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Conflict-Based Pedestrian Safety Scoring with All-Traffic Trajectory Data

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Abstract

The increasing urgency for pedestrian safety in urban areas underscores the necessity for advanced methodologies in traffic management, aligning with the Vision Zero initiative's goal to eradicate traffic-related fatalities and severe injuries. This dissertation introduces a novel model that utilizes all-traffic trajectory data obtained from LiDAR sensors to enhance pedestrian safety assessments at urban intersections. By leveraging a comprehensive set of variables—including near-miss incidents, pedestrian volumes, vehicular speeds, trajectory data, temporal patterns, lighting conditions, and crosswalk visibility—this model provides a holistic scoring methodology for pedestrian risk evaluation. Central to the model's efficacy is the application of the Post-Encroachment Time (PET), a critical temporal metric that measures the time interval between potentially conflicting trajectories, thus allowing for the anticipation and mitigation of collision risks. This innovative approach not only proposes a shift from reactive to proactive safety measures but also aims to establish a new approach to utilizing cutting-edge pedestrian data for urban safety enhancements. The findings from this study are poised to offer significant insights to urban planners, policymakers, and transportation engineers, aiming to cultivate safer pedestrian environments in growing urban landscapes.

In the case studies of applying the proposed scoring system, twelve intersections were selected for data collection and pedestrian safety scoring with the proposed method. Many of the studied sites with high-risk scores also had larger numbers of crashes, showing a possible positive correlation could be discovered as more locations are completed. This research initiates the foundation of a conflict-based pedestrian safety scoring system, which can be extended to accommodate more impacting factors, such as time of day, existing pedestrian safety treatments, pedestrian behavior patterns, and land uses. Analysis of correlation between pedestrian risks and those impacting factors with the innovative trajectory data can also initiate new research topics based on what is introduced in this dissertation.

Keywords: LiDAR, pedestrian safety, risk assessment, near-miss incidents, scoring system, Vision Zero

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1 Introduction

The significance of pedestrian safety within the context of the Vision Zero goal cannot be overstated. Vision Zero, a traffic safety strategy adopted by various cities around the world, aims to eliminate all traffic fatalities and severe injuries, with a particular focus on protecting vulnerable road users such as pedestrians. As urban areas continue to grow and evolve, the interaction between pedestrians and vehicles becomes increasingly complex, highlighting the urgent need for innovative solutions to ensure public safety. This necessity is underscored by the distressing statistics of pedestrian casualties in traffic incidents, which remain a persistent challenge for urban planners and traffic safety experts alike. The advancement of new traffic sensing and artificial intelligence (AI) technologies presents a timely opportunity to address this challenge head-on. These technologies offer unprecedented capabilities to monitor, analyze, and predict traffic behaviors in real time, providing a foundation for proactive safety measures rather than reactive responses post-crash.

However, despite these technological advances, there remains a significant methodological gap in effectively utilizing the data generated from advanced traffic sensing systems for pedestrian safety. Current approaches often rely on historical crash data to identify hazardous locations, methods that inherently look backward rather than forward. This dissertation recognizes the critical need for a paradigm shift toward proactive safety analysis. By proposing a novel method that leverages high-accuracy all-traffic trajectory data, it aims to fill this gap. This approach enables the grading or scoring of pedestrian safety based on traffic trajectory and behavior data before crashes occur. Such a proactive methodology not only aligns with the Vision Zero objective by anticipating and mitigating potential risks in advance but also sets a new standard for how cities can harness cutting-edge technology to protect their residents. Through this dissertation, the potential to guide and implement traffic safety improvements before incidents happen is explored, marking a significant step forward in the quest for safer urban environments for pedestrians.

This dissertation introduces a pioneering approach to conflict-based pedestrian safety scoring systems, aimed at bridging the gap between the potential of advanced traffic sensing technologies and the proactive measures required to achieve the Vision Zero goal. With urban areas witnessing ever-increasing interactions between pedestrians and vehicles, the need for innovative solutions to enhance public safety is more critical than ever. Leveraging the advancements in traffic sensing and artificial intelligence, this research develops a methodology for pre-emptively grading or scoring pedestrian safety. This methodology utilizes high-accuracy, all-traffic trajectory data to assess the safety of pedestrian environments before crashes occur, a shift from the traditional reactive analysis based on historical crash data.

The core of this dissertation lies in its novel use of advanced traffic sensing data to conduct a proactive safety analysis. By focusing on traffic trajectories and behaviors, the proposed method identifies potential risks to pedestrians and suggests interventions that can be made to mitigate these risks before they lead to crashes. This proactive approach not only aligns with the Vision Zero initiative's aim to eliminate traffic fatalities and severe injuries but also offers a practical framework for urban planners and traffic engineers to enhance pedestrian safety through data-driven insights.

This study aims to advance the field of pedestrian safety assessments through the introduction of a new model, based on the use of all traffic trajectories. This model operates on the premise of assigning a quantifiable risk score, thereby creating an evaluation of pedestrian safety dynamics at intersections. The methodology represents a comprehensive amalgamation of critical safety determinants, encompassing near-miss temporal parameters, pedestrian volume assessments, vehicular speed profiles, trajectory analyses, temporal considerations, lighting conditions, and the delineation of crosswalk markings. By integrating these multifaceted factors, the model encapsulates a holistic representation of the intricate interplay between pedestrians and vehicular traffic at intersections, providing a robust framework for strategic interventions aimed at bolstering urban pedestrian safety. This innovative approach not only extends the boundaries of current research but also holds the promise of significantly enhancing pedestrian safety strategies in urban environments.

This investigation capitalizes on all-traffic trajectory data gathered from LiDAR sensors, which offer an unparalleled depth of insight into the intricate dynamics governing the movements of pedestrians and vehicles. Central to this analysis is the concept of post-encroachment time (PET), a temporal metric that encapsulates the anticipated duration between the passage of a pedestrian and a vehicle through a congruent spatial position. PET is one such measure and represents the time difference between a vehicle leaving the area of encroachment and a conflicting vehicle entering the same area. (Peesapati, Hunter, and Rodgers 2018) This pivotal measure, informed by high-accuracy all-traffic trajectory data, assumes a foundational role in gauging the potential risk and likelihood of collision between pedestrians and vehicles at critical intersections or mid-block, thus marking a substantive advancement in the domain of urban pedestrian safety assessment. PET serves as a linchpin in the identification of "near-miss" incidents, denoting situations wherein a vehicle narrowly averts a collision with a pedestrian. This widely recognized application underscores the instrumental role of PET in pre-emptive safety measures and its indispensable contribution to the overall fabric of pedestrian safety strategies in urban environments. The proposed method also accounts for other critical factors such as pedestrian counts, speed, time of day, and trajectory. Additionally, a quick site visit enables the collection of valuable site characteristics like marked and unmarked crosswalks and proper lighting, as both tend to make pedestrians more visible and, therefore, safer. The findings of this study can provide valuable insights for urban planners, policymakers, and transportation engineers in developing effective measures to improve pedestrian safety at intersections.

In summary, this research marks a significant advancement in pedestrian safety analysis. It provides a comprehensive method that cities can adopt to not only understand but also preemptively address the complex dynamics of urban traffic safety. By focusing on proactive safety measures informed by advanced data analytics, this dissertation sets a new benchmark for leveraging technology to protect vulnerable road users and advance toward the ambitious goal of Vision Zero.

The framework and format of this dissertation unfold in a structured manner, aimed at rigorously exploring the research objectives and unveiling the pioneering methodology while also discussing the broader implications of findings for urban safety enhancements. It begins with an Introduction that outlines the urgent need for innovative pedestrian safety measures in the context of the Vision Zero goal, amidst the backdrop of increasingly complex pedestrian-vehicle interactions in urban settings. This chapter sets the stage for the significance of leveraging new traffic sensing and AI technologies to address these challenges.

Following the Introduction, the Literature Review provides a comprehensive examination of existing methodologies and research in the fields of pedestrian safety, traffic sensing technologies, and the application of artificial intelligence in traffic analysis. This section identifies a critical gap in existing methodologies—specifically, the lack of proactive evaluation approaches to pedestrian safety—and establishes the foundation for the novel methodology proposed in this dissertation.

At the heart of the dissertation, the proposed pedestrian safety scoring model is introduced to utilize high-accuracy, all-traffic trajectory data for proactive pedestrian safety assessment. This chapter is pivotal, as it elaborates on the analytical framework and technical processes that underpin the proactive safety scoring method to shift the paradigm from reactive to proactive, preventive measures.

The following chapter discusses the proposed model's application, which includes gathering and analyzing traffic data. It outlines the data selection criteria, the processing techniques applied, and the proposed pedestrian safety scoring method.

The dissertation concludes with the key insights gained and their contributions to the field of proactive pedestrian safety. It offers practical recommendations for urban planners, traffic engineers, and policymakers on implementing the research findings to enhance pedestrian safety proactively. Furthermore, it outlines future research directions to continue advancing the field, emphasizing the importance of innovative uses of data to create safer urban environments for pedestrians. This organization ensures a coherent narrative flow, meticulously addressing each research objective and culminating in a set of actionable insights for improving pedestrian safety through proactive, data-driven measures.

2 Literature Review and Existing Efforts

Pedestrian safety is a pressing concern in urban environments, where the intricate interaction between pedestrians and vehicular traffic poses significant challenges. As cities continue to grow and evolve, ensuring the safety of pedestrians becomes paramount. In the United States alone, thousands of pedestrians tragically lose their lives each year due to traffic-related incidents. According to the United States Department of Transportation (USDOT), in 2021, there were 7,388 pedestrians killed in traffic crashes, marking a 12.5 percent increase from the 6,565 pedestrian fatalities in 2020. This alarming statistic represents the highest number of pedestrian fatalities since 1981, when 7,837 pedestrians died in traffic crashes. Additionally, there were an estimated 60,577 pedestrians injured in traffic crashes in 2021, an 11 percent increase from 54,771 pedestrians injured in 2020. These numbers underscore the urgent need for effective measures to address pedestrian safety. On average, a pedestrian was killed every 71 minutes and injured every 9 minutes in traffic crashes in 2021, highlighting the frequency and severity of these incidents ("Pedestrians Traffic Safety Facts 2021 Data," n.d.). This introduction sets the stage for a comprehensive examination of pedestrian safety challenges and emphasizes the critical importance of prioritizing pedestrian safety in urban planning and transportation initiatives.

2.1 Pedestrian Safety Efforts Led by Federal, State and Local Agencies

Pedestrian safety is a complicated issue that requires a comprehensive approach involving various agencies and industries. In this section, the strategies and approaches used by these entities to enhance pedestrian safety are explored. By referencing current design and countermeasure manuals, federal reports, and state efforts, with an aim to provide insights into the initiatives undertaken to address pedestrian safety challenges, these countermeasures will provide a quick reference guide on how to improve traffic safety on various geometries to address various safety issues.

The federal government plays a crucial role in promoting pedestrian safety through the development of guidelines, standards, and initiatives. The Federal Highway Administration (FHWA) publishes various resources and manuals that outline best practices for pedestrian safety improvements. For example, the FHWA's "Pedestrian Safety Guide and Countermeasure Selection System" (Harkey and Zegeer 2004) provides detailed guidance on selecting appropriate countermeasures to address pedestrian safety issues in different contexts. Additionally, the National Highway Traffic Safety Administration (NHTSA) releases annual reports and research findings on pedestrian safety trends and effective interventions.

The USDOT and NHTSA have developed several guidance documents, manuals, and reports focusing on pedestrian safety trends and effective interventions. One such resource is the "Pedestrian Safety Strategic Plan" (Zegeer et al. 2010), which serves as a comprehensive and strategic blueprint for coordinating efforts among federal, state, and local agencies to tackle the multi-faceted challenges associated with pedestrian safety nationwide. Through extensive collaboration and consultation with stakeholders, this plan outlines a series of actionable steps and priorities aimed at reducing pedestrian crashes, injuries, and fatalities. It identifies key areas of focus, such as infrastructure improvements, education and outreach campaigns, enforcement strategies, and data-driven approaches to pedestrian safety management. By providing a structured framework for enhancing pedestrian safety, the plan empowers agencies at all levels of government to implement targeted interventions and allocate resources more effectively. Furthermore, it emphasizes the importance of partnerships with community organizations, advocacy groups, and other stakeholders to foster a holistic and inclusive approach to pedestrian safety. Through its strategic guidance and collaborative approach, the Pedestrian Safety Strategic Plan endeavors to create safer streets and communities for pedestrians across the United States.

The "Pedestrian Safety Guide and Countermeasure Selection System (PEDSAFE)" (Harkey and Zegeer 2004) is a user-friendly tool designed to assist transportation practitioners in selecting the most suitable pedestrian safety treatments for specific issues. It offers a wide range of evidence-based strategies, from infrastructure improvements to educational campaigns, tailored to address various pedestrian safety challenges. By providing easy access to proven methodologies and best practices, PEDSAFE empowers practitioners to make informed decisions and implement effective interventions. It promotes data-driven decision-making and fosters innovation in pedestrian safety, contributing to safer streets and communities for pedestrians nationwide.

The "Pedestrian Safety Enforcement Operations: A How-To Guide"(NHTSA 2014) serves as an invaluable resource specifically tailored for law enforcement agencies striving to mitigate pedestrian crashes through effective enforcement operations. This comprehensive guide equips officers with detailed instructions and best practices for implementing targeted enforcement strategies, including patrols, crosswalk enforcement, and speed enforcement. By emphasizing data-driven decision-making, collaboration with stakeholders, and education and outreach efforts, the guide empowers law enforcement personnel to address pedestrian safety concerns comprehensively. Through its practical insights and step-by-step guidance, the guide enables officers to navigate the complexities of pedestrian safety enforcement with precision and efficacy. It plays a crucial role in fostering safer streets and communities by equipping law enforcement agencies with the tools and knowledge necessary to protect pedestrians and reduce the incidence of pedestrian-related crashes and injuries.

The Highway Safety Manual (HSM) (National Research Council (US), Transportation Research Board, Task Force on Development of the Highway Safety Manual and Transportation Officials, Joint Task Force on the Highway Safety Manual 2010) serves as a comprehensive resource developed by the American Association of State Highway and Transportation Officials (AASHTO) that provides practitioners with tools and methodologies for evaluating and improving highway safety. While the HSM primarily focuses on vehicular safety, it also includes considerations for pedestrian safety within its framework. By integrating pedestrian safety into the broader context of highway safety, the HSM offers insights into the design, operation, and evaluation of transportation facilities to enhance safety outcomes for all road users.

Within the HSM, practitioners can find guidance on various aspects of pedestrian safety, including pedestrian crash prediction models, safety performance functions, and tools for assessing the effectiveness of pedestrian safety countermeasures. By utilizing these resources, transportation professionals can analyze existing conditions, identify potential safety risks for pedestrians, and prioritize interventions to mitigate those risks effectively.

Moreover, the HSM provides methodologies for conducting pedestrian safety audits and assessments, allowing practitioners to systematically evaluate the safety performance of pedestrian facilities such as crosswalks, sidewalks, and pedestrian crossings. These assessments help identify deficiencies and opportunities for improvement, enabling agencies to prioritize investments and allocate resources more effectively to enhance pedestrian safety.

Overall, the integration of pedestrian safety considerations into the HSM underscores the importance of prioritizing the safety of all road users in transportation planning, design, and operations. By leveraging the tools and methodologies provided in the HSM, practitioners can work towards creating safer, more accessible, and pedestrian-friendly transportation systems that promote mobility and improve community life quality.

These resources collectively contribute to the ongoing efforts to enhance pedestrian safety and reduce pedestrian crashes and fatalities nationwide. In addition to these efforts, the federal government supports pedestrian safety through the Strategic Highway Safety Plan (SHSP) (Torbic et al. 2004) and the Highway Safety Improvement Program (HSIP) (Tang 2015).

The SHSP represents a collaborative and data-driven framework designed to reduce traffic-related fatalities and injuries across federal, state, and local levels in the United States. At its core, the SHSP relies on a comprehensive analysis of traffic data, including crash statistics and road usage patterns, to identify key safety challenges. This approach is enriched by input from a wide array of stakeholders, including traffic safety experts, public health officials, law enforcement, and the public, ensuring a multi-faceted perspective on road safety issues. The incorporation of evidence-based strategies, alongside research findings and best practices in road safety, further grounds the SHSP in effective and innovative measures.

Collaboration under the SHSP is structured around leadership teams, typically spearheaded by a state's department of transportation, which bring together representatives from various agencies and organizations. These teams may form specialized working groups focused on critical safety areas, such as pedestrian safety or impaired driving. By establishing shared goals and objectives, and coordinating on the allocation of funding and resources, the SHSP fosters a unified effort towards improving roadway safety.

The tangible outputs of the SHSP include detailed action plans that outline specific strategies and projects aimed at tackling identified safety challenges. These plans not only specify infrastructure improvements, such as the construction of safer pedestrian crossings and traffic-calming measures, but also encompass behavioral change programs and recommendations for legislation and policy adjustments to support safety initiatives. The emphasis on data-driven, evidence-based strategies means that the SHSP is geared towards making systemic changes that mitigate the risk and severity of traffic crashes.

Specifically, for pedestrian safety, the SHSP's efforts are directed towards creating safer environments through improved infrastructure design, enhanced visibility, and the promotion of safe behaviors among both drivers and pedestrians. By leveraging the collective strengths and resources of a broad coalition of stakeholders, the SHSP aims to significantly reduce the incidences of traffic-related injuries and fatalities, making roads safer for everyone. This comprehensive approach, rooted in collaboration and informed by data, underscores the SHSP's pivotal role in advancing road safety across the nation.

Similarly, the HSIP is a critical component of the United States' approach to enhancing road safety, focusing specifically on reducing traffic fatalities and serious injuries on all public roads. HSIP operates through a systematic, data-driven process that identifies specific roadway safety problems and implements infrastructure-related improvements to address these issues. Unlike broader safety plans that may include education and enforcement strategies, HSIP is primarily concerned with physical roadway improvements and the application of engineering solutions to improve safety for all road users, including motorists, pedestrians, and cyclists.

Central to the HSIP is the use of traffic safety data and analysis to pinpoint locations and factors contributing to high crash rates. This data-driven approach ensures that investments are directed towards areas with the greatest potential for impact. State and local transportation agencies work closely to evaluate road conditions, crash patterns, and other relevant data to identify projects that will significantly enhance road safety.

Once safety needs are identified, the HSIP funds are allocated to a wide range of infrastructure projects aimed at mitigating identified risks. These projects may include the installation of guardrails, improvement of intersections, enhancement of signage and road markings, implementation of pedestrian crosswalks, and the modernization of traffic signals. Each project is chosen based on its potential to reduce crashes and is closely monitored for effectiveness after implementation.

Collaboration is a key element of the HSIP, involving coordination between state departments of transportation, local governments, and other stakeholders. This collaborative effort ensures that the HSIP projects complement other road safety initiatives and that resources are used efficiently to achieve the common goal of reducing traffic fatalities and injuries.

The HSIP stands out for its commitment to continuous improvement in road safety through the implementation of evidence-based, cost-effective strategies. By focusing on infrastructure improvements and leveraging detailed safety data, the HSIP plays a vital role in creating safer road environments. This program not only addresses current safety challenges but also sets the foundation for long-term reductions in traffic-related fatalities and injuries, contributing significantly to the overall goal of improving highway safety across the nation.

The state of Nevada and local governments have implemented various strategies to improve pedestrian safety, tailored to the specific needs and challenges of the region. For example, the Nevada Department of Transportation (NDOT) has embraced "Complete Streets" policies (NDOT Complete Streets Policy 2017) in urban areas such as Las Vegas and Reno. These policies prioritize the safety and accessibility of all road users, including pedestrians, by incorporating features such as wider sidewalks, bike lanes, and improved crosswalks into street design. Despite these efforts, Nevada experienced 80 pedestrian deaths statewide in 2021, highlighting the ongoing importance of implementing effective pedestrian safety measures and initiatives to reduce fatalities and improve safety for pedestrians across the state.

