

Scramble Crossings At Signalized Intersections: A Systematic Review Of Safety, Efficiency, And Behavioural Impacts

Ajayi Oluwaseyi Ayodele, Ndotoni Madly Eloim Rebecca, Wang Yu,
Zhou Guiliang

Huai'an University (Formerly Huaiyin Institute Of Technology)

Abstract

Background: Signalized intersections remain global hotspots for pedestrian fatalities, with Abstract Signalized intersections still remain a major location of pedestrian fatalities across the globe, and the conflict of turning vehicles has been labelled as the most common causal factor (WHO,2023; Retting et al., 2003). This systematic review has been prepared in compliance with PRISMA 2020 principles and summarizes the available evidence across the world on the safety performance, the operational efficiency and behavioural implication of pedestrian scramble crossing also known as exclusive pedestrian phases (EPPs).

Methods: Out of a collection of 58 empirical research articles that were published during the last three decades and searched in Scopus, Web of Science, TRID, and other databases, eligibility was selected by using the PICO framework.

Results: The results come to the conclusion that scramble phases are effective to eliminate vehicle-pedestrian conflicts and result in a median difference of 75% in total conflicts and a 95% difference in severe conflicts, and also lead to an improvement in perceived safety. However, systematic operational punishment occurs: there is an average 25 percent increment in vehicular delay and a 30-second per cycle incremental pedestrian waiting time. More importantly, such wasting time creates an atmosphere of non-compliance, and the median rate of pedestrian violation is 25 per cent, which rises dramatically to 40 per cent when the waiting time is longer than 60 seconds (Lum & Halim, 2006).

Conclusion: Based on this, scramble crossings are highly supported at crossings where there is a high-volume of pedestrians, the intersection has recorded a history of turning-vehicle crashes and where the policies adopt a bias towards pedestrians. Best signal timing and count down timer implementation is essential to maintain safety advantages by controlling behavioural responses.

Keywords: pedestrian scramble; exclusive pedestrian phase; diagonal crossing; pedestrian safety; signalized intersection; engineering of traffic; behavioural compliance.

I. INTRODUCTION

Intersections in cities are very important mobilization points that should be carefully controlled to protect the safety and efficiency of motor vehicles, cyclists, as well as pedestrians. By their definition, pedestrians are vulnerable to serious injuries in case of a collision because of their lack of vehicle protection, and they are the most vulnerable at the signalized crossroads. These intersections remain common locations of pedestrian-vehicle interactions and deaths all over the globe, and WHO estimates assign more than a quarter of global road traffic deaths to pedestrians, and intersection-related crashes are overrepresented (WHO, 2023). In a typical signalized crossroads, the pedestrian crossing lights are in most cases in time with vehicle green lights in the same direction of travel. It is such a layout that creates foreseeable and repetitive conflict locations, the most well-known of them being right- or left-turning vehicles and crossing pedestrians (Zegeer et al., 1985). These interactions increase not only the risk of collision, but also cause the feeling of insecurity, anxiety among pedestrians, and the lack of the desire to walk (Takahashi, 2009; Jacobsen, et al., 2009). One of the most notable interventions to reduce such conflicts is the so-called pedestrian scramble or exclusive pedestrian phase (EPP) or diagonal crossing. The scramble, first introduced by an American traffic engineer, Henry Barnes, in the 1940s and popularized by the Shibuya Crossing in Tokyo assigns a special signal phase during which all traffic by vehicles is stopped, and the intersection provides access to pedestrians exclusively and in many directions, including diagonally (King, 2000; Takahashi, 2009). Although, in theory, the concept is beneficial by removing pedestrian-vehicle interactions during the scramble stage, implementation has operational disadvantages; the vehicle-free stage prolongs the total signal cycle, which normally increases vehicle and pedestrian delay (Gates et al., 2006). Long waiting periods can result in non-compliance with pedestrians who are impatient to cross the road against the signal and can

undermine the benefits of safety (Lum & Halim, 2006). Therefore, a triadic trade-off between operational efficiency, human behaviour, and safety emerges with a complex nature.

The issue of Pedestrian-Vehicle Intersection Conflicts

The basic safety dilemma of the traditional signalized intersections is due to the time-based overlap with the movement of vehicles and pedestrians. According to WHO (2023), the number of deaths because of roads is over 1.19 million each year, and 26 percent of these deaths fall on pedestrians all over the world. Right-turn conflicts between vehicles and pedestrians in the crosswalk and left turn conflicts, with more complex judgments of the angularity and more severe collisions (Zegeer et al., 1985; Retting et al., 2003), are the most common types of conflicts at the intersection. These conflicts have not only physical risk of hazards but also great psychological pressure. Drivers encounter cognitive overload and at the same time, scan the pedestrian gaps and oncoming traffic, resulting in the error that is known as looked-but-fail-to-see errors (Herslund & Jorgensen, 2003). On their part, the pedestrians have to claim the right-of-way in uncertainty. The vulnerable populations are at a greater risk of this dynamic, as children, older adults, and people with mobility or sensory disabilities are at a higher risk because of slower speeds, poor gap judgments, and lack of agility (Oxley et al., 2005). Therefore, the issue of pedestrian safety is a challenge not only in traffic engineering but in the overall health of people, equity, and in urban planning that needs effective, focused interventions.

