Systemic and Systematic Countermeasures for Vulnerable Road User Safety: A Review

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Table of Contents

Abstract

Pedestrian safety is a critical concern in urban environments, where roadway and infrastructure design often places vulnerable road users at risk of injury when interacting with vehicles. Adopting both systemic and systematic safety approaches is crucial to mitigate these risks and protect all road users. The word "systemic" means "of, or relating to, a system" as a whole (MasterClass, 2021). A systemic approach to traffic safety would involve analyzing data to identify common risk patterns and underlying factors across the transportation network. The word "systematic" means "having, showing, or involving a system or plan" (MasterClass, 2021). A systematic approach to traffic safety might involve the development and implementation of a plan to address collisions on the roadway network. Prioritizing high-crash locations for improvements would be one systematic approach, but to address the root causes of crashes, the risks identified in those locations would be used to examine the system as a whole. This could lead to a different systematic application of low-cost, proven safety countermeasures across the transportation network based on factors like roadway characteristics and land uses, so that the systemic risks can be addressed. This document reviews existing frameworks and case studies that embody both systemic and systematic methods to improve pedestrian and bicyclist safety. This review emphasizes the importance of collecting and analyzing crash data, identifying systemic practices, and developing an implementation framework that highlights implementation challenges and recommendations. Understanding systemic safety and developing systematic evidence-based practices could enhance the design, operation, and management of transportation systems to better accommodate pedestrians and bicyclists.

Introduction

In recent years, the safety of vulnerable road users, including pedestrians and bicyclists, has emerged as a significant global concern. The heightened attention focused on this issue is spurred in part by a growing emphasis on sustainable transport, which promotes walking and cycling as eco-friendly alternatives to traditional vehicular commuting. The rise in active transportation has been accompanied by a surge in traffic crashes involving pedestrians and bicyclists. Factors such as a concurrent increase in vehicular traffic volumes, higher speeds, and the prevalence of larger and heavier vehicles have also significantly contributed to this trend. This report explores this complex issue and reviews the systematic and systemic practices of safety countermeasures for these vulnerable road users. The overarching goal is to offer planners, policymakers, engineers, and researchers guidance to assist them in creating environments where pedestrian and bicyclist fatalities and serious injuries are prevented.

In 2020, the United States experienced a notable increase in traffic-related fatalities among bicyclists and pedestrians, indicating an accelerating trend. Nationally, there were 948 fatal crashes involving bicyclists in 2020 and 976 in 2021, making up 2.4 percent of all traffic fatalities. This marked a 9 percent increase from 2019 (NCSA, 2022). In 2022, 1,105 bicyclists were killed in motor-vehicle traffic crashes, a 13% increase from 2021. In New Jersey, 26 bicyclists were killed in 2021 due to traffic crashes, 15 in 2022, and 23 in 2023 (NJDHTS, 2025). In 2020, 6,516 pedestrians lost their lives in traffic crashes across the country, accounting for 17 percent of all traffic fatalities (IIS-HLDI, 2023). This was a 3.9 percent increase from 2019 (NHTSA, 2022). In 2021, pedestrian involved traffic deaths exceeded 7,000. In New Jersey, 176 pedestrians were killed in 2019 due to traffic crashes, whereas 237 died in 2021 (NJSP, 2021). These numbers underscore the urgent need for comprehensive safety strategies to safeguard pedestrians and bicyclists on our roadways.

In recognition of this issue's importance, transportation agencies have been implementing broad strategies that can be categorized into two types: systemic and systematic. Each strategy contributes to safety uniquely. Though different in their focus, both approaches are crucial in developing comprehensive safety strategies.

Linguistically, "systemic" encapsulates a comprehensive, holistic perspective that aims to unravel the intricate network of interconnected factors contributing to safety concerns within a broader system. It delves into the underlying, pervasive issues that transcend specific locations, aiming to identify recurrent trends, commonalities, and inherent deficiencies responsible for safety challenges. This method recognizes that individual crashes or safety incidents are often symptomatic of broader, interconnected problems. It involves identifying common patterns and trends within the safety data rather than focusing on specific locations or incidents. A systemic approach is generally proactive and preventative in nature. According to the NCHRP 893 report (Thomas et al., 2018):

"A systemic approach is a data-driven, network-wide (or system-level) approach to identifying and treating high-risk roadway features correlated with specific or severe crash types. Systemic approaches seek not only to address locations with prior crash occurrence, but also those locations with similar roadway or environmental crash risk characteristics."

Crucially, a systemic approach recognizes that the presence of high-risk roadway features suggests that future roadway fatalities are likely even if no fatal crashes have occurred historically at a specific location. A systemic analysis would identify those roadway features as a contributing factor to crashes in other locations and acknowledge that those features are no less risky for road users in other locations.

The term "systematic," linguistically, denotes a methodical approach. A systematic approach follows a plan. Once risks are determined across a system, they can be addressed systematically with low-cost countermeasures—for example, rumble strips, enhanced signage, or improved lane markings—deployed uniformly on roadways that meet established criteria. By integrating safety enhancements into routine maintenance and infrastructure improvements, a systematic approach can be applied to prevent crashes before they occur, contributing to overall roadway safety.

Both systemic and systematic approaches rely on data. The systemic approach requires comprehensive data analysis to identify common risk factors and make data-driven decisions at the network level. The systematic approach can use data to create policies for identifying predefined criteria for the widespread application of proven safety countermeasures. Thus, data collection, analysis, and sharing are critical for the success of any pedestrian and bicyclist safety program.

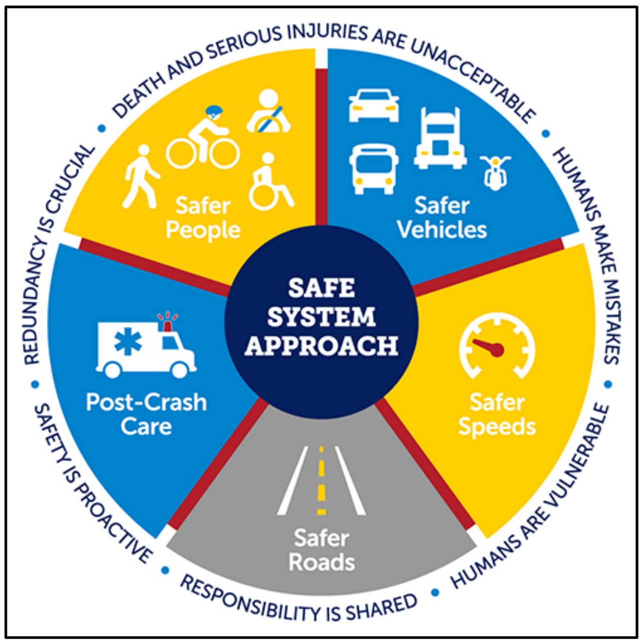

Figure 1 Safe System Approach (USDOT, 2022)

Considering the critical importance of data-driven decision-making in pedestrian and bicyclist safety, the Safe System Approach (SSA) offers a comprehensive framework that integrates these principles. Both systemic and systematic approaches to safety intersect with the SSA. As the U.S. Department of Transportation (USDOT) outlines, the SSA is built on the principle that human error is inevitable. Therefore, it focuses on designing and implementing solutions that anticipate and mitigate these errors, reducing their consequences. For instance, while a protected bike lane may not prevent the driver of a motor vehicle from leaving their lane, it significantly lowers the risk of a collision with a bicyclist. The SSA is a holistic framework that aims to eliminate traffic-related fatalities and severe injuries by creating roadway environments that are not only forgiving for motorists, but vulnerable road users as well. To this end, it seeks five key objectives that align closely with both systemic and systematic safety countermeasures:

- Safer People
- Safer Speeds
- Safer Roads
- Safer Vehicles
- Post-Crash Care

By focusing on pedestrian and bicyclist safety and integrating the Safe System Approach, traffic crashes, and their sometimes-fatal consequences, become preventable. This holistic perspective reinforces the significance of collecting, analyzing, and sharing data to inform safety strategies.

The available literature offers no comprehensive documentation that consolidates the installation practices of existing and emerging safety countermeasures. This report aims to bridge this gap by offering a detailed exploration of these strategies, thereby serving as a valuable resource for stakeholders tasked with tackling the multifaceted challenges of pedestrian and bicyclist safety. This report should empower policymakers, engineers, and researchers to make informed decisions and take practical actions to enhance the well-being of vulnerable road users and achieve the desired outcomes in their respective communities.

Section 2 of this report reviews the existing frameworks for systemic and systematic safety approaches. In Section 3, the study team highlights the importance of data collection and common data analysis methods found in the literature. Section 4 explores real-world case studies of safety measures on the system level that target improving safety for vulnerable road users. Lastly, Section 5 provides several takeaways and recommendations for implementation and evaluation for transportation safety planners, engineers, and policymakers.

Existing Frameworks for Systemic and Systematic Safety

In enhancing pedestrian and bicyclist safety, it is imperative to leverage contemporary resources, methodologies, and tools that allow for systemic safety analysis, project selection, and targeted interventions. This section delves into the advanced frameworks and tools available to transportation professionals and safety practitioners. These resources, designed to support data-driven decision-making, encompass a variety of solutions that range from project selection to safety assessment indices. As pedestrian and bicyclist safety remains a key priority in urban planning and road safety management, a comprehensive understanding of these existing tools is vital for developing effective strategies and ensuring safer streets. This section explores current tools, each with unique utility, in the context of safety enhancement for pedestrians and bicyclists. A summary table is included to facilitate a quick comparison and better understanding of these tools and help professionals make informed decisions in selecting the most appropriate tool or tools for their objectives and scenarios.

Safe System Roadway Design Hierarchy: Engineering and Infrastructure-related Countermeasures to Effectively Reduce Roadway Fatalities and Serious Injuries (Hopwood et al., 2024)

The Safe System Roadway Design Hierarchy is an engineering- and infrastructure-based tool designed to align with the SSA to eliminate traffic-related fatalities and serious injuries. This hierarchy assists transportation agencies and practitioners in identifying and prioritizing countermeasures and strategies when developing transportation projects. This tool aims to foster a greater understanding and increase application of SSA principles, ensuring that transportation projects address safety concerns.

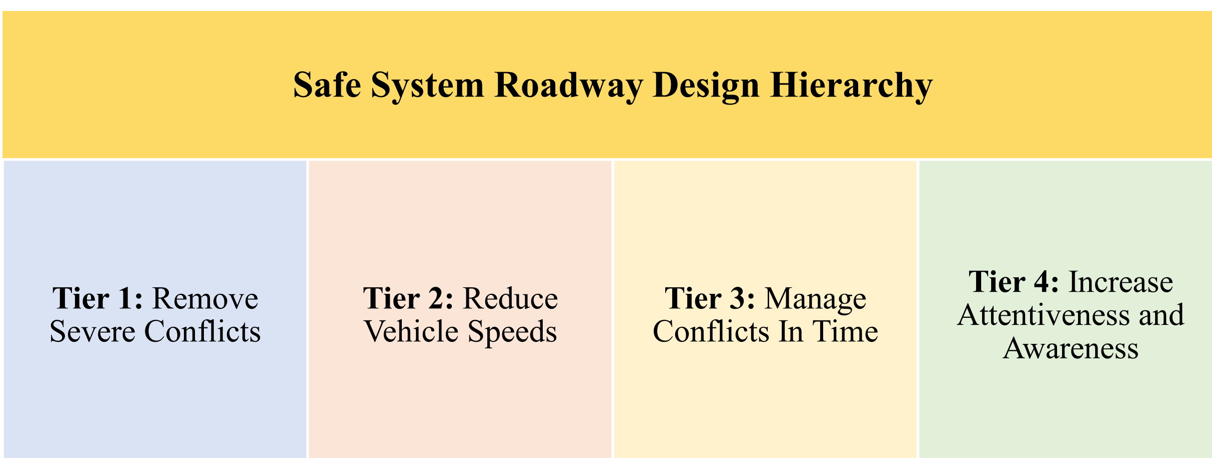

Figure 2: Safe System Roadway Design Hierarchy Process. Source: Hopwood et al., 2024.

