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Analyzing Pedestrian Safety Near Bus Stops in Northern Virginia

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EXECUTIVE SUMMARY

In the US, traffic-related pedestrian crashes have seen a significant increase, resulting in a higher rate of pedestrian fatalities. From 2012 to 2022, pedestrian fatalities rose by 56%, compared to a 26% increase in all motor vehicle deaths. In Virginia, pedestrian fatalities accounted for 18% of all traffic-related deaths in 2022, marking a 50% increase from 2017. These alarming statistics highlight the need to identify factors contributing to pedestrian crashes to implement effective countermeasures.

The Virginia Department of Transportation (VDOT) has developed several projects to improve pedestrian safety, including the Pedestrian Safety Action Plan (PSAP), the Strategic Highway Safety Plan (SHSP), and the Vulnerable Road User Safety Assessment (VRUSA). These reports emphasize the importance of addressing pedestrian safety and countermeasures to reduce pedestrian fatalities. A key finding included that, in Virginia between 2018 and 2022, about 26% of pedestrian fatalities on non-limited access roads occurred within 150 ft of a bus stop. This research analyzed pedestrian crashes in Northern Virginia (NOVA) to understand factors that may contribute to pedestrian crashes near bus stops. By analyzing pedestrian crash data from 2018 to 2024, bus stop locations, and census data, the study compared crashes within 150 ft of a bus stop to those more than 500 ft away.

Some key findings include that crashes within 150 ft of a bus stop were 3.1 times more likely to be near an intersection than crashes more than 500 ft from a bus stop. Crashes near bus stops were more likely to occur near traffic signals, while those farther away were more likely to occur where only traffic lanes were marked or without traffic control. Crashes near bus stops occurred more frequently on arterial roads, while those farther away from bus stops occurred more frequently on local roads. For crashes in the dark, crashes far from bus stops were less likely to have road lighting, which resulted in a higher proportion of severe or fatal crashes. Finally, crashes near bus stops were more likely to occur in areas with higher bus stops per capita, higher walkability scores, and higher population density, but lower overall social determinants of health. Some factors that were not influenced by the crash distance to the nearest bus stop included the traffic control device, weather or road conditions, or whether the crash was a hit and run. This research provides insights into the relationship between bus stop proximity and pedestrian crash risk, emphasizing the need for targeted safety improvements in NOVA's bus system.

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LIST OF ABREVIATIONS AND SYMBOLS

AADT	annual average daily traffic
BCDCOG	Berkeley Charleston-Dorchester Council of Governments
ECDF	empirical cumulative distribution function
FHWA	Federal Highway Administration
HOI	Health Opportunity Index
NOVA	Northern Virginia
NTM	National Transit Map
NTVC	Northern Virginia Transportation Commission
PBSAP	Pedestrian and Bicyclist Safety Action Plan
PSAP	Pedestrian Safety Action Plan
RRFB	Rectangular Rapid Flashing Beacons
SDOH	social determinants of health
SHSP	Strategic Highway Safety Plan
SSI	stop safety index
USDOT	United States Department of Transportation
VDOT	Virginia Department of Transportation
VRUSA	Vulnerable Road User Safety Assessment

CHAPTER 1. INTRODUCTION

In the US, there has been an alarmingly high increase in traffic-related pedestrian crashes, which overwhelmingly result in pedestrian fatalities. While all motor vehicle deaths have increased by 26% from 2012 to 2022, traffic-related pedestrian fatalities have increased by 56% in that same amount of time (IIHS-HLDI, 2024). In 2022, pedestrian deaths accounted for 18% of all traffic fatalities in the US (USDOT, 2024). These statistics were consistent in Virginia, with 171 pedestrian fatalities in 2022, which accounted for 18% of all traffic-related fatalities in the Commonwealth, which was a 50% increase from 2017 (Virginia State Crime Commission, 2023). These statistics emphasize the importance of identifying factors that relate to increased pedestrian crashes so that effective countermeasures can be put in place to prevent these crashes.

To address these crashes, the Virginia Department of Transportation (VDOT) has developed several reports that focus on ways to improve pedestrian safety through analyzing pedestrian crash reports and factors that may increase pedestrian crashes, injuries, and fatalities. The Pedestrian Safety Action Plan (PSAP; Cole & Read, 2018) was developed in 2018 by VDOT to address increasing pedestrian fatalities in Virginia. The 2022–2026 Strategic Highway Safety Plan (SHSP; VDOT, 2023) is the current 5-year plan for Virginia to address all roadway safety concerns, and also contains the newer Pedestrian and Bicycle Safety Action Plan (PBSAP). Virginia's Vulnerable Road User Safety Assessment (VRUSA) combines and updates these findings to represent "a comprehensive multi-disciplinary approach for monitoring and addressing VRU safety and reducing fatal and serious injury crashes in Virginia with additional actions for partners and stakeholders to implement" (VDOT, 2024).

These reports highlight the crucial areas where pedestrian safety can be improved. A key finding highlighted that, between 2012 and 2016, 51% of pedestrian injury crashes occurred at midblock crossing locations, and 74% occurred at locations without a marked crosswalk. Several news reports from Fairfax County also highlighted public frustration with unsafe intersections, and the need to implement pedestrian improvements (Annandale Today, 2024, November 15, December 12). Crash data from 2018 to 2022 also found that in Virginia about 50% of pedestrian fatalities on non-limited access roads occur within 500 ft of a bus stop, and 26% occur within 150 ft (Read, 2023a). This finding fueled the initial purpose of this research: to identify the underlying factors that may be contributing to the increased pedestrian crash risk in the vicinity of bus stops in Virginia. As this is an initial effort, we focused on pedestrian fatality data in Virginia's largest metropolitan areas, Northern Virginia (NOVA).

The NOVA Regional Bus Transit Analysis annual report found that "around 40% of the public transportation trips in Northern Virginia take place on buses, with 31.5 million trips on buses completed in 2023" (Cambridge Systematics, 2024). Pedestrian-vehicle interactions are more likely to occur in urban areas with denser populations, which increases crash risk due to increased exposure. Generally, bus stops are more prevalent in denser urban areas and may amplify pedestrian crash risk due to pedestrians needing to cross the street or consolidate in an area very close to the road. The Virginia Health Opportunity Index (HOI) also provides insight into social determinants of health (SDOH) and how these may influence crash risk in different areas (*About the Health Opportunity Index*, 2025). So, although crash risk is inherently increased near bus stops, investigating the contributing factors near bus stops is important to develop effective countermeasures.

This research combines publicly available data for pedestrian crashes, bus stops, and census data in NOVA to determine factors that may contribute to pedestrian crashes near bus stops, as compared to pedestrian crashes far from bus stops.

CHAPTER 2. LITERATURE REVIEW

Pedestrian safety has been a highly researched topic, with a specific focus on how these findings can help introduce countermeasures to reduce pedestrian fatalities. While public transit primarily aims to transport large groups of people efficiently, it also offers significant safety benefits like reducing pedestrian fatalities (Morency et al., 2018). Bertnman et al. (2010) found that bus passengers face a lower fatality risk during their journeys than drivers. However, they are at a higher risk of injury when walking to and from bus stops. Tang et al. (Tang, 2024) also found that pedestrian crashes were most frequent in census tracts with a higher number of bus stops, subway stations, and traffic intersections. So, while travelling by bus poses less risk than travelling by car, the journey to get on the bus may be more dangerous than the bus trip itself.

A bus stop serves as the initial point of contact between passengers and the bus service. However, the placement of bus stops, particularly on arterial roads and near intersections, significantly impacts pedestrian safety (Rahman et al., 2022). Bus stop locations are often deemed unsafe for pedestrians as they can encourage risky behaviors, such as passengers rushing to cross the road to catch an arriving or departing bus. When it comes to addressing pedestrian safety near bus stops, the Federal Highway Administration (FHWA) has developed a bus stop checklist to assist transit agencies in prioritizing pedestrian safety (Nebors et al., 2008). To develop effective checklists such as this, research is imperative to identify factors that positively influence safety near bus stops.

A common method is to identify pedestrian crash hot spots and then identify bus stops in these areas and the factors shared between them. Ulak et al. (2021) produced a stop safety index (SSI) and regression tree to screen and rank pedestrian safety around bus stops, as well as to test the safety potential of certain bus stop factors. The index developed helps in screening urban roadway networks and ranking bus stops based on pedestrian safety to identify high-risk locations before pedestrians become crash statistics. Anis et al. (2025) analyzed pedestrian safety near bus stops in Fort Worth, Texas, by using a Random Parameters Negative Binomial-Lindley statistical model. This model allows for the detailed analysis of variations between bus stop sites. They found that higher annual average daily traffic (AADT), greater pedestrian boarding activities, slower speed limits (<35 mph), proximity to schools, and the absence of crosswalks, medians, and adequate lighting contributed to a higher crash risk near bus stops. However, signalized intersections, far-side bus stops, mixed-use developments, and sidewalks were associated with a reduced crash risk. Truong and Somenahalli (2011) used severity indices, instead of crash counts, to identify unsafe bus stops in Adelaide, South Australia. Moran's I statistic was used to examine spatial patterns of pedestrian-vehicle crash data, and bus stops in identified crash hot spots were ranked based on the severity of crashes in their vicinity. They found a strong correlation between pedestrian-vehicle crashes and transit access, particularly bus stops.

While road crash statistics are commonly used to identify unsafe bus stops, other methods can be used to identify factors related to safety. Yendra et al. (2024) looked at factors that influence the safety of pedestrians accessing bus stops in countries of differing income levels. While crash data is common in high-income countries, the unavailability and unreliability of data hinders the identification of hazardous bus stops in low-income countries. The factors that influenced pedestrian safety were categorized between characteristics of road users, bus stops, and road traffic environment. Similarly, rather than focusing on crash data, Tubis et al. (2021) focused on infrastructure elements of bus stops and the vicinity of bus stops. They developed a method of assessing bus stop safety by auditing and designing point infrastructure in the city based on three groups of criteria: infrastructure, traffic conditions, and environmental factors. They evaluated 151 bus stops and rated each bus stop on their adherence to safety criteria, which highlighted the need for ongoing and long-term improvements to enhance public transport passenger safety. A study by Craig et al. (2019) looked at 16 crosswalk sites in Saint Paul, Minnesota, to investigate whether bus stops affect the likelihood of drivers yielding to pedestrians at marked, unsignalized crosswalks compared to other locations, and to assess the relative risk of these events near bus stops. The findings revealed that public transit vehicles yielded to pedestrians more frequently than general traffic. Over time, high-visibility enforcement led to improved yielding rates, despite the negative impact of high average daily traffic and the positive effect of crosswalk enhancements. However, the presence of a bus stop near an unsignalized, marked crosswalk was linked to lower yielding rates. Specifically for public transit, high average daily traffic resulted in poorer yielding, but this improved with increased law enforcement.

Projects like these have introduced the need for countermeasures to reduce pedestrian fatalities. A common countermeasure to address pedestrian safety is the rectangular rapid flashing beacon (RRFB), which is "a set of high-intensity yellow lights, mounted below a pedestrian warning sign, adjacent to a crosswalk" (Arlington Transit, 2024). The FHWA estimates that RRFBs can reduce pedestrian crashes up to 47% and increase motorist yield rates up to 98% (FHWA, 2018). Arlington County has already installed RRFBs in 36 locations as of April 2025 and found that the driver probability to yield to crossing pedestrians increased by 35% for one case study (Arlington Transit, 2024; Arlington County, 2025).

A more recent approach to addressing pedestrian safety has been understanding how SDOH may be correlated to an increased crash risk. While transportation plays a significant role in reducing health disparities by linking people to safe housing, nutritious food, physical activity, education, and job opportunities, some transportation infrastructure decisions have disproportionately burdened certain groups, leading to higher rates of fatal and serious injury crashes (Walker, 2023). Dumbaugh and Stiles (2025) found that lower-income areas experience 3 times the number of per capita pedestrian fatalities as affluent areas, on average. These disparities stem largely from historical and ongoing disinvestment in underserved communities and the underrepresentation of disadvantaged groups in the planning, development, construction, operations, and maintenance of transportation systems. As an example, Fairfax County in NOVA was chosen as an improvement example based on pedestrian crash history and proximity to historically disadvantaged or marginalized population (*"E is for Everybody": Using Equity to Prioritize Pedestrian Safety Projects and Make the Case for Greater State Funding*, 2023). Recommendations for safety improvement included the relocation of transit stops to encourage crossings near controlled intersections, signal modifications, improved lighting, and lane reduction.

While previous research has focused on using advanced statistical and spatial methods to identify bus stops with an increased crash risk, this research aims to combine environmental, infrastructural, and societal factors that may increase pedestrian crashes near bus stops as compared to crashes far from bus stops in NOVA.

CHAPTER 3. METHODOLOGY

The proposed research approach focused on analyzing pedestrian crashes via the PSAP map and then using publicly available data to find a variety of factors that may indicate a higher pedestrian crash risk. These data include infrastructure data, bus stop data, and societal factors. This section explains the choice for NOVA, the data sources used, and the statistical analysis methods used.

NOVA

As mentioned earlier, this analysis focused on one district of Virginia to assess the impact on a smaller scale, which can be expanded in future analyses. Out of the nine districts in Virginia, NOVA was chosen because it comprises the three most populous counties in the state (VDOT, 2025b). A map of NOVA, developed by VDOT, is shown in Figure 1. The other cities, counties, and towns included in NOVA are listed below:

- **Counties:** Arlington, Fairfax, Loudon, Prince William
- **Cities:** Alexandria, Fairfax, Falls Church, Manassas, Manassas Park
- **Towns:** Clifton, Dumfries, Hamilton, Haymarket, Herndon, Hillsboro, Leesburg, Lovettsville, Middleburg, Occoquan, Purcellville, Quantico, Round Hill, Vienna

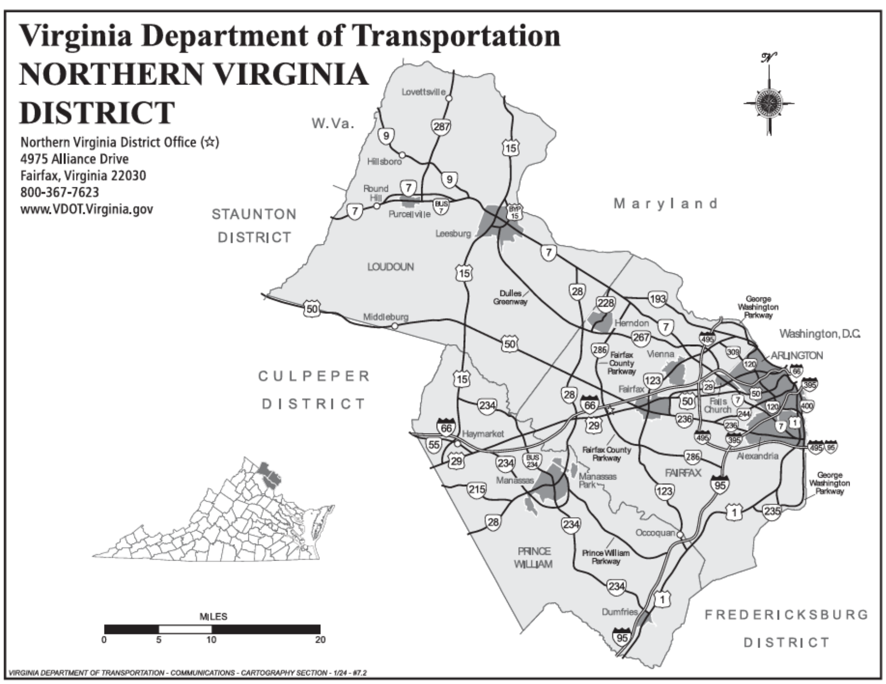

Figure 1. Map. NOVA district (VDOT, 2025b).

The PSAP also identified the number of pedestrian crashes and fatalities by district, and found that in 2012–2016, NOVA had the largest percentage of pedestrian injury crashes at 33.1% (Cole & Read, 2018). PSAP also took a representative sample to account for district population differences, and NOVA still had the highest percentage injury crashes sampled at 16.9%. As this detailed research works as a proposed effort, future research can include other districts in Virginia and across the US. Within NOVA, there are seven bus agencies identified by the Northern Virginia Transportation Commission (NVTC; Northern Virginia Transportation Commission, 2025), as shown in Table 1, with a total of 7,508 bus stops.