The Regional Transportation Commission of Southern Nevada (RTCNV) has been proactive in conducting a regional Complete Streets Initiative aimed at promoting the use of all transportation modes and making southern Nevada a more sustainable place to live (Ryan Snyder Associates 2013). This initiative focuses on designing roads to be safe for all users, including car drivers, transit riders, pedestrians of all ages and abilities, and bicyclists. The benefits of Complete Streets in Nevada include making walking, biking, and transit riding more attractive and safer, improving travel options for those with limited access to vehicles, and enhancing the economic situation for communities by improving safety and reducing air pollution emissions.

The Regional Transportation Commission of Washoe County (RTCWC) has developed a Complete Streets Master Plan (Partners 2015) aimed at improving the safety and accessibility of roads for all users in the Reno-Sparks area. This initiative includes redesigning streets to better accommodate pedestrians, cyclists, motorists, and transit riders, ensuring Americans with Disabilities Act (ADA) compliance, and incorporating community feedback from public meetings. Specific strategies include reconfiguring roadways and enhancing pedestrian and cyclist infrastructure to promote safer, more connected communities. This effort demonstrates RTC Washoe's commitment to fostering an inclusive, accessible urban environment.

Furthermore, NDOT supports these efforts by engaging in projects, programs, and studies aimed at enhancing roadway safety and accessibility. Through a wide range of transportation projects and safety engineering initiatives, NDOT aims to create safer road environments that accommodate the needs of all road users, reflecting the Complete Streets philosophy.

These efforts in Nevada serve as exemplary models of how state and local governments can collaborate to implement strategies tailored to their regions' specific needs and challenges. This will improve pedestrian safety and promote a more inclusive and sustainable transportation infrastructure.

Vision Zero (“Vision Zero,” n.d.) has also become a driving force in lowering pedestrian fatalities. Vision Zero represents a transformative approach to road safety, born from the belief that no loss of life on the roads is acceptable. Originating in Sweden in the 1990s and subsequently adopted by cities and countries worldwide, its fundamental goal is the elimination of all traffic fatalities and serious injuries, with a special focus on safeguarding pedestrians and other vulnerable road users. At the heart of Vision Zero's strategy is speed management, recognizing that the force of collisions—and consequently, the severity of injuries—increases significantly with speed. Therefore, reducing speed limits, particularly in densely populated urban areas, is a priority. Moreover, Vision Zero advocates for pedestrian-centered street design, introducing measures like pedestrian-only zones, wider sidewalks, enhanced lighting, and physical barriers to shield pedestrians from vehicles. The initiative also prioritizes the improvement of crosswalks and signals, incorporating features such as visible crosswalks, pedestrian countdown signals, and adjusted signal timings to prioritize pedestrian movements.

Education and awareness campaigns form another critical pillar, targeting both drivers and pedestrians to foster a culture of road safety and mutual respect. Vision Zero's approach is markedly data-driven, relying on traffic analysis to identify high-risk areas and behaviors, thereby enabling targeted interventions where they are most needed. Enforcement plays a crucial role as well, with stricter penalties for violations like speeding, impaired driving, and failing to yield to pedestrians, alongside the strategic use of automated enforcement tools to deter reckless behavior. A key to Vision Zero's success is its inclusive stakeholder engagement strategy, which brings together government bodies, traffic engineers, urban planners, law enforcement, public health experts, and community members to collaborate on developing and implementing safety strategies. Through these concerted efforts, Vision Zero aims not merely to reduce traffic-related deaths and serious injuries but to completely eradicate them, thereby making cities safer and more equitable for all residents.

2.2 Prioritization and Ranking for Traffic Safety Projects

Ranking similar traffic geometries based on safety is a crucial strategy in urban planning and traffic management, bringing multiple benefits through an efficient, data-driven approach. This process allows for the prioritization of resources, ensuring that the most hazardous areas receive attention first. By targeting resource allocation such as funds, labor, and time, cities can achieve the most significant improvements in safety with the resources available. This targeted intervention strategy maximizes the impact of each dollar spent, as resources are directed where they can make the most difference, enhancing road safety in high-risk areas first.

Understanding specific safety issues associated with different traffic geometries enables authorities to design targeted interventions (National Research Council (US), Transportation Research Board, Task Force on Development of the Highway Safety Manual and Transportation Officials, Joint Task Force on the Highway Safety Manual 2010). For example, if certain intersection types are identified as prone to specific types of crashes, targeted measures—like redesigned junction layouts or dedicated traffic signals—can be implemented. This not only improves safety but also ensures that interventions are cost-effective, avoiding the scattergun approach of broadly applied solutions that may not address specific local problems.

Incorporating a benefit-cost analysis into this process underscores the financial rationality behind prioritizing certain traffic interventions over others. By ranking traffic geometries by safety and implementing changes based on this ranking, cities can optimize the return on investment in public safety measures. Each intervention is evaluated not only for its potential to reduce crashes and save lives but also for its economic efficiency, considering both the immediate costs and the long-term savings in healthcare, emergency services, and traffic congestion management.

Moreover, the use of a ranking system provides a benchmark for evaluating the effectiveness of safety interventions over time. This ongoing assessment is vital for a dynamic urban environment where traffic patterns and technologies continually evolve. It ensures that resources continue to be used effectively and that traffic safety strategies are adapted to changing conditions. Continuous performance tracking and reevaluation also allow cities to fine-tune their spending, focusing on interventions that have proven effective and scaling back or modifying those that have not delivered expected results.

Public dissemination of ranking results and cost-benefit analyses enhances transparency and builds public trust and support for traffic safety measures. When the community understands the reasoning behind specific interventions and sees evidence of their effectiveness, they are more likely to support and comply with these measures. Additionally, making this data public encourages safer driving behavior and can lead to broader community engagement in traffic safety initiatives.

Finally, by identifying the most problematic areas through a systematic ranking process, researchers and policymakers can concentrate their efforts on developing innovative solutions that are not only effective in improving safety but are also cost-efficient. This ongoing focus on innovation fosters advancements in traffic safety technology and infrastructure, ensuring that road safety continues to improve while remaining economically sustainable.

Overall, integrating cost-benefit analysis into the ranking of traffic geometries enhances the strategic planning and implementation of traffic safety measures, ensuring that investments are both effective in improving safety and efficient in terms of economic expenditure. This holistic approach supports sustainable urban development and promotes a safer, more efficient, and economically viable traffic system.

2.3 Reactive and Proactive Traffic Safety Improvement

The transportation safety sector faces a significant challenge rooted in the reactive nature of current methodologies employed by many agencies (Mukherjee and Mitra 2022). Rather than proactively identifying and addressing pedestrian safety concerns, the prevailing approach is to wait until crashes occur before implementing interventions. This reactive stance not only results in delays in implementing crucial safety measures but also perpetuates a cycle of preventable injuries and fatalities. Compounding this issue is the reliance on anecdotal information or community feedback, which may lack substantial data support for decision making many of the previously mentioned policies show public input is valuable, however, may not always provide the comprehensive insights required for informed and targeted interventions. Additionally, the absence of a robust data-backed approach further limits the effectiveness of safety strategies. In many cases data is not available and has not been collected. Without a nuanced understanding of pedestrian exposure data, vehicular speed patterns, and trajectory analyses, transportation agencies find it challenging to effectively implement evidence-based countermeasures. To address these challenges, there is an imperative to transition towards a proactive and data-driven paradigm. This entails the development and implementation of an advanced pedestrian scoring system harnessing comprehensive data on pedestrian risk factors.

This transition towards a proactive and data-driven paradigm is crucial for providing the essential engineering, education, and information resources needed to effectively address the problem (Abdel-Aty, Pande, and Hsia 2010). By leveraging comprehensive data on pedestrian risk factors through an advanced pedestrian scoring system, transportation agencies can tailor engineering solutions to enhance infrastructure and roadway designs in high-risk areas. Moreover, education initiatives can be customized to address specific safety challenges identified through data analysis, ensuring that pedestrians and motorists are educated about safe behaviors and traffic laws. Furthermore, providing stakeholders with access to accurate and up-to-date information on pedestrian safety risks empowers them to make informed decisions and allocate resources effectively to mitigate the problem. Overall, the integration of engineering, education, and information resources within a proactive and data-driven approach is crucial for effectively addressing pedestrian safety concerns and reducing the incidence of crashes and fatalities. In this context, there is a pressing need to develop a process for ranking intersections based on observed risky behaviors, facilitating targeted interventions and proactive safety measures.

2.4 Pedestrian Safety Performance Evaluation Methods

Current traffic safety ranking methods depend on a combination of historical crash data and predictive modeling, rather than solely on perceived safety. While public perception and community feedback may influence some aspects of traffic safety planning and interventions, objective data on past crashes are crucial for identifying high-risk areas and prioritizing safety measures. Reactive safety analysis focuses on past crashes, analyzing incidents that have already occurred. In contrast, proactive analysis examines potential future risks, often considering different types of roadway geometry. or roadway attributes, compiling a score on what safety roadway features exist.

2.4.1 Historical Crash Data

Transportation agencies and safety researchers collect and analyze data on past traffic crashes, including the location, type, severity, and contributing factors of each incident (Abdel-Aty and Pande 2007). By identifying patterns and trends in crash occurrences, authorities can pinpoint locations with higher-than-average crash rates or specific risk factors, such as intersections with a history of rear-end collisions or road segments with a high incidence of pedestrian crashes.

Historical crash data, while a cornerstone of traffic safety analysis, presents several challenges that can compromise its reliability and usefulness. One significant issue is under-reporting, where many crashes, especially those involving minor injuries or property damage, are not reported to authorities. This can result in an incomplete picture of safety issues, skewing the analysis toward more severe incidents. Moreover, biases in reporting, influenced by factors such as law enforcement practices and public perceptions, can introduce inconsistencies and discrepancies in the data across different jurisdictions or communities. Quality concerns, including inaccuracies, missing information, and data entry errors, further hinder the reliability of crash data, making it difficult to draw accurate conclusions. Additionally, temporal and spatial variability in crash rates, coupled with limited contextual information about each incident, pose challenges in identifying underlying causes and trends. Inadequate data resolution and lag time in data availability exacerbate these issues, limiting the ability to develop targeted safety interventions and respond promptly to emerging concerns. Despite these challenges, historical crash data remains a valuable resource when complemented by other data sources and analytical methodologies, but careful consideration of its limitations is essential to ensure accurate and effective traffic safety analysis and decision-making.

2.4.2 Crash Severity and Consequences

Safety rankings often consider not only the frequency of crashes but also their severity and impact on public safety (K. Wang et al. 2019). Locations with a higher number of severe injuries or fatalities may be prioritized for targeted interventions, such as safety improvements, traffic enforcement, or public awareness campaigns.

Crash severity and its consequences present significant challenges in traffic safety analysis, complicating efforts to understand and mitigate the impact of traffic crashes. One prominent issue is the variability in how severity is defined and measured across different jurisdictions and data sources. This lack of consistency can make it difficult to compare crash data and identify trends accurately. Additionally, the consequences of crashes extend beyond mere injury or property damage; they can have long-term physical, emotional, and financial impacts on individuals and communities. The full extent of these consequences may not be captured by traditional crash severity metrics, limiting the effectiveness of safety interventions designed solely based on severity levels. Furthermore, crash severity does not always correlate with other factors such as the presence of vulnerable road users, environmental conditions, or infrastructure deficiencies, which are critical considerations for improving overall traffic safety. Addressing these challenges requires a nuanced understanding of the multifaceted nature of crash severity and its consequences, as well as the adoption of comprehensive strategies that prioritize prevention, enforcement, and post-crash care to mitigate the adverse effects of traffic crashes on society.

2.4.3 Predictive Modeling and Risk Assessment

In addition to analyzing historical crash data, transportation agencies may use predictive modeling techniques to forecast future crash risk and prioritize safety investments accordingly (Ancel et al. 2015). These models may incorporate factors such as traffic volumes, roadway characteristics, land use patterns, and demographic trends to identify areas with an elevated likelihood of future crashes.

Predictive modeling and risk assessment techniques play a crucial role in identifying potential hazards and prioritizing safety interventions in traffic safety planning. However, several challenges and limitations can affect the accuracy and reliability of these methods. One significant issue is the complexity of the systems being modeled, which often involve numerous interacting variables and uncertainties. Predictive models may struggle to capture the full complexity of traffic interactions and account for dynamic factors such as human behavior, environmental conditions, and emerging technologies. This can lead to inaccuracies and errors in predictions, undermining the effectiveness of safety interventions based on flawed assessments. Additionally, predictive models rely on historical data to identify patterns and trends, which may not fully reflect future conditions or potential changes in risk factors. This limitation can result in outdated or biased predictions, especially in rapidly evolving transportation environments. Furthermore, the availability and quality of data for predictive modeling can vary widely, posing challenges in data collection, validation, and interpretation. Inadequate data resolution, incomplete information, and data biases can all affect the reliability of predictive models and the accuracy of risk assessments. Finally, the inherent uncertainty associated with predicting future events introduces a level of risk and ambiguity into predictive modeling efforts, requiring decision-makers to exercise caution and consider multiple scenarios when interpreting results and making policy decisions. Despite these challenges, predictive modeling and risk assessment remain valuable tools in traffic safety planning, but their limitations must be carefully considered and addressed to ensure accurate and reliable predictions of future safety outcomes.

2.4.4 Method: Safe System Approach

The Safe System Approach is a comprehensive methodological framework aimed at reducing road traffic fatalities and serious injuries by fundamentally changing the design and operation of transportation systems, as demonstrated in **Error! Reference source not found.**. Originating from the field of roadway safety, this approach recognizes that humans are fallible and can make mistakes, and therefore aims to create forgiving systems that minimize the impacts of human errors.

Figure 1 Safety System Approach (USDOT 2012)

At the core of the Safe System Approach lies the principle that no loss of life or serious injury on the roadway is acceptable. To achieve this goal, the approach focuses on multiple interconnected elements, including roadway infrastructure design, vehicle safety features, speed management, behavior change interventions, and post-crash care.

One of the key principles of the Safe System Approach is the emphasis on designing forgiving roadway infrastructure that can accommodate human errors without resulting in severe consequences. This includes measures such as installing roadside barriers, improving roadway geometry to reduce the risk of crashes, and implementing traffic calming techniques in areas with high pedestrian or cyclist activity.

Another critical aspect of the Safe System Approach is the management of vehicle speeds. Recognizing that speed plays a significant role in determining the severity of crashes, the approach advocates for setting and enforcing speed limits that are appropriate for the road environment. This may involve the use of speed cameras, traffic calming measures, and public awareness campaigns to promote compliance with speed limits. The Safe System Approach places a strong emphasis on promoting safer behaviors among road users through education, enforcement, and social marketing campaigns. By raising awareness about the risks of speeding, drunk driving, and other dangerous behaviors, the approach seeks to foster a culture of responsible road use.

Furthermore, the Safe System Approach emphasizes the importance of providing prompt and effective post-crash care to minimize the impact of road traffic injuries. This includes ensuring rapid access to emergency medical services, implementing trauma care systems, and improving rehabilitation services for crash survivors.

Overall, the Safe System Approach represents a paradigm shift in roadway safety thinking, moving away from a focus solely on individual responsibility towards creating safer and more forgiving transportation systems that prioritize human life and well-being. By adopting this holistic approach, policymakers, transportation planners, and roadway safety professionals can work together to create roads that are inherently safer for all users.

2.4.5 Method: Pedestrian Safety Index (PSI)

The Pedestrian Safety Index (PSI) is a methodological approach designed to assess and quantify the safety of pedestrian infrastructure and conditions within urban areas. Developed by the FHWA in 2006 to address the increasing concerns surrounding pedestrian safety in modern cities, the PSI offers a comprehensive framework for evaluating several factors that contribute to pedestrian safety, including infrastructure design, traffic flow patterns, and socio-economic variables.

At its core, the PSI utilizes a combination of qualitative and quantitative measures to gauge the safety levels for pedestrians. This may involve analyzing data on pedestrian crash rates, infrastructure features such as crosswalks and pedestrian signals, as well as the presence of amenities like sidewalks and pedestrian-friendly zones. By synthesizing these diverse factors into a unified index, the PSI provides city planners, policymakers, and urban designers with valuable insights into the effectiveness of current pedestrian safety measures and areas for improvement. **Error! Reference source not found.** listed a n example of PSI scoring application.

One of the key advantages of the PSI is its versatility and adaptability to different urban contexts. Whether applied in bustling metropolises or smaller towns, the method can be tailored to account for local variations in pedestrian behavior, traffic dynamics, and built environment characteristics. Furthermore, the PSI framework can facilitate comparative analyses between different neighborhoods, cities, or regions, enabling stakeholders to identify disparities in pedestrian safety levels and allocate resources accordingly.

In practice, the implementation of the PSI can lead to targeted interventions aimed at enhancing pedestrian safety and accessibility. This may involve investments in infrastructure upgrades, traffic calming measures, public education campaigns, or policy changes to promote walkability and prioritize pedestrian needs in urban planning initiatives. By integrating the PSI into decision-making processes, cities can strive towards creating safer, more inclusive environments that prioritize the well-being and mobility of pedestrians.

Table 1 PSI Scoring Scheet (FHWA 2006)

	Name of approach leg	Approach 1	Approach 2	Approach 3	Approach 4
MAINADT	Main Street ADT				
MAINHISPD	Main street speed limit = 35 mph (1=yes, 0=no)				
TURNVEH	Presence of turning vehicle traffic across the path of through cyclists (1=yes, 0=no)				
RTLANES	Number of right turn traffic lanes on main street approach				
BL	Bike lane present (1=yes, 0=no)				
CROSSADT	Cross street traffic volume				
SIGNAL	Traffic Signal at intersection (1=yes, 0=no)				
PARKING	On street parking on main street approach (1=yes, 0=no)				
RTCROSS	Number of traffic lanes for cyclists to cross to make a right turn				
CROSSLNS	Number of through lanes on cross street				
LTCROSS	Number of traffic lanes for cyclists to cross to make a left turn				

2.4.6 Method: iRAP Star Rating for Pedestrians

The iRAP Star Rating for Pedestrians is a methodological tool developed by the International Road Assessment Program (iRAP) to assess and rate the safety of road infrastructure, specifically concerning pedestrian users. This approach aims to provide a systematic and standardized means of evaluating the safety performance of roads from a pedestrian perspective, facilitating targeted interventions to improve pedestrian safety.

At its core, the iRAP Star Rating for Pedestrians evaluates various attributes of roadway infrastructure that directly impact pedestrian safety. These attributes may include the presence and quality of pedestrian crossings, sidewalks, footpaths, pedestrian bridges, and underpasses, as well as the design of intersections and traffic calming measures. By assessing these factors against established safety criteria, the method generates a star rating that indicates the level of safety provided to pedestrians on a particular road segment or network.

The star rating system employed by iRAP typically ranges from one to five stars, with higher ratings indicating safer pedestrian infrastructure. A one-star rating signifies the lowest level of safety, indicating significant deficiencies and hazards for pedestrians, while a five-star rating represents the highest level of safety, with infrastructure designed to effectively mitigate risks and provide optimal conditions for pedestrian mobility.

One of the key strengths of the iRAP Star Rating for Pedestrians is its ability to identify specific deficiencies and risk factors in roadway infrastructure that pose threats to pedestrian safety. This enables roadway authorities, urban planners, and policymakers to prioritize interventions and investments to address these shortcomings and improve pedestrian safety outcomes. Additionally, the star rating system provides a simple and intuitive means of communicating the safety performance of roads to stakeholders and the public, facilitating informed decision-making and advocacy efforts.