The hierarchy consists of four tiers, each representing strategies that range from most to least aligned with SSA principles. Tiers 1 through 3 focus on removing potential roadway conflicts and separating vulnerable road users from motor vehicles to reduce the kinetic energy of a potential crash. Tier 4 provides critical information to road users to encourage safe decision-making. Agencies should begin with Tier 1 strategies, which involve physical changes to the roadway, and consider subsequent tiers if initial strategies are not feasible. The tool prioritizes physical changes to the built environment over attempts to make individual behavioral adjustments, emphasizing the importance of infrastructure solutions in enhancing safety.

Crucially, systemic tools assert that making physical changes to the roadway is more effective at changing behavior. According to FHWA, well-designed geometric features like medians and roundabouts reduces the number of individual judgments a road user must make to proceed along the route (FHWA, 2018). Furthermore, features such as tighter turning radii and narrower lanes reduce driver speeds as they proceed along the road and approach turns at intersections, which reduces necessary reaction times and stopping distances (FHWA, 2020).

The Safe System Road Design Hierarchy tool is a project-based, site assessment tool applicable to various roadway contexts, classifications, locations, and users. For instance, interstate freeways and city streets will reasonably apply different SSA-aligned countermeasures to address existing safety issues. Agencies could prioritize Tier 1 strategies, such as physical separation, to eliminate severe conflicts. If these are not feasible, they may move to lower tiers, implementing measures like traffic calming elements to reduce vehicle speeds (Tier 2), traffic control devices to separate users in time (Tier 3), and visibility enhancements to increase awareness (Tier 4).

Furthermore, countermeasures are often best applied in conjunction with one another. For example, a Pedestrian Hybrid Beacon can manage conflicts in time (Tier 3), increase attentiveness (Tier 4), and reduce vehicle speeds when combined with a raised crosswalk (Tier 2).

The Safe System Roadway Design Hierarchy emphasizes protecting vulnerable road users. For instance, Tier 1 strategies include physically separating motorized and non-motorized users, which helps to eliminate conflicts. In addition, Tier 2 strategies focus on reducing vehicle speeds through design features like raised crosswalks and smaller turn radii, further protecting non-motorized users by decreasing the kinetic energy involved in potential crashes.

The United States Road Assessment Program (usRAP) developed by the AAA Foundation for Traffic Safety (usRAP, 2023)

The United States Road Assessment Program (usRAP) is a tool developed by the AAA Foundation for Traffic Safety. It is a collaborative partnership involving government and non-government traffic safety entities (Harwood et al., 2008). The main objectives of usRAP are:

1. **Encouraging safety decisions**: usRAP promotes the use of risk assessment in the management of road networks, enabling safety-focused decision-making.
2. **Road inspection and ranking**: The program inspects roads and assigns rankings to facilitate safety investment planning, which helps prioritize resources and identify areas requiring improvements based on potential safety benefits and cost-effectiveness.
3. **Support for technical capacity building**: usRAP provides support for the development and maintenance of national, state, and local capabilities in road safety, fostering expertise and knowledge sharing.
4. **Road safety performance tracking**: The program tracks road safety performance to allow funding agencies to assess the effectiveness and benefits of their investments.

The rating system employed by usRAP offers an alternative to crash history data and aims to assess the risk of fatal and serious injury crashes for road users based on roadway infrastructure characteristics, including speed limit, average daily traffic (vehicle/ day), road type (interstate/freeway, multilane divided, multilane undivided, and two-lane undivided), road length (segment length), road system (interstate, US highway, state highway, and local road), and area type (urban and rural roads). usRAP is a user-friendly, data-driven planning tool for agencies that do not have access to the robust crash data needed for traditional safety assessment tools. Instead, it utilizes video recordings along with free software to produce a comprehensive and data-supported manual to implement based on local assessments, requirements, and preferences. The program is built upon the models of EuroRAP and AusRAP from Europe and Australia, respectively. The primary objectives of usRAP include:

- **Reducing death and serious injuries**: usRAP employs systematic risk assessment to identify significant safety deficiencies that can be addressed through practical road improvement measures, ultimately reducing fatalities and serious injuries on U.S. roads.
- **Integrating risk assessment into strategic decisions**: The program emphasizes the importance of risk assessment in strategic decisions regarding route improvements, crash protection, and safety management standards.
- **Establishing partnerships**: usRAP aims to foster collaborations among stakeholders responsible for maintaining a safe road system.
- **Empowering highway authorities**: The program enables all highway authorities, even those lacking comprehensive crash data and traditional risk assessment tools, to make data-driven decisions. This is achieved through video logs showcasing roadway features associated with crashes and investment plans that propose cost-effective solutions.

usRAP assigns separate star ratings for vulnerable road users (i.e., bicyclists and pedestrians) due to the substantial difference in features that factor into crash frequencies for these travel modes. The star rating is based on predefined criteria that consider the elements associated with crash likelihood and crash protection. These elements include movement along and across the road and movement at junctions for pedestrians and bicyclists.

Risk mapping is another tool offered by usRAP for areas with access to comprehensive crash data. Risk mapping protocol assesses risk and identifies locations with potential safety impairments. Road sections are color-coded on risk maps to indicate each section's risk level for fatal and serious injury crashes (Figure 3). This protocol includes four basic risk maps based on different safety performance measures:

1. **Crash density**: Representing the number of fatal and serious injury crashes per mile of road.
2. **Crash rate**: Illustrating the rate of fatal and serious injury crashes per 100 million vehicle-miles of travel.
3. **Crash rate ratio**: Comparing the crash rate for an individual road section to the average crash rate for similar roads, providing a ratio that indicates the relative risk.
4. **Potential crash savings**: Estimating the annual number of fatal and serious injury crashes that could be reduced if the crash rate for an individual road section could be lowered to the average crash rate for similar road sections.

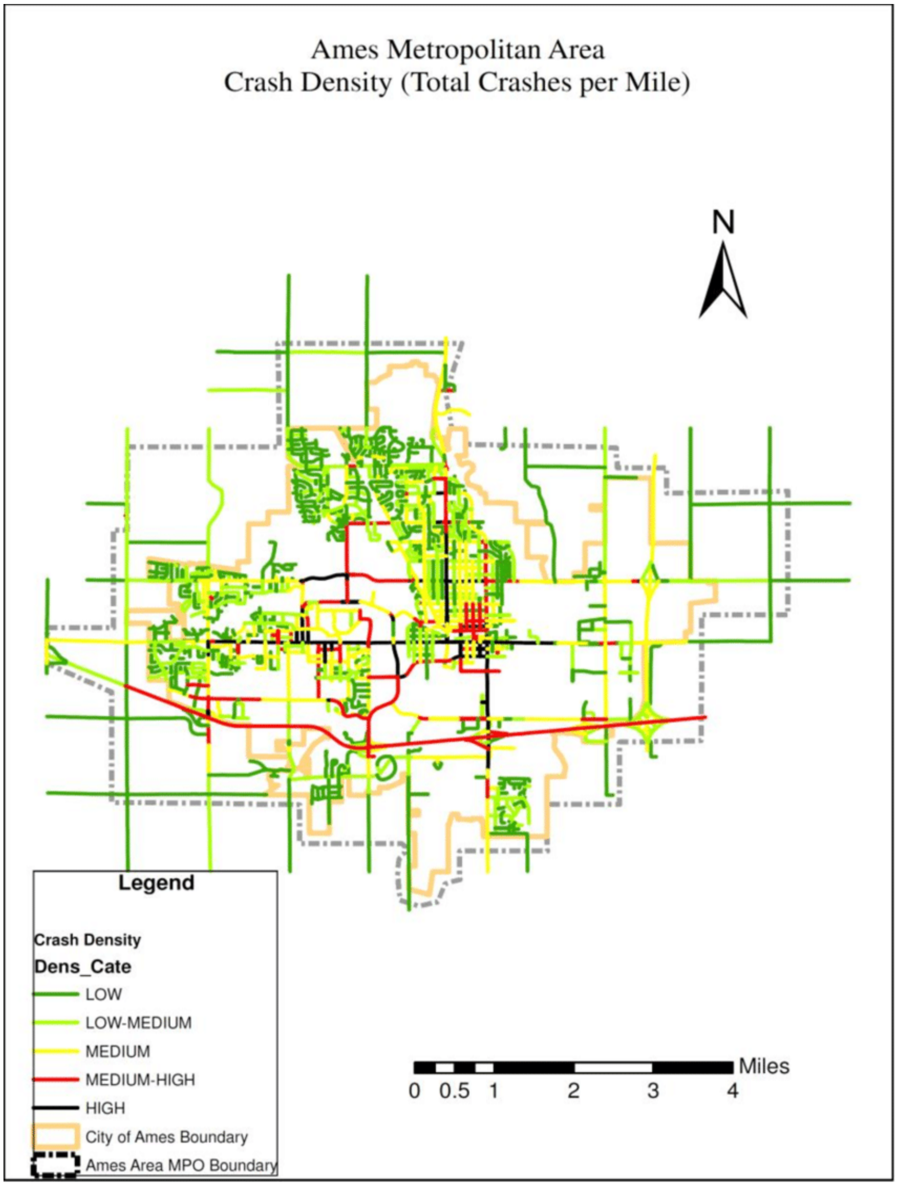

Figure 3 Crash Density Risk Map of usRAP (usRAP, 2023)

These risk maps facilitate the identification of locations with higher risk levels and help guide decision-making processes for implementing safety improvements. The tool's ability to identify high-risk locations, assess cost-effectiveness, and quantify the potential benefits of safety interventions makes it particularly valuable for prioritizing safety investments and strategies. By leveraging the insights provided by usRAP, agencies can make more informed, data-driven decisions to reduce fatalities and serious injuries on the roads effectively. Moreover, the risk mapping approach could be utilized for effective collaboration between different agencies and knowledge sharing.

Given the detailed nature of these assessments, transportation agencies and safety planners should consider integrating usRAP's star rating and risk mapping into their safety analysis and decision-making processes. It is critical to highlight that usRAP is not an alternative for professional engineering studies, Road Safety Audits (RSAs), or other initiatives implemented by highway agencies and traffic engineers. usRAP is a systematic tool that utilizes systemic approaches for safety planning, offering proactive risk assessment, mapping, user-friendliness, reliability, and a focus on cost-benefit considerations.

ActiveTrans Priority Tool developed by NCHRP (Lagerwey et al., 2015)

The National Cooperative Highway Research Program (NCHRP) has developed the ActiveTrans Priority Tool (APT) to assist agencies in prioritizing and implementing pedestrian and bicycle projects effectively (Lagerwey et al. 2015). The tool utilizes a data-driven methodology to enhance transparency in the prioritization process; however, it does not guide the selection of specific countermeasures.

Different agencies may use the APT in a variety of ways. State or regional bodies tasked with funding allocation may employ it to assess proposed enhancements aligned with policy goals. Meanwhile, local agencies might use the APT to prioritize bicycle or pedestrian improvements for implementation over short, medium, and long terms. Furthermore, agencies may apply the APT singularly or in iterative cycles. For instance, they might employ it initially to identify and rank corridors, then to pinpoint intersections within high-ranking corridors for field evaluation, and ultimately to prioritize improvements identified during the field assessment.

The methodology of the APT consists of two distinct phases and ten steps, as illustrated in Figure 4. Agencies can use this tool to generate a ranked list of pedestrian and bicycle improvement locations based on an objective analysis driven by data.

The ActiveTrans Priority Tool Guidebook proposes variables such as reported bicycle and pedestrian crashes, the proportion of pedestrians walking in the roadway, and the proportion of pedestrians adhering to "Don't Walk" signals as safety indicators. However, these variables may not be available based on existing data types or an analysis of risks across one or more networks.

