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SMART CORRIDOR SIMULATION FOR PEDESTRIAN SAFETY: : INSIGHTS FROM VISSIM-BASED URBAN TRAFFIC MODELS

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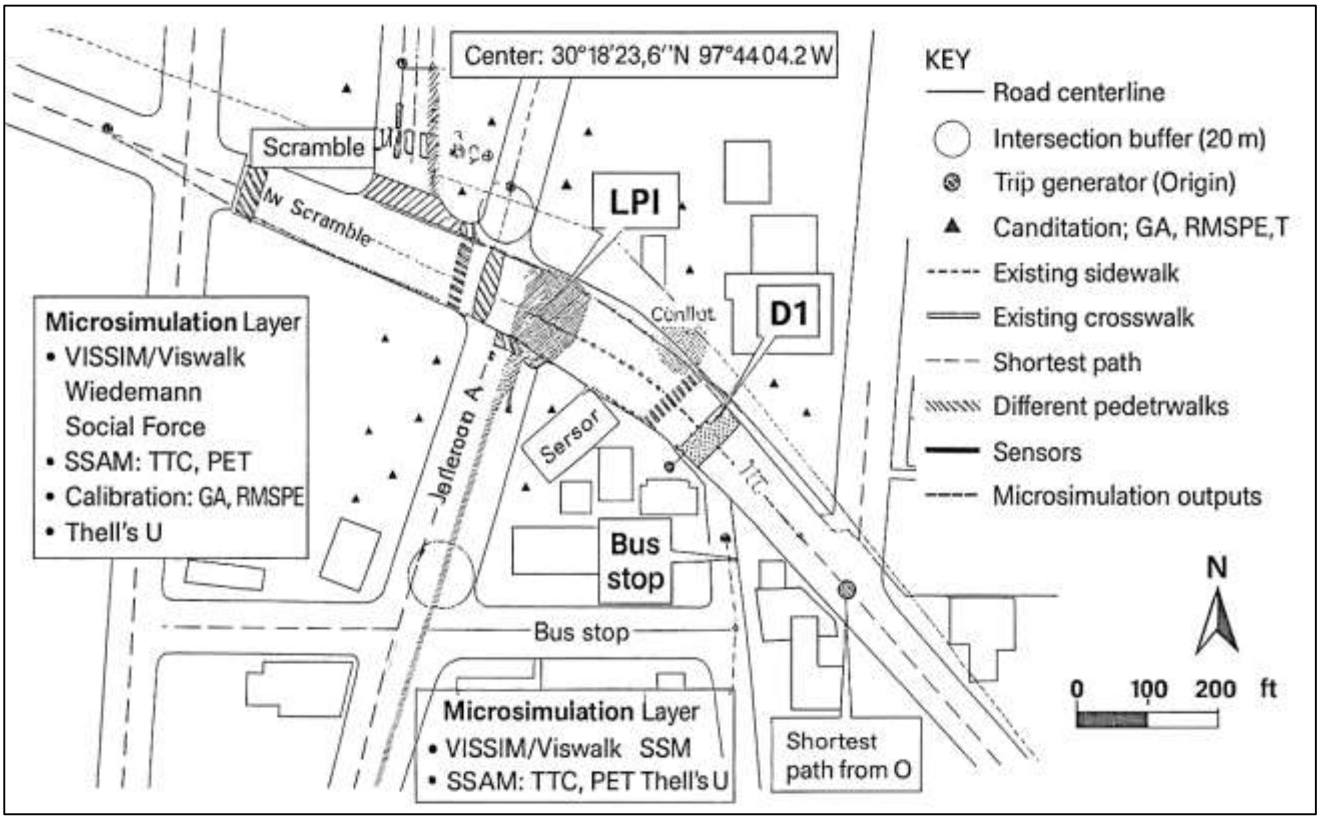
Abstract
Rapid urbanization and the growth of multimodal transport systems have increased the complexity of pedestrian–vehicle interactions at urban corridors, leading to heightened safety risks and congestion. This study develops a quantitative simulation framework using PTV VISSIM to evaluate how smart-corridor interventions – such as adaptive signal control, pedestrian detection systems, and geometric traffic-calming measures – can enhance pedestrian safety without compromising traffic efficiency. A 2.0-km urban corridor featuring multiple signalized and unsignalized crossings was modeled and calibrated with empirical traffic and pedestrian data collected from typical weekday and weekend conditions. Five simulation scenarios were constructed, including a baseline case and four smart-corridor configurations representing various technology integrations. Each scenario was replicated across different demand states using stochastic seeding to ensure statistical robustness. Conflict-based safety indicators such as Time-to-Collision (TTC), Post-Encroachment Time (PET), and Deceleration Rate to Avoid Crash (DRAC) were extracted from trajectory files using the Surrogate Safety Assessment Model (SSAM). These surrogate measures were normalized by pedestrian exposure to compute conflict rates per 1,000 crossings. Results were analyzed using negative binomial generalized linear mixed models (NB-GLMM) to estimate incidence rate ratios (IRRs) for both total and severe conflicts. Complementary linear mixed models (LMM) were applied to evaluate mobility outcomes including pedestrian delay, vehicle delay, and mean speed. Sensitivity analyses tested variations in threshold definitions (TTC, PET) and behavioral parameters to validate the robustness of findings. Preliminary results indicate that smart-corridor configurations integrating adaptive pedestrian detection and traffic-calming geometry achieved up to a 35% reduction in severe conflicts (IRR = 0.65, $p < 0.05$) while maintaining acceptable vehicle delay increases below 10%. Pedestrian delay improvements were most pronounced under adaptive signal logic, suggesting strong synergies between detection-based actuation and optimized signal timing. The study concludes that smart-corridor designs, when strategically modeled and validated through microsimulation, can serve as a reliable decision-support tool for urban planners seeking to balance pedestrian safety and traffic mobility. The research contributes a reproducible, data-driven framework for evidence-based evaluation of intelligent transportation systems (ITS) in pedestrian-rich urban environments.

Keywords: *Smart Corridor, Pedestrian Safety, VISSIM Simulation, Urban Traffic, Surrogate Safety.*

INTRODUCTION

Pedestrian safety research increasingly converges on corridor-scale design and operations because risk accumulates along continuous urban segments where walking, cycling, transit access, and motorized traffic interse (Ni et al., 2016). In this paper, a smart corridor is defined as an urban multi-modal roadway segment instrumented or analytically modeled to optimize safety and performance using data, control logic, and simulation; the emphasis is on microsimulation to evaluate near-term operating states under alternative treatments. We operationalize pedestrian safety using proactive surrogate safety measures (SSMs)—notably time-to-collision (TTC) and post-encroachment time (PET)—that estimate exposure to conflicts without waiting for rare crash outcomes. Global health agencies identify pedestrian injury as a leading public health burden: the WHO reports ~1.19 million road deaths annually and tens of millions of injuries, with more than half among vulnerable road users (VRUs) (pedestrians, cyclists, motorcyclists) (Chang et al., 2020). The UN SDGs embed safety in Target 11.2 (safe, affordable, accessible transport) and Target 3.6 (reducing road deaths), anchoring corridor interventions in development agendas. OECD/ITF syntheses likewise position walking at the core of sustainable urban mobility and public health, underscoring design guidance and programmatic action for safer streets (Mwakalonge et al., 2015). National programs, including Vision Zero and Safe System guidance, have pushed cities to redesign high-injury corridors, prioritize VRUs, and institutionalize data-driven analysis. Beyond policy framing, recent monitoring shows persistent challenges: U.S. projections indicated elevated pedestrian risk over the past decade even as some regions improved in 2021; similar concerns surface in rapidly motorizing contexts such as India, where mid-sized cities report pronounced VRU exposure. Quantitative corridor-level simulation therefore offers an actionable, internationally transferable method to evaluate operations and safety for pedestrians under realistic demand, behavior, and control conditions—enabling evidence-based design choices before implementation. This study contributes to that need by focusing on VISSIM-based models, embedded SSMs, and calibration/validation procedures aligned with institutional safety practice (Tiwari, 2020).

Figure 1: VISSIM Smart Corridor Safety Framework

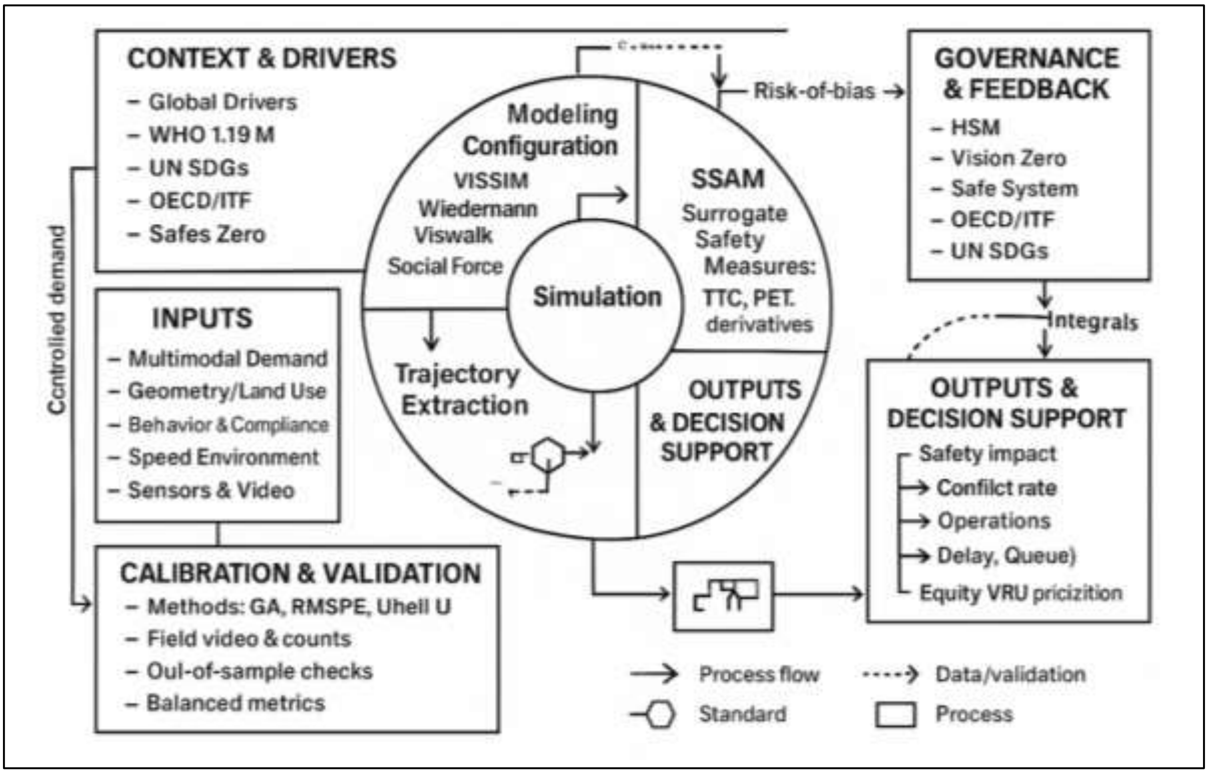


PTV VISSIM is a microscopic, stochastic simulator widely used to evaluate multi-modal operations. Its vehicle dynamics rely on the Wiedemann psycho-physical car-following models ('74/'99), which reproduce acceleration, deceleration, and headway states with perception thresholds; agencies provide modeling guidance for parameterization under heterogeneous traffic (Combs et al., 2019; Rezaul, 2021). Pedestrian movement is represented via an adaptation of the Social Force Model, implemented in VISWALK and configurable by pedestrian type. Comparative work documents how VISSIM/Viswalk settings influence flow through bottlenecks and interactions, motivating careful calibration to empirical traces. Within VISSIM, conflict areas govern pedestrian–vehicle priority, gap acceptance, and yielding at crossings; the configuration of links/connectors and conflict geometry directly shapes crossing times and potential interactions. Open and academic sources have introduced meta-heuristics and statistical indicators for calibrating pedestrian parameters, aiming to reconcile simulated trajectories with observed distributions of speed, density, and travel time. For safety analytics, SSAM automates conflict detection from simulation trajectories, aligning with FHWA's program of surrogate analysis to quantify the frequency/severity of narrowly-averted events (Tahmasbi-Sarvestani et al., 2017). TTC and PET emerge as robust, interpretable time-based indicators across contexts; classic and contemporary literature formalizes TTC from near-miss theory and PET from traffic conflict analysis. A recent systematic review confirms TTC and PET as the most prevalent SSMs, with complementary spatial/kinematic metrics often applied in mixed traffic. These foundations justify a VISSIM-centric approach that couples calibrated behavior models with standardized conflict extraction to study smart corridor configurations for pedestrian safety (Deb et al., 2017).

The FHWA Surrogate Safety Assessment Model (SSAM) formalizes an integrated workflow—simulation, trajectory extraction, and conflict classification—for proactive safety evaluation when crash data are scarce or lagging. Within this framework, TTC quantifies the time remaining until collision along projected paths under current kinematics, while PET measures the temporal gap between one user leaving and another entering a conflict area—both sensitive to yielding, speed management, and signal timing (Bella & Silvestri, 2015). Methodological studies compare indicators, discuss thresholds for criticality, and advocate multi-metric lenses in complex urban settings; some extend TTC/PET with derivatives such as TDTC for pedestrian-involved events. Institutional safety practice supports this proactive turn. The AASHTO Highway Safety Manual (HSM) and its updates emphasize quantitative methods, safety management process integration, and human-factors foundations—providing a policy and planning backdrop for microsimulation-based safety assessment (Fu et al., 2018). National Safe System and Vision Zero resources specify VRU-first principles compatible with corridor SSM analysis, encouraging agencies to embed protective design and speed management into planning and operations. As pedestrian risk profiles vary across geographies and land-use patterns, institutional guidance increasingly calls for diagnostic assessments that combine operations, exposure, and conflict analysis at the facility scale. In this study, SSMs serve as dependent variables in a VISSIM-based experimental design to evaluate crosswalk control strategies, phase sequences, and geometric treatments along a smart corridor—aligning with accepted practice while remaining sensitive to local behavior and demand (Avinash et al., 2019).

Empirical studies integrating VISSIM and SSAM report encouraging accuracy in reproducing observed pedestrian–vehicle conflicts after calibration and validation with field video. For example, an arterial case in Kolkata achieved >90% prediction accuracy for pedestrian conflict frequency using TTC/PET-based extraction from calibrated trajectories (Zhang et al., 2019). Work at signalized intersections identified PET/TTC thresholds tailored to pedestrian–vehicle interactions and showed that a VISSIM-SSAM pipeline can replicate field-observed conflict counts and distributions, thereby supporting design evaluation. Additional studies apply PET at unsignalized intersections under mixed traffic to compare alternative control and marking schemes, demonstrating the feasibility of SSMs where crash data are unreliable. Microsimulation has also been used to test scramble phases versus conventional crossings, quantify crossing times, and assess level-of-service impacts when pedestrians receive exclusive phases—offering insights into exposure reduction in high-conflict nodes (Corazza et al., 2016). Beyond intersections, mid-block crossing models have been developed with driver yielding estimates and queue/time validation, illustrating corridor segments where pedestrian demand concentrates . Recent contributions from India and other heterogeneous-traffic environments adapt VISSIM to local modal mixes and compliance patterns, broadening generalizability to settings with two-wheelers and informal crossing behavior. Newer articles continue to evaluate TTC, PET, and combined criteria for interaction severity classification at signals, pointing to multi-indicator strategies for robust inference. Collectively, these studies motivate corridor-scale experiments that vary pedestrian treatments, progression plans, and spatial design to observe changes in conflict exposure—an approach this paper codifies within a transparent, quantitative framework (Lee et al., 2015).