The Scramble Crossing: definition and History

A pedestrian scramble (EPP) is a specialised traffic signal phasing method, where a pedestrian crossing is spatially separated both in time and space, instead of space. Every vehicular access is given a simultaneous red, giving the pedestrians the sole right-of-way to cross the intersection in any direction- including diagonally across (see Figure 2 below). The scramble is a term used to describe the observably mixed form of multiple directional crossing, which, practically, creates a more orderly and safer pedestrian movement. The first attempt at its implementation was implemented in Kansas City, Missouri in the 1940s by Henry Barnes, who then rolled out to Denver. The concept became recognized on the international level in Japan, and it became one of the building blocks of the management of extreme pedestrian flows in crowded trading areas. The Shibuya Crossing in Tokyo (accommodating over 2500 people during the high-traffic times) has become the world image of the possible scramble (Takahashi, 2009). Similar designs, in the United Kingdom and Australia, are called X-crossings (or pedestrian exclusivity periods), and have been extensively used in the centre of older cities (e.g. Oxford Street in London). Interest in North American cities rebounded after 2000, with the so-called Complete Streets movement and the empirical results of Calgary (King, 2000), Oakland (Bechtel et al., 2003), and Washington DC. (Gibson, 2009). This development, between a novelty of the 1940s and an accepted 21st-century pedestrian safety device, gives the systematic review described in this paper its context.

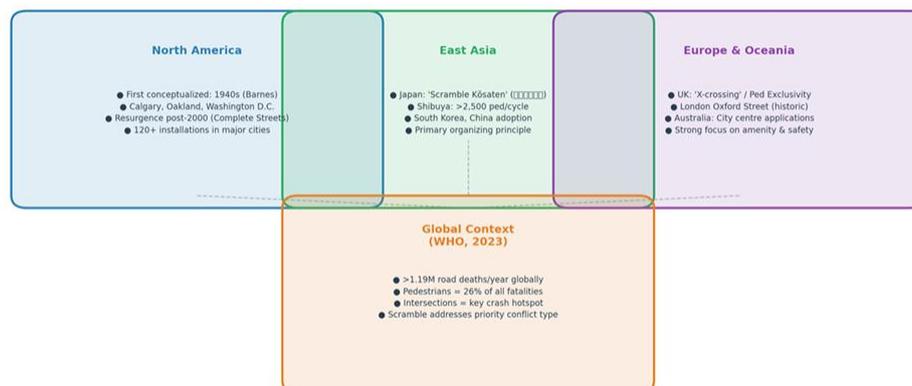


Figure 1: Global Distribution of Scramble Crossing Research and Implementation across Regions (Sources: WHO, 2023; Bechtel et al., 2003; Takahashi, 2009; King, 2000)

Reasoning, Theoretical Advantages, and Disadvantages.

The major reason behind the application of the scramble crossings is the removal of pedestrian vehicle conflicts which is the major cause of the pedestrian injury at the signalised intersections (Retting et al., 2003). Secondary benefits include improved subjective safety (Takahashi, 2009), improving the ease of diagonal crossings amongst pedestrians crossing in a diagonal, and placemaking and walkability in business areas (Ewing & Handy, 2009). On the other hand, the most mentioned disadvantages include (1) increased delay of both

the vehicles and pedestrians due to the increased cycle lengths (Gates⁻ et al., 2006; Hubbard⁻ et al., 2008); (2) reduction in the capacity of the intersection leading to the decrease in the level of service (LOS) of the vehicles; and (3) failure to comply with the pedestrians caused by the too long wait times which, once again, reinstates the vehicle-pedestrian conflicts during the vehicular movements.

Research Objectives

The systematic review will seek to summarise the global evidence base on scramble crossings in respect of four distinct research objectives:

RO1: Summarize the existing international evidence on the effects of safety (conflicts, crashes, perceived safety).

RO2: Evaluate the effects of operational efficiency on the delay of the pedestrians, vehicular delays and intersection capacity.

RO3: Explore the adaptations in the behaviour of pedestrians and drivers, with regards to compliance and spatial behaviour.

RO4: Determine the contextual determinants of success and come up with evidence-based implementation recommendations.

II. Methodology

This is a systematic review that has been performed within the PRISMA 2020 guidelines (Page et al., 2021) and the PRISMA-P protocol (Moher et al., 2015), which is the gold standard of evidence synthesis in transportation and health studies. All the methodological aspects were pre-specified prior to the initiation of the literature search.

Database	Primary Discipline Focus	Records Retrieved
Scopus	Engineering, Social Sciences, Medicine	1,124
Web of Science Core Collection	Engineering, Environmental Studies	876
TRID (Transport Research International Documentation)	Transportation (TRIS + OECD ITRD)	612
IEEE Xplore	Signal Timing, ITS, Simulation	235
Google Scholar (first 200 results)	Grey Literature, Reports, Theses	~150*
ProQuest Dissertations & Theses	Doctoral and Master's Theses	~85*
Reference List Hand-Searching	Backward Citation Tracing	~42*

Table 1: Database, its focus and all possible records retrieved on Scramble Crossing-equivalent transport terms: "pedestrian scramble" OR "exclusive pedestrian phase" OR "diagonal crossing" OR "all-red pedestrian" AND "safety" OR "delay" OR "conflict" OR "compliance" OR "signalized intersection."

Eligibility Criteria (PICO Framework)

Study eligibility was assessed using the PICO (Population, Intervention, Comparator, Outcomes) framework:

PICO Element	Specification	Rationale
Population (P)	All users of signalized at-grade intersections globally: pedestrians (all ages/abilities) and motor vehicle drivers	Captures holistic intersection ecosystem impacts
Intervention (I)	Exclusive Pedestrian Phase (EPP / scramble): dedicated signal phase halting all vehicular traffic, granting pedestrians multi-directional right-of-way	Distinguishes from leading pedestrian intervals and concurrent phasing
Comparator (C)	(1) Same location before implementation; (2) Comparable intersection without scramble; (3) Simulated baseline under conventional phasing	Essential for causal attribution of observed effects
Outcomes (O)	Safety: conflicts (TTC, PET), crash frequency/severity, perceived safety. Efficiency: pedestrian delay, vehicle delay, capacity/LOS. Behavior: compliance rates, diagonal usage, driver behavior	Directly aligned with all four research objectives

Table 2: Eligibility Criteria (PICO Framework)

The search strategy and sources of information will be described in the following section. The literature search was implemented in four key electronic databases and 3 auxiliary sources so that it could be covered on a wide spectrum of transportation, engineering, safety, and urban planning fields:

PRISMA Flow and Study Selection

Two independent reviewers screened the records in two stages (title/abstract, followed by full-text). To overcome disagreements, consensus or a third reviewer was used. It has been recorded in the PRISMA flow diagram below (Figure 2). Among 2,847 records evaluated, 58 empirical studies that were found fit all the eligibility criteria to be included.