Although the tool may not provide a comprehensive analysis of safety risks, it can complement a systemic pedestrian safety process by facilitating the prioritization steps for systemic projects in a well-documented manner. By incorporating the ActiveTrans Priority Tool with a systemic approach, agencies can enhance their understanding of project priorities and make informed decisions to improve pedestrian and bicyclist safety.

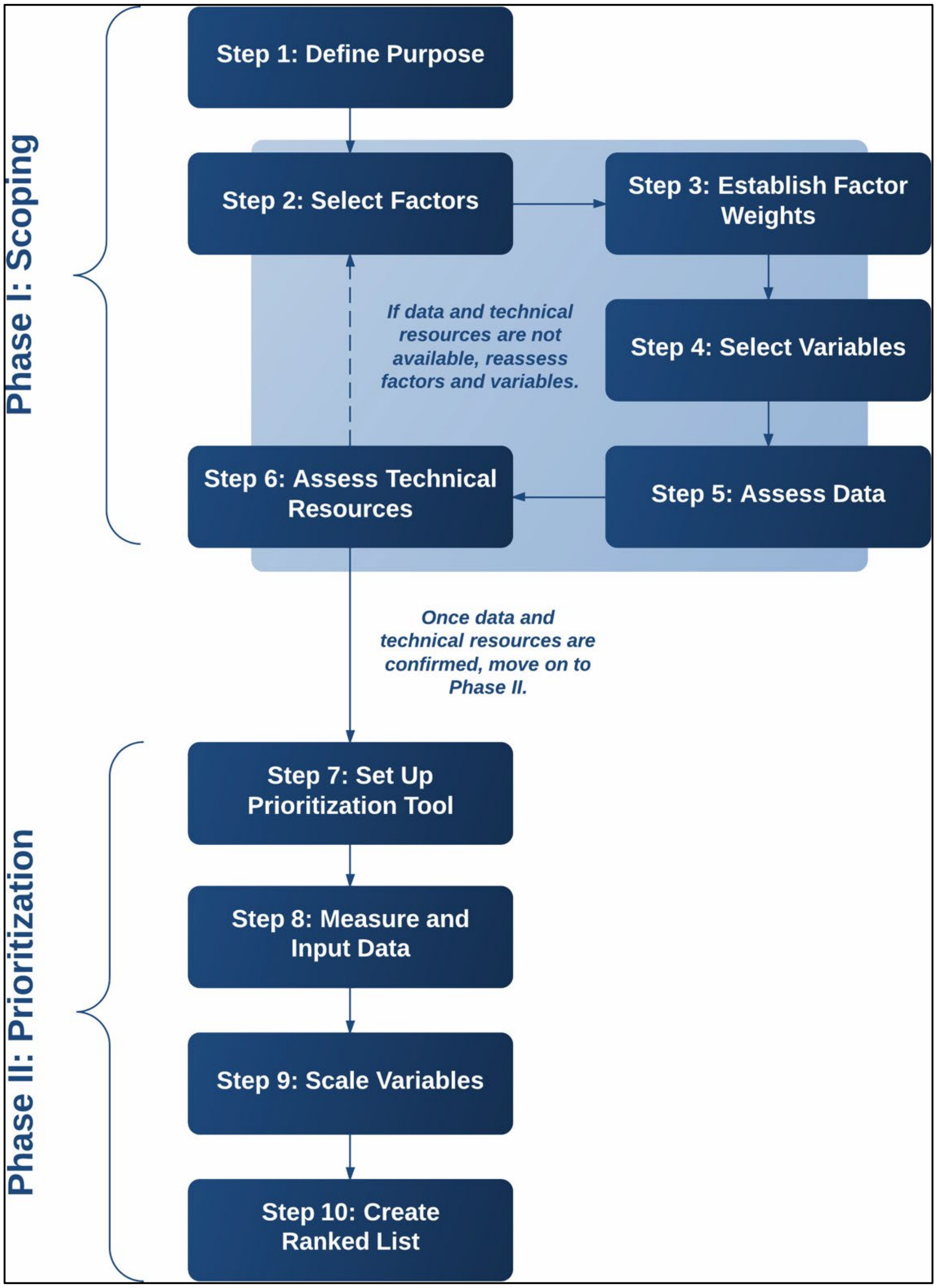

Figure 4 ActiveTrans Priority Tool methodology (Lagerwey et al. 2015)

Systemic Safety Project Selection Tool developed by FHWA ([Preston et al., 2013])

The Systemic Safety Project Selection Tool is a valuable resource for practitioners seeking to improve road safety. This tool provides a step-by-step approach and analytical techniques to conduct systemic safety analysis and quantify the benefits of a systemic program (Preston et al. 2013). The Systemic Safety Project Selection Tool is highly recommended for transportation agencies aiming to use crash data more effectively for the safety benefit of vulnerable road users. The fundamental principles of a systemic safety process, as outlined by the tool, include:

1. **Identifying Safety Concerns**: The process begins with evaluating system-level data to identify safety concerns. By analyzing crash data, practitioners can determine common characteristics and risk factors associated with locations where severe crashes frequently occur. This method of risk factor identification is an excellent example of a systemic analysis tool; it synthesizes the crash information further to produce a systemic understanding of the underlying risks that historically have led to crashes and are expected to contribute to future crashes.
2. **Emphasizing Low-Cost Countermeasures**: The systemic approach prioritizes cost-effective safety countermeasures targeting the identified underlying risk factors. This allows for efficient allocation of resources and implementation of measures to mitigate potential risks.
3. **Prioritizing Risk Factors**: The systemic process prioritizes locations across the entire roadway network where risk factors are present, regardless of prior crash history. By focusing on risk factors rather than historical crash data alone, practitioners can proactively address potential hazards before severe crashes occur.

The successful implementation of a systemic planning process requires a comprehensive evaluation of the entire system based on identified risk factors. The framework of the systemic planning process, as developed for the Systemic Safety Project Selection Tool, consists of three key elements:

Element 1: This element involves identifying focus crash types and risk factors, screening and prioritizing candidate locations, selecting appropriate countermeasures, and prioritizing projects for implementation.

Element 2: This element focuses on identifying funding for the systemic program and implementing the selected countermeasures across the roadway network.

Element 3: The final element entails performing a comprehensive systemic program evaluation to assess the effectiveness of the implemented measures and make any necessary adjustments or improvements.

Figure 5 Framework for the Systemic Safety Project Selection Tool (Preston et al., 2013)

The Systemic Safety Project Selection Tool offers two approaches to evaluate potential risk factors. The first approach involves using descriptive statistics to compare the occurrence of risk factors with the percentage of focus crash types at those locations. The second approach consists of reviewing crash modification factors (CMFs) from research or databases to identify roadway elements associated with positive effects on specific crash types.

It is important to note that the systemic methods outlined in the tool may not account for the randomness of crash locations or control for other factors present. These methods may identify factors associated with high crash frequencies at particular locations but may not establish a direct causal relationship. Factors such as random elements, considerable exposure, or underlying causes that are not measured or identified may contribute to associations with crash occurrences. This is the case for many analyses relying on historical crash data, and a systemic analysis based on this data provides an opportunity for agencies to focus on factors and contributing circumstances that are the most within their control.

It is crucial to account for pedestrian exposure in the analyses to ensure a comprehensive systemic pedestrian safety process. Traditional safety analyses commonly concentrate on locations with a higher number of crashes, which can lead to less attention to areas with lower pedestrian traffic despite the possibility of these areas having significant safety risks. A systemic approach, as outlined by the Systemic Safety Project Selection Tool, emphasizes the importance of a more inclusive approach in safety assessments, considering both high-incident areas and those less traveled by pedestrians where the risk of a vulnerable road user injury is high. Pedestrian exposure consideration becomes particularly significant as risks can be disproportionately high at locations with relatively low pedestrian volumes. Despite experiencing infrequent crashes, such locations could have considerable safety risks due to several factors, such as poor infrastructure, lack of visibility, or high-speed vehicular traffic. Therefore, collecting detailed inventory data and implementing appropriate analysis methods are essential for a practical systemic pedestrian safety approach.

Highway Safety Manual developed by AASHTO (AASHTO, 2010)

The American Association of State Highway and Transportation Officials (AASHTO) has adopted a roadway safety management system, which is outlined in the Highway Safety Manual (HSM) (AASHTO, 2010). The HSM is a reference for integrating quantitative safety analysis into the planning and development stages of highway transportation projects. It introduces scientific approaches for assessing the safety effectiveness of highways and streets, providing valuable insights for decision-making in highway transportation. The HSM guides the assessment of safety effectiveness across transportation networks.

The HSM presents a Six-Step Roadway Safety Management Process:

1. **Network Screening**: This step involves identifying and prioritizing locations or segments within the roadway network that require further analysis based on crash data, exposure data, and other relevant factors.
2. **Diagnosis**: Identified locations or segments are further analyzed to diagnose the specific safety issues and understand the underlying causes of crashes.
3. **Countermeasure Selection**: Once the safety issues are diagnosed, appropriate countermeasures or treatments are selected based on their potential effectiveness in addressing the identified issues. The selection process considers crash reduction potential, feasibility, and cost factors.
4. **Economic Appraisal**: This step evaluates the financial feasibility and benefits of implementing the selected countermeasures. Cost-benefit analysis and other economic evaluation techniques are employed to assess the potential return on investment.

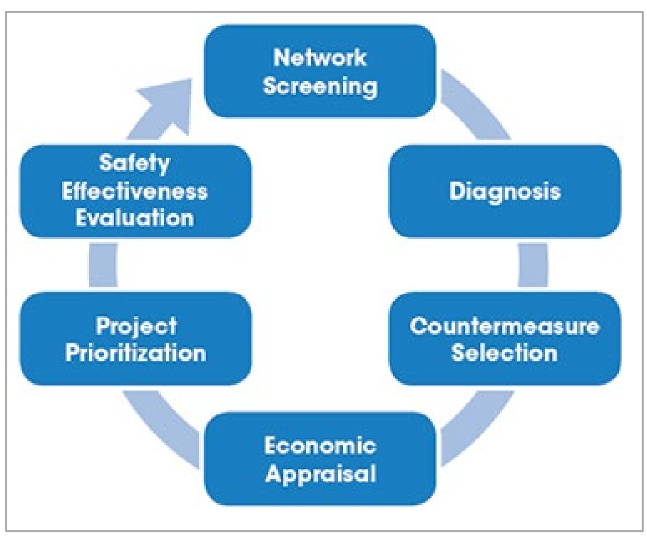

Figure 6 The Six-Step Roadway Safety Management Process (AASHTO, 2010)

5. **Project Prioritization**: Based on the results of the economic appraisal and other relevant considerations, the projects or countermeasure implementations are prioritized. Factors such as crash severity, crash frequency, cost-effectiveness, available funding, and other prioritization criteria are considered.
6. **Safety Effectiveness Evaluation**: After implementing countermeasures, this step involves evaluating their effectiveness in reducing crashes and improving safety. Monitoring and evaluation techniques are employed to assess the outcomes and benefits achieved.

The HSM's approach is not strictly systemic or systematic. The HSM provides a structured framework for identifying, diagnosing, and addressing safety concerns on roadways, with a focus on data-driven decision-making and evaluation of countermeasure effectiveness. More specifically, the Six-Step Roadway Safety Management Process focuses on a network screening based primarily on historical crash data and selecting countermeasures based on that historical crash data. Because the process does not include a synthesis of the roadway characteristics at a specific location, which may contribute to higher risk of crashes, agencies looking for systemic analysis tools are better suited to start with other methods outlined in this report.

Pedestrian and Bicyclist Intersection Safety Indices developed by the University of North Carolina Highway Safety Research Center (UNC-HSRC) (Carter et al., 2007)

The University of North Carolina Highway Safety Research Center (UNC-HSRC) has developed a methodology for the Federal Highway Administration (FHWA) that rates intersections based on their relative risk to pedestrians and bicyclists (Carter et al. 2007). This proactive screening method aims to identify higher-risk intersections for vulnerable road users, utilizing observable roadway characteristics.

