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Traffic safety engineering and crash analysis methods

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Abstract

Traffic safety engineering and crash analysis have played a critical role in advancing transportation systems by focusing on reducing fatalities, minimizing crash severity, and improving overall roadway conditions. This review compiles and interprets a broad spectrum of methodologies that have shaped the field in the United States, particularly those related to crash data acquisition, roadway geometric design, safety performance evaluation, and human factors integration. Emphasis has traditionally been placed on empirical approaches such as crash frequency models, empirical Bayes methods, and safety audits—tools that have provided a foundation for identifying high-risk locations and guiding countermeasure implementation.

Various techniques have been developed to evaluate the safety implications of roadway elements including signalized and unsignalized intersections, freeway segments, and multi-lane urban corridors. Key frameworks such as Safety Performance Functions (SPFs) and Crash Modification Factors (CMFs) have become instrumental in quantifying safety outcomes and comparing the effectiveness of engineering treatments. These tools have evolved to better account for behavioral dynamics, spatial distribution of crashes, and site-specific roadway features, thereby supporting more accurate and meaningful safety assessments.

Recent efforts have also focused on enhancing methodological rigor through advanced statistical tools, spatial analysis techniques, and refined use of disaggregated data. These developments contribute to a more detailed understanding of crash characteristics and roadway conditions. Complementing these methods are integrated data strategies that combine crash records, roadway inventory systems, and traffic exposure data to better isolate safety deficiencies and prioritize interventions.

Additionally, there has been a growing shift toward proactive safety management, with approaches such as systemic analysis and surrogate safety assessments helping to identify risk factors before crashes occur. Evaluations of specific engineering solutions—including roundabouts, pedestrian hybrid beacons, median treatments, and complete street implementations—provide insights into the application and outcomes of such measures across different geographic and operational settings. A notable dimension of recent work is the inclusion of vulnerable road users, such as pedestrians and cyclists, and considerations of demographic and equity-based disparities in exposure and safety outcomes.

This review consolidates foundational and evolving approaches within traffic safety engineering and crash analysis, offering transportation professionals and decision-makers a comprehensive understanding of current practices, tools, and applications aimed at improving road safety in the United States

Keywords: Traffic safety engineering; Crash analysis; Safety Performance Functions (SPFs); Crash Modification Factors (CMFs); Systemic safety evaluation; Pedestrian safety; Infrastructure improvements

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1. Introduction

Traffic safety engineering and crash analysis have become essential components of transportation system development in the United States, where roadway fatalities and injuries continue to pose significant public health and mobility concerns. As roadway networks have expanded in complexity and use, the need to ensure safe and reliable travel for all users has driven continuous advancements in analytical techniques and engineering interventions. The field has evolved from basic observational assessments of crash trends to comprehensive, data-driven practices that guide roadway design, traffic operations, and policy implementation with the goal of minimizing crash risk and severity.

Initial efforts in crash analysis often focused on reactive strategies, identifying locations with high crash frequencies and implementing treatments to address safety deficiencies. This approach, while foundational, was limited by statistical variability and regression-to-the-mean bias, which could misrepresent the true nature of crash risk. As a result, the empirical Bayes method was introduced as a more reliable alternative, combining observed crash data with estimates from reference sites to generate statistically adjusted predictions. This marked a pivotal shift in crash analysis, enabling transportation professionals to make more informed decisions based on normalized data rather than raw frequencies

In parallel with these methodological improvements, tools such as Safety Performance Functions (SPFs) and Crash Modification Factors (CMFs) were developed and standardized for broader use across transportation agencies. SPFs model the expected number of crashes as a function of traffic exposure and roadway features, allowing for predictive safety assessments. CMFs quantify the expected change in crash frequency resulting from the implementation of specific countermeasures or design changes. These tools are critical components of the Highway Safety Manual, which has served as a national guideline for integrating safety into roadway planning and project development processes. Local calibration of SPFs enhances their applicability by accounting for regional variations in traffic patterns, land use, and environmental factors.

Crash analysis has increasingly embraced sophisticated statistical techniques that improve the accuracy and depth of safety evaluations. The use of count-based regression models, particularly negative binomial models, has become standard for analyzing crash frequency data. Further advancements include the use of random parameters, hierarchical models, and Bayesian estimation techniques, which allow for a more nuanced understanding of crash causation by accounting for unobserved heterogeneity and site-specific variability. These models support comprehensive evaluations of the relationships between roadway attributes, traffic operations, and crash outcomes.