Table 1. List of bus agencies in NOVA from the NVTC.

Agency	Agency Full Name	Stops	Routes	Trips
ART	Arlington Transit (ART)	579	17	6,907
DASH	DASH - City of Alexandria	546	14	6,588
CUE	CUE - City of Fairfax	200	4	641
FFX	Fairfax Connector	3,086	91	24,020
LCT	Loudoun County Transit	500	48	14,986
WMATA	Metro (Virginia Only)	2,052	43	15,235
PRTC	OmniRide	545	32	3,553

DATA SOURCES

This project focused on using publicly available data to assess pedestrian crash risk near bus stops. The data sources included pedestrian and bicyclist crashes in Virginia, transit stop and intersection data from the United States Department of Transportation (USDOT), and census data from the US Census Bureau, the Virginia Open Data Portal, and the Virginia Department of Health Data Commons.

Pedestrian Crashes

As mentioned in the introduction, this project was originally informed by results from the PSAP. The VDOT PSAP map contains information about all pedestrian crashes in Virginia and highlights hot spots and especially unsafe corridors for pedestrians (Read, 2023b). Since then, crashes involving bicyclists have been added to the dataset to create the PBSAP.

The pedestrian crash data was originally sourced from the PBSAP map and downloaded from the VDOT Crash Dataset (VDOT, 2025a). The following filters were chosen to select data relevant to this analysis:

- Year: 2018–2024
- Pedestrian: yes
- Planning District: Northern Virginia

The date of the last crash recorded in this dataset at the time of being downloaded was December 31, 2024. After all filters were applied, 3,563 crashes were identified.

Bicycle Crashes

Although bicycle crashes were not originally part of the study proposal, since the PSBAP map has been updated to include cyclists, we included summarized data for bicycle crashes during the same time period and in the same area as the pedestrian crashes. Pedestrians and bicyclists are both included in the vulnerable road user (VRU) category, and so it may be beneficial to include bicyclists to understand the overall impact of VRU crashes near bus stops.

The bicyclist crash data was originally sourced from the PBSAP map and downloaded from the VDOT Crash Dataset (VDOT, 2025a). The following filters were chosen to select data relevant to this analysis:

- Year: 2018–2024
- Bike: yes
- Planning District: Northern Virginia

The date of the last crash recorded in this dataset at the time of being downloaded was December 30, 2024. After all filters were applied, 1,446 bicycle crashes were identified, of which 10 crashes overlapped with the pedestrian crashes identified above.

Bus Stop Data

The National Transit Map (NTM; Bureau of Transportation Statistics, 2024) provided data about the bus stops in NOVA. The NTM "is a nationwide catalog of fixed-guideway and fixed-route transit service in America." It contains basic information about each bus stop in America, which included the following in this analysis:

- Stop ID
- Stop Name
- Stop Description
- Stop Latitude and Longitude
- Location Type
- Agency ID

Since this dataset includes all transit stops in America, to reduce the size of the dataset to only include transit stops in NOVA, the latitudes and longitudes were filtered to only use the values between those listed in Table 2.

Table 2. Latitudes and longitudes that create a box around NOVA.

	Minimum	**Maximum**
Latitude	38.506353	39.318596
Longitude	-77.824212	-77.038523

This dataset also included all public transit stops. Therefore, it was further filtered to remove any Metro, commuter rail, and heavy rail stops. After these filtering methods, 13,440 bus stops were identified in this region. This number is much larger than the number of bus stops identified by the NVTC (7,508) because the filtering of the NTM data was geography based and might include some bus stops outside of the NVTC agencies. After reviewing both datasets, the NTM dataset was used because it included more stop-specific information, and the latitudes and longitudes from the NTM were more precise than the NVTC. However, the NOVA Transit Data Dashboard (Northern Virginia Transportation Commission, 2025), developed by the NVTC, was used as a reference for specific routes, along with the online Statewide Transit Data Map developed by the Virginia Department of Rail and Public Transportation (2025).

To understand which factors influence pedestrian crash frequency near bus stops, it is important to understand the exposure of pedestrians near each bus stop. While pedestrian traffic and ridership data is not available, the number of bus stops per capita in each census tract was used as an exposure proxy to reflect the potential service coverage for residents. To get the number of bus stops per census tract, data was taken from the National Neighborhood Data Archive, available via the Institute for Social Research at the University of Michigan (Pan et al., 2024). This dataset contains the total population, number of bus stops, stops per capita, and stops per square mile for every census tract in the US in 2020. This data was used especially for the community factors described in the HOI Data section and analyzed in the Community Factors section.

Intersection Data

While most bus stops are near intersections, it was also important to understand characteristics of the intersections that were near the crashes and the bus stops. This dataset was pulled from the approximately 440,000 intersections found throughout the state of Virginia through VDOT (Hetzer, 2024). The *Intersection_ID* from this dataset was matched to the *Node* variable in the pedestrian and bicyclist datasets. To reduce the size of the dataset to only include intersections in NOVA, the latitudes and longitudes were also filtered using the values in Table 2.

HOI Data

The HOI "is a group of indicators that provide broad insight into the overall opportunity Virginians have to live long and healthy lives, based on social determinants of health" (*About the Health Opportunity Index*, 2025). The HOI contains 13 indicators, which are listed below:

- Access to Care
- Employment Accessibility
- Affordability
- Air Quality
- Population Churning
- Education
- Food Accessibility
- Income Inequality
- Job Participation
- Population Density
- Segregation
- Material Deprivation
- Walkability

The indicators are combined to create four profiles based on the community environment, consumer opportunity, economic opportunity, and wellness disparity. These profiles are then combined to give an overall HOI score by principal component analysis. Each US census tract in Virginia has a value for each of the 13 indicators, four profiles, and overall HOI score. As an example, the indicator "Access to Care" examines the percentage of residents without health insurance and the number of full-time equivalent primary care physicians within 30 miles of the area. These values provide a quantifiable way to understand the resources available to residents within each census tract, which allows for the statistical analysis of factors that may correlate to some SDOH.

Two datasets were used to get HOI values. This is because the first dataset was missing values for 102 census tracts. The second dataset was missing values for five census tracts (with three overlapping missing census tracts between the two datasets). See Appendix A for a detailed list of the missing census tracts.

The first dataset was developed by the Virginia Open Data Portal (Anson-Dwamena, 2021) and contains values of each indicator, profile, and HOI. They are normalized on a Z-score system, so that values closer to 0 indicate poor access and 1 indicates high access.

The second dataset was developed by the Virginia Department of Health Data Commons (Virginia Department of Health Data Commons, 2020) and contained an interactive map that could be filtered for data download. The profiles and HOI score are given an integer score of 1 to 5. These values correspond to "very low," "low," "average," "high," and "very high" opportunity levels by census tract.

Census Data

To match the correct HOI data to the crash, the census tract of the crash had to be determined. This was done by using the Census Geocoder developed by the US Census Bureau (*Census Geocoder*, 2023). The latitude and longitude of each crash were batch uploaded to the Census site, which provided the full Federal Information Processing Standard (FIPS) tract for each crash, which corresponded to the 10-digit *Census Tract ID* found in the HOI.

ANALYSIS METHODS

This section describes how we defined if a crash was near a bus stop, how the data was concatenated, and the statistical test used to determine significance.

Finding the Nearest Bus Stop

To answer the research questions, we first had to determine how close each crash was to the nearest bus stop. To do so, the Haversine distance, in feet, between the latitude and longitude of each crash to each bus stop was calculated. The closest bus stop was then identified as the one with the shortest distance to the crash. It is important to note that this distance is "as the crow flies." Therefore, the closest identified bus stop may not be on the same road segment or route as the crash. However, this report generally focuses on crashes within 150 ft of a bus stop, so it is most likely that the crash is on the same segment, or on a nearby one that is still related to the bus stop.

This distance of the crash to the nearest bus stop was then separated into four distance buckets: less than 150 ft, less than 250 ft, less than 500 ft, and greater than 500 ft. Throughout VDOT pedestrian crash reports, crashes are often reported based on if they are within 150 ft of a bus stop or greater than 500 ft (Read, 2023a, 2023c; VDOT, 2024). We added another point of analysis at 250 ft to initially provide more detailed insight. This distance category was used to compare some of the high-level results of categorical and continuous variables. However, when determining if results were statistically meaningful, we instead just compared crashes that were within 150 ft or more than 500 ft from a bus stop.

To understand how these bus stop distance bins relate to actual bus stop locations, we looked at distance considerations when placing bus stops in NOVA. There are three common types of placements: far-side stop, mid-block stop, and near-side stop. Far-side stops are located after a bus has passed through an intersection. Mid-block stops are located approximately equidistant from the nearest intersections. Near-side stops are located prior to a bus approaching an intersection. Figure 2, taken from the Transit and Bus Stop Guidelines by the Berkeley-Charleston-Dorchester Council of Governments (BCDCOG; 2021), illustrates the different types of bus stop placements.

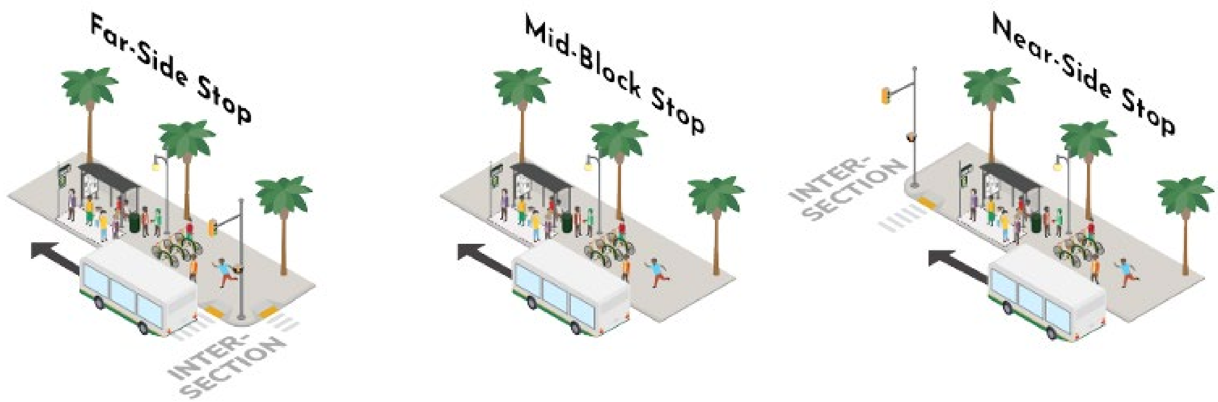

Figure 2. Illustrations. Bus stop placements from the BCDCOG Transit and Bus Stop Design Guidelines (Governments, 2021).

According to Arlington's Bus Stop Guidelines and Standards Manual (*Arlington's Bus Stop Guidelines and Standards Manual*, 2024), far-side bus stops should start a minimum of 60 ft after a crosswalk, and allow a minimum 10-ft buffer zone between the intersection and the stop. Near-side stops should be a minimum of 5 ft before an intersection stop bar or crosswalk, and the bus stop zone should be a minimum of 100 ft. Mid-block stops should have at least 135 ft of clearance from on-street parking. These guidelines are similar to the City of Alexandria's Guidelines for the Design and Placement of Bus Stops (KFH Group & AECOM, 2023), which are illustrated in Figure 3. It is important to note that both guidelines emphasize that mid-block stops are not preferred.

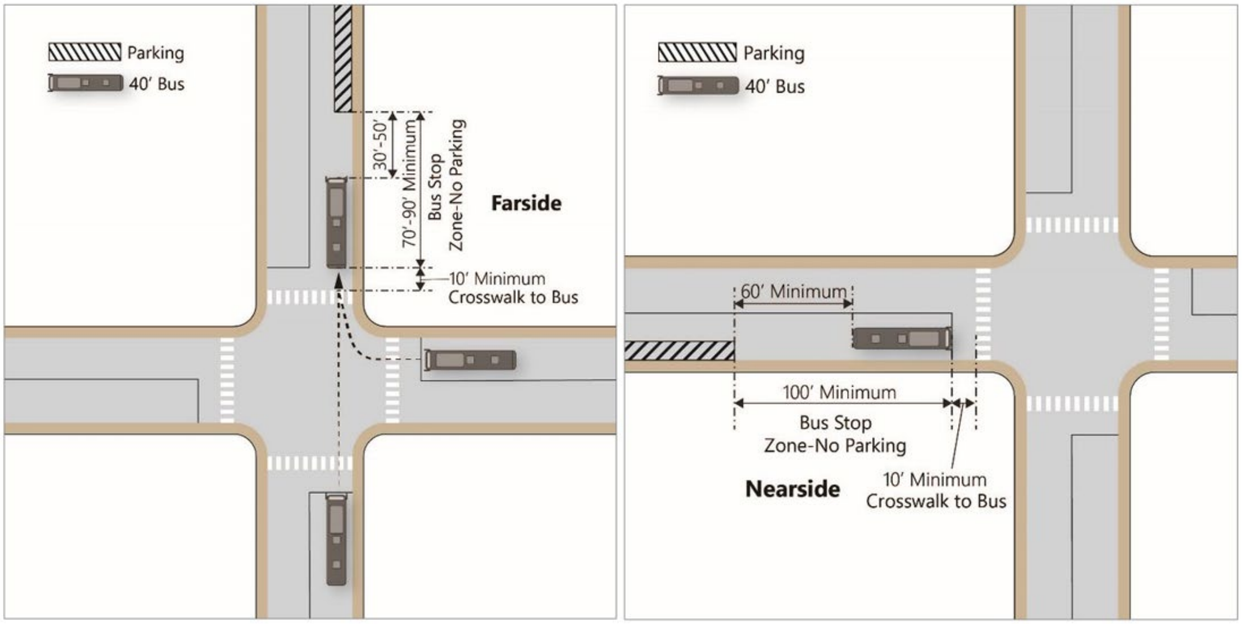

Figure 3. Diagram. Bus stop locations relative to intersections from the City of Alexandria's Guidelines for the Design and Placement of Bus Stops (KFH Group & AECOM, 2023).

In general, if a bus stop is near an intersection, it will most likely be within 150 ft of an intersection. We created Figure 4 to further illustrate the radius that represents crashes within 150 ft of a far-side bus stop to scale. While this illustration is "to scale" of a single-lane, four-way intersection, the 150 ft radius may look different for a variety of intersection types. This threshold distance of 150 ft was used to determine if a bus stop was at an intersection.

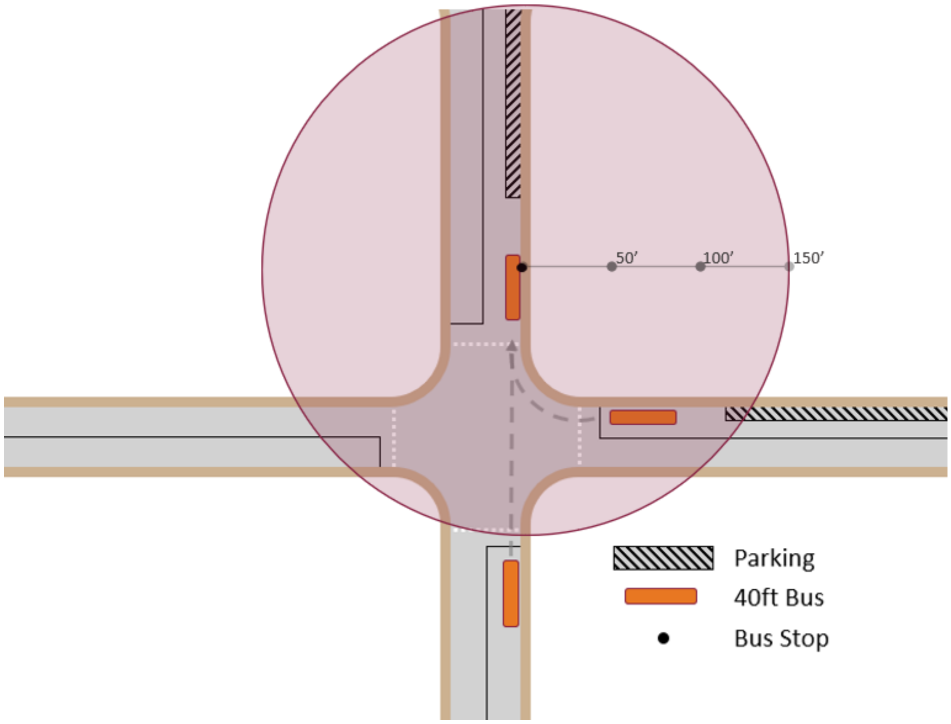

Figure 4. Diagram. Scaled illustration of the radius that represents crashes within 150 ft of a far-side bus stop.

