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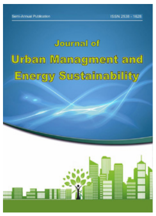

ORIGINAL RESEARCH PAPER

Efficiency Model for Pedestrian Overpasses Based on Movement Behavioral Patterns Using Game Theory

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ABSTRACT

Urban pedestrian infrastructure continues to pose a fundamental challenge in contemporary transportation and urban design research, particularly with regard to the gap between engineering provision and actual user behavior. Pedestrian overpasses are frequently underutilized despite their intended safety benefits, revealing a critical disconnect between physical design logic and behavioral decision-making. This study addresses the problem of how pedestrian bridge efficiency can be meaningfully evaluated beyond conventional engineering standards by incorporating behavioral, perceptual, and strategic dimensions of route choice. The primary objective is to develop a multidimensional analytical model the Pedestrian Bridge Efficiency Index grounded in game theory and movement behavioral patterns. The methodology adopts a sequential mixed-methods design integrating a four-round Delphi expert consultation, Fuzzy Analytic Hierarchy Process weighting, and agent-based computational simulation. Theoretical foundations draw from the Theory of Planned Behavior, environmental psychology, spatial movement analysis, and non-cooperative game theory, conceptualizing pedestrian–vehicle interaction as a strategic decision environment governed by bounded rationality. Findings from the Delphi process converged on six high-consensus indicators: Safety Level, Pedestrian–Vehicle Separation, Distance from Urban Nodes, Connection to Pedestrian Paths, Perceived Safety, and Total Crossing Time. FAHP weighting confirmed Safety Level and Pedestrian–Vehicle Separation as the dominant efficiency determinants, together accounting for 42% of the composite index. The study concludes that pedestrian bridge efficiency is an emergent behavioral property shaped by the interaction of spatial design, human cognition, and traffic dynamics. Future bridge planning should prioritize perceptual safety and spatial integration as primary design objectives, informed by behavioral modeling tools.

Running Title: Pedestrian Bridge Efficiency Model Based on Movement Behavioral Patterns

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INTRODUCTION

In recent decades, understanding behavioral patterns in urban spaces has become one of the central axes of urban planning and transportation research. The movement behavior of citizens in urban environments results from a complex interaction between individual perception, the physical characteristics of space, the structure of street networks, and traffic conditions (Gehl, 2011). Within this framework, pedestrian behavioral patterns are not solely determined by physical distance; rather, they are shaped by factors such as risk perception, time savings, route legibility, urban landscape quality, and prior experience. From a decision-making theory perspective, pedestrian movement cannot be regarded as a fully rational act based on absolute utility maximization. Instead, pedestrian decision-making operates within the framework of "bounded rationality," whereby individuals select a satisfactory rather than objectively optimal option based on incomplete information and subjective environmental perception (Simon, 1957). The spatial configuration of the city also plays a determinant role in shaping movement patterns. The structure of the street network, the degree of spatial integration, and the position of landmark urban elements can either reinforce or suppress movement flows. According to the theory of "natural movement," pedestrian patterns in the city are less a function of small-scale attractors and more a function of the macro-level structure of the spatial network (Hillier et al., 1993). Within such a framework, pedestrian movement is not merely physical displacement but constitutes part of the system of social and spatial actions of the city. The pedestrian is an active agent and decision-maker in the urban transportation system. Route choice, crossing time, and even the manner of crossing a street are the results of the individual's mental evaluation of safety, comfort, speed, and environmental desirability. Research has shown that if a proposed crossing route requires traversing a longer distance or ascending a large number of steps, the likelihood of its use decreases (Hamed, 2001). Furthermore, feelings of insecurity arising from insufficient lighting, inadequate sightlines, or the absence of social surveillance can redirect the individual's decision toward direct at-grade crossing. A distinction must be drawn between "physical safety" and "perceived security" a crossing facility may be entirely safe from an engineering standpoint, yet if the user does not feel psychologically secure, it will go unused.

In response to the increasing overlap between vehicular and pedestrian routes, grade-separated crossings particularly pedestrian overpasses have been proposed as solutions for the vertical segregation of traffic flows. These structures aim to improve safety and reduce accidents, enabling pedestrians to cross high-risk roads (Charles & Nicholas, 2006). Nevertheless, research has consistently shown that bridge utilization depends on factors such as comfort, safety, and appropriate location (Rasanen et al., 2007). The greater the ease of access and the more favorable the environmental conditions, the higher the probability of use; conversely, an increase in the number of steps, the absence of adequate ramps, or deficiencies in lighting can reduce efficiency (Hamed, 2001). Given that the pedestrian's decision to use or not use a bridge is the result of a simultaneous evaluation of perceived costs and benefits, this process can be understood as a form of interactive action within the traffic network. In this situation, the pedestrian is positioned against the flow of vehicles, the spatial structure of the corridor, and the available physical facilities. Such conditions align with the logic of game theory a framework that analyzes the decision-making of boundedly rational agents under conditions of mutual interdependence (Camerer, 2003). In recent years, the application of game theory in analyzing transportation systems has expanded considerably; research demonstrates that interactions among users of transportation networks can be modeled as strategic games in which the choice of each route is a function of time costs, perceived risk, and the responses of other users (Zhu & Levinson, 2015). Within this framework, behavioral equilibrium is established when no actor has an incentive to unilaterally change their strategy. This concept can be used to explain situations where pedestrians, even after the construction of a bridge, still prefer at-grade crossings; because their perception of costs and benefits, in interaction with traffic flow, has led to a different equilibrium. On the other hand, recent studies in urban behavioral modeling have shown that combining game theory with spatial analysis can provide a more precise understanding of user decision-making and explain the gap between engineering design and the actual behavior of users (Xu et al., 2020; Wang et al., 2022). This approach makes it possible to analyze a pedestrian bridge not merely as a physical structure, but as a strategic option within the set of pedestrian choices an option whose utility is determined through interaction with traffic conditions, spatial structure, and individual preferences. Accordingly, employing game theory can provide an analytical framework for evaluating the efficiency of pedestrian bridges and render pedestrian decisions measurable within an interactive model.