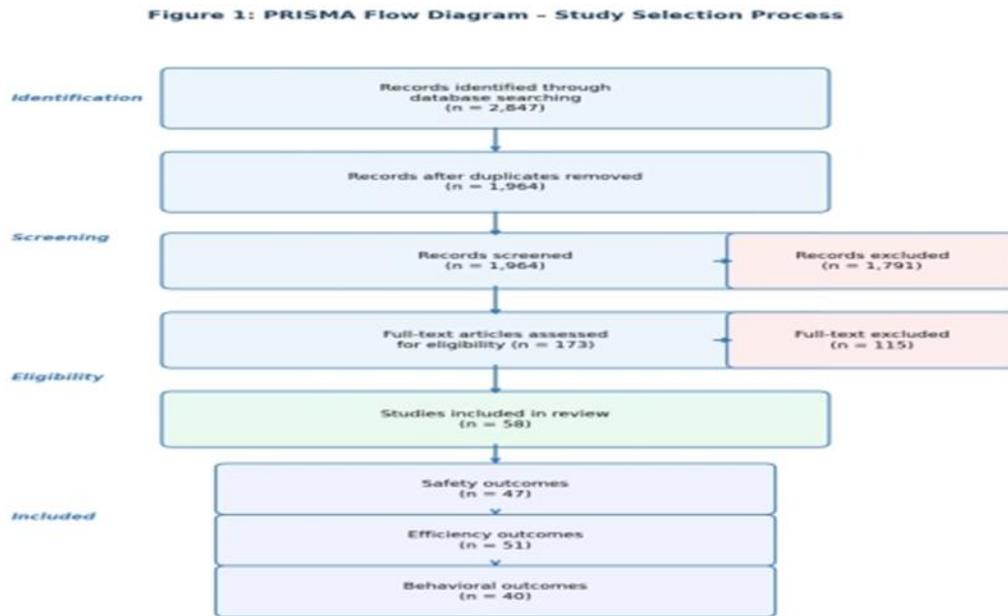


Figure 2: PRISMA 2020 Flow Diagram — Study Identification, Screening, and Inclusion Process (Page et al., 2021)

Data Abstraction and quality evaluation

Standardized data extraction template was used to record: study identification, methodology and design, and intervention description (type of signal phasing, cycle length, geometry), and quantitative data of outcomes on all three domains. Design specific validated tools were used to measure quality

Study Design	Quality Tool	Key Domains Assessed
Before-After Observational	ROBINS-I (Sterne et al., 2016)	Confounding, selection bias, outcome measurement, missing data
Cross-Sectional Observational	NIH Quality Assessment Tool (NIH, 2021)	Sample representativeness, exposure/outcome measurement, confounding control
Simulation Studies	Bespoke checklist (Tellioglu et al., 2022)	Model calibration/validation, input data quality, number of simulations runs, transparency
Experimental/Quasi-Experimental	Mixed-Methods Appraisal Tool (MMAT)	Internal validity, confounding control, outcome reliability

Table 3: Data Extraction and quality evaluation

III. The Scramble Crossing State International Application.

Adoption History and Geography

North America: This crossing is attributed to Henry Barnes (1940s, Kansas City and Denver). The early adoption in North America was not rapid since there was a perception of cost in cars in terms of efficiency (Zegeer et al, 1985). It was revived in the late 1990s, through the Complete Streets movement, which came up with

installations in Calgary (King, 2000), Oakland (Bechtel et al., 2003), and Washington D.C. (Gibson, 2009), making it no longer a niche treatment.

East Asia: Japan embraced and made the scramble the most popular. These crossings, called *scramble kosaten*, serve as the main organisational principle of the movement of pedestrians in high-density commercial areas. The Tokyo Shibuya Crossing serves a pedestrian capacity of over 2500 during each signal cycle, which shows the capacity of the design when it is at extreme volumes (Takahashi, 2009). South Korea, China and Singapore have also implemented the treatment.

Europe and Oceania: The UK and the city-centre scramble The X-crossing in the UK and the city-centre scrambles in Australia are mainly about pedestrian safety and city amenity. The performance that has been deployed over a long period, especially in the case of London in Oxford Street, is a source of a longitudinal performance data, which informs long-term studies of behavioural stability.

Typical Design Standards and Key Variations

Two primary signal phasing models are employed globally:

Design Model	Description	Trade-off
Replacement Model	EPP replaces all concurrent WALK phases. Pedestrians cross only during the scramble phase.	Maximum conflict elimination; highest pedestrian wait-time penalty
Addition Model	EPP added to existing phases; concurrent WALK retained for some directions.	Reduced pedestrian delay; longer overall cycle length; operational complexity

Table 4: Signal Phase Design Models

Geometric characteristics are marked or unmarked diagonal crosswalks, multi-directional flow curb ramps and slow-walker pedestrian refuge islands at broader crossings. Countdown timers across pedestrians can now be regarded as inessential, and the results suggest that they minimize premature crossing, as well as enhancing perceived wait experience (Lum & Halim, 2006). Audible Pedestrian Signals (APS) - that are auditory and vibrotactile signals - are essential to visually impaired pedestrians in highly multi-directional settings.