Pedestrian Crash Distribution

To calculate the difference in the distribution of pedestrian crashes across all census tracts of varying HOI scores, we compared the empirical cumulative distribution function (ECDF) of the HOI score in our crash sample to all census tracts in Virginia. The ECDF displays data points in a sample from lowest to highest against their percentiles. The two-sample Kolmogorov-Smirnov test then compares a sample ECDF with a population cumulative distribution function (CDF) by comparing the maximum difference between each CDF.

Categorical Variables

The main part of this project is to determine factors that might contribute to pedestrian crashes near bus stops. To do so, the following statistical tests were performed to determine if certain categorical variables associated with each crash were correlated to the distance of that crash from the nearest bus stop.

Chi-square Test and Cramer's V

The chi-square test of independence and Cramer's V were used to see the relationship between categorical variables and the distance of crashes to bus stops. The chi-square test is described in the equation below for sample size n of variables A and B:

A is observed for $i = 1, \ldots, r$ and $n_i = \sum_j n_{ij}$ is the number of times A_i is observed.

B is observed for $j = 1, \ldots, k$ and $n_j = \sum_i n_{ij}$ is the number of times B_j is observed.

n_{ij} = number of times the values (A_i, B_j) were observed.

$$\chi^2 = \sum_{i,j} \frac{\left(n_{ij} - \frac{n_i n_j}{n}\right)^2}{\frac{n_i n_j}{n}}$$

Cramer's V is an effect size measurement for the chi-square test and measures the association between two categorical variables. Cramer's V was calculated as below:

$$V = \sqrt{\frac{\chi^2/n}{\min(k-1, r-1)}}$$

It is a normalized value that ranges from 0 to 1, and was interpreted as follows:

- 0.0 to 0.1: very weak association
- 0.1 to 0.3: weak association
- 0.3 to 0.5: moderate association
- 0.5 to 0.8: strong association
- 0.8 to 1.0: very strong association

Risk Ratio and Odds Ratio

The risk ratio and odds ratio were also calculated to determine how certain categorical variables might increase the odds that a crash occurs near a bus stop, or how it might increase the crash severity risk. To calculate the risk ratio and odds ratio, a 2 × 2 contingency table is made that has two groups and two conditions (Table 3). The values in the table are the frequency of pedestrian crashes for each condition and group, or the frequency of variables present that we are comparing.

Table 3. Contingency table.

	Condition		
	Absent	**Present**	**Total**
Group 1	A1	P1	T1 = A1 + P1
Group 2	A2	P2	T2 = A2 + P2
Total	TA = A1 + A2	TP = P1 + P2	TA = TA + TP = T1 + T2

The risk ratio compares the probability of a condition being present in Group 1 to the probability of that condition being present in Group 2. The odds ratio compares the odds of the condition being present in Group 1 to the odds of it being present in Group 2.

Rate = proportion in group with condition present

$$Risk\ Ratio = \frac{A1/T1}{A2/T2}$$

$$Odds\ Ratio = \frac{P1/A1}{P2/A2}$$

In this analysis, the distance to the nearest bus stop category was separated into two groups so that the presence or absence of different variables could be used to see how they change the odds of a crash being near or far from a bus stop. The two groups were:

- Crashes within 150 ft of bus stop
- Crashes more than 500 ft from nearest bus stop

The *Crash Severity* variable was condensed to two separate conditions so that two groups of variables could be compared to see how they change the crash severity risk. The two conditions were:

- Present: fatal and severe injury
- Absent: visible injury and nonvisible injury

Continuous Variables

There were fewer continuous variables than categorical variables associated with each pedestrian crash, but the following statistical tests were used to determine the relationship between these variables and the number of crashes or the crash distance to the nearest bus stop.

Linear Regression

A linear regression model is used to estimate the relationship between two continuous variables, assuming linearity. In this analysis, it was used to see if there was a linear relationship between the number of crashes (y) in a census tract and the number of bus stops per capita (x) in that same census tract. The following values are used to interpret the outputs of the linear regression model:

- Slope (m): the slope of the linear relationship
- Pearson's correlation coefficient (r): normalized measure of the covariance (ratio between the covariance of two variables and the product of their standard deviations)
- Correlation coefficient (R^2): quantifies the strength and direction of the linear relationship (proportion of the variance)

Mann-Whitney U Test and Cohen's D

The Mann-Whitney *U* Test is useful to compare two independent group medians for a non-normal distribution. This was used for the crash time between crashes within 150 ft of a bus stop and crashes over 500 ft from the nearest bus stop.

Cohen's *D* is a measure of effect size with a simple calculation of the standardized mean difference between two groups. If M_1 and SD_1 are the mean and standard deviation of Group 1, respectively, and if M_2 and SD_2 are the mean and standard deviation of Group 2, respectively, then:

$$Cohen's\ D = \frac{M_2 - M_1}{SD_{pooled}}$$

where, $SD_{pooled} = \sqrt{\frac{SD_1^2 + SD_2^2}{2}}$

It is a normalized value that ranges from 0 to 1, and was interpreted as follows:

- 0.0 to 0.3: small effect
- 0.3 to 0.8: medium effect
- 0.8 to 1.0: large effect

T-test

A two-sample *t*-test is used to determine if there is a statistically significant difference between the means of two groups, assuming relatively normal distributions. The two groups used in this analysis were:

- Crashes within 150 ft of bus stop
- Crashes more than 500 ft from nearest bus stop

If M_1, SD_1, and n_1 are the mean, standard deviation, and number of observations for Group 1, respectively, and if M_2, SD_2, and n_2 are the mean, standard deviation, and number of observations for Group 2, respectively, then:

$$t = \frac{M_1 - M_2}{\sqrt{\frac{SD_1^2}{n_1} + \frac{SD_2^2}{n_2}}}$$

CHAPTER 4. RESULTS AND DISCUSSION

This section covers the results from the data sources and mentioned analysis methods, as well as a discussion of the results. Each subsection is broken down by the information/variable available for each crash, and the results that followed from the analyses.

CRASH SEVERITY

Figure 5 shows the number of pedestrian crashes by crash year and crash severity from 2018 to 2024 in NOVA. The crash severity is determined by the most severe injury of people involved in the crash. We can see that there was a significant dip in 2020 during the Covid-19 pandemic. However, the number of pedestrian crashes per year has been increasing steadily since. This trend follows results from previous research and was the original motivation for the PSAP, PBSAP, SHSP, VRUSA, and other research aimed to prevent pedestrian crashes.

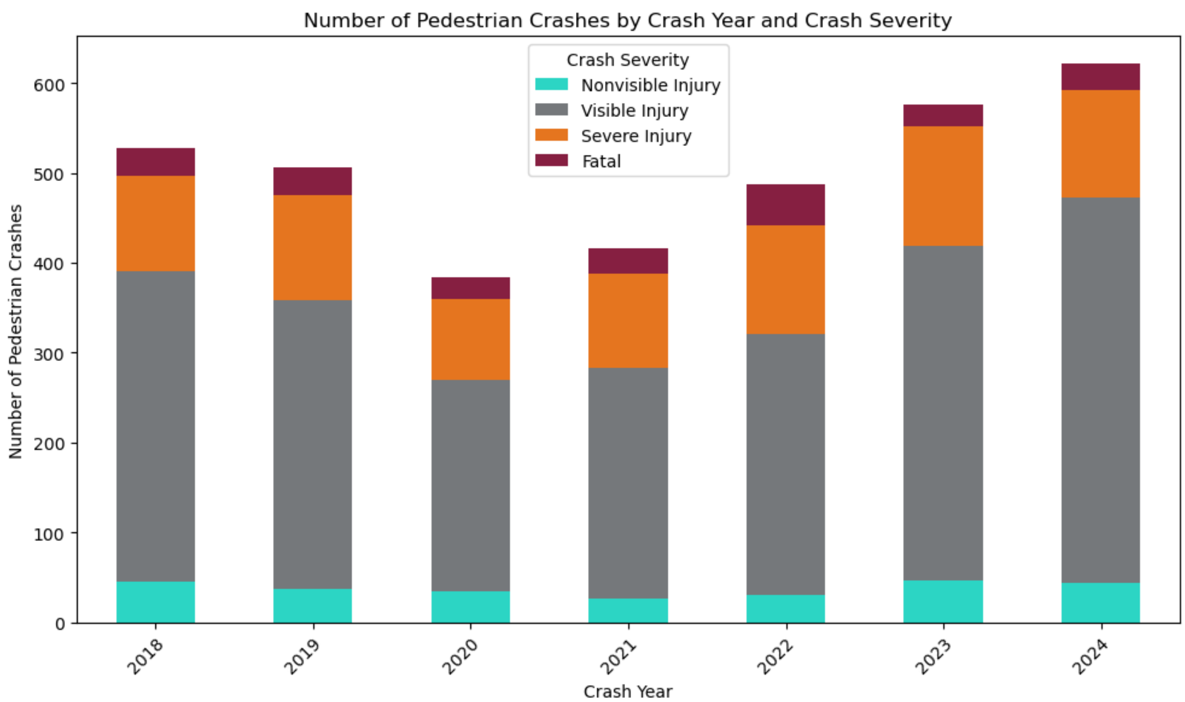

Figure 5. Graph. Number of pedestrian crashes in NOVA from 2018–2024 based on crash severity.

Table 4 shows the number of crashes involving pedestrians and bicyclists in NOVA throughout 2018–2024 separated by the crash severity. We can see that within both the pedestrian and bicyclist datasets, the largest number of crashes included a visible injury, followed by a severe injury, followed by nonvisible injury. The “property damage only” category was only present in the bicycle crash category. This is likely because a collision involving a pedestrian typically does not result in property damage unless there is at least an accompanying visible injury to the pedestrian. Conversely, a crash involving a bicycle or vehicle can cause damage to the bike or car even if the cyclist or driver remains uninjured. Finally, the smallest group of crashes resulted in fatalities: there were 213 crashes that resulted in 215 total pedestrian fatalities, and there were nine crashes that resulted in nine total bicyclist fatalities.

Table 4. Number of pedestrian and bicycle crashes in NOVA separated by crash severity.

Crash Severity	Code	Number of Pedestrian Crashes	Number of Bicycle Crashes
Nonvisible Injury	C	264	63
Visible Injury	B	2,250	1,037
Severe Injury	A	790	229
Fatality	K	213	9
Property Damage Only	O	0	108
Total		3,517	1,446

We do not include any further analyses with bicyclists in this research. While crashes involving bicyclists are important to incorporate for overall VRU safety, the analysis for bicycle crashes was out of scope for this project. However, the number of crashes was included in Table 4 to provide some preliminary information for future research that could be done to address crashes involving bicyclists.

CRASH PROXIMITY TO BUS STOPS AND INTERSECTIONS

Bus Stops

The main focus of this research is to identify factors that may contribute to more pedestrian crashes near or around bus stops. As mentioned in the introduction, VDOT identified that 50% of pedestrian crashes between 2018 and 2022 occurred within 500 ft of a bus stop, and 26% were within 150 ft of a bus stop (Read, 2023a). Figure 6 uses pedestrian crash data from 2018 to 2024 and shows that 65% of all pedestrian crashes occurred within 500 ft of a bus stop, while 34% were within 150 ft. This increase in crash rates near bus stops is *not* due to the addition of data from 2023 and 2024. Instead, this discrepancy in rates is likely due to a difference in the calculation used in determining the distance between each crash and the closest bus stop. Since the method VDOT used for measuring the distance between crashes and bus stops was not publicly available, this project developed the method described earlier in the Finding the Nearest Bus Stop section. This method was verified by cross-referencing a randomized set of 50 crashes from the identified dataset in the PSAP map and measuring the distance to the nearest bus stop using tools on Google Maps.

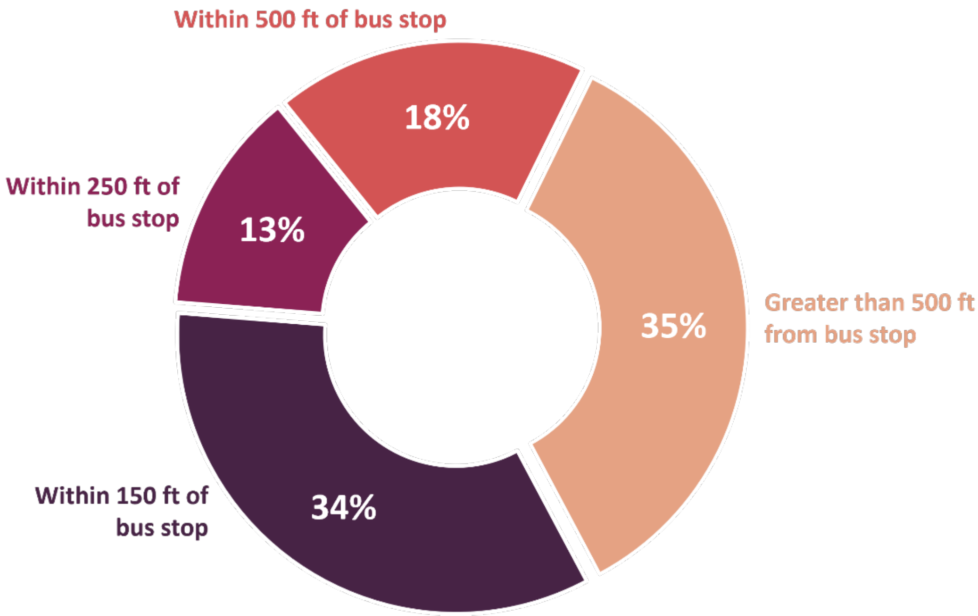

Figure 6. Graph. Percentage of crashes within 150 ft, 250 ft, and 500 ft of a bus stop.

Table 5 shows the number of crashes for each distance category and severity level. With nine degrees of freedom, the chi-squared test provided a chi-square value of 32.4696, a *p*-value of 0.0002, and Cramer's *V* value of 0.0472, which indicates a negligible correlation between crash severity and distance to the nearest bus stop.

Table 5. Number of crashes separated by severity level and distance to the nearest bus stop category.

Distance to nearest bus stop	Nonvisible Injury	Visible Injury	Severe Injury	Fatal	Total
Less than 150 ft	96	802	244	55	1,197
Between 150 ft and 250 ft	37	296	98	24	455
Between 250 ft and more than 500 ft	43	429	125	39	636
More than 500 ft	88	723	323	95	1,229
Total	264	2,250	790	213	3,517

Figure 7 is a histogram that shows the number of pedestrian crashes binned by the distance to the nearest bus stop (up to 500 ft) and stacked by the crash severity. While 35% of pedestrian crashes in NOVA occurred within 150 ft of a bus stop, 70% of those were within 100 ft of a bus stop.

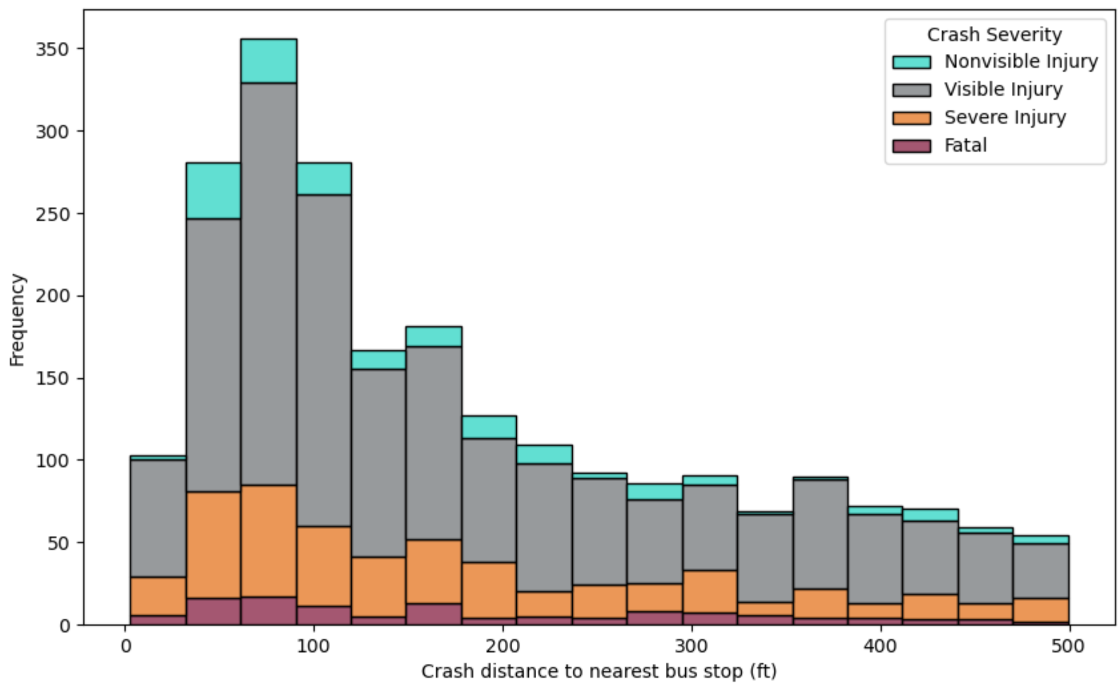

Figure 7. Histogram. Number of crashes separated by crash severity and distance to the nearest bus stop (ft).