The methodology involved developing models that predicted expert safety ratings for each crossing and conflicts and maneuvers (considered proxies for safety) during interactions between pedestrians and motorists. Due to limited crash data, the models were not crash-based but instead used descriptive factors for 68 pedestrian crossings at intersections. These factors included geometric characteristics, predominant land use, and traffic volumes and speeds.

Video data were collected for each crosswalk and subjectively rated for comfort and safety by traffic safety engineers, planners, and pedestrian safety professionals using structured data collection sheets based on the Pedestrian and Bicycle Intersection Safety Indices (PBISI). Hundreds of hours of video data capturing motor vehicle and pedestrian interactions are coded and analyzed. The analysis utilized a total of 1,095 pedestrian-motorist interactions, including conflicts and evasive maneuvers. Including these interactions offers a broader perspective on safety concerns, capturing not only the occurrences of crashes but also near-misses and instances where pedestrians or cyclists take action to avoid potential collisions. Such data is essential for understanding the full spectrum of risk scenarios, many of which do not result in crashes but still highlight significant safety issues. The study revealed many common risk factors by developing models for subjective ratings and behavioral data and then comparing results, providing a more detailed and comprehensive understanding of the dynamics at play in pedestrian and bicyclist safety at intersections.

Significant factors identified in the expert ratings model were retained in the PBISI models. Although the tool is not crash-based, it incorporates safety-related behavioral data, user interactions, conflicts, and expert judgments derived from videotaped observations. The final

Intersection Safety Index (ISI) procedure included risk factors associated with perceived risk rated by safety experts, and these characteristics are associated with pedestrian crash risk in other safety analyses. High-risk roadway variables incorporated in the final ISI model encompassed the presence/absence of traffic signals and stop controls, number of thru lanes, 85th percentile speed, traffic volume, and predominant land use.

A 6-point ISI rating scale was developed based on the important risk factors identified. Each pedestrian crossing at an intersection is assigned an index calculated based on roadway features, with a rating of 1 or 2 representing a very low risk crossing and a rating of 5 or 6 indicating a high-risk situation. Factors associated with greater risk in the pedestrian index included the absence of a traffic signal with a pedestrian signal, absence of a stop sign, a higher number of lanes, higher vehicle speed limits, higher traffic volume, and predominantly commercial land use.

Spreadsheets are available to facilitate the calculation of risk indices for intersection crossings. The PBISI tool requires data such as traffic volume, speed limits, and traffic control types, which may need to be collected. This tool is an initial step to identify intersection crossings that may warrant more comprehensive pedestrian safety assessments. In practical applications, combining PBISI values from each crossing can generate a single index value per intersection, and these index ratings have shown good correlation with user perspectives of risk, as demonstrated in screenings of crossings in a rail transit improvement area conducted by Nabors et al. in 2009.

PBISI methodology combines expert ratings, behavioral data, and roadway features, and allows for both systemic and systematic analysis. At a systemic level, the tool provides insights into overarching safety trends across transportation networks by identifying common risk factors and recurring safety concerns. This systemic understanding enables transportation agencies to develop targeted strategies and interventions to address systemic issues affecting pedestrian and bicyclist safety. On a systematic level, the PBISI tool can be used to apply standardized safety assessments across multiple intersections based on consistent criteria, without prioritizing specific locations or considering resource constraints. The tool enables widespread evaluations that can inform broader applications of safety treatments across a network, aligning with the principles of systematic safety planning. Therefore, the PBISI tool is recommended for transportation agencies seeking to enhance safety through comprehensive and targeted approaches. It is particularly useful in scenarios where detailed analysis at the intersection level is necessary.

Summary

By reviewing some of the existing tools for systemic and systematic safety, the potential pros and cons were explored and summarized in the table below (Table 1). Each tool offers unique methodologies and approaches aimed at enhancing road safety, some of which have a particular focus on vulnerable road users such as pedestrians and bicyclists. Defining the advantages and limitations of these tools provides insights into their effectiveness, applicability, and potential challenges in implementation. This comparative assessment provides guidance to transportation agencies, such as state DOTs, in selecting the most appropriate tools for their specific road safety needs and objectives. Some advantages and drawbacks were common between the five road safety tools. The shared advantage is that all five are based on data-driven approaches, offering structured frameworks for comprehensive safety management and decision-making, which enhances the effectiveness and efficiency of safety planning and promotes accountability. On the other hand, a common drawback is their complexity and resource intensiveness. Implementing these tools often requires extensive data collection and analysis, which can be challenging, especially for agencies with limited resources. Additionally, the detailed processes they entail can be time-consuming and may require a significant learning curve, potentially complicating their integration into existing safety protocols. Table 1 provides a detailed breakout for each tool’s pros and cons.

Table 1. Summary of the Pros and Cons of the Reviewed Safety Tools

Tool	Pros	Cons
Safe System Roadway Design Hierarchy	Encourages the use of infrastructure changes over behavioral adjustments, leading to more effective safety outcomes.	Implementation may be challenging in areas with limited space or existing infrastructure constraints.
	Flexible and applicable to various roadway contexts.	
The United States Road Assessment Program (usRAP) developed by AAA Foundation for Traffic Safety	Prioritizes areas that need improvement, which can be especially beneficial concerning pedestrian and cyclist safety.	The program's broad focus on road safety may not specifically address the unique needs and safety issues of pedestrians and cyclists.
	Fosters the development and maintenance of road safety capabilities at national, state, and local levels, enhancing overall expertise in pedestrian and cyclist safety.	
	Tracks road safety performance, allowing funding agencies to assess the effectiveness of investments in pedestrian and cyclist safety improvements.	The emphasis on roadway infrastructure characteristics might overlook other factors critical to pedestrian and cyclist safety, such as behavioral or environmental aspects.
	Enables highway authorities to make data-driven decisions, even in the absence of comprehensive crash data, by utilizing video logs and other tools.	
	Uses risk maps to facilitate the identification of high-risk locations and guides decision-making.	
ActiveTrans Priority Tool developed by NCHRP	Reflects the specific values and goals of the agency and community it serves, ensuring that prioritization aligns with local needs and objectives.	The tool's effectiveness depends on the availability and quality of data.
	Allows agencies the flexibility to choose the most suitable approach based on their unique values, priorities, and resource availability.	The linear process in Phase II limits the room for adjustments based on emerging nuances or complex decision-making needs.
	Offers mode-specific prioritization since the tool allows for the separate assessment of pedestrian and bicycle facility improvements.	Limited to facility improvement ranking and does not guide facility design solutions.
	Saves time and assists agencies in efficiently scoring and ranking projects through the included programmed spreadsheet and user guide.	

Tool	Pros	Cons
Systemic Safety Project Selection Tool developed by FHWA	Adaptable to agencies' needs and allows customization based on available data, program requirements, staff capabilities, and funding.	Requires significant time and effort to adapt the tool to fit specific agency needs and tailor the process effectively.
	Facilitates long-term program performance tracking, helps communicate results to stakeholders, and guides future safety efforts.	The comprehensive nature of the process may demand substantial resources in terms of time, staff, and funding.
	Balances investments between site-specific and systemic safety improvements, helping efficiently allocate safety funds.	Determining the appropriate balance of safety investments can be challenging, with no precise answer suitable for all agencies.
	Performs continuous evaluation and adjustment, which provides feedback for decision-making and enables ongoing adjustments to enhance program effectiveness. In addition, evaluating specific countermeasures helps understand their effectiveness and guide future funding and project selection.	Requires continuous review and updates.
		The need for comprehensive systemwide data may pose challenges for agencies with limited data availability or capabilities.
		Systemic methods may not account for the randomness of crash locations or control for other factors, potentially leading to misinterpretation of risk factors.
Highway Safety Manual developed by AASHTO	Provides structured roadway safety management that allows for a thorough and systematic approach to enhancing pedestrian and bicyclist safety.	Not explicitly focused on pedestrians and bicyclists.
	The economic appraisal step ensures that chosen safety measures are not only practical but also economically feasible, maximizing the return on investment.	It may require extensive data collection, which might be resource-intensive and challenging for some agencies.
	The project prioritization step allows for informed decision-making in implementing safety improvements, considering factors like crash severity and frequency, which are crucial for pedestrian and bicyclist safety.	The methodologies and guidelines are generalized and might not account for unique local conditions affecting pedestrian and bicyclist safety.
	The final step (evaluation) ensures that pedestrian and bicyclist safety measures remain effective over time.	Could be complex to implement, especially for smaller agencies with limited resources, due to multiple steps and detailed analysis.
		The safety effectiveness evaluation occurs after implementation, which may delay the identification of less effective or ineffective measures.

Tool	Pros	Cons
Pedestrian and Bicyclist Intersection Safety Indices developed by the University of North Carolina Highway Safety Research Center (UNC-HSRC)	Enables proactive identification and prioritization of intersections for pedestrian and bicycle safety improvements before crashes occur.	The tools are developed for urban and suburban intersections with specific characteristics, limiting their applicability to intersections outside these ranges.
	Users can selectively evaluate sites based on various criteria, such as planning stage, high pedestrian activity, or community input, without the need to assess all intersections simultaneously.	Incomplete safety assessment, high Ped ISI or Bike ISI scores do not necessarily indicate that an intersection is hazardous, as not all factors leading to pedestrian or bike crashes can be included.
	Provides easy-to-use index values.	Dependence on local knowledge may not always be readily available or accurate.
		Limited predictive capability.
		Requires continuous, usually annual, review and adjustment based on new data and changing intersection characteristics.

Data Collection And Analysis

Data collection and analysis are crucial not only in understanding crashes but also in gaining a comprehensive view of the overall transportation network and its safety. Transportation agencies and policymakers can identify trends, assess risk factors, and develop effective strategies to enhance pedestrian and bicyclist safety by gathering comprehensive and reliable information about their related crashes and transportation networks. Network data could include information on existing infrastructure conditions, traffic patterns, and pedestrian and bicyclist behavior. This section explores the importance of collecting and analyzing a broad range of data, discussing various methods used to do both. Here, we connect this and the previous section's findings, exploring which data points provide the most valuable inputs for the systemic and systematic models highlighted earlier.

Importance of Collecting Crash Data

Accurate and detailed data provide insights into the nature and magnitude of traffic crashes. This information helps stakeholders comprehend the extent of the problem, identify high-risk areas, and prioritize interventions accordingly. Moreover, data collection allows for identifying factors contributing to pedestrian and bicyclist crashes. In addition to factors like intersection design, traffic volume, lighting conditions, and pedestrian behaviors, data collection must also encompass aspects of human/operator behavior. This includes distracted driving, failure to yield, speeding, and other forms of negligence that significantly contribute to pedestrian and bicyclist crashes and fatalities. Analyzing these factors helps us understand the underlying causes of crashes in a more holistic manner. This comprehensive approach to data analysis is key to developing targeted and effective countermeasures that address all aspects of pedestrian and bicyclist safety.

Data sources that may be needed in a systemic process to perform activities such as identifying potential risk factors, screening locations for countermeasures, and prioritizing treatment plans can be categorized as below:

- Roadway inventory data, including posted speed limit, design speed, roadway width, number and width of lanes, roadway classification, presence of non-residential driveways, and the presence/type of medians, intersections, crosswalk markings, and roadway lighting.
- Motorized traffic data, including Average Daily Traffic (ADT) or Annual ADT (AADT), counts of turning vehicles, and presence/percentage of heavy vehicles.
- Non-motorized (i.e., pedestrian, bicycle, and micromobility) traffic data, including trip count, intersection or segment trip count, time/distance traveled, and behaviors (Patel et el., 2023).
- Land use data, including housing density, employment density, and land use type.
- Socioeconomic data including population, vehicle ownership rate, and income level (Thomas et al., 2018).

