

# Minimal Intervention, Maximum Throughput: Micro-Scale Optimization of Urban Rail Hubs

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**Abstract:** The global stock of operational urban rail hubs faces a performance challenge: designed under earlier demand assumptions, many now exhibit severe transfer bottlenecks, fragmented pedestrian connectivity, and poorly resolved station-city interfaces. Conventional responses—structural reconfiguration and large-scale reconstruction—are increasingly constrained by fiscal austerity and spatial fixity in dense built-up areas. This paper addresses the absence of a systematic framework for micro-scale optimization of existing hubs under such constraints. A Diagnosis–Optimization–Evaluation framework is proposed, operationalized through the Station-City Minimal Intervention Maturity Model (SC-MIMM), integrating three-dimensional spatial conflict detection, quantifiable intervention thresholds, demand-based facility allocation, and closed-loop implementation verification. The framework is tested through a case study of a constrained interchange hub in a large Asian metropolitan rail network. Results indicate that a 30% spatial compression of vertical circulation elements—reconfiguring a 4.3-m staircase into a combined stair-escalator system—yields an approximately 5.6-fold improvement in transfer capacity under simulation-based evaluation conditions at approximately one-fifth of reconstruction cost. Four generalizable threshold conditions are identified under which micro-intervention constitutes the optimal upgrading strategy. These findings challenge the assumption that significant hub performance improvements require major reconfiguration, and provide a transferable methodological foundation for incremental hub upgrading in dense urban contexts.

**Keywords:** Transit-Oriented Development; urban rail hub; micro-scale optimization; spatial compression; transfer efficiency; station-city integration

## 1. Introduction

The global expansion of urban rail transit has produced an extensive stock of operational interchange hubs that now face a fundamental performance challenge. Over the past three decades, Transit-Oriented Development (TOD) has provided the dominant planning paradigm for integrating rail infrastructure with urban growth, emphasizing compact, mixed-use, and transit-supportive built forms around new stations [1, 2]. Cities across Asia, Europe, and North America have invested heavily in rail network expansion. Empirical evidence indicates that well-designed hubs can reduce automobile dependence, lower per-capita transport emissions, and stimulate economic agglomeration [3, 4]. Yet the success of this model has created a new problem—the need to upgrade existing hubs designed under earlier demand assumptions and spatial conditions.

The scale of this challenge is substantial. In China, over 4500 route-kilometers of urban rail have been

constructed since 2010. The current Metro Phase V program in megacities such as Shenzhen encompasses 187 stations, the vast majority embedded within already-dense built-up areas. A growing share of urban rail planning challenges now concerns existing and operational hubs rather than new stations. Recent fiscal pressure on urban infrastructure investment has further increased the need for cost-effective upgrading strategies. There is, therefore, a need for theoretically grounded strategies that can extract disproportionate functional gains from minimal physical intervention.

### *1.1. Problem*

The operational deficiencies of existing rail hubs can be organized into three interrelated categories. Internal transfer inefficiency arises when vertical circulation elements—staircases, escalators, elevators—are insufficient for peak-hour demand. This problem is particularly acute in hubs serving airport-bound intercity rail lines, where luggage-carrying passengers face disproportionate difficulty. Fragmented external connectivity occurs when intermodal connections to pedestrian networks, cycling infrastructure, and bus services are discontinuous or poorly sited. This disproportionately affects slow-mode travelers who constitute the majority of access trips in dense urban contexts. Poorly resolved station-city interface in built-up areas reflects the fundamental difference between designing a hub on a greenfield site and stitching it into an existing urban fabric with established buildings, street patterns, and fragmented land ownership.

These three problems share a common root cause: the absence of a systematic methodology for micro-scale optimization of existing rail hubs. Current practice relies heavily on experience-based judgment, ad-hoc modifications, and reactive problem-solving. What is missing is a rigorous, data-driven framework capable of diagnosing spatial conflicts at high resolution, identifying intervention opportunities with quantifiable thresholds, and verifying implementation outcomes through closed-loop validation—all within the tight constraints of budget, time, and physical space that characterize incremental development contexts.

### *1.2. Objective and Contribution*

This study aims to develop and empirically validate a Minimal Intervention Framework for micro-scale optimization of existing urban rail hubs. The research pursues three objectives: (1) to establish quantifiable threshold criteria for micro-intervention feasibility; (2) to construct a 3D-driven decision framework integrating BIM-GIS spatial conflict detection, demand-based facility allocation, and tripartite alignment verification; and (3) to demonstrate applicability through a detailed case study and derive generalizable replication conditions.

The study makes three contributions. Theoretically, for analytical clarity, this study refers to this framework as the Station-City Minimal Intervention Maturity Model (SC-MIMM), which defines four progressive levels of hub optimization—precision diagnosis, micro-spatial restructuring, systemic synergy optimization, and value amplification—filling a theoretical void in existing hub upgrading. Methodologically, it develops the 3D-Driven Decision Framework (3D-DF) that operationalizes the SC-MIMM through integrated spatial conflict detection, demand-based allocation, and implementation verification. Empirically, it validates the framework through a case study demonstrating that a 30% spatial compression yields an approximately 5.6-fold capacity improvement under simulation-based evaluation conditions at approximately one-fifth of reconstruction cost, and identifies four generalizable conditions for micro-intervention optimality.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature on TOD evolution, hub performance assessment, and modeling applications. Section 3 presents the SC-MIMM model and the 3D-DF methodology. Section 4 describes the case study context and analytical methods. Section 5 reports the empirical results. Section 6 discusses theoretical and practical implications, including generalizability conditions and limitations. Section 7 concludes with directions for future research.

