on the other hand, is not a traditional crash dataset; rather it collects data on Safety and Security incidents occurring on public transportation systems. The Federal Transit Administration (FTA) manages NTD, which is a collection of agency-reported

annual financial, operational, and asset statistics (Federal Transit Administration, 2025). Among these statistics, agencies are required to report incidents that meet the Safety and Security reporting threshold. These incidents generally include fatalities (including suicides and assaults), injuries, property damage, crashes (resulting in a fatality, injury, or property damage; involving a transit vehicle; involving a security breach), and evacuations. Rather than focusing solely on transit stops, the reporting system covers all aspects of transit operations that meet major safety event reporting thresholds.

Since 2014, NTD has reported 5270 pedestrians involved in crashes with transit vehicles that met the reporting threshold for a major safety event (Federal Transit Administration, 2025). While NTD does not report the same detailed data fields as traditional crash datasets, such as infrastructure (e.g., speed limit, functional classification) and person characteristics (e.g. age, sex, driver/pedestrian impairment) it does specify whether the pedestrian was in a crosswalk at the time of the incident and whether the pedestrian was a transit rider, which adds valuable context for understanding pedestrian safety in transit environments. NTD also provides a description of each event, offering additional insights that may not be captured in structured data fields, which is not provided in FARS or CRSS.

While this search revealed that there are few national crash databases that report transit-related information, FARS, CRSS, and NTD are valuable resources for pedestrian safety research due to their detailed information, larger sample sizes (compared to individual state and local crash databases), and ability to capture nationwide trends, as summarized in **Table 3.1**. However, the sample size of transit bus stop-related crashes in FARS and CRSS is limited, which is a significant limitation of these databases. Although NTD offers a substantially larger sample of pedestrian-transit vehicle crashes, it does not have a specific field for crashes that are related to transit stops, which may limit the depth of analysis compared to FARS and CRSS.

State Databases

The review of state databases identified at least six crash databases that utilize the PBCAT or MMUCC framework to report transit-related information. North Carolina and

Table 3.1 Summary of national transit-related safety databases

Database	Agency	Years	Description of Data	Transit-Related Definition	Sample Size
Fatality Analysis Reporting System (FARS)	NHTSA	2014-2022	Population of fatal police-reported crashes	· Transit bus stop-related (2014): adapted version of PBCAT 2.0: transit bus must be present at the transit stop at the time of the crash · Related to a bus stop (2020): definition consistent with MMUCC	n = 197 (pedestrians involved)
Crash Reporting Sampling System (CRSS)	NHTSA	2016-2022	Nationally representative sample of police-reported crashes	· Transit bus stop-related (2014): adapted version of PBCAT 2.0: transit bus must be present at the transit stop at the time of the crash · Related to a bus stop (2020): definition consistent with MMUCC	n = 83 (pedestrians involved)
National Transit Database (NTD) – Safety and Security	FTA	2014-2024	Collection of annual financial, asset, and operating data from public transit agencies nationwide	· Meets reporting threshold (per Safety and Security manual) OR · Occurs at a transit revenue facility, maintenance facility, or rail yard · Happens on transit right-of-way infrastructure · Occurs during a transit-related maintenance activity	n = 5097 (pedestrians involved)

Florida use the PBCAT 2.0 framework (“*commercial bus-related*”), while Illinois, Louisiana, Nebraska, and Utah use the MMUCC framework (“*related to a bus stop*”) (Christofferson, 2021; Federal Highway Administration, 2025; GeoPlan Center (University of Florida), 2021; Louisiana Highway Safety Commission, 2023; Nebraska Department of Transportation, 2023; North Carolina Department of Transportation, 2025). While several states utilize these frameworks, the sample sizes were often limited or the datasets were only available upon specific requests.

At least three state agencies report transit-related safety information using classifications beyond the PBCAT and MMUCC frameworks. Idaho’s crash data, managed by the Idaho Transportation Department (ITD), includes a data field that documents damaged infrastructure, including “*Bus Shelter*” as one of the possible options (Olsen, n.d.). Georgia’s crash data, managed by the Georgia Department of Transportation (GDOT), documents crashes involving non-motorists “*Entering/Exiting a*

Bus" and specifies which transit agency was involved in the crash (Georgia Department of Transportation, 2025). Minnesota's crash data, managed by the Minnesota Department of Transportation (MnDOT), documents the action of the pedestrian prior to the crash, with a specific category for individuals "*Going To or From Public Transit*" (Minnesota Department of Transportation, 2025).

Although several state datasets were identified (see **Table 3.2**), it is presumed that there are many more states that include the "*related to a bus stop*" data element in their crash reporting, since the MMUCC framework is a standard used by many states. However, this may not be readily apparent because many state crash datasets are private or only available upon request. Moreover, states vary in their implementation of this framework, as it is voluntary. Some states may use an earlier version of MMUCC that was developed prior to the definition of the "*related to a bus stop*" crash type in the 5th edition. A similar pattern was observed with the PBCAT framework. While many states implement PBCAT 2.0, which includes the "*commercial bus-related*" crash type, this review did not identify any states openly using PBCAT 3.0, which classifies transit-related crashes into three distinct types and offers a more detailed level of reporting.

Local Databases

The review identified at least four relevant local databases. All four of the databases reported transit-related details that are outside of the scope of PBCAT and MMUCC. The Highway Safety Information System (HSIS) provides detailed bus route and bus stop amenity information for Charlotte, North Carolina, which is also supplemented by crash and roadway data for the city (Federal Highway Administration, 2025). In Cleveland, Ohio, the Enhanced Transit Safety Retrofit Package (E-TRP) was piloted for six months to assess the safety implications of pedestrian detection warning systems on buses, specifically documenting events from the "Pedestrian in Crosswalk Warning (PCW)"

Table 3.2 Summary of statewide transit-related safety databases

Database	Organization	Years	Description of Data	Transit-Related Definition	Sample Size
Florida Traffic Safety Dashboard (Signal4Analytics)	UF Geoplan Center	2014-2025	Statewide crash dashboard for police-reported crashes	Commercial bus-related: definition consistent with PBCAT 2.0	Unavailable (information not public)
Georgia Crash Dashboard	GDOT	2013-2023	Statewide crash dashboard for police-reported crashes	· Entering/Exiting Bus: no details provided; data dictionary not public Transit Agency Involvement	n = 681 (pedestrians involved)
Idaho Crash Dashboard	ITD	2008-2025	Statewide crash dashboard for police-reported crashes	· Item Damaged = Bus Shelter: indicates whether property was damaged as a result of the crash	Unavailable (information not public)
Illinois Crash Data	HSIS	2019-2022	Multistate database that contains crash, roadway, and traffic characteristics for a select group of states	· Related to a bus stop: definition consistent with MMUCC	Available upon request
Louisiana Crash Data	CARTS	Unknown	Raw statewide police-reported crash data	· Related to a bus stop: definition consistent with MMUCC · Going To or From Public Transit: prior action of the non-motorist	Unavailable (information not public)
Minnesota Crash Data	MnDOT	2016-2023	Raw statewide police-reported crash data; publicly available upon request	· Going To or From Public Transit: prior action of the non-motorist	n = 39 (crashes)
Nebraska Crash Data	NDOT	Unknown	Raw statewide police-reported crash data	· Related to a bus stop: definition consistent with MMUCC · Going To or From Public Transit: prior action of the non-motorist	Unavailable (information not public)
North Carolina Non-Motorist Crash Map	NCDOT	2007-2022	Map of police-reported pedestrian and bicyclist crashes in North Carolina	· Commercial bus-related: definition consistent with PBCAT 2.0	n = 126 (crashes)
Utah Pedestrian Crash Dashboard	UHSO	2010-2025	Statewide crash dashboard for police-reported crashes	· Related to a bus stop: definition consistent with MMUCC	Unavailable (information not public)

system installed on these buses (U.S. Department of Transportation, 2025). The City of Los Angeles Traffic Collision dataset, maintained by the Los Angeles Police Department, includes a field that specifies the location of the incident, with "*Bus Stop*" being one of the options (Los Angeles Police Department, 2025). The Washington Metropolitan Area Transit Authority (WMATA) established voluntary "close call" reporting system that provides rail transit and bus employees to confidentially report near miss safety and security incidents that had the potential for harm but were narrowly avoided (Bureau of Transportation Statistics, 2025). This system allows WMATA to proactively address safety concerns, with the agency reporting 200 preventable actions since the adoption of the program.

Ultimately, the availability of transit-related information in local databases is limited, as this review did not identify any databases that use the PBCAT or MMUCC frameworks (see **Table 3.3**). Instead, local databases provide detailed information outside of crash typing frameworks, many of which can be linked with local crash data to help address pedestrian safety at bus stops, particularly in Charlotte, Cleveland, and WMATA. However, these databases may not address the factors directly associated with transit bus stop-related crashes as effectively as databases that use the PBCAT or MMUCC frameworks.

Selection of Data

The review of transit-related safety databases indicates that the availability of data for transit-related pedestrian safety research is limited. While national datasets like FARS and CRSS provide valuable insights through their broad coverage, standardized reporting formats, and ability to identify nationwide trends, they are relatively limited in sample size. Several state and local agencies maintain public crash databases containing transit-related information, supporting a more granular approach to analyzing pedestrian safety in transit environments. However, these datasets generally have very small sample sizes or reported information outside of the PBCAT and MMUCC frameworks. Most importantly, none of the datasets identified in the review have been used to analyze pedestrian safety at bus stops in prior research.

Based on this review, FARS was selected for analysis in this thesis due to its generalizability, longitudinal scope, and focus on fatal crashes. By exclusively reporting crashes that result in at least one fatality, FARS allows for a more focused analysis of the highest-risk scenarios related to transit bus stops.

Table 3.3 Summary of local transit-related safety databases

Database	Agency	Years	Description of Data	Transit-Related Definition	Sample Size
Charlotte, NC	HSIS	2018-2022	Multistate database that contains crash, roadway, and traffic characteristics for a select group of States	· Detailed information regarding bus route and bus stop amenities	Available upon request
Enhanced Transit Safety Retrofit Package – Cleveland, OH	FTA	2018	Data from 24 transit buses 3 locations over a 6 month test period	· Pedestrian detection warning systems at crosswalks (Pedestrian in Crossing Warning – PCW)	n = 15,609 (PCW alerts)
City of Los Angeles, CA Traffic Collision Data	LAPD	2010-2025	Traffic collision incidents in the City of Los Angeles; transcribed from original traffic reports	· Crashes occurring at a bus stop: reported in the “premise codes” element: the type of structure or location where the incident took place	n = 7 (crashes)
Confidential Close Call Reporting System	WMATA	2013-2025	Voluntary reporting of “Close Calls” or near miss safety and security events by WMATA employees	· Any event observed by a rail transit or bus system employee that was potentially dangerous but did not result in any serious harm	n = 300 (close call reports)

CHAPTER 4 METHODOLOGY

This chapter summarizes the statistical methods used to analyze crash data from FARS in this thesis, which was done in three parts. Prior to the three-part analysis, crosstabulations were conducted between transit bus stop-related crashes and other nearby fatal pedestrian crashes, which were identified using a nearby "buffer zone." Then, binary logit models were used to assess the characteristics that increase the probability of transit bus stop-related crashes compared to other nearby fatal pedestrian crashes. Next, hierarchical clustering was performed on the transit bus stop-related crashes to identify different crash scenarios. Additionally, the clustering was conducted on the combined samples of the transit bus stop-related crashes and other nearby fatal pedestrian crashes to evaluate whether the clustering would distinguish between the characteristics of transit bus stop-related crashes and other nearby crashes. Finally, a comparison of bus stop infrastructure was conducted at each bus stop where a fatal crash occurred to assess whether any changes in amenities may have been implemented in response to safety concerns at the bus stop.