Risk Analysis Methods

Different methodologies have been used to identify risk factors associated with pedestrian crash frequency, including the Bayesian modeling approach (Strauss et al., 2014), generalized linear model (Pulugurtha and Sambhara, 2011), negative binomial regression (Schneider et al., 2009), Empirical Bayes (Thomas et al., 2017), and conditional logistic regression (Bennet and Yiannakoulias 2015). Table 2 presents the characteristics of the most common models.

Table 2. Most common crash frequency analysis methodologies

Methodology	Description	Pros	Cons	Reference
Negative Binominal (NB)	Used for modeling crash frequency (mean and variance are not assumed to be equal).	Appropriate for count data	Assumes that the shape parameter of the negative binomial distribution is fixed for all locations	Lin et al. (2019), Gates et al. (2016), Fernandes et al. (2012), Miranda-Moreno et al. (2011)
		Accounts for overdispersion in crash data by providing more accurate estimates *	Complexity	
		Flexibility - allows for both categorical and numerical data	Assumes that the observations are independent of each other	
		Provides estimates of the regression coefficients		
Poisson regression	Used for modeling crash frequency where the mean number of crashes is assumed to be equal to the variance. Effective where crash occurrences are rare and independent over a fixed period or space.	Appropriate for count data	Does not account for overdispersion	Kraidi R, Evdorides (2020), Hu and Cicchino (2018)
		Simplicity	Assumes that the observations are independent of each other	
		Provides estimates of the regression coefficients	Limited flexibility - assumes a linear relationship between the predictors and the log-rate of the count outcome	
		Computationally efficient		
* Overdispersion often occurs when the variance exceeds the mean. Crash occurrences often vary widely due to numerous unpredictable factors. In both cases, the NB model provides more accurate estimates by accommodating this variability, avoiding biases present in models assuming equal mean and variance.				

Different models have also been used by researchers to determine risk factors associated with specific pedestrian crash severity, including logistic regression (Kröyer, 2014; Sarkar et al., 2011; Rosén and Sander, 2009; Sze et al., 2007), mixed logit modeling approach (Haleem et al.,2015), conditional logistic regression (Bennet and Yiannakoulias 2015), mixed generalized ordered (Eluru et al., 2008), and partial proportional odds (Rosén and Sander, 2009). The most common methodologies are explained in Table 3.

Table 3. Common crash severity analysis methodologies

Methodology	Description	Pros	Cons	Reference
Multinomial logistic regression (ML)	An extension of the binary logistic regression model, which enables researchers to predict more than two categories of the dependent variable.	Allows for the modeling of categorical outcomes with more than two categories of severity levels	Assumes that the observations are independent of each other	Kröyer (2014), Sarkar et al. (2011), Rosén and Sander (2009), Sze et al. (2007)
		Flexibility (allows for both categorical and numerical data)		
		Provides estimates of the regression coefficients	Requires a large sample size compared to binary logistic regression due to the increased number of categories	
		Provides model quality evaluation through statistical tests and measures of model fit significance		
Mixed logistic regression	Extends the standard multinomial logit model by allowing for individual-level heterogeneity in preferences and accounting for unobserved variation.	Accommodation of unobserved heterogeneity	Computational intensity	Franceschi et al. (2022), Hasan et al., (2022); Shiran et al. (2021), Chen and Fan (2019)
		Allows for the inclusion of multiple explanatory variables and their interactions	Difficulty in interpretation	
		Accounts for the correlation of observations from the same individual or group by including random effect	Choice of which variables to include as random effects can be challenging and somewhat subjective	

Regarding determining the factors associated with crashes, the literature introduces several methods that utilize historical crash data to determine the significant contributing factors to crashes. These methods include regression analysis techniques, such as ordinary least-squares (OLS) regression (Bernhardt et al., 2021), mixed logit regression (Rella Riccardi et al., 2023), and negative binomial regression (Rahman et al., 2022); multiple correspondence analysis (MCA) (Baireddy et al., 2018; Jalayer et al., 2018; Natarajan et al., 2020); empirical Bayes (EB) data mining (Das et al., 2019); statistical significance tests, such as Mann Whitney U test (Patel et al., 2021; Hasan et al., 2022; Patel et al., 2024); and machine learning techniques which have been used heavily in the recent years (Yue et al., 2020; Hasan et al., 2023; Nayeem et al., 2023).

Case Studies Of Systemic Implementation

Safety measures often involve changes to the physical environment to improve pedestrian and bicyclist safety. These can include changes to urban design and planning, such as creating more pedestrian-friendly streetscapes, implementing speed management strategies to reduce vehicle speeds, using traffic calming measures to discourage aggressive driving, and others. Appendix A provides a comprehensive literature review of these strategies. This section presents case studies of systemic approaches to implement safety countermeasures for improving pedestrians' and bicyclists' safety. Case studies include local-level and state-level initiatives.

Local-level Implementations

Hoboken, Jersey City, and Middlesex County in New Jersey – Vision Zero Initiatives

Hoboken, New Jersey, stands as evidence of the effective implementation of safety measures for pedestrians and cyclists, achieving zero roadway fatalities for four consecutive years under its Vision Zero Action Plan. This remarkable success is attributed to a series of strategic safety interventions that are not only proven to be effective but also relatively low-cost and quick to implement, including the installation of high-visibility crosswalks, bike lanes, raised intersections, and curb extensions (NJ Bicycle and Pedestrian Resource Center, 2024). For instance, crash records showed that 88% of crashes between 2014 and 2018 in the city occurred at intersections; in response, the city used curb extensions to daylight intersections, preventing illegal parking within 25 feet of crosswalks and mitigating intersection conflicts. These initiatives, supported by strong political backing and a proactive approach to city planning, have significantly reduced crash frequency and severity. In addition, by 2020, Hoboken had installed a bike lane network of 16.3 miles, which covers almost half of the city's streets. Key measures like daylighting intersections, introducing leading pedestrian intervals at traffic signals, and implementing road diets during repaving have been instrumental in this achievement. Hoboken's emphasis on lowering speed limits citywide and enhancing bicycle infrastructure has contributed to creating a safer, more livable city. This holistic approach, combining infrastructure improvements with policy and enforcement changes, demonstrates how targeted safety strategies can effectively reduce crashes and enhance the well-being of pedestrians and cyclists.

Jersey City and Middlesex County also adopted Vision Zero plans in 2018 and 2022, respectively. Both aim to reduce traffic crashes and improve road safety for all users, and vulnerable road users in particular. Jersey City defined five major themes in their Vision Zero plan: focusing on designing safer streets, promoting a culture of safety, embedding Vision Zero in city practices, evaluating city laws and developing enforcement strategies, and planning (developing design guides and enhancing data collection and analysis) (City of Jersey City, 2019; 2023). Each of the themes consisted of several action items. "Designing safer streets" had 17, including prioritizing projects at high injury locations, establishing dedicated school pick-up/drop-off zones, and increasing visibility at pedestrian crossings. In 2022, the city highlighted a significant reduction in fatal traffic crashes, recording only five on all roads and, notably, zero fatalities on city streets.

Middlesex County, the first county in New Jersey to adopt a Vision Zero plan, focuses on identifying crash locations, mapping high-injury corridors, and documenting existing programs. The plan outlines actions to prevent crashes through engineering, education, enforcement, evaluation, and partnerships, following the five elements of the Safe System Approach. It also introduces a project prioritization criterion based on the impact on safety improvements, emphasizing high-injury network projects when funding is available. Furthermore, Middlesex County's proactive, systemic approach to safety includes a sub-granting program for municipalities, enabling the application of Vision Zero actions across the county's transportation network.

New York City – Turn Calming Treatments (NYC DOT, 2024)

In New York City, the Turn Calming Program is a citywide initiative that aims to reduce speeds during left and right turns to encourage safer turning behaviors. Generally, turn calming treatments include geometric reconfigurations of intersections to make turning radii smaller, compelling drivers to take turns at a slower speed. Lower speeds while turning reduce the risk of fatalities and serious injuries at intersections in accordance with the principles of the Safe System Approach. Specifically, drivers who turn their vehicles more slowly are more likely to see and stop for pedestrians and bicyclists in their path.

This effort is a part of the City's Vision Zero strategy, which aims to eliminate traffic-related fatalities and serious injuries. The New York City Department of Transportation (NYC DOT) initiated this program to address crashes resulting from failure to yield to pedestrians during left turns. By the end of 2023, the program had enhanced safety at 931 intersections across the city with turn-calming treatments.

These treatments are specifically designed for problematic left and right turns and vary depending on the intersection type. For instance, the Basic Hardened Centerline (Left Turns) treatment, used where one-way or two-way streets intersect with two-way streets, has been implemented at 627 locations since 2016. The Complete Hardened Centerline (Left Turns) is applied where one-way roads meet two-way roads, with 145 installations since 2016. Additionally, the Slow Turn Wedge (Left & Right Turns), suitable for intersections of one-way streets, has been installed at 141 locations citywide since 2016.

Figure 7 Slow Turn Wedge (left) and Basic Hardened Centerline (right) (Source: NYC DOT, 2024)

Lastly, the Bike Island Channelization (Left Turns), for intersections of one-way roads with protected bike lanes, has seen 40 installations since 2017. The Bike Island Channelization treatment is only installed adjacent to existing bike islands—designated spaces, often raised or protected, that provide a refuge for cyclists at intersections or mid-block crossings. Bike Island Channelization consists of a Bike Island Channelization box with flexible plastic posts or rubber speed bumps.

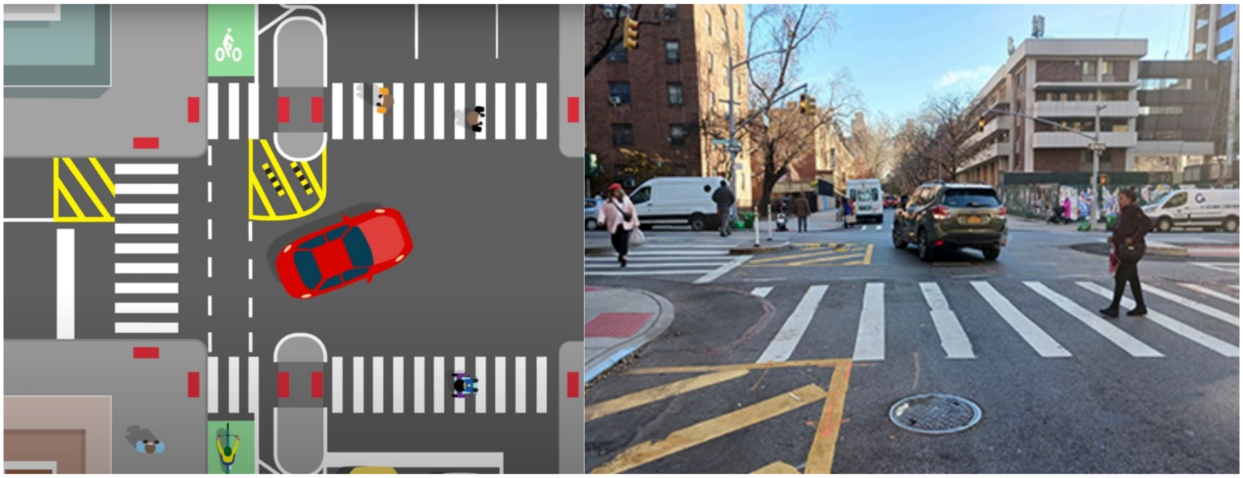

Figure 8 Bike Island Channelization Box (Source: NYC DOT, 2024)

The implementation of turn calming treatments in New York City has led to a notable decline in pedestrian injuries at these intersections, outpacing the reductions seen at comparable nearby locations. These treatments have significantly lowered turning speeds and contributed to a substantial decrease in traffic-related incidents. Specifically, pedestrian injuries have been reduced by 18%, severe injuries to pedestrians by 33%, injuries to senior pedestrians by 19%, and fatalities or severe injuries to senior pedestrians by 60%.