## **2. Literature Review**

### *2.1. TOD and Station-Area Integration*

The intellectual foundations of Transit-Oriented Development were established by Calthorpe [1], who

articulated a normative vision of compact, mixed-use, pedestrian-friendly neighborhoods organized around transit stations. This vision was subsequently elaborated into prescriptive design principles—density, diversity, design—that have guided station-area planning across multiple continents [5]. Empirical research has largely confirmed these benefits: TOD stations generate higher ridership, lower vehicle kilometers traveled, and increased property values compared to conventional transit-adjacent development [4]. Evidence from Asian cities shows similar patterns. The node-place model developed by Bertolini [3] has provided a widely used analytical framework for assessing transport-accessibility balance at station locations.

Despite this substantial body of work, a critical limitation pervades the TOD literature: its overwhelming orientation toward new development. As Suzuki et al. [6] acknowledge, most TOD implementation has occurred on vacant or underutilized land. The applicability of TOD principles to dense, established urban fabrics remains poorly understood. Previous studies have introduced the concept of Transit-Adjacent Corridors (TAC) to describe station areas that possess transit infrastructure but lack supportive urban form, yet the TAC framework remains diagnostic rather than prescriptive. Studies by Ewing and Cervero [7] and Stevens [8] have demonstrated that the “design” dimension of TOD has significant effects on travel behavior, suggesting that micro-scale spatial interventions can meaningfully improve station-area performance. However, the mechanisms through which such interventions should be designed, prioritized, and implemented have not been systematically theorized.

## *2.2. Accessibility and Transfer Efficiency in Rail Hubs*

Transport engineering research has focused on quantifying transfer penalties—the disutility associated with making a transfer compared to a direct trip. Wardman and Hine [9] estimated that passengers value transfer time at 1.5 to 2.5 times in-vehicle time, a finding supported by subsequent research across multiple contexts. Research by Lam and Cheung [10] in Hong Kong demonstrated that vertical circulation capacity is often the binding constraint on hub throughput during peak periods, a finding confirmed by subsequent studies in other high-density Asian cities.

Architectural and planning research has examined spatial configuration through the lens of wayfinding and passenger experience. Previous studies have shown that legibility of transfer routes significantly affects perceived transfer time and satisfaction. However, these findings have been applied primarily to new stations rather than to retrofitting existing ones. A notable gap is the absence of systematic attention to micro-scale spatial adjustments that can improve transfer efficiency within existing structural constraints. Most studies assume that significant improvements require major reconfiguration—widening platforms, adding new vertical circulation cores—without examining whether modest spatial adjustments could yield disproportionate improvements. Recent advances in energy-efficient 3D reconstruction, multimodal medical image analysis, multi-task visual prediction, and efficient Transformer training likewise point to a broader methodological shift toward high-dimensional spatial-perceptual analytics under computational constraints [11–15].

## *2.3. Micro-Scale Optimization in Built Environments*

The concept of micro-scale optimization has emerged in several related fields. In urban design, the “tactical urbanism” movement has demonstrated that low-cost, temporary interventions can generate significant improvements in street-level experience and safety [16], though its application has been limited to surface streets rather than multi-level underground rail hubs. In transport engineering, micro-simulation has been widely used to model passenger flows and evaluate design alternatives, but its application has been predominantly evaluative rather than generative. In facility management, BIM has been extensively applied to new construction for clash detection. Its application to existing infrastructure—“scan-to-BIM”—has grown with laser scanning technologies. However, the integration of BIM, GIS, and micro-simulation into a structured diagnosis-intervention-verification loop for hub upgrading has not been realized. Although these studies are outside transport planning, graphene/midinfrared and terahertz detection research demonstrates how compact sensing platforms can generate fine-grained signals, a capability analogous to the real-time evidence needed for hub monitoring [17–20].

Research on incremental versus comprehensive approaches to infrastructure upgrading provides theoretical

support for micro-intervention. Studies by Flyvbjerg et al. [21] have documented systematic cost overruns in large-scale transport projects. Research on adaptive infrastructure planning has argued for strategies that maintain option value. Yet these arguments have not been operationalized at the scale of individual rail hubs. At a methodological level, this logic is also consistent with inverse-identification research in mechanics, where localized tests are used to infer hidden material parameters and guide broader characterization [22,23].

#### 2.4. Research Gap

The literature reviewed above reveals a consistent pattern: while each relevant field has developed concepts and tools that could inform micro-scale optimization of existing rail hubs, these resources remain fragmented. Three specific gaps are identified.

**First, the TOD literature lacks a micro-intervention paradigm.** The dominant frameworks prescribe ideal station-area characteristics for new development but offer little guidance on how to achieve these characteristics incrementally in existing contexts [6]. The concept of retrofitting has been explored in relation to suburban sprawl and auto-oriented corridors, but its application to urban rail hubs—particularly the micro-scale spatial adjustments that characterize minimal intervention—remains theoretically underdeveloped.

**Second, no quantifiable threshold criteria exist for determining micro-intervention feasibility.** Key parameters—spatial compression rate of vertical circulation elements, peak-hour transfer demand thresholds, cost-benefit ratios of minimal versus comprehensive strategies—have not been systematically studied. Without such criteria, intervention choices remain experience-based and context-dependent, precluding the development of generalizable knowledge.