The iRAP Star Rating for Pedestrians can be applied across diverse urban and rural road networks, providing valuable insights into the safety challenges faced by pedestrians in different contexts. By systematically assessing and improving the safety of roadway infrastructure for pedestrians, this methodological approach plays a crucial role in advancing roadway safety objectives, reducing pedestrian fatalities and injuries, and creating more walkable and inclusive communities.

2.4.7 Method: Pedestrian Experience Index

The Pedestrian Experience Index (PEI) is a methodological tool designed to evaluate and quantify the quality of the pedestrian environment within urban and suburban areas. Developed to address the growing importance of pedestrian-friendly infrastructure and public spaces in contemporary urban planning, the PEI offers a systematic approach to assess various aspects of the pedestrian experience, including safety, accessibility, comfort, and attractiveness.

At its core, the PEI considers a wide range of factors that influence the pedestrian experience, encompassing both physical and social dimensions. These factors may include sidewalk width and condition, presence of crosswalks and pedestrian signals, availability of amenities such as seating, lighting, and shade, as well as the level of pedestrian activity and interaction within the area. By capturing these diverse elements, the PEI provides a holistic view of the pedestrian environment, helping to identify strengths, weaknesses, and opportunities for improvement.

The PEI typically employs a combination of qualitative and quantitative measures to assess the pedestrian experience. This may involve on-the-ground observations, surveys of pedestrian perceptions and behaviors, analysis of pedestrian flow patterns, and evaluation of built environment characteristics using standardized criteria or rating systems. Through this multidimensional approach, the PEI generates a composite score or index that reflects the overall quality of the pedestrian experience within a specific area or along a particular route. Below are two of the main tables incorporated in the PCI framework, Table 2 is the overall scores given to intersections based on overall attributes, and Table 3 shows points awarded for each attribute for corridors.

One of the key advantages of the PEI is its ability to capture subjective aspects of the pedestrian experience, such as perceived safety, comfort, and enjoyment, in addition to objective indicators of infrastructure and design quality. This allows urban planners, policymakers, and community stakeholders to gain insights into the lived experiences of pedestrians and prioritize interventions that enhance overall satisfaction and well-being.

The PEI can serve as a valuable tool for benchmarking and comparing pedestrian environments across various locations or over time. By establishing baseline measures and tracking changes in the pedestrian experience, cities can evaluate the effectiveness of interventions, monitor progress toward pedestrian-friendly goals, and identify areas in need of further attention or investment.

Table 2 PEI Scoring Descriptions (City of Fort Worth 2019)

Intersection PEI Score	Description
1	These intersections are comfortable and accessible for everyone old enough to cross streets independently. All approaches have ADA-compliant curb ramps. Pedestrians need only cross two travel lanes at most without the aid of a traffic signal.
2	These intersections are mostly comfortable, but there may be more travel lanes to cross and traffic speeds may be higher. All approaches have ADA-compliant curb ramps. Parents may not be at ease with children crossing unaccompanied. Pedestrians may have to cross three lanes at most without the aid of a traffic signal.
3	Higher traffic speeds and more travel lanes to cross make for a pedestrian experience less comfortable than PEI 2. There may not be ADA-compliant curb ramps on all approaches, so some intersection legs may not be accessible to those using wheelchairs or other mobility devices.
4	These intersections tend to be both wide and fast and/or lacking accessible curb ramps entirely. These intersections are uncomfortable and potentially unsafe for pedestrians to cross. Intersections with PEI scores of 4 can be major barriers for people walking.

Table 3 PCI Scoring Factor (City of Fort Worth 2019)

Factor	Scoring Criteria	Score
Number of Lanes to Cross	1-2	1
	3	2
	4	3
	5+	4
Speed to Cross	< 35	1
	35	2
	40	3
	> 40	4
ADA Ramps Existing/Expected	All	1
	Partial	3
	None	4
Signalization /All-Way Stop (Traffic Light/RRFB/HAWK) /Crosswalk Presence	Present	-1 from highest (Number of Lanes to Cross and/or Speed to Cross scores)
	None	Nothing

Overall, the PEI offers a comprehensive framework for assessing and improving the quality of pedestrian environments, fostering more walkable, livable, and inclusive communities. By incorporating the perspectives and needs of pedestrians into urban planning and design processes, the PEI contributes to the creation of vibrant, sustainable, and people-centered cities.

2.4.8 Method: Predictive Analytics Modeling

Predictive Analytics Modeling within the context of the Highway Safety Manual (HSM) refers to the application of statistical and data-driven techniques to predict roadway safety outcomes. The HSM, published by the American Association of State Highway and Transportation Officials (AASHTO), provides guidance for quantitatively evaluating the safety effects of various transportation infrastructure and operational improvements.

Incorporating predictive analytics into HSM involves leveraging historical crash data, along with information on roadway characteristics, traffic volumes, and other relevant factors, to develop models that forecast future crash frequencies or rates. These predictive models utilize advanced statistical methods, such as regression analysis, machine learning algorithms, and spatial analysis techniques, to identify patterns, relationships, and risk factors associated with roadway safety.

One common application of predictive analytics within the HSM framework is the development of Crash Prediction Models (CPMs). These models use historical crash data to quantify the expected number of crashes on a particular road segment or at a specific location, based on various roadway and traffic attributes. By analyzing the relationships between crash occurrence and factors such as roadway geometry, traffic control devices, and environmental conditions, CPMs enable transportation agencies to prioritize safety investments and target resources effectively.

Another application of predictive analytics in HSM is the assessment of safety performance functions (SPFs). SPFs are statistical models that estimate the relationship between roadway characteristics and the likelihood of crashes occurring. By calibrating SPFs using historical crash data, transportation agencies can predict the safety performance of different roadway designs, configurations, or treatments, helping to inform decision-making processes and optimize safety outcomes.

Predictive analytics modeling within the HSM framework offers several benefits for transportation agencies and roadway safety practitioners. It provides a data-driven approach to understanding and addressing safety challenges, allowing for evidence-based decision-making and resource allocation. By identifying high-risk locations and evaluating the potential safety impacts of proposed interventions, predictive analytics modeling helps prioritize investments and maximize the effectiveness of safety improvement strategies.

Furthermore, predictive analytics can support proactive, preventive approaches to roadway safety by enabling agencies to anticipate and mitigate potential safety risks before they lead to crashes or injuries. By integrating predictive modeling into ongoing safety management processes, transportation agencies can continuously monitor and improve the safety performance of their roadway networks, saving lives and reducing the societal costs of traffic-related incidents.

2.4.9 Method: Road Safety Audits (RSA)

Road Safety Audits (RSAs) represent a systematic and proactive approach to identifying and mitigating potential safety hazards on new or existing roadway infrastructure projects (Pietrantonio and Bornsztein 2015). The process involves a comprehensive review of roadway design plans, construction projects, or existing roadways by a multidisciplinary team of safety experts who assess the safety performance of the infrastructure from various perspectives.

The RSA process typically consists of several stages. First is the pre-audit review phase, where project documentation, including design plans, specifications, and relevant data, is examined to understand the proposed or existing roadway infrastructure. Then, a field inspection is conducted, allowing auditors to observe potential safety concerns firsthand and gather additional information not available in the project documentation.

Based on the findings from the pre-audit review and field inspection, the audit team identifies and evaluates potential safety risks associated with the roadway infrastructure in a risk assessment phase. Subsequently, recommendations and mitigation measures are developed to address identified safety concerns and improve the overall safety performance of the infrastructure. These recommendations may range from minor adjustments, such as installing additional signage or pavement markings, to more substantial changes, such as modifying intersection layouts or adding traffic calming measures.

The findings and recommendations of the RSA are documented in a formal report, which is typically submitted to the project stakeholders, including transportation agencies, designers, and contractors. It is essential for stakeholders to review the recommendations and incorporate appropriate changes into the project design or implementation to enhance safety. Follow-up audits may also be conducted to assess the effectiveness of implemented measures and identify any remaining safety issues. Road Safety Audits play a critical role in preventing crashes, reducing injuries, and saving lives by proactively addressing safety concerns in roadway infrastructure projects. They ensure that road designs prioritize safety and comply with established standards and guidelines while fostering collaboration among experts to develop innovative solutions for improving roadway safety.

2.4.10 Method: Community Engagement and Stakeholder Input

While objective data on crash occurrences form the foundation of traffic safety rankings, community engagement, and stakeholder input are also valuable sources of information. Public feedback, concerns raised by residents or advocacy groups, and input from transportation professionals and law enforcement agencies may help identify safety issues that are not adequately captured by crash data alone. This is usually called "perceived safety" (Kamel 2013).

Perceived safety, while valuable in understanding public attitudes and perceptions, can pose several challenges when used as the sole basis for traffic safety assessment and decision-making. One significant issue is that perceptions of safety may not always align with objective measures of safety. People's perceptions can be influenced by several factors, including personal experiences, media coverage, social norms, and cultural biases. As a result, areas perceived as unsafe may not necessarily have higher crash rates, while locations with significant safety risks may be perceived as relatively safe. Relying solely on perceived safety can lead to misallocation of resources, where interventions may be directed toward addressing perceived rather than actual safety concerns.

Moreover, perceptions of safety may be subjective and vary among different demographic groups, communities, and individuals. Factors such as age, gender, socioeconomic status, and mode of transportation can influence how people perceive safety on roadways. Failing to consider these differences in perceptions can result in safety interventions that do not adequately address the diverse needs and concerns of all roadway users. Additionally, perceptions of safety may be influenced by biases and stereotypes, leading to disparities in safety perceptions and outcomes for marginalized or vulnerable populations.

Furthermore, perceived safety may not capture the full range of safety issues and concerns faced by communities. While perceptions of crime, vandalism, or social disorder may influence perceptions of safety, other factors such as traffic volume, speed, road design, and infrastructure conditions also play significant roles in shaping safety outcomes. Focusing exclusively on perceived safety may overlook these underlying systemic issues that contribute to safety risks and inhibit the development of comprehensive and effective safety interventions.

Overall, while perceptions of safety provide valuable insights into public attitudes and concerns, they should be considered alongside objective measures of safety, such as crash data, engineering assessments, and observational studies, to ensure a comprehensive understanding of traffic safety issues and inform evidence-based decision-making. Integrating both subjective perceptions and objective measures can help prioritize safety interventions, address community-specific concerns, and promote equitable and effective approaches to improving traffic safety for all roadway users.

2.5 New and Advanced Technologies for Pedestrian Safety Improvements

In recent years, significant strides have been made in the realm of pedestrian safety through the development of new and advanced technologies and research initiatives. One notable area of progress involves the integration of artificial intelligence (AI) and machine learning algorithms into pedestrian detection systems (Lan et al. 2018; Zhao et al. 2019; Rohling, Heuel, and Ritter 2010). These sophisticated algorithms can analyze vast amounts of data from various sensors such as cameras, radar, and LiDAR to accurately identify pedestrians and predict their behavior in real-time. Additionally, advancements in vehicle-to-pedestrian communication technologies hold promise for enhancing safety by enabling vehicles to detect and respond to pedestrians' presence, even when they are not directly within the vehicle's line of sight. Moreover, research into advanced materials for vehicle design, such as energy-absorbing materials and pedestrian-friendly vehicle structures, aims to reduce the severity of pedestrian injuries in the event of a collision. These combined efforts underscore a multifaceted approach to pedestrian safety, leveraging innovative technologies and interdisciplinary research to mitigate risks and create safer environments for pedestrians worldwide.

Radar sensors, based on Radio Detection and Ranging principles, are widely recognized for their resilience and adaptability across diverse weather conditions, making them a robust option for object detection and tracking. By emitting radio waves and analyzing their reflections, radars can accurately determine the distance and speed of objects in their vicinity. This technology's reliability is particularly evident in challenging weather scenarios such as fog, rain, or snow, where other sensor technologies might falter due to reduced visibility. Moreover, radars excel in long-range detection, making them indispensable in applications where early detection of objects is crucial, such as air traffic control or maritime navigation. Despite these advantages, radar sensors do face limitations, notably in resolution and object classification. They may struggle to distinguish between several types of objects, leading to potential false alarms or missed detections. Additionally, radar signals can be affected by interference and clutter, requiring sophisticated signal processing techniques to filter out unwanted signals.

Vision-based cameras, another prevalent technology, capture visual data from the environment and are widely used for detecting pedestrians and vehicles. These cameras are cost-effective and provide high-resolution imaging capabilities, making them versatile for various applications. However, their effectiveness can diminish in low-light conditions or when visibility is poor. Cameras also are affected by distance and that distance affects the accuracy as distance from sensor location increases, sometimes requiring multiple cameras at given locations. Additionally, the use of cameras often raises privacy concerns, as they have the capability to capture and store visual data.

Infrared sensors provide a dependable solution for detecting pedestrians and vehicles, particularly in situations where visibility is compromised, such as low-light conditions or nighttime environments. These sensors function by detecting the heat signatures emitted by objects, offering an alternative method of detection that complements visual and radar-based systems. By sensing the infrared radiation emitted by objects, even in darkness, infrared sensors can effectively identify the presence of pedestrians and vehicles. However, despite their effectiveness, infrared sensors face challenges related to the similarity of heat signatures emitted by different objects. For instance, a warm engine and a human body may emit similar infrared signatures, potentially leading to false detections or misinterpretations.

LiDAR (Light Detection and Ranging) sensors are renowned for their remarkable capabilities. Utilizing laser pulses, LiDAR sensors emit beams that accurately measure distances and generate detailed 3D maps of the surrounding environment. This precision enables them to effectively detect pedestrians and vehicles in real-time, providing invaluable spatial information for navigation and collision avoidance systems. However, despite their effectiveness, LiDAR sensors are often associated with higher costs compared to other sensing technologies, which can pose a barrier to widespread adoption. Additionally, LiDAR systems may encounter difficulties in adverse weather conditions such as heavy rain or fog, where the laser beams may be scattered or absorbed, resulting in reduced visibility and compromised performance. Despite these challenges, ongoing advancements in LiDAR technology continue to enhance its capabilities, making it an indispensable tool in the pursuit of pedestrian safety and autonomous driving systems. Through improved weather resilience and cost-effective solutions, LiDAR sensors hold significant promise for improving pedestrian safety in a variety of environments.

Another critical methodology is the Geographic Information System (GIS) mapping of pedestrian incidents, which allows for the visual representation of data on maps to easily identify hotspots for pedestrian crashes (Ma, Huang, and Tang 2021). This approach is instrumental in understanding spatial patterns and the distribution of pedestrian-vehicle conflicts across urban areas, facilitating targeted interventions.

3 Data for This Research

Data collection and extraction processes specific to the study of pedestrian safety at intersections and midblock crossings emphasize the sophisticated setup procedures required to gather high-precision LiDAR data. The equipment arrangement and configuration for data acquisition includes not only the essential components such as batteries and a computer but also the advanced LiDAR sensor, all of which are crucial for capturing detailed traffic and pedestrian movement data.

Central to this setup is the use of a state-of-the-art 32-channel Velodyne LiDAR sensor. This sensor, known for its high accuracy and reliability, operates at a frequency of 10 hertz, enabling it to capture rapid temporal changes in the environment. Its ability to perform a 360-degree horizontal rotation ensures comprehensive coverage of the area surrounding the intersection or midblock crossings, leaving no blind spots in the data collection process. Furthermore, the sensor's vertical scanning range of 10 degrees, with a 5-degree upward and downward tilt, allows for a detailed capture of objects at various heights, enhancing the dataset's utility for analyzing pedestrian safety.

The data captured by the LiDAR sensor is meticulously recorded in pcap (Packet Capture Data) files, each spanning a duration of 30 minutes. These files are then stored on an external hard drive, ensuring that the vast amounts of data generated are securely archived for subsequent analysis. This approach to data storage not only facilitates the efficient management of large datasets but also supports the integrity and accessibility of the data for detailed traffic behavior and trajectory analysis (Wu et al. 2018).

The choice of LiDAR technology, coupled with the strategic setup of the data collection equipment, underscores the dissertation's commitment to leveraging advanced technological solutions for enhancing pedestrian safety. By capturing detailed and comprehensive data on traffic movements and interactions at the intersection and midblock crossing, this methodology provides a solid foundation for the subsequent analysis and development of proactive safety measures, aligning with the overarching goal of reducing pedestrian vulnerabilities in urban traffic environments.

3.1 Model Setup and Configuration

Setting up a model for analyzing pedestrian safety at intersections and midblock crossings using advanced traffic data, such as LiDAR, necessitates a comprehensive and methodical approach. The journey begins with a clearly defined objective for the model. For example, the aim might be to identify hazardous traffic behaviors that compromise pedestrian safety or to pinpoint potential conflict zones where pedestrians and vehicles are most likely to collide at these specific urban locales. This clear objective is pivotal, as it shapes every subsequent phase of the modeling process, from the meticulous selection of relevant data to the crafting of sophisticated analytical frameworks.

With intersections and midblock crossings as the focal points, the model seeks to dissect and understand the complex dynamics at play where pedestrian paths intersect with vehicular flows. The intricacies of these environments require a model that not only accurately captures the spatial and temporal patterns of movement but also interprets these patterns in the context of pedestrian safety. By anchoring the model on a well-articulated goal, researchers can ensure that each step—from the strategic gathering of LiDAR data to the nuanced analysis and interpretation of findings—contributes directly towards actionable insights. These insights aim to mitigate risks and enhance safety measures for pedestrians, thereby addressing the critical urban challenge of ensuring pedestrian safety in the face of busy traffic movements at intersections and midblock crossings.

3.2 Processing Steps

The processing of trajectory data for assessing pedestrian safety at intersections and midblock crossings involves a sequence of intricate steps designed to distill critical safety metrics from raw data, including vehicle speed, direction, angle of interaction, timing, location relative to crosswalks, vehicle size, and notably, the Post Encroachment Time (PET), which serves as a proxy for near-miss events. Initially, the process begins with data pre-processing, where noise reduction techniques are applied to cleanse the data of inaccuracies or anomalies that could skew results, such as GPS jitter or irregular sensor outputs. Following this, the data is segmented to isolate individual trajectories, distinguishing between pedestrian paths and vehicle movements, based on spatial and temporal parameters.

In the subsequent feature extraction phase, specific attributes are calculated from the segmented data. Speed is determined by analyzing the change in position over time for each trajectory, providing insight into vehicle and pedestrian movement dynamics. Direction and angle of interaction are deduced from the trajectory paths, offering a view into the potential conflict points and the nature of these encounters. Timing and location data are scrutinized to evaluate whether movements occur within designated crosswalks or potentially hazardous zones, while the size of the vehicle is noted as a factor in the severity of potential incidents.

3.3 Trajectory Data

Trajectory data is used to unravel the movement patterns of both pedestrians and vehicles, identifying risky interactions and potential conflict zones that compromise pedestrian safety. Trajectory data is critical as it shapes the entire modeling process, guiding the collection, processing, and analysis of trajectory data to yield meaningful insights. The significance of trajectory data results from its ability to capture the detailed movements of subjects within the monitored environment. For intersections and midblock crossings, this means closely tracking the paths taken by pedestrians and vehicles, moment by moment. Such granular data allows for a nuanced understanding of how these paths intersect, overlap, or come dangerously close, providing a dynamic picture of the potential safety hazards present in these urban settings. Figure 2 is an example of trajectory data for pedestrians, which can itself be used to show were problems of learned behavior could be problematic and cause safety issues, one that arises very easily is identifying where crosswalks are not being used, and where crosswalks could be created to help with safety at intersections or midblock.