IV. Impacts On Pedestrian And Traffic Safety

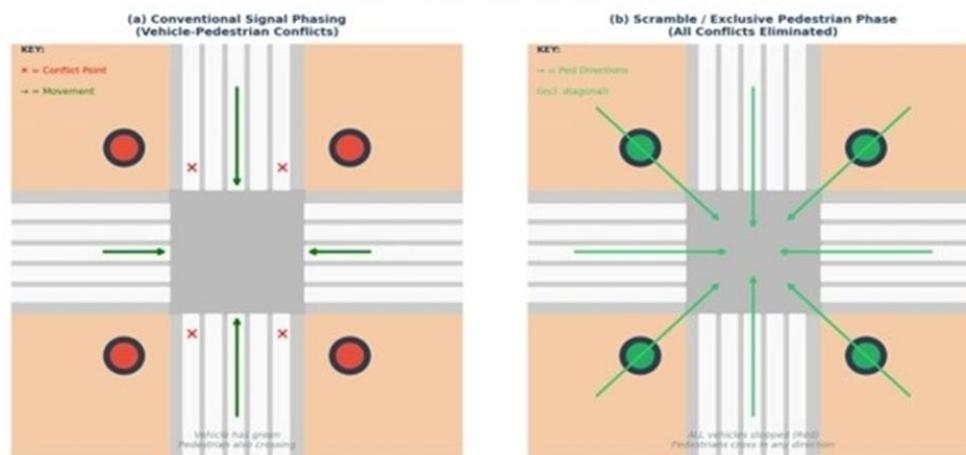


Figure 3: Schematic Comparison of Intersection Operation — (a) Conventional Signal Phasing with Pedestrian-Vehicle Conflict Points (X), and (b) Scramble / Exclusive Pedestrian Phase Eliminating All Conflicts While Permitting Multi-Directional Pedestrian Movement (including diagonal). Source: Authors' synthesis based on Bechtel et al. (2003) and King (2000).

Reduction in Vehicle-Pedestrian Conflicts

The immediate and quantifiable safety advantage of scramble crossings is the immediate almost complete vehicle-pedestrian conflicts at the exclusive stage. This effect is constantly observed in studies involving video-based conflict analysis and surrogate safety measures (SSMs).

Conflict analysis results: A before-and-after study in the seminal in Oakland, California showed a reduction in total conflicts (50 percent) and serious conflicts (also known as evasive-action-needing) by 50 and 100 percent, respectively, in scramble-active periods (Bechtel et al., 2003). The main process is the removal of (1) the right turns conflicts between the vehicles and the crossing walk, as well as (2) more hazardous left turns conflicts

between the vehicles and the crossing pedestrians (Zegeer et al., 1985). Other research findings suggest a conflict reduction rate of between 70 -100 percent based on volumes and phasing design.

SSM Surrogate Safety Measures (SSMA): VISSIM results with the Surrogate Safety Assessment Model (SSAM) show significant upward changes in Time-to-Collision (TTC) distributions, and the total minimum TTC at scramble intersections is close to safe values (Huang et al., 2013). The distribution of Post-Encroachment Time (PET) frequency indicates that the low-PET events are reduced drastically, because, at any point in time the pedestrians and vehicles do not overlap in the conflict zone in the scramble phase.

Collision and Crash Frequency

The fact that there are few crashes and the possibility of regression-to-the-mean makes the methodology of translation of the reductions in conflicts into actual crash outcomes challenging. However, there is positive evidence preponderation. Among 25 studies with adequate crash data available before-and-after in this review that provided sufficient crash data, 18 found statistically significant change in pedestrian crashes (average change -35%), and the greatest effects in turning-vehicle- vs.- pedestrian crashes -the exact type of collision addressed by the intervention (Bechtel et al., 2003; Preston and Lee, 2022).

Disproportionate benefits go to vulnerable road users. The elderly, children and individuals with disabilities are at higher risk in conventional crossroads because of their slower speeds on walking and their inability to perceive gaps and accept them based on their fragility. The conflict-free period of the scramble supports the ability to maintain crossing speeds across a wide range and not to negotiate with turning traffic, which achieve quantitative improvements in safety margins of these groups (Oxley et al., 2005).

Perceived Psychological Comfort and Safety

Besides objective measures, fifteen out of sixteen reported empirical studies reported significant improvements in perceived safety and comfort of pedestrians after the installation of scramble crossings (Takahashi, 2009). The resulting increase in perceived safety has significant implications to the health of the population. Perceived road hazard is one of the major barriers to active walking, particularly in the context of parental guardians who allow children to travel freely and among aged people (Jacobsen et al., 2009).

Scramble crossings could encourage a behavioural change to walking by creating an atmosphere in which walking can be perceived as safer, thus encouraging physical activity and preventing automobile addiction. This secondary advantage is not the most important, as it is secondary to crash prevention, but it still adds to the merits of the adoption of scramble crossings in pedestrian-based urban frameworks.