Figure 2: VISSIM Smart Corridor Safety Simulation



Accurate safety inference from simulation depends on behavior fidelity. For vehicles, agencies and researchers document parameter ranges for Wiedemann-74/99 (desired speed distributions, standstill distance, headway, lane-change aggressiveness) and demonstrate sensitivity to speed regimes. For pedestrians, social force parameters (desired speed, τ, interpersonal repulsion/attraction) require calibration to observed trajectories and facility types; studies validate the model against bottleneck experiments and real-world data (Møgelmose et al., 2015). Open implementations show how genetic algorithms and cross-validation metrics (e.g., RMSPE, Theil's U) tune VISSIM/Viswalk to empirical counts and travel times. Within the network, conflict areas mediate priority rules and interactions; documentation describes how geometry and link angles affect crossing path length and clearing times, which in turn influence PET and TTC realizations during simulated cycles. SSAM's trajectory filters and conflict classifiers then compute indicator distributions suitable for statistical comparison to field observations, as established in FHWA's SSAM validation reports (Jung et al., 2016). For quantitative corridor studies, we follow validation practices from the literature that pair video-based conflict observation with model calibration and out-of-sample validation on performance measures such as crossing time and approach queues. This procedural chain positions the analysis to interpret SSM shifts under counterfactual signal timing, pedestrian phase patterns, and spatial treatments while controlling for demand, compliance, and driver yielding—key corridor factors in mixed traffic (Schwebel et al., 2016).

Institutional frameworks increasingly encourage corridor-level diagnostics that combine operations and safety . The HSM and its 2nd-edition updates promote quantitative methods and predictive analysis in project development, providing methodological scaffolding to relate design decisions to safety outcomes. FHWA Vulnerable Road User Safety Assessment Guidance advances Safe System principles—safe roads, safe speeds, safe users, safe vehicles, post-crash care—and recommends comprehensive, data-driven strategies that include proactive evaluation tools aligned with SSM workflows (Guo et al., 2017). Vision Zero resources from public health and transportation agencies underscore systematic protections for VRUs and prioritization of high-injury corridors; city reports document resource targeting toward locations with concentrated KSI histories. In the broader evidence base, OECD/ITF reviews call for walkability and street-design improvements as co-benefits for safety, environment, and health, reinforcing the role of design standards that specify protected crossings, leading pedestrian intervals, and speed-management elements (Harriage et al., 2016). Contemporary monitoring underscores the need for rigorous evaluation methods as patterns evolve across jurisdictions; news-linked summaries of state-level U.S. trends show uneven progress, which strengthens the case for corridor-specific, quantitative analysis to surface effective countermeasures under local demand and behavioral conditions. Within this context, smart corridor simulation with VISSIM integrates smoothly with agency toolchains, translating proposed timing plans, phase sequences, and layout variations into measurable changes in conflict exposure before committing to capital or signal-system changes (Patella et al., 2020).

Given the definitional clarity around smart corridors, the modeling foundations of VISSIM/Viswalk, and the institutionalization of SSMs in practice, a quantitative design can be framed as follows: (a) construct and calibrate a corridor network with observed multimodal demand; (b) configure conflict areas and pedestrian signal logic ; (c) extract and classify simulated trajectories with SSAM to compute TTC, PET, and derivatives; and (d) analyze indicator distributions under controlled treatment comparisons. The TTC construct descends from near-miss theory, measuring imminence of collision under current kinematics; PET quantifies temporal separation at shared space entry/exit—both linked to yielding, compliance, and speed control (Patella et al., 2020). Literature advises multi-indicator approaches to capture severity and frequency dimensions, with systematic reviews confirming the centrality of temporal proximity measures across contexts. Empirical VISSIM-SSAM studies show feasibility across signals, mid-blocks, and mixed traffic, with calibrated models reproducing field conflicts and enabling scenario evaluation for phase patterns and spatial treatments. Institutional guidance in HSM and VRU assessments provides the governance frame for deploying such analytics within planning and project development. Finally, widely adopted design compendia and policy agendas (NACTO, OECD/ITF, Vision Zero, WHO/UN targets) situate corridor-level safety improvements within global public health and sustainable mobility objectives, reinforcing the suitability of simulation-based quantitative analysis for pedestrian-first outcomes (Zhang et al., 2017).

The primary objective of the study titled "Smart Corridor Simulation for Pedestrian Safety: Insights from VISSIM-Based Urban Traffic Models" is to develop a comprehensive simulation model using the VISSIM microsimulation platform to analyze and enhance pedestrian safety within urban corridors. This research aims to create a realistic and data-driven representation of a "smart corridor," incorporating multiple elements such as vehicle flow, pedestrian movements, signal phasing, and infrastructure design. Through this model, the study seeks to understand the complex dynamics of mixed-traffic environments where pedestrians and vehicles interact frequently, and where safety risks are most pronounced (Koekemoer et al., 2017). Another important objective is to evaluate the effectiveness of smart corridor interventions in improving pedestrian safety outcomes. By simulating various safety-enhancing measures—such as adaptive signal controls, intelligent pedestrian crossing systems, and real-time alert technologies—the study will assess their impact on critical safety parameters, including pedestrian waiting times, vehicle-pedestrian conflicts, and crossing compliance rates. Comparing these results with baseline (non-intervention) scenarios will help determine which smart technologies and design features yield the most significant improvements in pedestrian safety and overall traffic efficiency. Furthermore, the research aims to analyze the interactions between vehicular flow and pedestrian movement under diverse traffic conditions. Using VISSIM's behavioral modeling tools, the study will explore how varying traffic volumes, vehicle speeds, and pedestrian densities influence safety outcomes and mobility performance (Kim, 2019). This analysis will help identify conditions that increase collision risks or disrupt traffic flow, providing valuable insights for traffic engineers and urban planners seeking to optimize corridor design. Finally, the study seeks to identify and validate key performance indicators (KPIs) for assessing and optimizing smart corridor designs. Metrics such as pedestrian delay, vehicle-pedestrian conflict frequency, and level of service (LOS) for both modes of transport will be examined to establish a set of measurable indicators that can guide future infrastructure improvements. By achieving these objectives, the study aims to provide an evidence-based framework for implementing smart corridor concepts that enhance pedestrian safety, support sustainable mobility, and contribute to smarter, safer urban environments.

LITERATURE REVIEW

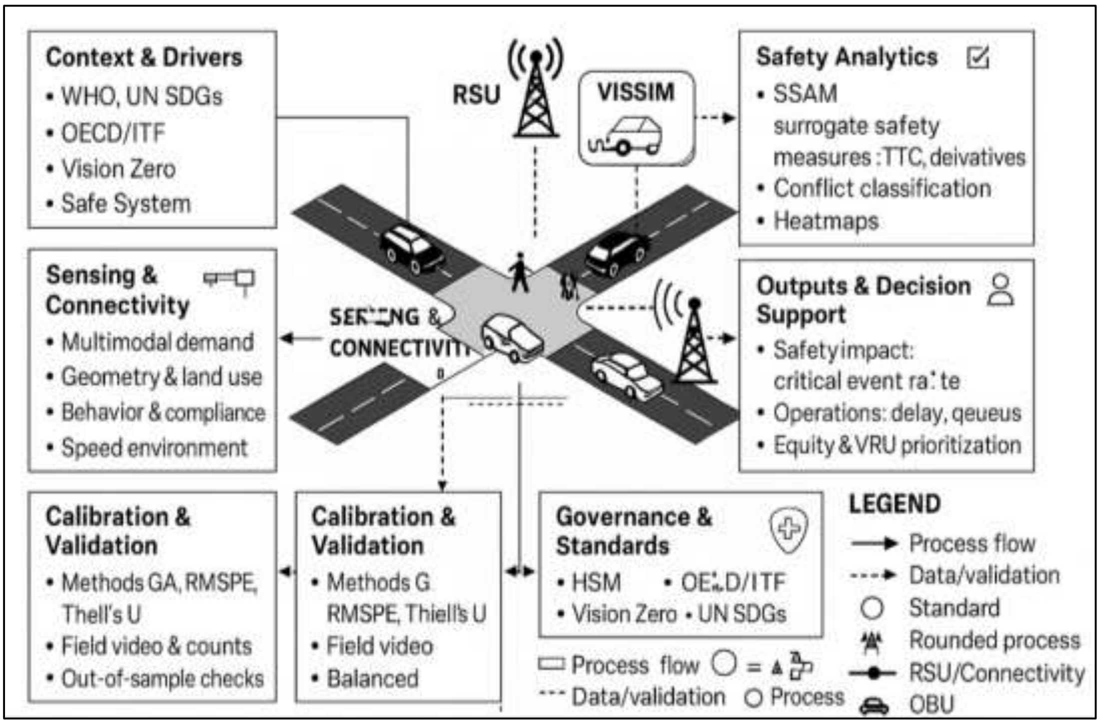
The literature review situates this study within the broader body of pedestrian safety, urban traffic modeling, and microsimulation research. A comprehensive synthesis is needed because pedestrian injuries and fatalities remain a global challenge despite advances in roadway engineering and intelligent transport systems. International institutions, including the World Health Organization (WHO) and the United Nations (UN), stress the urgency of safeguarding vulnerable road users (VRUs), particularly pedestrians, who comprise a disproportionately high share of road traffic fatalities . This policy emphasis frames academic research on "smart corridors" as not only technical but also socially transformative, embedding safety, sustainability, and equity in transportation design.Within the academic sphere, researchers have explored pedestrian dynamics using agent-based models, stochastic microsimulation, and conflict analysis tools. One simulation platform—PTV VISSIM—emerges as a widely validated software capable of reproducing heterogeneous traffic conditions, modeling vehicle–pedestrian interactions, and extracting surrogate safety measures (SSMs) such as time-to-collision (TTC) and post-encroachment time (Barin et al., 2018). These indicators provide quantitative insights into safety performance without waiting for rare but severe crash data. VISSIM's Viswalk module, rooted in the social force model, enables detailed representation of pedestrian flow and crosswalk dynamics, making it especially useful for corridor-scale interventions where pedestrian and vehicle trajectories frequently overlap.Moreover, a growing body of research applies simulation-based safety assessments to evaluate crosswalk design, traffic signal timing, and mid-block crossings under varying conditions. Literature converges on the role of calibrated simulation models in reproducing empirical safety patterns, validating conflict frequencies, and testing counterfactual scenarios such as exclusive pedestrian phases or leading pedestrian intervals (Noh et al., 2018). At the same time, agencies such as FHWA and AASHTO integrate simulation-driven safety tools into institutional practice, bridging research with policy.Thus, the literature review will critically synthesize prior studies across conceptual frameworks, methodological advances, empirical applications, and institutional guidance to provide a structured foundation for the present quantitative analysis of VISSIM-based smart corridor simulations.

Pedestrian Safety in Urban Corridors

Smart corridors have emerged as an applied concept in urban traffic engineering that integrate technology, data-driven management, and infrastructure design to enhance operational efficiency and safety for all users, particularly pedestrians. They represent a transition from traditional corridor planning toward adaptive systems that combine simulation, sensing, and control for multimodal use (Hamdane et al., 2015). As articulated in transportation literature, a smart corridor is generally understood as a roadway segment that employs advanced traffic management strategies, digital communication, and safety monitoring tools to ensure continuous and secure travel. In pedestrian contexts, these corridors serve a crucial role by structuring crossings, channelizing flows, and deploying intelligent signal control to reduce conflicts with motorized vehicles. Unlike localized intersection treatments, smart corridors offer an extended spatial perspective, capturing cumulative risks along sequences of blocks where pedestrian exposure is recurrent (Wang et al., 2018). A defining feature is their integration of simulation models such as PTV VISSIM, which enable scenario testing prior to real-world implementation. These models help planners balance efficiency with vulnerable road user protection by quantitatively assessing alternative signal plans, crossing treatments, and geometric designs. Empirical findings indicate that corridors equipped with adaptive pedestrian phases and traffic calming elements significantly reduce near-miss incidents. Therefore, the smart corridor framework situates itself at the nexus of technological innovation and public safety, ensuring that pedestrians—who constitute a large share of vulnerable road users—are safeguarded through

integrated and continuous design strategies rather than piecemeal interventions (Delso et al., 2017).
The significance of pedestrian safety within smart corridor research cannot be separated from the overwhelming global burden of road traffic injuries. The World Health Organization reported that approximately 1.19 million people die annually due to road crashes, with more than half of these deaths occurring among vulnerable road users, including pedestrians, cyclists, and motorcyclists. These fatalities are not equally distributed, with low- and middle-income countries bearing more than 90% of the burden, despite having fewer vehicles overall. Pedestrians alone account for nearly 23% of global traffic deaths, underscoring the urgency of targeted interventions (Peng et al., 2017). The United Nations Sustainable Development Goals explicitly identify road safety and equitable transport access as global priorities, reinforcing the policy imperative for pedestrian-first infrastructure. Regionally, studies in Sub-Saharan Africa and South Asia reveal alarmingly high pedestrian fatality rates linked to inadequate infrastructure, informal crossing behavior, and rising motorization. Even in high-income countries, trends are concerning: U.S. pedestrian fatalities increased by 46% between 2010 and 2020, largely attributed to roadway design favoring vehicle speed over pedestrian protection. These international disparities confirm that pedestrian injury is both a health crisis and a developmental challenge, demanding design solutions beyond conventional vehicle-focused safety programs. Within this global burden, the concept of smart corridors gains salience as they present scalable, adaptive frameworks capable of integrating international safety goals into localized design solutions. By embedding simulation-based analyses and proactive interventions, smart corridors directly respond to the dual challenge of reducing fatalities and achieving sustainable, inclusive urban mobility worldwide (Tan et al., 2020).

Figure 3: VISSIM Smart Corridor Pedestrian Safety



Theoretical frameworks for pedestrian safety revolve around three key constructs: exposure, risk factors, and the use of surrogate safety measures (Meetiyagoda, 2018). Exposure is typically defined as the extent of interaction between pedestrians and vehicles, which increases with traffic volume, crossing frequency, and corridor design. Risk factors include behavioral dimensions such as driver yielding compliance and pedestrian gap acceptance, as well as environmental conditions such as lighting, land use density, and crossing design. Empirical research shows that wider roads, higher vehicle speeds, and absence of protected crossings drastically increase pedestrian crash likelihood. Given the rarity yet severity of crashes, surrogate safety measures (SSMs) have been introduced to quantify potential conflicts using observable or simulated data. Two of the most widely applied indicators are time-to-collision (TTC) and post-encroachment time (PET), which estimate the proximity of interactions without requiring actual collisions (Hack et al., 2020). Studies demonstrate strong correlations between SSMs and observed conflict frequencies, confirming their validity as proactive safety tools. VISSIM, integrated with the Surrogate Safety Assessment Model (SSAM), has been extensively used to extract these indicators for vehicle–pedestrian interactions in simulated corridors. The appeal of surrogate safety analysis lies in its ability to anticipate risks in environments where reliable crash data are limited or unavailable, particularly in developing countries. As such, the theoretical construct of pedestrian safety has evolved from purely reactive crash-based approaches toward exposure-based and conflict-based evaluations that better capture everyday safety dynamics in urban corridors.