Of the 1,197 pedestrian crashes that were near bus stops, these crashes occurred at 780 unique bus stops. Table 6 includes the bus stops that had over six pedestrian crashes within 150 ft from 2018 to 2024. Unfortunately, we do not have information about the ridership of each bus stop or bus route, which could provide information about pedestrian exposure to each bus stop.

Table 6. Top 12 bus stops by the number of pedestrian crashes within 150 ft of the bus stop and the corresponding city.

Stop Name	Number of crashes	Physical Juris Name
Columbia Pk+S Courthouse Rd	9	Arlington County
Columbia Pk+S Walter Reed Dr	9	Arlington County
Rt 1+23 St S	8	Arlington County
PENTAGON CITY	8	Arlington County
Arlington Bl+Annandale Rd	8	Fairfax County
Duke St + N Paxton St	7	City of Alexandria
Columbia Pk+S Columbus St	7	Arlington County
N GLEBE RD NB @ N PERSHING DR NS	6	Arlington County
Columbia Pk+S Barton St	6	Arlington County
Richmond Hwy and Sacramento Dr	6	Fairfax County
S GLEBE RD SB @ COLUMBIA PIKE NS	6	Arlington County
Annandale and Maple	6	Fairfax County

However, as a proxy to exposure information, we do have information about the number of bus stops and bus stops per capita for each census tract in which there was a pedestrian crash. Figure 8 shows, for each census tract, the number of crashes compared to the bus stops per capita for that census tract. Using a linear regression model, the relationship between crashes within 150 ft of a bus stop and the number of bus stops per capita was statistically significant ($p = 0.000$, $r = 0.427$, $R^2 = 0.182$, $m = 0.395$). That is, pedestrian crashes near a bus stop were more likely to happen in a census tract that had more bus stops per capita. However, the number of pedestrian crashes more than 500 ft from a bus stop was not linearly related to the number of bus stops per capita ($p = 0.3114$, $r = -0.045$, $R^2 = 0.002$, $m = -0.036$). That is, the number of bus stops per capita did not influence the number of crashes that were more than 500 ft from a bus stop. This indicates that bus stop exposure was related to the frequency of crashes near bus stops.

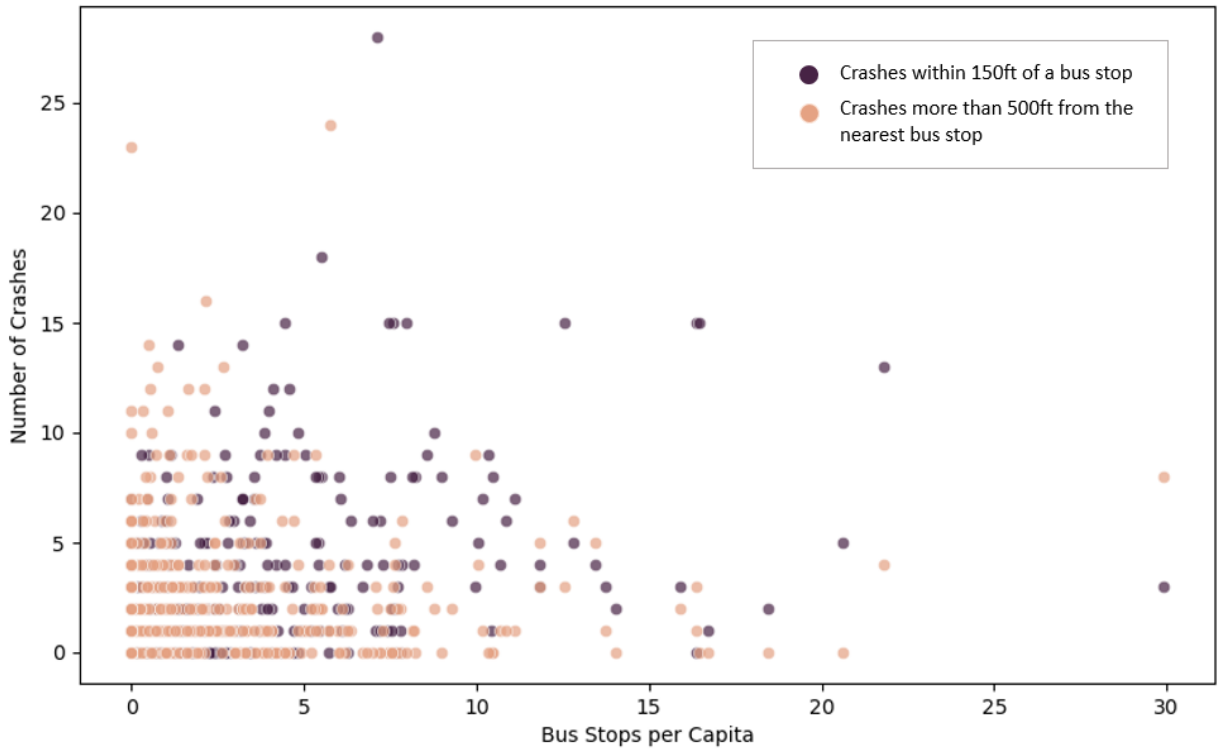

Figure 8. Chart. For each census tract, the number of pedestrian crashes vs. the bus stops per capita, separated by the crash distance to the nearest bus stop.

Intersections

As discussed in the Finding the Nearest Bus Stop section, most bus stops that are near an intersection are most likely within at least 150 ft of the intersection. Table 7 shows that 74% of bus stops in NOVA are within 150 ft of an intersection. We reviewed a handful of bus stop locations and found that those that were not within 150 ft of an intersection were usually at a specific location like a school, mall, or public library, or were connected to larger Metro stop platforms. This review indicates that these mid-block stops might generally be found in areas with lower vehicle traffic speed and volumes.

Table 7. Number and percentage of bus stops within 150 ft of an intersection in NOVA.

	Number of bus stops	Percentage of bus stops
Within 150 ft of an intersection	9,938	73.9%
Not within 150 ft of an intersection	3,502	26.1%
Total	13,440	

Using the *Intersection Type* variable from the PSAP map, Table 8 shows that 79.4% ($n = 951$) of pedestrian crashes that occurred within 150 ft of a bus stop also occurred within an intersection, or were intersection related. From the chi-square test of independence, this percentage is significantly different from the percentage of bus stops at intersections (73.9%), but the effect size is negligible ($p = 0.000$, chi-square = 17.199, Cramer's $V = 0.034$). Thus, bus stops within 150 ft of an intersection are only slightly more likely to have a pedestrian crash than bus stops further than 150 ft of an intersection. However, if we compare within crashes, crashes within 150 ft of a bus stop are 3.1 times more likely to be near an intersection than crashes more than 500 ft from a bus stop.

Table 8. Number of pedestrian crashes by intersection relation and the distance to the nearest bus stop.

Distance to nearest bus stop	Within an intersection or intersection related	Not at an Intersection	Total
Less than 150 ft	951	246	1,197
Between 150 ft and 250 ft	316	139	455
Between 250 ft and more than 500 ft	418	218	636
More than 500 ft	683	546	1,229
Total	2,368	1,149	3,517

BUS STOP TYPE

This section shows the different location types of bus stops distributed throughout NOVA. From the bus stop data, the variable *location type* was used to identify the type of bus stop, as shown in Table 9.

Table 9. Description of *location type* variable for bus stops.

Location Type	Code	Description
Stop (or Platform)	0 (or blank)	A location where passengers board or disembark from a transit vehicle. Is called a platform when defined within a parent station.
Station	1	A physical structure or area that contains one or more platforms.
Entrance/Exit	2	A location where passengers can enter or exit a station from the street. If an entrance/exit belongs to multiple stations, it may be linked by pathways to both, but the data provider must pick one of them as parent.

Location Type	Code	Description
Generic Node	3	A location within a station, not matching any other location type, that may be used to link together pathways defined in pathways.txt.
Boarding Area	4	A specific location on a platform where passengers can board and/or alight vehicles.
Null	Null	Field did not exist in original data submission.

Within this dataset, Table 10 shows the number of bus stops in NOVA based on location type, as well as the number of crashes that were within 150 ft of each location type bus stop. Unfortunately, a large portion of bus stops did not have the location type variable available (shown as *Null*).

Table 10. Number of bus stops and crashes near bus stops separated by location type.

Location Type	Number of bus stops in NOVA	Number of crashes within 150 ft
Stop (or Platform)	9,315	708
Station	0	0
Entrance/Exit	3	1
Generic Node	720	22
Boarding Area	0	0
Null	3,402	466
Total	13,440	1,197

The relative proportions of the total types of bus stops and the number of crashes within 150 ft of these bus stops were relatively consistent (degrees of freedom = 3, p = 0.000, chi-square = 122.062, Cramer's V = 0.091); thus, there is a negligible association of location type on crash risk. Unfortunately, there was no publicly available data on the ridership for each bus stop, so it is unknown how the number of passengers might affect these rates. Additionally, there is no other infrastructure information available for every stop (i.e., the bus stop shelter, crosswalk, bus stop placement, etc.). Therefore, only this location type feature can be compared between bus stops that did not have any crashes to crash rates near bus stops.

ROADWAY CHARACTERISTICS

Functional Class and Roadway Description

The functional class of the roadway categorizes streets and highways based on their intended function in serving traffic movement and providing access to adjacent properties. Figure 9 shows, for each functional class, the relative percentage of crashes for each distance to the nearest bus stop category. From the chi-square analysis, there is a moderate association between the functional class of the roadway that the crash occurred on and the distance to the nearest bus stop (p-value = 0.000, chi-square = 242.340, Cramer's V = 0.321).

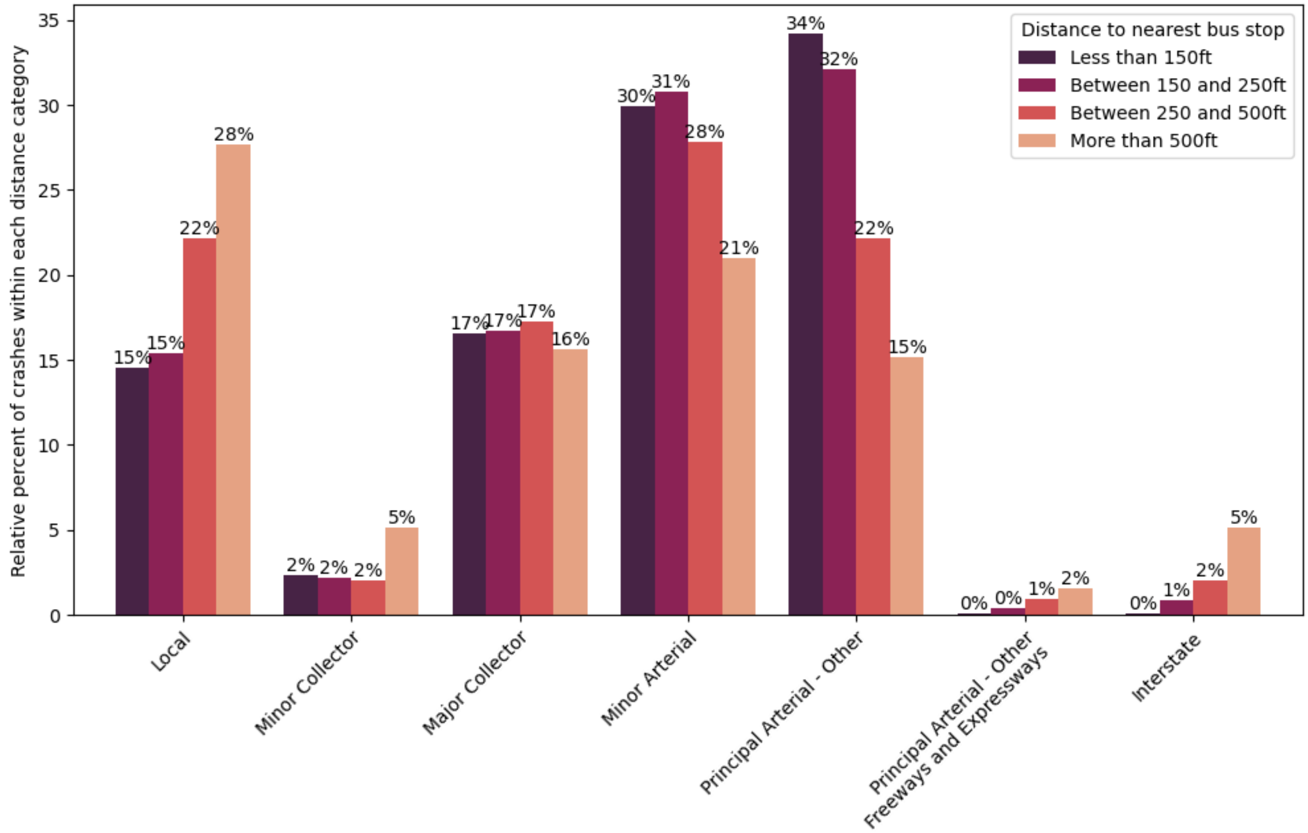

Figure 9. Chart. Relative percentage of crashes within each distance to the nearest bus stop category, separated by functional class.

We can see that pedestrian crashes within 150 ft of a bus stop were most likely to occur on arterial roads (30% on minor arterial and 34% on principal arterial), while pedestrian crashes more than 500 ft to the nearest bus stop were most likely to occur on local roads (28%). This is most likely due to bus stops being located on more arterial roads than local roads. Unfortunately, the functional class data was only available for pedestrian crashes, and not for all bus stops, so we cannot determine if that is the case.

Roadway description categorizes the roadway on the direction of travel, and if the roadway is divided or not. Like in the previous figure, Figure 10 shows, for each roadway description, the relative percentage of crashes for each distance to the nearest bus stop category. Compared to the functional class, there is a smaller difference between relative crash rates in each distance category for each roadway description. There is only a weak association between the roadway description and the crash distance to the nearest bus stop (p = 0.000, chi-square = 38.018, Cramer's V = 0.118).