As safety concerns have expanded beyond vehicle occupants to include pedestrians, bicyclists, and other vulnerable road users, crash analysis has adapted to reflect this broader scope. Urban environments, with their high density of multimodal activity, present unique safety challenges that require tailored approaches. Factors such as crosswalk design, signal timing, land use patterns, and socioeconomic variables have been integrated into crash prediction models to better understand the risk profiles of different user groups [1]. The inclusion of these variables enhances the ability of safety professionals to develop equitable and context-sensitive countermeasures.

2. Evolution of Crash Analysis Practices in the United States

The evolution of crash analysis in the United States reflects the growing complexity of roadway systems and the expanding need for accurate, reliable methods to assess and mitigate safety risks. From its early days grounded in basic descriptive statistics to the current landscape characterized by sophisticated statistical models and predictive tools, crash analysis has undergone a significant transformation [2]. This section outlines the historical context of crash analysis, discusses limitations inherent in earlier methodologies, and describes the emergence of more advanced, data-driven techniques that form the foundation of current practice.

2.1. Early Approaches: Crash Frequency and Rate-Based Analysis

Crash analysis initially relied heavily on descriptive methods that focused on crash frequency and crash rate metrics. These included the absolute number of crashes at a given location over a specified time period or normalized measures such as crashes per million vehicle miles traveled (MVMT) or per intersection. These metrics were easy to compute and interpret, making them popular tools for early transportation agencies in identifying high-crash locations and justifying intervention strategies.

In practice, crash frequency was often used to identify sites with the most severe safety issues. However, frequency alone did not account for differences in exposure—such as traffic volume or roadway length—making it difficult to compare locations with varying levels of vehicular activity. To address this, rate-based analyses were introduced. Crash rates allowed practitioners to compare safety performance across locations by incorporating exposure measures such as Average Annual Daily Traffic (AADT) or segment length. For example, a roadway segment with a high crash frequency might not necessarily have a high crash rate if traffic volumes were also high.

Despite their practicality, these early methods were limited by their simplicity and inability to reflect the stochastic nature of crashes. Both crash frequency and rate-based analysis assumed that all sites with similar geometric and traffic conditions should exhibit similar safety performance, an assumption rarely observed in real-world data. These methods also failed to account for temporal variation, unobserved heterogeneity, and the regression-to-the-mean phenomenon, leading to potentially flawed conclusions and misallocation of safety resources.

2.2. Limitations of Traditional Approaches

One of the most significant challenges with traditional crash frequency and crash rate methods was the issue of regression-to-the-mean. This statistical effect refers to the tendency of extreme values, such as very high crash counts, to naturally regress toward the average over time—even without any intervention. If crash-prone sites were selected for treatment based solely on their observed crash counts, there was a high likelihood that future crash reductions could be misattributed to the treatment rather than natural statistical fluctuation.

Moreover, these early methods lacked the capacity to control for confounding variables. For example, two intersections with the same crash frequency might differ significantly in terms of traffic control devices, geometric design, or land use context. Traditional approaches were ill-equipped to capture these differences, leading to inconsistent and potentially misleading assessments of crash risk.

These limitations led to a gradual realization that more sophisticated, statistically robust methods were required. Particularly, there was a growing need to develop analytical frameworks that could account for variability in site conditions, adjust for exposure and randomness, and better quantify the expected safety performance of roadway elements.

2.3. Emergence of Empirical Bayes and the Shift to Predictive Modeling

The introduction of the Empirical Bayes (EB) method represented a watershed moment in crash analysis. The EB approach provides an estimate of the expected number of crashes at a given site by combining observed crash data with crash predictions from similar sites, typically derived from statistical models such as Safety Performance Functions (SPFs). This combination reduces the influence of random variation and provides a more reliable estimate of underlying safety performance.

The EB method is particularly effective in mitigating the regression-to-the-mean problem, as it avoids over-reliance on short-term crash data. Instead of treating observed crash frequency as an absolute measure of risk, the method incorporates a prior estimate derived from model predictions, which reflects the expected crash frequency based on relevant site characteristics. The final EB estimate balances observed and expected values based on the variability of the data—giving more weight to the prediction when data is sparse or uncertain.