**Third, modeling tools remain underutilized in the intervention design-implementation loop.** BIM and GIS applications are largely confined to visualization without extending to systematic conflict detection, design scheme optimization, or implementation verification, resulting in implementation error rates that frequently exceed 25% in practice.

These three gaps converge on a single unmet need: a theoretically grounded, empirically validated framework for micro-scale optimization of existing urban rail hubs that integrates spatial conflict diagnosis, quantifiable intervention thresholds, demand-based facility allocation, and closed-loop implementation verification. The present study aims to develop and test such a framework.

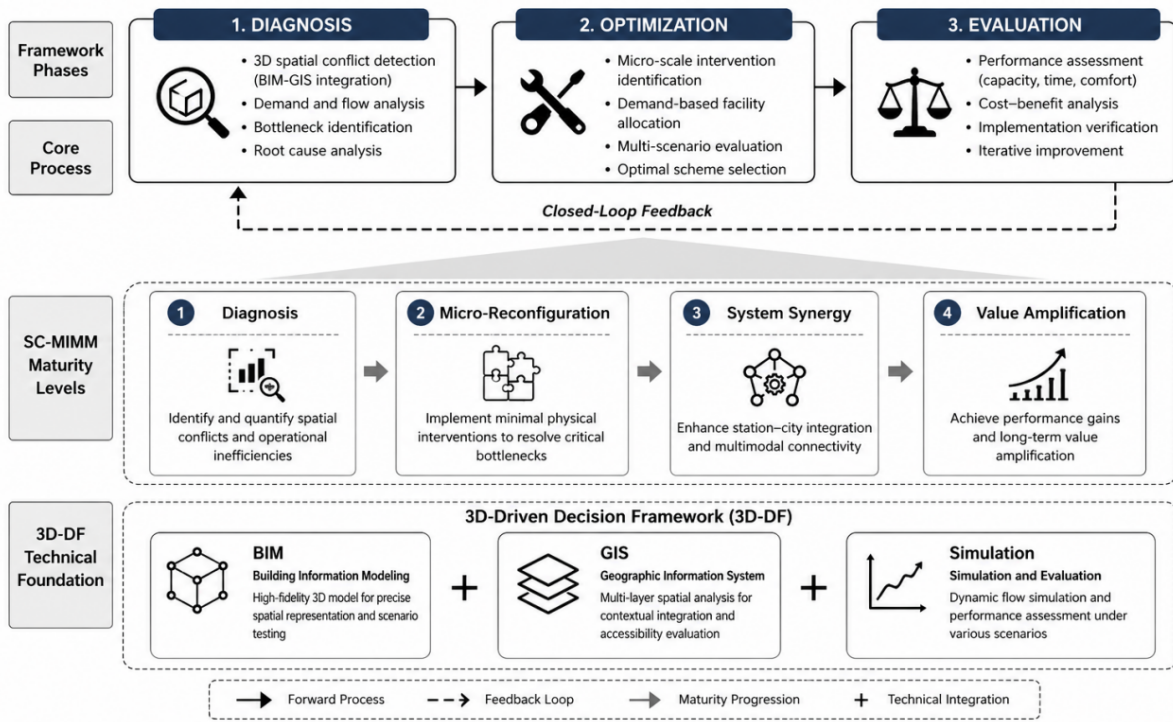
### 3. Methodology

#### 3.1. Conceptual Architecture of the Framework

The case data are derived from official planning documents, engineering design drawings, and simulation-based evaluation materials developed during the Minzhi North Hub project.

This study proposes a planning methodology organized around a core conceptual distinction: the difference between “scaling” an existing spatial configuration and “reconfiguring” it. Scaling—adding more of the same type of facility—is the conventional response to capacity deficits. Reconfiguring—changing the mode of operation within a fixed structural envelope—is the alternative this framework operationalizes. The framework is designed to identify conditions under which reconfiguration is feasible and to guide its implementation (as shown in Figure 1).

The methodology is structured as a three-phase analytical sequence—Diagnosis, Optimization, Evaluation—that together constitute a closed-loop planning mechanism. The sequence is not case-specific but generic: it can be applied to any multi-level interchange hub where the structural envelope is fixed and the intervention budget is constrained. Each phase is governed by a distinct logic. Diagnosis identifies the binding constraint through systematic comparison of spatial configuration against demand. Optimization translates the diagnosed constraint into a targeted spatial reconfiguration bounded by quantifiable feasibility thresholds. Evaluation verifies that the reconfiguration produces the expected functional improvement and assesses the conditions under which the approach can be replicated.



**Figure 1.** SC-MIMM and 3D-DF framework for micro-scale optimization of existing urban rail hubs.

### 3.2. Theoretical Basis of the Diagnostic Logic

The diagnostic logic is grounded in a principle that applies across infrastructure types: in any multi-component system, overall performance is determined by the component with the largest gap between capacity and demand—the binding constraint. Improving non-binding components yields negligible system-level improvement. The methodological challenge is to identify the binding constraint with precision sufficient to guide intervention design.

For interchange hubs, the system can be decomposed into three generic functional dimensions: vertical circulation (movement between platform levels), pedestrian connectivity (movement between the hub and surrounding urban blocks), and circulation network continuity (movement within the hub’s internal spaces). These dimensions are not case-specific; they derive from the fundamental function of any interchange hub as a multi-level node connecting multiple transport modes and urban destinations. The diagnostic methodology operationalizes this decomposition by defining, for each dimension, a quantifiable indicator and a threshold value that distinguishes acceptable from unacceptable performance. The threshold values are derived from transport engineering standards and can be recalibrated for different regulatory contexts.