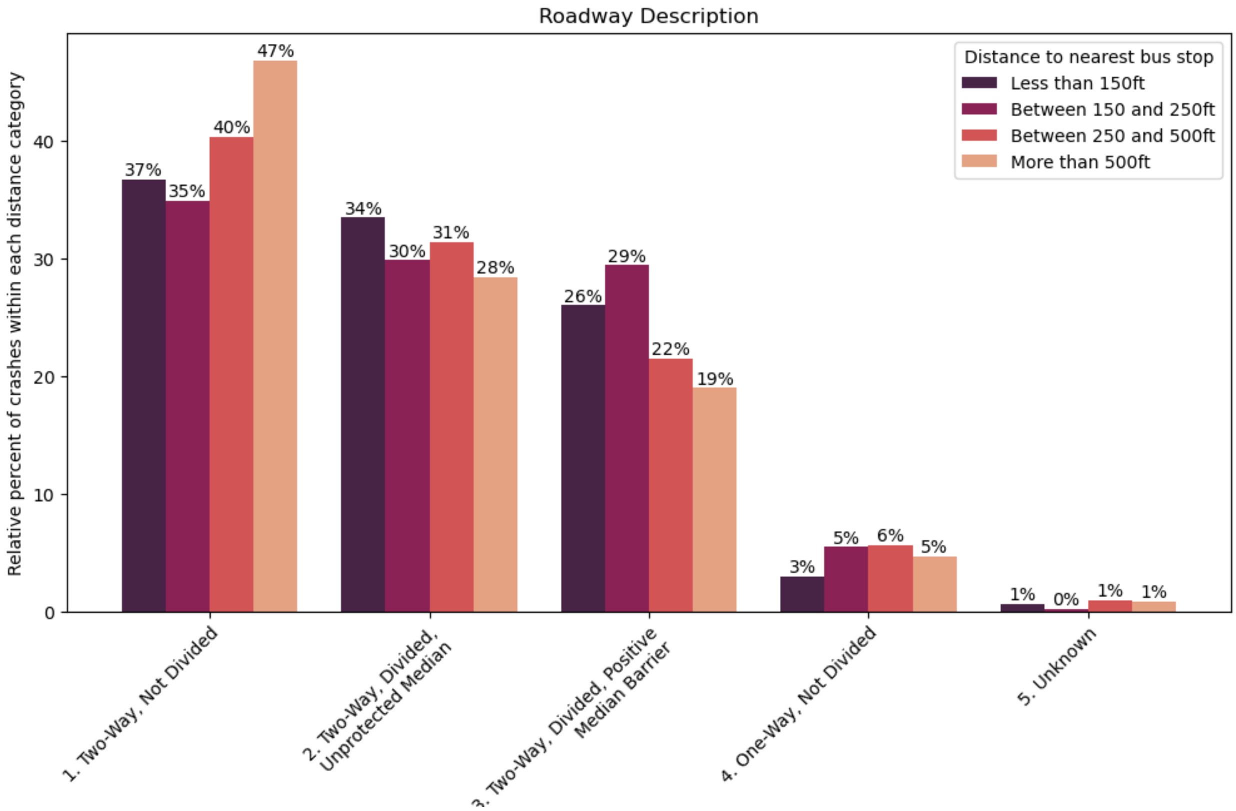

Figure 10. Chart. Relative percentage of crashes within each distance to the nearest bus stop category, separated by roadway description.

Relation to Roadway

The *Relation to Roadway* variable relates closely to the *Intersection Type* variable: it describes what roadway characteristics the crash was nearby, including if that crash was within the intersection or intersection related. Figure 11 shows the *Relation to Roadway* variable for the 246 crashes that were within 150 ft of a bus stop but not at an intersection (see Table 8). Each square represents one crash at these mid-block bus stops. We can see that there are three crashes whose relation to roadway is “Intersection Related – Within 150 ft.” These three crashes were manually reviewed and were determined to be within 150 ft of an intersection (i.e., the *Intersection Type* variable was incorrect). Appendix B lists the details of these crashes.

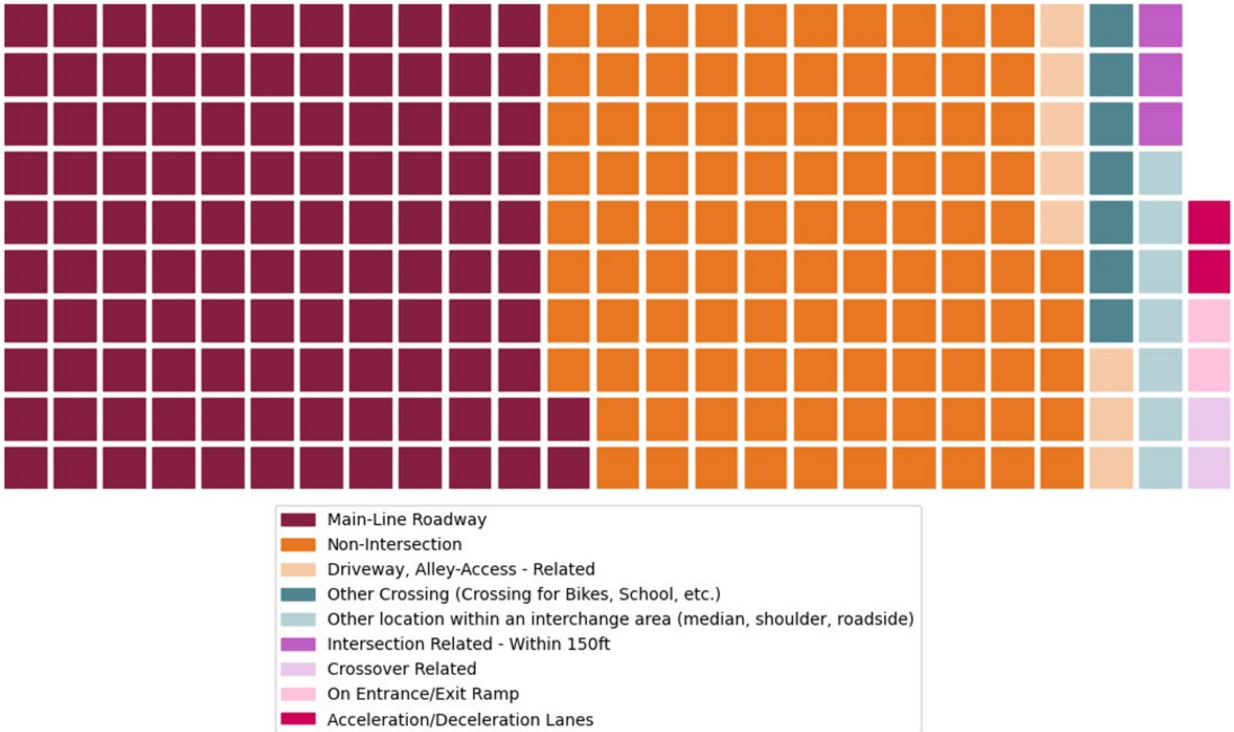

Figure 11. Illustration. Number of crashes within 150 ft of a bus stop but not at an intersection by relation to roadway.

We can see that the majority of crashes that occurred within 150 ft of a bus stop but not near an intersection occurred on the main-line roadway (n = 112, 45.5%) and were most likely mid-block stops, followed closely by 103 crashes (41.9%) that occurred at a non-intersection. Unfortunately, this variable was very nondescript and there is not much more detailed information. However, Figure 12 shows the relative percentage of crashes that occurred within 150 ft of a bus stop and more than 500 ft from the nearest bus stop by relation to roadway. This expresses the relative crash rate for each relation to roadway, even with the small sample of crashes that occurred at locations other than the main-line roadway or non-intersection. However, with only a small sample of crashes at these locations, there is only a weak association between the relation to roadway and the distance to the nearest bus stop (p = 0.001, chi-square = 26.577, Cramer's V = 0.153).

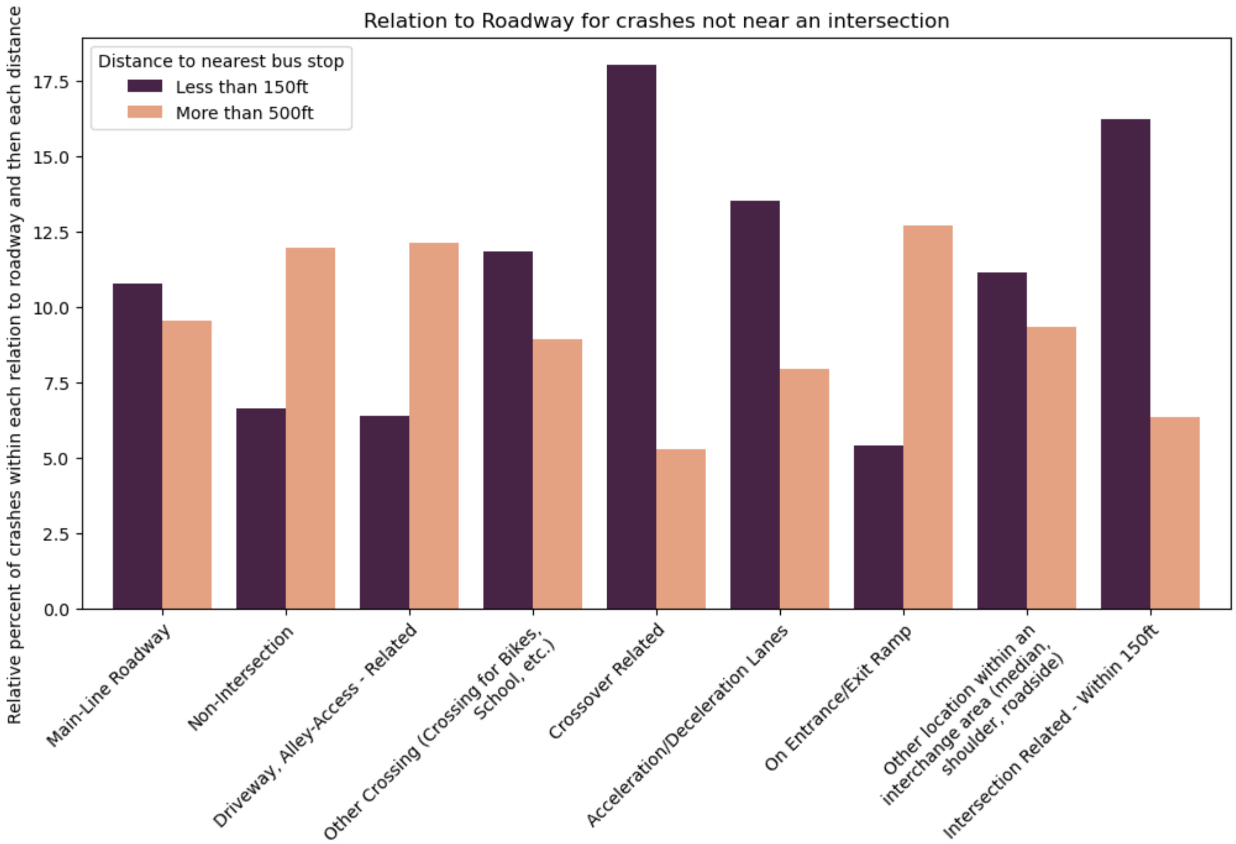

Figure 12. Chart. Relative percentage of crashes based on relation to roadway and distance from a bus stop for crashes that are not at an intersection.

Traffic Control

This section looks at the traffic control device and the status of the traffic control device. Figure 13 shows the percentage of pedestrian crashes that occurred for each type of traffic control device. Overall, 97.5% of crashes occurred near a traffic signal, pedestrian crosswalk, stop sign, or near marked traffic lanes or without any traffic control. The remaining traffic control devices are included in the bar chart for reference but are combined as the “other” category for further statistical analysis.

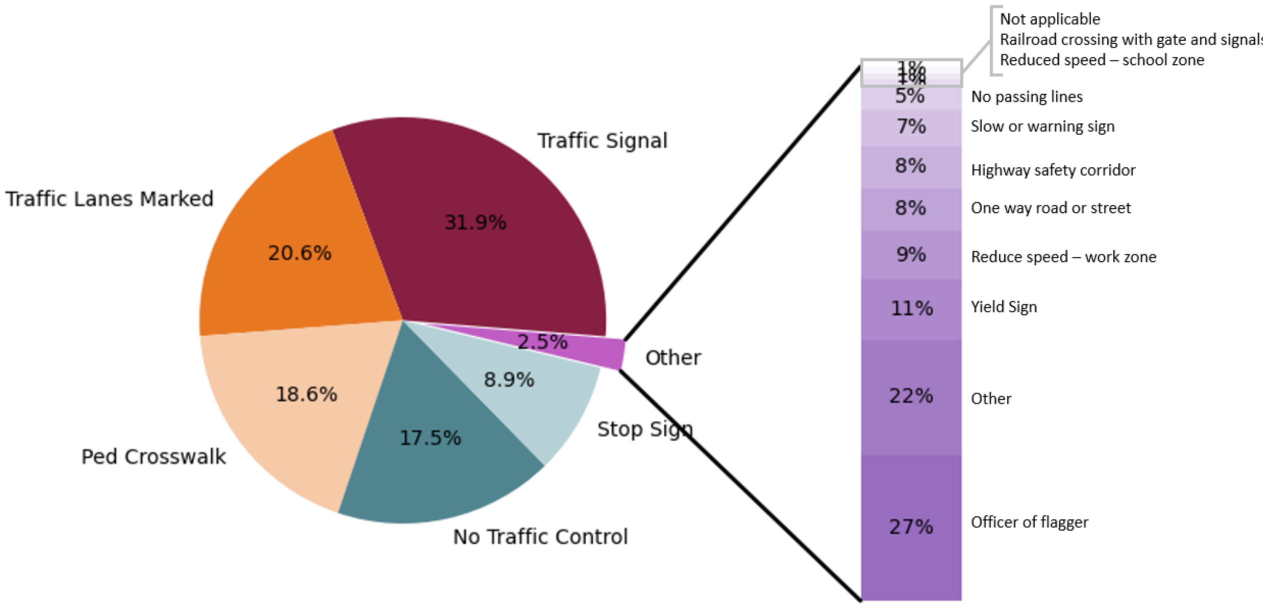

Figure 13. Chart. Percentage of crashes that occurred for each type of traffic control device.

Figure 14 shows the relative percentage of crashes that occurred for each traffic control device separated by the distance to the nearest bus stop. We can see that pedestrian crashes within 150 ft of a bus stop were most likely to occur near a traffic signal (42%), while pedestrian crashes more than 500 ft to the nearest bus stop were most likely to occur where traffic lanes were marked (28%) or when there was no traffic control (25%). From the chi-square analysis, there is a moderate association between the traffic control device during the crash and the distance to the nearest bus stop (p-value = 0.000, chi-square = 266.626, Cramer's $V = 0.329$). A crash within 150 ft of a bus stop is 3.2 times more likely to occur by a traffic signal than a crash more than 500 ft from a bus stop. If we assume that a traffic signal is only present at intersections, these results closely match the results from the Intersections section, where crashes within 150 ft of a bus stop were 3.1 times more likely to occur near an intersection than a crash more than 500 ft from a bus stop.

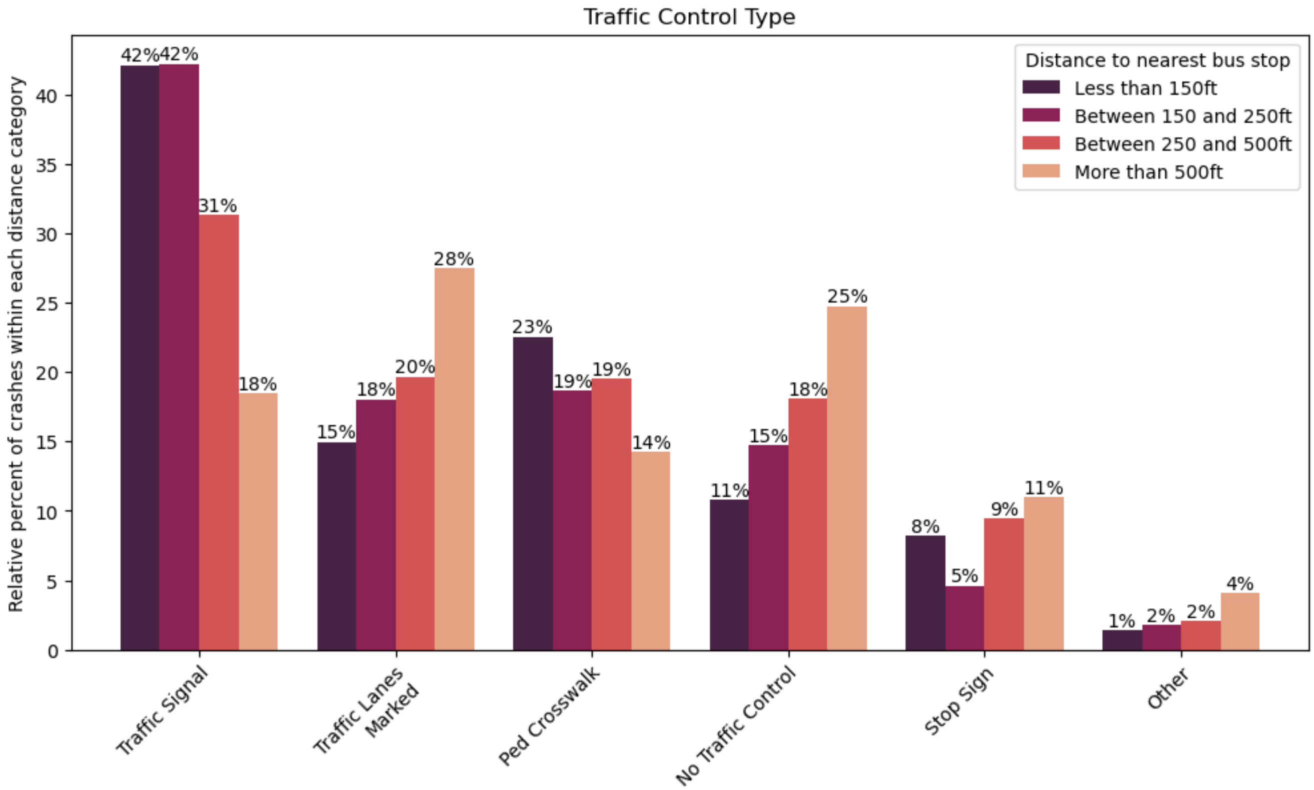

Figure 14. Chart. Relative percentage of each traffic control device by distance to nearest bus stop category.