The adoption of EB methods coincided with the development of the Highway Safety Manual (HSM), which codified many best practices in crash analysis and introduced standardized tools such as SPFs and Crash Modification Factors [3]. SPFs are mathematical models that relate crash frequency to traffic volume and roadway characteristics, while CMFs are multipliers used to estimate the effect of changes to roadway features or operational controls. These tools collectively enabled a shift from reactive, hotspot-focused analysis to proactive, system-wide safety management.

3. Crash Data Collection and Integration Techniques

Effective crash analysis in traffic safety engineering relies fundamentally on the quality, scope, and structure of the data used to assess crash patterns and safety risks. The development and implementation of robust safety countermeasures are only as good as the information upon which they are based. Over the past several decades, data collection practices in the United States have undergone considerable improvement, moving from isolated datasets to comprehensive, integrated systems that support deeper analysis and informed decision-making. This section explores the various types of data typically used in crash analysis, examines challenges related to data quality and completeness, and discusses contemporary strategies for integrating and managing large-scale safety datasets.

Crash data collection traditionally begins with police-reported crash records, which constitute the primary source for documenting motor vehicle collisions. These records typically include details about the crash event, including date, time, location, weather, lighting conditions, roadway surface, collision type, vehicle involvement, and contributing factors. Many states in the U.S. maintain centralized crash databases compiled from these reports, which are accessible to transportation agencies and researchers for analysis and safety evaluation purposes. These crash reports are standardized to some extent through the Model Minimum Uniform Crash Criteria (MMUCC), which encourages consistency across jurisdictions and enhances the comparability of crash data nationally.

In addition to crash reports, traffic volume data plays a critical role in crash analysis by providing the necessary exposure metrics required to normalize crash counts. Metrics such as Annual Average Daily Traffic (AADT) and vehicle miles traveled (VMT) are used to calculate crash rates and to estimate expected crash frequencies in predictive models. These data are generally collected through permanent count stations, temporary sensors, or manual counts conducted by state departments of transportation. For more granular analysis, agencies may use segment-based or turning movement counts, especially when assessing specific intersections or corridors.

Roadway inventory data provides another essential layer of information. This includes geometric characteristics such as lane widths, shoulder presence, number of lanes, curvature, intersection configuration, median types, traffic control devices, and signage. These attributes are critical inputs in the development of Safety Performance Functions (SPFs) and in the estimation of Crash Modification Factors (CMFs). Such data are usually maintained in Geographic Information System (GIS)-based roadway inventory systems, which allow for the spatial mapping of roadway features and their alignment with crash occurrences. When accurately maintained, these systems facilitate efficient site diagnosis and safety improvement planning.

Despite their importance, crash databases and related datasets have historically suffered from challenges related to data quality, completeness, and consistency. Incomplete crash reports, inconsistent coding of variables, lack of uniform formats across states, and missing location references are among the most common problems encountered in safety data management. These issues can introduce bias into analytical models and weaken the reliability of safety assessments. Underreporting of crashes, particularly those involving minor injuries or property damage only, is a longstanding concern that can skew the perceived safety performance of a location. Additionally, human error in data entry or interpretation of crash circumstances contributes to data inaccuracies that may compromise downstream analysis.

4. Safety Performance Functions and Crash Modification Factors

Safety Performance Functions and Crash Modification Factors are cornerstone tools in the practice of traffic safety engineering. These models and coefficients allow for the estimation, evaluation, and prediction of crash frequencies on various roadway facilities under differing operational and geometric conditions. Their widespread adoption across transportation agencies in the United States has enabled a more standardized, objective, and data-driven approach to identifying safety issues and assessing the effectiveness of roadway treatments. This section explores the conceptual foundation of SPFs and CMFs, their development and calibration, their usage in both project-level and systemic evaluations, and key practical considerations surrounding their implementation.

SPFs are mathematical functions that estimate the expected number of crashes for specific roadway types and configurations as a function of exposure variables such as traffic volume and segment length. These models typically employ negative binomial regression to account for the overdispersion commonly found in crash count data. By modeling the statistical relationship between crash occurrence and key roadway parameters, SPFs provide a baseline or "expected" crash frequency under normal conditions without intervention. This allows practitioners to compare observed crash frequencies at a location against statistically expected values to identify sites with higher-than-anticipated crash experience, often termed as high-risk or "hot spot" locations.