Three conflict grades are defined:

**Grade I—Vertical transfer bottleneck:** The capacity of vertical circulation elements is insufficient for peak-hour demand. Indicator: capacity gap (demand minus capacity as a percentage of demand). Threshold: >80%.

**Grade II—Pedestrian continuity disruption:** Pedestrian pathways between the hub and surrounding urban blocks are interrupted by physical barriers. Indicator: continuous pathway disruption length. Threshold: >30 m.

**Grade III—Spatial fragmentation:** The hub’s internal circulation network forces indirect routes. Indicator: detour ratio (actual walking distance divided by straight-line distance). Threshold: >1.5.

The diagnostic logic is tool-independent. While this study implements spatial analysis through BIM-based geometric modeling and pedestrian flow simulation, the logic—systematic comparison of spatial configuration against demand requirements—can be implemented through alternative three-dimensional modeling tools.

### 3.3. The Spatial Compression Principle

The optimization phase is governed by a single design principle: the spatial compression rate. This principle addresses a generic planning problem—how to introduce higher-throughput circulation modes within a fixed

structural envelope—by defining the maximum proportion of existing space that can be reallocated without triggering structural reconstruction.

The spatial compression rate is defined as:

$$\text{Compression Rate} = (W_{\text{original}} - W_{\text{modified}}) / W_{\text{original}}$$

where  $W_{\text{original}}$  is the original width of a circulation element and  $W_{\text{modified}}$  is its post-reconfiguration width. The threshold of  $\leq 30\%$  is derived from the convergence of three constraints common to underground hubs across jurisdictions that follow international building codes: minimum staircase width for fire egress (typically 1.2–1.5 m), standard escalator width (approximately 1.0–1.5 m), and typical structural bay dimensions (approximately 6–8 m). Beyond this rate, at least one of these constraints cannot be satisfied without structural modification.

The compression principle is not a design rule in the engineering sense but a planning heuristic: it defines the boundary within which mode-changing reconfiguration is feasible. Below the threshold, the intervention changes the operating mode of the circulation system (e.g., from stair-dominant to escalator-dominant). Above the threshold, the intervention would merely scale the existing mode, yielding proportional rather than disproportionate improvement.

### 3.4. Optimization Strategies by Conflict Type

Each conflict grade corresponds to a generic optimization strategy that applies the spatial compression principle to a specific functional dimension.

**Grade I—Vertical circulation reconfiguration.** The strategy reallocates space within the existing structural envelope by reducing the width of underutilized staircases and reallocating the saved space to mechanical vertical circulation (escalators). The reconfigured staircase must maintain minimum width for fire egress and bidirectional flow. The capacity gain arises not from adding circulation space but from substituting a higher-throughput mode (escalator) for a lower-throughput mode (staircase)—a qualitative change in the system’s operating mode.

**Grade II—Intermodal connectivity insertion.** The strategy creates new pedestrian connections by activating latent spatial reserves within the existing structure—specifically, the column grid intervals that were reserved during the original construction for potential future expansion. These spaces, common in phased construction projects, represent underutilized connectivity potential that can be activated at minimal cost.

**Grade III—Circulation network integration.** The strategy completes discontinuous internal circulation routes by reconfiguring non-structural elements (e.g., relocating facility rooms within the same structural bay) to free circulation space. This opening-up of blocked routes transforms the hub’s internal network from a fragmented set of dead-end paths into a continuous circulation system.

**Facility allocation.** Street-level intermodal facilities are allocated through demand-based calibration with a redundancy coefficient to absorb demand uncertainty. The allocation logic—calibrating facility provision to forecast demand with a defined margin—is transferable, though specific values (parking space count, bus stop distance thresholds) are context-dependent.

### 3.5. Evaluation Logic

The evaluation phase employs a pre-post comparison framework structured around three generic metrics. Capacity improvement ratio measures the functional gain from mode-changing reconfiguration. Transfer efficiency captures the user-experience dimension through average transfer time and level-of-service change. Implementation precision assesses the fidelity of the modeling-to-construction translation, a critical parameter for micro-scale interventions where centimeter-level accuracy determines feasibility. The importance of field validation is reinforced by process-based nitrogen-removal modeling, where model development, dissertation-scale synthesis, and independent field validation show that calibrated equations must be tested against observed operating conditions [24–27]. The level-of-service terminology follows the Highway Capacity Manual [28].

The evaluation logic is designed to test not only whether the intervention worked in this case, but whether the diagnostic and optimization principles that guided it are sound. If the diagnosis correctly identified the

binding constraint and the optimization correctly applied the compression principle, the outcome should be a disproportionate improvement—improvement exceeding what the physical scale of the intervention would predict. This disproportionate-improvement test is the framework’s internal validity check.

### 3.6. Generalizability Mechanism

The framework is designed as a transferable planning methodology, not a case-specific solution. Generalizability is supported by three design features.

**Parameterized thresholds.** All diagnostic and design thresholds—spatial compression rate ( $\leq 30\%$ ), capacity gap for Grade I conflict ( $\geq 80\%$ ), pedestrian connectivity standards—are derived from generic properties of interchange hubs and international building code constraints, not from case-specific characteristics. They can be recalibrated for different regulatory contexts and service standards.

**Tool-independent logic.** The diagnostic logic—systematic comparison of spatial configuration against demand requirements—does not depend on specific software platforms. Alternative three-dimensional modeling tools can substitute for BIM and GIS.