There was also information on whether the traffic control device was working. Table 11 shows the number of crashes for each traffic control status separated by the crash severity. Because it was a rare event if the traffic control device was not working, across 12 degrees of freedom, there was a very weak association between the traffic control status and the crash severity (p = 0.000, chi-square = 35.743, Cramer's V = 0.048). Even if we only compare crashes when the traffic control device was working to crashes when there was no traffic control device, there is only a very weak association to crash severity (p = 0.007, chi-square = 7.219, Cramer's V = 0.042). We did the same to compare the traffic control status and if the crash was near a bus stop and found similar results.

Table 11. Number of crashes by traffic control status and crash severity.

Traffic Control Status	Fatal	Severe Injury	Visible Injury	Nonvisible Injury	Total
Working	191	628	1,745	214	**2,778**
No Traffic Control Device Present	22	155	502	48	**727**
Working and Obscured	0	5	3	1	**9**
Not Working	0	1	0	1	**2**
Not Working and Obscured	0	1	0	0	**1**
Total	**213**	**790**	**2,250**	**264**	**3,517**

ENVIRONMENTAL FACTORS

A large portion of pedestrian crashes tend to happen at night or during darkness due to low visibility. This section looks at pedestrian crashes that occur during different lighting conditions throughout different time points in the day, along with the weather conditions for all crashes.

Lighting and Time of Day

From the Mann-Whitney *U* test, it was determined that there was a negligible difference between crash distances to the nearest bus stop and the mean time of day ($p = 0.012$, *U*-stat = 692,152.500, Cohen's $d = 0.127$). This means that pedestrian crashes near bus stops do not happen disproportionally at certain times of the day compared to pedestrian crashes not near bus stops. Figure 15 shows the number of pedestrian crashes within 150 ft of the nearest bus stop based on the time of day (military time) and the light condition at the time of the crash. The lighter blue represents bright lighting conditions and the darker blue represents dark lighting conditions. We can see that the majority (51.2%) of pedestrian crashes within 150 ft of a bus stop occurred during daylight; 42.9% ($n = 513$) of pedestrian crashes within 150 ft of a bus stop occurred during darkness, 80.3% ($n = 412$) of which had road lighting.

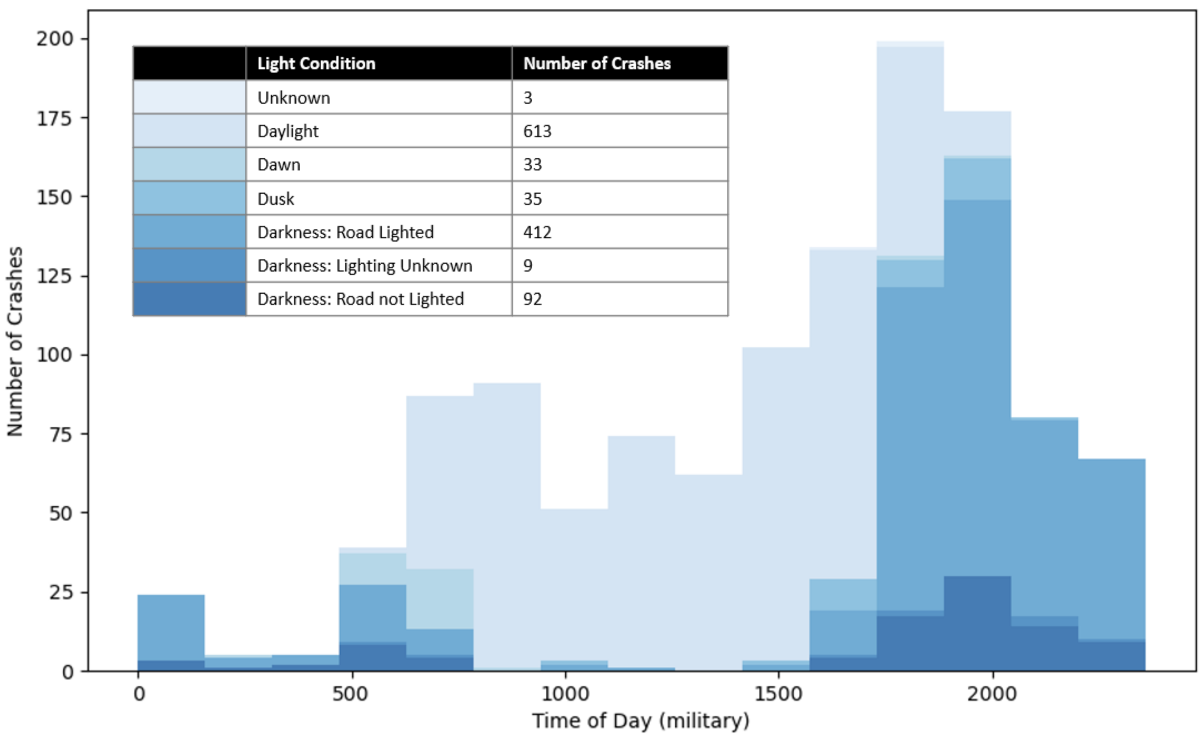

Figure 15. Chart. Number of pedestrian crashes within 150 ft of the nearest bus stop based on the time of day and lighting conditions.

A weak correlation was found between the crash distance from the nearest bus stop and the lighting condition ($p = 0.000$, chi-square = 91.927, Cramer's $V = 0.188$). Specifically, pedestrian crashes occurring in darkness are 1.5 times more likely to have road lighting if they are within 150 ft of a bus stop than if they are over 500 ft from the nearest bus stop. This is likely due to the majority of bus stops being located near intersections, which typically have lighting. However, Table 12 shows that 73.9% (n = 68) of pedestrian crashes within 150 ft of a bus stop, in the dark, with no lighting, occurred at an intersection or were intersection related. Since the percentage of bus stops near intersections (73.9%) is not significantly different, this indicates that mid-block bus stops have similar lighting to bus stops near intersections.

Table 12. Number of crashes within 150 ft of a bus stop that occurred in the dark, and their relation to an intersection.

Light Condition	Within an intersection or intersection related	Not at an Intersection	Total
Darkness: Road Lighted	325	87	**412**
Darkness: Road not Lighted	68	24	**92**
Darkness: Lighting Unknown	6	3	**9**
Total	**399**	**114**	**513**

Figure 16 illustrates how the lighting condition relates to the severity of crashes that occurred in the dark. The purple represents crashes that were within 150 ft of a bus stop, while the peach represents crashes that are more than 500 ft from the nearest bus stop. The more saturated bars represent fatal/severe crash outcomes, while the less saturated bars represent *not* fatal/severe crash outcomes. When the crash occurred in the darkness on an unlighted road, it was equally likely to be a fatal/severe crash or a not fatal/severe crash. However, when a crash occurred in the darkness on a lighted road, it was 1.9 times more likely to *not* be fatal or result in severe injury.

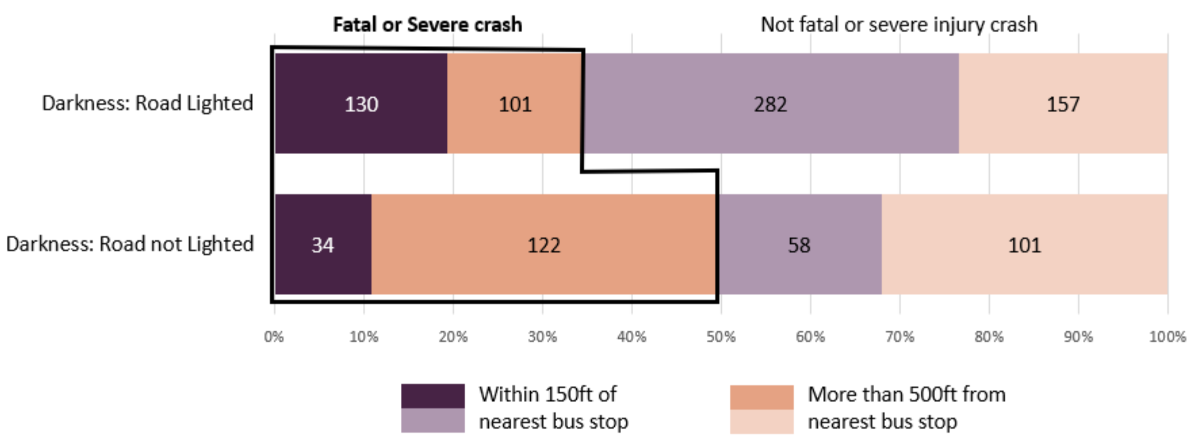

Figure 16. Chart. Relative percentage and number of pedestrian crashes in the dark, separated by crash severity, lighting, and distance to the nearest bus stop.

Weather and Road Condition

We wanted to understand if there was more likely to be a crash near a bus stop during bad weather or road conditions. From the chi-square analysis, the weather and road conditions did not contribute to whether the crash was near or far from a bus stop (p = 0.001, chi-square = 17.913, Cramer's V = 0.078).

Table 13. Number of crashes based on weather and road conditions and distance to the nearest bus stop.

Weather	Road Condition	Number of Crashes	
		Within 150 ft of a bus stop	Over 500 ft from a bus stop
No adverse Condition (Clear/Cloudy)	Dry	967	1,052
	Wet	13	18
	Ice/Slush/Snow	2	3
Rain/Sleet/Hail	Wet	199	133
Snow	Ice/Slush/Snow	7	10
Other	Other	9	13
	Total	**1,197**	**1,229**

COMMUNITY FACTORS

A unique portion of this research was to understand how crash risk might be correlated to SDOH. Two HOI datasets were used for this analysis (see more in the HOI Data section). The first dataset contains continuous normalized values from 0 to 1 that indicate the opportunity for those living in the area to live a long and healthy life (*About the Health Opportunity Index*, 2025; Anson-Dwamena, 2021). The second dataset contains discrete values ranging from 1 to 5, which correspond to "very low," "low," "average," "high," and "very high" opportunity levels by census tract (Virginia Department of Health Data Commons, 2020). Each score is a population-weighted average of each indicator, but differences in weighting mean that the HOI score and each profile score are stand-alone measures and may have different distributions.

HOI Score

Continuous

To first understand how crashes may be distributed throughout different HOI values, we first looked at the single continuous HOI score. Figure 17 shows the frequency of crashes across all HOI scores, separated by the distance of each crash to the nearest bus stop. There is a bimodal distribution between crashes that are less than 150 ft from a bus stop and crashes that are more than 500 ft from a bus stop.

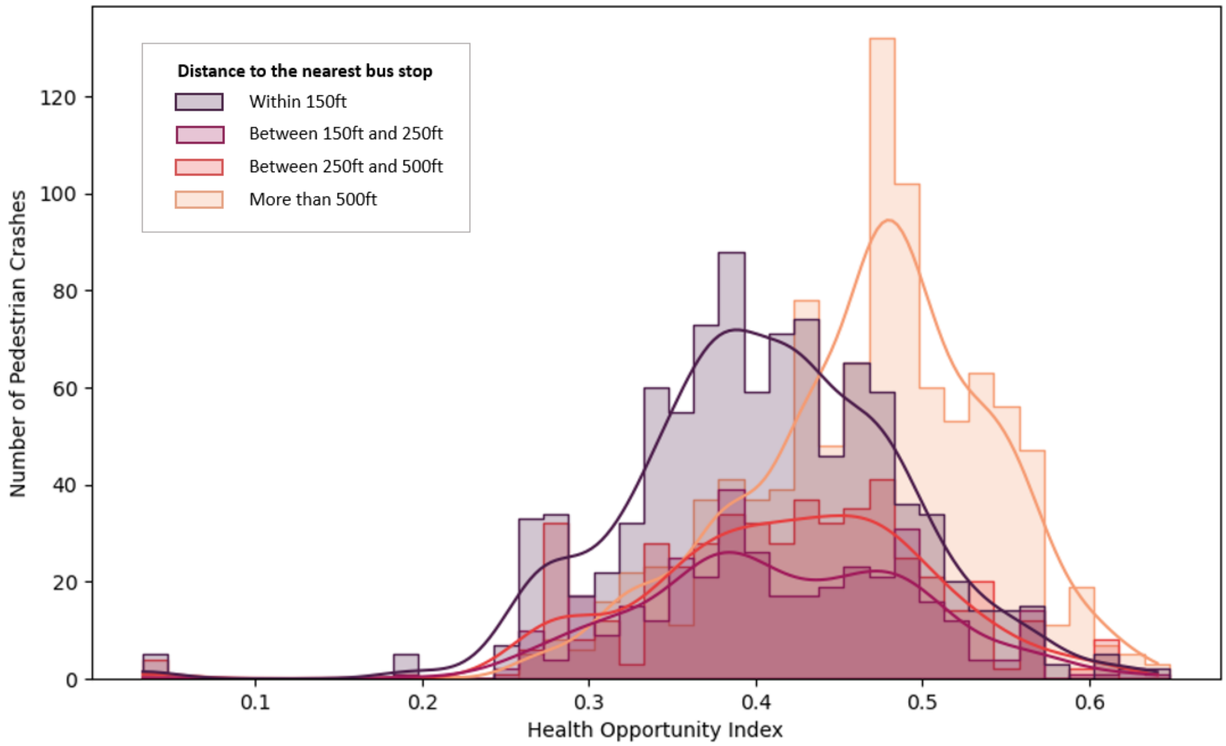

Figure 17. Histogram. Number of pedestrian crashes based on the census HOI and distance to the nearest bus stop.

This points to the possibility that crashes near bus stops may be more likely to occur in areas with lower HOI scores. Table 13 shows that crashes that were 150 ft from the nearest bus stop had a lower HOI score on average (.404 ± 0.007) than crashes that were more than 500 ft from the nearest bus stop (.466 ± .006). The highest frequency of pedestrian crashes within an HOI score bin (bin size = .015) occurred more than 500 ft from a bus stop (p = 0.000, t-statistic = 17.425).

Table 14. Mean, median, standard deviation, and variance of HOI scores for crashes within 150 ft from the nearest bus stop and crashes more than 500 ft from the nearest bus stop.

Crash distance to nearest bus stop	Count	HOI Score Mean	Median	Std	Var
Closer than 150 ft	950	0.404	0.404	0.081	0.007
Further than 500 ft	996	0.466	0.474	0.074	0.006

While prior research has established a link between pedestrian crashes and the presence of bus stops or transit commuting, this relationship has often been presumed to be driven by increased pedestrian exposure in these areas (Dumbaugh & Stiles, 2025). To isolate the relationship between HOI scores and pedestrian crashes near bus stops, it is necessary to first determine whether HOI scores are associated with pedestrian crash frequency in general or the number of bus stops in the area. This step helps ensure that the observed increase in crashes near bus stops in areas with lower HOI scores is not simply a reflection of a broader trend in pedestrian crash patterns or number of bus stops across those areas. To do so, the chart on the left in Figure 18 compares the ECDF of the HOI scores for each census tract in Virginia and the HOI scores of each crash used in these analyses. The *p*-value of 0.001 from a two-sample Kolmogorov-Smirnov test indicates that the pedestrian crashes in these analyses are distributed relatively evenly across HOI scores throughout Virginia. The chart on the right in Figure 18 shows the number of bus stops for each census tract, based on the HOI score for that census tract.