Buffer Zone Crashes

To compare transit bus stop-related crashes to other nearby fatal pedestrian crashes, a comparison group was established consisting of fatal pedestrian crashes that have occurred near the transit bus stop-related crashes. This involved identifying and extracting relevant pedestrian crashes from the FARS database from 2014 to 2022. The process followed a similar approach to previous studies that used the location-based assumption and was conducted in ArcGIS, as described below:

1. The locations of transit bus stop-related pedestrian crashes were imported as the first layer (n = 175).
2. The full sample of crashes involving vulnerable road users over the same study period were imported as the second layer (n = 66,245).
3. A "buffer zone" with a radius of a quarter- and half-mile was defined around the location of each transit bus stop-related crash. The quarter-mile radius was chosen based on prior literature, which determined that most transit passengers are

willing to walk a maximum of a quarter mile to reach a bus stop (Goughnour et al., 2022). The half-mile radius was also used, as this was the greatest buffer radius identified in the review of previous studies using the location-based assumption (Singh et al., 2022). Two buffer radii were chosen to evaluate the sensitivity of the results as a response to varying buffer zone sizes.

4. A spatial join was performed to identify only those crashes that occurred within the buffer zones.

The study considers "pedestrians involved in fatal crashes" instead of individual crashes. As a result, each pedestrian is treated as a separate observation, rather than evaluating each crash as a whole. This approach is particularly important for crashes involving multiple pedestrians, as it allows for an examination of individual pedestrian-specific characteristics (e.g., demographic factors such as age, sex, and race) as well as circumstances specific to each pedestrian's involvement, such as impairment, distraction, or other contributing factors. This resulted in a final sample of 185 pedestrians involved in crashes within the quarter-mile buffer zone and 420 pedestrians within the half-mile buffer zone. As a result, for every 1 pedestrian involved in a transit bus stop-related crash, there were 0.9 pedestrians involved in a crash in the quarter-mile buffer zone and 2.1 pedestrians involved in a crash in the half-mile buffer zone.

Binary Logit Model

Next, a binary logit model was used to analyze the characteristics of transit bus stop-related crashes and compare them with other nearby fatal crashes. The results of this analysis provide insights into the factors that significantly increase the likelihood of a transit bus stop-related crash, highlighting how they differ from other fatal crashes occurring within close proximity.

Two models were estimated in total, one for each buffer zone. The dependent variable represented the crash type: "1" for transit bus stop-related crashes and "0" for other crashes within the buffer zone. The purpose of the varying buffer zones was to determine whether the results were sensitive to the buffer radius, which may provide insights into whether the characteristics of nearby crashes change significantly as the

buffer radius increases. The independent variables were chosen based on their significant association with the crash type in the crosstabulation. Each variable was tested iteratively in the model, and only the significant variables were retained in the final model.

Hierarchical Clustering Analysis

Hierarchical clustering is an unsupervised machine learning technique that groups observations with similar characteristics into clusters (Nielsen, 2016). This method is different than other clustering methods because it emphasizes the nested structure of the data. This study uses agglomerative hierarchical clustering, which assigns each observation to its own cluster and then iteratively combines them until there is a single cluster (Nielsen, 2016). In the context of pedestrian crash data, hierarchical clustering is typically used to identify similar crash types and reveal the underlying hierarchy of crash characteristics that might not be immediately apparent through other statistical models (Manasa et al., 2024; Nafis et al., 2022; Raihan et al., 2018).

First, a distance measure is specified to compute the dissimilarity of each observation. The Gower distance was used in this study because of its ability to handle mixed data types (Gower, 1971). First, the Gower similarity coefficient computes the average contribution of each variable. The result is a number between 0 (completely dissimilar) and 1 (identical observations) that is subtracted from 1 to obtain the Gower distance (Gower, 1971). The Gower distance was computed using the “cluster” package in RStudio (Maechler, 2018). The relationship is defined as follows:

$$d_{ij} = \frac{\sum_{k=1}^p w_k \delta_{ij}^{(k)} d_{ij}^{(k)}}{\sum_{k=1}^p w_k \delta_{ij}^{(k)}} \quad (1)$$

where d_{ij} is the Gower distance, w_k is the weight associated with the k^{th} variable, $\delta_{ij}^{(k)}$ is an indicator variable for binary variables (0 when both observations have a value of 0, 1 otherwise), and $d_{ij}^{(k)}$ is the dissimilarity between two observations for the k^{th} variable (Gower, 1971; Maechler, 2018).

Then, a linkage method is used to compute the distance between clusters. This study used Ward’s linkage method because it reduces variance within clusters (Ward Jr,

1963). After each iteration of merging, Ward's method minimizes within-cluster variance by evaluating the increase in the sum of squared differences.

The results of a hierarchical clustering analysis are typically displayed in a dendrogram, which is a tree-like structure that arranges the hierarchy of clusters based on the similarity within successive clusters. To interpret the dendrogram, first, the optimal number of clusters can be determined by comparing the average silhouette width of various cluster configurations (Kassambara, 2017). The average silhouette widths range from -1 to 1, with positive values indicating that the observations are appropriately clustered, and negative values indicate the potential misassignment of observations. Then, the dendrogram can be interpreted by horizontally cutting at the height that corresponds with the cluster configuration with the maximum average silhouette value. Greater vertical distances between clusters indicate greater dissimilarities, offering insight into the relationships among clusters (Nielsen, 2016).

Before-and-After Analysis of Bus Stop Infrastructure

Although FARS provides data on various crash characteristics, it does not include detailed bus stop information, which is a limitation shared by most crash datasets. Linking bus stop infrastructure data with traditional crash datasets like FARS can support an in-depth analysis of bus stop design and pedestrian safety. Therefore, an inventory of bus stop infrastructure was manually compiled for each bus stop in which a fatal transit bus stop-related crash occurred, and a comparison of the infrastructure from before and after the date of the crash was conducted to assess whether changes were made. This analysis builds upon the findings from parts 1 and 2 of this study by examining the conditions at the bus stop and identifying potential opportunities to implement countermeasures at the bus stop-level.

While FARS does not specify at which bus stop the crash occurred, it does provide coordinates for each transit bus stop-related crash (NHTSA, 2022c). Using this information, a bus stop inventory was compiled by the authors using a visual assessment and the Google Maps Street View application. The bus stop that was related to each crash was determined manually by using the crash details provided in FARS, such as the

intersection leg and the direction of travel of both the pedestrian and the motorist. In the case that the bus stop could not be clearly identified using these details, the crash was excluded from the following analysis. At each bus stop, an inventory of the presence of a sidewalk, crosswalk, shelter, seating, bus pad, signage, and street lighting was manually collected. Additionally, the inventory specified if the bus stop was an in-lane or curbside pull-out stop (Nabors et al., 2008).

This information was collected both before and after the date of the crash to determine whether improvements were made to the bus stop following the crash. The “before” sample was collected using available imaging from a date as close as possible to, but before, the crash. The “after” sample was taken from the most recent imaging available after the crash. By making this comparison, this analysis quantifies countermeasures implemented at the bus stop that were potentially a result of pedestrian safety concerns.

CHAPTER 5

RESULTS AND DISCUSSION

This chapter presents the results of the analysis of fatal transit bus stop-related pedestrian crashes in FARS, followed by a discussion of the findings. The purpose of this analysis is to examine the characteristics of these crashes and the bus stops where they occurred, and to identify how they differ from other nearby pedestrian crashes. The chapter begins with a descriptive analysis of transit bus stop-related crashes, followed by a crosstabulation comparing these crashes to those occurring within a nearby buffer zone. It then presents the results from the three-part methodology, which includes a binary logit model, hierarchical clustering analysis, and a before and after analysis of bus stop infrastructure.

Descriptive Analysis of Transit Bus Stop-Related Crashes

Since the introduction of transit bus stop-related crashes into FARS in 2014, and up to the most recent year of available data in 2022, there have been 175 transit bus stop-related crashes involving 196 pedestrians. **Figure 5-1** shows the yearly distribution of pedestrians involved in transit bus stop-related crashes, averaging 21.8 per year. While this is a relatively small sample, this may be because the definition of this crash in FARS requires the transit bus to be present at the bus stop at the time of the crash. Therefore, crashes that may be related to a bus stop but did not occur in the presence of the transit bus were excluded from this sample, and this crash type may be underreported.

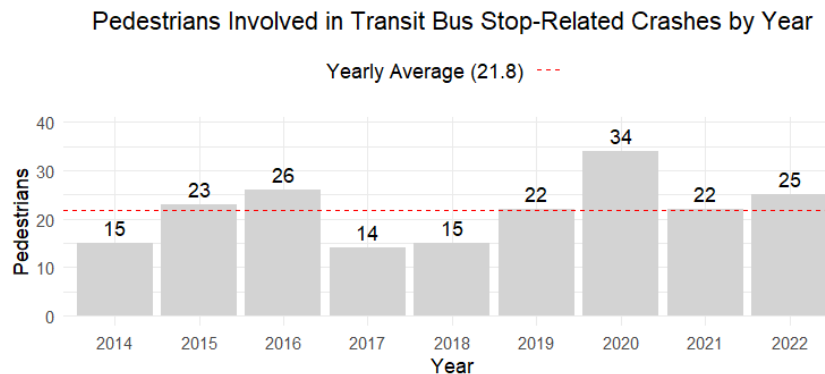
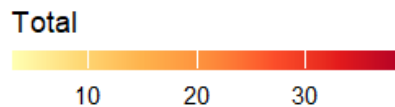
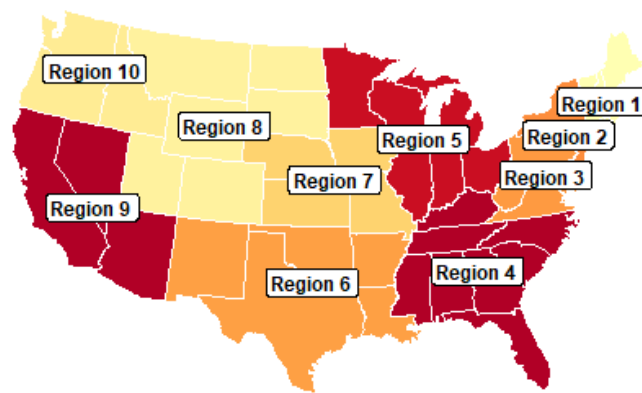


Figure 5-1 Yearly total of transit bus stop-related crashes in FARS.

Figure 5-2 shows the geographic distribution of pedestrians involved in crashes by USDOT region. A bivariate analysis of crash counts in each region was highly significant, indicating that the geographic distribution of transit bus stop-related crashes is not uniform. Specifically, 58.2% of all pedestrians involved in these crashes occurred in Region 4, Region 5, and Region 9. Further analysis is needed to understand this relationship, including potential differences in population density, ridership, and pedestrian safety measures across regions. Next, several crash characteristics were analyzed to determine the characteristics of transit bus stop-related crashes. Descriptive statistics are presented for the following key variables: location of the crash, crosswalk and sidewalk presence, position of pedestrian, prior action of the pedestrian, functional system, and the contact vehicle. These variables were selected for the descriptive analysis based on their significance in prior studies. The results of the descriptive analysis are shown in **Table 5.1** and discussed in the following paragraphs.

Pedestrians Involved in Transit Bus Stop-Related Crashes by USDOT Region



n = 196
p-value = < 0.0001

Figure 5-2 Geographic distribution of transit bus stop-related crashes from FARS

Next, several crash characteristics were analyzed to determine the characteristics of transit bus stop-related crashes. Descriptive statistics are presented for the following key variables: location of the crash, crosswalk and sidewalk presence, position of pedestrian, prior action of the pedestrian, functional system, and the contact vehicle. These variables were selected for the descriptive analysis based on their significance in prior studies. The results of the descriptive analysis are shown in **Table 5.1** and discussed in the following paragraphs.

First, 77.6% of transit bus stop-related crashes occurred at non-intersection locations. As FARS defines “*Not At Intersection*” as the crash occurred at least 50 feet away from an intersection and was unrelated to the flow of traffic through an intersection. Therefore, this suggests that many of these crashes were related to midblock bus stops, where marked crossing facilities, such as crosswalks and pedestrian signals may be less common than bus stops located at intersections.

Most transit bus stop-related crashes reported the presence of a sidewalk (70.9%). Sidewalks are typically included in bus stop infrastructure to provide both access to the stop and a designated space for pedestrians to wait for the bus. However, crosswalks were less common near transit bus stop-related crashes. Only 26.5% of transit bus stop-related crashes reported the presence of a crosswalk, supporting the previous finding that many of these crashes may be related to a midblock bus stop where such facilities are relatively scarce.