Despite numerous studies on the safety and design of pedestrian bridges, most research has adopted a descriptive or engineering approach and has not analyzed pedestrian decision-making as an interactive and strategic process. In many cases, it is observed that pedestrians, despite the existence of a bridge, prefer to cross the street directly; a behavior indicating a significant gap between engineering logic and users' perceptual logic. What has received less attention is the analysis of this decision as a strategic choice within the context of interaction among the pedestrian, traffic flow, and the spatial structure of the city. In such a context, the pedestrian's decision to use or not use the bridge can be modeled as an interactive problem, where each actor selects a strategy based on perceived benefits and costs. This analytical framework is consistent with the logic of game theory a theory that examines the behavior of bounded rational actors in conditions of interaction and interdependence. Given the necessity of improving pedestrian safety on major urban arterials and the low usage rate of some pedestrian bridges, pedestrian behavior can be analyzed from the perspective of interactive decision-making. Game theory provides a suitable tool for understanding these interactions, because route choice and the use of crossing facilities are not only a function of individual preferences but are also influenced by the decisions of other users and vehicles (Sun et al., 2022). Recent studies show that pedestrians, when faced with changing environmental conditions such as heavy traffic or long detours, adjust their behavior strategically and are likely to choose a shorter or safer route based on risk and prior experiences (Arafat et al., 2025). Using game theory frameworks, especially Bayesian and dynamic ones, enables the simulation of pedestrian decisions in complex urban situations. These models show that even in conditions where traffic rules and technical-engineering facilities are properly observed, the interactions of pedestrians with the environment and with each other determine the actual usage rate of bridges (Rahmati & Talebpour, 2018; Wang et al., 2023). Therefore, a game-theoretic analysis can simultaneously incorporate individual, social, and environmental factors into users' decision-making models and lead to the design and placement of bridges that are both safe and efficient, while also increasing their actual usage rate. The present study, focusing on the behavioral pattern of pedestrian movement, seeks to provide an analytical model for evaluating the efficiency of pedestrian bridges a model in which traffic characteristics, environmental factors, and perceptual variables are examined within an interactive framework. The ultimate goal is to provide a theoretical basis for improving the design, placement, and increasing the usage rate of pedestrian bridges in the urban context. Accordingly, the present study, focusing on pedestrian movement behavioral patterns, seeks to develop an analytical model for evaluating pedestrian bridge efficiency a model in which traffic characteristics, environmental factors, and perceptual variables are examined within an interactive framework grounded in game theory.

MATERIALS AND METHODS

The theoretical framework of this research integrates multiple disciplinary perspectives spanning behavioral planning theory, environmental psychology, spatial movement analysis, rational decision-making models, and game theory. Each theoretical lens contributes a distinct explanatory dimension to the overarching question of pedestrian bridge efficiency. Together, these frameworks establish that pedestrian decision-making is simultaneously shaped by individual cognition, spatial configuration, traffic dynamics, and social interaction a multi-causal structure that resists reduction to any single explanatory model. Central to this framework is the Theory of Planned Behavior (Ajzen, 1991), which posits that human behavior is governed by attitudes, subjective norms, and perceived behavioral control. Environmental psychology (Rapoport, 1982) complements this by demonstrating how the physical environment including bridge height, entrance design, lighting, and material quality shapes perception and ultimately behavior. Spatial movement theory (Hillier & Hanson, 1984) further contextualizes individual decisions within the macro-structure of the urban network. Game theory (Nash, 1950; Von Neumann & Morgenstern, 1944) provides the integrating analytical structure: pedestrian–traffic interaction is conceptualized as a non-cooperative game in which each agent pursues independent objectives under conditions of mutual interdependence. Nash equilibrium explains conditions under which pedestrians adopt stable crossing strategies that may diverge from engineering design intentions. (Tab. 1)

Table 1: Theoretical Framework of the Research, Multidisciplinary Foundations of Pedestrian Bridge Efficiency

No.	Theoretical Domain	Core Theoretical Proposition	Relevance to Pedestrian Bridge Efficiency	Key References
1	Theory of Planned Behavior (Ajzen)	Behavior is a function of attitude, subjective norm, and perceived behavioral control.	Explains pedestrian tendency to use the bridge versus at-grade crossing.	Ajzen (1991); Fishbein & Ajzen (2015)
2	Environmental Psychology (Rapoport)	The physical environment shapes human perception and behavior.	Examines effect of bridge design, height, and accessibility on usage.	Rapoport (1982); Nasar (2017)
3	Spatial Movement Theory (Goffman, Hillier)	Urban movement reflects social interactions and spatial organization.	Analyzes pedestrian movement in transitional spaces around bridges.	Hillier & Hanson (1984); Penn (2020)
4	Spatial Efficiency Theory (Lynch)	Efficiency depends on legibility, accessibility, and route continuity.	Measures functional connectivity of bridges within the street network.	Lynch (1984); Jiang & Claramunt (2019)
5	Rational Decision-Making Models (Simon)	Individuals decide based on utility maximization.	Models rational pedestrian choice between crossing options.	Simon (1957); Gigerenzer (2018)
6	Route Choice Theory (Ben-Akiva)	Route choice is a function of perceived time, security, and comfort.	Analyzes criteria for safe route selection by pedestrians.	Ben-Akiva & Bierlaire (2019); Handy (2022)