Philadelphia, Pennsylvania – Parking-Separated Bike Lanes (Ahramjian and Rowe, 2021)

In 2021, Philadelphia collaborated with Kittleson and Associates and undertook a study focusing on the implementation and efficacy of parking-separated bike lanes (PSBLs). This initiative was a part of the city's dedication to Vision Zero. PSBLs, designed to separate bicyclists from moving vehicle traffic with a parking lane and buffer area, were installed on various PennDOT state roads, including Market Street, JFK Boulevard, and Race Street. This systemic approach was reinforced by analyzing safety data from other cities, including New York City, Oakland, and San Francisco, to assess the impact of PSBLs.

Figure 9 PSBL on JFK Boulevard (Ahramjian and Rowe, 2021)

The study revealed noteworthy outcomes, including a decrease in overall crashes and fatalities, a 6% reduction in vehicle speeds, and a remarkable 96% increase in bicycle usage, especially on JFK Boulevard and Market Street. These findings underscore the impact of PSBLs in enhancing pedestrian and bicyclist safety. Following this pilot, Philadelphia plans to continue the expansion and evaluation of PSBLs, focusing on gathering more data and considering the adoption of more permanent safety features.

Portland, Oregon – Bike Boxes (Jeffrey Trombly and Associates, 2019)

This case study highlights the implementation and effectiveness of bike boxes at signalized intersections. Bike boxes are designated areas at the front of traffic lanes, providing bicyclists with a safe and visible space to position themselves ahead of queued traffic during red signals. The design features of bike boxes include a marked ingress area connecting the bike lane to the box, a bicycle symbol indicating the area reserved for cyclists, and a stop bar for vehicles. Additional signage for motorists is often employed to further enhance safety, such as 'Stop Here on Red' and 'No Turn on Red' signs to prevent right-turn crashes.

Figure 10 Bike box at signalized intersection (Source: Jeffrey Trombly and Associates, 2019)

These boxes are particularly beneficial at signalized intersections with high volumes of bicycle and motor vehicle traffic, especially with frequent bicyclist left turns and/or motorist right turns. Other typical applications include locations with right- or left-turning conflicts between bicyclists and motorists, where there is a need to accommodate left-turn bicycle traffic, and in scenarios where cyclists need to turn left to stay on a designated bike route, connect to a shared-use path, or when the bike lane shifts to the left side of the road.

Bike boxes provide multiple benefits, such as minimizing signal delays for cyclists and enabling safe left-turn positioning at red lights, especially for boxes spanning the entire intersection. They also make it easier to switch from right-side to left-side bike lanes during red signals and help prevent conflicts with vehicles turning right when the light turns green.

An evaluation by Portland State University demonstrated the positive impact of bike boxes. The study found a decrease in bicycle-vehicle conflicts and an increase in yielding behavior at intersections equipped with bike boxes. Furthermore, the perception of safety significantly improved among road users: approximately 42% of non-cyclist motorists and 77% of cyclists reported feeling safer when proceeding through these intersections. Currently, Portland has implemented bike boxes at 15 signalized intersections and plans to install additional boxes, highlighting the city's ongoing efforts to enhance cyclist safety and promote harmonious road sharing between bicyclists and motorists.

Santa Monica, California – Road Diet in a School Zone (Archibald, 2011)

In 2008, Santa Monica implemented a temporary Road Diet on Ocean Park Boulevard, aiming to enhance safety for both pedestrians and bicyclists in the vicinity. Ocean Park Boulevard is a busy city road that underwent a significant transformation as part of this pilot project aimed at improving road safety. The project involved a "road diet" where two of the four lanes were removed and replaced with left-hand turn pockets, bicycle lanes, and on-street parking in certain areas. This reconfiguration was meant to slow motor vehicle traffic through a two-block section near a middle school, where injury-producing crashes had been a concern. Over a two-year period, city staff collected data on the impact of these changes, focusing on crash rates, public bus transit times, and feedback from residents and law enforcement.

Figure 11 Ocean Park Boulevard after road dieting project (Source: Archibald, 2011)

The data showed a substantial improvement in road safety. Crashes dropped to 12 compared to 35 in a similar nine-month period in the previous year, and this reduced rate persisted into the second year. Crashes with injuries decreased by 60%, with pedestrian-related crashes confined to signalized intersections outside of the project area. Moreover, the reconfiguration led to a significant reduction in speeding, with 85% of motorists traveling at or below 27 mph, below the posted speed limit. This initiative achieved its primary goal of reducing vehicle speeds in the school zone.

State-level Implementations

Florida – LED Lighting at Signalized Intersections *(*Jeffrey Trombly and Associates, 2019*)*

Lighting has a significant impact on pedestrian safety at signalized intersections, particularly at night. Poor night lighting at intersections poses a significant risk to people on foot, making it difficult for drivers to see them. This has been proven by several research studies that show installing adequate roadway lighting can reduce nighttime fatal crashes by up to 60% (Jeffrey and Associates, 2019); studies found a 64% reduction in fatal crashes post-lighting installation (Elvik et al., 2009), and some showed a 28% reduction in injury crashes and a significant reduction in fatal crashes (Wanvik, 2009).

The Florida Department of Transportation (FDOT) took proactive steps to address increased pedestrian and bicycle fatalities and injuries at signalized intersections. Their initiatives include extensive research and increased funding for improving lighting at these intersections statewide. A key project involved field testing the installation of LED lighting at a signalized intersection. This test focused on improving pedestrian visibility, assessing technical aspects such as fixture mounting and the extent of visibility enhancement. The results showed a marked improvement in pedestrian visibility, especially for those wearing dark clothing. In addition to research, FDOT has allocated substantial funding to adopt a systemic approach and retrofit signalized intersections with enhanced lighting standards. This initiative, backed by a $100 million budget, aims to upgrade or install lighting at about 2,500 intersections across the state. Moreover, FDOT plans to include intersection lighting in all signal reconstructions in urbanized areas with pedestrian facilities, making it a standard practice for future projects.

Figure 12 Before (left) and after (right) LED installation for pedestrians dressed in dark clothing (Source: Jeffrey Trombly and Associates, 2019)

Implementation And Evaluation

The implementation and evaluation phases of a pedestrian or bicyclist systemic safety approach involve putting the pedestrian/bicyclist systemic safety plan into action and then assessing its effectiveness. This includes implementing the selected countermeasures across the roadway network, identifying funding for the systemic program, and performing a program evaluation to assess the effectiveness of the implemented measures and make any necessary adjustments or improvements.

Implementation of Pedestrian/Bicyclist Systemic Safety Plan

The implementation of a systemic safety plan is a process that requires concerted efforts from various stakeholders. It involves translating the identified strategies and interventions into actionable steps. This process can encompass a variety of activities.

One of the key aspects of implementation is making physical modifications to the built environment. This could involve the installation of new marked crosswalks and bike lanes, which provide designated and visible areas for pedestrians and bicyclists. Traffic calming measures, such as speed humps, roundabouts, and curb extensions, can also be implemented to slow motorists. In addition to these physical changes, a plan may also call for the launch of public education campaigns. These campaigns can raise awareness about pedestrian and bicyclist safety, educate the public about the new changes in the environment, and promote safe behaviors among these vulnerable road users and drivers. Furthermore, the implementation process should involve collaboration with local communities. Engaging with community members can provide valuable insights into specific pedestrian/bicyclist safety issues in different areas and ensure that the implemented measures effectively address these issues (Williams, 2022). Lastly, securing adequate funding and political support is crucial for implementing the plan (Osuret et al., 2021). These resources can ensure the necessary changes are made and sustained over time.

Regular Evaluation of Pedestrian/Bicyclist Systemic Safety Measures

Regular evaluation of pedestrian and bicyclist systemic safety measures is a critical component of any comprehensive safety plan. For instance, the Systemic Safety Project Selection Tool developed by FHWA (USDOT, 2013) features continuous evaluation of, and adjustment to, countermeasures to help understand and enhance their effectiveness and guide future funding and project selection. This process allows stakeholders to assess the effectiveness of the implemented strategies and interventions, ensuring they are achieving the desired outcomes. The results of these evaluations should be used to inform adjustments to the pedestrian/bicyclist systemic safety plan. This could involve modifying existing interventions, introducing new ones, or changing the focus of the plan to better align outcomes with the overarching systemic safety project goals. For example, if the data shows that pedestrian crashes are most common at intersections, the plan could be adjusted to include more interventions targeting these areas.

Implementation Challenges

Several challenges can impede the implementation of a systemic safety program for bicyclists and pedestrians. The table below summarizes the several aspects of implementation challenges.

Table 4. Implementation challenges of safety countermeasures

Aspect	Challenge
Funding and Resource Constraints	Achieving consensus and navigating local politics, competing priorities and differing stakeholders' interests can hinder the allocation of adequate funding for pedestrian and bicyclist safety projects.
Coordination and Stakeholder Engagement	Varied agendas between stakeholders might be difficult to align and could affect the sustainability of collaborations.
Data Collection and Analysis	Inconsistent data collection methods and defined criteria between agencies that collect data
	Underreporting and lack of pedestrian and bicyclist counts
	Limited access to relevant information sources (For example, due to privacy regulations, medical records and police reports may not be accessible.)
Public Awareness and Education	Safety campaigns target individual behaviors, and do not directly alter the physical or systemic factors contributing to safety risks.
	Human behavior is inherently resistant to change and may not always respond effectively to traditional safety campaigns.
Infrastructure Improvements	Retrofitting existing infrastructure to accommodate pedestrians and bicyclists can be logistically complex and local political may be low or met with opposition.
	Gaining the political support that is needed for allocating needed resources, implementing policy changes, and overcoming resistance to proposed infrastructure improvements.
Evaluation and Accountability	Evaluation of safety measures may be underprioritized or overlooked.

Recommendations

The successful implementation of a systemic safety program for bicyclists and pedestrians, while subject to various challenges, is critical for enhancing road safety. The preceding section outlined key challenges that can hinder effective implementation. To address these issues, it is essential to propose practical and strategic recommendations. This section presents a series of targeted recommendations designed to overcome the identified challenges. These recommendations aim to provide actionable guidance for transportation agencies, policymakers, and other stakeholders. By following these suggestions, stakeholders can navigate the complexities of implementation, increasing the likelihood that safety measures are not only planned but also executed efficiently and effectively.

Overall, it is recommended to apply a suitable safety approach that would provide a thorough analysis of pedestrian and bicyclist safety requirements, prioritizing locations, selecting appropriate countermeasures, and implementing effective solutions. Among the several reviewed systemic and systematic safety frameworks, the FHWA Systemic Safety Project Selection Tool (USDOT, 2013) is recommended for its structured approach to identifying and addressing safety concerns. This tool includes identifying problems, screening locations, selecting countermeasures, and prioritizing projects, leading to a thorough approach to safety planning.

The following recommendations are structured to correspond directly with the challenges previously discussed.

- **Funding and Resource Constraints**
  - Collaborate with local, county, and state transportation departments to initiate systemic implementation of bicycle and pedestrian safety improvements during routine repaving projects.
  - Apply for grant opportunities specifically earmarked for pedestrian and bicyclist safety initiatives.
  - Collaborate with local, state, and federal agencies to secure the necessary resources for project implementation.
  - Use low-cost materials in preliminary implementations of systemic safety improvements to reduce the expense and increase the number of implementations that can be done with limited resources.

- **Coordination and Stakeholder Engagement**
  - Establish multi-disciplinary task forces or committees that bring together relevant stakeholders to foster collaboration and ensure the cohesive execution of safety initiatives.
  - Collaborate with local safety advocacy groups and Transportation Management Associations (TMAs) to allow them to bring forward their priority locations and provide feedback on plans for systemic safety improvements.