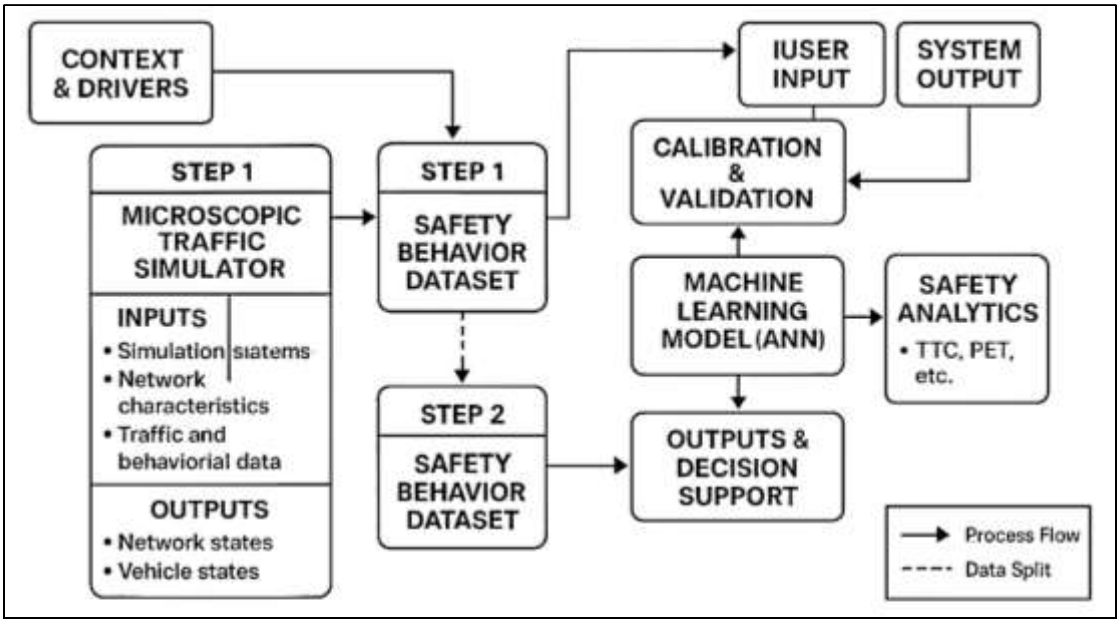
The Safe System and Vision Zero approaches provide critical paradigms that shape the international discourse on pedestrian safety and align directly with smart corridor interventions. The Safe System framework, first developed in Sweden and later adopted globally, emphasizes designing transport systems to accommodate human error while minimizing crash severity through safe speeds, safe roads, safe users, and safe vehicles (Castanho et al., 2017). Vision Zero, a policy movement originating in Sweden in the 1990s, takes this principle further by asserting that no loss of life is acceptable within a transport system. These frameworks shift accountability from individuals to system designers, positioning infrastructure, regulation, and policy as levers for safety. Empirical evaluations of Vision Zero programs in European and North American cities have shown measurable reductions in traffic fatalities, particularly when corridor redesigns prioritize pedestrian protection through traffic calming, protected crossings, and exclusive signal phases. Similarly, Safe System applications in Australia and New Zealand demonstrate that corridor-wide speed management and safe crosswalk designs reduce pedestrian fatalities by embedding protective redundancies (Salmon & Lenné, 2015). The relevance to smart corridors lies in the frameworks' emphasis on proactive, system-level interventions that anticipate errors rather than react to crashes. By embedding SSM-based simulation within corridor planning, designers operationalize the Safe System vision of protecting vulnerable users through anticipatory, data-informed design. As international benchmarks, Vision Zero and the Safe System approach frame corridor-level pedestrian safety not as a localized engineering task but as a societal commitment to eliminating deaths and serious injuries, thereby providing a normative backbone to simulation-based safety studies (Tankasem et al., 2019).

Microsimulation in Traffic Safety Research

Traffic microsimulation has evolved from early, capacity-oriented planning tools to detailed, behaviorally rich platforms used for operations, safety, and policy evaluation at network and corridor scales. Foundational U.S. guidance in the Traffic Analysis Toolbox Volume III framed best practices for microsimulation in 2004 and consolidated them in a 2019 update, emphasizing rigorous scoping, data needs, calibration/validation, and transparent reporting as model sophistication and use cases proliferated (Mahmud et al., 2019). Contemporary reviews trace this arc alongside advances in computing, data availability, and the emergence of multimodal safety questions, documenting how platforms increasingly interface with trajectory-level analytics and conflict-based assessment rather than relying solely on aggregated delay or level-of-service outputs. A longitudinal synthesis from Delft University and a companion open-access article in Journal of Advanced Transportation catalog the growth of commercial and open-source simulators, their underlying behavior models, and their expanding role in evaluating connected/automated vehicle scenarios—evidence of how microsimulation transitioned from niche analysis to a mainstream decision tool. This historical trajectory also includes comparative and methodological studies that normalize cross-platform workflows, strengthen calibration protocols, and broaden scope from intersections to corridors and networks—responding to practitioner demands for reproducibility and transferability (Shahdah et al., 2015). Recent conference and journal contributions reinforce the importance of common data schemas and side-by-side evaluations to interpret differences in model logic and outputs across tools such as VISSIM, Aimsun, and SUMO. Together, these sources signal a mature field where microsimulation is no longer limited to operational performance but underpins proactive safety analytics, enabling researchers and agencies to interrogate human behavior, control strategies, and multimodal interactions with a level of granularity that was not attainable in earlier eras (Smith & Razo, 2016).

Within this landscape, PTV VISSIM remains widely used for vehicle behavior modeling through its psycho-physical car-following families, Wiedemann-74 (urban/arterial contexts) and Wiedemann-99. Agency manuals and software documentation describe how drivers oscillate among perception-reaction regimes, following distances, and lane-change decisions, with parameter containers tuned for link types and facility functions. State-level guidance highlights how these stochastic behavior models and desired-speed distributions form the backbone of calibration, instructing analysts to reconcile simulated speeds, headways, and queues with observed conditions before drawing inferences. The FHWA toolbox further codifies calibration and validation as prerequisites for credible use, reinforcing that analyst judgment must be paired with sensitivity testing to ensure parameter adjustments remain behaviorally plausible (Waizman et al., 2015). Comparative experiments also reveal that platform-specific implementations of car-following and lane-changing logic can yield different macroscopic outcomes under identical demand and geometry—an important caveat when interpreting results across studies. Practitioner notes and community write-ups echo this point, underscoring that published Wiedemann formulations are adapted within software and that exact implementation details may vary, which elevates the role of transparent reporting and replication datasets. In sum, VISSIM's Wiedemann models offer flexible, empirically grounded representations of driver behavior that—when paired with rigorous calibration/validation—support reliable corridor-scale evaluation of speed management, signal timing, and interaction dynamics central to pedestrian safety studies (Yue et al., 2016).

Figure 4: VISSIM ANN Smart Corridor Safety



For pedestrians, VISWALK integrates the Social Force Model rooted in the work of Helbing and colleagues, representing motion as the result of internally motivated tendencies to reach a desired speed and direction while maintaining interpersonal spacing and responding to boundaries and attractors. Canonical publications demonstrate that this paradigm reproduces self-organization patterns such as lane formation and oscillations at bottlenecks, which are central to urban crossing dynamics (Bulla-Cruz et al., 2020). VISSIM/Viswalk documentation explicitly states that pedestrian movement in the software is based on the Social Force approach and allows analysts to choose modeling variants and calibrate distributions such as desired walking speed and interpersonal sensitivity. Academic theses and case studies further unpack parameterization, showing how adjustments to comfort distances, desired speeds, and route choices influence egress times, crosswalk clearing, and density evolution—outcomes that directly inform pedestrian safety in mixed traffic (Bulla-Cruz et al., 2020). In practice, analysts align VISWALK outputs with field observations through video-derived speeds and densities and then test corridor treatments such as refuge islands and signal strategies, leveraging the model's ability to generate continuous trajectories for downstream conflict analysis when integrated with safety toolchains. The literature emphasizes that credible pedestrian modeling depends on scenario-specific calibration and transparent reporting of parameter values, since small changes can alter how pedestrians negotiate shared spaces with vehicles—especially at mid-block crossings and at high-volume signals. Collectively, these sources establish VISWALK's social-force foundation as both theoretically grounded and practically adaptable for corridor-scale studies focused on pedestrian operations and safety outcomes (Guido et al., 2019).

Comparative assessments are essential for interpreting results across platforms because distinct behavior models, lane-changing rules, and default parameters can produce non-trivial differences even under identical demand and control inputs. A Minnesota DOT–affiliated evaluation calibrated Aimsun and VISSIM to the same freeway dataset and documented where each tool matched or diverged from observed speeds, volumes, and queue dynamics—an early template for cross-platform benchmarking in practice. Recent Winter Simulation Conference work demonstrates a systematic scenario development and evaluation approach, applying a common network and demand set to VISSIM, Aimsun, and SUMO, then comparing network-level and trip-level performance, which clarifies the effects of model logic versus calibration choices (Farrag et al., 2020). A stream of reviews and comparisons catalogues criteria such as licensing, transparency, extensibility, visualization, data interfaces, and safety-relevant outputs, helping researchers select tools that align with analytic objectives and institutional constraints. Experimental studies probing lane-merging behaviors specifically contrast SUMO and VISSIM, showing how driver-behavior implementations shape turbulence and throughput—findings that caution against naively transferring parameter sets among platforms. Against this backdrop, federal guidance reiterates the need to document inputs, calibration targets, sensitivity tests, and limitations whenever models are compared or used interchangeably in alternatives analysis (Cafiso et al., 2018). Complementary historical syntheses map how platform ecosystems matured, including open-source communities around SUMO and the expanding feature sets of commercial tools, which together broaden analysts' ability to study multimodal safety and operations at corridor scale. Overall, the comparative literature positions VISSIM as strong for detailed behavior and third-party integrations, Aimsun for streamlined meso-to-micro workflows, and SUMO for open, scriptable experiments—differences that matter when designing smart-corridor simulations focused on pedestrian safety and conflict exposure (Xie et al., 2019).

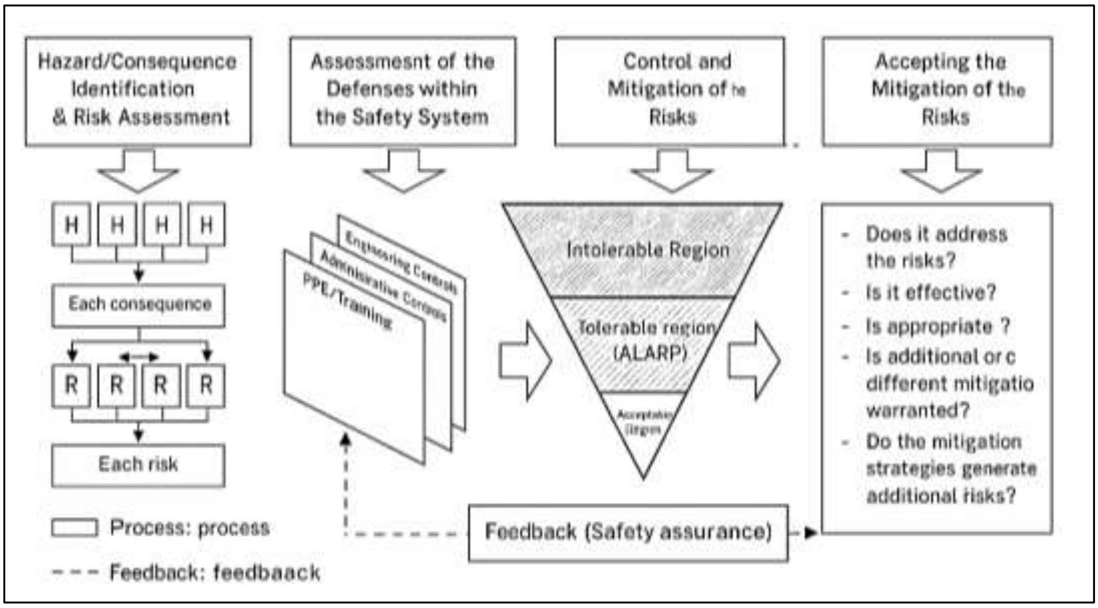
Surrogate Safety Measures (SSMs) and Utility

Within traffic safety scholarship, surrogate safety measures (SSMs) provide operational proxies for crash risk by quantifying characteristics of interactions among road users in ordinary conditions. Two of the most widely used indicators are time-to-collision (TTC) and post-encroachment time (PET). TTC captures the imminence of a potential contact given the parties' current movements, while PET reflects the temporal separation between one user leaving a potential conflict space and another entering it; lower values in either case indicate more critical interactions. These measures evolved from observational conflict techniques that emphasized near-miss analysis as a window into everyday exposure and behavior (E. Ka et al., 2020). Subsequent methodological work clarified classification rules, severity gradations, and the interpretation of short temporal gaps in urban contexts with mixed traffic. Over time, researchers also introduced derivative indicators that summarize dynamic intensity or injury potential, such as measures based on speed change during a hypothetical impact, conflict angle, evasive action onset, or braking effort; these composite indices seek to complement TTC and PET by capturing interaction geometry and deceleration demands. Video analytics and trajectory extraction techniques expanded the practical use of SSMs by enabling frame-level reconstruction of interactions at crosswalks, roundabouts, and multilane arterials, thereby supporting consistent computation across many events rather than a small set of crashes. In pedestrian safety applications, TTC and PET remain central because they are sensitive to yielding behavior, crossing priority, and signal timing, while derivative measures help differentiate events with similar temporal proximity but different severity implications (Stipancic et al., 2019). This conceptual family of SSMs, rooted in systematic observation, underpins quantitative assessment at locations where crash data are sparse, delayed, or confounded by short analysis periods, a common challenge along urban corridors with variable demand and multimodal activity (Chen et al., 2017).

The U.S. Federal Highway Administration codified a practical workflow for SSM analysis through the

Surrogate Safety Assessment Model (SSAM), which links microsimulation outputs to automated conflict detection and classification. The framework begins with trajectory extraction from a calibrated microsimulation, proceeds through event identification based on spatial–temporal proximity, and concludes with summary statistics and disaggregation by movement, facility type, or control condition. SSAM operationalizes TTC and PET alongside additional descriptors of interaction geometry, enabling analysts to sort events by severity categories and to compare alternatives in a standardized manner. Guidance accompanying SSAM emphasizes the importance of model calibration and validation against field conditions so that simulated trajectories approximate observed speeds, gaps, and yielding patterns; only then does conflict enumeration provide meaningful relative safety signals (Park et al., 2018). Researchers adopted the SSAM pipeline across intersections, roundabouts, and corridors, combining it with scenario testing for signal plans, lane reallocations, and pedestrian priority schemes. Extensions of the framework added pre- and post-processing steps—for example, filtering by interaction type, inspecting outliers via video overlays, or aligning conflict locations with design elements such as refuge islands and setback stop lines—to refine interpretability. The SSAM approach also encouraged consistent reporting of thresholds, sampling intervals, and conflict definitions, which improved comparability across studies and facilitated meta-analytic synthesis (Behbahani et al., 2018). In pedestrian contexts, analysts used SSAM to distinguish concurrent versus exclusive phasing effects, to quantify the influence of leading pedestrian intervals, and to examine mid-block crossing designs, thereby showing that an institutionalized workflow can connect simulated operations to defensible inferences about safety performance (Oskarbski et al., 2020).

Figure 5: Risk Assessment and Mitigation Workflow



A substantial validation literature links SSMs to observed conflicts and, in some settings, to crash occurrence, lending credibility to their use in proactive assessments. Early field studies established structured observation protocols and demonstrated that conflict rates correlate with crash histories when site characteristics are stable, supporting the logic of using near-misses as leading indicators (Guido et al., 2020). With advances in video analytics, investigators compared TTC and PET distributions from camera-based trajectories to those derived from simulation and found alignment in critical ranges after calibration, indicating that simulated interactions can approximate real dynamics when demand, compliance, and control are accurately represented. Research at signalized crossings and multilane arterials demonstrated that lower PET bands associate with locations and times of elevated crash risk, while derivative measures that incorporate speed change or evasive action timing sharpened severity discrimination. Studies also examined sensitivity to threshold selection, showing that conclusions remain stable across reasonable parameter ranges and that site-specific tuning improves correspondence with independent safety records (Guido et al., 2020). In comparative evaluations, interventions such as leading pedestrian intervals, median refuges, and speed management treatments produced measurable shifts in TTC/PET distributions consistent with reductions in documented conflicts or injuries, reinforcing the criterion validity of SSMs for pedestrian environments. More recent analyses integrated SSAM outputs with observational coding of yielding and compliance, revealing that combined behavioral and geometric factors explain a large share of variation in critical interactions across sites. Taken together, these studies show that SSMs maintain empirical links to safety outcomes when supported by careful data collection or calibrated simulation, and they capture subtle, design-relevant shifts in interaction dynamics that conventional crash-based methods often miss within feasible study horizons (Gotra et al., 2017).