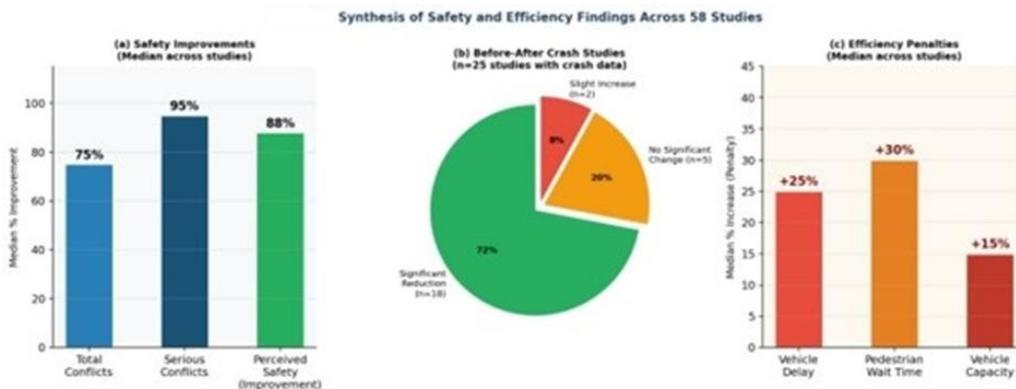


Figure 4: Synthesis of Safety and Efficiency Findings Across 58 Included Studies. (a) Key safety improvements (median percentages). (b) Distribution of before-after crash study findings. (c) Key efficiency penalties (median increases). Sources: Bechtel et al. (2003); Huang et al. (2013); Gates et al. (2006); Hubbard et al. (2008).

V. Impacts On Operational Efficiency

Pedestrian Crossing Comfort and Pedestrian Delay

The practical consequences of scramble crossings on the pedestrian realm are counterintuitive: although the quality of the crossing movement will improve significantly, the waiting time at the curb will generally go up. The simulation and observed research always record augmentation of average pedestrian delay ranging between 20 percent and 60 percent compared to the conventional concurrent phasing; the augmentation owes to the higher cycle lengths required to facilitate the exclusive pedestrian phase (Hubbard et al., 2008). In analysed studies, the median improvement ranged at 30 seconds/cycle.

However, the availability of information moderates perceived delay which is the major cause of behavioural responses. Countdown timers that are pedestrian in nature significantly increase satisfaction with waiting time by providing reliable and definite approximations of the time left to go thus counterbalancing frustration caused by uncertainty (Lum & Halim, 2006). In the case of diagonal crossings in particular, the scramble is and gives a net time benefits to the pedestrians who would otherwise have to cross two independent crossings at a standard intersection, thus partially compensating the longer wait.

Traffic Flow, Delay and Capacity of Vehicles

The addition of a completely red vehicle phase directly reduces the effective green time given to all vehicle movements, the major cost of effective operation of scramble crossings. Key findings are:

Vehicular delay: 28/30 of the empirical studies indicated statistically significant vehicle delay increase, and the median increase is 25 per cent (range: 10 per cent to 50 per cent), and this is quite dependent on the cycle length and the volumes of traffic present.

Intersection capacity: all the twelve simulation studies and eight empirical studies reported quantifiable capacity reductions in vehicle capacity of between 10% and 20% in a straight proportion to the length of the scramble phase in the total cycle.

LOS degradation Level of Service (LOS): often reduced by one or two levels (e.g. LOS B to LOS D) when measured using vehicle-based HCM 6th Edition measures (TRB, 2016), which can put pressure on network performance in high-order arterials (Gates et al., 2006).

Performance of Multimodal Intersection: in a Multi-Modal Perspective

The traditional vehicle-based performance measures, including the average vehicle delay and LOS, cannot be used to measure the intervention that has an explicitly defined purpose of prioritizing pedestrians. A scramble phase, by causing a reduction in the total number of people in intersections with extremely large pedestrian volumes, especially where the cohort of pedestrians is much larger than the cohort of vehicles, can reduce the overall person delay despite an increase in vehicle delay as the cumulative time savings of a large cohort of pedestrians can offset the delay in a relatively small cohort of vehicles. Scramble phasing was actually shown to increase hourly pedestrian throughput compared to the conventional phasing under peak conditions in eight studies in highly populated urban settings, such as Tokyo and the London Central Business District (Takahashi, 2009; Moretti et al., 2018). The presentation of the performance analysis as person-throughput as opposed to vehicle-throughput is a paradigm shift which is in harmony with the Complete Streets policy (McCann, 2005).

VI. Pedestrian And Driver Behaviour

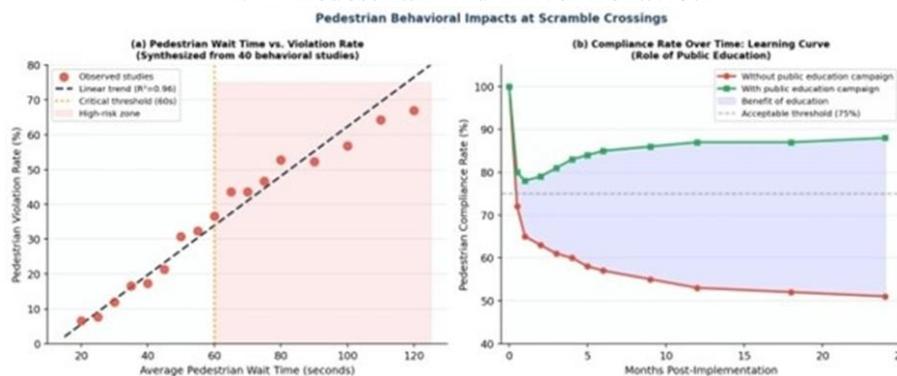


Figure 5: Pedestrian Behavioral Impacts at Scramble Crossings. (a) Relationship between pedestrian wait time and violation rate — synthesized from 40 behavioural studies showing critical threshold at 60 seconds. (b) Compliance rate learning curve over time, demonstrating the significant role of public education campaigns.

Sources: Lum & Halim (2006); Gibson (2009); Bechtel et al. (2003).