The majority of pedestrians (56.3%) were hit while in the travel lane, which is expected given that 59.1% of the crashes involved pedestrians crossing the roadway at the time of the crash. Among those crossing, 79.1% were in the travel lane, while 16.5% were in the crosswalk area. These findings highlight the need for improved access to crosswalks and enhanced visibility of crosswalks near transit stops. This relationship is shown in **Figure 5-3**.

Despite most of the crashes involving a pedestrian crossing the roadway, many pedestrians were hit on the roadside. Specifically, 21.9% of crashes involved a pedestrian hit while on a sidewalk, shared-use path, and driveway access, and 27.0% of pedestrians were stationary and adjacent to the roadway at the time of the crash. However, some

Table 5.1 Descriptive statistics of transit bus stop-related crashes in FARS

Variable		Total
Location	At Intersection	24 (12.2%)
	Intersection-Related	20 (10.2%)
	Not At Intersection	152 (77.6%)
Sidewalk Presence	None Noted	55 (28.1%)
	Yes	139 (70.9%)
	Unknown	2 (1.0%)
Crosswalk Presence	None Noted	143 (73.5%)
	Yes	52 (26.5%)
	Unknown	1 (0.5%)
Position of Pedestrian	Crosswalk Area	21 (10.7%)
	Intersection Area	5 (2.6%)
	Paved Shoulder/Bicycle Lane/Parking Lane	5 (2.6%)
	Sidewalk/Shared-Use Path/Driveway Access	43 (21.9%)
	Travel Lane	111 (56.6%)
	Unpaved Right-of-Way	3 (1.5%)
	Other/Unknown	8 (4.1%)
Non-Motorist Prior Action	Crossing Roadway	116 (59.2%)
	Entering/Exiting Parked or Stopped Vehicle	6 (3.1%)
	In Roadway - Other (Working, Playing, Etc.)	11 (5.6%)
	Movement Along Roadway	1 (0.5%)
	Stationary and Adjacent to Roadway (e.g., Shoulder, Median, Sidewalk)	53 (27.0%)
	Other	6 (3.1%)
Not Reported/Unknown		3 (1.5%)
Functional System	Arterial	156 (79.6%)
	Collector	20 (10.2%)
	Interstate	1 (0.5%)
	Local	19 (9.7%)
Speed Limit	> 40 MPH	74 (37.8%)
	0-19 MPH	1 (0.5%)
	20-29 MPH	21 (10.7%)
	30-39 MPH	88 (44.9%)
	> 40 MPH	74 (37.8%)
	Not Reported/Unknown	12 (6.1%)
Contact Vehicle	Bus	44 (22.5%)
	Heavy Truck	4 (2.0%)
	Light Truck	37 (18.9%)
	Motorcycle	1 (0.5%)
	Sedan/Coupe	64 (32.7%)
	SUV	28 (14.3%)
	Van/Minivan	11 (5.6%)
Unknown		7 (3.6%)
Bus Involvement	Not a Bus	148 (75.5%)
	Charter/Tour	1 (0.5%)
	Intercity	5 (2.6%)
	Transit/Commuter	37 (18.9%)
	Unknown	4 (2.0%)
Not Reported		1 (0.5%)

pedestrians were on a paved shoulder, bicycle lane, parking lane, or unpaved right-of-way, as shown in **Figure 5-3**. The combination of these factors reflects the scenario in which a passenger was waiting at a bus stop when a vehicle departed the roadway into the bus stop.

Transit bus stop-related crashes predominantly occurred on arterial roadways (79.6%), with many taking place on higher-speed roads, as 82.5% of these crashes occurred on roads with speed limits greater than 30 miles per hour. Prior research has studied these factors and their negative implications for pedestrian safety (Rosén et al., 2011). This finding is particularly important because bus stops generate pedestrian activity, potentially increasing pedestrian exposure to higher-risk conditions.

Last, in 71.4% of these crashes, a passenger vehicle was the contact vehicle (sedan/coupe, SUV, van/minivan, light trucks). However, buses were relatively common in transit bus stop-related crashes, with 22.5% of these crashes reporting that a bus was the contact vehicle. Moreover, transit/commuter buses were the most common type of bus involved (18.9%). This is a key area of concern, given that the mass and size of a bus can potentially result in more severe outcomes.

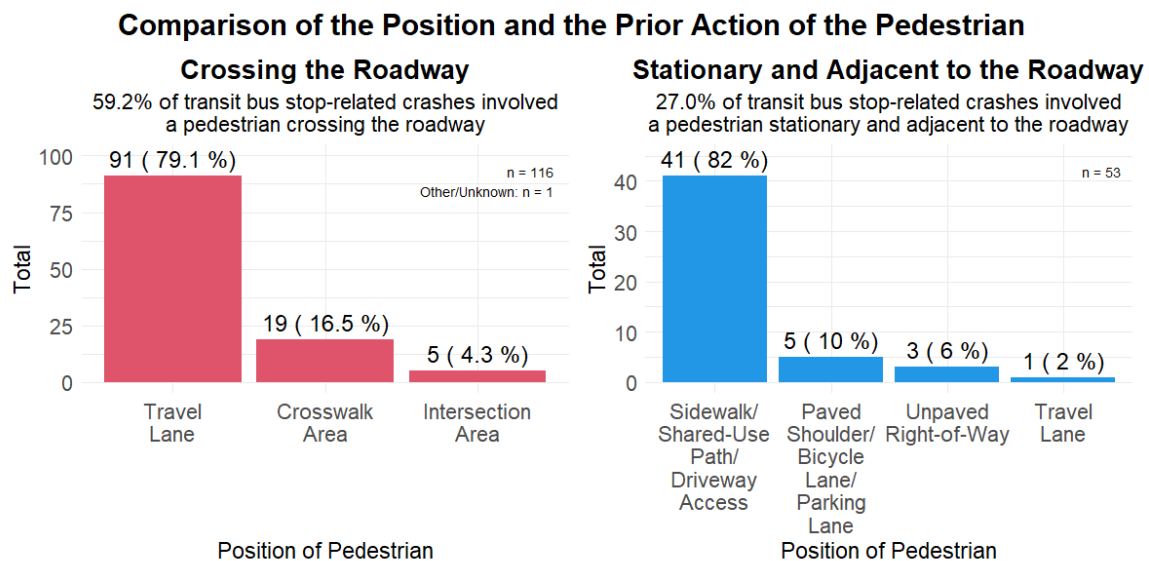


Figure 5-3 Relationship between the action and the position of the pedestrian during the crash

Crosstabulation

Next, a crosstabulation was conducted to compare the key characteristics of transit bus stop-related crashes with those of the buffer zone crashes. The crosstabulation was conducted separately for the quarter- and half-mile buffer zones. The relationship between the two groups is tested for significance and the results are shown in **Table 5.2**.

Compared to transit bus stop-related crashes, **Table 5.2** shows that a significantly higher proportion of quarter- and half-mile buffer zone crashes occurred at intersections or intersection-related locations. Of the intersection crashes reported in the combined sample of transit bus stop-related and buffer zone crashes, 71% were in the quarter-mile buffer zone, while 84.0% were in the half-mile buffer zone. Similarly, 50.0% of the intersection-related crashes were in the quarter-mile buffer zone, while 73.0% were in the half-mile buffer zone. This comparison reinforces the previous finding that midblock bus stops may be a priority to address pedestrian safety concerns at bus stops, given that transit bus stop-related crashes occur slightly more frequently at midblock locations compared to other nearby pedestrian crashes.

The proportion of sidewalk presence was relatively higher near transit bus stop-related crashes compared to buffer zone crashes. Only 63.3% of quarter-mile and 61.9% of half-mile buffer zone crashes reported the presence of a sidewalk compared to 70.9% of transit bus stop-related crashes. In contrast, crosswalks were more common in buffer zone crashes: 57.0% of crashes that reported the presence of a crosswalk were those within the quarter-mile buffer zone and 74.1% were those within the half-mile buffer zone. This aligns with the previous finding from the descriptive analysis that most of the transit bus stop-related crashes were related to a midblock bus stop, where marked crossing facilities may be less common.

Pedestrians in both the transit bus stop-related crashes and those within the buffer zones were most frequently hit while in the travel lane. In **Table 5.2**, pedestrians hit in the travel lane account for 57.7% of crashes in the combined quarter-mile buffer zone sample, and 57.5% in the combined half-mile buffer zone sample. This may be associated with the pedestrian behavior before the crash, as most of both transit bus stop-related

Table 5.2 Crosstabulation of transit bus stop-related crashes and buffer zone crashes

		Quarter-Mile Buffer Zone				Half-Mile Buffer Zone			
		BZ	TR	Total	p-value	BZ	TR	Total	p-value
Location	At Intersection	60 (71.4%)	24 (28.6%)	84 (22.1%)	<0.0001	126 (84.0%)	24 (16.0%)	150 (24.4%)	<0.0001
	Intersection-Related	20 (50.0%)	20 (50.0%)	40 (10.5%)		54 (73.0%)	20 (27.0%)	74 (12.0%)	
	Not At Intersection	103 (40.4%)	152 (59.6%)	255 (66.9%)		236 (60.8%)	152 (39.2%)	388 (63.0%)	
	Non-Trafficway Location	-	-	-		2 (100.0%)	0 (0.0%)	2 (0.3%)	
	Unknown/Insufficient Information	2 (100.0%)	0 (0.0%)	2 (0.5%)		2 (100.0%)	0 (0.0%)	2 (0.3%)	
Crosswalk Presence	None Noted	116 (44.8%)	143 (55.2%)	259 (68.0%)	0.0277	269 (65.3%)	143 (34.7%)	412 (66.9%)	0.0734
	Yes	69 (57.0%)	52 (43.0%)	121 (31.8%)		149 (74.1%)	52 (25.9%)	201 (32.6%)	
	Unknown	0 (0.0%)	1 (100.0%)	1 (0.3%)		2 (66.7%)	1 (33.3%)	3 (0.5%)	
Sidewalk Presence	None Noted	64 (53.8%)	55 (46.2%)	119 (31.2%)	0.3526	157 (74.1%)	55 (25.9%)	212 (34.4%)	0.0524
	Yes	119 (46.1%)	139 (53.9%)	258 (67.7%)		260 (65.2%)	139 (34.8%)	399 (64.8%)	
	Unknown	2 (50.0%)	2 (50.0%)	4 (1.1%)		3 (60.0%)	2 (40.0%)	5 (0.8%)	
Position of Pedestrian	Crosswalk Area	49 (70.0%)	21 (30.0%)	70 (18.4%)	<0.0001	107 (83.6%)	21 (16.4%)	128 (20.8%)	<0.0001
	Intersection Area	13 (72.2%)	5 (27.8%)	18 (4.7%)		19 (79.2%)	5 (20.8%)	24 (3.9%)	
	Paved Shoulder/Bicycle Lane/Parking Lane	3 (37.5%)	5 (62.5%)	8 (2.1%)		8 (61.5%)	5 (38.5%)	13 (2.1%)	
	Sidewalk/Shared-Use Path/Driveway Access	5 (10.4%)	43 (89.6%)	48 (12.6%)		26 (37.7%)	43 (62.3%)	69 (11.2%)	
	Travel Lane	109 (49.6%)	111 (50.5%)	220 (57.7%)		243 (68.6%)	111 (31.4%)	354 (57.5%)	
	Unpaved Right-of-Way	1 (25.0%)	3 (75.0%)	4 (1.1%)		1 (25.0%)	3 (75.0%)	4 (0.7%)	
	Other/Unknown	5 (38.5%)	8 (61.5%)	13 (3.4%)		16 (66.7%)	8 (33.3%)	24 (3.9%)	
Non-Motorist Prior Action	Crossing Roadway	146 (55.7%)	116 (44.3%)	262 (68.8%)	<0.0001	292 (71.6%)	116 (28.4%)	408 (66.2%)	<0.0001
	Disabled Vehicle Related	-	-	-		7 (100.0%)	0 (0.0%)	7 (1.1%)	
	Entering/Exiting Parked or Stopped Vehicle	0 (0.0%)	6 (100.0%)	6 (1.6%)		3 (33.3%)	6 (66.7%)	9 (1.5%)	
	Going To or From School (K-12)	-	-	-		1 (100.0%)	0 (0.0%)	1 (0.2%)	
	In Roadway - Other	7 (38.9%)	11 (61.1%)	18 (4.7%)		21 (65.6%)	11 (34.4%)	32 (5.2%)	
	Jogging/Running	2 (100.0%)	0 (0.0%)	2 (0.5%)		3 (100.0%)	0 (0.0%)	3 (0.5%)	
	Movement Along Roadway	6 (85.7%)	1 (14.3%)	7 (1.8%)		25 (96.2%)	1 (3.9%)	26 (4.2%)	
	Stationary and Adjacent to Roadway	5 (8.6%)	53 (91.4%)	58 (15.2%)		18 (25.4%)	53 (74.7%)	71 (11.5%)	
	Waiting to Cross Roadway	2 (100.0%)	0 (0.0%)	2 (0.5%)		3 (100.0%)	0 (0.0%)	3 (0.5%)	
	Other	6 (50.0%)	6 (50.0%)	12 (3.2%)		16 (72.7%)	6 (27.3%)	22 (3.6%)	
	Not Reported/Unknown	11 (78.6%)	3 (21.4%)	14 (3.7%)		31 (91.2%)	3 (8.8%)	34 (5.5%)	