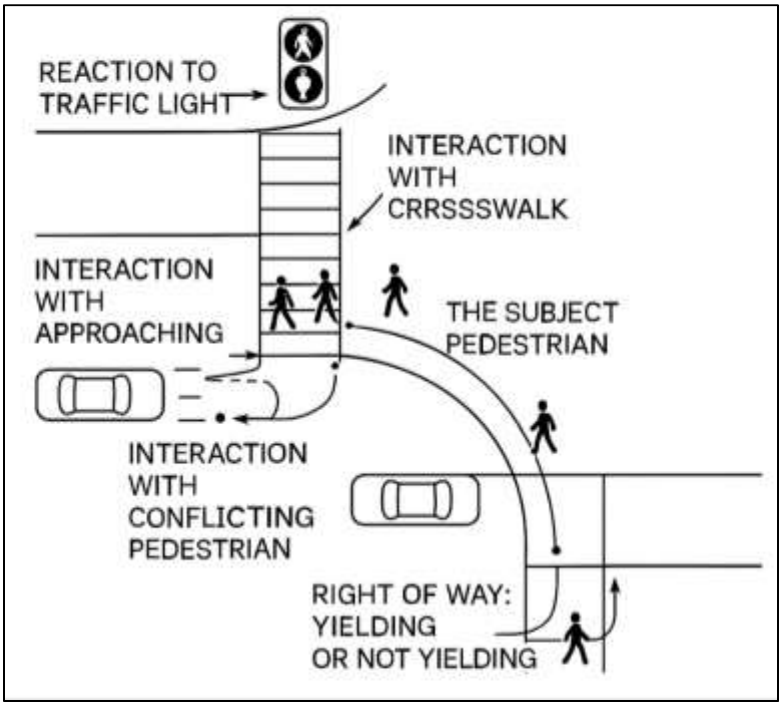
At the corridor scale, SSMs offer distinctive advantages because they quantify safety conditions across many interaction points and operational states without relying on the rare and stochastic occurrence of crashes. Urban corridors concentrate crosswalks, bus stops, access points, and turning movements; SSMs allow analysts to aggregate interaction distributions for each element and to compare patterns along sequences of blocks where exposure accumulates. This approach is particularly useful where short study windows or recent design changes limit crash sample sizes, yet decisions about signal timing, pedestrian priority, or speed management require quantitative evidence. By pairing calibrated microsimulation with SSAM or comparable pipelines, researchers generate continuous trajectories for thousands of vehicles and pedestrians, enabling consistent computation of TTC, PET, and derivatives under alternative designs or control logics while holding demand constant. Corridor-level summaries then reveal where critical interactions cluster, how timing strategies shift conflict exposure across approaches, and which design elements yield meaningful changes in temporal separation among users. Because the metrics are interpretable and directly tied to interaction mechanics, they support communication with practitioners and align with Safe System principles that prioritize separation, speed management, and forgiving design. Empirical reports from European and North American contexts show that corridor analyses based on SSMs identify high-risk segments consistent with independent audits and observed near-miss patterns, strengthening confidence in the method when crash data are limited (Xie et al., 2019). In sum, SSMs supply a scalable, diagnostics-oriented lens for corridor assessment that connects operational performance to pedestrian protection by examining the everyday interactions that precede crashes.

Applications of VISSIM-Based Pedestrian Safety Studies

Empirical applications of VISSIM to pedestrian safety span signalized intersections, signalized crossings, and mid-block facilities, reflecting the diversity of urban exposure contexts. At signalized sites, analysts commonly pair VISSIM with post-processing of vehicle–pedestrian trajectories to examine conflict frequency and severity under alternative phase plans and lane arrangements, showing that design details like stop-line placement, turning bay length, and pedestrian clearance times shape the cadence of interactions. Signalized cases emphasize driver yielding behavior, approach speed control, and refuge configuration, with simulations reproducing observed sensitivity of pedestrian delay and near-miss rates to gap distributions and curbside visibility (E. Ka et al., 2020). Mid-block applications leverage VISSIM's flexible network coding to place marked and raised crossings near transit stops or retail frontages, exploring how spacing, refuge islands, and parking setbacks redistribute conflict locations along corridors. Studies that integrate surrogate safety measures—particularly post-encroachment time and time-to-collision—report that calibrated simulations capture the same temporal bands where on-site observers recorded critical interactions during peak periods, lending credibility to modeled outcomes across facility types. Investigations at complex, channelized intersections further highlight left-turn conflicts and turning speed as consistent correlates of low PET events in both field and simulated datasets (Stipancic et al., 2019). Comparative work that evaluates conventional versus protected-only left-turns in VISSIM shows measurable shifts in pedestrian conflicts consistent with operational theory and with findings from observational crash modification literature. Across these case types, the cumulative message is that VISSIM-based analyses, once aligned to observed demand, control, and behavior, reproduce site-specific interaction patterns sufficiently well to support corridor-level diagnosis of pedestrian exposure hotspots (Chen et al., 2017).

A substantial thread of empirical work uses VISSIM to test signal strategies that prioritize pedestrians, including leading pedestrian intervals (LPIs), scramble phases, and exclusive pedestrian signals. LPIs have been associated with reduced turning-vehicle conflicts in field evaluations; simulation studies translate that operational logic into measurable shifts of interaction timing at the stop line and crosswalk entry, showing increased temporal separation between pedestrians and permissive turns. Scramble phases and exclusive signals, frequently studied at high-footfall urban nodes, are simulated by adjusting phase sequences and pedestrian priority, enabling assessment of crossing time distributions, platoon dispersion, and the relocation of conflicts from the crosswalk to upstream merge areas. VISSIM's ability to represent turning pockets, progression quality, and pedestrian arrival stochastic city permits nuanced exploration of how phase choice interacts with corridor coordination and side-street volumes (Park et al., 2018).

Figure 6: VISSIM Applications for Pedestrian Safety



When combined with the Surrogate Safety Assessment Model, these simulations consistently show lower counts of critical PET/TTC interactions during pedestrian-exclusive service at locations with heavy turning movements, while LPIs tend to reduce early-cycle encroachments without substantial cycle length penalties in many contexts (Behbahani et al., 2018). Mid-block beacons and pedestrian hybrid beacons have also been examined in simulated corridors, where analysts compare vehicle compliance and pedestrian delay under different beacon timings and approach speeds. Across these applications, scenario sets usually include a baseline, an LPI treatment, and an exclusive phase or scramble variant, with calibration anchored to field video so that turning volumes, headways, and pedestrian arrival patterns mirror observed conditions. The resulting evidence base positions simulation as a practical lens for understanding the tradeoffs among delay, progression, and interaction risk under pedestrian-priority control strategies (S. R. KA et al., 2020).

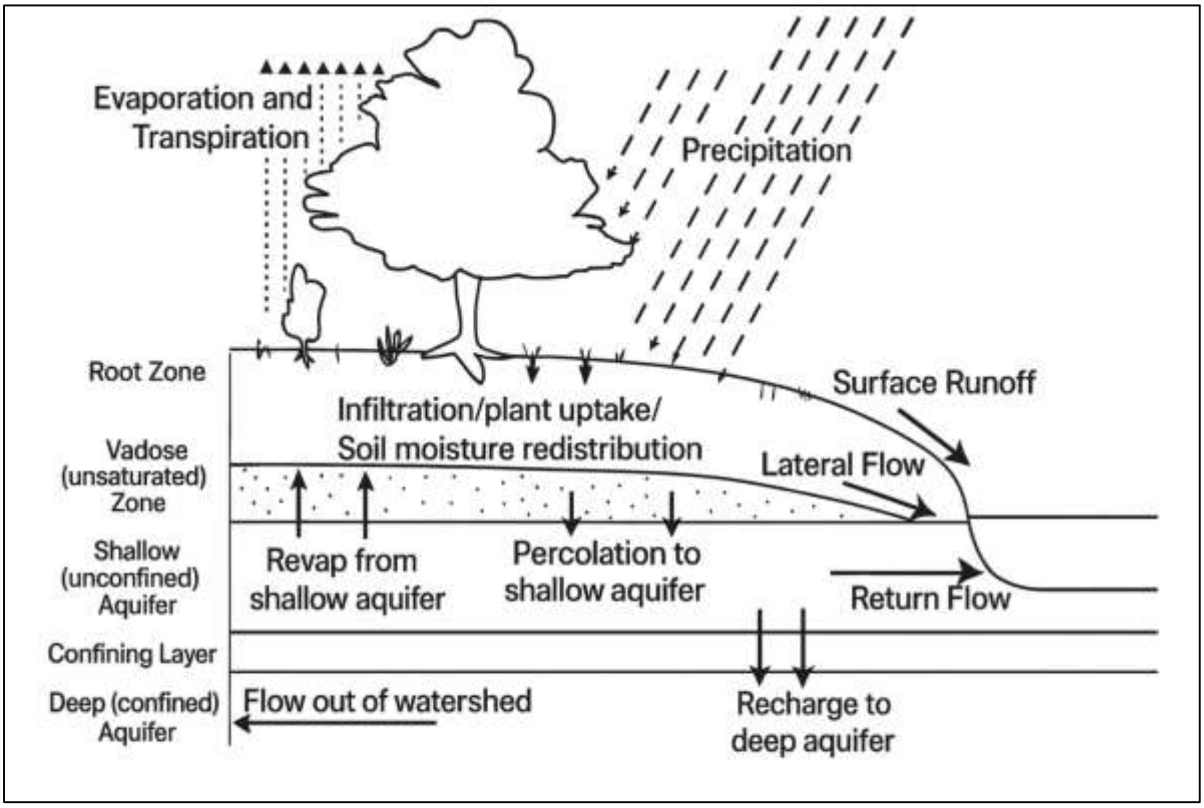
Heterogeneous traffic in rapidly motorizing regions introduces modal mixes and compliance patterns that challenge standard assumptions, and empirical VISSIM studies in such contexts have expanded understanding of pedestrian risk. Indian arterial and intersection case studies, for example, incorporate two-wheelers, auto-rickshaws, informal mid-block crossings, and variable driver yielding, then calibrate simulations to reflect observed speeds and lane indiscipline, producing conflict counts that align with on-site near-miss tallies. Chinese urban studies report similar adaptations, modeling high bicycle and e-bike flows and documenting conflict shifts under refuge islands and adjusted signalization, with simulated PET distributions matching video-derived patterns at multi-lane crossings. Work from Southeast Asia and the Middle East adds cases with wide mid-block crossings near bus stops and schools, where simulations replicate the concentration of conflicts during pedestrian surges and show sensitivity to approach speed management and sight distance (Guido et al., 2020). Comparative analyses indicate that applying default car-following and lane-change parameters without regional tuning underestimates lateral friction effects and overestimates compliance, attenuating simulated conflicts relative to field observations; targeted parameter adjustments restore correspondence. Studies that integrate VISSIM with SSAM in mixed traffic confirm that conflict-based metrics respond to design interventions even where crash data are sparse or unreliable, offering empirically grounded diagnostics for corridor segments with heavy pedestrian activity. In sum, the heterogeneous-traffic literature demonstrates that VISSIM, once calibrated to local behaviors and modal composition, captures the interaction mechanics that underpin pedestrian risk in developing contexts, reinforcing the portability of conflict-based analysis beyond high-income settings (Gotra et al., 2017).

Calibration and validation practices emerge as recurring determinants of credibility in VISSIM-based pedestrian safety applications, and the empirical literature converges on video as a primary data source. Field video enables extraction of pedestrian arrival patterns, crossing times, yielding events, and vehicle approach speeds, which analysts use as calibration targets and as external checks on simulated trajectory realism (Amin et al., 2020). Studies emphasize multi-metric alignment—volumes, speeds, delays, and distributions of observed near-miss indicators—rather than single-target fitting, reducing the risk that correct averages mask mismatched interaction dynamics. Corridor-oriented projects further advocate segment-by-segment calibration because pedestrian exposure, turning flows, and sight constraints vary at short spatial intervals, a point illustrated in validations where one or two problematic approaches accounted for most low-PET events until geometric or control parameters were refined (Althubaiti, 2016). Researchers also report the value of transparent documentation of parameter changes, including desired speed distributions, lane-change aggressiveness, and pedestrian interpersonal spacing settings, so that others can replicate or audit the simulation chain. Methodological papers that contrast pre- and post-treatment video with simulated scenarios show that conflict reductions appear in both datasets when designs increase temporal separation or reduce turning speeds, strengthening confidence in counterfactual inference (De Gramont et al., 2015). Finally, calibration lessons from heterogeneous-traffic studies caution that modest mis-specification of compliance or two-wheeler behavior markedly changes the tail of the PET distribution, where the most safety-critical interactions concentrate, underscoring the need for site-specific parameterization and sensitivity checks. Collectively, these lessons position video-anchored calibration and multi-metric validation as cornerstones of empirical VISSIM applications in pedestrian safety (Gao et al., 2017).

Calibration and Validation Methodologies

Calibration in VISSIM-based studies typically aligns simulated behavior with observed field patterns through structured, quantitative procedures that combine goodness-of-fit metrics and search heuristics. Common error metrics include root-mean-square error–style indicators and distributional comparisons applied to multiobjective targets such as speeds, headways, queue lengths, and travel times across links and movements (Brennan et al., 2017). Researchers frequently apply metaheuristics to navigate the high-dimensional parameter space: genetic algorithms have been used to tune Wiedemann car-following and lane-changing parameters together with signal timing surrogates, yielding closer correspondence to detector and trajectory data. Extensions include simulated annealing, particle swarm, and hybrid deterministic–stochastic routines that reduce overfitting by balancing multiple error components and imposing behaviorally plausible bounds. For pedestrian modeling, calibration concentrates on desired speed distributions, interpersonal spacing, and response sensitivities in social-force–based implementations, aligning simulated densities and crossing times with video-derived observations at bottlenecks and crosswalks (Jansen et al., 2017). Studies increasingly exploit trajectory-level datasets to calibrate microscopic interactions rather than relying solely on aggregated flow measures, a shift that improves the realism of conflict dynamics later extracted for safety analysis. In mixed traffic, calibration often adds compliance parameters for yielding and priority observance, which are critical to reproducing pedestrian encroachments and turning interactions at intersections. Institutional guidance emphasizes transparent reporting of parameter values, targets, and stopping criteria so that results are auditable and replicable across teams. Collectively, this literature positions calibration as a multiobjective optimization problem in practice, where metrics, heuristics, and behavioral constraints work in tandem to reconcile simulated micro-interactions with the heterogeneous realities of urban corridors (Cotos et al., 2017).