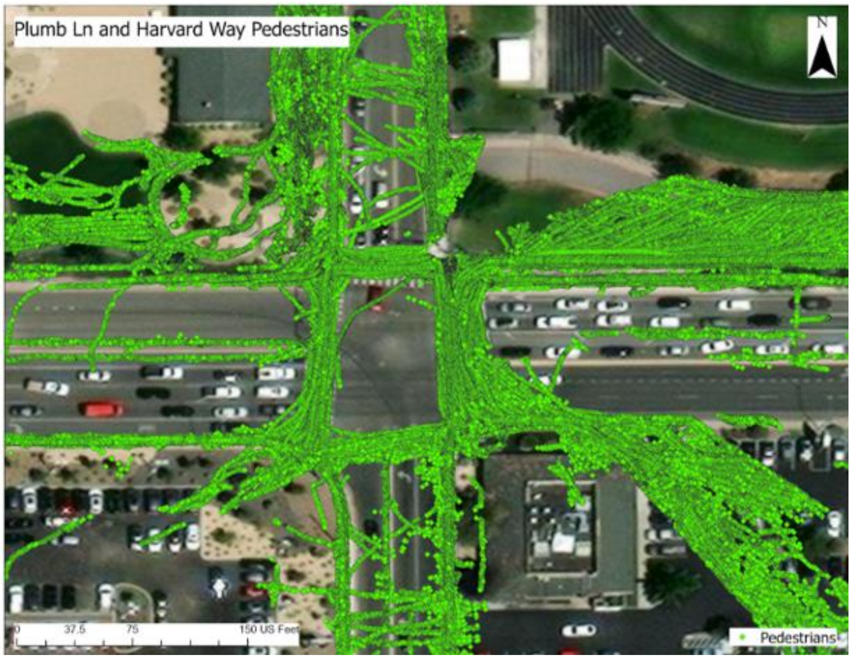

Figure 2 Example of Pedestrian Trajectory Data

To effectively utilize trajectory data, the model must incorporate sophisticated data processing techniques capable of managing the complexity and volume of the data collected. This includes filtering noise from the data, segmenting trajectories to identify relevant events, and applying advanced analytical methods to discern patterns and predict outcomes. The aim is to transform the raw trajectory data into actionable insights that can inform the development of targeted interventions to enhance pedestrian safety.

By focusing on the trajectories of all individuals involved, the model not only identifies existing safety issues but also offers the potential to predict future incidents, allowing urban planners and traffic safety professionals to proactively address risks. The use of trajectory data in analyzing pedestrian safety at intersections and midblock crossings offers a powerful tool for improving urban environments, making them safer for the most vulnerable road users.

4 Proposed Pedestrian Safety Scoring Model

4.1 Vehicle-Pedestrian Conflict Factors

Understanding and addressing pedestrian safety requires a thorough analysis of various data points crucial for risk assessment and intervention prioritization. Post Encroachment Time (PET), speed data, crosswalk angles, crash times, and lighting conditions all play integral roles in identifying potential hazards and implementing effective safety measures. PET measures the time available for pedestrians to avoid collisions after entering conflict zones like crosswalks, informing improvements such as signal upgrades or traffic calming measures. Analyzing vehicle speeds near pedestrian-heavy areas highlights high-risk zones, aiding in the implementation of speed management strategies. Evaluation of crosswalk angles identifies locations with compromised visibility or increased conflict potential, guiding design modifications. Crash time data reveals temporal trends, enabling targeted interventions during high-risk periods, while assessing lighting conditions helps identify areas in need of illumination enhancements for improved pedestrian visibility and safety. Through comprehensive data analysis, transportation agencies can prioritize interventions to create safer environments for pedestrians, promoting walkability and reducing the risk of pedestrian-related crashes.

4.1.1 Post Encroachment Time

Post Encroachment Time (PET) (Peesapati, Hunter, and Rodgers 2018) not only provides insights into pedestrian safety but also helps define near-miss events. A near-miss occurs when a pedestrian enters a conflict zone, such as a crosswalk, and encounters a vehicle with insufficient time to avoid a potential collision. In such instances, PET acts as a critical measure of proximity to a collision, indicating how close pedestrians come to being struck by vehicles. By establishing a threshold for acceptable PET values, transportation planners can identify near-miss events and assess the frequency and severity of potential collisions. Analyzing near-miss incidents based on PET values allows for proactive interventions to mitigate risks and improve pedestrian safety. Thus, PET not only informs safety analysis but also serves as a tool for identifying and addressing near-miss events, contributing to the reduction of pedestrian-related crashes and injuries on roadways.

4.1.2 Vehicle Speed

Collecting speed data is essential for assessing safety risks for pedestrians as it provides critical insights into the potential for collisions and the severity of their outcomes. Vehicle speed directly impacts the likelihood of pedestrian-vehicle collisions, with higher vehicle speeds increasing the risk of crashes due to reduced reaction times and longer stopping distances for drivers. By analyzing speed data, transportation planners can identify areas with high-speed traffic where pedestrians are at greater risk of being involved in crashes. Moreover, speed data helps evaluate compliance with speed limits, detect speeding violations, and assess the effectiveness of speed management measures such as traffic calming devices or speed enforcement efforts. Understanding the relationship between vehicle speeds and pedestrian safety allows for targeted interventions to mitigate risks and create safer environments for pedestrians to walk and cross streets. Therefore, collecting speed data is crucial for accurately assessing safety risks and implementing evidence-based strategies to protect pedestrians from potential hazards on roadways.

The velocity of a vehicle exerts a pivotal influence on the potential severity of a pedestrian collision (Ditcharoen et al. 2018). Broadly, an elevated vehicle speed correlates with an escalated likelihood of a more severe impact. This relationship stems from the diminished time available for the vehicle to react and come to a stop prior to contact. Additionally, higher speeds augment the force of impact, thereby increasing the probability of injury or fatality to the pedestrian involved. According to data provided by the National Highway Traffic Safety Administration (NHTSA 2021), a pedestrian struck by a vehicle traveling at 20 miles per hour faces a 10% likelihood of fatality or serious injury, whereas the risk spikes to 80% if the vehicle is traveling at 40 miles per hour (AAA Foundation 2011).

Table delineation of the relationship between speed and severity, as defined by the State of Florida and corroborated by NHTSA, underscores the significance of this association (NHTSA 1999). A vehicle operating at speeds less than 20 miles per hour is associated with a 1.1% probability of resulting in a fatality, in stark contrast to the 46 miles per hour and above category, which exhibits a higher fatality risk of 36.1%. Specifically, speeds below 20 miles per hour correspond to a 35.6% likelihood of a Crash with Possible Injury (C) or Property Damage Only (PDO) classification, while speeds exceeding 46 miles per hour entail an 8.4% chance of the same severity classification (NHTSA 1999). Table 4 shows the breakdown by crash severity and by speed of the vehicle.

Table 4 Vehicle Travel Speed and Pedestrian Injury Severity (NHTSA 1999)

	Travel Speed (MPH)					
Crash Severity	**<20**	**21-25**	**26-31**	**31-35**	**36-45**	**46+**
K	1.1%	3.7%	6.1%	12.5%	22.4%	36.1%
A	19.4%	32%	35.9%	39.3%	40.2%	33.7%
B	43.8%	41.2%	36.8%	31.6%	24.7%	20.5%
C/O	35.6%	23%	21.2%	16.6%	12.7%	8.4%

Speed is directly proportional to the probability of fatal and serious injury to a pedestrian in the event of a collision with a vehicle. The relationship between vehicle speed and the severity of pedestrian injuries follows a well-established principle: the faster a vehicle is traveling, the greater the force exerted upon impact. This increased force significantly elevates the risk of severe injuries or fatalities for pedestrians struck by vehicles traveling at higher speeds. Research consistently demonstrates that even small increases in vehicle speed can have a profound impact on the outcome of pedestrian collisions, with higher speeds drastically reducing the likelihood of survival and increasing the severity of injuries sustained.

Based on this review, the provided table will be used to calculate risk based on speed, identified by the all-trajectory data. The table categorizes risk by severity and speed, providing corresponding percentages. These percentages will be multiplied by the societal cost of each severity level and then summed across all speed groupings to determine the overall societal cost (risk) by speed.

4.1.3 Angle of impact

The angle of impact in a pedestrian vs vehicle crash is crucial as it significantly influences the severity and type of injuries sustained by the pedestrian (Yang, Yao, and Otte 2005). The angle at which a pedestrian is struck by a vehicle determines the direction and force of the impact, determining the likelihood of certain types of injuries.

For example, a pedestrian struck head-on by a vehicle is more likely to suffer severe injuries to the lower extremities, pelvis, and torso due to the direct impact force. In contrast, a pedestrian struck from the side may experience rotational forces leading to injuries such as head trauma or fractures.

Understanding the angle of impact is crucial for analyzing crash dynamics, determining injury mechanisms, and developing effective countermeasures to mitigate pedestrian injuries. The vehicle's trajectory will be a pivotal factor. This consideration is crucial as research indicates that instances involving straight-line movements or impacts occurring at a right angle exhibit a 20% greater likelihood of resulting in fatal or serious injuries compared to turning movements. This phenomenon can be attributed to the elevated speeds typically associated with vehicles traveling in a straight path as opposed to those executing turns, aligning with the observations.

Based on this review, it is determined that interactions with angles of 0 – 5 Degrees, 85-95 Degrees, and 175-180 Degrees will have a 20% increase in risk. This allows for a +/- of five degrees, which is considered a straight-on movement, as discussed previously and referenced.

4.1.4 Marked Cross Walk Present

Marked crosswalks play a pivotal role in enhancing pedestrian safety (Monsere et al. 2016). They provide a clear indication to drivers of potential pedestrian crossing points and often incorporate control measures to alert drivers and guide pedestrians during crossings. The absence of a marked crossing elevates the associated risk, warranting a 25% increase in the risk score, as stipulated by the Federal Highway Administration (Zegeer et al. 2005).

The presence of a crosswalk significantly influences pedestrian crash outcomes by enhancing visibility, clarifying legal right-of-way, influencing pedestrian behavior, and facilitating infrastructure enhancements. Marked crosswalks are typically equipped with pavement markings, signage, and sometimes traffic signals, making them more visible to both pedestrians and drivers. This increased visibility helps drivers anticipate pedestrians crossing the road, reducing the likelihood of collisions. Moreover, crosswalks indicate designated areas where pedestrians have the legal right-of-way to cross, reinforcing pedestrians' entitlement and encouraging drivers to yield. Pedestrians are also more likely to use designated crossing points when crosswalks are present, reducing the risk of jaywalking or crossing at hazardous locations. Additionally, crosswalks often come with infrastructure enhancements such as pedestrian signals or refuge islands, further improving pedestrian safety. However, the effectiveness of crosswalks depends on numerous factors such as design, location, maintenance, and enforcement. Therefore, while crosswalks play a crucial role in pedestrian safety, comprehensive approaches that integrate infrastructure improvements, traffic management strategies, education, and enforcement are essential for effectively reducing pedestrian crashes at crosswalks.

Based on the review, the provided information will be used, and any leg of an intersection that does not have a marked crosswalk will have its associated risk increased by 25% to reflect the increased danger of crossing a street without a marked crosswalk.

4.1.5 Time of Day

The time of day significantly influences the outcome of pedestrian crashes due to variations in visibility, traffic volume, and pedestrian behavior (Song et al. 2021). During daylight hours, visibility is higher, allowing both drivers and pedestrians to see each other more clearly and react promptly to potential hazards, which can reduce the severity of crashes. However, pedestrian crashes during daylight hours may still occur due to factors such as distracted driving, failure to yield, or reckless pedestrian and or driver behavior. In contrast, pedestrian crashes at night or during low-light conditions pose increased risks due to reduced visibility for both drivers and pedestrians. The limited visibility makes it more challenging for drivers to detect pedestrians, especially if they are not wearing reflective clothing or using appropriate lighting. As a result, pedestrian crashes during nighttime hours are more likely to result in severe injuries or fatalities. Additionally, nighttime conditions may be associated with higher speeds and more impaired or fatigued driving, further increasing the risk of crashes. Moreover, pedestrian behavior may also differ depending on the time of day, with increased alcohol consumption and risky behavior observed during nighttime hours, contributing to the likelihood of crashes. Overall, the time of day plays a critical role in pedestrian crash outcomes, with daylight hours associated with lower crash severity due to better visibility, while nighttime hours present increased risks of severe crashes due to reduced visibility and other contributing factors. Therefore, implementing strategies to improve visibility, such as enhanced street lighting and pedestrian visibility measures, as well as promoting safe pedestrian and driver behavior, are essential for reducing pedestrian crashes during all times of the day.

According to the National Highway Traffic Safety Administration (NHTSA), incidents occurring at night exhibit a staggering 90% higher likelihood of resulting in severe outcomes compared to similar occurrences during daylight hours ("Driving at Night - National Safety Council," n.d.)Reduced visibility during nighttime hours can pose significant challenges for drivers in detecting pedestrians, especially if they are not clad in reflective attire or if the area lacks adequate illumination. Potential factors like alcohol impairment or excessive speed compound this, heightening the risk of pedestrian crossings during nocturnal hours. Conversely, while visibility is superior during the daytime, other variables, such as distracted driving or non-compliance with traffic regulations, pose hazards to pedestrians.

Based on the review, the provided information will be used for any near-miss observed during the nighttime hours. A nighttime vehicle-pedestrian conflict will have its associated risk increased by 90% to reflect the increased danger of crossing at night.

4.1.6 Lighting Present

The presence of lighting at an intersection significantly influences the outcome of pedestrian crashes by improving visibility and reducing the likelihood of collisions, particularly during low-light conditions such as nighttime (Sullivan and Flannagan 2007). Adequate lighting illuminates the intersection, making it easier for both drivers and pedestrians to see each other and react appropriately. Improved visibility enables drivers to detect pedestrians crossing the intersection more readily, reducing the risk of collisions caused by failed detection. Likewise, pedestrians are more visible to drivers, enhancing their safety as they navigate the intersection. In addition to facilitating better detection, lighting at intersections can also increase drivers' awareness of pedestrian crossings and aid in identifying pedestrian traffic signals or signage, reinforcing the importance of yielding to pedestrians. Moreover, well-lighted intersections contribute to a sense of security and comfort for pedestrians, encouraging more people to walk and use pedestrian facilities, which can further improve safety by increasing pedestrian visibility and reducing conflicts with vehicular traffic. Overall, the presence of lighting at an intersection plays a crucial role in enhancing pedestrian safety by improving visibility, reducing collision risks, and promoting safer interactions between pedestrians and vehicles, particularly during low-light conditions.

Therefore, ensuring adequate lighting infrastructure at intersections is essential for mitigating the risk of pedestrian crashes and creating safer environments for all road users. Lighting at a crosswalk plays a vital role in increasing pedestrian safety, particularly during nighttime or low-light conditions. Having adequate lighting at crossing events when it comes to nighttime crossing lighting has been shown to decrease the risks to pedestrians by up to 40% during night crossing events (Waite, Nelson, and Spinney 2023).

Based on the review, the provided information will be used. Any near-miss event observed during the nighttime hours, where lighting is present, will have its associated risk decreased by 40% to reflect the decreased danger of crossing at night when the area is well-lit.

4.1.7 Size of Vehicle

The size of vehicles involved in near-miss incidents is a critical determinant in assessing pedestrian safety, warranting attention for several compelling reasons (Monfort, Hu, and Mueller 2024). Firstly, larger vehicles such as trucks or buses represent a substantial threat to pedestrian well-being due to their sheer mass and the force they can exert upon impact. The magnitude of potential harm escalates with the size and weight of the vehicle, amplifying the risk of severe injury or fatality in the event of a collision.

Secondly, vehicle size significantly influences drivers' visibility of pedestrians, a pivotal factor in crash prevention. Larger vehicles inherently possess expansive blind spots, complicating drivers' task in spotting pedestrians, especially at intersections and during turns where near-miss incidents tend to occur with greater frequency. This compromised visibility exacerbates the risk of near-misses progressing into full-blown collisions, highlighting the crucial role of vehicle dimensions in mitigating pedestrian hazards.

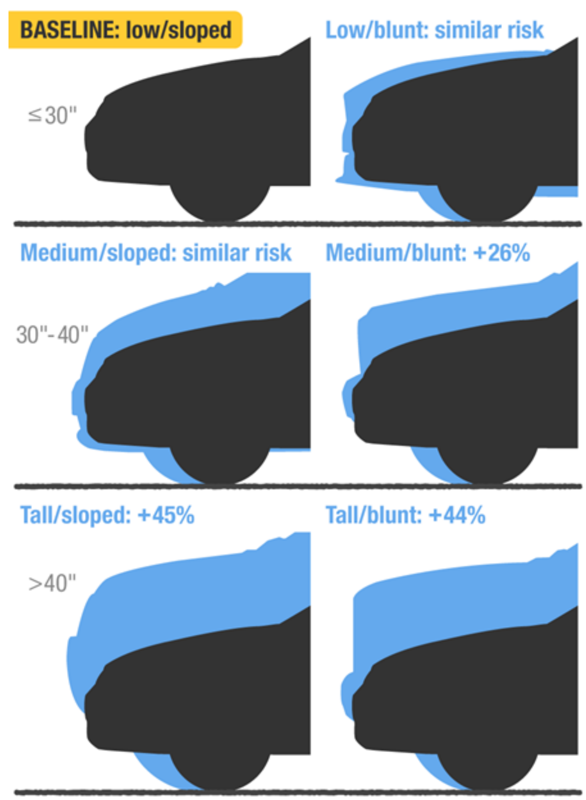

Figure 3 Size of Vehicle vs Severity (IIHS 2023)

Moreover, the stopping distance of vehicles correlates directly with their size and weight, underscoring another dimension of risk in near-miss scenarios. Larger vehicles necessitate extended stopping distances, which could prove pivotal in determining whether a near-miss situation transpires into an actual collision. Particularly in bustling urban environments teeming with pedestrian activity, the ability of larger vehicles to navigate safely and anticipate pedestrian movements becomes paramount for crash prevention. Figure 3 shows how different front ends cause different problems; for this study it is used all large vehicles are +40% riskier. Currently, the data set only has large or normal-sized vehicles as the two options.

Furthermore, beyond the physical ramifications, near-misses involving larger vehicles can exact a profound toll on pedestrian psychology, shaping perceptions of safety and influencing subsequent behavior. The heightened anxiety and apprehension stemming from such encounters may compel pedestrians to alter their routes or adopt more cautious approaches, thereby reshaping the dynamics of urban mobility and pedestrian flow.

In summary, the size of vehicles in near-miss incidents serves as a multifaceted determinant of risk, influencing the severity of potential outcomes, visibility parameters, stopping distances, and the psychological well-being of pedestrians. A comprehensive grasp of these dynamics is indispensable for crafting targeted interventions geared toward enhancing pedestrian safety and curbing the risk of collisions in densely populated urban landscapes.

Based on the review, the provided information will be used at any near-miss that is observed where a large vehicle is involved and will have its associated risk increased by 40% to reflect the increased danger of encountering a large.

4.2 Near-miss Definition.

In traffic safety, a “near-miss” refers to an incident where two or more entities, such as vehicles, pedestrians, or cyclists, come dangerously close to colliding but avoid a crash. This concept captures critical moments of elevated risk, defined by both temporal and spatial dimensions. Temporally, it identifies instances where the time until a potential collision is minimal, indicating an immediate danger. Spatially, it is characterized by the distance between the entities involved shrinking to a critical minimum, often to the point where a crash seems likely. The analysis of near-misses, focusing on these dimensions, sheds light on traffic interaction dynamics, considering various parameters like vehicle speed, acceleration, reaction times, and environmental factors, including roadway and intersection layout and visibility.

Despite its significance in identifying safety risks, the term “near-miss” does not have a universally accepted definition within the traffic safety realm, partly due to the subjective nature of assessing the severity and potential outcome of these incidents. The interpretation of a near-miss can vary based on individual perceptions, cultural norms, and specific event circumstances. This subjectivity is compounded by factors such as the entities’ relative speeds, environmental conditions, and human elements, which influence the perception of risk associated with each near-miss event.

Nevertheless, near-misses are invaluable for traffic safety research and practice, indicating potential dangers and areas requiring intervention. They highlight vulnerabilities in transportation systems and guide the development of strategies to mitigate the risk of future crashes. By analyzing near-misses and their contributing factors, safety experts can devise more effective measures to enhance road safety.