Table 5.2 (continued) Crosstabulation of transit bus stop-related crashes and buffer zone crashes

		Quarter-Mile Buffer Zone				Half-Mile Buffer Zone			
		BZ	TR	Total	p-value	BZ	TR	Total	p-value
Functional System	Arterial	148 (48.7%)	156 (51.3%)	304 (79.8%)	0.2083	313 (66.7%)	156 (33.3%)	469 (76.1%)	0.0073
	Collector	14 (41.2%)	20 (58.8%)	34 (8.9%)		29 (59.2%)	20 (40.8%)	49 (8.0%)	
	Interstate	6 (85.7%)	1 (14.3%)	7 (1.8%)		23 (95.8%)	1 (4.2%)	24 (3.9%)	
	Local	17 (47.2%)	19 (52.8%)	36 (9.5%)		55 (74.3%)	19 (25.7%)	74 (12.0%)	
Speed Limit	0-19 MPH	0 (0.0%)	1 (100.0%)	1 (0.3%)	0.0005	0 (0.0%)	1 (100.0%)	1 (0.2%)	0.0011
	20-29 MPH	24 (53.3%)	21 (46.7%)	45 (11.8%)		71 (77.2%)	21 (22.8%)	92 (14.9%)	
	30-39 MPH	51 (36.7%)	88 (63.3%)	139 (36.5%)		132 (60.0%)	88 (40.0%)	220 (35.7%)	
	> 40 MPH	80 (52.0%)	74 (48.1%)	154 (40.4%)		166 (69.2%)	74 (30.8%)	240 (39.0%)	
	Unknown/Not Reported	30 (71.4%)	12 (28.6%)	42 (11.0%)		51 (81.0%)	12 (19.1%)	63 (10.2%)	
Contact Vehicle	Bus	6 (12.0%)	44 (88.0%)	50 (13.2%)	<0.0001	11 (20.0%)	44 (80.0%)	55 (9.0%)	<0.0001
	Heavy Truck	7 (63.6%)	4 (36.4%)	11 (2.9%)		18 (81.8%)	4 (18.2%)	22 (3.6%)	
	Light Truck	24 (39.3%)	37 (60.7%)	61 (16.1%)		48 (56.5%)	37 (43.5%)	85 (13.9%)	
	Motorcycle	4 (80.0%)	1 (20.0%)	5 (1.3%)		5 (83.3%)	1 (16.7%)	6 (1.0%)	
	Sedan/Coupe	72 (52.9%)	64 (47.1%)	136 (35.9%)		162 (71.7%)	64 (28.3%)	226 (36.9%)	
	SUV	30 (51.7%)	28 (48.3%)	58 (15.3%)		82 (74.6%)	28 (25.5%)	110 (17.9%)	
	Van/Minivan	11 (50.0%)	11 (50.0%)	22 (5.8%)		32 (74.4%)	11 (25.6%)	43 (7.0%)	
	Not Reported/Unknown	29 (80.6%)	7 (19.4%)	36 (9.5%)		59 (89.4%)	7 (10.6%)	66 (10.8%)	
Bus Involvement	Not a Bus	169 (53.3%)	148 (46.7%)	317 (83.2%)	<0.0001	381 (72.0%)	148 (28.0%)	529 (85.9%)	<0.0001
	Charter/Tour	0 (0.0%)	1 (100.0%)	1 (0.3%)		1 (50.0%)	1 (50.0%)	2 (0.3%)	
	Intercity	0 (0.0%)	5 (100.0%)	5 (1.3%)		0 (0.0%)	5 (100.0%)	5 (0.8%)	
	School	2 (100.0%)	0 (0.0%)	2 (0.5%)		2 (100.0%)	0 (0.0%)	2 (0.3%)	
	Transit/Commuter	4 (9.8%)	37 (90.2%)	41 (10.8%)		8 (17.8%)	37 (82.2%)	45 (7.3%)	
	Not Reported/Unknown	10 (66.7%)	5 (33.3%)	15 (3.9%)		28 (84.9%)	5 (15.2%)	33 (5.4%)	
Total		185 (48.6%)	196 (51.4%)	381 (100.0%)		420 (68.2%)	196 (31.8%)	616 (100.0%)	

Note: TR – transit bus stop-related; BZ – buffer zone

as most of both transit bus stop-related crashes and buffer zone crashes involved a pedestrian crossing the roadway, with 68.8% of crashes in the combined quarter-mile sample, and 66.2% in the combined half-mile sample.

Compared to transit bus stop-related crashes, very few buffer zone crashes involved a pedestrian hit while standing on a sidewalk, shared-use path, or driveway. In the combined transit bus stop-related and buffer zone samples, only 10.4% of pedestrians on the roadside in the quarter-mile sample and 37.7% in the half-mile sample were buffer zone crashes. This trend may also be related to pedestrian behavior, as a substantially larger proportion of transit bus stop-related crashes involved pedestrians who were stationary and adjacent to the roadway before the crash. Specifically, 91.4% of these cases in the combined quarter-mile sample and 74.7% in the combined half-mile sample were transit bus stop-related.

Most transit bus stop-related crashes and crashes within the buffer zones occurred on arterial roadways, accounting for 79.9% of the combined quarter-mile sample and 75.1% of the combined half-mile sample. Additionally, these crashes commonly occurred on roads with speed limits greater than 30 miles per hour, accounting for 76.9% of the combined quarter-mile sample and 74.7% of the combined half-mile sample. Therefore, countermeasures targeting higher-speed arterials may benefit both transit passengers and pedestrians in these areas.

Last, the most common vehicle types involved in all of the crashes were passenger vehicles (i.e., sedans/coupes, SUVs, vans/minivans, and pickup trucks). However, there was a significant difference in the proportion of bus-involved crashes. Of the crashes where a bus was reported as the contact vehicle, 88.0% in the combined quarter-mile sample and 80.0% in the combined half-mile sample were transit bus stop-related (see **Table 5.2**). Transit/commuter buses were the most frequently involved bus type. In 90.2% of these crashes in the combined quarter-mile sample and 82.2% in the combined half-mile sample, the crashes were related to a transit stop. Therefore, pedestrian-bus crashes are concentrated around bus stops.

Binary Logit Model

Understanding the factors that may influence the likelihood of a crash being related to a bus stop can assist decision-makers in prioritizing specific safety countermeasures. To explore these factors, two binary logit models were estimated to examine the relationship between fatal transit bus stop-related crashes and other nearby crashes. Model 1 evaluated crashes within a quarter-mile buffer zone of transit bus stop-related crashes, and Model 2 evaluated crashes within the half-mile buffer zone. The results of the preferred model are shown in **Table 5.3**, where the crash type is evaluated based on crash location, speed limit, pedestrian age, peak hour travel, non-motorist prior action, and bus involvement. This model was preferred over others because it included the most significant variables from the crosstabulation, and the quarter- and half-mile buffer zones had a McFadden's R^2 of 0.264 and 0.258, respectively. The following discussion will interpret the variables that were significant in both Model 1 and Model 2.

First, the location of the crash is a significant predictor of transit bus stop-related crashes. Compared to crashes at intersections, crashes occurring at non-intersection locations are 5.2 and 4.7 times more likely to be transit bus stop-related than other nearby crashes within quarter- and half-mile buffer zones, respectively. This aligns with prior research (Yu, 2024), and suggests that midblock bus stops should be a primary focus for improving pedestrian safety. Specifically, midblock bus stops are generally less likely to be equipped with pedestrian facilities like sidewalks and crosswalks compared to bus stops at intersections. Therefore, this is a potential area for infrastructure improvements that may reduce transit bus stop-related crashes.

The age of the pedestrians was also significantly associated with transit bus stop-related crashes. The model suggests that, compared to pedestrians aged 0-19 years, pedestrians aged 20-39 years are less likely to be involved in transit bus stop-related crashes than other nearby crashes. This result indicates a relationship between age and the likelihood of transit bus stop-related crashes, potentially due to behavioral differences or exposure patterns. However, further research is needed to clarify this association.

Peak hour travel was also significantly associated with transit bus stop-related crashes, indicating that, compared to off-peak hours, crashes during the morning peak

Table 5.3 Binary logit model results.

	Quarter Mile		Half Mile	
	Coef.	OR	Coef.	OR
Intercept	-0.212 (-0.959)	0.809	-2.394*** (-0.632)	0.091***
Pedestrian Location: At Intersection (ref)	-		-	
Pedestrian Location: Intersection-Related	1.418** (-0.574)	4.129	0.637 (-0.481)	1.891
Pedestrian Location: Not At Intersection	1.652*** (-0.428)	5.217	1.542*** (-0.367)	4.674***
Speed Limit: 0-29 MPH (ref)	-		-	
Speed Limit: 30-39 MPH	0.536 (-0.497)	1.709	0.961** (-0.413)	2.614**
Speed Limit: > 40 MPH	-0.18 (-0.505)	0.835	0.666 (-0.429)	1.946
Pedestrian Age: 0-19 years (ref)	-		-	
Pedestrian Age: 20-39 years	-1.972** (-0.864)	0.139	-1.002* (-0.526)	0.367*
Pedestrian Age: 40-59 years	-1.489* (-0.864)	0.226	-0.541 (-0.518)	0.582
Pedestrian Age: 60+ years	-1.758** (-0.867)	0.172	-0.556 (-0.52)	0.573
Peak Hour: Off-Peak (ref)	-		-	
Peak Hour: AM	1.725*** (-0.522)	5.613	1.292*** (-0.373)	3.640***
Peak Hour: PM	0.574 (-0.387)	1.775	0.314 (-0.312)	1.369
Non-Motorist Prior Action: Crossing Roadway (ref)	-		-	
Non-Motorist Prior Action: Stationary and Adjacent to Roadway	2.169*** (-0.566)	8.750	2.105*** (-0.395)	8.207***
Non-Motorist Prior Action: Other	-0.794 (-0.565)	0.452	-1.338*** (-0.436)	0.262***
Bus Involvement: Not a Bus (ref)	-		-	
Bus Involvement: Transit/Commuter	2.583*** (-0.626)	13.237	3.354*** (-0.559)	28.617***
Bus Involvement: Other bus type	16.184 (-682.573)	10681245.451	16.886 (-698.222)	21552448.768
Observations	288		459	
McFadden's Pseudo R ²	0.258		0.264	
Note:				
Dependent Variable: Transit Bus Stop-Related Crash = 1; Buffer Zone = 0				
*p<0.1; **p<0.05; ***p<0.01				
Coef. = Coefficient; OR = Odds Ratio				

hour are 5.6 and 3.6 times more likely to be transit bus stop-related than other nearby crashes, within the quarter- and half-mile buffer zones, respectively. During peak periods, transit ridership and vehicular traffic tend to be higher, which increases the risk for

pedestrians at bus stops. Given this, countermeasures should address the higher pedestrian risk during peak travel periods.

The pedestrian's action before the crash was significantly associated with transit bus stop-related crashes. Compared to pedestrians hit while crossing the roadway, those hit while stationary and adjacent to the roadway were 8.8 and 8.2 times more likely to be transit bus stop-related in the quarter- and half-mile buffer zones, respectively. This may reflect the added exposure of standing and waiting at bus stops. Moreover, the magnitude of the odds ratios were larger than most other odds ratios in the models, suggesting that this action is a strong indicator of transit bus stop-related crashes. This finding indicates that while crossing improvements are necessary to enhance overall pedestrian safety in these areas, targeted countermeasures should address pedestrians waiting at transit stops.