**Scalable principles.** The optimization principles—reallocating space within existing structural envelopes, activating latent spatial reserves, calibrating facility allocation to demand profiles—apply across hub sizes, configurations, and modal compositions. Intervention schemes will vary; diagnostic logic and optimization rules remain consistent.

## 4. Case Study

### 4.1. Case Background

The case examined in this study is a constrained interchange hub within a large Asian metropolitan rail network—a large metropolitan interchange hub (hereafter referred to as the Minzhi North Hub). The hub is situated at the intersection of two arterial roads, approximately 8 km from the city’s central business district, within a corridor connecting a commercial super circle and an international business district. It functions as a T-shaped interchange between an intercity rail line serving an international airport and a new urban metro line, both under concurrent construction. The intercity line generates a passenger profile with a substantial proportion of luggage-carrying travelers.

The case exhibits the defining characteristics of incremental development contexts: the hub is embedded within a high-density built-up area where large-scale demolition and reconstruction are infeasible; the structural envelope was largely fixed by ongoing construction; the intervention window was constrained by the construction schedule; and the available budget was a fraction of structural reconfiguration cost.

### 4.2. Station-Area and Hub Context

The station area encompasses a core zone of approximately 42 hectares, with an extended influence zone of around 200 hectares. The area is characterized by a mix of urban village settlements, commercial markets, residential compounds, and ongoing urban renewal projects. The hub is a three-level underground structure: the concourse level houses fare gates and retail spaces; the intercity rail platform level serves the airport-bound line; and the metro platform level serves the urban metro line. The surrounding street network is dominated by two arterial roads that create a barrier effect, fragmenting pedestrian connectivity. One quadrant of the intersection lacks direct pedestrian access to the hub.

### 4.3. Existing Bottlenecks

The diagnostic framework described in Section 3 was applied to the case to identify critical spatial conflicts. Application of the three-dimensional spatial conflict detection methodology identified three bottlenecks. Grade I—Vertical transfer insufficiency: The connection between platform levels consisted of a single 4.3-m staircase and a single elevator, providing throughput of approximately 800–950 persons per hour against forecast peak-hour demand of approximately 3900 persons per hour—a capacity gap exceeding 80%. Grade II—Pedestrian connectivity

fragmentation: One quadrant lacked direct pedestrian connection, adding approximately 110 m of detour distance. Grade III—Internal circulation disconnection: The non-fare-paid circulation network was incomplete, forcing passengers to exit to street level to move between entrances.

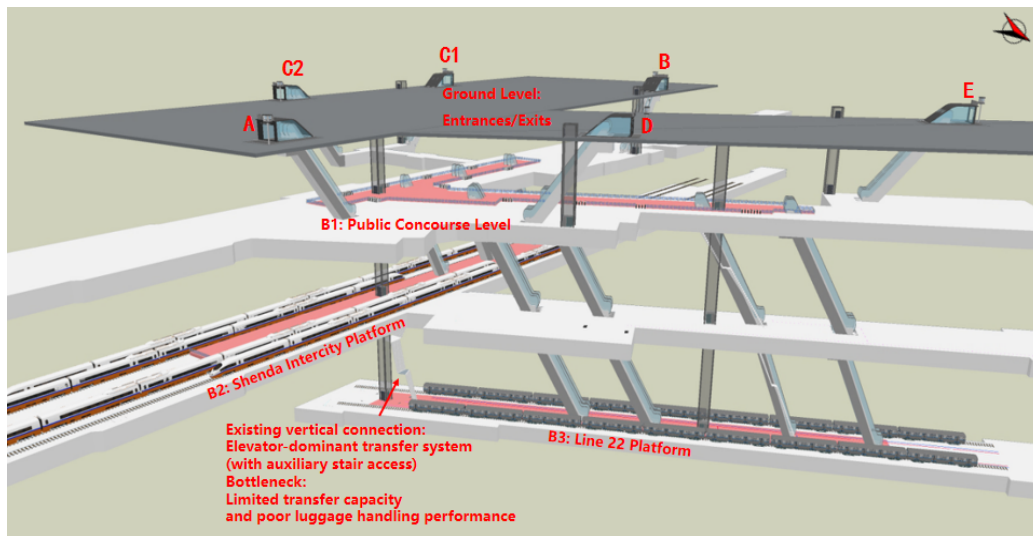
#### 4.4. Spatial Constraints

The optimization scheme was bounded by structural fixity (column spacing of approximately 6.5 m defining maximum passage width), safety and regulatory constraints (fire egress minimum widths, a 30-m rail safety protection zone, and an existing gasoline station requiring removal), temporal constraints (approximately 12-month construction window), and fiscal constraints (budget approximately one-fifth of structural reconfiguration cost).

#### 4.5. Low-Cost Optimization Strategy

The optimization strategy applied the spatial compression principle. Vertical circulation reconfiguration: The 4.3-m staircase was reconfigured into an upward escalator (1.5 m), a bidirectional staircase (1.3 m), and a downward escalator (1.5 m), achieving a spatial compression rate of approximately 30%. Intermodal connectivity insertion: A new 6-m-wide pedestrian passage was created using the 6.5-m column grid spacing, connecting the concourse to the previously disconnected quadrant. Circulation network integration: The non-fare-paid route was opened up by relocating an electrical room within the same structural bay. Facility allocation: Non-motor vehicle parking was provided at approximately 1600 spaces (exceeding forecast demand of 1300 by approximately 20%), bus stops were relocated to within 100 m, and weather-protected connections were installed along all major access routes.