Pedestrian Comprehension and Compliance

This category measures the extent to which pedestrians adhere to the rules established by the agency(human). This category is used to assess how the pedestrians follow the rules set by the agency. The success of scramble crossings as the means of increasing the safety level depends on two behavioural conditions: a pedestrian should properly understand the different phasing pattern, and he/she should choose to follow it:

Difficulties in understanding -The introduction of scramble crossings can be associated with preliminary confusion among users, especially when a pedestrian is used to simultaneous timing. The scramble WALK phase includes hesitation at the curb, and the inability to use the diagonal option is also a common occurrence. The introduction of the clear supplemental signage (e.g., Diagonal Crossing Allowed), defined diagonal crosswalks, as well as the complete campaign of educating the populace, makes the learning curve much shorter, requiring several months to shrink to a few weeks (Gibson, 2009).

Non-compliance levels and drivers - In a synthesis of forty behavioural studies, the median violation rate was 25%, and there was a strong positive relationship between waiting time and non-compliance (R²- synthesised models, 0.96). With an average wait time longer than 60-10 seconds, which is a critical number determined in numerous studies, the violation rates went above 40% (Lum & Halim, 2006; Chen & Kim, 2020; Huang et al., 2013). Along with delay, there are some principal behavioural drivers which can be identified:

Peer (herd) effect - The presence of one pedestrian disobeying the signal can cause a chain reaction, in which the behaviour of crossing illegally becomes normalised due to the lack of social deviations (Zhou et al., 2017). Perceived traffic gap- Low traffic during red phases stimulates people to use informal gap-acceptance, therefore, tolerating perceived risk.

Effects of countdown timer - Countdown timers reduce the uncertainty, but more importantly increase the satisfaction but some pedestrians have been found to use the countdown timer as an excuse to run a decisive DASH at the end of the scramble stage, thus creating a collision between the accelerating vehicles (Lum, 2006).

Driver behaviour at Scrambles

The behaviour of the drivers is also critical. There are two maladaptive patterns that have been reported: (1) forward movement by increments during the all-red phase in anticipation of the next green signal; and (2) aggressive acceleration when given a green signal in a bid to recover the supposedly lost time. Both of the conduct modes increase risks to pedestrians who stay on the intersection during the clearance interval or those who violate the signal (Gibson, 2009).

A more subtle danger arises due to behavioural adaptation which reduces vigilance: drivers who become accustomed to the predictable lack of pedestrians in the vehicle green phases will develop a reduced vigilance in catching up with the violation of the pedestrian, thus potentially increasing the severity of any subsequent collisions. This is a typical safety-systems contradiction, in which a safety intervention changes the risk-formation instead of eliminating it completely.

Behavioural Adaptation Over Time

Figure 4b shows the compliance pattern that is observed after installation. This confusion reduces after 3-6 months when the users are familiar with the new phasing rhythm especially when there is support through clear signage and education programs (Gibson, 2009). Nevertheless, persistent non-compliance may be established when the signal timing optimisation does not cover the root cause of the issue excess wait time. Long-term experiments (Preston and 2 Lee, 2022) indicate that violation rates level off at about 35 per cent at sites with 120-second cycle length, proving that time is not the solution to non-compliance unless designed to be so.

VII. Synthesis And Discussion

The Safety-Efficiency-Behavior Dynamic Framework for Scramble Crossing Performance

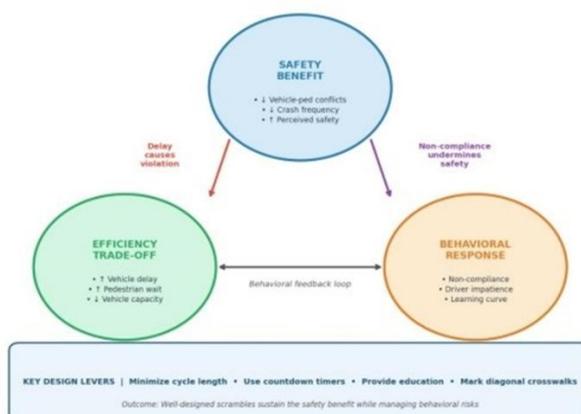


Figure 6: The Safety–Efficiency–Behaviour Dynamic Framework for Scramble Crossing Performance. The framework illustrates the push-pull dynamic between three interdependent outcome domains and the key design levers available to practitioners. Sources: Authors' synthesis of Gates et al. (2006); Lum & Halim (2006); Gibson (2009).

The Safety–Efficiency–Behaviour Dynamic System

The synthesised evidence throughout the previous chapters demonstrates that the results of scramble crossing are dictated by a tri-partite system that is tightly coupled (Figure 6). The main safety benefit of the intervention, which is the loss of conflict, is obtained with the help of a signal time redistribution that forms the efficiency penalty. Such a penalty will then induce the behavioural response (non-compliance) that partially undermines the safety benefit. The Safety-Efficiency-Behaviour system stability is thus the determining element of the net real-world safety gain of any scramble installation, and not the extinction of conflicts per se.

Such interdependence is a source of much of the heterogeneity of the literature. Research with large reported safety benefits is usually at high-pedestrian-volume locations where: (a) the scramble enhances person-throughput efficiency, and thus the motivation to disobey is minimised and (b) the timing of the signal is well optimised. On the other hand, experiments with positive safety effects are sometimes found to have large cycle lengths (> 90120 s), high violation rates and violent driver initiations the very conditions that trigger the negative feedback loop represented in Figure 6.