7	Game Theory (Von Neumann & Nash)	Individual decisions depend on the behavior of other players.	Models pedestrian–vehicle–environment interaction under conflict.	Nash (1950); Osborne (2020)
8	Behavioral Game Theory (Camerer)	Real decision-making is accompanied by perceptual and emotional biases.	Explains irrational pedestrian behavior when confronted with risk.	Camerer (2019); Glimcher (2021)
9	Agent-Based Models	System behavior arises from self-organized agent interaction.	Simulates group pedestrian decisions in bridge usage.	Bonabeau (2020); Crooks et al. (2019)
10	Efficiency Evaluation Models (DEA/MCDM)	Performance of spaces measured with multiple indicators.	Evaluates bridge efficiency based on behavioral and physical indicators.	Lin et al. (2020); Reisi et al. (2023)
11	Safety Perception & Perceived Risk Theory	Sense of danger and security influences crossing decisions.	Analyzes relationship between perceived risk and bridge choice.	Yannis et al. (2017); Zhao et al. (2021)
12	Person–Environment Interaction (Proshansky)	Behavior is product of mutual relationship between person and environment.	Explains role of design quality and spatial experience in behavior.	Proshansky (1978); Gifford (2020)
13	Social Sustainability & Active Transportation	Pedestrian-oriented infrastructure strengthens spatial equity and health.	Measures role of bridges in enhancing social vitality and urban safety.	Litman (2022); Gössling (2023)
14	Complex Urban Systems Theory (Batty)	The city is a self-organizing system with multi-level interaction.	Explains collective behavioral dynamics of pedestrians in urban network.	Batty (2018); Portugali (2021)
15	Combined Game Theory–Agent-Based Framework	Combines strategic decision-making with behavioral simulation.	Theoretical basis for designing the pedestrian bridge efficiency model.	Helbing (2020); Hoogendoorn (2019)

Methodology

This study adopts a pragmatist paradigm, treating pedestrian bridge efficiency as an empirically grounded and theoretically structured phenomenon that can be understood through both qualitative expert judgment and quantitative indicator analysis. The research is applied in orientation and exploratory–analytical in nature, seeking to construct a validated efficiency model rather than test a pre-specified hypothesis. In terms of epistemological stance, the study operates at the intersection of post-positivism and interpretivism: the use of structured expert consultation reflects a post-positivist commitment to systematic evidence, while the integration of behavioral and perceptual variables acknowledges the interpretive dimension of pedestrian decision-making. This methodological positioning aligns with mixed-methods traditions in urban transportation research (Creswell, 2018), enabling the study to move from qualitative indicator identification to quantitative prioritization within a unified analytical structure. The research employs a two-stage sequential mixed-methods design. In the first stage, a multi-round Delphi technique is used to identify, screen, and achieve consensus on the key determinants of pedestrian bridge efficiency. The Delphi method is selected because the research problem involves complex, multidimensional phenomena where structured expert knowledge is more reliable than direct empirical measurement alone (Linstone & Turoff, 1975). A purposive panel of specialists in urban design, transportation engineering, and behavioral science was consulted across four iterative rounds. In each round, participants rated the importance of a set of indicators using a five-point Likert scale. Indicators failing to reach a mean score threshold set at 2.5 in Round 1, 3.5 in Round 2, and 4.0 in Round 3 were eliminated, enabling progressive convergence toward the most critical variables. In the second stage, the Fuzzy Analytic Hierarchy Process (FAHP) is applied to determine the relative weights of the final Delphi-derived indicators. FAHP extends the standard AHP method by incorporating triangular fuzzy numbers to handle the inherent imprecision and subjectivity of expert judgments regarding the comparative importance of criteria (Chang, 1996; Buckley, 1985). Pairwise comparison matrices were constructed based on expert input, and consistency ratios were verified ($CR < 0.10$) to ensure reliability. The resulting weight vector constitutes the quantitative backbone of the Pedestrian Bridge Efficiency Index (PPEI), formally defined as: Efficiency = f (Safety, Accessibility, Behavioral Compatibility). (Fig. 1 and Tab. 2)

Table 2: Research Design Framework (Operational Research Design Framework: Dimensions, Criteria, Indicators, and Measures)Physical Quality to Bridge Efficiency (PPEI))