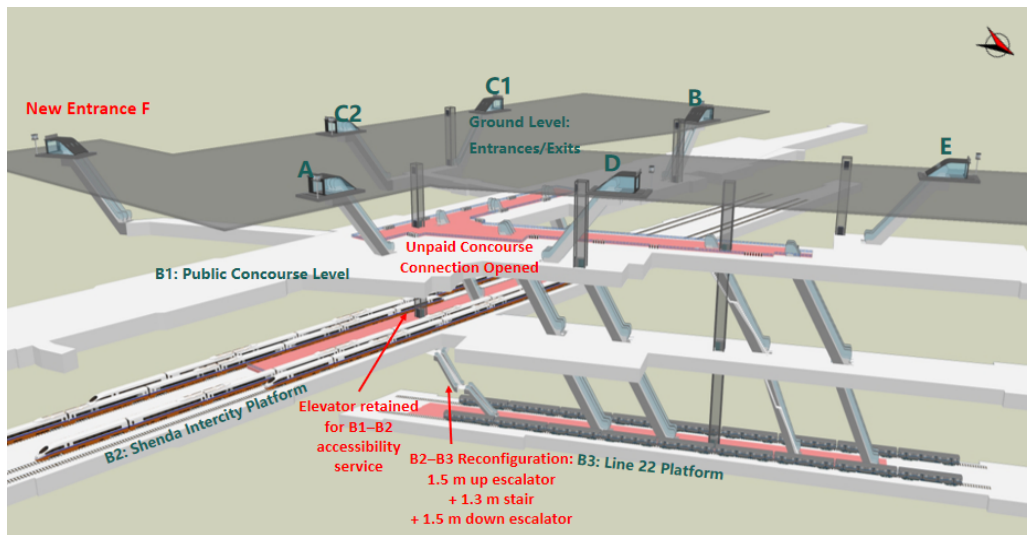
To illustrate the baseline spatial configuration and existing operational constraints, the current station layout is presented in Figure 2.



**Figure 2.** Existing configuration of vertical circulation and station connectivity in the case hub, characterized by elevator-dominant transfer between B3 and B2 levels and limited transfer capacity.

Following targeted micro-scale interventions, the optimized spatial configuration is shown in Figure 3 for comparison.

Compared with Figure 2, the optimized scheme significantly improves vertical transfer capacity and reduces congestion bottlenecks.



**Figure 3.** Optimized configuration introducing escalator-assisted multi-channel vertical circulation, improved concourse connectivity, and a new entrance to enhance transfer efficiency.

#### 4.6. Transfer Efficiency Improvement

Post-intervention evaluation documented substantial improvements. Vertical transfer capacity increased to approximately 5300 persons per hour—an approximately 5.6-fold improvement under simulation-based evaluation conditions—exceeding forecast demand and eliminating the Grade I bottleneck. Average transfer time was reduced by approximately 30% overall and approximately 60% for luggage-carrying passengers. Pedestrian connectivity improved with a 110-m reduction in detour distance and continuous underground movement across all quadrants. Intermodal connectivity achieved 100% coverage of bus stops within 100 m and weather-protected connections along all major access routes.

#### 4.7. Generalizable Insights for TOD Integration

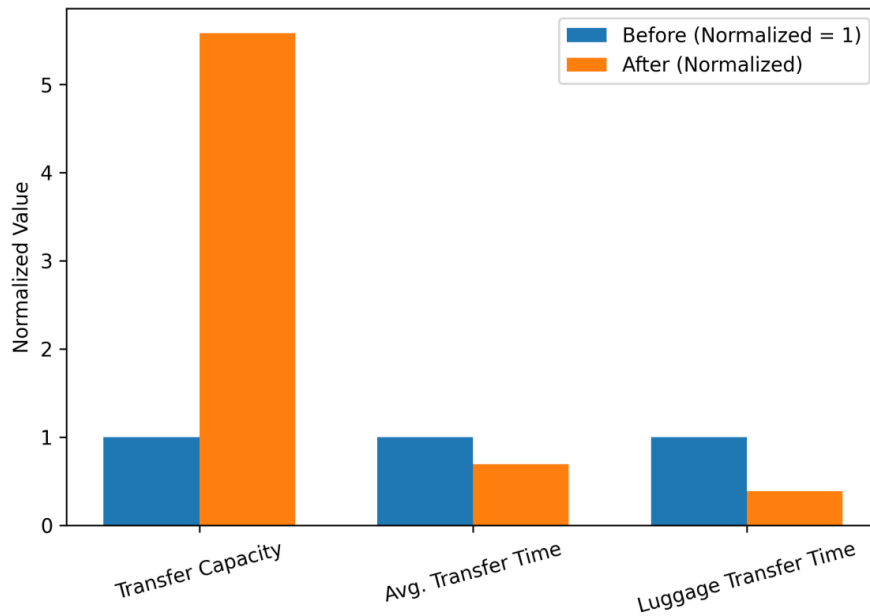
This case yields three insights extending beyond its specific context. First, vertical circulation reconfiguration within the spatial compression principle ( $\leq 30\%$ ) can resolve severe transfer capacity deficits without structural reconstruction, challenging the assumption that significant improvements require major reconfiguration. Second, utilizing existing structural reserved spaces can create new pedestrian connections that stitch together fragmented urban fabrics, transforming disconnected quadrants into accessible parts of the hub’s catchment area. Third, demand-based facility allocation with calibrated redundancy can improve intermodal connectivity without over-allocating scarce street-level space. These insights are context-specific in empirical details but generalizable in underlying logic.