The development of SPFs requires the compilation of a comprehensive dataset that includes crash data, traffic volume, and roadway geometric features over a statistically meaningful time frame. These models are often specific to facility type—such as rural two-lane highways, urban arterials, or freeway segments—and may even vary between states or regions due to differences in driving behavior, environmental conditions, and design standards. As such, local calibration is frequently recommended to adjust the base SPF to the specific conditions of the area under consideration. Calibration factors are calculated by comparing observed crashes to expected crashes predicted by the base SPF across multiple sites and then applying this factor to refine future predictions.

Crash Modification Factors quantify the expected change in crash frequency as a result of implementing a specific safety countermeasure or change in roadway conditions. These factors are expressed as multipliers; for instance, a CMF of 0.80 suggests a 20% reduction in crashes, while a CMF of 1.20 implies a 20% increase. CMFs are widely catalogued in databases such as the Federal Highway Administration's CMF Clearinghouse, which provides practitioners with empirically derived values for hundreds of engineering treatments. These include modifications such as converting an intersection to a roundabout, adding dedicated left-turn lanes, installing pedestrian hybrid beacons, or implementing road diets.

In practice, SPFs and CMFs are often used in tandem. For project-level analysis, a practitioner may estimate the expected number of crashes using a calibrated SPF for a particular road segment or intersection and then apply relevant CMFs to predict how those numbers would change if specific treatments are introduced. This combined application enables agencies to prioritize safety investments based on anticipated benefits, often using cost-benefit analysis frameworks. For example, the predicted reduction in crash frequency can be translated into expected reductions in fatalities, injuries, and property damage, which can then be monetized and compared against the cost of the intervention.

Systemic safety evaluations also benefit significantly from the use of SPFs and CMFs. Unlike traditional hotspot analysis, which focuses on individual locations with high crash frequencies, systemic approaches aim to identify and treat locations with common risk factors across the entire roadway network [4]. SPFs are used to develop network-wide crash prediction models, while CMFs help to simulate the effect of different countermeasures applied at multiple sites. This allows for the implementation of proactive safety programs that address systemic issues, such as run-off-road crashes on rural curves or angle crashes at unsignalized intersections, even before they become severe problem areas.

5. Evaluation of Safety Treatments and Infrastructure Improvements

The evaluation of roadway safety treatments and infrastructure enhancements plays a central role in traffic safety engineering by enabling practitioners to quantify the effectiveness of interventions designed to reduce crash frequency and severity. As roadway networks grow in complexity and demand increases from both motorized and non-motorized users, it becomes critical to assess the performance of physical modifications and traffic control strategies through rigorous, data-driven methods. Treatments such as roundabouts, pedestrian hybrid beacons (PHBs), median installations, and complete street designs are widely implemented across the United States and have undergone extensive evaluation to determine their safety benefits across diverse operational environments. These assessments inform future design and investment decisions and support the strategic allocation of limited safety improvement resources.

Roundabouts have been widely adopted as a safety treatment at intersections due to their proven ability to reduce the frequency and severity of crashes. Traditional signalized or stop-controlled intersections are often associated with angle and left-turn collisions, which can result in high injury severity. Roundabouts, by contrast, reduce vehicular speeds and eliminate perpendicular conflict points by converting all movements into circulating flows.

Research conducted in the United States indicates that roundabouts result in substantial safety benefits. According to a synthesis of evaluation studies, the installation of roundabouts has been associated with an average reduction of 37 percent in total crashes and 51 percent in injury crashes [5]. Multilane roundabouts offer similar benefits, although their performance can vary depending on driver familiarity, signage clarity, and pedestrian accommodations.

Pedestrian Hybrid Beacons (PHBs), also known as HAWK signals, are another widely implemented treatment aimed at improving pedestrian safety on midblock or uncontrolled crossing locations. PHBs operate by stopping traffic only when a pedestrian is present and activating a pedestrian-specific signal sequence. Evaluations of PHB installations have shown substantial reductions in pedestrian crashes—often in the range of 50 to 60 percent—particularly in locations where vehicle speeds and volumes are high, and traditional crosswalks are insufficient [6]. Additionally, driver compliance with PHB signals tends to be higher than with unsignalized crossings, further enhancing their effectiveness in providing safe crossing opportunities.