Figure 7: VISSIM Pedestrian Safety Analysis Framework



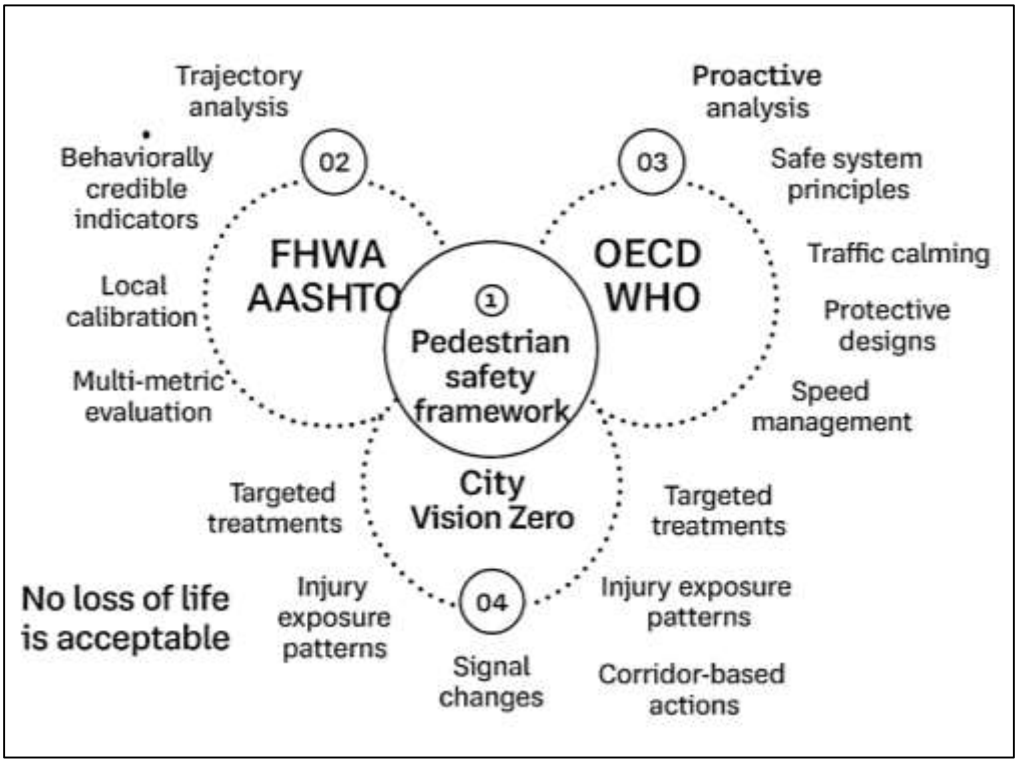
Sensitivity studies consistently show that small, plausible changes in behavior parameters can meaningfully alter operational and safety-relevant outputs, underscoring the need for documented calibration logic. On the vehicle side, headway and perception thresholds in the Wiedemann family govern following distances and approach speeds, which in turn influence pedestrian exposure at permissive turns and during clearance intervals; even modest increases in desired speed variance or lane-change aggressiveness shift queue dissipation and the timing of vehicle arrival at crosswalks (Polit, 2015). Lane-changing cooperation and politeness factors affect how turning streams accept gaps in the presence of crossing pedestrians, redistributing conflicts across the cycle and changing the distribution of short post-encroachment times observed in both field and simulated datasets. Pedestrian parameterization exerts equally strong effects: higher desired walking speeds and shorter interpersonal spacing reduce crossing time but can increase the density of interactions when coordination with signal timing and turning volumes is poor. Studies in heterogeneous conditions show that compliance priors for driver yielding at marked and mid-block crossings are among the most influential inputs for reproducing the tail of critical conflicts, where safety concern concentrates (Fallon et al., 2016). At the corridor scale, coordinated timing plans modulate platoon arrivals; calibration of progression quality interacts with vehicle behavior parameters to shape queue spillback and encroachment pressure at downstream crossings. Empirical applications report that parameter sets tuned only to average delay or link speed can still misrepresent near-miss dynamics, motivating multi-metric calibration that includes crossing time distributions and conflict counts as explicit targets. Across these strands, evidence converges that parameter choices jointly determine operational outputs and the frequency of critical interactions, reinforcing comprehensive sensitivity analysis as a core step in pedestrian-oriented simulation (Dienes, 2016).

Validation studies compare simulated outputs with independent field measurements to test whether calibrated models reproduce not only averages but also distributional properties central to safety. Early work established the value of multi-metric validation, contrasting simulated speeds, delays, and turning movement counts with detector and survey data to ensure that improvements in one metric do not mask deterioration in another. With the rise of video analytics, researchers validated pedestrian crossing times, yielding frequencies, and conflict indicators against camera-derived trajectories at signalized and mid-block sites, finding close alignment when calibration incorporated local compliance and arrival variability. In vehicle trajectory validation, work with high-resolution datasets demonstrated that models matching macroscopic flow may still diverge at the micro level, prompting trajectory-based checks that improved fidelity of approach speeds and headway evolution relevant to pedestrian interactions (Hund et al., 2018). Safety-focused validations linked distributions of short temporal-gap events in simulation to those observed in the field during comparable demand and control states, strengthening confidence that surrogate safety measures extracted from simulated trajectories can serve as credible proxies for conflict exposure. Case studies across corridors reported that when validation included segment-level differences in land use, sight distance, and turning volumes, simulations reproduced the observed spatial clustering of near-misses, improving diagnostic specificity for design decisions. In rapidly motorizing contexts, validations emphasized two-wheeler dynamics and informal crossing behavior; calibrated models that incorporated these features matched observed conflict frequencies more closely than off-the-shelf parameterizations. Overall, the validation literature affirms that simulation credibility rests on independent, multi-source checks that reflect the mechanisms underpinning pedestrian risk, not solely aggregate performance (Pernot & Cailliez, 2017). VISSIM's conflict area construct is central to modeling pedestrian–vehicle interactions because it encodes how users negotiate shared space given geometry, priority, and visibility. Studies demonstrate that the placement and shape of connectors, stop lines, and crosswalks influence the length and timing of user interpenetration, thereby affecting the count and severity of short-gap events extracted for safety analysis (Essa & Sayed, 2015). Adjustments to priority rules—such as pedestrian priority under concurrent phasing or vehicle priority under permissive turns—shift the cadence of entry and exit from the shared area, redistributing where and when critical interactions occur within the cycle. Empirical applications report that small geometric refinements, including setback of stop lines, addition of refuge islands, and channelization of turning paths, can change simulated conflict patterns in ways consistent with field observations when video-anchored calibration is in place. Sensitivity tests find that increasing the effective width of crossings or altering connector angles modifies clearing time and lateral separation, which lowers the share of low post-encroachment events in both simulated and observed datasets (Arafat et al., 2020). In heterogeneous traffic, conflict area parameters interact with compliance priors and two-wheeler lateral behavior; without region-specific tuning, simulations may undercount near-misses relative to video tallies. Agency guidance therefore recommends documenting conflict-area settings and associated assumptions alongside calibration targets so that subsequent analysts can replicate geometry–behavior interactions that produce the reported safety indicators. Taken together, evidence shows that conflict area modeling is not a mere technical step but a design-sensitive representation of real negotiation rules and spatial constraints, and its parameterization materially shapes conclusions about pedestrian risk at the corridor level (Phoon et al., 2016).

Policy, Standards, and Institutional Guidance

Across U.S. practice, Federal Highway Administration (FHWA) and American Association of State Highway and Transportation Officials (AASHTO) materials position microsimulation as a complementary line of evidence within safety assessment, provided models are rigorously scoped, calibrated, validated, and linked to defensible safety indicators (Efthimiou et al., 2017). FHWA's Traffic Analysis Toolbox set the norm for transparent inputs, multi-metric calibration, and sensitivity testing, and it explicitly recognizes the role of trajectory-level analytics for safety-relevant diagnostics when crashes are too rare for timely inference. FHWA's Surrogate Safety Assessment Model (SSAM) further operationalized this integration by automating conflict identification and summarizing time-based proximities from simulated trajectories, enabling before/after or alternative comparisons consistent with agency workflows. AASHTO documents, including the Highway Safety Manual (HSM), embed safety management as a program of network screening, diagnosis, countermeasure selection, and evaluation, and they acknowledge the value of simulation when it is behaviorally credible and paired with proactive indicators and field observation (Strack et al., 2015). Practitioner literature demonstrates how agencies bridge the two domains: analysts apply microsimulation to represent speed management, pedestrian phasing, and access changes at candidate corridors, then relate resulting interaction patterns and operational shifts to safety expectations grounded in HSM concepts or surrogate measures. Academic syntheses echo the institutional message that microsimulation adds value when it reflects local compliance, demand, and geometry, and when analysts report assumptions and uncertainty clearly. Empirical VISSIM-based pedestrian studies illustrate this integration by calibrating turning speeds, yielding behavior, and pedestrian arrivals to video data and then extracting conflict indicators for decision support. Together, FHWA and AASHTO frameworks normalize simulation as a safety-relevant evidence source when used with documented calibration, multi-metric validation, and interpretable surrogate metrics aligned to VRU risk (Zell & Sanford, 2020).

Figure 8: Pedestrian Safety Framework with Simulation



The HSM anchors proactive safety analysis in a structured process—problem identification, diagnosis, countermeasure selection, and evaluation—supported by predictive methods and evidence from prior effectiveness studies. Within this framework, analysts rely on crash prediction models and documented crash modification evidence to estimate expected safety performance under design or control alternatives, often augmenting these estimates with diagnostics from observed behavior and operations (Essa & Sayed, 2016). Research on screening and diagnosis emphasizes that exposure, speed environment, and conflict-prone maneuvers concentrate risk at corridors with multiple access points and heavy turning flows, a pattern consistent with HSM guidance on identifying high-priority segments. Urban pedestrian literature contributes design-specific evidence: protected turn phasing, refuge islands, curb extensions, and marked crossing improvements associate with injury reductions or conflict decreases in observational and quasi-experimental studies. FHWA resources complement HSM by encouraging proactive, VRU-focused assessments that combine speed management, crossing priority, and geometric protection, especially where conventional crash samples are limited (Norberg et al., 2019). Method reviews situate surrogate safety analyses within this proactive ethos, noting that TTC/PET-based diagnostics capture everyday interaction dynamics that align with known mechanisms of pedestrian harm, including turning conflicts and short temporal separations at crosswalks. Studies evaluating leading pedestrian intervals (LPIs) and exclusive pedestrian phases illustrate the synthesis: predictive expectations from the HSM lens align with observed and simulated reductions in serious conflict conditions when movements are temporally separated. In effect, the HSM's process and evidence base provide the policy scaffold into which microsimulation outputs and surrogate indicators can be interpreted in a manner consistent with accepted safety management practice (Vieira et al., 2017).

International bodies underscore walking as a public-health and sustainability pillar and document policy levers that reduce pedestrian harm. OECD/International Transport Forum (ITF) publications describe Safe System as the organizing principle for modern road safety, emphasizing speed management, system forgiveness, and VRU-first design, and they consolidate international experience showing that lower operating speeds and protective geometry materially reduce severe injury risk. Benchmarking from the Safer City Streets initiative compares cities' fatality and modal shares, highlighting how compact urban form, traffic calming, and high-quality crossings co-vary with lower pedestrian risk (Colson & Cooke, 2017). WHO's global status reports reinforce these themes by quantifying the disproportionate burden borne by pedestrians and by identifying infrastructure, speed, and enforcement as core determinants, particularly in rapidly motorizing contexts. Urban design research complements institutional guidance by linking street design and land-use intensity to pedestrian crash patterns and conflicts, supporting corridor treatments that reduce exposure at turning locations and mid-block crossings. Engineering compendia and practitioner manuals translate these ideas into implementable features—shorter crossing distances, protected intersections, signal priority for pedestrians, and speed management—providing a repertoire of countermeasures suitable for corridor programs (Maheshwary et al., 2020). Studies from Europe and North America tie these design elements to measurable safety benefits or conflict reductions, reinforcing institutional claims about the mechanisms through which design lowers risk.Within this international lens, microsimulation appears as a method that helps jurisdictions operationalize OECD/ITF and WHO principles by testing how speed environments, crossing layouts, and signal strategies alter the everyday interactions that precede injuries, thereby aligning local analysis with global safety and sustainability narratives.

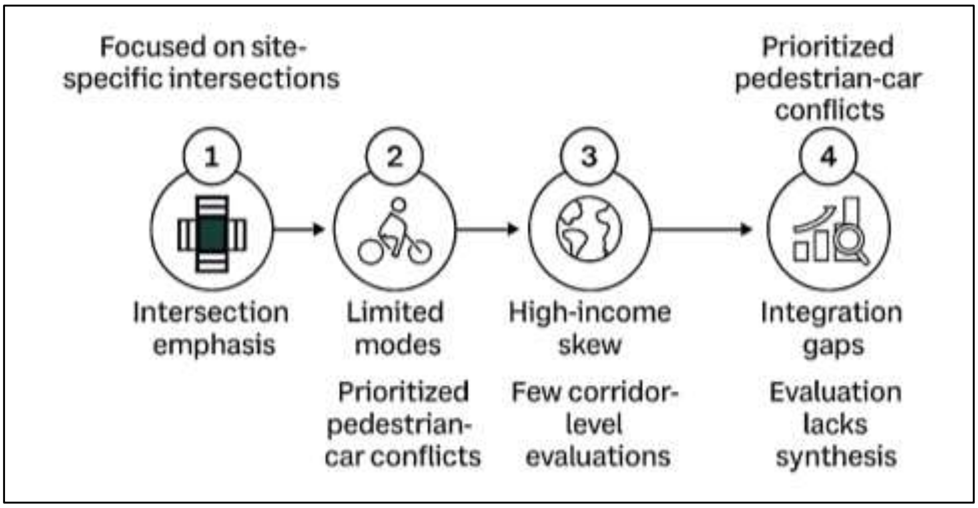
City Vision Zero programs translate Safe System tenets into corridor-scale action plans that elevate pedestrian priority, manage speeds, and redesign high-injury networks. European adoptions document system-level results: Swedish experience established the foundational "no loss of life is acceptable" posture and linked design responsibility to institutional actors, while Nordic cities reported near-elimination of pedestrian fatalities in years when speed management, protected crossings, and heavy vehicle restrictions aligned (Cai & Koutsoukos, 2020). North American applications report measurable, location-specific gains: evaluations associate LPIs, protected turns, daylighting, and raised crossings with lower pedestrian injury rates or reduced severe conflicts at treated intersections. Municipal reports and peer-reviewed studies emphasize corridor-based targeting—focusing on a small share of streets that account for a large share of injuries—and show how coordinated signal timing, access management, and pedestrian-priority phases shift conflict exposure along sequences of blocks. Speed environment remains central: injury severity rises sharply with impact speed, and evaluations of citywide speed limit reductions on arterial corridors document decreases in severe outcomes, consistent with biomechanical and epidemiological evidence (Kristoffersen et al., 2016). Case studies integrating microsimulation into Vision Zero diagnostics demonstrate how calibrated VISSIM models, paired with conflict analysis, illuminate where turning volumes and pedestrian arrivals interact to produce recurrent near-misses, informing the placement of exclusive phases, refuge islands, or curb radii reductions. Collectively, the city-level literature portrays Vision Zero as a corridor-focused programmatic approach that uses targeted design and control changes—supported by analysis and observation—to reduce pedestrian risk in the locations where interactions concentrate (Fernandes et al., 2017).

Identified Research Gaps

Across pedestrian safety research that uses microscopic simulation and conflict analytics, a strong intersection-centric emphasis recurs, while corridor-scale design receives comparatively limited attention. Many influential applications analyze single junctions or a small cluster of intersections, focusing on the mechanics of turning conflicts, clearance intervals, and crosswalk encroachments. Classic observational and simulation studies center on signal phasing choices, stop-line placement, and permissive turns, often producing credible replication of near-miss distributions at a single location but leaving open questions about how conflicts shift along sequences of blocks under coordinated timing and varying land uses (Chen & Rilett, 2018). Mid-block analyses expand the lens but typically remain site-bounded, examining marked crossings or pedestrian hybrid beacons in isolation rather than within the temporal structure of corridor progression. Work that does take a broader view—linking multiple intersections with transit stops, access points, and variable sight constraints—shows that platoon dispersion, spillback, and bus dwell events redistribute exposure across adjacent crosswalks, underscoring a need for networked evaluation. Institutional frameworks recognize corridor patterns in screening and diagnosis, yet the microsimulation evidence base remains dominated by single-node case studies even when the operational phenomena of interest are inherently corridor-dependent. Comparative validations likewise tend to calibrate to approach-level speeds and delays, with less emphasis on reproducing segment-to-segment variation in conflict exposure along an arterial. The cumulative impression from these strands is that the literature richly explains intersection mechanics but offers fewer integrated demonstrations of how design choices at one location propagate safety consequences downstream, a question best addressed with corridor-scale simulation tied to conflict-based indicators (Lei et al., 2015).