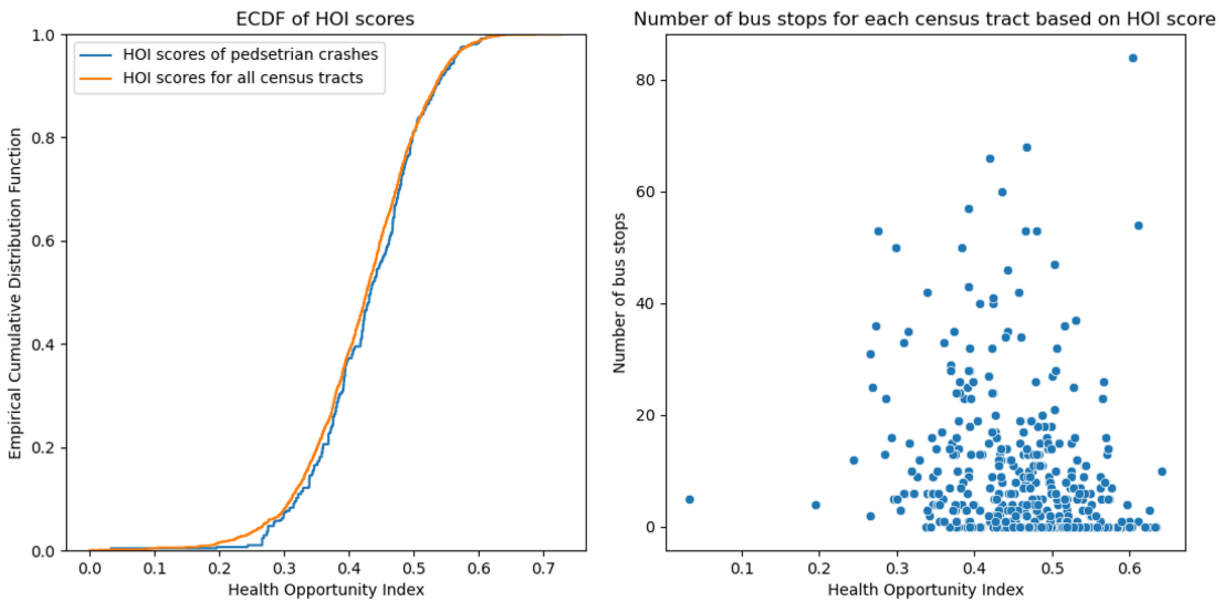

Figure 18. Graphs. Left: ECDF HOI score for pedestrian crashes in NOVA vs. all census tracts in NOVA; right: number of bus stops for each census tract based on HOI score.

Taking both of these factors into account, Figure 19 shows that there is still a slight bimodal distribution across HOI scores for the total number of crashes per total bus stops in each census tract. While this analysis does not take direct pedestrian exposure into account, it shows that crashes near bus stops are more likely to occur in areas with lower HOI scores, regardless of the number of bus stops in that area. This supports research that found that although minority groups (often residing in areas with lower HOI scores) tend to walk less on average than White people, they experience disproportionately higher rates of pedestrian crashes (Raifman & Choma, 2022). Future research should combine walking or commuting data along with the number of bus stops in each census tract to understand this relationship further.

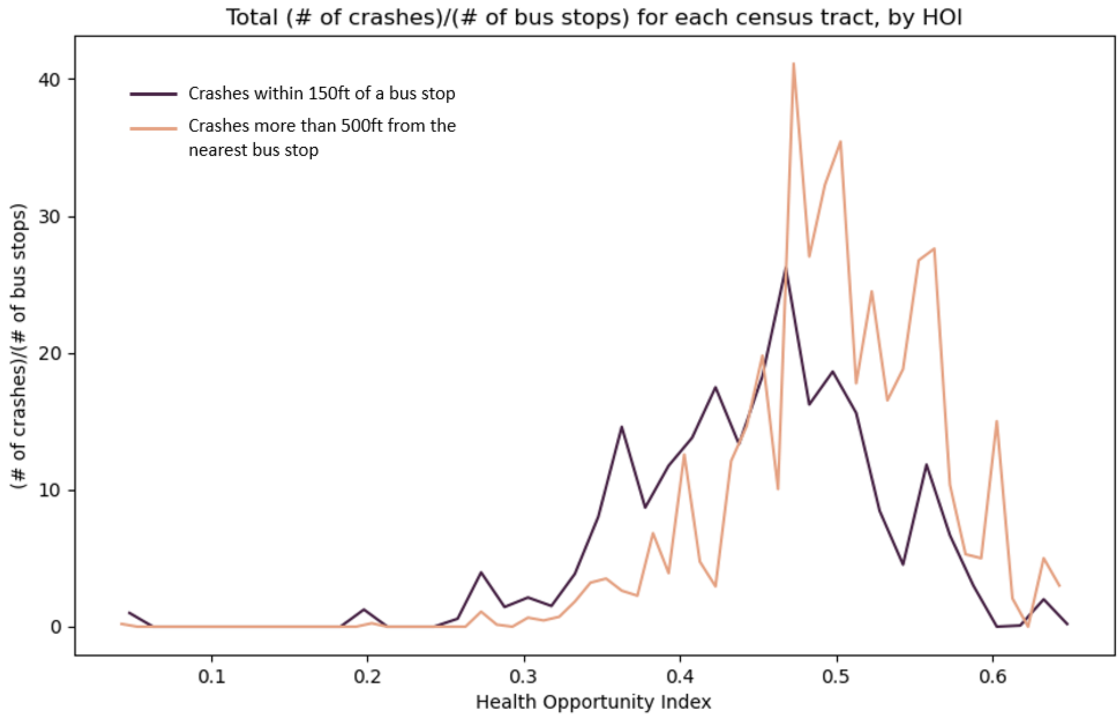

Figure 19. Graph. Total number of crashes per total bus stop in each census tract, separated by HOI score.

Discrete

The same analysis was done above for the discrete HOI (see Figure 20). However, from the chi-square analysis, there was a very weak association between the HOI values and the distance of the crash to the nearest bus stop (p = 0.004, chi-square = 28.6960, Cramer's V = 0.040). This is most likely because the nuances of HOI values that are found in a continuous normalized value are lost.

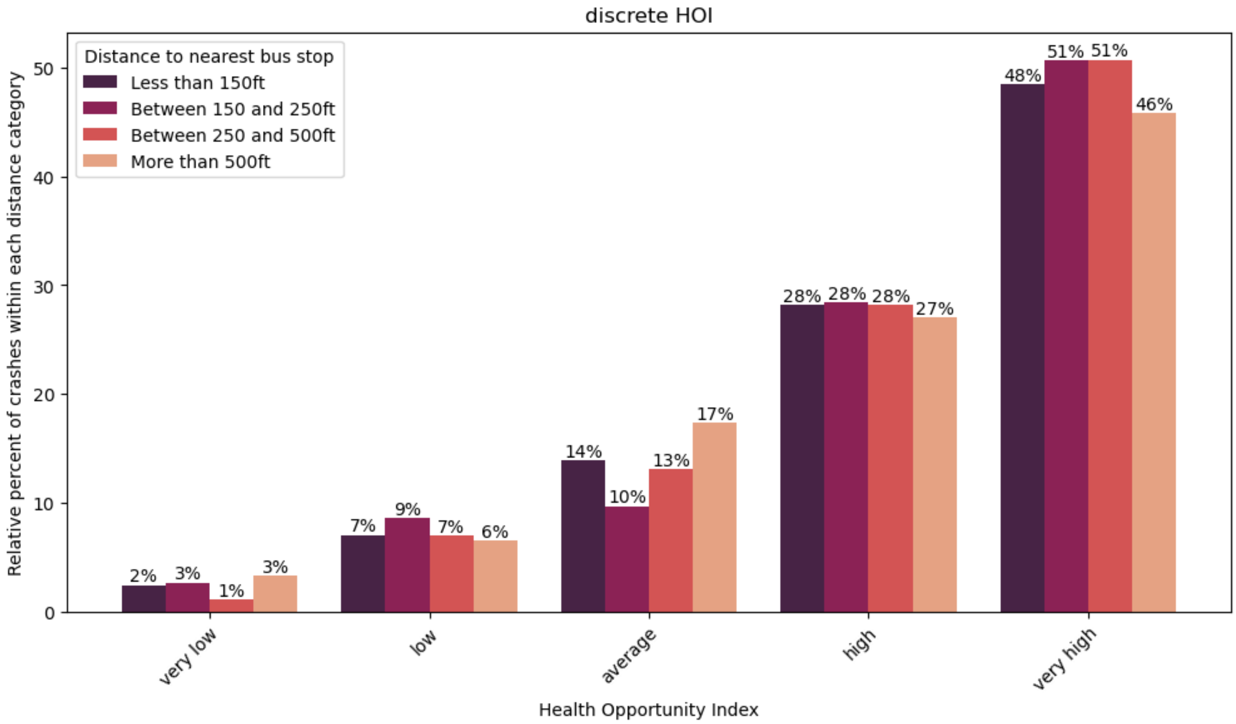

Figure 20. Graph. Relative percentage of crashes within each distance category for the discrete HOI categories.

On the left, Figure 21 compares the number of bus stops per census tract, which can be compared to the chart on the right side of Figure 18. From this violin plot, it looks like census tracts with a low HOI score had fewer bus stops than census tracts with a high HOI score. On the right, Figure 21 shows the bus stops per capita for each census tract, which follows a similar trend to the overall number of bus stops.

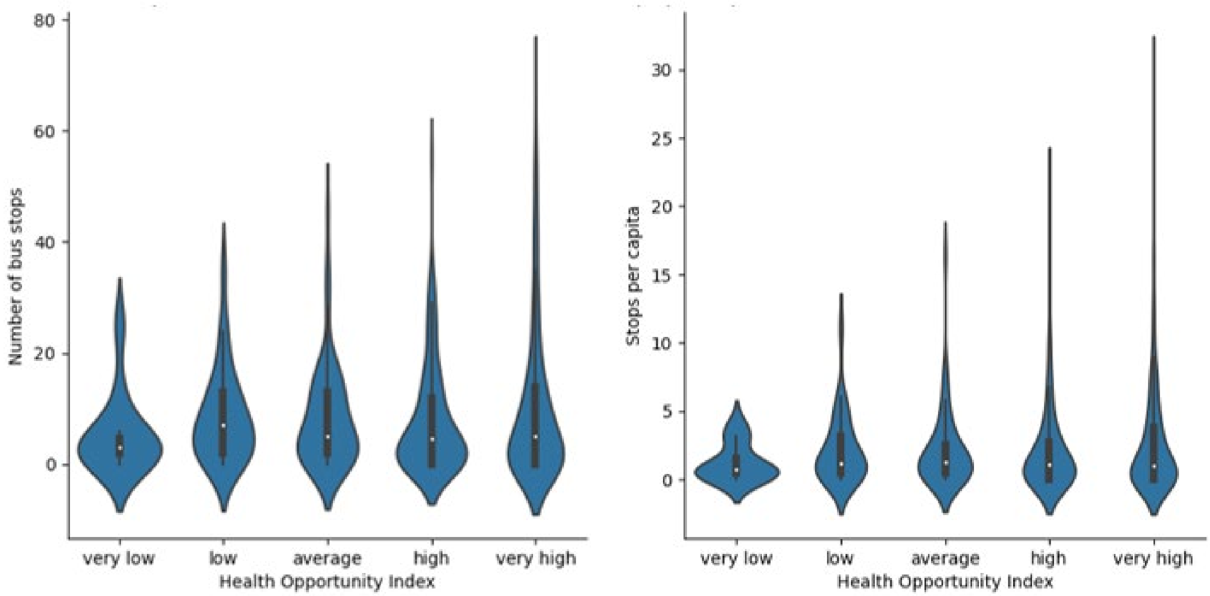

Figure 21. Graph. Number of bus stops (left) and stops per capita (right) per census tract for each discrete HOI score.

Table 15 includes the number of pedestrian crashes, the number of unique census tracts, the number of unique bus stops, and the mean number of bus stops per capita for each discrete HOI value for census tracts that had a pedestrian crash (p = 0.000, chi-square = 130.561). We can see that as the HOI decreased, the number of census tracts that had a pedestrian crash decreased, along with the number of bus stops and bus stops per capita. However, the last column shows the number of crashes that occurred, on average, per bus stop in each census tract (separated by HOI). Therefore, as the HOI value decreased, the average number of pedestrian crashes per bus stop in that census tract increased. This follows the findings from the continuous HOI values above.

Table 15. Bus stop information for each census tract grouped by discrete HOI score.

HOI	Number of crashes	Number of unique census tracts that had a crash	Total unique number of bus stops in census tracts that had a crash	Mean bus stops per capita for census tracts that had a crash	Average number of crashes per bus stop
Very High	1,688	285	2,887	2.661	0.585
High	973	142	1,098	2.179	0.886
Average	504	62	523	2.094	0.964
Low	246	29	246	2.174	1.000
Very Low	88	12	63	1.268	1.397
NaN	18	6	-	-	-
Total	**3,517**	**536**	**4,817**	**-**	**-**

HOI Indicators

The overall HOI score shown above is a combination of 13 indicators (as described in the HOI Data section). Table 16 shows the mean, standard deviation, *p*-value, and *t*-statistic for each indicator between crashes that are within 150 ft of a bus stop and crashes that are over 500 ft from the nearest bus stop.

Table 16. Statistical values for all 13 HOI indicators, separated by distance to the nearest bus stop.

Indicator	<150		>500		Mean difference	*p*-value	*t*-statistic
	Mean	Std	Mean	Std			
Access to Care	0.484	0.118	0.466	0.067	0.018	0.000	4.147
Employment Accessibility	0.118	0.032	0.119	0.023	-0.001	0.378	-0.882
Affordability	0.631	0.074	0.624	0.097	0.008	0.045	2.002
Air Quality	0.816	0.116	0.754	0.114	0.062	0.000	11.844
Population Churning	0.834	0.084	0.797	0.110	0.036	0.000	8.234
Education	0.776	0.095	0.786	0.091	-0.010	0.019	-2.356
Food Accessibility	0.956	0.041	0.945	0.031	0.011	0.000	6.828
Income Inequality	0.510	0.071	0.474	0.073	0.036	0.000	11.023
Job Participation	0.747	0.094	0.762	0.080	-0.015	0.000	-3.724
Population Density	0.068	0.062	0.128	0.110	-0.060	0.000	-14.929
Segregation	0.754	0.160	0.765	0.159	-0.011	0.120	-1.555
Material Deprivation	0.492	0.145	0.411	0.135	0.080	0.000	12.659
Walkability	0.229	0.120	0.305	0.115	-0.075	0.000	-14.168

The "population density" and "walkability" scores had the largest absolute *t*-statistic value, which indicates a more significant difference between indicator scores for crashes near bus stops versus crashes far from bus stops. Figure 22 shows the distributions of each.

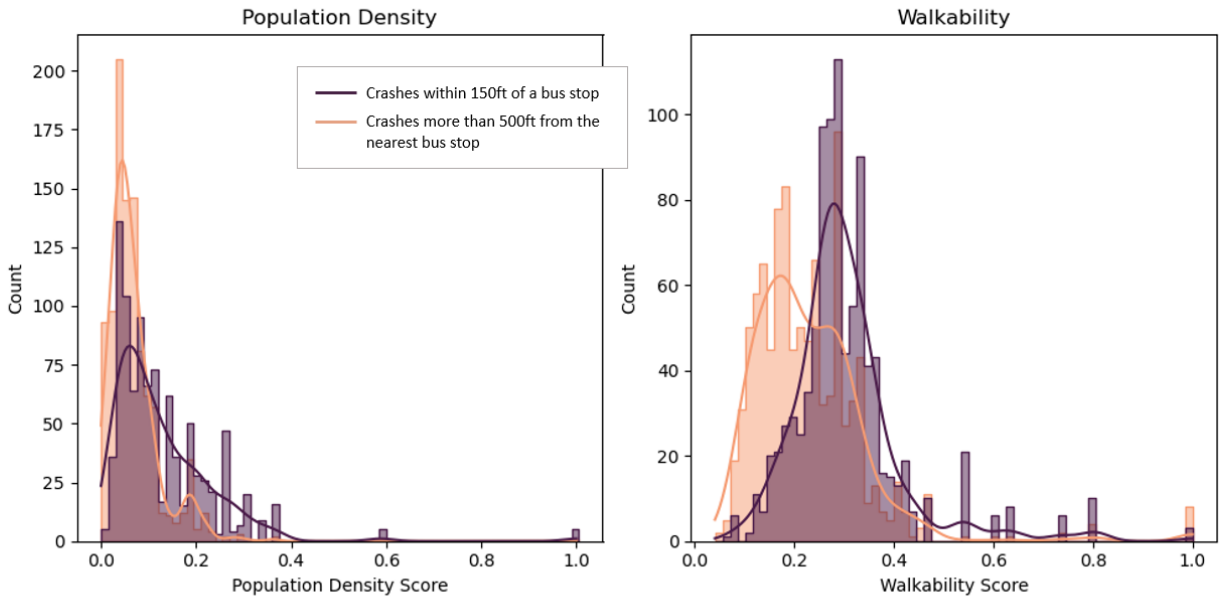

Figure 22. Histogram. Crashes separated by population density score (left) and walkability score (right).