For the purposes of this study, a “near-miss” was defined as a traffic incident where entities—be it vehicles, pedestrians, or cyclists—avoided a collision with a separation time difference equivalent to about 2.5 seconds or less, and where the pedestrian, the more vulnerable user, occupies the space first. This definition, focusing on a specific temporal threshold, aims to standardize the concept of near-misses, enabling uniform data collection and analysis across various scenarios. This standardization includes a PET of less than 2.5 seconds, where the pedestrian occupies the space before the vehicle does, and the vehicle has a greater speed than 15 mph. Although recognizing the challenges in assessing near-misses due to their subjective nature, this operational definition provides a solid foundation for exploring traffic dynamics and developing effective interventions to decrease the likelihood of crashes on the road.

The process of determining a near-miss risk score involves a multi-step approach aimed at comprehensively evaluating pedestrian safety dynamics at intersections. Initially, a near-miss risk score is established by integrating potential severity outcomes with the corresponding ratio of monetized value by severity across different speed ranges. This calculation results in a foundational score for each speed range, serving as the basis for assessing near-miss risks. After this initial calculation, a near-miss risk score undergoes potential refinement by incorporating LiDAR data and intersection features gathered during site visits. These supplementary assessments offer valuable insights into real-world conditions and pedestrian behaviors at intersections, allowing for adjustments and enhancements to an initial risk score. By iteratively refining a near-miss risk score based on additional data and observations, the assessment process becomes more precise and comprehensive, providing a more accurate representation of pedestrian safety risks at intersections.

4.3 Model Inputs

The data for conducting this analysis encompasses a range of critical factors, including vehicle speed, time, angle, dimensions, time of day, lighting conditions, and the presence of crosswalks. These elements can be efficiently gathered through the use of high-accuracy all-traffic trajectory data and through direct observational visits to the site. By collecting this comprehensive data set, the analysis can accurately assess the conditions and potential risks at intersections or pedestrian crossings. Such detailed information is vital for understanding how numerous factors contribute to safety or risk, enabling more informed decision-making and targeted interventions to enhance roadway safety. This approach ensures that the analysis is grounded in accurate, real-time data, providing a robust foundation for improving pedestrian and vehicle interaction dynamics.

4.3.1 Societal Cost

Societal cost is used as the starting point, which USDOT employs for benefit-cost analyses related to crash-based traffic safety analysis, providing benchmarks for assessing the economic impact of several types of crashes. As of 2020, these valuations are set as follows: a fatal (K-type) crash holds a value of $11,600,000, while a property damage-only (O-type) crash is valued significantly less at $3,900. One notable observation arising from these valuations is the stark disparity in value between fatal (K-type) crashes and property damage-only (O-type) crashes, with the former being approximately 2,974 times more severe than the latter. Table 5 shows the breakdown by all severity types and shows the ratio of how much larger each severity type is to a PDO (O-type) crash. This ratio serves as a powerful tool for evaluating crashes based on their severity, offering an alternative approach to assessing crashes beyond strict monetary values. By considering this ratio, analysts can conduct more nuanced and balanced assessments of the impact and consequences associated with different crash types, aiding in the development of effective strategies for improving roadway safety and reducing the incidence of severe crashes.

Table 5 Monetized Societal Cost Value by Severity (FHWA 2020)

Severity	Monetized Value (2020)	Ratio
K	$11,600,000	2974
A	$554,800	142
B	$151,100	39
C	$77,200	20
O	$3,900	1

4.3.2 Driver Reaction Time

The development of a model to understand and predict "near-misses" in traffic safety intricately links to the study of driver reaction times. These times vary significantly due to a myriad of external and personal factors like age, vision, and distractions, ranging from 0.3 to 1.7 seconds. By taking the average of these extremes, one second emerges as a critical threshold. This average is a pivotal foundation upon which the model is built, incorporating linear and parabolic relationships to account for the complex interplay of variables affecting reaction and stopping times. The choice to anchor the definition of a near-miss at a cutoff time of 2.5 seconds is deliberate, marking the boundary beyond which an incident no longer qualifies as such. This threshold underscores the importance of timing in the dynamics of traffic safety and the prevention of crashes.

Parabolic relationships offer a nuanced framework for analyzing such dynamics, especially in the realm of stopping distances—a key factor in averting collisions. Stopping distance itself bifurcates into two essential components: reaction distance and braking distance. Reaction distance accounts for the span a vehicle covers from the initial perception of a hazard to the commencement of braking. Conversely, braking distance is the length a vehicle travels from the onset of braking to a complete stop. Segmenting stopping distance into its constituent parts helps us understand the parabolic relationship between vehicle speed and the distance needed to stop safely. This parabolic model is crucial for analyzing near-misses, where the precise interaction of speed, distance, and driver reaction time can determine the difference between a safe stop and a potential collision. The parabolic model was chosen due to the lack of a universally accepted standard for near-misses based on time. Typically, PET values between 1.5 and 2.5 seconds are considered acceptable for the upper range of a near-miss. The parabola is used instead of a straight line because it allows the critical value of 1.5 seconds to be above the line, which would only intersect at 2.5 seconds if a linear model were adopted.

Incorporating these insights, the model employs a piecewise function to articulate the relationship under scrutiny. For values of x ranging from 0 to 1, the function adopts a linear form, $-10x+100$, reflecting a straightforward decrease in function value with an increase in x. Beyond this, for x values between 1 and 2.5, the function transitions to a parabolic form, $-36(x-1)^2+90$, capturing a more complex, non-linear relationship that could represent the increasing risk or decreasing safety margin as conditions move away from the optimal. This dual approach, blending linear and parabolic elements, mirrors the layered complexity of real-world traffic scenarios, where the interplay of multiple factors dictates the outcome of potential near-miss incidents. Through this model, the critical role of timing, speed, and human factors in traffic safety and the prevention of crashes is elucidated, offering valuable insights into mitigating risks and enhancing roadway safety.

The function can be interpreted as follows:

- For $0 \leq x \leq 1$, the function is defined as $-10x + 100$.
- For $1 < x \leq 2.5$, the function is defined as $-36(x-1)^2 + 90$.

This function is then displayed in figure 4 showing the change in the line at 1 second, and then tapering off to 0 risk at 2.5 seconds.

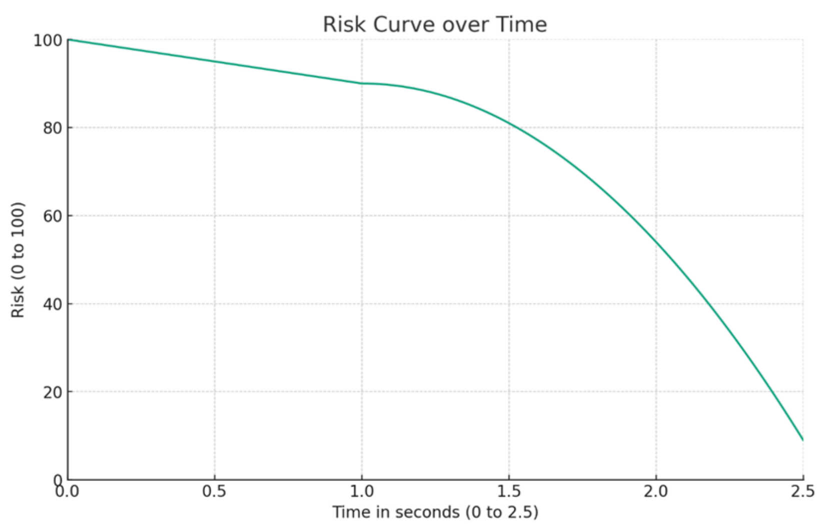

Figure 4 Risk Curve Over Time

4.3.3 Summary of Impacting Factors

Selection 4.1 has all the information on where these factors get their percentages. Several factors are critical in assessing traffic risk. This is all displayed in Figure 5, where the top half of the equation is the societal cost multiplied by time, followed by the bottom half that displays all the other impacting factors; this includes the angle of movement significantly influencing risk, with straight movement increasing it by 20%. The presence of a crosswalk also affects risk, where areas without crosswalks have a 25% increase in risk compared to those with crosswalks show no increase. Time of day is another major factor; nighttime sees a risk increase of 90% compared to daytime shows

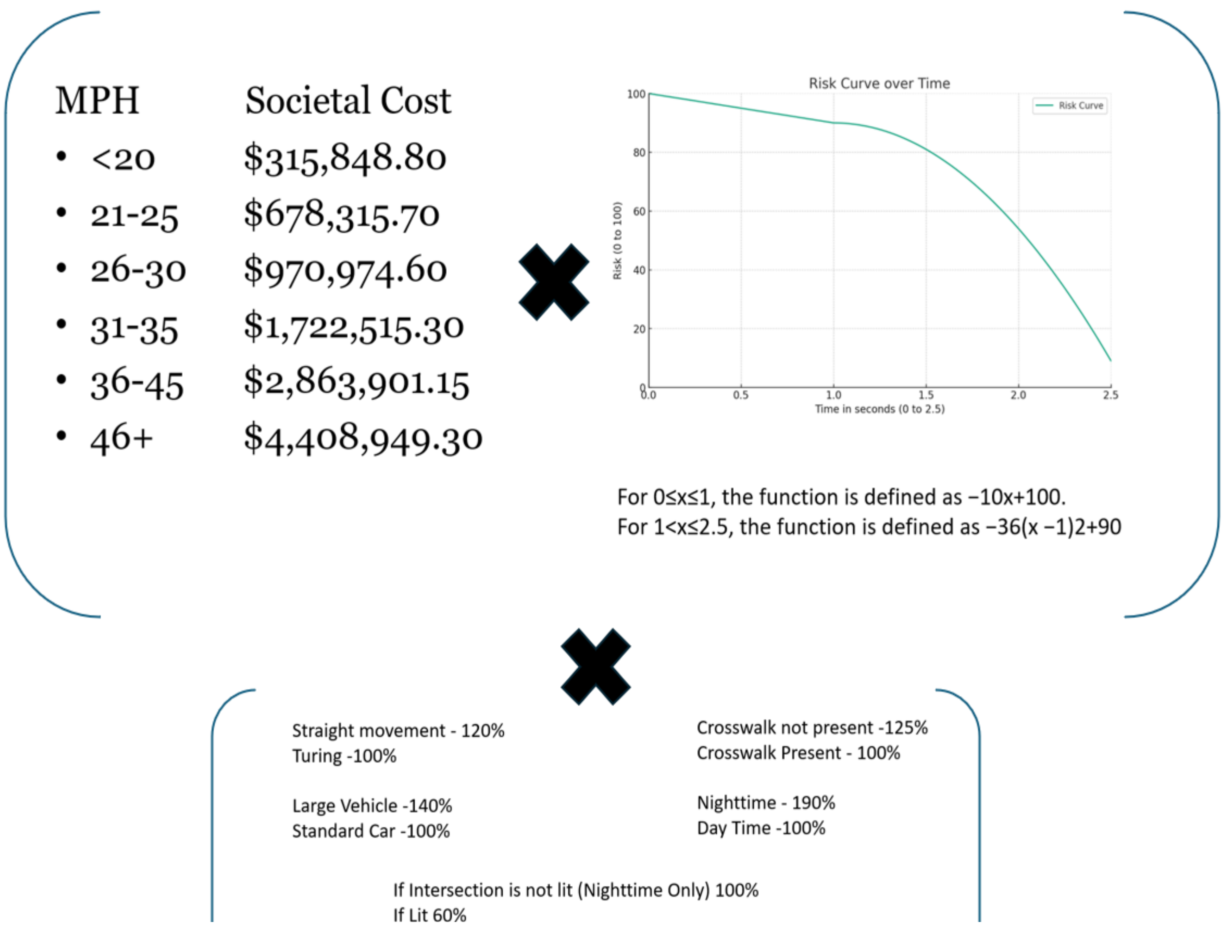

Figure 5 Scoring Outline

no increase. Lighting conditions compound this, as intersections not lit at night maintain no change in risk level, while those that are lit reduce risk to 60%. Finally, the size of the vehicle plays a role; large vehicles increase risk by 40%, whereas standard cars are set as a baseline risk level. These percentages highlight the multifaceted nature of traffic risk assessment.

4.4 Model Output

The model output shows a process for giving a risk score for individual pedestrian near-misses. In the realm of traffic management and safety, accurately evaluating the risks associated with mode movement is crucial for implementing effective safety measures. To enhance this assessment, a sophisticated model has been developed that integrates various dynamic and static factors influencing traffic conditions. This model not only considers the basic parameter of vehicle speed but also incorporates a nuanced calculation of societal costs tied to the probability of crash severity. Through a meticulously constructed risk curve and additional situational modifiers, the model provides a detailed and comprehensive risk profile. Below is a visual representation of the model.

The LiDAR data yields critical information, including the vehicle's speed, the angle at which a potential crash might occur, the timing of near-miss incidents, and the on-site assessment of the presence of pertinent features like lighting and marked crosswalks. This comprehensive dataset equips professionals and subject matter experts with a framework for effectively evaluating and ranking pedestrian crossings. By integrating these key metrics, a nuanced and data-driven approach is established to measure and prioritize pedestrian safety at intersections. Table 6 shows how an score is broken down at the individual near-miss leavel

Table 6 Model Example

6th St @ University	Example			
May 9, 2023 at 10:41am				
Time	DAY		1.00	These are multiplied Together
Conflict Angle	1.98	Straight	1.20	
Crosswalk	NO		1.25	
Speed	22		$678,315.70	
Vehcile	Large		1.40	
PET	0.5		0.95	
Lights	DAY	N/A	1.00	
Total Risk Score for this Instance			$1,353,239.82	

The model determines the average risk score for each crossing by dividing the total risk score by the total number of crossings observed. This yields an average risk score per crossing, customizable to display either the total or average risk score, depending on an organization's preferences. Table 7 shows how scores can be normalized and how normalization can be used to rank locations.

Table 7 Possible Scoring Outputs for Intersections

6th St @ University Way			
Total Risk		$18,460,878.21	
Total Observed Near-Misses	46	$401,323.44	Total Risk / Total # Near-miss
Total Number Pedestrians Observed	2900	$6,365.82	Total Risk / # Observed Pedestrian
Hours of Detection	120	$153,840.65	Total Risk / # Hours Detection

5 Application of the Proposed Model

Between 2022 and 2024, a study employing LiDAR technology was conducted at 12 locations within Washoe County, Nevada. Data were collected at each site for 72 or 120 hours, which facilitated the assessment of total societal risk, average societal risk per hour, and societal risk per pedestrian. Subsequently, these sites were ranked accordingly.

It is noteworthy that 6th Street, including its intersections at University and Wells, falls under Washoe County's "Safe Streets for All" grant, which aims to mitigate risks in one of the region's most dangerous corridors. Following the study, the intersection of Wells and 6th Street and Wells and University underwent reconstruction to enhance pedestrian safety. All these intersections were selected by Washoe RTC, and the intersections were selected as before analysis for projects to be completed in the future; an after-study will be conducted on all these sites later. Figure 6 displays all the locations of the following sites spatially. Table 32 shows these locations ranked by total risk, and then normalization methods including total risk normalized by total number of pedestrians and normalized by total number of hours observed. Pedestrian and all crashes are also provided, then the highest ranked for each method is highlighted by colors to show, if rankings are related. The accompanying table and images provide a clear ranking of the sites based on various metrics, providing a useful resource for transportation professionals.

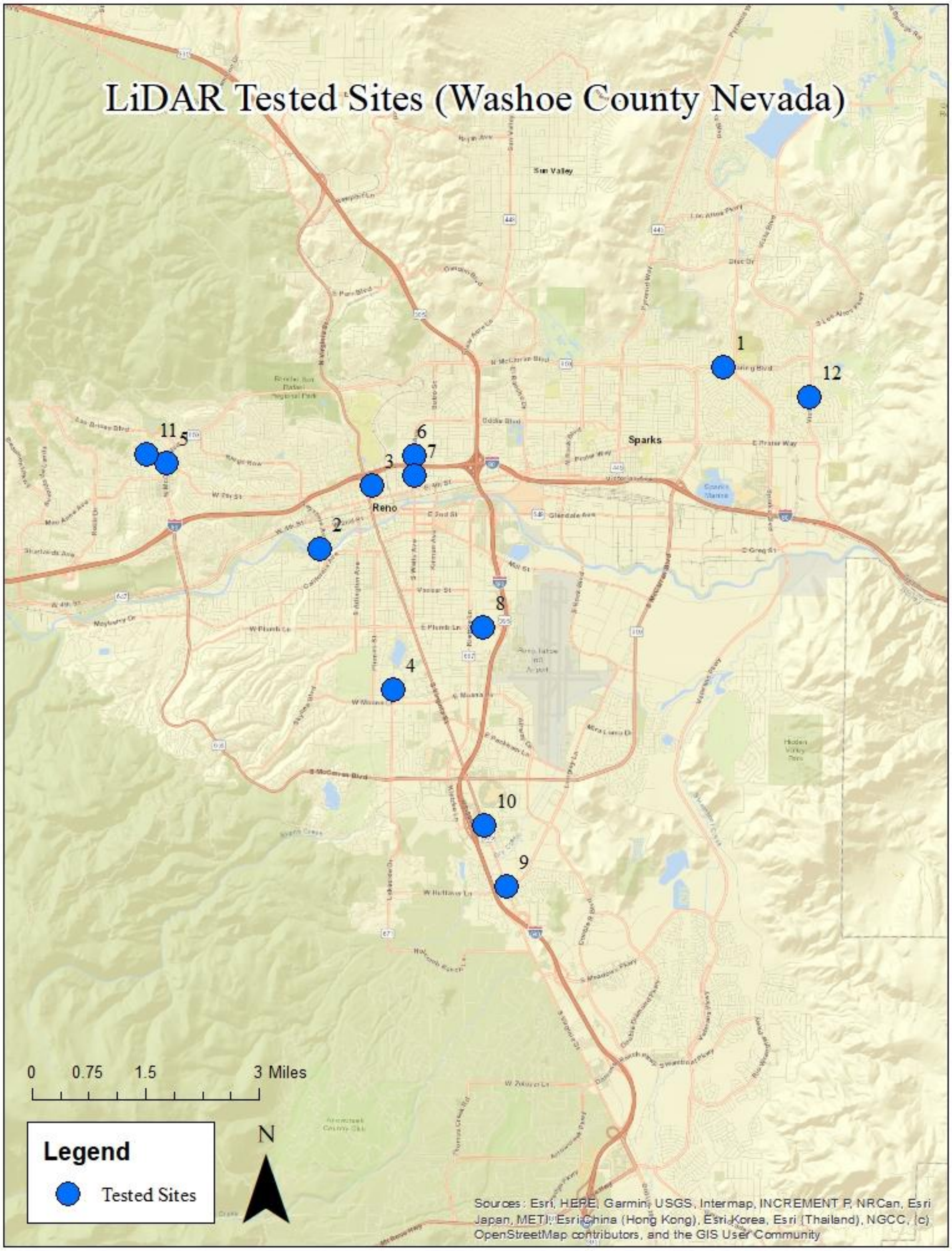

Figure 6 LiDAR Tested Sites – Proposed Model

5.1 Site 1 - Barring Avenue and Goldy Way - Sparks, NV

Barring Avenue and Goldy Way in Sparks, NV, is a suburban signalized protected-permissive intersection with pedestrian signals and has overhead streetlights; the area has a speed limit of 30 and 25 mph, with marked crosswalks at all legs of the intersection. All pertinent intersection characteristics are listed in Table 8. This intersection is located less than a half mile in both directions to commercial areas and parks and less than half a mile from a high school. Figure 7 shows the aerial map of this intersection, and Table 9 lists the pedestrian conflict score calculated with the proposed model. This site observed 261 pedestrians and 3 conflicts, and the compiled score was $791,855, which is low when compared to other sites due to low usage. Figure 8 displays the observed pedestrian movements for the intersection and all observed conflict points are presented in Figure 9.