Compared to crashes that do not involve a bus, transit bus stop-related crashes are 13.2 and 28.6 times more likely to involve a transit or commuter bus than other nearby crashes, within the quarter- and half-mile buffer zones, respectively. Among all of the significant predictors of transit bus stop-related crashes, this predictor had the largest odds ratios in both of the models, indicating that it is the strongest factor influencing the likelihood of transit bus stop-related crashes. This finding may reflect the increased exposure pedestrians experience while waiting at bus stops as transit buses pull into or away from the bus stops. Prior research has identified this interaction as a particularly problematic occurrence at bus stops (Yendra et al., 2024). Safety improvements should be made to mitigate pedestrian-bus interactions and lessen the risk of transit bus stop-related crashes.

Hierarchical Clustering Analysis

The purpose of the hierarchical clustering analysis was two-fold: (1) to identify if there were different types of transit bus stop-related crash scenarios, and (2) to assess whether the clustering distinguished between the characteristics of transit bus stop-related crashes and other nearby fatal pedestrian crashes. The clustering was performed on three subsets of the FARS data: (1) the fatal transit bus stop-related crashes only, (2) the combined sample of transit bus stop-related crashes and quarter-mile buffer zone crashes, and (3) the

combined sample of transit bus stop-related crashes and half-mile buffer zone crashes, which will be referred to in this section as Model 1, Model 2, and Model 3, respectively.

For Model 1, the average silhouette widths of various clustering configurations revealed that three clusters was the optimal clustering configuration (see **Figure 5-4**). The relatively small number of clusters also assures that the number of observations in each cluster was reasonably large (since there were only 196 pedestrians involved in transit bus stop-related crashes). The average silhouette value for three clusters was approximately 0.156, indicating that, on average, the observations were appropriately clustered. For Models 2 and 3, however, the two-cluster configuration was the optimal clustering configuration (see **Figure 5-4**). The average silhouette widths for the two-cluster configuration in Models 2 and 3 are 0.186 and 0.191, respectively, suggesting that larger buffer sizes improve the clustering quality, which may be related to the increasing sample sizes. Despite this, the three-cluster configuration was chosen for presentation to allow for a direct comparison with Model 1 and because the difference in average silhouette width was very small.

The results of Model 1, 2, and 3 are shown in **Table 5.4**, **Table 5.5**, and **Table 5.6**, respectively. The characteristics of each cluster were extracted to evaluate the cluster size and variable distribution. The following tables report the total and percentage of observations in each cluster, along with the count and percentage of crashes for the most frequent category of each variable. In the following discussion, the results will be presented cluster by cluster, rather than model by model, to directly compare how the clustering distinguishes between transit bus stop-related crashes and other nearby crashes.

Crash Scenario 1: Pedestrian Crossing at an Intersection

In Model 1, the clustering of transit bus stop-related crashes revealed the crash scenario in which pedestrians are hit while crossing at an intersection as they are going to or from a bus stop. Specifically, 48% of this cluster occurred at an intersection and 76% of this cluster involved a pedestrian crossing the roadway. Additionally, 68% of Cluster 1 reported the presence of a crosswalk, which is comparatively more than the other clusters. Lastly, although only 36% of the crashes in this cluster involved a bus as the contact vehicle, this

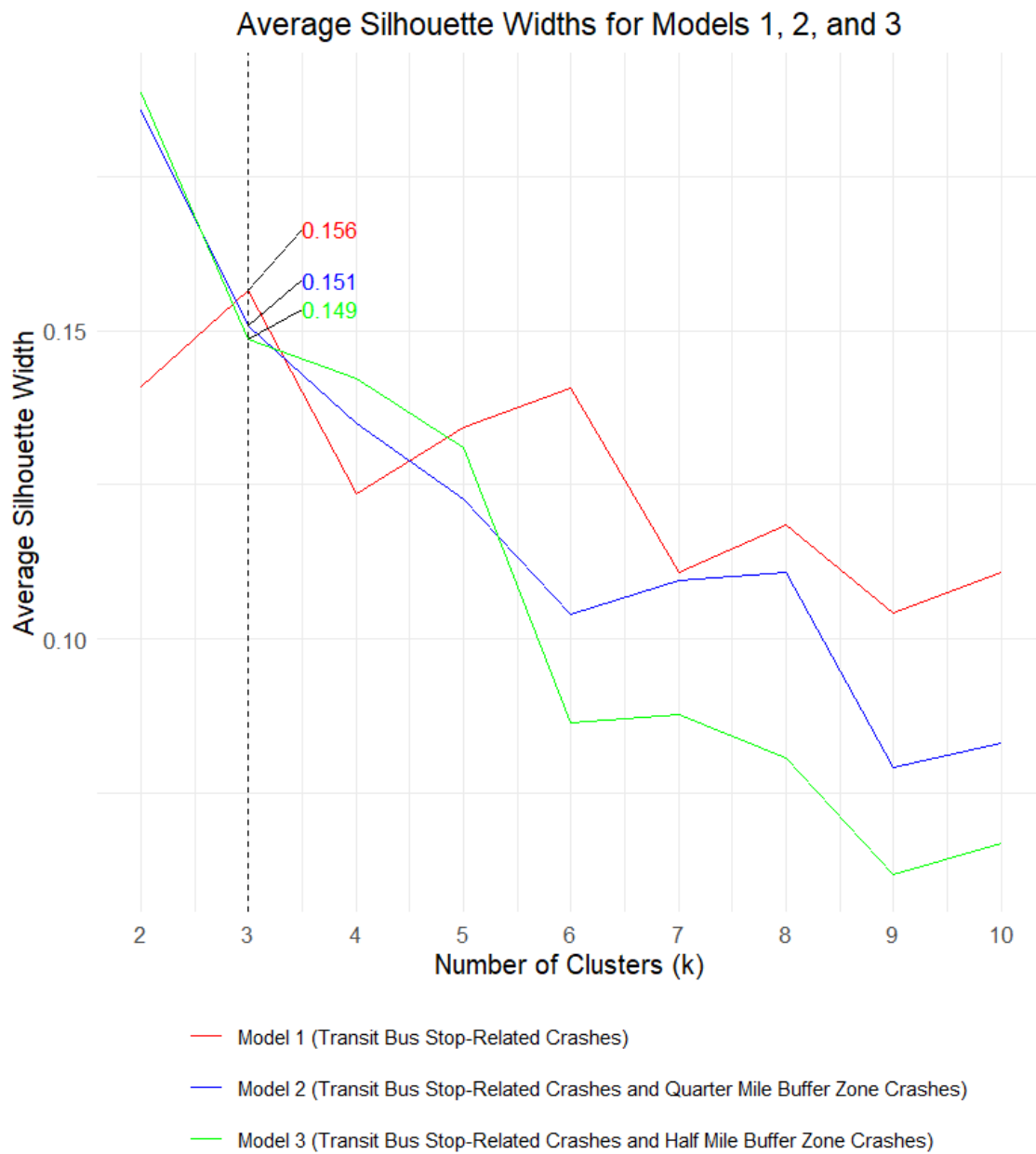


Figure 5-4 Average silhouette widths for various clustering configurations

Table 5.4 Hierarchical clustering results for Model 1 (transit bus stop-related crashes only)

Cluster 1				Cluster 2				Cluster 3			
Variable	Category	f	%	Category	f	%	Category	f	%		
Crosswalk Presence	Yes	34	68	None Noted	46	98	None Noted	81	82		
Sidewalk Presence	Yes	41	82	Yes	39	83	Yes	59	60		
Location	At Intersection	24	48	Not At Intersection	47	100	Not At Intersection	95	96		
Position	Crosswalk Area	18	36	Sidewalk/Shared-Use Path/Driveway Access	36	77	Travel Lane	93	94		
Relation to Junction (Y/N)	No	50	100		No	47	100	No	99	100	
Relation to Junction (Location)	Intersection-Related	35	70	Non-Junction	45	96	Non-Junction	92	93		
Type of Intersection	Four-Way Intersection	32	64	Not an Intersection	45	96	Not an Intersection	96	97		
Relation to Trafficway	On Roadway	46	92	On Roadside	41	87	On Roadway	98	99		
Functional System	Arterial	38	76	Arterial	39	83	Arterial	79	80		
Trafficway	Two-Way, Not Divided	30	60	Two-Way, Not Divided	20	43	Two-Way, Not Divided	36	36		
Number of Lanes	Two Lanes	21	42	Four Lanes	12	26	Two Lanes	36	36		
Speed Limit	30-39 MPH	24	48	30-39 MPH	23	49	> 40 MPH	49	49		
Alignment	Straight	48	96	Straight	38	81	Straight	87	88		
Profile	Level	43	86	Level	37	79	Level	78	79		
Surface Condition	Dry	33	66	Dry	40	85	Dry	82	83		
Age of Pedestrian	40-59 years	23	46	40-59 years	18	38	40-59 years	36	36		
Sex of Pedestrian	Male	32	64	Male	27	57	Male	62	63		
Race of Pedestrian	White	19	38	Not a Fatality (not Applicable)	15	32	White	50	51		
Lighting Condition	Dark - Lighted	27	54		Daylight	29	62	Dark - Lighted	42	42	
Land Use	Urban	50	100	Urban	47	100	Urban	99	100		
Prior Action	Crossing Roadway	38	76	Stationary and Adjacent to Roadway	44	94	Crossing Roadway	78	79		
Hit and Run	No	38	76	No	35	74	No	87	88		
Speeding Related	No	38	76	No	31	66	No	91	92		
Drinking	No (Alcohol Not Involved)	21	42	Not Reported	25	53	No (Alcohol Not Involved)	46	46		
Drugs	No (Drugs Not Involved)	20	40	Not Reported	29	62	No (Drugs Not Involved)	48	48		
Hour	Off Peak Hours	29	58	Off Peak Hours	33	70	Off Peak Hours	60	61		
Vision Obscured	No Obstruction Noted	39	78	No Obstruction Noted	43	91	No Obstruction Noted	77	78		
Contact Vehicle	Bus	18	36	Sedan/Coupe	20	43	Sedan/Coupe	35	35		
Bus Involvement	Not a Bus	33	66	Not a Bus	45	96	Not a Bus	70	71		
Cluster Size		50	100		47	100		99	100		

Average Silhouette Width = 0.156

Note: f = frequency; % = percentage

Table 5.5 Hierarchical clustering results for Model 2 (combined sample of transit bus stop-related and quarter-mile buffer zone crashes)

Cluster 1				Cluster 2			Cluster 3		
Variable	Category	f	%	Category	f	%	Category	f	%
Crosswalk Presence	Yes	85	66	None Noted	42	98	None Noted	174	83
Sidewalk Presence	Yes	96	75	Yes	40	93	Yes	122	58
Location	At Intersection	83	65	Not At Intersection	42	98	Not At Intersection	201	96
Position	Crosswalk Area	65	51	Sidewalk/Shared-Use Path/Driveway Access	35	81	Travel Lane	188	90
Relation to Junction (Y/N)	No	124	97		No	43	100	No	209
Relation to Junction (Location)	Intersection-Related	88	69	Non-Junction	42	98	Non-Junction	192	91
Type of Intersection	Four-Way Intersection	99	77	Not an Intersection	42	98	Not an Intersection	201	96
Relation to Trafficway	On Roadway	123	96	On Roadside	38	88	On Roadway	199	95
Functional System	Arterial	100	78	Arterial	35	81	Arterial	169	80
Trafficway	Two-Way, Not Divided	60	47	Two-Way, Not Divided	19	44	Two-Way, Not Divided	65	31
Number of Lanes	Two Lanes	42	33	Four Lanes	11	26	Two Lanes	54	26
Speed Limit	30-39 MPH	42	33	30-39 MPH	18	42	> 40 MPH	103	49
Alignment	Straight	125	98	Straight	35	81	Straight	190	90
Profile	Level	107	84	Level	36	84	Level	169	80
Surface Condition	Dry	102	80	Dry	38	88	Dry	176	84
Age of Pedestrian	40-59 years	49	38	40-59 years	17	40	60+ years	73	35
Sex of Pedestrian	Male	77	60	Male	23	53	Male	144	69
Race of Pedestrian	White	53	41	Not a Fatality (not Applicable)	13	30	White	99	47
Lighting Condition	Dark - Lighted	76	59	Daylight	27	63	Dark - Lighted	107	51
Land Use	Urban	127	99	Urban	43	100	Urban	208	99
Prior Action	Crossing Roadway	104	81	Stationary and Adjacent to Roadway	41	95	Crossing Roadway	158	75
Hit and Run	No	98	77	No	34	79	No	168	80
Speeding Related	No	98	77	No	27	63	No	177	84
Drinking	No (Alcohol Not Involved)	51	40	Not Reported	23	53	No (Alcohol Not Involved)	84	40
Drugs	No (Drugs Not Involved)	50	39	Not Reported	27	63	No (Drugs Not Involved)	85	40
Hour	Off Peak Hours	87	68	Off Peak Hours	28	65	Off Peak Hours	146	70
Vision Obscured	No Obstruction Noted	106	83	No Obstruction Noted	39	91	No Obstruction Noted	169	80
Contact Vehicle	Sedan/Coupe	32	25	Sedan/Coupe	17	40	Sedan/Coupe	87	41
Bus Involvement	Not a Bus	104	81	Not a Bus	41	95	Not a Bus	172	82
Cluster Size		128	100		43	100		210	100