Crashes within 150 ft of a bus stop were more likely to have a higher population density score, by an average mean of 0.060. To compare the population density score to the actual population density and number of bus stops for each census tract, Figure 23 illustrates the stops per capita for each census tract of pedestrian crashes, separated by the crash severity and the distance to the nearest bus stop. Across all crash severity levels, the average stops per capita for the census tract in which the crash occurred is 2.3 bus stops per person higher for crashes within 150 ft of a bus stop than crashes more than 500 ft from the bus stop ($p = 0.000$, t-statistic = 13.680). This is expected, as an increased exposure (more bus stops per person) likely leads to relatively more crashes near bus stops.

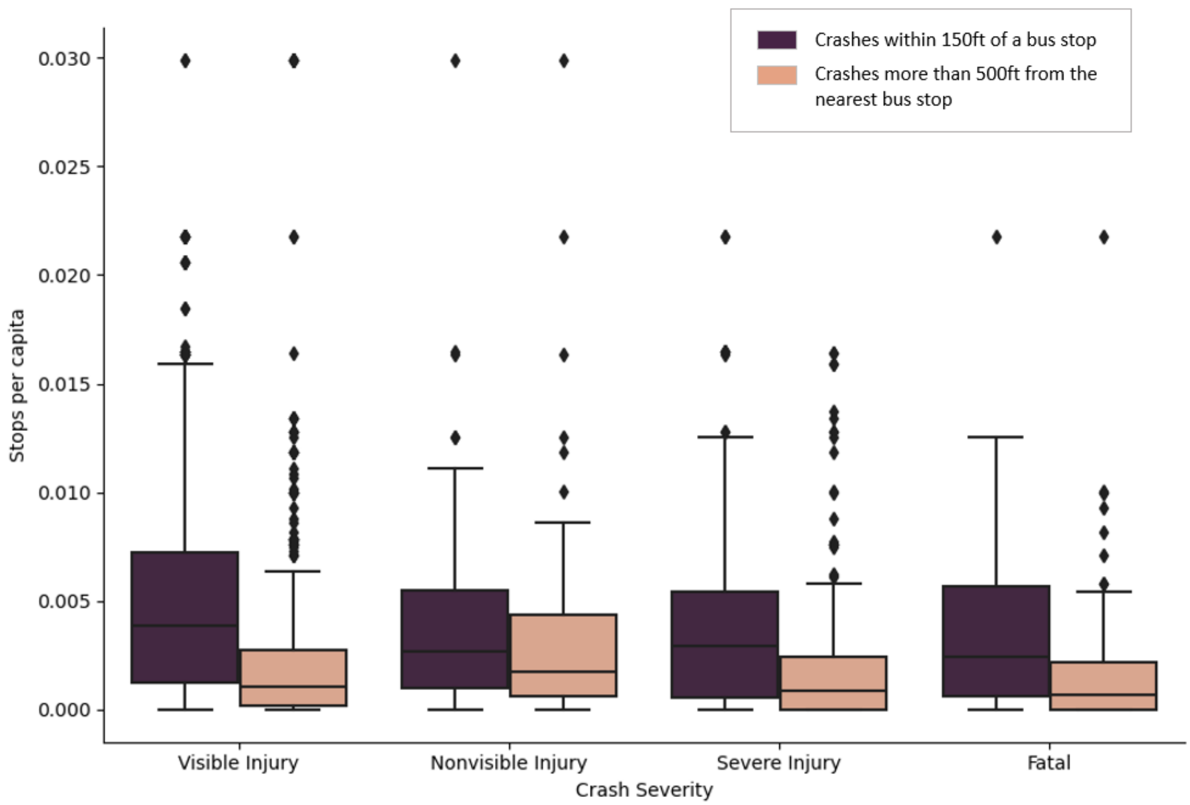

Figure 23. Box and whisker plot. Stops per capita of each census tract for pedestrian crashes separated by crash severity and distance to the nearest bus stop.

Additionally, crashes within 150 ft of a bus stop were more likely to have a higher walkability score by an average mean of 0.075. The walkability score is determined by four variables: design of the built environment, land use diversity, distance to transit, and residential and employment density (Crow & Anson-Dwamena, 2015). Again, the walkability score relates to an increased exposure to bus stops, and so there are more crashes near bus stops in areas with a higher walkability score.

OTHER

Hit and Run

Each pedestrian crash was also identified as a hit and run or not. This section looks at the probability of a pedestrian crash near a bus stop being a hit and run. Table 16 shows that 14.6% (n = 513) of all pedestrian crashes were hit and runs, 148 of which were less than 150 ft from a bus stop. From the chi-square analysis (chi-square = 9.165, p = 0.027, Cramer's V = 0.042), there is a very weak association between the distance of the crash to the nearest bus stop and whether it was a hit and run. Therefore, hit and runs do not significantly occur more or less near bus stops.

Table 17. Number of hit and run crashes separated by the distance to the nearest bus stop.

Distance to nearest bus stop	Hit and run	Not hit and run	Total
Less than 150 ft	148	1,049	1,197
Between 150 ft and 250 ft	65	390	455
Between 250 ft and more than 500 ft	95	541	636
More than 500 ft	205	1,024	1,229
Total	513	3,004	3,517

LIMITATIONS

Limitations to this study have been discussed throughout this report. A few key limitations are listed below.

Data was limited to NOVA. To stay within the project scope, one district of Viriginia was chosen to analyze crashes near bus stops. This district was chosen because it has the largest population in the Commonwealth, has the most pedestrian crashes, and has the most transit stops. Analyzing additional districts in Virginia may provide results that differ from the results found in this report due to large differences in population density, infrastructure, and transit use.

Missing bus stop, infrastructure, and exposure data. This was the largest limitation to this study, since we did not have many variables to compare crash rates at bus stops. The pedestrian crashes themselves had many variables available, but this same data was not available for other intersections or bus stops in which a pedestrian crash did not occur.

As mentioned in the Bus Stop Data section, there was limited data available for each bus stop. There was no publicly available data on the ridership for each bus stop or bus route. Additionally, there was no other infrastructure information available for every stop (i.e., the bus stop shelter, crosswalk, bus stop placement, etc.). Only the crash rates comparing the location type feature between bus stops was available. Future research should include data from a map-matching application programming interface (API) to understand map-based features near bus stops.

The census data was used as a surrogate to some of the data we did not have. However, any information was from the census tract itself, which could span a few miles, and might not accurately describe the exact road type or infrastructure around where the crash actually occurred.

CHAPTER 5. CONCLUSIONS

As pedestrian crashes are on the rise, this research aimed to identify the underlying factors that may be contributing to the increased pedestrian crash risk in the vicinity of bus stops in Virginia. As this is an initial effort, we focused on pedestrian fatality data in Virginia's largest metropolitan areas, NOVA. We used publicly available data for all pedestrian and bicyclist crashes in NOVA, along with basic information for all bus stops, intersections, and census tracts in NOVA to compare how these factors affect pedestrian crashes within 150 ft of a bus stop versus crashes more than 500 ft to the nearest bus stop.

By analyzing 3,563 pedestrian crashes in NOVA from 2018 to 2024, we found that nearly an equal proportion of pedestrian crashes occurred within 150 ft of a bus stop (34%) and more than 500 ft from the nearest bus stop (35%). The distance of a pedestrian crash to the nearest bus stop had a negligible impact on crash severity risk. With 74% of bus stops in NOVA being within 150 ft of an intersection, 79% of pedestrian crashes that occurred within 150 ft of a bus stop also occurred within an intersection, or were intersection related. Crashes within 150 ft of a bus stop were 3.1 times more likely to be near an intersection than crashes more than 500 ft from a bus stop. Additionally, pedestrian crashes within 150 ft of a bus stop were most likely to occur near a traffic signal (42%), while pedestrian crashes more than 500 ft to the nearest bus stop were most likely to occur where traffic lanes were marked (28%) or when there was no traffic control (25%). The higher frequency of pedestrian crashes near bus stops and intersections is most likely due to an increase in pedestrian traffic, or exposure, near these bus stops. To better understand how specific features near bus stops influence crash risk, future research should control for ridership data at the stop or route level. This would help isolate the effects of environmental or infrastructural factors from exposure-related influences. In this study, the number of bus stops per capita within each census tract was used as a proxy for exposure, reflecting the potential service coverage for residents. However, more detailed ridership and pedestrian traffic data is needed to accurately capture how many individuals actually use each bus stop or are typically present in its vicinity.

There was found to be a moderate association between the functional class of the roadway that the pedestrian crash occurred on, and the distance to the nearest bus stop. Pedestrian crashes within 150 ft of a bus stop were most likely to occur on arterial roads (30% on minor arterial and 34% on principal arterial), while pedestrian crashes more than 500 ft to the nearest bus stop were most likely to occur on local roads (28%). This is most likely due to bus stops being located on more arterial roads than local roads, but, unfortunately, we did not have information about the functional class for all bus stops in NOVA. The only bus stop information we had was the stop type (Stop [or Platform], Station, Entrance/Exit, Generic Node, or Boarding Area). However, we found a negligible association of stop type on crash risk. Future research would benefit from including additional map-specific data for all bus stops in the research area (e.g., functional class, distance to nearest crosswalk, building types nearby), as well as information about the characteristics of the bus stop (e.g., sheltered, bench, lighted, etc.).

The majority of pedestrian crashes within 150 ft of a bus stop (51%) occurred during daylight; 43% of pedestrian crashes within 150 ft of a bus stop occurred during darkness, 80% of which had road lighting. Specifically, pedestrian crashes occurring in darkness were 1.5 times more likely to have road lighting if they were within 150 ft of a bus stop than if they were over 500 ft from the nearest bus stop. Seventy-four percent (*n* = 68) of pedestrian crashes within 150 ft of a bus stop, in the dark, with no lighting, occurred at an intersection or were intersection related, which is not significantly different from the percentage of bus stops near intersections. This indicates that mid-block bus stops have similar lighting to bus stops near intersections. Additionally, when the crash occurred in the darkness on an unlighted road, it was equally likely to be a fatal/severe crash or a not fatal/severe crash. However, when a crash occurred in the darkness on a lighted road, it was 1.9 times more likely to *not* be a fatal/severe crash.

This research also focused on census data and SDOH. To determine if having more bus stops led to more pedestrian crashes, we compared the bus stops per capita in each census tract to the crash risk near a bus stop. We found that pedestrian crashes within 150 ft of a bus stop were more likely to happen in a census tract that had more bus stops per capita. Across all crash severity levels, the average stops per capita for the census tract in which the crash occurred is 2.3 bus stops per person higher for crashes within 150 ft of a bus stop than crashes more than 500 ft from the bus stop. However, the number of bus stops per capita did not influence the number of pedestrian crashes that were more than 500 ft from a bus stop.

Additionally, crashes that were 150 ft from the nearest bus stop had a lower HOI score on average than crashes that were more than 500 ft from the nearest bus stop. As the HOI score decreased, the number of census tracts that had a pedestrian crash decreased, along with the number of bus stops and bus stops per capita. However, as the HOI value decreased, the average number of pedestrian crashes per bus stop in that census tract increased by 240%. Additionally, crashes within 150 ft of a bus stop were more likely to have a higher walkability score and a higher population density. These results highlight that pedestrian crash risk near bus stops is increased in areas with poorer SDOH. While more pedestrians may be exposed to bus stops in areas with lower HOI score (because of a higher walkability score and population density), the number of bus stops servicing these communities has not increased. Understanding the traits that lead to social vulnerability might better explain the heightened pedestrian crash risk in these areas (Dumbaugh & Stiles, 2025). The other HOI indicators (Access to Care, Employment Accessibility, Affordability, Air Quality, Population Churning, Education, Food Accessibility, Income Inequality, Job Participation, Segregation, Material Deprivation) had a negligible impact on the distance of a pedestrian crash to the nearest bus stop.

With the growth of the bus system in NOVA planned by the NVTC (Cambridge Systematics, 2024), it is imperative to understand the factors that might influence crashes near bus stops. Without knowing the features near bus stops that did not have a pedestrian crash nearby, we cannot determine how those features might affect the crash risk at certain stops. However, by using the crash data that was available, we can understand how factors influence crashes near bus stops versus crashes far from bus stops.

APPENDIX A. MISSING CENSUS TRACTS IN HOI DATA

The following three tables list the missing census tracts (Full FIPS) in the HOI data for each data set used. The Virginia Open Data Portal (Anson-Dwamena, 2021) had 102 missing census tracts in the HOI data, which corresponded to a missing 718 pedestrian crashes. The Virginia Department of Health Data Commons (2020) had five missing census tracts in the HOI data, which corresponded to a missing 18 pedestrian crashes. There were three census tracts that were missing from both datasets combined. The three missing census tracts each had one pedestrian crash.

Virginia Open Data Portal			
51013101405	51059461603	51107611807	51153901703
51013101406	51059461604	51107611808	51153901704
51013101407	51059461605	51107611809	51510200108
51013101408	51059461606	51107611810	51510200109
51013101409	51059471204	51107611811	51510200110
51013101501	51059480204	51107611812	51510200111
51013101502	51059480205	51107611813	51510200304
51013101503	51059480302	51107611901	51510200305
51013101704	51059482204	51107611902	51510200408
51013101705	51059482205	51153900301	51510200409
51013101804	51059482206	51153900302	51510200704
51013101805	51059482505	51153900503	51510200705
51013102803	51059482603	51153900504	51510201205
51013102804	51059482604	51153900601	51510201206
51013102903	51059490105	51153900602	51510201601
51013102904	51059491706	51153900803	51510201602
51013103403	51059491707	51153900804	51510201803
51013103404	51059980100	51153901013	51510201804
51013103405	51107611026	51153901014	51510201805
51013103504	51107611028	51153901015	51685920201
51013103505	51107611029	51153901016	51685920202
51059431602	51107611030	51153901102	
51059440503	51107611031	51153901418	
51059440504	51107611032	51153901419	
51059460503	51107611701	51153901420	
51059460504	51107611702	51153901421	

Virginia Department of Health Data Commons
51013980100
51107980100

Both Datasets
51013980200
51059980200
51153980100

APPENDIX B. CONTRADICTORY PEDESTRIAN CRASH LOCATION VARIABLES

This appendix contains the six pedestrian crashes from the PSAP (VDOT, 2025a) in which the *Intersection Type* variable was labeled as “1. Not at Intersection” but the *Relation to Roadway* variable was labeled as “10. Intersection Related – Within 150 Feet” The variable values clearly contradict each other and may be due to different personnel recording data at the scene of the crash or the incorrect entering of information. After reviewing the longitudes and latitudes of each crash, each of these six crashes was determined to be within 150 ft of an intersection, but the values of the *Intersection Type* and *Relation to Roadway* variables were not changed for the analysis.

OBJECTID	Document Nbr	Crash Year	Crash Date	Crash Severity	Longitude	Latitude
362751	180405143	2018	2018-02-09 05:00:00	Visible Injury	-77.12007986	38.83834486
372735	181305115	2018	2018-04-30 04:00:00	Nonvisible Injury	-77.27544985	38.89334415
773222	220775330	2022	2022-03-18 04:00:00	Visible Injury	-77.07411429	38.89422312
1102058	242765058	2024	2024-09-30 04:00:00	Nonvisible Injury	-77.30811318	38.82779748
1111592	240435175	2024	2024-01-31 05:00:00	Nonvisible Injury	-77.26742025	38.89966273
1113989	242715399	2024	2024-09-27 04:00:00	Visible Injury	-77.08483523	38.89074808

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