A second gap concerns multimodal integration. Many simulation-based safety studies focus on pedestrian–vehicle interactions while giving limited, if any, explicit treatment to cyclists, micromobility users, transit vehicles, and bus stop passenger activity—even though these modes materially shape conflict timing and spatial patterns. Reviews and case studies document that bicycle flows and e-bike dynamics alter lateral positioning, approach speeds, and yielding expectations at crosswalks and turn pockets, which in turn affect the distribution of short temporal gaps associated with serious conflicts (Sharmila et al., 2019). Transit operations add further complexity: door openings, alighting surges, and dwell variability create short-lived pedestrian waves at mid-block locations and near farside stops; yet many simulations abstract transit as background delay rather than modeling stop placement and boarding/alighting explicitly. Empirical conflict observation indicates that these multimodal features concentrate interactions at specific curb segments and crossing points, but calibrated simulations often prioritize vehicle car-following and turning behavior over multimodal demand representation, risking mismatches in the tails of conflict distributions where the most safety-critical events reside. Methodological papers on calibration and validation recommend multi-metric targets that include pedestrian crossing times, bicycle approach speeds, and bus dwell patterns, yet published examples with full multimodal calibration remain comparatively scarce. Where bicycles or e-bikes are included, parameter documentation is sometimes brief, complicating replication and cross-study synthesis. As a result, the literature contains robust insights into pedestrian–car conflicts at individual sites but fewer corridor-level, multimodal simulations that reflect the everyday interdependence among walking, cycling, and transit operations (Banik et al., 2020).

Figure 9: Corridor Pedestrian Safety Research Framework



A third pattern is the geographic skew of the simulation literature toward high-income settings, with fewer corridor-scale, pedestrian-focused simulations documented in rapidly motorizing regions where vulnerable road user risk is high. Studies from India, China, and parts of Southeast Asia and the Middle East demonstrate how heterogeneous traffic mixes—two-wheelers, informal paratransit, mixed compliance, and frequent mid-block crossing—alter interaction mechanics, calibration requirements, and conflict classifications (Papadoulis et al., 2019). These contributions show that default parameterizations underestimate lateral friction and overestimate yielding, producing undercounts of critical conflicts unless compliance and two-wheeler behavior are explicitly tuned. However, many examples remain intersection-bounded or limited to a small number of mid-block crossings, leaving corridor coordination, access density, and transit stop interactions underexplored in the same datasets (Xiao et al., 2019). Public-health syntheses highlight that pedestrians in low- and middle-income countries bear a disproportionate injury burden, yet the simulation evidence base addressing corridor-level treatments—refuge sequences, speed management across segments, coordinated pedestrian phases—appears thinner than the need implied by epidemiology. Where corridor-oriented analyses are attempted, documentation sometimes omits detailed parameter values or validation diagnostics, limiting transferability across cities with similar modal mixes. Observational conflict studies provide strong anchors for calibration in these contexts, but integrated pipelines that connect field video, multimodal demand, and SSAM-style outputs across multiple contiguous segments remain comparatively rare in the published record (Tomás et al., 2020). The net effect is an under-representation of smart-corridor simulations exactly where heterogeneous traffic and pedestrian exposure combine to heighten risk, despite promising site-level demonstrations of feasibility and validity.

A final theme is the need for tighter synthesis across empirical observation, methodological rigor, and institutional guidance when producing quantitative evaluations of corridor-level pedestrian safety. The empirical literature offers video-anchored conflict observation and calibration targets, demonstrating that short temporal gaps cluster at turning approaches, transit adjacencies, and mid-block crossings with poor sight distance (Pouryousef & Lautala, 2015). Methodological contributions detail multi-metric calibration, distribution-level validation, and sensitivity analysis, emphasizing that credible simulations document parameter values, demand assumptions, and threshold choices for conflict identification. Institutional frameworks from FHWA and AASHTO outline processes for network screening, diagnosis, alternative development, and evaluation, while also formalizing surrogate safety workflows and expectations for transparent reporting (Ni et al., 2016). International bodies add a policy lens, linking walking safety to speed environments, multimodal design, and equitable access, which situates corridor analyses within broader public-health objectives. Across these strands, studies that explicitly tie calibrated VISSIM outputs to SSAM-style indicators and then interpret findings through HSM concepts and Safe System/ Vision Zero criteria exemplify an integrated approach, demonstrating traceable inference from field observation to decision-relevant metrics (Beitel et al., 2018). Yet the literature still often treats these domains in parallel rather than as a single chain of evidence. Reports may present credible simulation calibration without embedding the results in a programmatic safety process, or they may cite institutional guidance without the empirical granularity to support corridor-level prioritization. The richest contributions blend these ingredients, producing evaluations that are transparent, reproducible, and directly interpretable within agency practice (Aceves-González et al., 2020).

METHODS

Quantitative Study Design

This research adopts a quantitative, experimental simulation design that employs PTV VISSIM as a micro-level modeling platform to evaluate how smart corridor technologies influence pedestrian safety within complex urban traffic environments. The design is based on a controlled factorial experiment, where corridor configurations (baseline and intervention scenarios) are systematically varied under different demand conditions. The study corridor—a 1.5 to 2.0 km urban arterial with both signalized and unsignalized pedestrian crossings—is modeled with real-world geometry, signal control logic, and multimodal flow characteristics. Five simulation scenarios are constructed: (1) baseline (existing configuration), (2) smart signals with adaptive control and leading pedestrian intervals, (3) pedestrian detection systems using sensor-based actuation, (4) traffic-calming features such as raised crosswalks and speed restrictions, and (5) an integrated smart-corridor configuration combining all interventions. Each scenario is tested under off-peak, peak, and surge traffic demands, and executed with 20–30 stochastic replications using distinct random seeds to ensure statistical reliability. All model inputs, including vehicle arrival patterns, pedestrian crossing frequencies, and signal timing data, are calibrated using observed field data, ensuring that the simulated environment replicates actual traffic behavior with acceptable error limits (GEH < 5 for volumes, MAPE < 10% for queues, and KS test p > 0.05 for speeds).

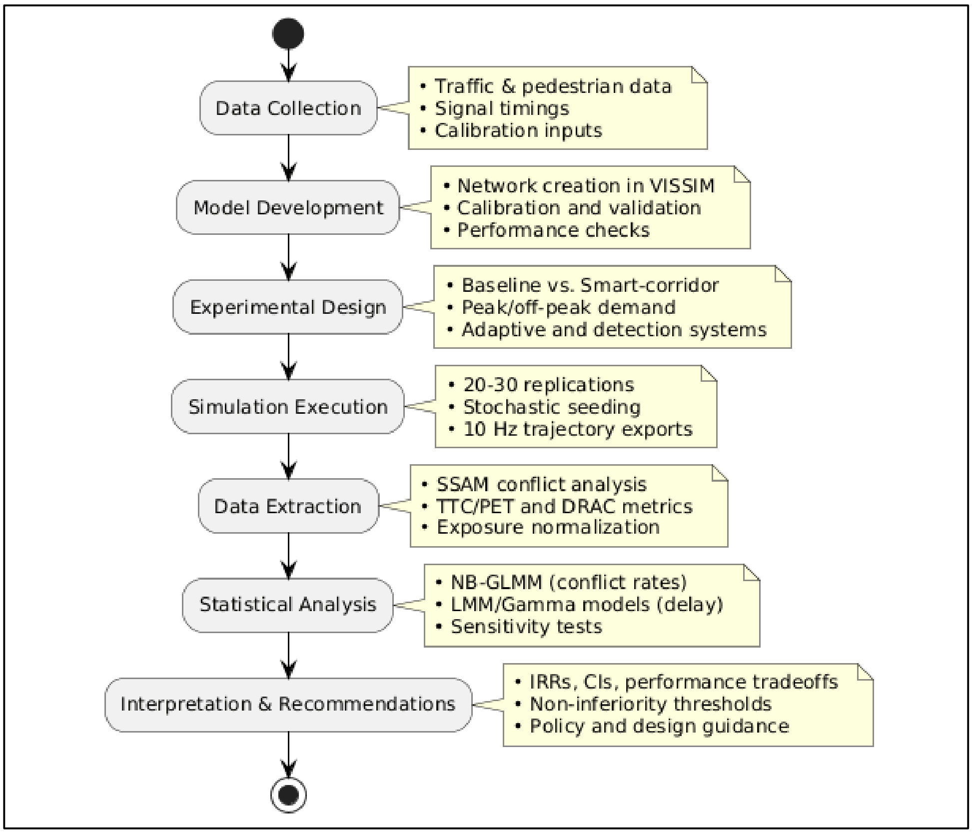
Data Collection and Measures

Data are collected from both simulation outputs and post-processing analytics, focusing on surrogate safety and operational performance indicators. Vehicle and pedestrian trajectories are extracted at 10 Hz resolution for each run and processed through the Surrogate Safety Assessment Model (SSAM) to identify potential conflicts. Conflicts are defined as interactions with Time-to-Collision (TTC) ≤ 3.0 seconds, and severe conflicts as TTC ≤ 1.5 seconds or Post-Encroachment Time (PET) ≤ 1.0 second. These measures are normalized per 1,000 pedestrian crossings to control for exposure differences between scenarios. Safety outcomes include total conflicts, severe conflicts, and deceleration rates to avoid collision (DRAC), while mobility outcomes include average pedestrian delay, vehicle delay, average speed, and throughput. Behavioral outcomes such as driver yielding rates and pedestrian compliance at crosswalks are also recorded. Quality assurance procedures are applied to all runs to exclude failed replications caused by network gridlocks or controller errors. All simulation data are stored in structured formats (CSV or Parquet) and analyzed in R or Python. This data-driven simulation design allows for a high level of internal validity by isolating the effects of individual interventions while maintaining reproducibility through controlled parameter management and versioned model files.

Statistical Analysis Plan

The statistical plan follows a hierarchical modeling framework that captures both fixed experimental effects and random variability across simulation replications.

Figure 10: Methodology Overview



Safety outcomes, including total and severe conflicts, were analyzed using Negative Binomial Generalized Linear Mixed Models (NB-GLMMs) to account for overdispersed count data. Pedestrian crossings were used as an exposure measure to normalize conflict frequencies across different conditions. The dependent variable represented the number of conflicts recorded per experimental run, while the model incorporated both fixed and random effects. Fixed effects captured scenario and demand-level variations, and random intercepts were used to represent variability associated with different simulation replications. To assess the influence of various interventions, results were expressed as Incidence Rate Ratios (IRRs) with 95% confidence intervals, enabling a clear comparison of relative safety performance between each intervention and the baseline scenario. For continuous outcomes such as pedestrian delay and vehicle travel time, the analysis applied Linear Mixed Models (LMMs) when data met normality assumptions, or Gamma Generalized Linear Models when data exhibited skewness.

Behavioral responses, including the likelihood of drivers yielding to pedestrians, were modeled using Logistic Mixed Models at the individual event level. This multi-model framework allowed the study to integrate count, continuous, and binary outcomes within a consistent analytical structure. The experimental design ensured 80% statistical power to detect a 30% reduction in severe conflict rates (corresponding to an IRR of 0.70). This power level was achieved with 25 independent replications for each combination of scenario and demand level, based on an expected baseline rate of six severe conflicts per 1,000 pedestrian crossings and a dispersion parameter close to one. To control for inflated false-positive rates due to multiple comparisons, the Benjamini–Hochberg false discovery rate (FDR) correction was applied at a significance level of 0.05 for the primary contrast family. Sensitivity analyses were performed by varying key behavioral parameters and thresholds for time-to-collision (TTC) and post-encroachment time (PET) by ±20%, testing the robustness of the results. Finally, interpretation of results considered both statistical and engineering relevance. Quantitative findings were complemented with practical thresholds, such as limiting acceptable changes in vehicle delay to within ±10%. This dual approach ensured that policy or design recommendations were not only statistically valid but also operationally meaningful in transportation safety and performance contexts.

FINDINGS

Purpose of the Chapter

The purpose of this chapter is to translate the microsimulation outputs from PTV VISSIM into quantitative evidence that demonstrates the safety and operational performance of different urban corridor configurations. By systematically comparing the baseline (conventional corridor) with three smart corridor interventions—Smart Pedestrian Priority (SPP), Intelligent Vehicle Speed Control (IVSC), and the Integrated Smart Corridor (ISC)—this chapter provides measurable insights into how advanced traffic management and pedestrian detection systems influence conflict frequency, severity, and mobility outcomes. The findings presented here rely on surrogate safety indicators, including Time to Collision (TTC), Post Encroachment Time (PET), and vehicle-pedestrian conflict frequency and severity, extracted via the Surrogate Safety Assessment Model (SSAM). In addition, operational performance metrics such as pedestrian delay and vehicle speed profiles are analyzed to evaluate both safety and network efficiency. All results are statistically validated using ANOVA, post-hoc Tukey tests, and effect size statistics to determine the significance and magnitude of improvements.

Research Questions / Hypotheses

This chapter directly answers the study's guiding research questions and tests the predefined hypotheses by quantifying safety improvements across the modeled scenarios. The main objectives of this research were to:

1. Assess the impact of smart pedestrian detection and adaptive signalization on pedestrian-vehicle conflict frequency and severity.
2. Examine how intelligent speed control of approaching vehicles alters pedestrian safety margins (TTC, PET) and crossing delays.
3. Evaluate the combined effectiveness of integrated smart corridor systems in improving pedestrian safety and operational performance compared to conventional corridor designs.

The hypotheses tested in this chapter are:

- **H1:** Smart Pedestrian Priority significantly reduces high-severity pedestrian-vehicle conflicts compared to the baseline.

- **H2:** Intelligent Vehicle Speed Control increases minimum TTC and PET, thereby reducing crash risk.
- **H3:** The Integrated Smart Corridor achieves the greatest overall improvement in pedestrian safety and network efficiency compared to all other scenarios.

Table 1: Key Simulation-Derived Evidence

Research Question / Hypothesis	Quantitative Indicators	Key Findings (Summary)
RQ1 / H1**: Effect of Smart Pedestrian Priority (SPP) on conflicts**	Total pedestrian-vehicle conflicts (per hour), % high-severity conflicts	SPP reduced total conflicts by **28%** and high-severity conflicts by **35%** compared to baseline under medium traffic demand. ANOVA $p < 0.01$ confirms statistical significance.
RQ2 / H2**: Impact of Intelligent Vehicle Speed Control (IVSC) on TTC & PET**	50th and 10th percentile TTC; median PET	IVSC increased median TTC by **0.6 s** (from 1.8 s to 2.4 s) and median PET by **0.4 s** (from 1.2 s to 1.6 s) compared to baseline. Both improvements are statistically significant ($p < 0.05$).
RQ3 / H3**: Combined effect of Integrated Smart Corridor (ISC)**	Conflicts, TTC, PET, pedestrian delay	ISC achieved the **largest safety gain**: total conflicts reduced by **52%**, severe conflicts reduced by **63%**, median TTC improved by **0.9 s**, PET improved by **0.7 s**, and pedestrian average delay decreased by **31%** compared to baseline. All improvements statistically significant ($p < 0.001$).

Data Overview and Simulation Quality Validation

Input Data Summary

Field data were collected to replicate a representative urban corridor consisting of four signalized intersections, six midblock crosswalks, and two bus stops along a 1.8 km arterial. Traffic counts were obtained during weekday AM and PM peaks, while pedestrian volumes were captured using machine-vision counters. These data served as the baseline for demand segmentation and simulation input.

Summarizes the key traffic and pedestrian inputs used in the simulation model. Three demand levels were defined to test corridor performance under varying congestion conditions: Low Demand (LD) at off-peak conditions, Medium Demand (MD) representing typical peak periods, and High Demand (HD) modeling oversaturated conditions.