Average Silhouette Width = 0.151

Note: *f* = frequency; % = percentage

Table 5.6 Hierarchical clustering results for Model 3 (combined sample of transit bus stop-related and half-mile buffer zone crashes)

Cluster 1				Cluster 2				Cluster 3			
Variable	Category	f	%	Category	f	%	Category	f	%		
Crosswalk Presence	Yes	160	71	None Noted	56	98	None Noted	292	87		
Sidewalk Presence	Yes	177	79	Yes	54	95	Yes	168	50		
Location	At Intersection	143	64	Not At Intersection	55	96	Not At Intersection	316	95		
Position	Crosswalk Area	120	53	Sidewalk/Shared-Use Path/Driveway Access	41	72	Travel Lane	302	90		
Relation to Junction (Y/N)	No	220	98		No	56	98	No	321	96	
Relation to Junction (Location)	Intersection-Related	172	76	Non-Junction	56	98	Non-Junction	293	88		
Type of Intersection	Four-Way Intersection	168	75	Not an Intersection	57	100	Not an Intersection	315	94		
Relation to Trafficway	On Roadway	209	93	On Roadside	42	74	On Roadway	322	96		
Functional System	Arterial	172	76	Arterial	42	74	Arterial	255	76		
Trafficway	Two-Way, Not Divided	108	48	Two-Way, Not Divided	28	49	Two-Way, Not Divided	90	27		
Number of Lanes	Two Lanes	78	35	Two Lanes	21	37	Two Lanes	84	25		
Speed Limit	30-39 MPH	81	36	30-39 MPH	27	47	> 40 MPH	171	51		
Alignment	Straight	215	96	Straight	48	84	Straight	305	91		
Profile	Level	193	86	Level	47	82	Level	250	75		
Surface Condition	Dry	182	81	Dry	52	91	Dry	274	82		
Age of Pedestrian	60+ years	76	34	40-59 years	20	35	40-59 years	116	35		
Sex of Pedestrian	Male	124	55	Male	31	54	Male	239	72		
Race of Pedestrian	White	82	36	Not a Fatality (not Applicable)	16	28	White	164	49		
Lighting Condition	Dark - Lighted	119	53	Daylight	34	60	Dark - Lighted	172	52		
Land Use	Urban	224	100	Urban	57	100	Urban	330	99		
Prior Action	Crossing Roadway	174	77	Stationary and Adjacent to Roadway	43	75	Crossing Roadway	234	70		
Hit and Run	No	172	76	No	45	79	No	260	78		
Speeding Related	No	168	75	No	34	60	No	276	83		
Drinking	No (Alcohol Not Involved)	93	41	No (Alcohol Not Involved)	24	42	No (Alcohol Not Involved)	118	35		
Drugs	No (Drugs Not Involved)	91	40	Not Reported	28	49	No (Drugs Not Involved)	125	37		
Hour	Off Peak Hours	150	67	Off Peak Hours	41	72	Off Peak Hours	242	72		
Vision Obscured	No Obstruction Noted	189	84	No Obstruction Noted	53	93	No Obstruction Noted	270	81		
Contact Vehicle	Sedan/Coupe	70	31	SUV	18	32	Sedan/Coupe	139	42		
Bus Involvement	Not a Bus	196	87	Not a Bus	53	93	Not a Bus	280	84		
Cluster Size		225	100		57	100		334	100		

Average Silhouette Width = 0.148

Note: f = frequency; % = percentage

a relatively large share compared to other clusters. Compared to Cluster 1 in Model 1, Cluster 1 in Models 2 and 3 are highly similar, reflecting a similar scenario in which a pedestrian is hit at an intersection while crossing the roadway. However, only 38% of Cluster 1 in Model 2 are transit bus stop-related crashes, and only 22% of Cluster 1 in Model 3 are transit bus stop-related crashes. This suggests that for instances in which a pedestrian is hit while crossing at an intersection, the clustering does not distinguish between transit bus stop-related crashes and other nearby crashes. Given this, these crashes may be similar in nature and safety improvements targeting intersection crossings may benefit both transit passengers and other pedestrians in the immediate area.

Crash Scenario 2: Pedestrian Waiting at a Midblock Bus Stop

Cluster 2 in Model 1 suggested that there is a specific transit bus stop-related crash scenario in which a pedestrian is hit while waiting at a midblock transit stop. Specifically, 100% of this cluster occurred at a non-intersection location, 94% of this cluster involved a pedestrian stationary and adjacent to the roadway, and 77% of this cluster involved a pedestrian standing on a sidewalk, shared-use path, or a driveway. Moreover, the characteristics of Cluster 2 in Models 2 and 3 mirror those of Cluster 2 in Model 1 very closely. Notably, 96% of Cluster 2 in Model 2 are transit bus stop-related crashes, and 71% of Cluster 2 in Model 3 are transit bus stop-related crashes. Given that the distribution of crashes in Cluster 2 is dominantly transit bus stop-related in Models 2 and 3, this suggests that the clustering identified a meaningful distinction between transit bus stop-related crashes and other crashes in the immediate area. Therefore, there is an opportunity to focus on this type of transit bus stop-related crash to improve the safety of waiting transit passengers.

Crash Scenario 3: Pedestrian Crossing Midblock

The characteristics of Cluster 3 in Model 1 suggest that there is a transit bus stop-related crash scenario in which a pedestrian is hit while they are crossing the roadway as they are going to or from a midblock transit stop. The clustering resulted in 96% of Cluster 3 occurring at a non-intersection location, 79% involving a pedestrian crossing the roadway,

and 82% reporting that there was not a crosswalk at the crash location. In Models 2 and 3, the characteristics of Cluster 3 reflect what was observed in Model 1. However, in Models 2 and 3, Cluster 3 is a blend of both transit bus stop-related crashes and crashes in the buffer zones. Specifically, 51% of Cluster 3 in Model 2 are transit bus stop-related, and 32% of Cluster 3 in Model 3 are transit bus stop-related. Since the clustering classified transit bus stop-related crashes and other nearby crashes together in Cluster 3, this suggests that crashes involving pedestrians crossing at midblock locations are common to both transit passengers and other pedestrians in areas with transit services. Countermeasures addressing this crash scenario will likely improve overall pedestrian safety throughout these areas.

Assessment of Clustering Quality

Figure 5-5 shows the dendrograms for each of the models. The height at which branches merge indicates how similar the crashes are within each cluster. The distance between each successive merge reflects the relative dissimilarity between clusters as they combine. For example, a greater distance between parent clusters and child clusters suggests that the parent cluster was distinct enough to form its own group, while the child clusters (further downstream) may exhibit more variation in their characteristics. In contrast, small distances between successive clusters indicate that the crashes within the successive clusters are highly similar. Additionally, the silhouette plot depicts the clustering quality in **Figure 5-6**, with the silhouette width of each observation plotted within its corresponding cluster.

Cluster 2 consistently merges at the lowest height in Models 2 and 3. This suggests that, within the combined samples of transit bus stop-related and buffer zone crashes, the crash scenario involving pedestrians hit while standing on the roadside exhibits the highest relative similarity within the cluster. Additionally, the profile of Cluster 2 across all three models shows that most crashes in this cluster have a silhouette width higher than average. Very few crashes fall within the negative range, suggesting that the crashes were properly clustered. Given that Cluster 2 was predominantly transit

bus stop-related in Models 2 and 3, these characteristics further reinforce the conclusion that this scenario is distinct from other nearby crashes and specific to bus stops.