- **Data Collection and Analysis**
  - Invest in advanced data collection technologies and methodologies, including traffic surveillance cameras and crash analysis tools.
  - Collaborate with research institutions to develop robust data analysis techniques.
  - Implement passive data collection devices, such as counters and traffic cameras, as part of ongoing safety projects, repaving, and intersection redesigns.

- **Public Awareness and Education**
  - Launch targeted public awareness campaigns that emphasize the importance of safety for all road users.
  - Partner with local schools, TMAs, and community organizations to integrate safety education into curricula and community events.
  - Work with local police to develop pedestrian and bicycle safety enforcement programs, training officers to understand and enforce laws designed to protect vulnerable road users.

- **Infrastructure Improvements**
  - Develop a prioritized plan for infrastructure improvements focusing on high-risk areas, incorporating Complete Street designs and traffic calming.
  - Seek federal and state grants to fund local bicycle and pedestrian safety projects.
  - Incorporate proven safety countermeasures in every project.

- **Evaluation and Accountability**
  - Implement a rigorous evaluation framework with before-and-after assessments of safety projects.
  - Establish performance metrics and regularly report on progress to hold agencies accountable.

Conclusion

This report reviewed various systemic and systematic safety countermeasures within the context of pedestrian and bicyclist safety. Systemic safety programs prioritize identifying fundamental issues and root causes of crashes, allowing for a more proactive and holistic approach to safety management. Systemic implementations use crash data and roadway characteristic data to identify the underlying risks built into roads and intersections so that those risks can be addressed consistently – and systematically - across a jurisdiction. Importantly, a systemic safety program implementation focuses on improving safety conditions for all road users at a scale beyond locations where crashes resulting in fatalities and serious injuries have occurred. Systematic safety emphasizes the structured and organized implementation of safety measures, focusing on consistency and adherence to protocols.

Traffic crashes are the result of many contributing factors, and it is important to understand that just because a crash has not occurred at a specific location, it does not suggest that the risk of a future crash is not elevated. On the contrary, agencies should understand where these risks are present to reduce or eliminate the likelihood of a fatal crash before it happens.

The findings from our examination of various tools and methodologies, including the Systemic Safety Project Selection Tool, Pedestrian and Bicycle Intersection Safety Indices, ActiveTrans Priority Tool, Highway Safety Manual, and the United States Road Assessment Program, underscore the importance of integrating both systemic and systematic approaches to achieving comprehensive safety improvements. Nonetheless, successfully integrating both approaches requires a concerted effort from organizations, regulators, policymakers, and safety professionals.

In reviewing existing systemic and systematic frameworks, there is a consistent theme involving a strong emphasis on data-driven approaches for identifying and mitigating road safety hazards. These methodologies are instrumental in prioritizing interventions, ensuring efficient resource allocation, and fostering transparency in decision-making processes. However, a common difficulty identified is the complexity and resource-intensive nature of these tools, which can lead to implementation challenges in resource-constrained settings. Moreover, some of these methods lack ability to specifically address the unique, and sometimes the local, needs of pedestrians and cyclists.

As part of this work, the team reviewed case studies in systemic applications of safety countermeasures. The reviewed case studies underscore the significant impact of well-adapted road safety initiatives in reducing crashes and enhancing the safety of vulnerable road users. These initiatives, ranging from the implementation of parking-separated bike lanes to the strategic introduction of improved lighting at intersections and the adoption of road diets, have demonstrated substantial benefits in terms of crash reduction and traffic safety enhancement of the built environment. Each initiative was carefully adapted to achieve defined goals to address prevalent safety concerns, such as reducing vehicle-bicycle conflicts and pedestrian fatalities, particularly in high-risk areas. A key takeaway from these studies is the critical importance of tailoring safety measures to the unique characteristics and needs of each location. This approach ensures effectiveness in addressing specific safety challenges and maximizes the impact of the measures implemented. Furthermore, the reviewed case studies highlight the necessity of a proactive stance in road safety management, where potential risks are anticipated and addressed before they escalate into more severe problems. The positive impact of these initiatives offers valuable insights into the implementation of similar safety measures in other contexts, emphasizing the need for continuous evaluation, adaptation, and learning from best practices to create safer road environments for all.

Several tangible recommendations could be concluded from this review. One practical recommendation is to select tools that align with the agency's specific values, goals, and resource availability. For example, usRAP is a risk assessment approach, prioritizing areas for improvement based on roadway characteristics. Similarly, the APT allows for mode-specific prioritization, reflecting the agency and community's unique needs and objectives. The Systemic Safety Project Selection Tool supports evidence-based decision-making, offering a framework for balancing investments between site-specific and systemic safety improvements. The HSM emphasizes a process for identifying and prioritizing road safety issues, while the Pedestrian and Bicyclist Intersection Safety Indices enable proactive identification of intersections for safety improvements. All reviewed approaches share a mutual feature of being data-driven approaches. This emphasizes the importance of enhancing data collection and analysis for informed decision-making. More detailed data concerning pedestrians and cyclists will enable more precise risk assessments and intervention planning. Additionally, community involvement is paramount in the safety improvement process, providing local insights for more effective solutions.

Investing in capacity building for local agencies is important to effectively utilize these tools. Equipping them with the skills and resources needed to apply these frameworks ensures efficient planning, selection, and implementation of safety measures. Finally, advocating for policy changes and funding support that prioritize pedestrian and cyclist safety is vital, ensuring these efforts are well-supported and aligned with broader safety objectives.

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Appendix A: Safety Measures At The System Level (Literature Review)

Safety measures at the system level involve changes to the physical environment to improve pedestrian safety. These can include changes to urban design and planning, such as creating more pedestrian-friendly streetscapes, implementing speed management strategies to reduce vehicle speeds, using traffic calming measures to discourage aggressive driving, and others. The following sub-sections provide a discussion of these safety measures.

Urban Design and Planning

Urban design and planning are fundamental to creating pedestrian-friendly environments. By prioritizing the needs of pedestrians in the design and planning process, we can create urban spaces that are not only safe but also enjoyable for walking. This can be done by implementing strategies such as widening sidewalks, improving street lighting, and adding pedestrian-friendly features.

Kweon et al. (2021) found that the design of pedestrian environments, including sidewalks, buffer strips, and street trees, affects people's perceptions of pedestrian safety and their willingness to walk. It was found that the effects of trees on parents' walking, and perception of pedestrian safety are greater when there is a wide buffer rather than a narrow buffer. Another study by Lee and Kim (2019) indicated that the design strategies of Pedestrian Priority Street projects, which involve various paving design techniques, reduced vehicle speed and increased perceptions of pedestrian safety. Lastly, green space, sidewalks, and intersections on the roads were found to significantly affect elderly pedestrian safety in a study conducted by Lv et al. (2021).

Speed Management Strategies

There are numerous studies providing empirical evidence that higher crash speeds result in injuries that are more severe for pedestrians (Santos-Cuadros et al., 2019, Uddin and Ahmed, 2018, Islam and El-Basyouny, 2013). Moreover, higher speeds reduce the driver's field of vision and increase vehicle stopping distance. Hence, speed management is a critical component of pedestrian safety.

Engineering initiatives to manage speed include both making changes to the road to encourage drivers to comply with the speed limit, such as road diets, and implementing safety countermeasures such as speed display signs and speed monitoring trailers.

Figure 13 The effect of speed on a driver's field of vision and the risk of pedestrian fatality (LADOT, 2015)

Figure 15 A visualization of Livingston Avenue, New Brunswick, NJ with a road diet (Noland et al., 2015)

A road diet entails reducing the width and/or number of lanes of an existing road.

For example, a road diet could consist of converting a four-lane road to a three-lane road, where the middle lane is a two-way turning lane (Figure 15). By reducing the number of lanes, road diets can help to lower vehicle speeds and reduce the number of lanes for pedestrians to cross, making the road safer for all users. Also, studies have shown that road diets can reduce the number and severity of crashes (Noland et al., 2015; Huang and Stewart, 2002).

Speed display signs, a prominent traffic safety countermeasure, have proven to be effective tools in mitigating vehicle speeds and enhancing pedestrian safety. These interactive signs provide real-time feedback to motorists by displaying the speed of their vehicles (Figure 16). The incorporation of speed display signs in various urban settings has yielded promising results. Several studies, including those conducted by Karimpour et al. (2021), Flynn et al. (2020), and Malin and Luoma (2020), have shown that these signs can substantially influence vehicle speed reduction. Motorists tend to respond to the immediate feedback presented by these signs, resulting in speed reductions of up to 4 mph, a significant reduction that can lead to a remarkable 22% decrease in the probability of fatal pedestrian crashes.

Figure 16 A display speed sign (Karimpour et al., 2021)

Figure 17 A speed-monitoring trailer (PEDBIKESAFE, 2013)

Speed-monitoring trailers, a valuable tool in traffic enforcement and road safety, serve as a visual reminder to motorists about their vehicle's speed. These trailers are strategically positioned at the roadside, featuring a real-time display of approaching vehicles' speed (Figure 17). Particularly effective in residential areas, speed-monitoring trailers have improved speed compliance and the yielding rate of drivers. Studies, such as the one conducted by Dangeti et al. (2010), have demonstrated their capacity to reduce driver speeds. By providing an immediate and visible indication of a vehicle's speed, these trailers encourage drivers to adhere to speed limits, enhancing safety for pedestrians and other road users. The deployment of speed-monitoring trailers exemplifies a proactive approach to enforcing speed limits and fostering safer driving behavior in residential and areas of particular safety priority, such as school zones.

Traffic Calming

Traffic calming involves making physical changes to streets to slow down traffic and improve safety for pedestrians. This can include several measures, such as:

- Speed humps
- Chicanes, creating a horizontal redirection of traffic, which can vary in intensity from gentle to more restrictive depending on the design (FHWA, 2024)
- Speed kidneys, a longitudinal speed bump shaped like a kidney, designed to reduce vehicle speeds by requiring drivers to select one of two slower paths (USDOT, 2015)
- Raised pedestrian crossings
- Curb extensions

Speed humps are a type of traffic calming measure designed to slow down vehicles. They are raised areas placed across the roadway, typically made of asphalt or rubber (Figure 18). The effectiveness of speed humps in reducing vehicle speed has been well-documented. It has been shown that the installation of speed humps contributed greatly to reducing vehicle speed, the flow of traffic, and the traffic crash rate (Shwaly et al., 2018). Moreover, it has been indicated that the installation of speed humps reduced child and adolescent pedestrian-involved crashes by 37.5% (Arbogast et al., 2018).

Figure 18 A speed hump in a residential area (NACTO, 2023)

Raised crosswalks or intersections span the full width of a road or intersection, serving as ramps. They are frequently installed at midblock crossing points and are typically the same width as a crosswalk (Figure 19). Raised crossings enhance pedestrian visibility to drivers. The approach ramps can also help to slow down vehicles and encourage drivers to yield. This measure has been found to decrease pedestrian-related crashes by up to 45% (PEDBIKESAFE, 2023). Moreover, raised crosswalks have been shown to be effective in increasing the driving yielding rate from 10% to 55% (City of Cambridge, 2000).


Figure 19 Raised pedestrian crossing (PEDBIKESAFE, 2023)

Curb extensions, also referred to as bulb-outs or neckdowns, are modifications that expand the sidewalk or curb line into the area typically reserved for parking (Figure 18). By narrowing the effective width of the street, curb extensions enhance pedestrian safety in several ways. They shorten the distance pedestrians need to cross, thereby reducing their exposure to traffic. They also make the roadway appear narrower, which can help slow down traffic. Furthermore, they improve visibility between pedestrians and drivers. An additional benefit of curb extensions is that they provide extra space for the installation of a curb ramp (PEDBIKESAFE, 2023). The results of a study conducted by Bella and Silvestri (2015) showed that curb extensions induced the most appropriate driver speed behavior among the studied countermeasures (curb extensions, parking restrictions, and advanced yield markings).