Dimension	Criteria	Indicators	Observable Measures / Variables
Physical–Functional	Location & Accessibility	Distance from urban nodes	Distance to bridge entrance (m)
		Connection to pedestrian paths	Presence of ramp or elevator
		Bridge slope & height	% of direct accessibility
	Design & Space Quality	Lighting level	Illuminance (Lux)
		Entrance/exit design	Direct sightline to crossing route
		Material quality	Maintenance condition rating
	Traffic Performance	Pedestrian–vehicle separation	Conflict rate
		Traffic throughput	Vehicle volume/hr; average speed
Behavioral–Perceptual	Usage Motivation	Willingness to use under varying conditions	Willingness score (Likert scale)
		Safety perception; attitude toward bridge	Perceived security level
	Movement Behavior & Route Choice	Decision: bridge vs. at-grade crossing	% bridge users; movement pattern in ABM simulation
	Spatial & Environmental Perception	Legibility	Ease-of-movement rating
		Visual attractiveness	Environmental aesthetics score
		Physical comfort	Pavement quality rating
Traffic & Safety	Vehicle Volume & Speed	Instantaneous vehicle density; avg. crossing speed	Veh/hr; Average Speed (km/h)
	Safe Crossing Time Gap	Safe pedestrian crossing time window	Mean inter-vehicle time gap (sec)
	Incident Rate	Accidents; high-risk pedestrian behavior	No. of at-grade violations; % unsafe crossings

Game-Theoretic–Analytical	Strategic Game Definition	Players (pedestrian, vehicle, environment) and objectives	Payoff matrix between behavioral options
	Game Type & Information	Static/dynamic; complete/incomplete; non-cooperative game	Pedestrian awareness; visibility & perceived control
	Equilibrium & Behavioral Efficiency	Nash equilibrium in bridge usage decision	% stable states in ABM simulation; decision convergence level
	Overall System Efficiency	Total crossing time; safety level; perceptual satisfaction	Composite Efficiency Index = f(time, safety, satisfaction)

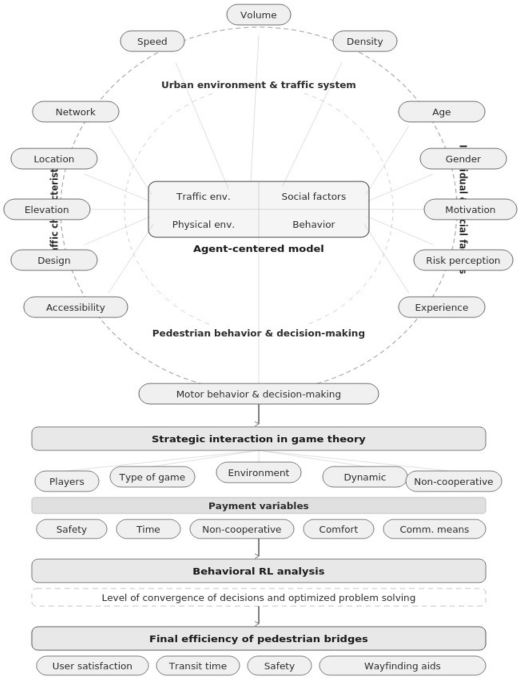

Figure 1: Conceptual Model-Agent-Based & Game-Theoretic Framework for Pedestrian Bridge Efficiency (Causal Chain from Physical Quality to Bridge Efficiency (PPEI))

DISCUSSION AND FINDINGS

Application of the Fuzzy Delphi–AHP Method (FAHP–Delphi)

The Delphi process was conducted across four successive rounds with a panel of experts in urban design, transportation engineering, and behavioral science. In each round, indicators were evaluated using a five-point Likert scale. The iterative structure enabled progressive elimination of low-consensus variables, converging toward a final set of high-priority efficiency indicators.

Delphi Round 1-Initial Screening

In the first Delphi round, thirty candidate indicators spanning spatial, behavioral, traffic, and game-theoretic domains were submitted for expert evaluation. Indicators with a mean score below 2.5 were removed at this stage, resulting in the elimination of five variables (Vehicle Density, Average Speed, Accident Risk, Static/Dynamic Game, Non-cooperative Game, Complete/Incomplete Information) due to insufficient expert consensus. (Tab. 3 and Fig. 2)

Table 3: Delphi Round 1-Initial Screening of Candidate Indicators (n = 30)

No.	Factor	Mean	Std.Dev	Min	Max
1	Distance from Urban Nodes	4.2	0.80	3	5
2	Connection to Pedestrian Paths	4.0	0.80	3	5
3	Bridge Slope	3.2	0.80	3	5
4	Bridge Height	3.1	0.80	3	5
5	Lighting Level	3.8	0.80	3	5
6	Visibility Level	3.9	0.80	3	5
7	Visual Safety	4.1	0.80	3	5
8	Entrance and Exit Design	3.6	0.80	3	5
9	Material Quality	3.5	0.80	3	5

10	Pedestrian–Vehicle Separation	4.3	0.80	3	5
11	Traffic Volume	3.7	0.80	3	5
12	Willingness to Use	3.4	0.80	3	5
13	Perceived Safety	4.0	0.80	3	5
14	Attitude Toward Bridge	3.9	0.80	3	5
15	Decision: Bridge vs. At-grade Crossing	3.8	0.80	3	5
16	Legibility	3.3	0.80	3	5
17	Visual Attractiveness	3.2	0.80	3	5
18	Physical Comfort	3.1	0.80	3	5
19	Vehicle Density	2.3	0.80	3	5
20	Average Speed	2.4	0.80	3	5
21	Safe Crossing Time Gap	3.6	0.80	3	5
22	Accident Risk	2.2	0.80	3	5
23	Player Identification	3.0	0.80	3	5
24	Static/Dynamic Game	2.1	0.80	3	5
25	Non-cooperative Game	2.0	0.80	3	5
26	Complete/Incomplete Information	2.2	0.80	3	5
27	Equilibrium in Bridge Usage	3.9	0.80	3	5
28	Total Crossing Time	4.1	0.80	3	5
29	Perceived Satisfaction	3.8	0.80	3	5
30	Safety Level	4.4	0.80	3	5