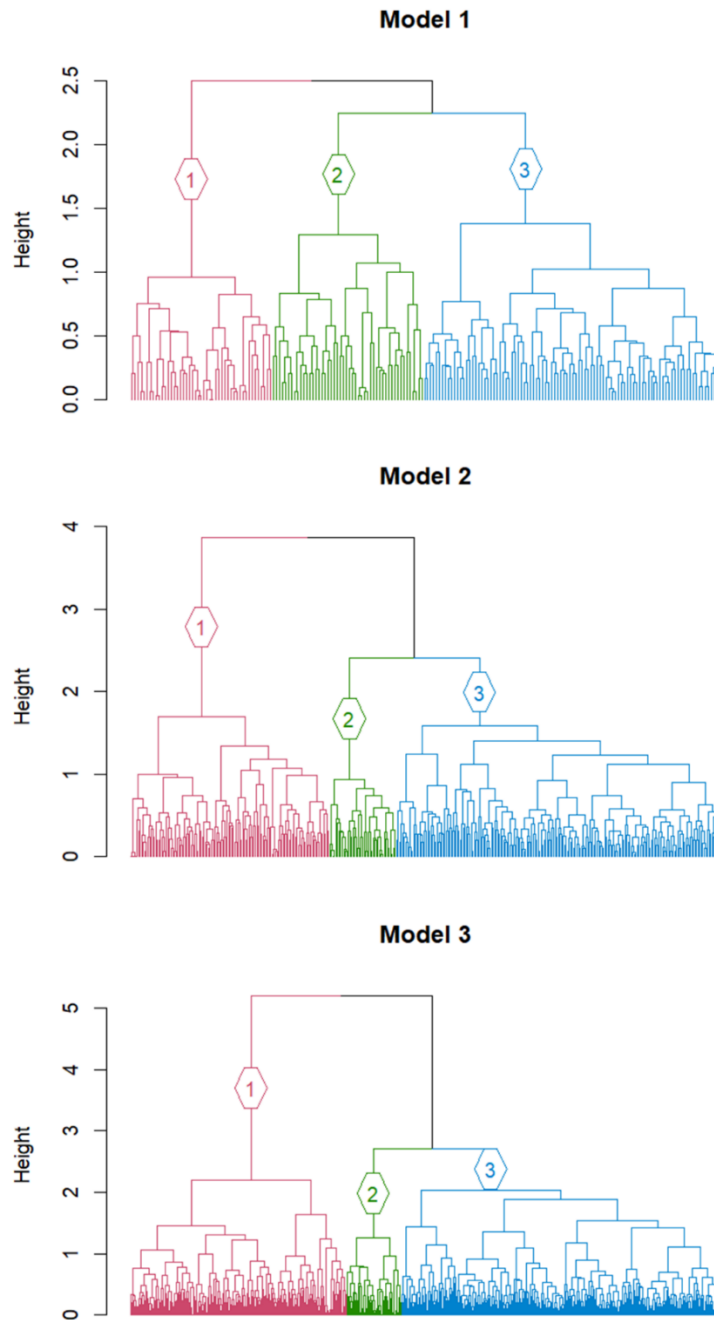


Figure 5-5 Hierarchical clustering dendrograms for Models 1, 2, and 3

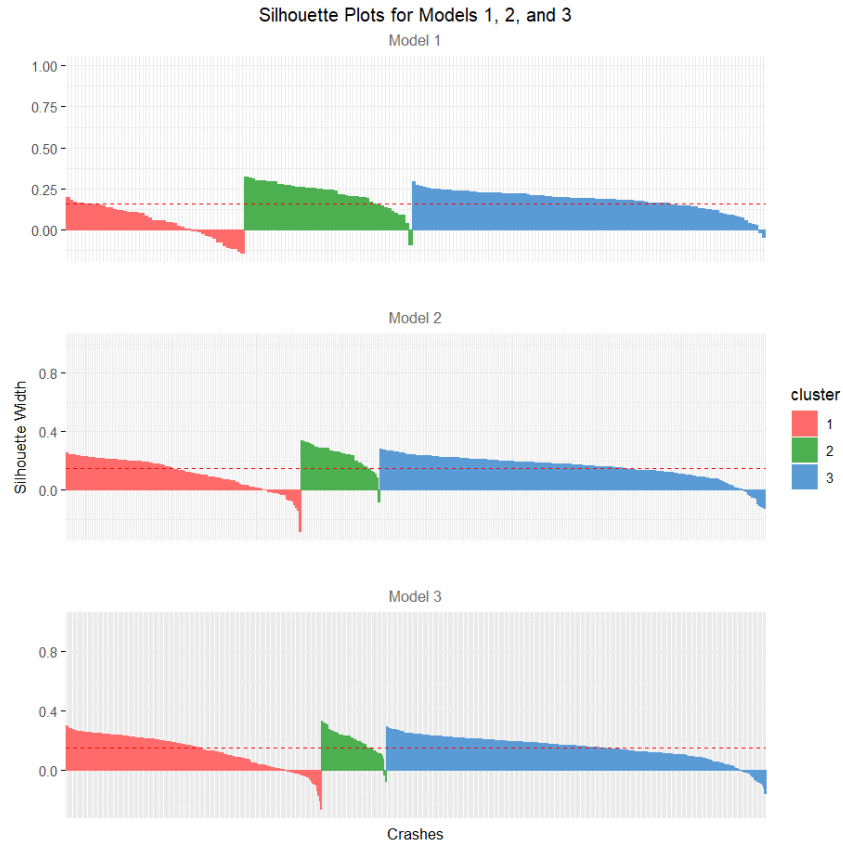


Figure 5-6 Cluster profiles for Models 1, 2, and 3

Before-and-After Analysis of Bus Stop Infrastructure

Last, a before-and-after inventory of bus stop infrastructure was manually compiled. Expanding on the findings from the first two parts of this analysis, the bus stop inventory not only examines the general conditions of all bus stops but also compares the conditions of stops where a pedestrian was hit while crossing to or from the bus stop with those where a pedestrian was hit while waiting at the bus stop.

Of the 196 pedestrians involved in fatal transit bus stop-related crashes, there were 175 bus stops at which a crash occurred. There were 38 crash locations that were unclear or unavailable on Google Maps and excluded from the analysis. In total, the analysis considered 137 transit bus stops. The results of this analysis are shown in **Table 5.7** and the percentages were computed by dividing the observed number by the total number of crash locations for each type of crash. In general, **Table 5.7** reveals that conditions at each bus stop either remained the same or improved in the after period.

Table 5.7 Results of the before-and-after bus stop infrastructure analysis

	Pedestrian Crossing Roadway (n = 91)					Pedestrian Stationary and Adjacent to Roadway (n = 30)					All Bus Stops (n = 137)				
	Before		After		Change	Before		After		Change	Before		After		Change
Sidewalk	83	91.2%	83	91.2%	0.0%	30	100.0%	30	100.0%	0.0%	137	93.2%	137	93.2%	0.0%
Crosswalk	58	63.7%	62	68.1%	4.4%	25	83.3%	26	86.7%	3.3%	103	70.1%	108	73.5%	3.4%
Shelter	30	33.0%	34	37.4%	4.4%	16	53.3%	16	53.3%	0.0%	84	57.1%	87	59.2%	2.0%
Seating	51	56.0%	56	61.5%	5.5%	23	76.7%	22	73.3%	-3.3%	90	61.2%	95	64.6%	3.4%
Lighting	80	87.9%	80	87.9%	0.0%	30	100.0%	30	100.0%	0.0%	135	91.8%	135	91.8%	0.0%
Signage	91	100.0%	91	100.0%	0.0%	30	100.0%	30	100.0%	0.0%	147	100.0%	147	100.0%	0.0%
Bus Pad	14	15.4%	14	15.4%	0.0%	5	16.7%	6	20.0%	3.3%	117	79.6%	123	83.7%	4.1%
In-Lane	72	79.1%	72	79.1%	0.0%	25	83.3%	25	83.3%	0.0%	115	78.2%	111	75.5%	-2.7%
Pull Out	19	20.9%	19	20.9%	0.0%	5	16.7%	5	16.7%	0.0%	32	21.8%	36	24.5%	2.7%

Bus Stop Infrastructure at the Crossing-Related Crash Locations

The conditions specifically at crossing-related crash locations (n=91) are shown in **Figure 5-7**. Before the crash, almost all bus stops involving a pedestrian who was hit while crossing the road had a sidewalk (92%) but only 64% had a nearby crosswalk. After the crash, no additional sidewalks were noted, but there was a 4% increase in the presence of a crosswalk. This change may suggest that crossing facilities may have been installed in response to safety concerns following the crash while a pedestrian was crossing to or from a bus stop. Nevertheless, many bus stops associated with crossing-related crashes did have access to a crosswalk, suggesting that efforts should either target enhancing crosswalk visibility to improve motorists' yielding behavior or guiding pedestrians to use the existing crosswalks rather than crossing at unmarked locations. Additionally, 33% of these bus stops had a shelter and 56% had seating before the crash, with the presence of these amenities increasing by 4% and 6% after the crash, respectively. Street lighting was present at 88% of these bus stops. Only a small portion of these bus stops had a bus pad (15%), and most were in-lane stops (79%). The presence of street lighting, a bus pad, and the stop type remained unchanged after the crash, suggesting that these features may not have been a priority for pedestrian safety improvements. All of the bus stops had signage.

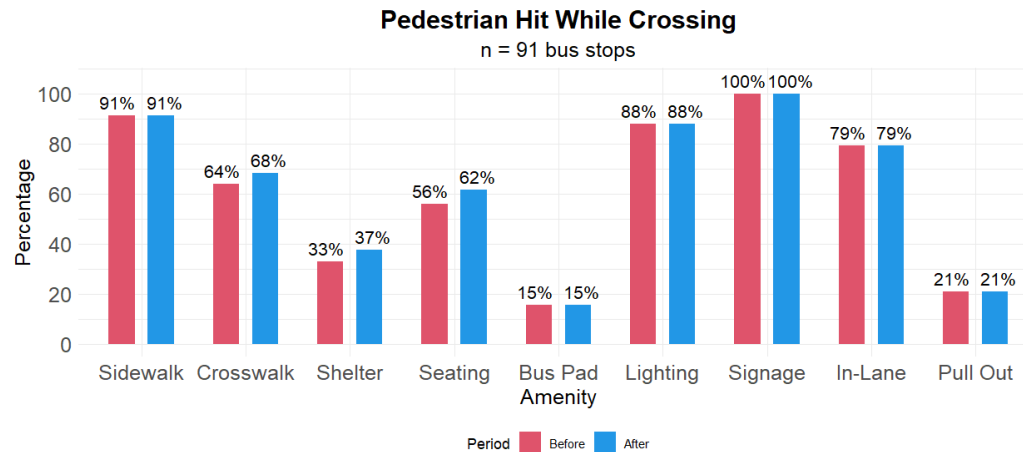


Figure 5-7 Bus stop infrastructure at crossing-related crash locations

Bus Stop Infrastructure at Waiting-Related Crash Locations

Shown in **Figure 5-8**, there were 30 bus stops related to a pedestrian hit while waiting on the roadside. Among these crashes, there were minor differences in the bus stop infrastructure between the before and after periods (see **Figure 5-8**). All of the bus stops had sidewalks, street lighting, and signage. Before the crash, 83% of the bus stops had access to a crosswalk, with a 3% increase in the presence of a crosswalk after the crash. Shelter was present at 53% of these bus stops and 77% had seating. After the crash, no additional shelters were installed, and surprisingly, the presence of seating decreased by 3%. Bus pads were present at 17% of bus stops before the crash, and this increased by 3% after the crash. Last, 83% of these bus stops were in-lane stops and this feature did not change after the crash. Given that this crash scenario typically involved vehicles departing from the roadway and hitting pedestrians waiting at the bus stop, many of the amenities documented, such as shelters and seating, may have had a limited impact in preventing this type of crash. If any safety improvements were made at these bus stops, they might have addressed factors beyond the scope of this bus stop inventory. However, the bus stop inventory highlights the potential for many in-lane stops to be converted to curbside pull-out stops, which could improve pedestrian safety in this crash scenario by increasing the physical separation between waiting pedestrians and vehicular traffic (Yendra et al., 2024).

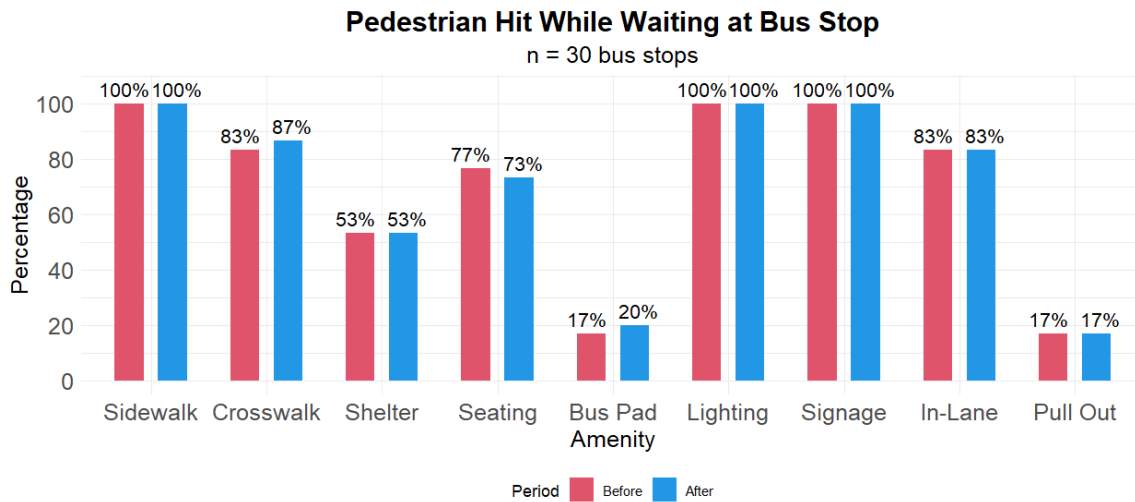


Figure 5-8 Bus stop infrastructure at waiting-related crash locations

Given that this crash scenario typically involved vehicles departing from the roadway and hitting pedestrians waiting at the bus stop, many of the amenities documented, such as shelters and seating, may have had a limited impact in preventing this type of crash. If any safety improvements were made at these bus stops, they might have addressed factors beyond the scope of this bus stop inventory. However, the bus stop inventory highlights the potential for many in-lane stops to be converted to curbside pull-out stops, which could improve pedestrian safety in this crash scenario by increasing the physical separation between waiting pedestrians and vehicular traffic (Yendra et al., 2024).

Identifying Bus Stop Infrastructure Priorities to Improve Safety

Comparing the bus stop infrastructure at the crossing- and waiting-related bus stops, notable disparities were observed among certain amenities, with a 20% difference in the presence of crosswalks, a 20% difference in the presence of shelters, and a 21% difference in the presence of seating. Therefore, the substantial gap in crosswalk presence indicates a critical area for improvement to address the crossing-related crash locations. Marked crossing facilities could potentially reduce the risk of this crash scenario, which accounted for 59% of all of the transit bus stop-related crashes.