Table 8 Site #1 - Characteristics

Barring Ave @ Goldy Wy	
9/14/2023-9/16/2023	
Time	3 Days - 72 Hours
Days of week	Thurs, Fri, Sat
Surrounding landuse	Residential
Pedestrian generators within .5 mile	School, Commercial, and Parks
Type of Intersection	4 Way
Signalized	Yes
Singal type	Protected Permissive
Overhead Lights	Present
Pedestrian signals present	Yes
Crosswalk at legs	All 4 Legs

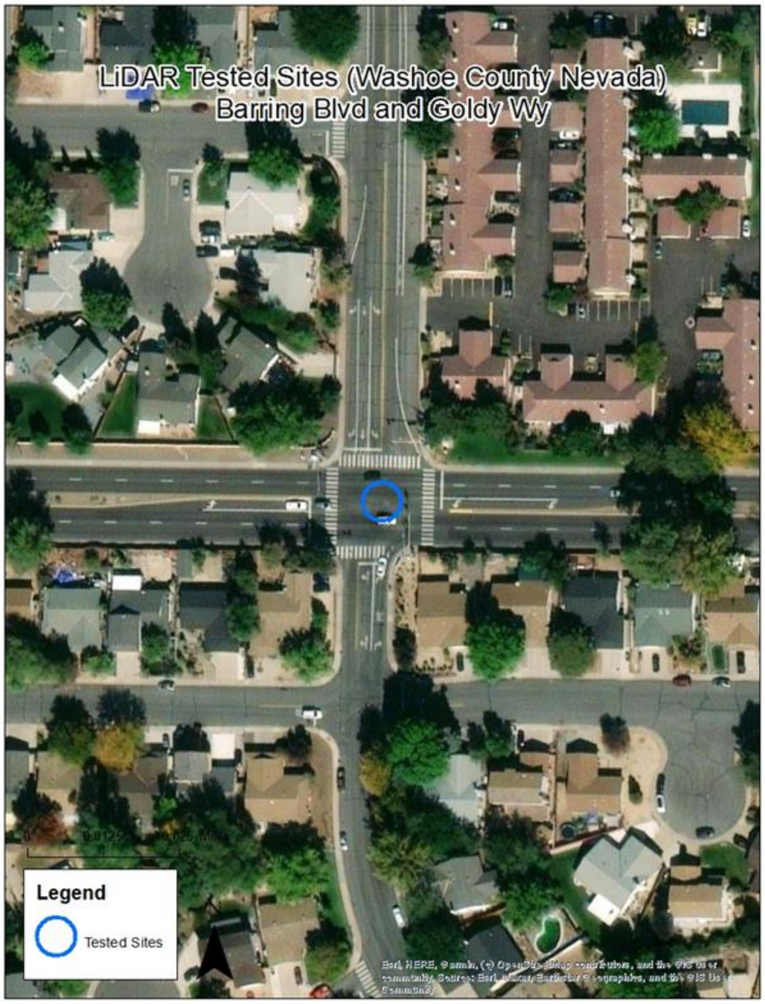

Figure 7 LiDAR Testing Site #1

Table 9 Site #1 Risk Score and Counts

Number of near-misses	3
Total societal risk	$791,855
Total pedestrians	261
Total number of vehicles observed	51,333

Figure 8 Pedestrian Movements for Site #1

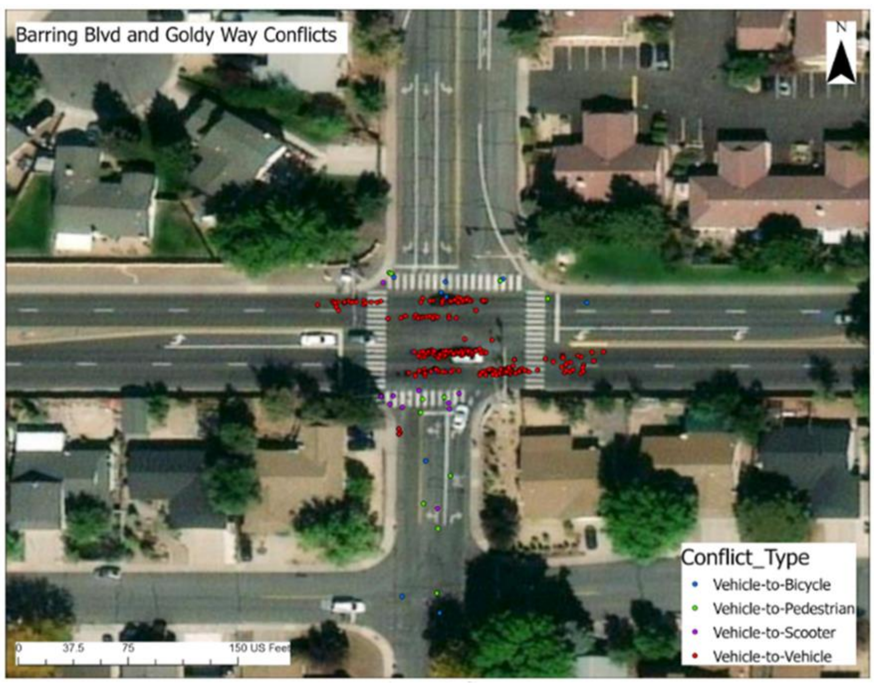

Figure 9 All Conflicts for Site #1

5.2 Site 2 - Booth Streett and Riverside Drive - Reno, NV

Booth Street and Riverside Drive in Reno, NV, is a dense suburban unsignalized intersection without pedestrian signals and has limited overhead streetlights. The area has speed limits of 25 and 15 mph, with marked crosswalks at one of the three legs of the intersection. All pertinent intersection characteristics are listed in Table 10. This intersection is located less than a half mile from commercial areas and parks and less than half a mile from a high school. Figure 10 shows the aerial map of this intersection, and Table 11 lists the pedestrian conflict score calculated with the proposed model. This site observed 3389 pedestrians and 6 conflicts, and the compiled score was $991,377, which is low when compared to other sites due to low speeds. Figure 11 displays the observed pedestrian movements for the intersection and all observed conflict points are presented in Figure 12.

Table 10 Site #2 - Characteristics

Booth St @ Riverside Dr	
9/28/2023-9/30/2023	
Time	3 Days - 72 Hours
Days of week	Thurs, Fri, Sat
Surrounding landuse	Residential/Public
Pedestrian generators within .5 mile	School, Commercial, and Parks
Type of Intersection	3 Way
Signalized	No
Singal type	N/A
Overhead Lights	Present
Pedestrian signals present	No
Crosswalk at legs	Yes 1-Leg

Figure 10 LiDAR Testing Site #2

Table 11 Site #2 Risk Score and Counts

Number of Near-misses	6
Total societal risk	$991,377
Total pedestrians	3389
Total number of vehicles observed	23,458

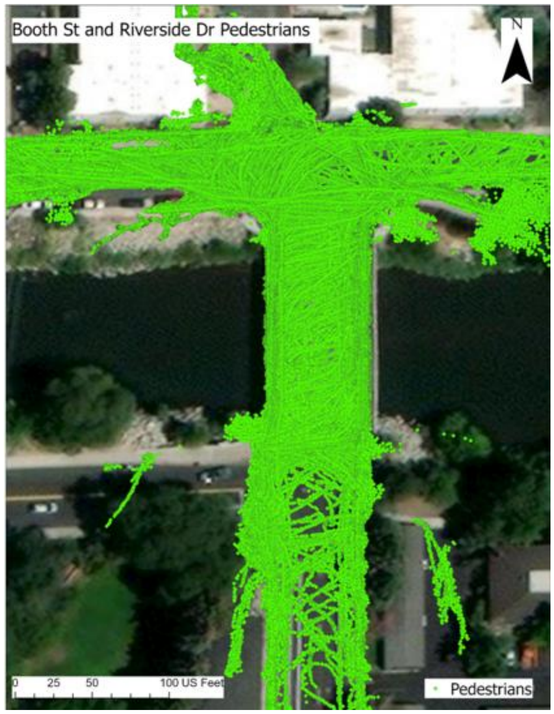

Figure 11 Pedestrian Movements for Site #2

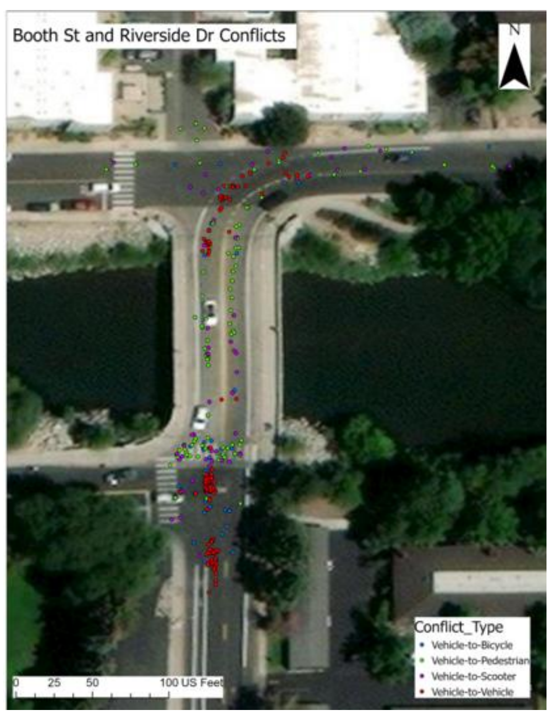

Figure 12 All Conflicts for Site #2

5.3 Site 3 – East 6th Street and University Way - Reno, NV

East 6th Street and University Way in Reno, NV, is an urban signalized intersection with pedestrian signals and has limited overhead streetlights. The area has a speed limit of 30 mph, with marked crosswalks at all the four legs of the intersection. All pertinent intersection characteristics are listed in Table 12. This intersection is located less than a half mile from commercial areas with drinking establishments and less than half a mile from a college. Figure 12 shows the aerial map of this intersection, and Table 13 lists the pedestrian conflict score calculated with the proposed model. This site observed 2900 pedestrians and 46 conflicts, and the compiled score was $18,460,878, which was the highest observed for all sites tested during this study because of risky behavior and the five days of testing. Figure 14 displays the observed pedestrian movements for the intersection and all observed conflict points are presented in Figure 15.

Table 12 Site #3 - Characteristics

East 6th St and University Wa	
5/4/2023-5/9/2023	
Time	5 Days - 120 Hours
Days of week	Thurs, Fri, Sat, Sun, Mon, Tues
Surrounding landuse	Residential/Vacant
Pedestrian generators within .5 mile	Commercial with Drinking Establicment
Type of Intersection	4 Way
Signalized	Yes
Singal type	Protected
Overhead Lights	Present
Pedestrian signals present	Yes
Crosswalk at legs	All 4 Legs

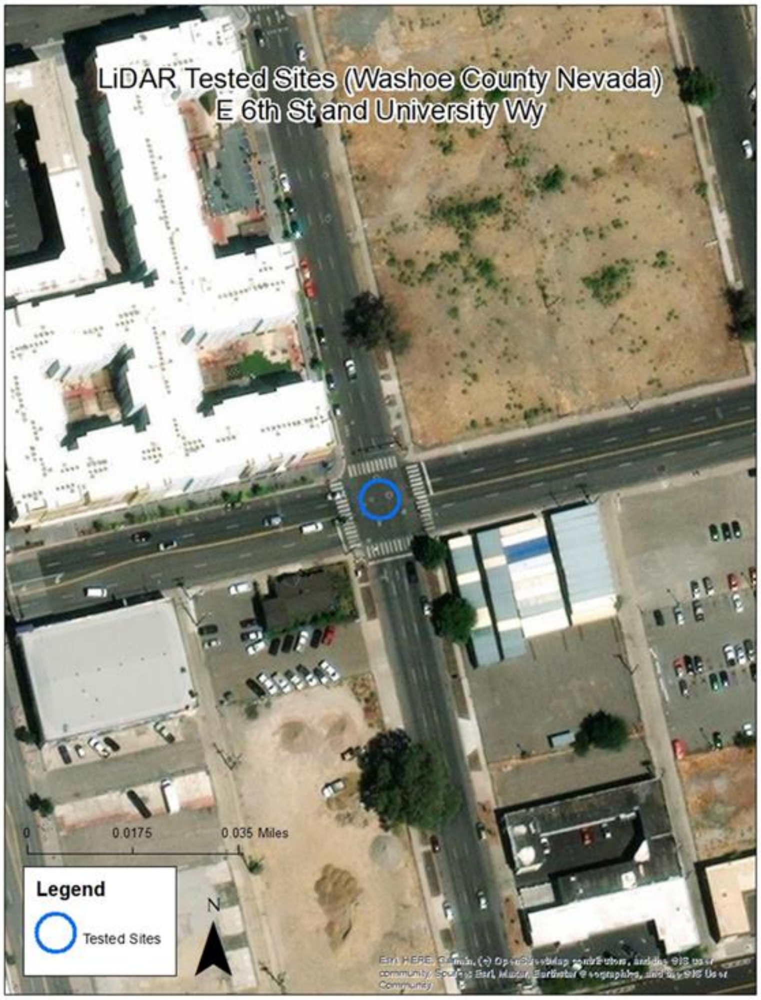

Figure 13 LiDAR Testing Site #3

Table 13 Site #3 Risk Score and Counts

Number of Near-misses	46
Total societal risk	$18,460,878
Total pedestrians	2900
Total number of vehicles observed	78,689

Figure 14 Pedestrian Movements for Site #3

Figure 15 All Conflicts for Site #3

5.4 Site 4 – Lakeside Drive and Berrum Lane - Reno, NV

Lakeside Drive and Berrum Lane in Reno, NV, is a dense suburban unsignalized intersection with no pedestrian signals and limited overhead streetlights. The area has a speed limit of 30 mph, with a 15-mph school zone, with marked crosswalks at one of the three legs of the intersection. All pertinent intersection characteristics are listed in Table 14. This intersection is located less than a half mile from commercial areas with drinking establishments and less than half a mile from a college. Figure 16 shows the aerial map of this intersection, and Table 15 lists the pedestrian conflict score calculated with the proposed model. This site observed 1609 pedestrians, and 4 conflicts, and the compiled score was $1,192,610, which was the average observed for all 12 sites tested during this study due to low speeds and geometry. Figure 17 displays the observed pedestrian movements for the intersection and all observed conflict points are presented in Figure 18.

Table 14 Site #4 Characteristics

Lakeside Dr @ Berrum Ln	
5/11/2023-5/13/2023	
Time	3 Days - 72 Hours
Days of week	Thurs, Fri, Sat
Surrounding landuse	Residential/Commercial
Pedestrian generators within .5 mile	Commercial, Education
Type of Intersection	3 Way
Signalized	No
Singal type	N/A
Overhead Lights	Present
Pedestrian signals present	No
Crosswalk at legs	2 of 3 legs

Figure 16 LiDAR Testing Site #4

Table 15 Site #4 Risk Score and Counts

Number of Near-misses	4
Total societal risk	$1,192,610
Total pedestrians	1609
Total number of vehicles observed	23,431

Figure 17 Pedestrian Movements for Site #4

Figure 18 All Conflicts for Site #4

5.5 Site 5 – North McCarran Boulevard and West 7th Street - Reno, NV

N McCarran Boulevard and W 7th Street in Reno, NV, is a commercial signalized intersection, with pedestrian signals and overhead streetlights. The area has speed limits of 50 and 35 mph, with marked crosswalks at all the 4 legs of the intersection. All pertinent intersection characteristics are listed in Table 16. This intersection is located less than a half mile from commercial areas with drinking establishments. Figure 19 shows the aerial map of this intersection, and Table 17 lists the pedestrian conflict score calculated with the proposed model. This site observed 792 pedestrians and 18 conflicts, and the compiled score was $4,600,345, which was above average observed for all 12 sites tested during this study due to high speeds and geometry. Figure 20 displays the observed pedestrian movements for the intersection and all observed conflict points are presented in Figure 21.

Table 16 Site #5 - Characteristics

N McCarran and W 7th St	
9/28/2023-9/30/2023	
Time	3 Days - 72 Hours
Days of week	Thurs, Fri, Sat
Surrounding landuse	Residential/Commercial
Pedestrian generators within .5 mile	Commercial, Drinking Establishments
Type of Intersection	4 way
Signalized	Yes
Singal type	Protected
Overhead Lights	Present
Pedestrian signals present	Yes
Crosswalk at legs	All Legs

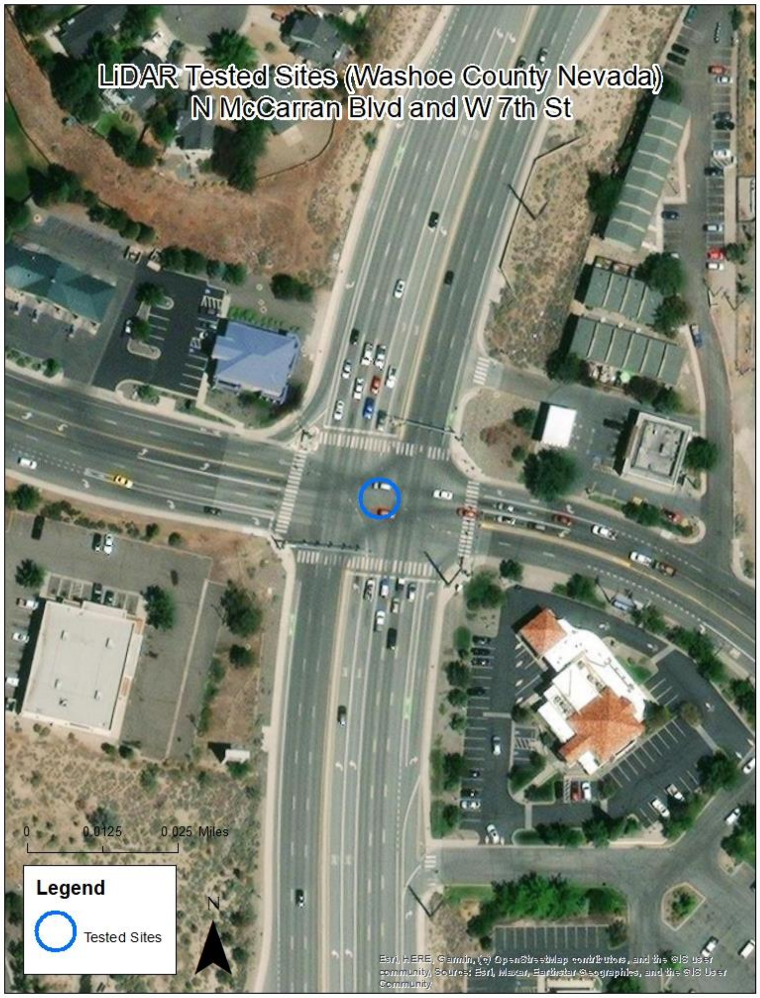

Figure 19 LiDAR Testing Site #5

Table 17 Site #5 Risk Score and Counts

Number of Near-misses	18
Total societal risk	$4,600,345
Total pedestrians	792
Total number of vehicles observed	110,817

Figure 20 Pedestrian Movements for Site #5

Figure 21 All Conflicts for Site #5

5.6 Site 6 – North Wells Avenue and East 9th Street - Reno, NV

N Wells Avenue and E 9th Street in Reno, NV is a commercial signalized intersection with pedestrian signals and overhead streetlights. The area has speed limits of 35 and 25 mph, with marked crosswalks at 2 of the 3 legs of the intersection. All pertinent intersection characteristics are listed in Table 18. This intersection is located less than a half mile from commercial areas with drinking establishments. Figure 22 shows the aerial map of this intersection, and Table 19 lists the pedestrian conflict score calculated with the proposed model. This site observed 186 pedestrians and 5 conflicts, and the compiled score was $8,942,516, which was above average observed for all 12 sites tested during this study due to high speeds and pedestrian usage. Figure 23 displays the observed pedestrian movements for the intersection and all observed conflict points are presented in Figure 24.