Complete streets policies, which aim to accommodate users of all ages and abilities regardless of their mode of travel, represent a broader infrastructural approach rather than a single treatment. These designs incorporate features such as bicycle lanes, pedestrian refuge islands, traffic calming devices, and improved lighting. Although the impacts of complete street implementations are context-specific, evaluations generally indicate a positive effect on safety for non-motorized users [7]. Roads retrofitted with complete street elements have reported reductions in pedestrian and bicycle crashes while also maintaining or improving traffic flow for motor vehicles. Moreover, these improvements contribute to increased walking and cycling activity, which has ancillary public health and environmental benefits.

6. Equity and Vulnerable Road User Considerations in Crash Analysis

Equity in traffic safety has emerged as a central concern in the development and implementation of modern transportation policies, reflecting a broader shift toward inclusivity in public health and infrastructure planning. As disparities in crash exposure, severity, and outcomes become increasingly evident across demographic and socioeconomic groups, integrating equity considerations into crash analysis has become essential for ensuring just and effective safety interventions. Vulnerable road users—including pedestrians, bicyclists, and individuals from underserved communities—often experience disproportionate levels of risk, yet they are frequently underrepresented in traditional safety models. Addressing these imbalances requires the development of analytical frameworks and policy strategies that prioritize equity without compromising technical rigor or data quality.

Demographic and socioeconomic dimensions are closely intertwined with transportation safety outcomes. Communities characterized by higher poverty rates, lower vehicle ownership, and greater proportions of minority populations often face greater exposure to traffic hazards. This increased vulnerability is frequently due to a combination of infrastructure deficits, such as inadequate pedestrian facilities or poorly maintained roadways, and behavioral factors driven by necessity, such as walking or biking due to lack of access to private vehicles. Research has consistently shown that fatality and injury rates for pedestrians and cyclists are significantly higher in low-income and minority neighborhoods than in more affluent areas with better infrastructure and traffic controls.

The spatial distribution of these disparities often reflects historical patterns of disinvestment in infrastructure and planning decisions that have favored automobile-oriented development. Major arterials cutting through lower-income urban areas, often lacking safe crossings, traffic calming measures, or sufficient lighting, can pose deadly hazards to those who rely on walking or biking as a primary mode of transportation [8]. Moreover, these corridors often coincide with higher pedestrian activity due to the presence of transit stops, schools, or commercial centers, further compounding exposure to risk. Understanding the interplay between demographic characteristics and environmental context is critical in modeling safety outcomes and identifying priority locations for intervention.

One of the primary challenges in crash modeling for vulnerable road users lies in the limited availability and quality of data. Pedestrian and cyclist crashes, particularly those that result in minor injuries or do not involve motor vehicles, are significantly underreported in official databases. Furthermore, traditional exposure measures such as vehicle miles traveled (VMT) are not directly applicable to pedestrians and cyclists, making it difficult to calculate meaningful crash rates or risk metrics. While some cities have begun collecting pedestrian and bicycle counts, these efforts are not yet widespread or standardized, and often lack the temporal and spatial resolution needed for rigorous analysis.

In the absence of robust exposure data, proxy variables such as land use patterns, presence of sidewalks or bike lanes, and proximity to transit stops are sometimes used to estimate pedestrian and bicycle activity levels. However, these proxies may introduce additional uncertainty and limit the comparability of results across studies. Furthermore, standard safety performance functions (SPFs) often do not account for vulnerable user behavior or built environment characteristics relevant to non-motorized modes, leading to potential underestimation of risk in areas heavily used by these groups.

Another challenge is the variability in crash types and contributing factors associated with vulnerable road users. Pedestrian crashes are often influenced by visibility, driver yielding behavior, signal compliance, and pedestrian crossing strategies, which may not be adequately captured in conventional crash data. Similarly, cyclist crashes may involve complex interactions with vehicles, roadway geometry, and traffic flow that require more detailed observational or behavioral data to understand [9]. Incorporating such nuances into predictive models necessitates richer data sources and more complex modeling techniques, often involving spatial analysis and multilevel modeling frameworks.