Figure 20 A curb extension in a residential setting (PEDBIKESAFE, 2023)

In Vehicle Pedestrian and Bicyclist Detection System

This system represents a critical advancement in road safety technology. These systems typically combine radar, lidar, and camera sensors to identify pedestrians and cyclists in the vicinity of the vehicle. Through advanced algorithms and machine learning, the system can distinguish these vulnerable road users from other objects and track their movements in real-time. When a potential collision is detected, the system can trigger warnings for the driver, such as visual or auditory alerts, and in some cases, it can even apply automatic emergency braking to mitigate or avoid a collision. An example of this technology can be found in Volvo vehicles equipped with the pedestrian detection system, which uses radar and camera technology to detect pedestrians and cyclists, demonstrating the industry's commitment to reducing crashes and improving road safety for all road users. This system has been implemented in various Volvo models and has contributed to reducing pedestrian fatalities and injuries (Volvo, 2019).

Education

In order to enhance pedestrian and driver awareness, education and training is part of the solution. Educational campaigns can be divided into three categories: public awareness campaigns, targeted campaigns, and individual campaigns. Public awareness campaigns can increase the pedestrian safety level. Targeted campaigns are designed to change the behavior of specific groups of people (e.g., the elderly), while individual campaigns reach the audience through an intermediary (e.g., safety guards, doctors, and other authority figures) (PEDBIKESAFE, 2023). Several studies have advocated safety awareness and education campaigns as effective ways to enhance pedestrian safety (Lin et al., 2019; Ni et al., 2016; Patel, 2020; Jalayer et al. 2020).

Several education campaigns have resulted in significant improvements in drivers' and pedestrians' behavior. For instance, the Elementary School Crosswalk Enhancement Program in Bellevue, Washington included a combination of engineering solutions – such as, installing raised crosswalks, adding curb extensions – and educational components, where brochures on safe walking practices were distributed to parents and students. The program also featured a pedestrian mascot, PedBee, which provided safety tips to students. The results showed that the average vehicle speed was reduced by 3 mph, and the campaign received positive feedback from parents and residents (PEDSAFE, 2023). The observed outcomes can be attributed to the integrated approach of combining educational and engineering interventions.

Enforcement

Pedestrians' right-of-way and creating a safe environment for all road users can be preserved by police enforcement, which can be done through different strategies such as increasing police presence around school zones, residential neighborhoods, and other areas with high pedestrian activity (PEDBIKESAFE, 2023). There are several enforcement programs being implemented in the U.S. to enhance pedestrian safety. Some of these programs include Cops in Crosswalks, New Jersey, Best Foot Forward for Pedestrian Safety, Florida, and Pedestrian Program, Washington, DC (NHTSA, 2023). The results of the Cops in Crosswalks program showed that continuous enforcement (at least six weeks or more) is more effective than spot enforcement when the goal is to increase awareness and change behavior. As a result of the Best Foot Forward for Pedestrian Safety program, the driver-yielding rate increased from 5 to 28%. Additionally, a before and after survey was conducted to evaluate the effectiveness of the Pedestrian Program on public awareness, and the results showed significant improvement (NHTSA, 2023). Moreover, there are some studies emphasizing the importance of law enforcement in pedestrian safety (Xie et al., 2018; Kim et al., 2017; Jung et al., 2016; Patel, 2020). Kim et al. (2017) suggested that more severe punishments should be allocated to traffic violations that cause severe pedestrian injuries.

Appendix B: Factors Leading to Increased Pedestrian Crash Risk/Severity

The following risk factors have been identified as causes of increased pedestrian crash risk/severity.

Roadway Geometric Characteristics

Numerous studies, including those by Quistberg et al. (2015), Harwood et al. (2008), and Carter et al. (2007), consistently underline the significance of roadway width as a contributor to pedestrian crash risk. Wider roadways often correlate with higher vehicle speeds, which can increase both the stopping distance for vehicles and the risk of higher-speed crashes, which are more likely to be fatal. In addition, wider roads require pedestrians to spend more time crossing, thereby increasing their exposure to potential vehicle conflicts.

Complex intersections with more than four segments, as highlighted by Quistberg et al. (2015) and Dumbaugh and Li (2010), introduce a multitude of traffic movements, crosswalks, and turning lanes. Such intricacies in intersection design can challenge pedestrian safety as they navigate these areas. The sheer volume of potential conflict points within these intersections poses a greater risk to pedestrians, requiring heightened vigilance on both the part of pedestrians and drivers.

The presence of bus stops near pedestrian crossings, a factor emphasized by Ukkusuri et al. (2012) and Harwood et al. (2008), adds an additional layer of complexity to pedestrian safety. Bus stops are pedestrian trip generators, leading to higher pedestrian traffic around these areas. This can result in increased interactions between pedestrians and buses, as well as potential sightline problems when buses are close to intersections. These issues are compounded by the behavior of drivers who may swerve around stopped buses, increasing the risk of conflicts. Conversations with transit agencies (i.e., NJ TRANSIT) have highlighted considerations such as relocating bus stops to after intersections to mitigate some risks, although this may lead to pedestrians having to recross busy intersections, potentially increasing their exposure to traffic.

Motorized Traffic/Operational Characteristics

Tefft (2013), Rosen et al. (2011), and Dumbaugh and Li (2010) have conducted research revealing a strong link between speed limits and pedestrian crash risk. Higher speed limits and vehicle speeds significantly elevate the probability of severe pedestrian crashes. The faster the vehicles are moving, the longer the reaction times and the greater the stopping distances, increasing the likelihood of drivers colliding with pedestrians. It’s important to note that roadway geometry can significantly influence driving speeds. Wider lanes, straight road designs, and the absence of traffic calming measures often encourage higher speeds. Addressing these geometric aspects is crucial in managing vehicle speeds and enhancing pedestrian safety.

Studies by Haleem et al. (2015) and Zhao et al. (2013) underscore the impact of heavy vehicles on pedestrian safety. The size and stopping distances of trucks and other heavy vehicles make them particularly hazardous in pedestrian crashes. In the presence of these large vehicles, the severity of pedestrian crashes is often higher, as they are less agile and more challenging to stop in emergency situations.

Furthermore, Haleem et al. (2015) and Obeng and Rokonuzzaman (2013) have consistently found that higher traffic volumes equate to a greater probability of pedestrian-vehicle interactions. While increasing traffic volumes are often indicative of urban growth and vitality, they simultaneously pose a challenge to pedestrian safety. The more interactions there are between pedestrians and vehicles, the higher the risk of crashes, making the management of these interactions critical. Effective management strategies may include modifying roadway geometries to naturally reduce vehicle speeds and enhance pedestrian safety.

Human Behavior-Based Factors

Current research highlights the significant role that human behavior plays in pedestrian crash risk and severity. Impaired driving and walking are particularly concerning. Intoxication, whether experienced by a pedestrian or a driver, drastically reduces judgment, situational awareness, and physical coordination, leading to poor decision-making while navigating roadways. Jang et al. (2013) and Zajac and Ivan (2003) confirmed this in their studies, which demonstrate that intoxicated pedestrians are at greater risk of being involved in crashes due to their impaired ability to assess traffic risks. Simultaneously, intoxicated drivers pose a risk of causing severe pedestrian crashes (Rahman, 2022). Similarly, Pour-Rouholamin, & Zhou, 2016) found that intoxicated drivers are disproportionally over-represented compared to those under normal condition in severe pedestrian crashes. Research consistently shows that impaired driving is a leading factor in fatal crashes, including those involving pedestrians (Schneider et al., 2010). Furthermore, distracted driving is also a growing concern. Numerous studies have identified distracted driving as a primary factor in pedestrian fatalities, with drivers failing to notice pedestrians on time to avoid collisions (Harwood et al., 2008).

Age is another pivotal factor in crash risk for both pedestrians and drivers, as indicated by Jang et al. (2013) and Zajac and Ivan (2003). Older pedestrians, particularly those aged 55-65 years or more, are vulnerable to severe injury in crashes due to a decline in physical resilience, slower reaction times, and potentially impaired vision or hearing. Similarly, older drivers may experience reduced reaction times and sensory impairments that can compromise their ability to navigate complex traffic situations safely. These characteristics underline the necessity for complete streets that account for and protect vulnerable populations, emphasizing the importance of creating environments that minimize potential hazards for all road users, including both older pedestrians and drivers.

Schneider et al. (2010) and Harwood et al. (2008) have found that locations with high pedestrian volumes often experience elevated risk, especially in areas with limited pedestrian infrastructure. The greater the number of pedestrians and vehicles traversing a given area, the higher the probability of conflicts. This highlights the need for dedicated infrastructure, such as wider sidewalks, pedestrian overpasses, and better lighting, to reduce risks for pedestrians, as well as operational improvements, including leading pedestrian intervals and turn on red restrictions, which separate motor vehicle and vulnerable road user movement temporally. Simultaneously, drivers must be attentive and cautious in high-density areas to avoid potential conflicts.

Addressing these factors requires a holistic approach to road safety that emphasizes the shared responsibilities of both drivers and pedestrians, as well as the need for thoughtful urban planning to create safer environments for all.

Land Use, Density, and Socioeconomic Characteristics

Research indicates that areas with higher pedestrian density, such as residential, commercial, and office zones, tend to experience increased pedestrian activity, which can heighten the risk of pedestrian-vehicle conflicts. For example, Moudon et al. (2011) note that residential areas attract a high density of pedestrians, especially around homes and apartment complexes, which can lead to conflicts with vehicles, particularly in areas lacking sufficient pedestrian infrastructure. Similarly, commercial office zones, as highlighted by Quistberg et al. (2015) and Schneider et al. (2010), attract large numbers of pedestrians during business hours, increasing the potential for conflicts at intersections, crosswalks, and transit stops.

The presence of transit hubs and bus stops, as studied by Quistberg et al. (2015), further contributes to this dynamic. Areas with high bus ridership observe high volume of pedestrians, particularly during peak hours, which necessitates careful urban planning and enhanced pedestrian accommodations to manage pedestrian-vehicle interactions safely.

Socioeconomic factors also play a crucial role in pedestrian safety. Research shows that socioeconomically disadvantaged areas often experience higher pedestrian crash and fatality rates (Patwary et al., 2024; Li et al., 2022). This disparity is largely due to the proximity of these communities to high-speed roads and the lack of adequate investment in pedestrian safety infrastructure, as these areas typically have less political capital. This underscores the importance of balanced investment in pedestrian safety measures across all communities, ensuring that high-risk areas receive the necessary improvements to protect all road users.

By focusing on the density and intensity of land use, alongside socioeconomic considerations, urban planners and policymakers can understand and address the complex factors contributing to pedestrian crash risks, thereby creating safer and more inclusive environments for all pedestrians.

Environmental Factors

Research by Jang et al. (2013) and Eluru et al. (2008) underscores the significant impact of the time of day on pedestrian safety. Pedestrian crashes are more likely to occur during nighttime hours, primarily due to reduced visibility and challenges associated with drivers perceiving pedestrians in low-light conditions. Reduced visibility can make it difficult for both pedestrians and drivers to identify each other, increasing the likelihood of crashes.

Weather conditions play a notable role in pedestrian safety, as highlighted by Haleem et al. (2015) and Jang et al. (2013). Rainy weather, in particular, poses risks due to slippery road surfaces and diminished visibility. Wet and slippery road conditions can impede a driver's ability to stop, especially at high speeds, increasing the severity of crashes involving pedestrians.

Mohamed et al. (2013) emphasizes the impact of inadequate roadway lighting on pedestrian safety. When roadways lack proper lighting, visibility is substantially reduced at night. Pedestrians may not be readily visible to drivers, and the limited illumination poses significant challenges in identifying and avoiding pedestrians, increasing the risk of crashes in poorly lit areas.

Understanding these factors within the specified subsections is essential for urban planners, traffic engineers, and policymakers to develop targeted interventions and pedestrian safety measures. Addressing these multifaceted elements is crucial for enhancing pedestrian safety in urban environments.