## 5. Results and Discussion

### 5.1. The Mechanism of Disproportionate Improvement

The intervention produced an approximately 5.6-fold improvement in vertical transfer capacity under simulation-based evaluation conditions—from approximately 950 to 5300 persons per hour—through a 30% spatial compression. The critical analytical question is not whether capacity improved, but “why” a modest spatial adjustment produced a multifold functional gain. The evidence points to a qualitative shift in the circulation system’s operating mode rather than a quantitative scaling of capacity (as shown in Figure 4).

Pre-intervention, the system operated in a single-mode configuration: a staircase handling bidirectional flow, with marginal elevator contribution. In this mode, throughput is bounded by the physical limit of stair climbing—approximately 200 persons per meter-width per hour for bidirectional movement [29]. Post-intervention, the system operates in a multi-mode configuration: the evaluated one-way escalator capacity reaches approximately 5265 passengers per hour in the design assessment, while the reduced-width staircase serves bidirectional and emergency functions. The capacity gain arises from substituting a higher-throughput mechanical mode for a lower-throughput pedestrian mode within the same structural envelope.



**Figure 4.** Normalized performance improvement after micro-scale reconfiguration (simulation-based assessment).

This finding challenges a tacit assumption in transport engineering: that capacity improvement is proportional to the scale of physical intervention. The case demonstrates that when the intervention changes the “mode” of operation rather than scaling the existing mode, the improvement function is nonlinear. The spatial compression threshold ( $\leq 30\%$ ) defines the boundary within which such mode-changing reconfiguration is feasible. Below this threshold, the system can transition from single-mode to multi-mode operation. Above it, the intervention would merely scale the existing mode—widening a staircase—yielding proportional rather than disproportionate improvement.

The result also validates the diagnostic logic. The Grade I classification correctly identified vertical circulation as the binding constraint. Had the diagnostic focus been elsewhere—on platform width, fare gate capacity, or corridor dimensions—the intervention would have addressed non-binding constraints, yielding negligible system-level improvement. This confirms the theoretical principle underlying the diagnostic methodology: in any multi-component system, improving non-binding components produces no measurable performance gain.

### 5.2. Accessibility and Equity: A Differential Effect

Accessibility improvements operated at two spatial scales, each revealing a distinct theoretical implication.

At the hub scale, average inter-platform transfer time decreased by approximately 30% (from approximately 13 to 9 min). More consequential is the differential effect: transfer time for luggage-carrying passengers decreased by approximately 60% (from approximately 18 to 7 min). This differential reveals an equity dimension that aggregate metrics obscure. The pre-intervention configuration imposed a disproportionate penalty on passengers with physical constraints—those carrying luggage, traveling with children, or with limited mobility. The staircase-only vertical connection required these passengers to use the single elevator, creating queuing and delay. The intervention selectively removed this penalty by introducing mechanical vertical circulation as the primary mode, relegating stair climbing to a supplementary function.

This finding has implications for how accessibility is measured and evaluated in rail hub studies. Standard metrics—average transfer time, level-of-service, throughput—capture system-level performance but mask distributional effects. The differential improvement documented here suggests that micro-interventions targeting vertical circulation can produce equity benefits that exceed their aggregate efficiency gains. This is consistent with the finding of Wardman and Hine [9] that transfer penalties are disproportionately borne by vulnerable users, but extends their argument by demonstrating that targeted micro-interventions can selectively remove

these penalties.

At the neighborhood scale, the new pedestrian passage changed the connectivity structure of the station area in a way that standard accessibility metrics do not capture. Pre-intervention, the hub functioned as a barrier: passengers destined for the disconnected quadrant had to exit to street level and cross at grade. Post-intervention, the hub functions as a connector enabling continuous underground movement. This is a topological change—the hub’s role in the pedestrian network shifted from a node that must be circumvented to a link that enables through-movement. Graph-theoretic measures of network connectivity (e.g., betweenness centrality) would capture this change; distance-based measures (e.g., average walking distance) would not.

### 5.3. What This Study Challenges in TOD Theory

The results challenge three assumptions embedded in the TOD literature, each with distinct boundary conditions.

**Assumption 1: Density and diversity are the primary determinants of station-area performance.** *The TOD paradigm, following Calthorpe [1] and Cervero and Kockelman [5], prescribes compact, mixed-use, pedestrian-friendly built form as the primary mechanism for transit-supportive urban development. This case reveals a boundary condition: in built-up areas where density and diversity are already present—as they are in most Asian megacity station catchments—vertical circulation capacity can become the binding constraint on hub performance. Under this condition, land-use intensification without vertical circulation upgrading would increase demand without increasing throughput capacity, worsening rather than improving performance. The implication is a reordering of intervention priorities: for existing hubs in dense contexts, vertical circulation optimization should precede land-use intensification.*

**Boundary condition:** This finding applies when (a) the station catchment already exhibits moderate-to-high density and mixed land use, (b) vertical circulation is the binding constraint (Grade I conflict), and (c) the structural envelope permits spatial compression within the  $\leq 30\%$  threshold. It does not apply to greenfield stations, low-density catchments, or hubs where the binding constraint is horizontal rather than vertical.