7. Current Challenges and Future Directions

The evolution of traffic safety engineering and crash analysis has led to the development of more refined methodologies, improved data integration practices, and a greater emphasis on vulnerable road users and equity. However, the field continues to face several ongoing challenges and complexities that limit the effectiveness and scope of current practices [10]. These include persistent data gaps, shifts in road use patterns, integration issues with emerging vehicle technologies, and evolving policy frameworks. Addressing these challenges will require a coordinated effort among researchers, transportation agencies, and policymakers to ensure that the future of traffic safety is equitable, adaptive, and grounded in accurate and actionable information.

One of the most significant challenges in crash analysis remains the quality, availability, and completeness of data. Despite improvements in data collection and reporting systems, crash databases across many jurisdictions still suffer from underreporting, particularly for non-fatal crashes and those involving vulnerable road users. In many regions, pedestrian and cyclist crashes are less likely to be reported unless they involve motor vehicles or result in serious injury. Moreover, crash reports often lack key contextual variables such as lighting, weather conditions, behavioral indicators, and precise location data, all of which are critical for comprehensive safety assessments. These gaps hinder the accuracy of statistical models and reduce the reliability of intervention strategies.

Another data limitation arises from the challenge of estimating exposure for non-motorized users. Unlike vehicular traffic, which is commonly measured through traffic counts and loop detectors, pedestrian and cyclist exposure data is rarely collected systematically. This limits the ability to compute accurate crash rates or develop risk-based safety performance functions for these user groups. Some agencies have attempted to estimate pedestrian and bicycle volumes using proxy variables such as land use or census data, but these approaches often introduce significant uncertainty. Expanding the coverage and consistency of non-motorized traffic counts remains a critical step in overcoming these analytical limitations.

The dynamic nature of road use patterns also presents challenges for traditional safety analysis frameworks. The emergence of new mobility forms—such as e-scooters, ride-hailing services, and microtransit—has changed how individuals interact with the transportation system. These modes often blur the lines between pedestrian and vehicular travel and introduce new safety risks that are not yet fully understood or incorporated into existing models [11]. For example, conflicts between bicycles and e-scooters, or between ride-hailing vehicles and pedestrians at pick-up/drop-off locations, represent safety concerns that are difficult to assess using legacy crash data systems designed for conventional vehicles.

8. Conclusion

The field of traffic safety engineering and crash analysis has made substantial strides in recent decades, driven by a growing demand for safer and more equitable transportation systems across the United States. From its early reliance on descriptive statistics and frequency-based approaches, crash analysis has matured into a sophisticated discipline underpinned by predictive modeling, systemic risk assessment, and multidimensional data integration. The evolution of methods—ranging from the application of empirical Bayes techniques to the development of Safety Performance Functions and Crash Modification Factors—has transformed how transportation professionals identify safety issues, evaluate interventions, and allocate resources.

One of the most prominent achievements in the field is the shift from reactive to proactive safety management. Traditionally, interventions were deployed after high crash rates had already occurred. Today, systemic approaches allow for the identification of risk-prone areas based on shared characteristics, rather than waiting for crash histories to accumulate. Tools such as surrogate safety measures and system-wide risk models are increasingly used to forecast crash potential and guide early action, ensuring that safety improvements are distributed more effectively and equitably across the network.

Another important development has been the enhanced ability to model and evaluate a diverse array of safety treatments. Infrastructure improvements such as roundabouts, pedestrian hybrid beacons, medians, and complete street retrofits have all been rigorously evaluated and proven effective in reducing crash frequency and severity. Importantly, these evaluations now consider the needs of both motorized and non-motorized users, acknowledging that different user groups experience the roadway environment in fundamentally different ways. The growing inclusion of pedestrian, cyclist, and equity-related considerations in crash analysis frameworks represents a necessary correction to historic imbalances and supports more inclusive and just safety planning.

Data quality and integration remain central themes throughout the field's progression. The ability to accurately collect, geocode, and integrate crash data with roadway inventory, traffic volume, and demographic information has elevated the depth and reliability of safety evaluations. Yet, challenges persist—particularly regarding the underreporting of vulnerable road user crashes, limited pedestrian and cyclist exposure data, and inconsistent data formats across jurisdictions. Overcoming these challenges requires continued investment in data infrastructure, capacity building among local agencies, and greater standardization at the federal level.

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