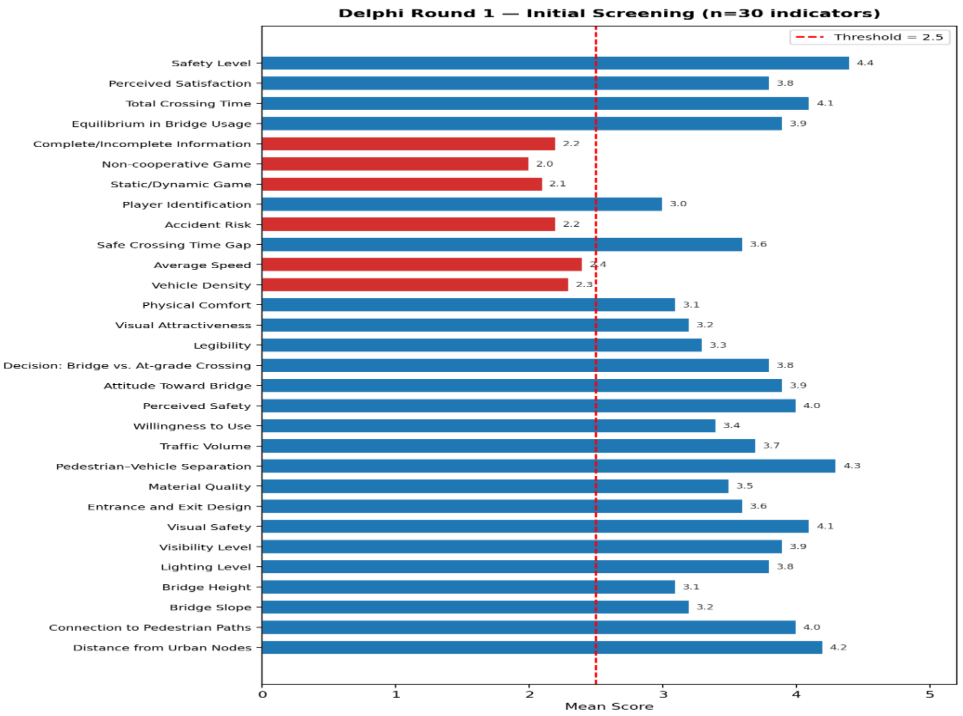

Figure 2: Delphi Round 1-Mean Scores for All 30 Indicators (red bars = eliminated, threshold = 2.5)

Delphi Round 2, Emerging Consensus

Following the removal of six indicators, the second round was conducted with the remaining twenty-four items. The consensus threshold was raised to 3.5, leading to stronger convergence around behavioral safety and spatial configuration variables. The reduction in standard deviations across most items indicates improved agreement. (Tab. 4 and Fig. 3)

Figure 2: Delphi Round 1-Mean Scores for All 30 Indicators (red bars = eliminated, threshold = 2.5)

No.	Factor	Mean	Std.Dev	Min	Max
1	Distance from Urban Nodes	4.5	0.65	3	5
2	Connection to Pedestrian Paths	4.3	0.65	3	5
3	Bridge Slope	3.5	0.65	3	5
4	Bridge Height	3.4	0.65	3	5
5	Lighting Level	4.1	0.65	3	5
6	Visibility Level	4.2	0.65	3	5
7	Visual Safety	4.4	0.65	3	5
8	Entrance and Exit Design	3.9	0.65	3	5
9	Material Quality	3.8	0.65	3	5
10	Pedestrian–Vehicle Separation	4.6	0.65	3	5
11	Traffic Volume	4.0	0.65	3	5
12	Willingness to Use	3.7	0.65	3	5
13	Perceived Safety	4.3	0.65	3	5
14	Attitude Toward Bridge	4.2	0.65	3	5
15	Decision: Bridge vs. At-grade Crossing	4.1	0.65	3	5
16	Legibility	3.6	0.65	3	5
17	Visual Attractiveness	3.5	0.65	3	5
18	Physical Comfort	3.4	0.65	3	5
19	Safe Crossing Time Gap	3.9	0.65	3	5
20	Player Identification	3.3	0.65	3	5
21	Equilibrium in Bridge Usage	4.2	0.65	3	5
22	Total Crossing Time	4.4	0.65	3	5
23	Perceived Satisfaction	4.1	0.65	3	5
24	Safety Level	4.7	0.65	3	5