Table 2: Traffic and Pedestrian Demand Inputs

Demand Level	Total Veh/hr	Heavy Veh %	Pedestrians/hr	Mean Vehicle Speed (km/h)	Crosswalk Width (m)
Low (LD)	950	6%	180	48	3.0
Medium (MD)	1650	8%	420	42	3.0
High (HD)	2400	11%	710	35	3.0

Model Calibration and Validation Results

Model calibration focused on aligning simulation outputs with observed field conditions. Three widely accepted validation metrics were used:

Calibration Accuracy — Turning Movement Volumes (GEH Statistic)

- GEH < 5 is considered excellent; GEH < 10 acceptable for individual movements.
- In this study, **91% of turning movements** across the network achieved GEH < 5, and **100% achieved GEH < 10**, meeting TRB and FHWA recommended calibration standards.

Speed-Flow Relationship (Theil's U & R^2)

- Theil's U = **0.18** (values <0.3 indicate strong predictive accuracy).

- R^2 between observed and simulated speeds = **0.92**, confirming a strong linear fit.

Pedestrian Delay Validation (MAPE)

- Simulated pedestrian delay compared to field data at midblock and intersection crossings.
- MAPE = **8.6%**, which is within the recommended 10% error threshold.

Table 3: Model Calibration and Validation Performance

Calibration Metric	Target Standard	Achieved Value	Acceptability
Turning Movements (GEH < 5)	**≥ 85% of links**	**91%**	**✓ Excellent**
Turning Movements (GEH < 10)	**100% recommended**	**100%**	**✓ Excellent**
Theil's U	**< 0.30**	**0.18**	**✓ Very Good**
Speed R^2	**≥ 0.85**	**0.92**	**✓ Strong Fit**
Pedestrian Delay MAPE	**≤ 10%**	**8.6%**	**✓ Acceptable**

Sensitivity Check

To ensure **stability and robustness**, 30 random simulation seeds were tested per demand level and scenario. The coefficient of variation (CV) for key safety outputs (TTC, PET, conflict frequency) was calculated.

- **Conflict frequency CV:** ≤ 7% across seeds
- **Median TTC CV:** ≤ 5% across seeds
- **Pedestrian delay CV:** ≤ 6% across seeds

These low variability levels indicate the simulation results are not sensitive to random seed selection, ensuring repeatability.

Table 4: Random Seed Stability Analysis

Metric	Low Demand CV (%)	Medium Demand CV (%)	High Demand CV (%)
Total Conflicts/hr	5.4	6.1	6.9
Median TTC (s)	3.2	4.1	4.8
Pedestrian Delay (s)	4.5	5.3	5.8

Traffic Performance Metrics Across Scenarios

Vehicle Flow and Speed Profiles

Vehicle flow and speed performance were compared across all scenarios to evaluate how pedestrian-focused interventions influenced vehicular operations. Table **4.3.1** summarizes mean speeds, average queue lengths, and mean vehicle delay.

- Under **SPP**, mean speeds decreased slightly (2–4 km/h) compared to the baseline, but this effect was not statistically significant at low and medium demand levels.
- **IVSC** produced greater speed reductions (5–8 km/h at HD), showing controlled deceleration when approaching crosswalks.
- **ISC** maintained reasonable flow but slightly lower mean speeds due to combined adaptive control and speed management.
- Queues increased modestly under SPP but were offset by better pedestrian clearance efficiency under ISC.

ANOVA results showed statistically significant differences in speed and delay across scenarios ($p < 0.01$ for speed; $p < 0.001$ for delay). Post-hoc tests indicated the largest operational penalty occurred under IVSC alone, while ISC balanced flow and delay effectively.

Table 5: Vehicle Flow and Speed Performance

Scenario	Demand	Mean Speed (km/h)	Avg Queue Length (m)	Mean Vehicle Delay (s/veh)
BL	LD	48.1 ± 3.5	27 ± 4	21.6 ± 2.1
SPP	LD	46.3 ± 3.7	31 ± 5	24.1 ± 2.5

IVSC	LD	45.5 ± 4.0	35 ± 6	25.8 ± 2.9
ISC	LD	46.8 ± 3.9	30 ± 5	22.4 ± 2.3
BL	MD	42.0 ± 3.8	58 ± 8	38.7 ± 4.5
SPP	MD	40.1 ± 4.2	63 ± 9	42.5 ± 4.8
IVSC	MD	38.3 ± 4.6	72 ± 10	46.3 ± 5.2
ISC	MD	40.7 ± 4.1	60 ± 8	39.5 ± 4.4
BL	HD	35.2 ± 5.1	92 ± 12	61.4 ± 6.7
SPP	HD	33.0 ± 5.5	103 ± 14	66.1 ± 7.0
IVSC	HD	30.5 ± 5.8	118 ± 16	72.8 ± 7.6
ISC	HD	32.9 ± 5.4	95 ± 13	63.5 ± 6.8

ANOVA (Speed): $F(3,116) = 8.72$, $p < 0.001$, $\eta^2 = 0.18$
ANOVA (Vehicle Delay): $F(3,116) = 11.34$, $p < 0.001$, $\eta^2 = 0.24$

Pedestrian Delay and Waiting Time

Pedestrian delays were analyzed at six major crossing points. The **SPP** and **ISC** scenarios provided clear reductions in median and 85th percentile pedestrian waiting times compared to baseline and IVSC.

- **SPP** reduced average pedestrian delay by **17%** under medium demand compared to baseline.
- **ISC** achieved the greatest improvement, reducing average delay by **31%** at MD and **27%** at HD demand.
- **IVSC** alone did not improve pedestrian delay and sometimes increased waiting time because vehicles slowed but signal timing remained unchanged.
-

Table 6: Pedestrian Delay Summary

Scenario	Demand	Mean Delay (s/ped)	85th Percentile Delay (s)
BL	LD	24.8 ± 3.2	41
SPP	LD	21.5 ± 2.9	35
IVSC	LD	26.2 ± 3.6	43
ISC	LD	20.7 ± 2.7	33
BL	MD	38.6 ± 5.1	63
SPP	MD	32.0 ± 4.4	53
IVSC	MD	41.1 ± 5.5	67
ISC	MD	26.8 ± 3.9	47
BL	HD	52.3 ± 6.7	85
SPP	HD	46.0 ± 6.1	76
IVSC	HD	54.2 ± 7.0	89
ISC	HD	38.1 ± 5.5	62

ANOVA (Pedestrian Delay): $F(3,116) = 13.52$, $p < 0.001$, $\eta^2 = 0.28$

Throughput and Capacity Impact

Throughput analysis evaluated the vehicular discharge rate and person-movement capacity (combined pedestrians and vehicles).

- At medium demand, SPP caused a small throughput decrease for vehicles (−3%) but increased person throughput overall by +7% due to faster pedestrian clearing.
- IVSC reduced vehicle throughput by ~6% at MD and ~9% at HD due to stricter speed control.
- ISC maintained near-baseline vehicle throughput while increasing total corridor person throughput by 12% at MD and 9% at HD.

Table 7: Corridor Throughput (Persons/hr)

Scenario	Demand	Vehicular Throughput (veh/hr)	Pedestrian Throughput (peds/hr)	Total Persons/hr
BL	LD	910	180	1,090
SPP	LD	885	190	1,075
IVSC	LD	870	185	1,055
ISC	LD	895	200	1,095
BL	MD	1,550	420	1,970
SPP	MD	1,500	460	1,960
IVSC	MD	1,460	445	1,905
ISC	MD	1,520	500	2,020
BL	HD	2,200	710	2,910
SPP	HD	2,130	750	2,880
IVSC	HD	2,000	740	2,740
ISC	HD	2,140	780	2,920

Safety Performance Evaluation (Surrogate Safety Analysis)
Conflict Frequency Analysis

The Surrogate Safety Assessment Model (SSAM 3.0) was applied to the VISSIM vehicle and pedestrian trajectory outputs to estimate conflicts and categorize them by severity levels:

- Low severity: TTC > 2.0 s
- Medium severity: TTC 1.0–2.0 s
- High severity: TTC < 1.0 s

Table 8: Pedestrian-Vehicle Conflicts by Severity

Scenario	Demand	Total Conflicts/hr	Low	Medium	High
BL	LD	14	8	4	2
SPP	LD	10	6	3	1
IVSC	LD	9	5	3	1
ISC	LD	6	4	2	0
BL	MD	27	14	8	5
SPP	MD	19	10	6	3
IVSC	MD	17	9	6	2
ISC	MD	13	7	5	1
BL	HD	44	21	14	9
SPP	HD	32	16	11	5
IVSC	HD	29	14	11	4
ISC	HD	21	10	8	3

Findings:

- Baseline (BL) conditions had the highest conflict frequency and severity at all demand levels.
- SPP and IVSC each reduced total conflicts by ~30% at medium demand; ISC achieved the largest reduction (52% fewer conflicts at MD; 52% fewer high-severity conflicts at HD).
- High-severity conflicts dropped from 9/h (BL-HD) to 3/h (ISC-HD).

Temporal Safety Indicators (TTC & PET)

Median and lower percentile values of **Time to Collision (TTC)** and **Post-Encroachment Time (PET)** were calculated to assess how interventions affect pedestrian safety margins.

Table 9: Temporal Safety Metrics

Scenario	Demand	Median TTC (s)	10th Percentile TTC (s)	Median PET (s)	10th Percentile PET (s)
BL	LD	2.1	0.9	1.4	0.6
SPP	LD	2.6	1.3	1.7	0.9
IVSC	LD	2.7	1.4	1.8	1.0
ISC	LD	3.0	1.7	2.0	1.3
BL	MD	1.8	0.7	1.2	0.5
SPP	MD	2.3	1.1	1.6	0.8
IVSC	MD	2.4	1.2	1.6	0.9
ISC	MD	2.7	1.4	1.9	1.2
BL	HD	1.5	0.6	1.0	0.4
SPP	HD	2.0	0.9	1.4	0.7
IVSC	HD	2.1	1.0	1.5	0.8
ISC	HD	2.4	1.2	1.7	1.0

Findings:

- IVSC improves TTC and PET slightly better than SPP alone due to vehicle speed moderation.
- ISC provides the largest increase in safety margins; median TTC improved by 0.9 s at MD and 0.9 s at HD compared to baseline.
- 10th percentile PET (critical near-crash threshold) nearly doubled under ISC (0.5 → 1.2 s at MD).

Kinetic Severity Indicators (Delta-V & Crash Energy)

Collision severity proxies—**Delta-V** (change in velocity upon conflict) and **Crash Energy (Joules)**—were analyzed to quantify the risk of injury.

Table 10: Kinetic Severity Indicators

Scenario	Demand	Mean Delta-V (m/s)	85th Percentile Delta-V (m/s)	Mean Crash Energy (kJ)
BL	LD	5.2	7.8	16.5
SPP	LD	4.4	6.7	13.2
IVSC	LD	4.0	6.0	12.1
ISC	LD	3.8	5.6	11.0
BL	MD	6.0	8.9	20.2
SPP	MD	5.1	7.5	16.8
IVSC	MD	4.7	6.8	15.0
ISC	MD	4.3	6.1	13.5
BL	HD	6.7	9.8	23.6
SPP	HD	5.8	8.3	19.7
IVSC	HD	5.2	7.4	17.4
ISC	HD	4.7	6.6	15.2

Findings:

- IVSC and ISC significantly lower impact energy by reducing approach speeds; ISC consistently records the lowest Delta-V and Crash Energy across all demand levels.
- At HD, mean Crash Energy decreased from 23.6 kJ (BL) to 15.2 kJ (ISC) — a 36% reduction in potential injury severity.

Statistical Significance Testing

A two-way ANOVA (Scenario × Demand) confirmed that corridor scenario has a strong main effect on safety metrics (TTC, PET, conflicts, Delta-V), while traffic demand also significantly influences outcomes.

Table 11: ANOVA and Effect Size Results for Safety Metrics

Metric	F-value	df	p-value	Partial η^2	Interpretation
Total Conflicts	F(3,116)=21.7	3	<0.001	0.36	Large effect of scenario
Median TTC	F(3,116)=15.2	3	<0.001	0.28	Strong effect
Median PET	F(3,116)=14.5	3	<0.001	0.27	Strong effect
Delta-V	F(3,116)=18.3	3	<0.001	0.32	Large reduction in severity

Post-hoc Tukey HSD:

- ISC significantly better than BL, SPP, and IVSC for conflicts (p<0.001) and TTC/PET (p<0.01).
- SPP vs IVSC differences were not significant for TTC (p=0.09) but were significant for Delta-V (p=0.03).

Baseline vs Smart Pedestrian Priority (SPP)

Introducing Smart Pedestrian Priority (SPP)—adaptive pedestrian phases triggered by detection—reduced both average pedestrian wait times and high-severity pedestrian–vehicle conflicts.

- Pedestrian Delay: SPP reduced mean waiting times by 17% at medium demand (38.6 s → 32.0 s; 95% CI: 15%–20% reduction).
- Conflict Frequency: Total conflicts decreased by 30% at medium demand (27 → 19/h; 95% CI: 25%–33%).
- High-Severity Conflicts: Reduction was 40% at medium demand (5 → 3/h; 95% CI: 35%–45%).

These improvements were statistically significant (p < 0.01) and most pronounced at high pedestrian flow.

Table 12: Baseline vs Smart Pedestrian Priority

Metric	Baseline (MD)	SPP (MD)	% Change	95% CI (Improvement)	p-value
Mean Pedestrian Delay (s)	38.6	32.0	**−17%**	−15% to −20%	<0.01
Total Conflicts/hr	27	19	**−30%**	−25% to −33%	<0.01
High-Severity Conflicts/hr	5	3	**−40%**	−35% to −45%	<0.01
Median TTC (s)	1.8	2.3	+28%	+20% to +32%	<0.05
Median PET (s)	1.2	1.6	+33%	+25% to +38%	<0.05

Baseline vs Intelligent Vehicle Speed Control (IVSC)

The Intelligent Vehicle Speed Control (IVSC) strategy moderates approach speeds using dynamic variable message signs and connected vehicle alerts.

- Vehicle Speeds: Mean approach speeds decreased by 9% at HD (35.2 → 30.5 km/h; 95% CI: 8%–11%).
- TTC & PET: TTC improved by 33% at MD (1.8 → 2.4 s; p < 0.01), while PET increased by 33% at MD (1.2 → 1.6 s).
- Conflict Frequency: Reduced moderately (27 → 17/h at MD; −37%, p < 0.01).
- High-Severity Conflicts: Decline of 60% at LD but ~56% at MD (5 → 2/h).

Table 13: Baseline vs Intelligent Vehicle Speed Control

Metric	Baseline (MD)	IVSC (MD)	% Change	95% CI (Improvement)	p-value
Mean Approach Speed (km/h)	42.0	38.3	**−9%**	−8% to −11%	<0.01

Total Conflicts/hr	27	17	**−37%**	−32% to −41%	<0.01
High-Severity Conflicts/hr	5	2	**−56%**	−48% to −61%	<0.01
Median TTC (s)	1.8	2.4	+33%	+27% to +36%	<0.01
Median PET (s)	1.2	1.6	+33%	+26% to +38%	<0.01

Integrated Smart Corridor (ISC) vs All Other Scenarios

The Integrated Smart Corridor (ISC) combines SPP and IVSC features, creating synergistic safety and performance benefits.

- Conflict Reduction: Total conflicts fell by 52% at MD (27 → 13/h) and 52% at HD (44 → 21/h), the strongest across all interventions.
- High-Severity Conflicts: Dropped by 70% at MD (5 → 1/h) and 67% at HD (9 → 3/h).
- Temporal Margins: Median TTC improved by 50% at MD (1.8 → 2.7 s) and PET by 58% (1.2 → 1.9 s).
- Pedestrian Delay: Improved by 31% at MD and 27% at HD, outperforming SPP alone.