Table 18 Site #6 - Characteristics

N Wells @ E 9th St	
9/14/2023-9/16/2023	
Time	3 Days - 72 Hours
Days of week	Thurs, Fri, Sat
Surrounding landuse	Commercial/Education
Pedestrian generators within .5 mile	Commercial, Government, Education
Type of Intersection	3 way
Signalized	Yes
Singal type	Protected
Overhead Lights	Present
Pedestrian signals present	Yes
Crosswalk at legs	2 of 3 Legs

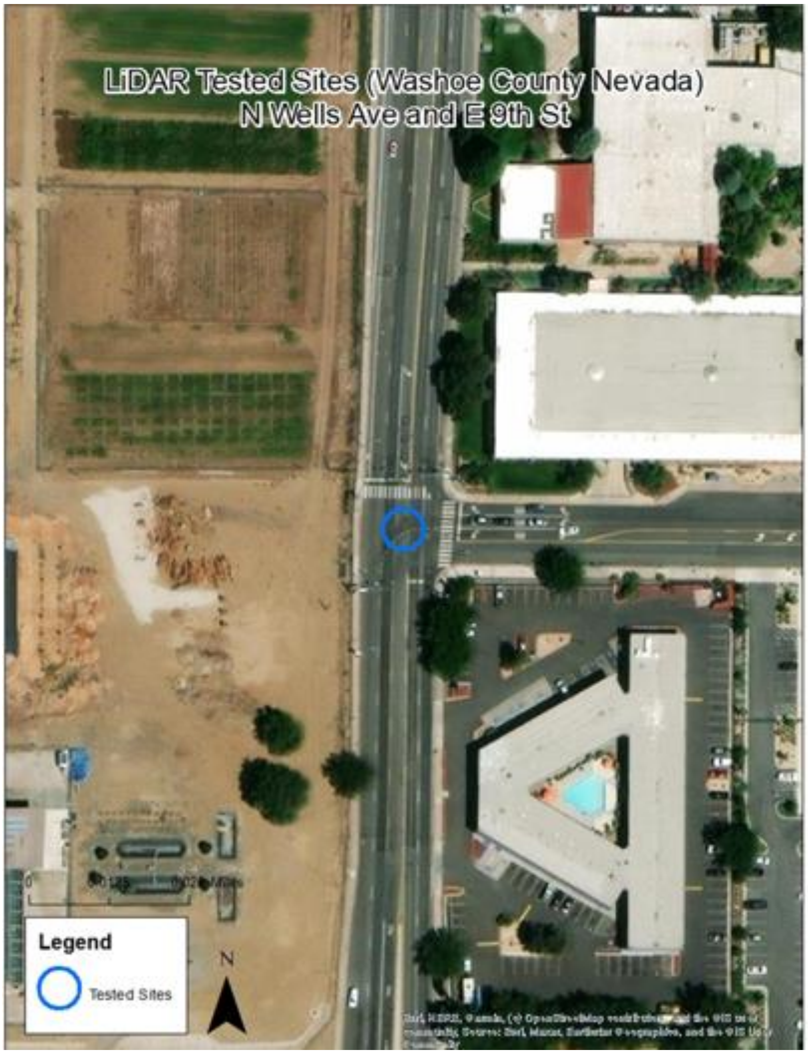

Figure 22 LiDAR Testing Site #6

Table 19 Site #6 Risk Score and Counts

Number of Near-misses	18
Total societal risk	$4,600,345
Total pedestrians	792
Total number of vehicles observed	54,553

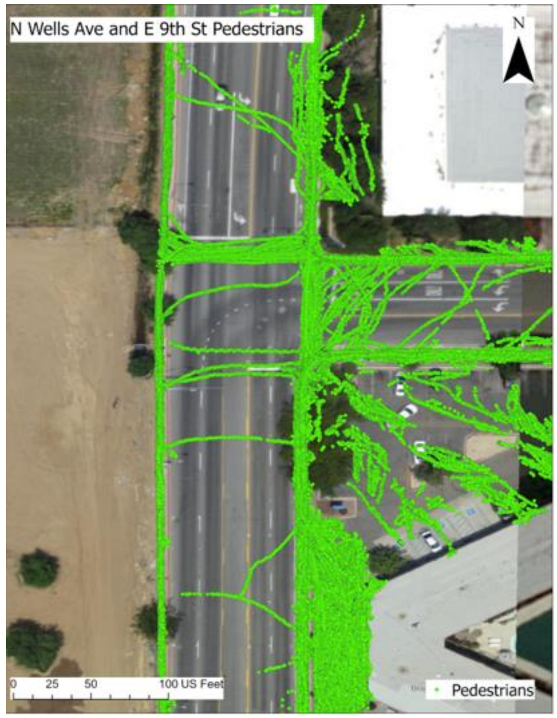

Figure 23 Pedestrian Movements for Site #6

Figure 24 All Conflicts for Site #6

5.7 Site 7 – North Wells Avenue and East 6th Street - Reno, NV

N Wells Ave and E 6th Street in Reno, NV is a commercial signalized intersection with pedestrian signals and overhead streetlights. The area has speed limits of 45 and 35 mph, with marked crosswalks at all 4 legs of the intersection. All pertinent intersection characteristics are listed in Table 20. This intersection is located less than a half mile from commercial areas with drinking establishments. Figure 25 shows the aerial map of this intersection, and Table 21 lists the pedestrian conflict score calculated with the proposed model. This site observed 1373 pedestrians, and 42 conflicts, and the compiled score was $13,732,142, which was the second highest observed for all 12 sites tested during this study due to high speeds, high volumes, pedestrian improper usage, and geometry. Figure 26 displays the observed pedestrian movements for the intersection and all observed conflict points are presented in Figure 27.

Table 20 Site #7 - Characteristics

N Wells @ E 9th St	
9/14/2023-9/16/2023	
Time	3 Days - 72 Hours
Days of week	Thurs, Fri, Sat
Surrounding landuse	Commercial
Pedestrian generators within .5 mile	Commercial, Drinking Establishments
Type of Intersection	4 Way
Signalized	Yes
Singal type	Protected
Overhead Lights	Present
Pedestrian signals present	Yes
Crosswalk at legs	All Legs

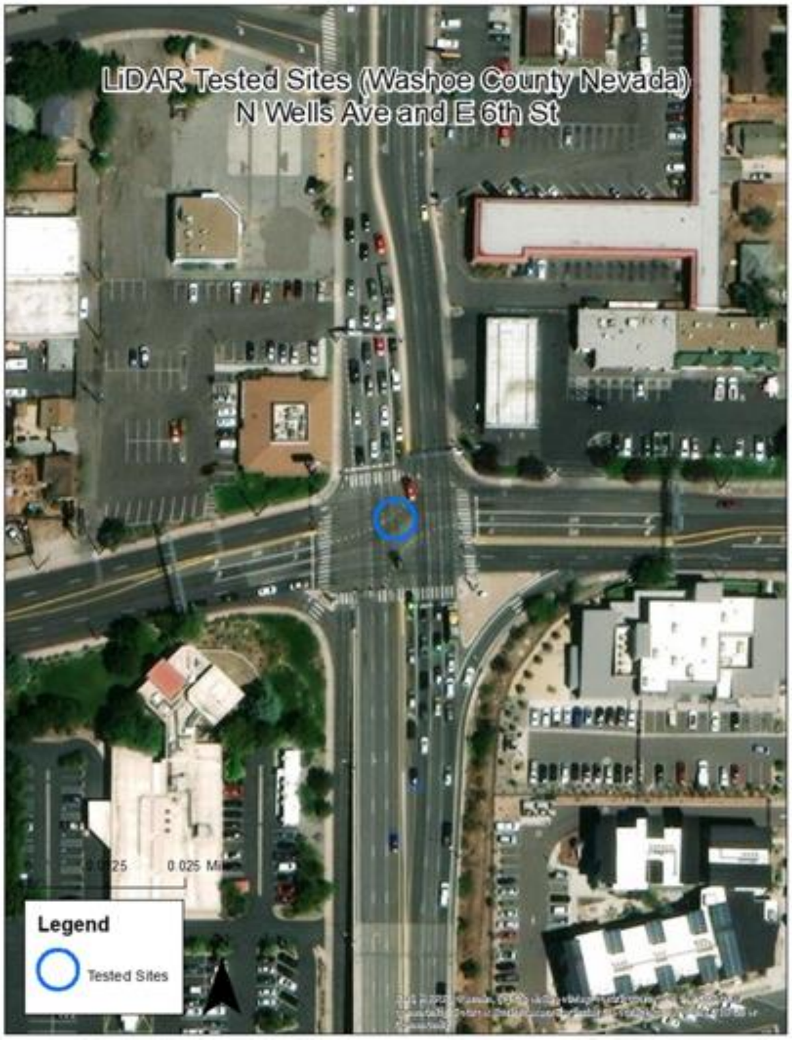

Figure 25 LiDAR Testing Site #7

Table 21 Site #7 Risk Score and Counts

Number of Near-misses	42
Total societal risk	$13,732,142
Total pedestrians	1373
Total number of vehicles observed	94,927

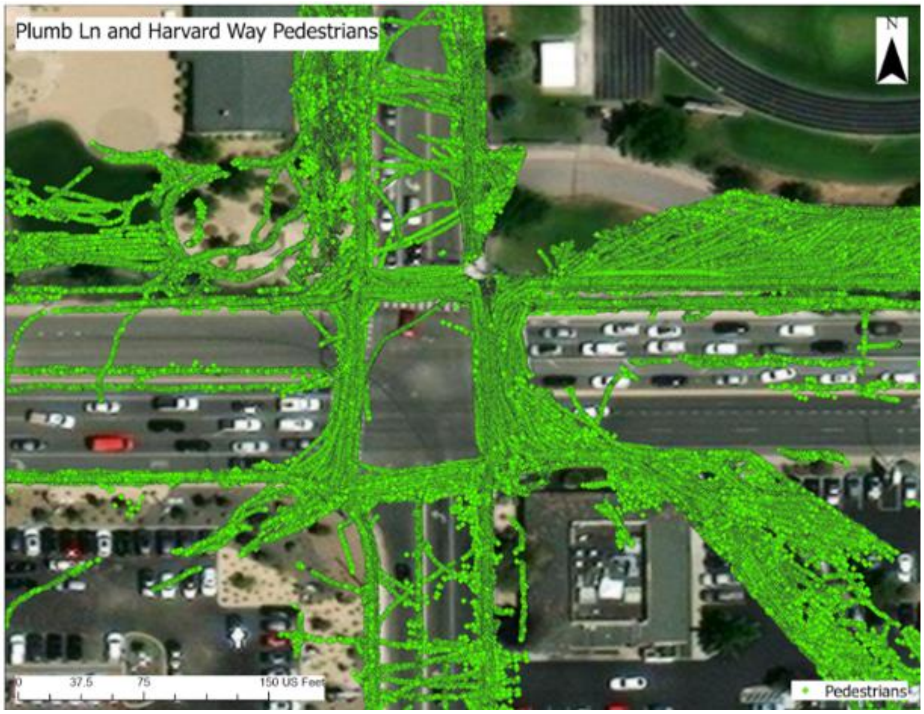

Figure 26 Pedestrian Movements for Site #7

Figure 27 All Conflicts for Site #7

5.8 Site 8 – Plumb Lane and Harvard Way - Reno, NV

Plumb Lane and Harvard Way in Reno, NV, is a commercial and education signalized intersection with pedestrian signals and overhead streetlights; the area has a speed limit of 30 and 25 mph, with marked crosswalks at all 4 legs of the intersection, all pertinent intersection characteristics are listed in Table 22. This intersection is located less than a half mile from commercial areas with drinking establishments. Figure 28 shows the aerial map of this intersection, and Table 23 lists the pedestrian conflict score calculated with the proposed model. This site observed 1373 pedestrians, and 42 conflicts, and the compiled score was $13,732,142, which was the second highest observed for all 12 sites tested during this study due to high speeds, high volumes, pedestrian improper usage, and geometry. Figure 29 displays the observed pedestrian movements for the intersection and all observed conflict points are presented in Figure 30.

Table 22 Site #8 - Characteristics

Plumb Ln @ Harvard Wy	
5/11/2023-5/13/2023	
Time	3 Days - 72 Hours
Days of week	Thurs, Fri, Sat
Surrounding landuse	Commercial and Education
Pedestrian generators within .5 mile	Commercial, Education
Type of Intersection	4 Way
Signalized	Yes
Singal type	Protected
Overhead Lights	Present
Pedestrian signals present	Yes
Crosswalk at legs	All Legs

Figure 28 LiDAR Testing Site #8

Table 23 Site #8 Risk Score and Counts

Number of Near-misses	24
Total societal risk	$7,216,108
Total pedestrians	2748
Total number of vehicles observed	130,336

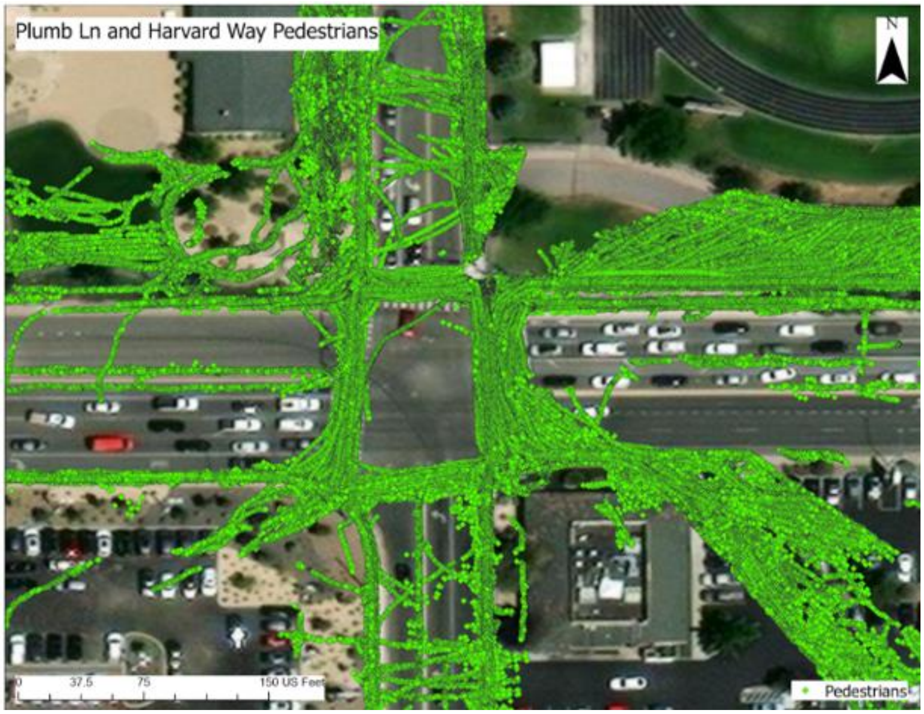

Figure 29 Pedestrian Movements for Site #8

Figure 30 All Conflicts for Site #8

5.9 Site 9 – South Virginia Street and Longley Lane/West Huffaker Lane - Reno, NV

South Virginia Street and Longley Lane/W Huffaker Lane in Reno, NV, is a commercial signalized intersection with pedestrian signals and overhead streetlights. The area has speed limits of 45 and 35 mph with marked crosswalks at all four legs of the intersection. All pertinent intersection characteristics are listed in Table 24. This intersection is located less than a half mile from commercial areas with drinking establishments. Figure 31 shows the aerial map of this intersection, and Table 25 lists the pedestrian conflict score calculated with the proposed model. This site observed 195 pedestrians and 4 conflicts, and the compiled score was $565,890, which was the second lowest observed for all 12 sites tested during this study due to high speeds and low pedestrian numbers. Figure 32 displays the observed pedestrian movements for the intersection and all observed conflict points are presented in Figure 33.

Table 24 Site #9 - Characteristics

S Virginia @ Longley	
9/28/2023-9/30/2023	
Time	3 Days - 72 Hours
Days of week	Thurs, Fri, Sat
Surrounding landuse	Commercial
Pedestrian generators within .5 mile	Commercial, Drinking Establishments
Type of Intersection	4 Way
Signalized	Yes
Singal type	Protected
Overhead Lights	Present
Pedestrian signals present	Yes
Crosswalk at legs	All 4

Figure 31 LiDAR Testing Site #9

Table 25 Site #9 Risk Score and Counts

Number of Near-misses	4
Total societal risk	$565,890
Total pedestrians	195
Total number of vehicles observed	100,502

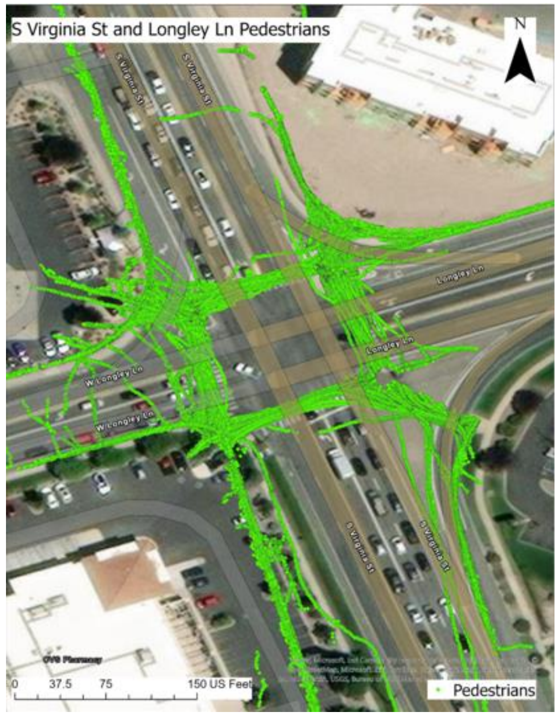

Figure 32 Pedestrian Movements for Site #9

Figure 33 All Conflicts for Site #9

5.10 Site 10 – South Virginia and Neil Road - Reno, NV

South Virginia Street and Neil Road in Reno, NV, is a commercial signalized intersection with pedestrian signals and overhead streetlights. The area has speed limits of 35 and 45 mph, with marked crosswalks at 3 of the 4 legs of the intersection. All pertinent intersection characteristics are listed in Table 26. This intersection is located less than a half mile from commercial areas with drinking establishments. Figure 34 shows the aerial map of this intersection, and Table 27 lists the pedestrian conflict score calculated with the proposed model. This site observed 583 pedestrians and 13 conflicts, and the compiled score was $2,809,637, which was about average observed for all 12 sites tested during this study due to high speeds, high volumes, pedestrian improper usage, and geometry. Figure 35 displays the observed pedestrian movements for the intersection and all observed conflict points are presented in Figure 36.