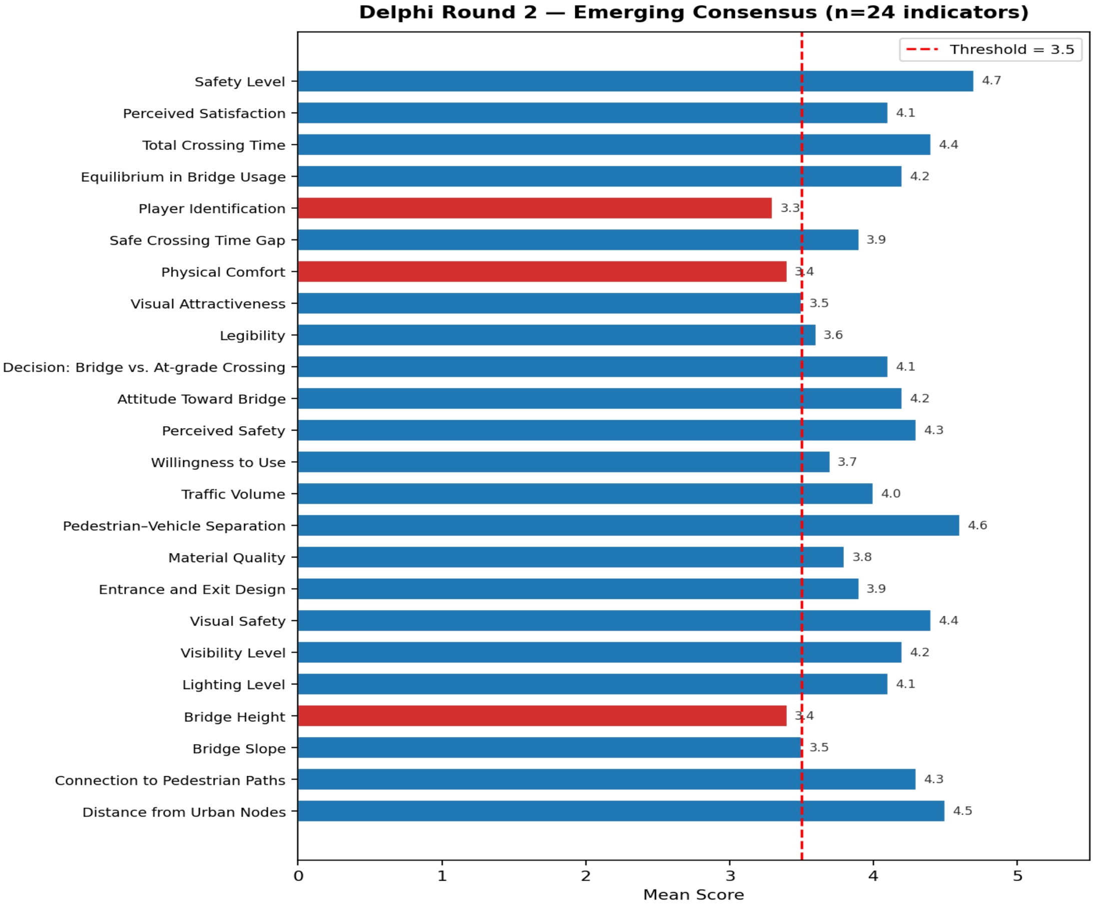

Figure 3: Delphi Round 2 -Mean Scores After First Elimination Round (threshold = 3.5)

Delphi Round 3-Analytical Consolidation

The third round applied a stricter threshold of 4.0, retaining only indicators with high expert consensus. Three indicators (Bridge Height, Player Identification, and Visual Attractiveness) were dropped at this stage. The hierarchy emerging from Round 3 highlights the centrality of perceived safety and pedestrian–vehicle separation. (Tab. 5 and Fig. 4)

Table 5: Delphi Round 3-Analytical Consolidation (n = 21)

No.	Factor	Mean	Std.Dev	Min	Max
1	Distance from Urban Nodes	4.9	0.50	4	5
2	Connection to Pedestrian Paths	4.7	0.50	4	5
3	Bridge Slope	3.9	0.50	4	5
4	Lighting Level	4.5	0.50	4	5
5	Visibility Level	4.6	0.50	4	5
6	Visual Safety	4.8	0.50	4	5
7	Entrance and Exit Design	4.3	0.50	4	5

8	Material Quality	4.2	0.50	4	5
9	Pedestrian–Vehicle Separation	5.0	0.50	4	5
10	Traffic Volume	4.4	0.50	4	5
11	Willingness to Use	4.1	0.50	4	5
12	Perceived Safety	4.7	0.50	4	5
13	Attitude Toward Bridge	4.6	0.50	4	5
14	Decision: Bridge vs. At-grade Crossing	4.5	0.50	4	5
15	Legibility	4.0	0.50	4	5
16	Visual Attractiveness	3.9	0.50	4	5
17	Safe Crossing Time Gap	4.3	0.50	4	5
18	Equilibrium in Bridge Usage	4.6	0.50	4	5
19	Total Crossing Time	4.8	0.50	4	5
20	Perceived Satisfaction	4.5	0.50	4	5
21	Safety Level	5.0	0.50	4	5