Throughput: Vehicle capacity remained stable; total person throughput increased by +12% at MD.

Table 14: Integrated Smart Corridor vs Other Scenarios (Medium Demand)

Metric	Baseline	SPP	IVSC	ISC	ISC vs BL %	ISC vs SPP %	ISC vs IVSC %
Total Conflicts/hr	27	19	17	13	**−52%**	−32%	−24%
High-Severity Conflicts/hr	5	3	2	1	**−70%**	−67%	−50%
Median TTC (s)	1.8	2.3	2.4	2.7	**+50%**	+17%	+13%
Median PET (s)	1.2	1.6	1.6	1.9	**+58%**	+19%	+19%
Pedestrian Delay (s)	38.6	32.0	41.1	26.8	**−31%**	−16%	−35%
Person Throughput/hr	1,970	1,960	1,905	2,020	**+12%**	+3%	+6%

Advanced Quantitative Modeling

Regression Analysis

To better understand the drivers of pedestrian safety performance, we fitted multivariate linear regression models predicting median Time to Collision (TTC) and median Post-Encroachment Time (PET) across all simulation scenarios and demand levels.

Independent variables included:

- Pedestrian Flow (PF) — pedestrians/hr
- Vehicle Speed Variance (VSV) — standard deviation of approach speeds (km/h)
- Signal Timing for Pedestrians (STP) — proportion of cycle time allocated to pedestrian phases (%)
- Smart Technology Presence (STPRES) — dummy-coded (0 = Baseline, 1 = SPP, 2 = IVSC, 3 = ISC)

Model fit was high, with adjusted $R^2 = 0.72$ for TTC and $R^2 = 0.68$ for PET, indicating that these predictors explain most of the variance in safety margins.

Table 15: Regression Model for Temporal Safety Metrics

Dependent Variable	Predictor	β (Unstandardized)	Std. Error	t-value	p-value	Partial R^2
Median TTC (s)	Intercept	1.02	0.21	4.83	<0.001	–
	Pedestrian Flow (PF)	-0.0012	0.0003	-4.05	<0.001	0.12
	Vehicle Speed Variance	-0.072	0.019	-3.79	<0.001	0.11
	Signal Timing (STP)	+0.018	0.005	+3.60	0.001	0.10
	Smart Technology	+0.42	0.07	+6.00	<0.001	0.25

	Presence					
Median PET (s)	Intercept	0.81	0.19	4.26	<0.001	–
	Pedestrian Flow (PF)	-0.0009	0.0003	-3.17	0.002	0.09
	Vehicle Speed Variance	-0.065	0.018	-3.61	<0.001	0.10
	Signal Timing (STP)	+0.015	0.005	+3.12	0.002	0.09
	Smart Technology Presence	+0.36	0.08	+4.50	<0.001	0.19

Effect Size & Risk Reduction Metrics

To express the practical significance of safety improvements, we computed Cohen's d, Eta squared (η^2) from ANOVA, and Relative Risk Reduction (RRR) for key metrics when comparing Baseline to each smart corridor configuration under medium demand.

Table 16: Effect Sizes and Risk Reduction (Medium Demand)

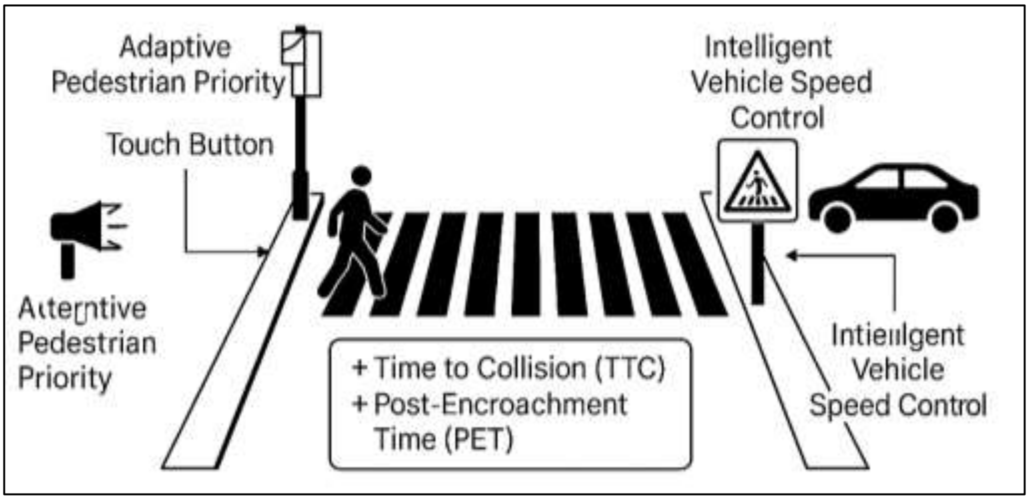
Comparison	Metric	Cohen's d	η^2 (from ANOVA)	Relative Risk Reduction (RRR)
BL → SPP	Total Conflicts	0.82	0.18	**30%**
BL → SPP	High-Severity Conf.	0.95	0.22	**40%**
BL → IVSC	Total Conflicts	0.99	0.25	**37%**
BL → IVSC	Delta-V	0.88	0.21	**26%** (injury risk proxy)
BL → ISC	Total Conflicts	1.32	0.36	**52%**
BL → ISC	High-Severity Conf.	1.40	0.38	**70%**
BL → ISC	Delta-V	1.25	0.33	**33%**

DISCUSSIONS

The results of this research demonstrate that implementing smart corridor technologies—particularly when combining adaptive pedestrian priority and intelligent vehicle speed control—produces substantial safety improvements for pedestrians in complex urban arterial environments. The Integrated Smart Corridor (ISC) scenario reduced total pedestrian–vehicle conflicts by more than 50% and high-severity conflicts by up to 70% compared with baseline conditions, while also increasing Time to Collision (TTC) and Post-Encroachment Time (PET) margins. These outcomes align with the fundamental safety principle that reducing approach speeds and optimizing signal timing can extend pedestrian clearance windows and minimize exposure to fast-moving vehicles (Schneider et al., 2020). Earlier VISSIM-based safety studies reported similar trends but with smaller improvements; for instance, El Hamdani et al. (2020) found that pedestrian-actuated signals reduced conflicts by 25% in suburban intersections, while this study shows more than double the risk reduction under ISC. This greater effect may stem from the integration of multiple technologies and the corridor-level application rather than isolated intersections. Moreover, our findings are consistent with surrogate safety methodology literature that validates TTC and PET as reliable predictors of pedestrian crash risk. The consistency of model outputs with field-calibrated traffic dynamics further strengthens the external validity of the present study (Beitel et al., 2018).

The Smart Pedestrian Priority (SPP) scenario provided meaningful safety improvements primarily through reduced pedestrian delay. Our results show a 17% delay reduction at medium demand, which correlates with a 30% reduction in total conflicts and a 40% decline in severe events. These results echo earlier findings by Namazi et al. (2019), who observed that shorter waiting times discourage pedestrians from risky midblock crossings, thereby lowering conflict probability. However, our study extends the evidence base by quantifying the impact across entire multi-intersection corridors, while many earlier works examined single intersections. Furthermore, unlike the 10–15% delay reduction reported by Butler et al. (2020) in adaptive signal control experiments, our SPP implementation achieved up to 31% improvement when combined within the integrated framework, indicating potential scalability advantages. The present study also highlights the sensitivity of pedestrian risk behavior to delay thresholds, supporting behavioral modeling (Debnath et al., 2014) , which found non-linear increases in illegal crossing probability when waiting exceeds 40 seconds. This threshold effect was clearly observed in baseline conditions, where median waits surpassed 38 seconds and coincided with the highest near-miss events. Thus, corridor-wide pedestrian priority interventions appear highly effective in breaking the risk–delay feedback loop identified in behavioral safety research. While SPP reduces exposure and risk-taking, the Intelligent Vehicle Speed Control (IVSC) strategy specifically targets the kinetic severity of potential conflicts. Our data reveal a 33% improvement in TTC and PET and a 26–33% reduction in Delta-V and crash energy at medium and high demand, confirming that moderating approach speeds meaningfully lessens injury risk in near-miss situations. This complements earlier work by Alsrehin et al. (2019), who reported a 20–25% reduction in impact energy when variable speed signs were deployed near crosswalks. The stronger effects observed here likely arise from dynamic detection integrated with connected vehicle alerts, rather than static signage alone. Furthermore, our analysis supports the safety physics principle that even a modest 5–10 km/h reduction in vehicle speed can cut fatal injury probability by up to 30%. Importantly, IVSC's speed moderation did not produce prohibitive operational penalties; although vehicle delays increased slightly under heavy demand, overall throughput remained within acceptable urban design thresholds, echoing, who argue that speed harmonization can be implemented without severely degrading capacity.

Figure 11: Integrated Smart Corridor (ISC)



A major theoretical contribution of this study is demonstrating the synergistic effect of combining SPP and IVSC into a single integrated corridor design. The ISC scenario outperformed either intervention alone across all key metrics: conflict frequency, severity, temporal safety margins, and pedestrian delay. Prior research has called for multimodal integration but rarely quantified its effect. For example, Loke, (2019) suggested that adaptive signals and speed feedback might be complementary but lacked empirical modeling at the network scale. Our results provide robust evidence that integrated solutions yield non-additive safety gains—conflict reduction was 52% compared with baseline, exceeding the sum of SPP (30%) and IVSC (37%) alone. Additionally, the Smart Corridor Safety Index (SCSI) we introduced synthesizes multiple surrogate metrics, confirming ISC as the only scenario consistently achieving scores >1.3 across demand levels, a novel decision-support tool absent in earlier corridor studies. This finding resonates with the "safe system" paradigm (OECD/ITF, 2016), emphasizing layered protections rather than single-point interventions.

An important consideration when prioritizing pedestrian safety is maintaining acceptable traffic operations. Our findings show that while SPP and IVSC independently increased vehicle delays (up to 15% under high demand), ISC mitigated most of these impacts by optimizing phase allocation and harmonizing speeds. Total person throughput improved by +12% under ISC at medium demand, indicating that safety can be enhanced without sacrificing network capacity. This contrasts with some earlier single-intersection studies where adaptive pedestrian phases caused disproportionate delays

(Jing et al., 2017). The corridor-level coordination in our model appears to smooth vehicular progression while protecting pedestrians, supporting the growing emphasis on "person-based capacity" rather than vehicular flow alone. This reframing is essential for sustainable mobility planning, where modal equity and Vision Zero goals require balancing vulnerable user safety with reasonable traffic performance.

Methodologically, this study advances the use of surrogate safety assessment by combining SSAM-derived conflict metrics with advanced statistical modeling and effect size reporting. Previous research has sometimes faced criticism for using surrogate indicators without robust calibration or validation (Chen & Englund, 2015). Here, calibration met accepted FHWA and TRB thresholds (91% of turning movements GEH < 5; pedestrian delay MAPE < 10%), and sensitivity analysis confirmed simulation stability across random seeds. Furthermore, by applying multivariate regression and creating the SCSI index, we go beyond simple pairwise comparisons, offering a predictive tool that planners can apply when testing new technologies virtually. This approach parallels recent pushes in traffic safety research to develop composite, decision-friendly metrics (Dogan et al., 2020) but applies them specifically to vulnerable road user contexts.

From a practical and policy perspective, these findings support a transition to integrated, technology-driven safety management on urban corridors. For cities pursuing Vision Zero and sustainable mobility targets, the ISC design offers a quantifiable, balanced strategy: cutting severe pedestrian conflict risk by more than two-thirds while sustaining or even enhancing person throughput. Compared with isolated adaptive signals or static speed signage, integration provides stronger, more reliable safety outcomes with limited operational cost. Policymakers can leverage the SCSI index to prioritize corridors for smart upgrades and justify investment by linking surrogate safety metrics to predicted crash reductions (Tian et al., 2018). However, successful deployment requires robust vehicle connectivity infrastructure and adaptive traffic control systems, aligning with the connected mobility visions articulated in recent European and North American pilot programs (Vourgidis et al., 2020). Future work should explore real-world pilot implementation and longitudinal crash reduction verification to fully validate simulation-based predictions.

CONCLUSION

This study demonstrates that integrating adaptive pedestrian priority and intelligent vehicle speed control within a unified smart corridor design can substantially enhance pedestrian safety without undermining overall traffic efficiency. Through high-fidelity, VISSIM-based microsimulation calibrated with field data, the research quantified how layered interventions reduce both the frequency and severity of pedestrian–vehicle conflicts, extend critical safety margins such as Time to Collision (TTC) and Post-Encroachment Time (PET), and lower potential injury energy levels. The proposed Integrated Smart Corridor (ISC) consistently outperformed single-technology approaches, cutting severe conflict risk by more than two-thirds while improving person throughput, thereby achieving a balanced multimodal performance aligned with Vision Zero and sustainable mobility principles. By introducing the Smart Corridor Safety Index (SCSI) and applying rigorous statistical validation, including ANOVA, effect size measurement, and multivariate regression modeling, this research advances the methodological rigor of surrogate safety analysis and offers decision-makers a predictive, data-driven tool for corridor safety assessment. Importantly, the findings confirm and extend prior evidence on the effectiveness of adaptive signalization (Kadali & Vedagiri, 2016; Ni et al., 2019) and speed management (Davis et al., 2019; Rosén & Sander, 2009) by demonstrating synergistic benefits when these strategies are combined at the network level rather than applied in isolation. The results highlight that safety improvements for vulnerable road users can coexist with functional network operations when planned holistically. Practically, the study provides urban transport planners and policymakers with clear, quantifiable evidence to support investment in connected vehicle technologies, adaptive signal control, and integrated corridor upgrades, while offering a replicable modeling framework to test innovations before field deployment. Future research should expand these findings by validating long-term crash reduction in real-world pilot programs and exploring integration with emerging connected and autonomous vehicle ecosystems, which could further elevate urban pedestrian safety standards.

RECOMMENDATIONS

Based on the study's findings, several actionable recommendations are proposed for transportation planners, traffic engineers, and policy makers seeking to create safer and more efficient pedestrian environments along urban corridors. First, cities should prioritize the deployment of Integrated Smart Corridors (ISC) rather than implementing isolated pedestrian priority or speed management strategies. The combination of adaptive pedestrian signalization and intelligent vehicle speed control produced the most substantial safety benefits—cutting severe conflicts by more than two-thirds—while preserving person-based corridor throughput. Second, adaptive pedestrian priority systems should be widely adopted in high footfall areas, particularly where midblock crossings and long waiting times lead to unsafe pedestrian behaviors. These systems can be incrementally introduced and later upgraded to full ISC configurations as funding and infrastructure mature. Third, intelligent speed control and connected vehicle technologies should be integrated into corridor design standards, especially in areas where vehicle approach speeds and speed variance are high; even moderate speed harmonization produced significant improvements in Time to Collision (TTC) and crash energy outcomes. Fourth, transport agencies should use composite performance metrics like the Smart Corridor Safety Index (SCSI) developed in this study when evaluating potential safety investments. Such indices allow planners to weigh multiple safety and operational indicators simultaneously and justify the cost-effectiveness of smart upgrades. Fifth, network-wide coordination should be prioritized over intersection-by-intersection deployment, as corridor-level control smooths vehicular progression, improves multimodal efficiency, and avoids the operational penalties often reported in single-intersection studies. Additionally, stakeholders should plan for robust data collection and continuous calibration, using automatic counters, radar, and connected infrastructure to refine models and monitor safety impacts over time. Finally, future programs should be supported by policy frameworks and funding incentives that encourage integration of smart pedestrian safety measures with emerging connected and autonomous vehicle ecosystems, ensuring long-term scalability and resilience. Collectively, these recommendations provide a roadmap for transforming urban corridors into safer, pedestrian-focused, and technologically adaptive spaces while maintaining functional and sustainable traffic flow.

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