CHAPTER 6

CONCLUSIONS AND FUTURE RESEARCH

Prior research has addressed pedestrian safety at bus stops; however, none of the existing studies have used pedestrian crash data that explicitly identifies bus stops as contributing factors in crashes. Instead, prior studies have used a location-based assumption, analyzed crash narratives, and/or collected field observations to infer the relationship between pedestrian safety and bus stops. This thesis begins to address this gap in the literature by first conducting a comprehensive review of transit-related safety datasets applicable for this type of analysis. Although such data was somewhat limited, FARS was ultimately selected for further analysis to identify the characteristics of transit bus stop-related crashes and compare these characteristics to other pedestrian crashes in close proximity, revealing similarities and differences between the two groups. This was accomplished with a three-part methodology. First, a binary logit model was estimated to compare transit bus stop-related pedestrian crashes to other nearby fatal pedestrian crashes. Hierarchical clustering was then used to identify the primary transit bus stop-related crash scenarios and assess how the clustering distinguished between these crashes and other nearby crashes. Finally, an inventory of bus stop infrastructure was conducted for each bus stop where a transit bus stop-related crash occurred, comparing the infrastructure before and after the crash date to evaluate whether safety improvements were made potentially in response to pedestrian safety concerns. By addressing this research gap, this study identified important distinctions between transit bus stop-related crashes and other pedestrian crashes in areas with transit services, thereby supporting targeted countermeasures to improve safety not only for transit passengers but also for all pedestrians in surrounding areas. The following sections discuss the key findings from each chapter, as well as this study's limitations and areas for future research.

Key Findings from the Literature Review and Transit-Related Safety Data Review

The foremost method used in prior literature on pedestrian safety at bus stops involved using a location-based assumption, which assumes that all crashes within a given distance of a bus stop are directly related to the stop itself. This approach may impact the accuracy

of the results, since the extent of the pedestrian involvement in bus stop-related crashes may not be accurately captured simply by the distance between the location of a crash and the nearest bus stop. Many studies used this approach since it only required pedestrian crash data and bus stop locations, both of which are typically readily available and easy to access. Further, a comprehensive search of transit-related safety databases revealed the scarcity of data that explicitly identifies transit bus-stop related crashes; these datasets were limited in both sample size and public/private availability. While well-known crash typing frameworks (e.g., PBCAT and MMUCC) do specify whether a crash was related to a bus stop, many real-world datasets have not adopted the most recent versions of these frameworks. As a result, this type of crash may be unreported or miscategorized.

Even databases that use the PBCAT and MMUCC crash typing frameworks may still underreport transit bus-stop related crashes. For instance, FARS and CRSS only reported 196 and 83 pedestrians involved in transit bus stop-related crashes, respectively. However, these databases use an adapted definition of PBCAT 2.0, which requires a transit bus to be present at the bus stop at the time of the crash. This definition excludes other crashes that were potentially related to a bus stop, regardless of the presence of the bus. Furthermore, the scope is limited to the immediate area around bus stops and fails to account for the entire walking trip to or from a transit stop. PBCAT 3.0 addresses both of these issues, but FARS and CRSS have not yet adopted this version.

It is important to recognize that the absence of such crash data does not equate to the absence of pedestrian safety concerns. Prior research found that pedestrians' perception of safety directly influences their walking behavior (Kweon et al., 2021); therefore, it may be that this crash type is underreported because pedestrians are avoiding bus stops that are perceived as unsafe or are choosing not to use transit altogether. Ferencak and Marshall (2019) explored safety concerns arising from trip suppression using data on suppressed child pedestrian and bicyclist trips, derived from a survey of parental perceptions and trip frequencies. They developed a proactive approach to evaluate safe access to schools by creating a trip-suppression model, a framework that can also be applied to improving safe access to transit. Therefore, while crash data is

essential for addressing pedestrian safety at bus stops, a proactive approach could incorporate additional data sources to more fully understand the factors influencing safe access to transit.

Key Findings from Comparing Transit Bus Stop-Related Crashes with Other Nearby Crashes

Although the FARS data has limitations, it was used in this thesis in binary logit models and hierarchical clustering analysis to provide insights into the characteristics of fatal transit bus stop-related crashes and how they compared to nearby pedestrian crashes. The results revealed that there were three main transit bus stop-related crash scenarios: (1) a pedestrian crossing to or from a transit stop at an intersection, (2) a pedestrian waiting on the roadside at a midblock transit stop, and (3) a pedestrian crossing to or from a midblock transit stop.

Compared to nearby crashes, the clustering analyses revealed that transit bus stop-related crashes involving a pedestrian crossing at an intersection or midblock location shared similar characteristics with other nearby crashes. This aligns with previous studies that have linked pedestrian crossing behavior with bus stops (Pessaro et al., 2017; Singleton et al., 2024; Voorhes Transportation Center, 2012). However, the binary logit model and the hierarchical clustering revealed that the scenario involving a pedestrian waiting on the roadside at a midblock location was specific to transit bus stop-related crashes. Although fewer crashes were assigned to this cluster scenario (24% of transit bus stop-related crashes), countermeasures targeting this situation could specifically improve the safety of transit passengers waiting at midblock bus stops.

In addition to the binary logit model and the hierarchical clustering analysis, the transit bus stop-related crashes from FARS were further analyzed by compiling a manual inventory of bus stop infrastructure. The results revealed that at the bus stops that were related to a passenger hit while waiting for the bus, many of the surveyed amenities were already in place when the crash occurred, with minor improvements made after the crashes. However, since this crash type involved a vehicle departing the roadway into the bus stop, amenities such as sidewalks and seating may not have had an impact on preventing this type of crash. Therefore, if safety improvements were implemented in

response to these crashes, they may not have been captured within the scope of this inventory. To address this crash scenario, the positioning of the bus stop relative to the travel lane may be more relevant than the presence of certain amenities at the bus stops. Bus stops that are offset from the roadway, such as curbside pull-out stops, could reduce the pedestrian's exposure to the path of impact in the event of a roadway departure (Yendra et al., 2024). Additionally, installing barriers or bollards near bus stops may reduce the risk of this crash scenario by creating a clear separation between the roadway and the bus stop and by potentially absorbing some of the impact in the event of a roadway departure (Grzebieta & Rechnitzer, 2013). Since many of these transit bus stop-related crashes occurred on higher-speed arterials, speed reductions may be necessary along these corridors to safely accommodate transit passengers and other pedestrians.

Efforts to address crash scenarios where pedestrians are hit while crossing midblock or at an intersection would benefit not only transit passengers but all pedestrians in areas with transit services. The analysis of bus stop infrastructure where crossing-related crashes occurred revealed that access to crosswalks was limited at some locations. Specifically, only 63.7% of these bus stops had access to a nearby crosswalk at the time of the crash. This suggests that increasing access to marked crosswalks and enhancing the visibility of existing crosswalks could improve pedestrian safety in these areas. Specifically, NHTSA's Proven Safety Countermeasures stated that high-visibility crosswalks have the potential to reduce pedestrian injury crashes by up to 40% (Albee, 2021; Chen et al., 2012). Moreover, to address pedestrian crossing behavior, barriers may be installed along the sidewalks to guide pedestrians to cross at marked crossing facilities, as suggested by a previous study (Pessaro et al., 2017). Last, relocating midblock bus stops to signalized intersections when feasible may reduce the risk of this type of crash, as suggested prior research (Anis et al., 2024; Yu, 2024).

Last, the findings of this thesis reiterate the importance of inter-agency partnerships to facilitate safer access to transit (Goughnour et al., 2022). Transit agencies, state DOTs, and local government organizations all have important roles in addressing pedestrian safety at bus stops. While transit agencies may have the authority to make improvements to the bus stops themselves, they must collaborate with state and local

organizations to ensure that transit routes and bus stops are located on roadways with a connected pedestrian and bicyclist network. For example, while a transit agency may control whether a bus stop has a shelter, collaboration may be needed to ensure access to a sidewalk and/or crosswalk near the bus stop. Increased collaboration between transit agencies, state DOTs, and local government organizations may help to enhance the safety of both the bus stop environment and pedestrian access to it.

Areas for Improvement and Future Research

While this thesis provides insights into pedestrian safety at bus stops from the FARS database, several limitations exist. First, this study only considered fatal pedestrian-involved crashes, as only fatal crashes are included in the FARS database due to its reporting requirements. Therefore, further analysis is needed to understand the factors influencing injury severity outcomes in transit bus stop-related crashes. Additionally, as previously mentioned, FARS should consider adopting PBCAT 3.0 to address the various types of transit bus stop-related crashes. Moreover, FARS does not provide information about the conditions at the bus stop itself, nor does it indicate whether the affected pedestrian was a passenger or simply a passerby. Last, Sanchez Rodriguez and Ferencsik (2024) conducted a study on pedestrian fatalities from 1999 to 2020 and found that the locations of these crashes are shifting to suburban areas. Given this, FARS should consider redefining land uses to include suburban contexts.

This thesis considered demographic characteristics and pedestrian/motorist impairment, but no significant associations were identified using the FARS dataset. Therefore, these factors should be explored further in future research using other datasets. Moreover, this study did not address the potential causes of the geographic distribution of transit bus stop-related crashes, which may necessitate further analysis of FARS data or other datasets to understand this relationship. Additionally, the current limitations in reporting transit-related information in safety databases can be addressed by improving data collection methods, which would better support this type of research moving forward.

A significant focus of this thesis was the comparison of fatal transit bus stop-related crashes with other nearby fatal crashes. However, since the sample of nearby crashes was drawn from areas where a transit bus stop-related crash had already occurred, these locations may be higher-risk or "hot spots" for fatal pedestrian crashes. This could introduce bias into the comparison by overrepresenting areas with higher crash frequencies. An alternative approach would be to obtain a randomized sample of pedestrian crashes from FARS rather than selecting crashes based on proximity to transit bus stop-related crashes. This would establish a baseline for comparison between transit bus stop-related crashes and other pedestrian crashes, rather than limiting the analysis to those occurring nearby.

Additionally, this thesis did not directly assess the accuracy of the location-based assumption that was commonly used in the prior literature. Instead, the thesis compared characteristics of transit bus stop-related crashes and those in the immediate area by defining a buffer zone around each transit bus stop-related crash location, whereas the location-based assumption defines a buffer zone around each bus stop. Therefore, the two approaches cannot be directly compared, making it challenging to draw conclusions about the accuracy of the location-based assumption. Given the extensive use of this method in prior literature and the limited availability of transit bus stop details in pedestrian crash data, future research should address this gap.

In light of recent trends in rising pedestrian fatalities across the United States and the research gaps surrounding the relationship between pedestrian safety and bus stops, further research is important to ensure that the safety benefits of transit are fully realized for all road users. Data collection plays a critical role in this effort, as trip purpose information, particularly trips made to and from transit, can offer a more direct approach for identifying pedestrian involvement and reducing uncertainties in future research on pedestrian safety at bus stops. Both transit and walking are key components of urban mobility. Therefore, by closing data gaps, future research on pedestrian safety at bus stops can help to support initiatives aimed at achieving zero traffic fatalities and also promote transit as a safer and more attractive mode, potentially encouraging ridership and improving urban mobility.

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VITA

Allison Rewalt was born and raised in Las Cruces, New Mexico, where she attended New Mexico State University and obtained her Bachelor of Science degree in Mechanical Engineering with a minor in Physics. Passionate about research, Allison eagerly explored graduate school opportunities when she connected with Dr. Candace Brakewood at the University of Tennessee, Knoxville (UTK), where she decided to pursue a Master of Science in Transportation Engineering. Allison's research interests entail the intersection between pedestrian safety and public transit. Specifically, understanding the risk factors pedestrians face during their journeys to and from transit stops. During her time in graduate school, Allison was awarded the Center for Pedestrian and Bicyclist Safety (CPBS) Outstanding Student of the Year, where she was recognized at the Council of University Transportation Center (CUTC) Annual Winter Meeting & Annual Awards Banquet in Washington, D.C. in January of 2025. Additionally, Allison was selected to participate in the Dwight D. Eisenhower Transportation Fellowship Program (DDETFP), where she had the opportunity to present her research on pedestrian safety at bus stops at the Transportation Research Board Annual Meeting (TRBAM) in January of 2025. She has also been named a Traffic Safety Scholar (TSS) by the Lifesavers Conference on Roadway Safety, where she was provided an opportunity to travel to Long Beach, CA to attend the largest gathering of traffic safety professionals in the nation. Following graduation, Allison intends to pursue her Doctor of Philosophy in Transportation Engineering, continuing under the supervision of Dr. Candace Brakewood at UTK, and expanding on her current research on pedestrian safety at bus stops. Allison is deeply grateful for the constant support she has received from the transportation engineering faculty at the UTK, especially Dr. Candace Brakewood, who has provided invaluable opportunities for growth during Allison's time in graduate school. Allison is also grateful to her family back home in New Mexico, as well as her friends who have supported her throughout this journey.