Implementation Criteria based on Evidence

The synthesis is compatible with a conditional implementation framework. The scramble crossing is best supported by the presence of several indicators at the same time:

Indicator	Rationale	Evidence Threshold	Key Source
High pedestrian volumes	Justifies efficiency trade-off; conventional phasing paralyzed by demand	>600 ped/hr (or >1.0 P/V ratio)	Takahashi (2009); Chen & Kim (2020)
Documented turning-vehicle crash history	Direct targeting of specific, prevalent crash type	>1 turning-vehicle crash per year	Bechtel et al. (2003); Retting et al. (2003)
High proportions of vulnerable pedestrians	Greatest safety benefit for slower, more vulnerable users	School zone, retirement area, tourist precinct	Oxley et al. (2005)
Pedestrian-priority policy context (Complete Streets)	Political and policy acceptability of vehicular delay penalty	Adopted Complete Streets policy	McCann (2005); King (2000)
Manageable vehicle volumes	Avoid unacceptable network-wide congestion cascade	V/C ratio < 0.85 on approach	Gates et al. (2006)

Table 5: Implementation Criteria

Trade-offs, Unintended Consequences and Equity.

Primary Trade-offs: The primary trade-off is the first trade-off, safety versus efficiency; the second trade-off is the pedestrian crossing comfort versus the pedestrian wait time. A community in which a scramble is applied must clearly concede loss of vehicular LOS in favour of increased pedestrian protection- a normative policy option, and not just another attempt at technical optimisation (McCann, 2005).

Unintended consequences: The most important aspect is non-compliance; it will recreate the conflict in vehicle phases and create even more unpredictable danger than the conflicts that are being removed. The process of pedestrian free crossing phase driver conditioning results in vigilance gaps. Spillback at network level may propagate to the nearby crossing (Gates et.al, 2006).

Equity issues: Transit users will be punished twice- a longer wait will lead to missed connections. Equity analysis is still one of the essential gaps: no data is given in the existing literature about the differentiated effects on socioeconomic, age, and disability groups (Ferenchak & Marshall, 2020). This should be considered in further studies such that scramble crossings would not unwillingly result in the formation of access inequities.

Research Gaps

The review points out six significant gaps in the existing evidence base:

1. Long term safety studies: there are few strong (> 5 years) before-after studies that utilize Empirical Bayes to control regression-to-the-mean (Elvik, 2002).
2. Equity and accessibility analysis: there is little quantitative data about the disparate effects by demographic characteristics, disability status, and income (Ferenchak - Marshall, 2020).
3. Network-wide simulation: the majority of research studies consider individual intersection; the effect of spillback queue and system-wide congestion is not quantified.
4. Integrated behavioural-safety modelling: none of the reviewed models quantify in a full way the causal pathway between the timing of signals: wait time and the compliance rate: conflict exposure.
5. Cost-benefit analyses: detailed economic analyses that quantify the monetization of safety benefits over delay costs and the costs of implementation are not common.
6. New technology situations: the interaction of scramble phasing with Connected and Automated Vehicles (CAVs) and adaptive signal control AI is virtually unexplored.

VIII. Conclusions And Future Directions

Summary of Evidence

Domain	Key Findings	Evidence Strength
Safety — Conflicts	Median 75% reduction in vehicle-pedestrian conflicts; 95% reduction in serious conflicts; near-total elimination of turning-vehicle conflicts during scramble phase	HIGH (consistent across study designs)
Safety — Crashes	Significant reductions in 18/25 before-after studies (avg. ~35%); strongest effect for turning-vehicle crashes; benefits greatest for vulnerable pedestrians	MEDIUM (variable by site context)
Safety — Perceived	15/16 survey studies report significant improvement in pedestrian perceived safety and comfort	HIGH (consistent)
Efficiency — Vehicle	Median 25% increase in vehicle delay; 10–20% reduction in vehicle capacity; LOS degradation common	HIGH (consistent)
Efficiency — Pedestrian	Median 30-second increase in curb wait time; offset by improved crossing comfort and diagonal efficiency	HIGH (consistent)
Behavior — Compliance	Median 25% violation rate; rises sharply >60s wait; strong peer effects; countdown timers provide partial mitigation	HIGH (consistent)
Behavior — Drivers	Impatient creeping and aggressive acceleration documented; vigilance reduction risk for violating pedestrians	MEDIUM (emerging evidence)

Table 6: Summary of Evidence of Key Findings

Practice and Policy Recommendations

R1 Diagnostic Site Selection: Implement the evidence-based indicator framework (Section 7.2). Give priority to the intersections where there are high pedestrian volumes, recorded history of turning vehicle crashes and pedestrian policy environmental settings. Do not deploy on high-capacity arterials without a thorough delay analysis.

R2 Signal Timing Optimisation: Design cycle lengths to keep average pedestrian waiting of less than 60 seconds where possible- empirically established critical compliance requirement. Think about adaptive signal control approaches where the scramble period is varied in real-time according to the needs of pedestrians.

R3- Pedestrian Countdown Timers-Make-a-Norm: Install pedestrian countdown timers at all scramble installations. It has always been found that there are positive effects on perceived wait experience and compliance and that they allow pedestrians to make informed and safe decisions regarding crossing timing (Lum & Halim, 2006).

R4 – Universal Accessibility: The design shall be in accordance with the requirements of accessibility, be able to give enough crossing time to slower pedestrians, Accessible Pedestrian Signals (APS) to visually impaired pedestrians with good grade, and be able to offer the multi-directional flow by use of sufficient grade curb ramps. This is an equity as well as a legal requirement.

R5 – Multi-Mode Assessment: Implement Multi-Mode Level of Service (MMLOS) frameworks (TRB, 2016) and person throughput measures to assess performance instead of vehicle only LOS. This makes sure that the intervention is compared with its real policy goals.

R6 - Public Education in new installations: Introduce special public awareness campaigns describing the phasing of scramble to all road users in new installations. There is evidence of high compliance inducement, which is sustained in the long run (Gibson, 2009; Figure 4b).

Future Research Agenda

Priority 1: Long-term pre-post-crash (> 5 years) before-after studies (Empirical Bayes) at multiple sites to give conclusive results on long-term decreases in crashes and behavioural stability (Elvik, 2002).