Table 26 Site #10 - Characteristics

S Virginia @ Neil Rd	
9/28/2023-9/30/2023	
Time	3 Days - 72 Hours
Days of week	Thurs, Fri, Sat
Surrounding landuse	Commercial
Pedestrian generators within .5 mile	Commercial, Drinking Establishments
Type of Intersection	4 Way
Signalized	Yes
Singal type	Protected
Overhead Lights	Present
Pedestrian signals present	Yes
Crosswalk at legs	3 of 4 Legs

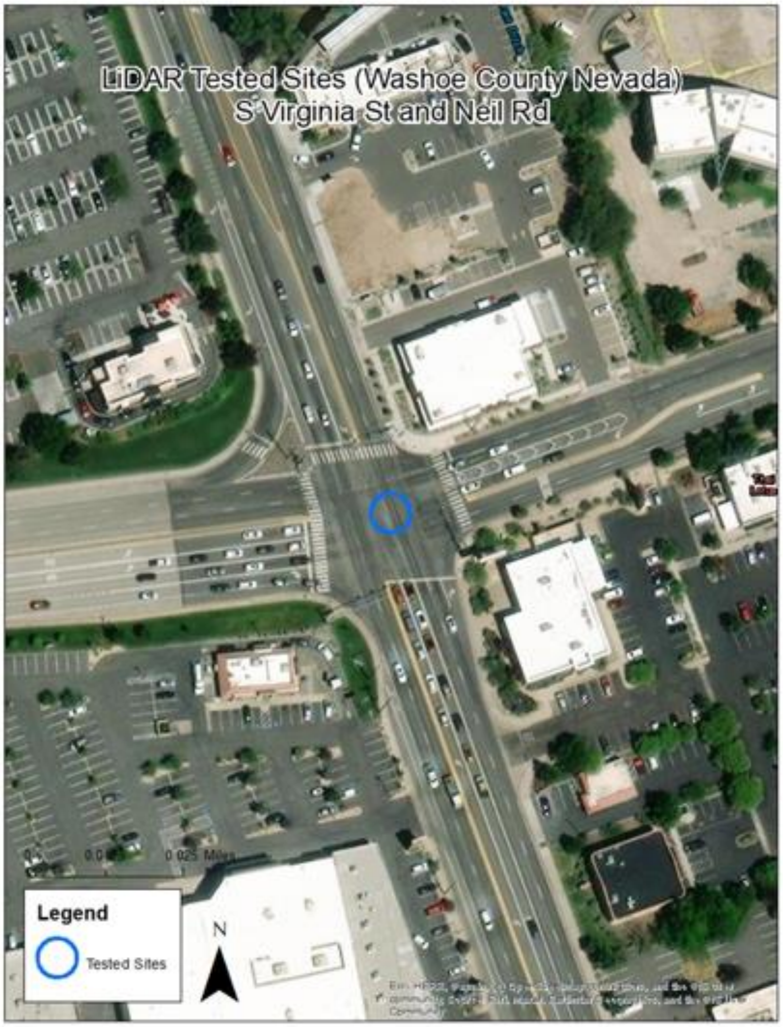

Figure 34 LiDAR Testing Site #10

Table 27 Site #10 Risk Score and Counts

Number of Near-misses	13
Total societal risk	$2,809,637
Total pedestrians	583
Total number of vehicles observed	113,684

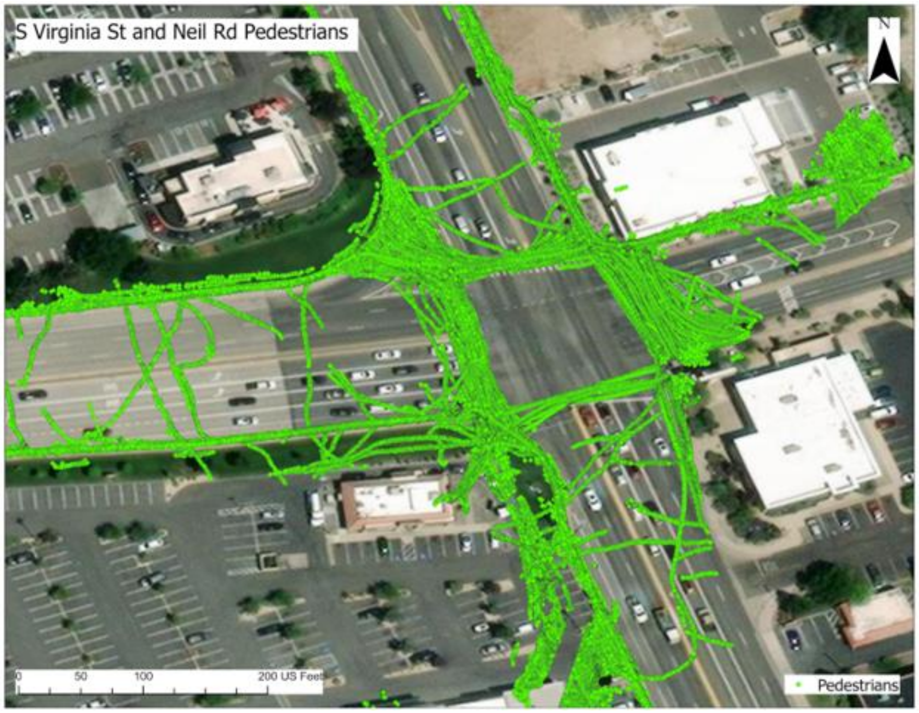

Figure 35 Pedestrian Movements for Site #10

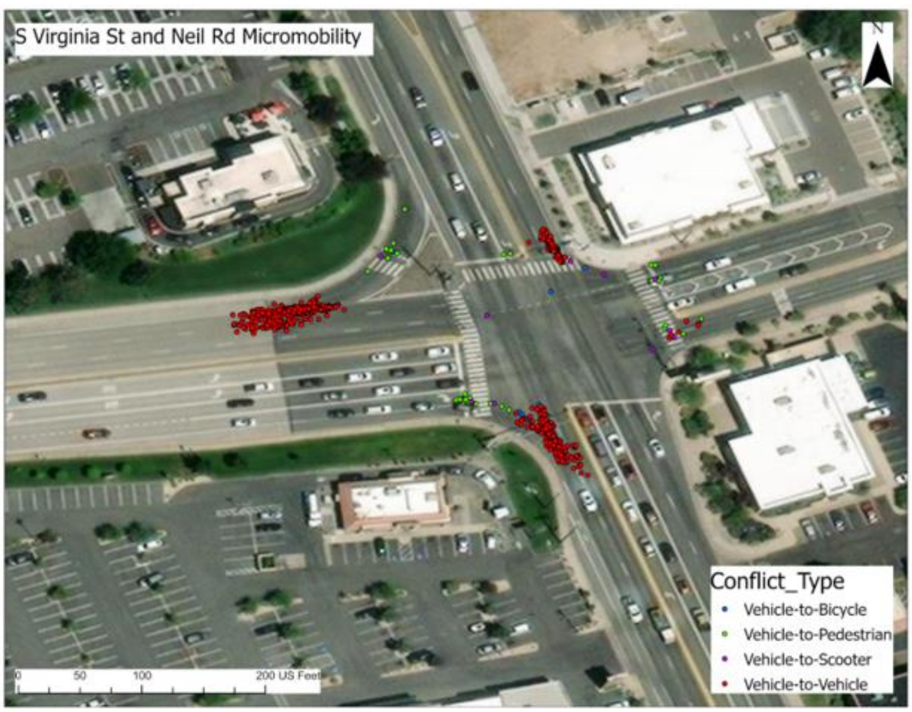

Figure 36 All Conflicts for Site #10

5.11 Site 11 – Sierra Highlands and W 7th Street - Reno, NV

Sierra Highlands and W 7th Street in Reno, NV is a dense residential unsignalized intersection, with no pedestrian signals, and does not have overhead streetlights, the area has a speed limit of 35 mph, with marked crosswalks at 2 of the 4 legs of the intersection, all pertinent intersection characteristics are listed in Table 28. This intersection is located less than a half mile from commercial areas with drinking establishments. Figure 37 shows the aerial map of this intersection, and Table 29 lists the pedestrian conflict score calculated with the proposed model. This site observed 293 pedestrians and 5 conflicts, and the compiled score was $496,948, which is the lowest of all observed for all 12 sites tested during this study due to low speeds and low pedestrian volumes. Figure 38 displays the observed pedestrian movements for the intersection and all observed conflict points are presented in Figure 39.

Table 28 Site #11 - Characteristics

Sierra Highlands Dr @ W 7th St	
9/28/2023-9/30/2023	
Time	3 Days - 72 Hours
Days of week	Thurs, Fri, Sat
Surrounding landuse	Residential and Commerical
Pedestrian generators within .5 mile	Commercial, Drinking Establishments
Type of Intersection	4 Way
Signalized	No
Singal type	N/A
Overhead Lights	No
Pedestrian signals present	No
Crosswalk at legs	2 of 4 Legs

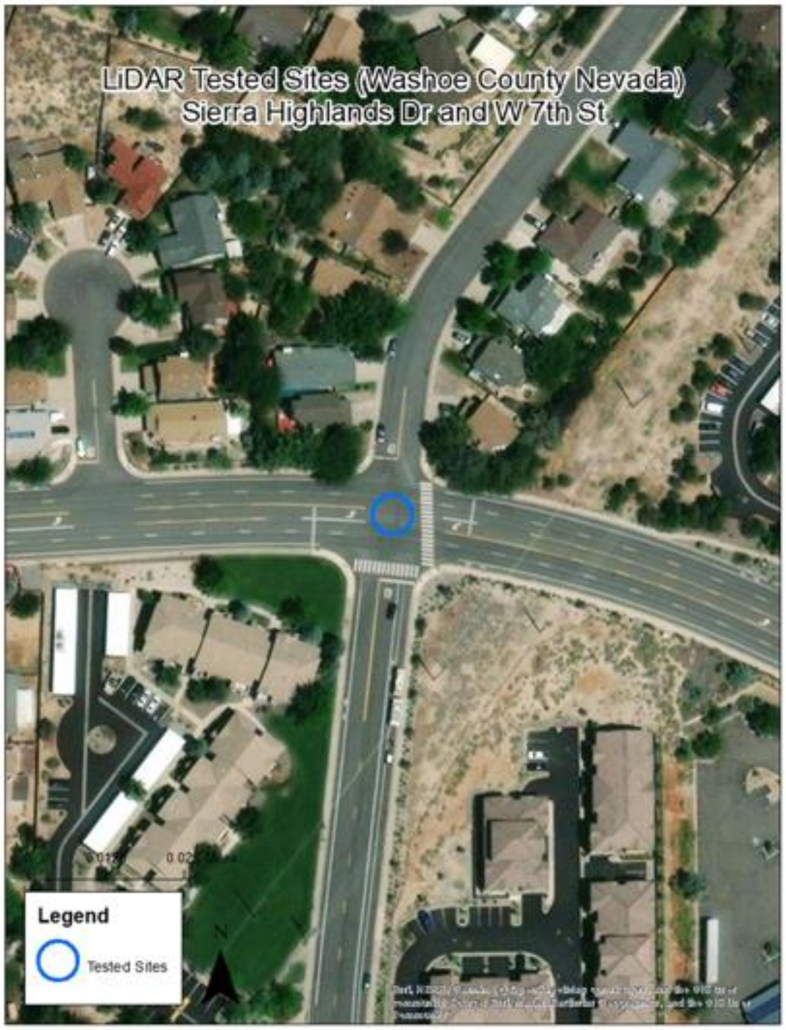

Figure 37 LiDAR Testing Site #11

Table 29 Site #11 Risk Score and Counts

Number of Near-misses	5
Total societal risk	$496,948
Total pedestrians	293
Total number of vehicles observed	33,060

Figure 38 Pedestrian Movements for Site #11

Figure 39 All Conflicts for Site #11

5.12 Site 12 – Vista Blvd and Whitewood Dr/Geno Martini Pkwy - Sparks, NV

Vista Blvd and Whitewood Dr/Geno Martini Pkwy in Sparks, NV is a suburban and education signalized intersection, with pedestrian signals and overhead streetlights, the area has a speed limit of 40 and 25 mph, with a school zone of 25 mph, with marked crosswalks at all four legs of the intersection, all pertinent intersection characteristics are listed in Table 30. This intersection is located less than a half mile from commercial areas with drinking establishments. Figure 40 shows the aerial map of this intersection, and Table 31 lists the pedestrian conflict score calculated with the proposed model. This site observed 532 pedestrians, and 6 conflicts, and the compiled score was $4,956,624, which was the 5th highest observed for all 12 sites tested during this study due to high speeds and volumes of vehicles and pedestrians. Figure 41 displays the observed pedestrian movements for the intersection and all observed conflict points are presented in Figure 42.

Table 30 Site #12 - Characteristics

Vista Blvd @ Whitewood Dr 5/11/2023-5/13/2023	
Time	3 Days - 72 Hours
Days of week	Thurs, Fri, Sat
Surrounding landuse	Residential and Educatoin
Pedestrian generators within .5 mile	Commercial, Education
Type of Intersection	4 Way
Signalized	Yes
Singal type	Protected
Overhead Lights	Yes
Pedestrian signals present	Yes
Crosswalk at legs	All 4 legs

Figure 40 LiDAR Testing Site #12

Table 31 Site #12 Risk Score and Counts

Number of Near-misses	6
Total societal risk	$4,956,624
Total pedestrians	532
Total number of vehicles observed	100,022

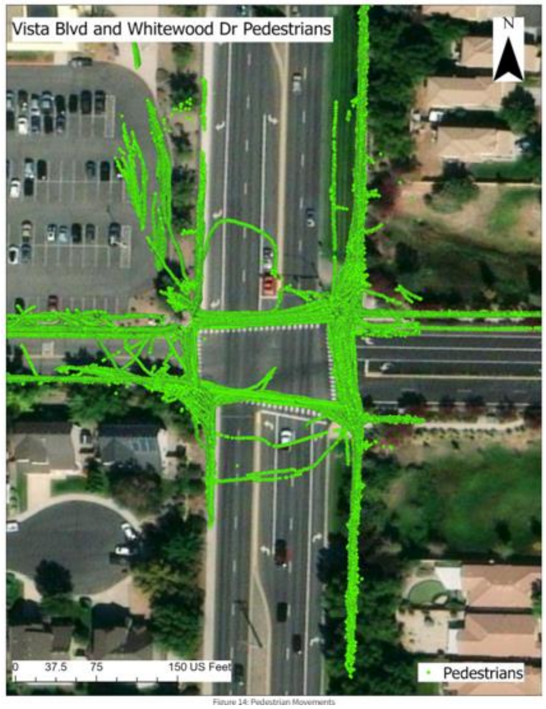

Figure 41 Pedestrian Movements for Site #12

Figure 42 All Conflicts for Site #12

Table 32 Scoring Method Results Compared to Observed Crashes

Intersections	Site Number	Near Misses	Societal Risk	Total Ped Counts	Societal Risk/ Pedestrian	Hours	Societal Risk per Hour	Pedestrian-Vehicle Crashes	Pedestrian-Fatal Crashes	Total All Crashes	All Fatal Crashes	Vehicle Counts
E 6th St and University Wy	3	46	$18,460,878.21	2900	$6,365.82	120	$153,840.65	1	0	89	0	78,689
N Wells Ave and E 6th St	7	42	$13,732,142.11	1373	$10,001.56	72	$190,724.20	3	1	87	2	94,927
N Wells Ave and E 9th St	6	5	$8,942,515.71	186	$48,078.04	72	$124,201.61	0	0	31	0	54,553
Plumb Ln and Harvard Wy	8	24	$7,216,107.86	2748	$2,625.95	72	$100,223.72	2	1	106	1	130,336
Vista Blvd and Whitewood	12	6	$4,956,623.82	532	$9,316.96	72	$68,842.00	0	0	25	0	100,022
N McCarran Blvd and W 7th St	5	18	$4,600,345.35	792	$5,808.52	72	$63,893.69	1	0	108	0	110,817
S Virginia and Neil Rd	10	13	$2,809,637.30	583	$4,819.27	72	$39,022.74	0	0	65	0	113,684
Lakeside Dr and Berrum Ln	4	4	$1,192,610.49	1609	$741.21	72	$16,564.03	0	0	10	0	23,431
Booth St and Riverside Dr	2	6	$991,377.01	3389	$292.53	72	$13,769.13	2	0	19	0	23,458
Barring Blvd and Goldy Wy	1	3	$791,854.67	261	$3,033.93	72	$10,997.98	2	0	37	1	51,333
S Virginia and Longley	9	4	$565,889.87	195	$2,902.00	72	$7,859.58	0	0	36	0	100,502
Sierra Highlands Dr and W 7th St	11	5	$496,947.77	293	$1,696.07	72	$6,902.05	1	0	31	0	33,060

Top 1-2
Top 3-4
Top 5-6

6 Conclusions and Recommendations

The proposed method, involving LiDAR technology, offers significant benefits for traffic safety and urban planning due to its proactive and comprehensive nature. Unlike traditional methods that depend on the analysis of historical crash data—which must be collected, processed, and quality-checked—the proposed method provides real-time, accurate 3D mapping of roads and their surroundings. This enables engineers and planners to quickly identify and rectify hazardous roadway features, such as inadequate curvatures or obscured signage, before they contribute to crashes, thereby enhancing road safety preemptively.

Additionally, the proposed method excels in analyzing dynamic patterns, including pedestrian movements, across various times and areas. This capability allows for infrastructure design adjustments to better suit road users' actual behavioral patterns rather than relying on less dynamic or outdated models. For instance, planners can modify pedestrian pathways or traffic signals to better accommodate local behaviors observed via the proposed method's scanning, such as common paths taken by pedestrians or typical illegal driving maneuvers.

An important advantage of the proposed method is its objectivity and inclusivity in data collection. It is "blind" to characteristics such as color, age, or any other personal defining features, focusing solely on the geometry and movement within its range. This ensures that the data gathered is purely based on the environmental and behavioral elements necessary for safety analyses, without any bias related to visual identifiers. This aspect is particularly crucial in creating fair and effective traffic safety measures and urban designs that address the needs of all users equally.

Overall, by incorporating the proposed method into urban and traffic planning efforts, municipalities and safety organizations cannot only react more quickly to potential hazards but also gain a deeper understanding of the environmental and behavioral factors that influence roadway safety. This proactive and inclusive approach significantly enhances the effectiveness of safety interventions and promotes a safer urban environment for everyone.

Nonetheless, there is room for further development and refinement within the system's methodology. The implementation of a standardized definition for near-miss incidents, particularly with a specific focus on temporal thresholds, highlights an area ripe for additional research. The 2.5-second threshold defined in this dissertation could be redefined to a different number, or this number could be accepted. Exploring the potential to expand this timeframe could enhance the system's relevance across various situations. Introducing an adaptable timing curve aligned with the selected temporal parameters may allow for a more detailed assessment of pedestrian risks under different traffic conditions.

The rapid advancement of detection technologies also calls for a reassessment of variables such as the age of pedestrians and the size of vehicles in risk analyses. Acknowledging the unique risks faced by vulnerable groups like older adults and children, incorporating more detailed age or height data could sharpen the accuracy of safety evaluations. Moreover, factoring in vehicle size and design features that focus on pedestrian safety may refine the system's predictive capabilities regarding collision risks. Investigating the potential of high-accuracy all-traffic trajectory data to classify vehicle types and integrate this information into the model could significantly augment the analysis.

Adopting a precise definition of a "near-miss" could significantly fortify the proposed scoring system for pedestrian safety by providing a clearer framework for identifying and analyzing incidents that have the potential to escalate into serious crashes. By delineating what constitutes a near-miss through specific temporal and spatial parameters, the model can incorporate a more nuanced understanding of the risk factors and conditions that lead to close calls between pedestrians and vehicles. This refinement allows for including a broader spectrum of data points, capturing incidents that may not result in collisions but still indicate significant safety risks. Furthermore, a standardized near-miss definition facilitates the consistent collection and comparison of data across different settings, enhancing the model's reliability and validity.

Incorporating a more precise definition of a "near-miss" into the analysis would significantly enhance the model by creating a widely accepted risk equation. This equation would quantify the relationship between near-miss incidents and the likelihood of actual crashes, thereby strengthening the model's predictive accuracy. A clear and universally recognized definition of a near-miss would standardize the criteria for a close call, allowing for the aggregation and comparison of data across various environments and studies. Standardization is crucial for developing a robust equation that accurately reflects the continuum of risk from near-misses to actual collisions.

Despite these opportunities for improvement, the mathematical basis of the proposed scoring system stands as a robust and practical instrument for pinpointing pedestrian safety hazards. Its current iteration offers a valuable and immediately applicable solution to bolster pedestrian protection. As the field of transportation safety advances, propelled by technological progress and a deeper understanding of human behavior, the continual refinement of this system will be crucial. Anticipated future enhancements, rooted in empirical research and technological breakthroughs, are expected to further improve the efficacy of pedestrian safety evaluations, thereby making urban spaces safer for everyone.

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