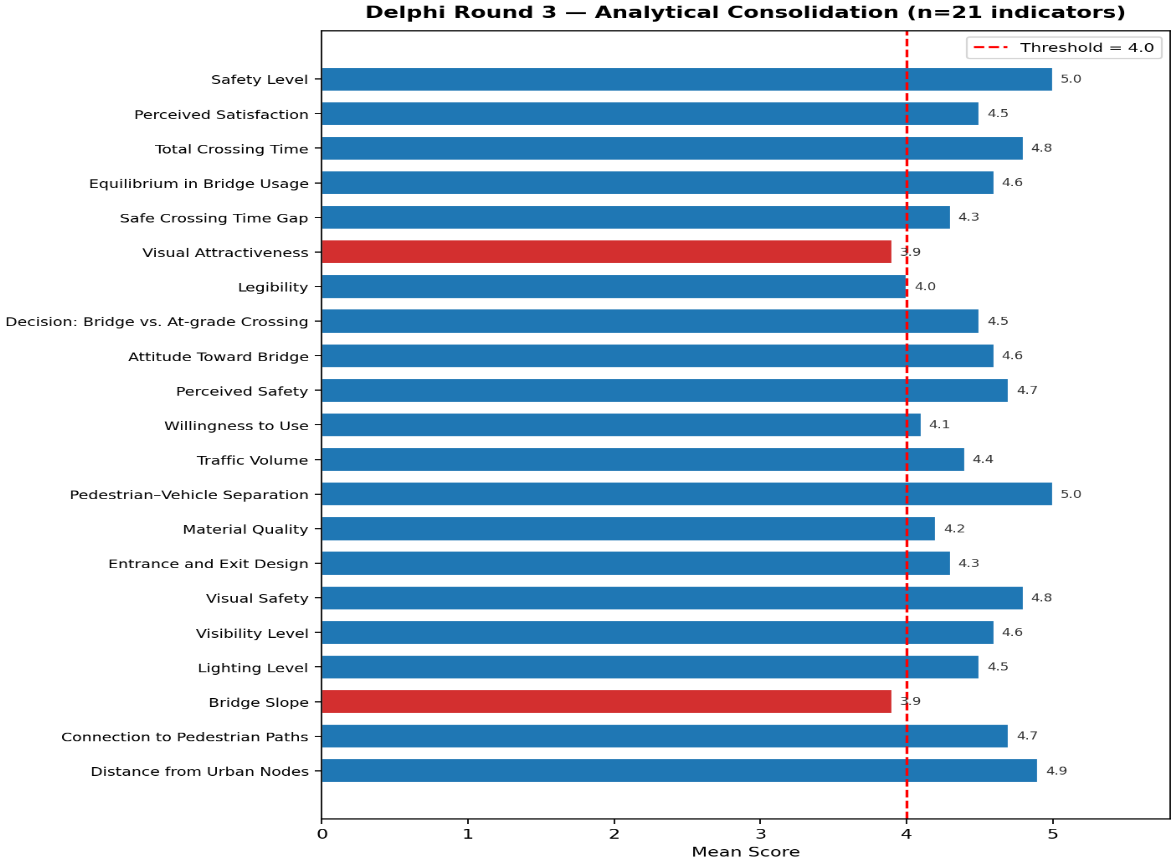

Figure 4: Delphi Round 3-Mean Scores (threshold = 4.0; red bars = eliminated)

Delphi Round 4-Final Indicator Set

The fourth and final round produced a stabilized decision structure comprising six high-priority indicators. These factors collectively define the behavior-oriented efficiency framework applied in the FAHP weighting stage. (Tab. 6 and Fig. 5)

Table 6: Delphi Round 4-Final Six High-Consensus Indicators

Rank	Factor	Mean	Std.Dev	Min	Max
1	Safety Level	4.8	0.35	4	5
2	Pedestrian–Vehicle Separation	4.7	0.36	4	5
3	Distance from Urban Nodes	4.6	0.33	4	5
4	Connection to Pedestrian Paths	4.5	0.34	4	5
5	Perceived Safety	4.4	0.37	4	5
6	Total Crossing Time	4.3	0.38	4	5

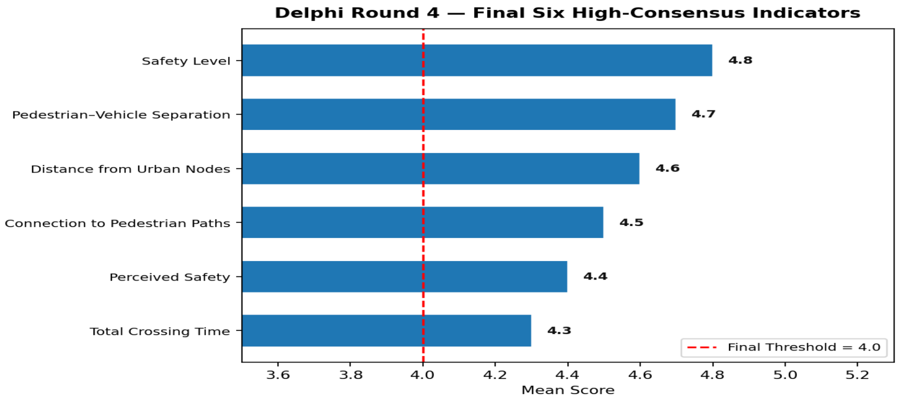

Figure 5: Delphi Round 4-Final Six Indicators (Mean Scores)

FAHP Weighting Results

The Fuzzy Analytic Hierarchy Process was applied to the six final Delphi indicators to derive a relative weight vector. Pairwise comparison matrices were constructed from expert judgments and processed using the extent analysis method (Chang, 1996). All pairwise comparisons yielded consistency ratios below 0.10, confirming the reliability of the weighting procedure. (Tab. 7 and Fig. 6)

Table 7: FAHP Weighting Results for Final Efficiency Indicators

Rank	Criterion	FAHP Weight	Cumulative Weight
1	Safety Level	0.22	0.22
2	Pedestrian–Vehicle Separation	0.20	0.42
3	Distance from Urban Nodes	0.18	0.60
4	Connection to Pedestrian Paths	0.16	0.76
5	Perceived Safety	0.13	0.89
6	Total Crossing Time	0.11	1.00