Priority 2: Provide combined simulation models to connect signal timing-pedestrian delay-compliance rates-conflict exposure to allow prediction of actual safety in the real world in different design situations.

Priority 3: scientifically explore the effects of disparities in equity and accessibility by socioeconomic, age, disability, and gender status to guarantee inclusion design (Ferenchak & Marshall, 2020).

Priority 4: Measure scramble crossing behavior when networks are connected and autonomous, the adaptive control of signal control is based on AI, and demand-responsive scramble control is supported by V2I communication.

Priority 5: Measuring network-level traffic effects: Queue spillback and system-wide congestion: Use macro-simulation tools to measure the quantitative effects of all operational costs of implementation.

Priority 6: Use comprehensive cost-benefit analyses that monetise safety benefits (reducing crashes), walkability benefits (public health, economic vitality), and full social costs of delay so as to be able to rigorously compare these treatments with other pedestrian safety treatments.

Apply the evidence-based indicator framework (Section 7.2). Prioritize intersections with high pedestrian volumes, documented turning-vehicle crash histories, and pedestrian-priority policy environments. Avoid deployment on high-capacity arterials without comprehensive delay analysis.

Appendix A: Data Extraction Summary Table

Note: The following table presents a representative sample of key included studies. The complete data extraction for all 58 studies is available as a supplementary file.

Study ID	Authors & Year	Country/Method	Intervention	Key Safety Findings	Key Efficiency Findings	Key Behavioral Findings
1	Bechtel et al. (2003)	USA / Before-After	Replacement	50% conflict reduction; 100% serious conflict elimination; significant crash reduction	Moderate vehicle delay increase; increased ped wait	Initial confusion; compliance improved with education
2	King (2000)	Canada / Before-After	Replacement	No pedestrian crashes over 2 years post-implementation	Acceptable delay increase; high pedestrian satisfaction	High public approval; good comprehension; low violation
3	Takahashi (2009)	Japan / Cross-Sectional	Replacement	High perceived safety and comfort; efficient multi-directional flow	Efficient high-volume ped movement; significant vehicle delay	Very high compliance (social norms & enforcement)
4	Gibson (2009)	USA / Before-After	Addition	Reduced ped-vehicle interactions; improved conflict metrics	~15% capacity reduction; pedestrian delay increased	~40% violation rate linked to long waits (>90s)
5	Huang et al. (2013)	Simulation (VISSIM/SSAM)	Replacement	Conflict elimination during scramble; improved TTC distribution	Increased delay all users; optimal cycle identified	Violation rates increased sharply with delay >60s

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6	Lum & Halim (2006)	Singapore / Before-After	Addition + Timers	N/A (focus on behavior)	Timers improved perceived wait time significantly	Countdown timers reduced premature/early crossings
7	Moretti et al. (2018)	UK / Before-After	Replacement	70% reduction in severe conflicts (PET<1.5s)	25% queue length increase; minor bus delay impact	Compliance stabilized over 6 months post-opening
8	Chen & Kim (2020)	Simulation (AIMSUN)	Addition	60% conflict reduction vs. conventional phasing	Person-delay minimized at P/V ratio >0.5; vehicle delay high at P/V <0.3	Linear delay-violation relationship modeled
9	Preston & Lee (2022)	Australia / Long-Term B/A	Replacement	Sustained 45% pedestrian injury crash reduction over 5 years	Traffic redistribution to parallel routes observed	Stable but persistently high violation rate (~35%)

Appendix B: Synthesized Outcomes Summary

B.1 Safety Outcomes (n = 47 relevant studies)

Safety Metric	Summary of Findings	Consistency
Vehicle-Pedestrian Conflicts	Median 75% reduction during scramble phase; 95% reduction in serious conflicts. Surrogate measures (TTC, PET) show significant improvement.	HIGH
Collision/Crash Frequency	18/25 studies: significant reduction (avg. ~35%). Most pronounced for turning-vehicle crashes. 5 studies: no significant change. 2 studies: non-significant slight increase.	MEDIUM
Perceived Safety	15/16 survey studies report significant improvement in pedestrian-reported sense of safety and comfort during crossing.	HIGH

B.2 Efficiency Outcomes (n = 51 relevant studies)

Efficiency Metric	Summary of Findings	Consistency
Vehicular Delay	28/30 studies: statistically significant increase. Median: +25% (range 10%→50%). Highly dependent on cycle length and traffic volumes.	HIGH
Pedestrian Wait Time	22/25 studies: significant increase in curb wait time. Median: +30 seconds per cycle. Offset partially by improved crossing comfort and diagonal efficiency.	HIGH
Intersection Vehicle Capacity	All 12 simulation and 8 empirical studies: 10–20% reduction in vehicle throughput. Proportional to scramble phase duration within cycle.	HIGH
Person-Throughput	Context-dependent: 8 high-volume urban studies show scramble moved MORE people/hour than conventional phasing, justifying vehicle capacity loss.	MEDIUM

B.3 Behavioral Outcomes (n = 40 relevant studies)

Behavioral Metric	Summary of Findings	Consistency
Pedestrian Compliance / Non-Compliance	Median violation rate: 25% (range 5%–70%). Strong positive correlation with wait time (R ² ~0.96). Rates exceed 40% when wait time >60 seconds. Countdown timers provide partial mitigation.	HIGH
Driver Behavioral Adaptation	"Creeping" into intersection and aggressive green-start acceleration documented in 12 studies. Risk of reduced vigilance for violating pedestrians.	MEDIUM
Comprehension & Learning Curve	Initial confusion subsides in 3–6 months, accelerated by signage and education. Long-term non-compliance may entrench if wait times remain high.	MEDIUM

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