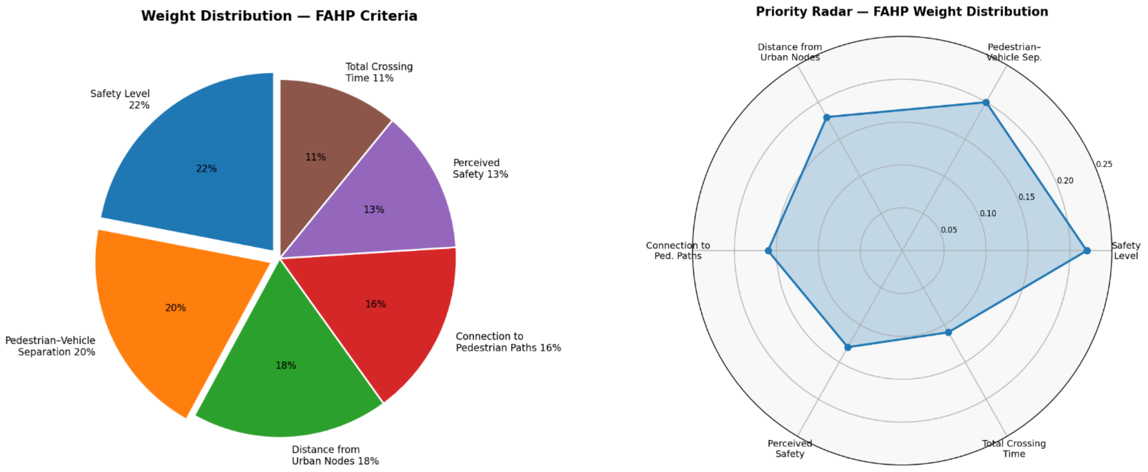

Figure 6: FAHP Weight Distribution-Pie Chart and Priority Radar-Weight Distribution Across Six Criteria

The weight distribution reveals that Safety Level (w = 0.22) and Pedestrian–Vehicle Separation (w = 0.20) together account for 42% of the composite efficiency index, confirming safety as the primary determinant of bridge performance. Distance from Urban Nodes (w = 0.18) and Connection to Pedestrian Paths (w = 0.16) collectively contribute 34%, underscoring the decisive role of spatial location and network integration. Perceived Safety (w = 0.13) and Total Crossing Time (w = 0.11) complete the framework, introducing the perceptual and temporal dimensions of user experience.

RESULTS AND CONCLUSION

The integrated Delphi–FAHP analysis conducted in this study provides a structured and evidence-based framework for understanding the efficiency of pedestrian bridges through the lens of behavioral movement patterns and game-theoretic decision processes. The sequential refinement of indicators across four Delphi rounds reveals a clear trajectory of expert consensus formation, moving from a broad and exploratory set of variables toward a focused hierarchy of safety- and accessibility-driven criteria. In the initial stage, the diversity of evaluated factors reflected the complexity of pedestrian bridge performance, where spatial configuration, perceptual safety, environmental conditions, and strategic behavioral interactions were simultaneously considered. As the Delphi process advanced into subsequent rounds, the numerical convergence of mean scores revealed a shift toward behavioral safety as the central organizing principle of pedestrian bridge efficiency. The rising prominence of indicators such as Safety Level, Pedestrian–Vehicle Separation, and Distance from Urban Nodes reflects a growing recognition that bridge usage is fundamentally shaped by perceived risk and spatial clarity. From an analytical standpoint, this convergence suggests that pedestrians evaluate bridges not merely as physical infrastructures but as dynamic environments where the cost–benefit balance between safety, travel time, and effort determines route choice.

The application of the FAHP method complements the Delphi findings by translating qualitative consensus into a quantitative hierarchy of priorities. The weighting results reveal that Safety Level receives the highest relative importance (w = 0.22), confirming that experts perceive risk mitigation as the foundational dimension of pedestrian bridge performance. The second-ranked factor, Pedestrian–Vehicle Separation (w = 0.20), reinforces this interpretation by emphasizing the role of spatial segregation in shaping behavioral trust. The balanced distribution of weights suggests a holistic understanding of pedestrian movement, where safety, accessibility, and spatial readability function as mutually reinforcing components. Beyond the numerical results, the integration of game-theoretic concepts introduces an additional layer of interpretation. Pedestrian bridge usage can be understood as a strategic interaction between pedestrians, vehicles, and the spatial environment, where each actor continuously adjusts behavior based on perceived risks and rewards. The high ranking of behavioral safety variables indicates that design interventions capable of influencing perception such as improved visibility, clear circulation paths, and intuitive spatial organization may be more effective than purely structural modifications. The interpretation of results also reveals important implications for the integration of architectural design with transportation planning. Distance from Urban Nodes and Connection to Pedestrian Paths emerged as key variables, suggesting that location and connectivity play a decisive role in shaping user behavior. This finding highlights the importance of context-sensitive design strategies that align bridge placement with natural pedestrian desire lines and existing movement patterns.

Ultimately, the findings of this research point toward a broader conceptual understanding of pedestrian bridge efficiency one that transcends physical infrastructure metrics and encompasses the behavioral, perceptual, and strategic dimensions of pedestrian decision-making. The proposed PPEI model situates bridge efficiency as an emergent property of the interaction between spatial design, human cognition, and traffic dynamics, providing a replicable framework for evidence-based pedestrian infrastructure planning. In conclusion, the integrated Delphi–FAHP framework provides a comprehensive and theoretically grounded approach for evaluating pedestrian bridge efficiency within complex urban contexts. Future pedestrian bridge projects should prioritize perceptual safety and spatial integration as primary design objectives, while incorporating behavioral modeling tools to anticipate user responses. Future research should examine additional variables including courtyard height-to-width ratios, the role of digital wayfinding, and longitudinal behavioral monitoring to further refine the model.

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