**Assumption 2: Station-city integration requires large-scale urban design intervention.** *The station-city integration literature emphasizes comprehensive approaches—deck structures, superblock redevelopment, integrated mixed-use complexes—that require substantial capital investment and land assembly [6]. This case demonstrates that a 6-m-wide pedestrian passage, inserted within an existing column grid at minimal cost, can transform a disconnected urban quadrant into an accessible part of the hub’s catchment area. The mechanism is not the scale of the intervention but its topological effect: activating a latent connection that changes the network’s connectivity structure.*

**Boundary condition:** This finding applies when (a) latent structural reserves exist within the hub (e.g., reserved column-grid intervals), (b) the regulatory environment permits minor structural modifications, and (c) the disconnected urban area is within the hub’s functional catchment (typically  $< 500$  m). It does not apply where no structural reserves exist, where regulatory constraints prohibit any structural modification, or where the connectivity deficit requires new infrastructure beyond the hub’s structural envelope.

**Assumption 3: Comprehensive reconfiguration is the default response to hub performance deficits.** *The planning and engineering literature implicitly assumes that significant performance improvements require major intervention—platform widening, new vertical circulation cores, structural reconfiguration [10]. This case provides empirical evidence that micro-intervention can achieve an approximately 5.6-fold capacity improvement under simulation-based evaluation conditions at approximately one-fifth of reconstruction cost. The implication is not that comprehensive reconfiguration is never appropriate, but that the burden of proof should shift: proponents of comprehensive reconfiguration should demonstrate why micro-intervention is insufficient before committing to more expensive and disruptive strategies.*

**Boundary condition:** Micro-intervention is the optimal strategy when (a) the capacity deficit can be resolved through mode-changing reconfiguration within the  $\leq 30\%$  compression threshold, (b) the construction window is constrained ( $< 12$  months), (c) the budget is limited ( $\leq 20\%$  of reconstruction cost), and (d) peak-hour transfer demand is below approximately 5000 person-trips per hour. Above these thresholds, comprehensive reconfiguration may be necessary.

#### 5.4. Generalizability and Its Limits

The framework's generalizability rests on the transferability of its core components. The diagnostic criteria—vertical circulation capacity gap, pedestrian connectivity disruption, circulation network fragmentation—derive from generic properties of interchange hubs, not from case-specific characteristics. The optimization principles—spatial compression, activation of latent reserves, demand-based allocation—are grounded in structural and regulatory constraints common to underground hubs across jurisdictions that follow international building codes. The threshold conditions—construction window  $< 12$  months, transfer demand  $< 5000$  person-trips per hour, spatial compression rate  $< 30\%$ , fiscal constraint  $\leq 20\%$  of reconstruction cost—are parameterized boundaries that can be recalibrated for different regulatory and operational contexts.

However, generalizability has limits that must be explicitly stated. The framework is designed for multi-level underground interchange hubs in dense urban contexts where the structural envelope is fixed. It is not designed for at-grade stations, single-level hubs, or contexts where the binding constraint is external to the hub (e.g., inadequate feeder bus service, insufficient road capacity). The threshold values are calibrated to Chinese regulatory standards (fire egress requirements, rail safety protection zones) and may require recalibration for jurisdictions with different building codes. A preliminary applicability assessment across ten hub typologies within the same metropolitan network indicated that approximately 60% meet the threshold conditions for micro-intervention, though this figure is based on expert assessment rather than systematic survey and should be interpreted with caution.

#### 5.5. Limitations and Boundary Conditions

Five limitations define the boundaries within which these findings should be interpreted.

**Single-case basis.** The findings are derived from one hub in one city. Multi-case validation across different hub typologies (e.g., cross-platform interchange, multi-line convergence), urban contexts (e.g., European, North American), and regulatory regimes (e.g., different fire egress standards) is necessary to establish the framework's generalizability. Until such validation is conducted, the framework should be treated as a theoretically grounded hypothesis rather than a validated planning tool.

**Forecast-based evaluation.** The evaluation relies on forecast rather than observed demand. While the forecasts were produced through standard transport modeling methods, post-implementation monitoring will provide more robust evidence of actual performance improvement. The differential improvement for luggage-carrying passengers is particularly sensitive to this limitation, as forecast models may not accurately capture the queuing dynamics of elevator-dependent users.

**Cost estimation uncertainty.** The cost comparison (one-fifth of reconstruction cost) is based on engineering estimates rather than actual expenditure. It does not account for transaction costs—design fees, coordination meetings, monitoring, contingency—that can add 20–40% to project costs. The actual cost ratio may be higher, though still substantially below comprehensive reconfiguration.

**Absence of long-term assessment.** Maintenance costs, equipment reliability, and passenger adaptation over time have not been assessed. Escalators have higher maintenance costs than staircases, and the long-term cost-effectiveness of the intervention depends on the trade-off between initial capital savings and ongoing operational expenditure.

**Unassessed climate resilience.** The framework's performance under extreme climate conditions—flooding, extreme heat, power outages—has not been tested. Underground hubs are vulnerable to flooding, and the increased reliance on mechanical vertical circulation introduces a failure mode that the staircase-only configuration did not have.

These limitations do not invalidate the findings but establish the conditions under which they should be interpreted. The threshold values (30% compression, 80% capacity gap, 1.5 detour ratio) are context-calibrated rather than universal; their applicability to other regulatory and operational contexts requires recalibration.

## 6. Conclusions

### 6.1. Summary of Research Objective

This study addressed a gap at the intersection of TOD theory and transport engineering practice: the absence of a systematic framework for micro-scale optimization of existing urban rail hubs under the spatial and fiscal constraints that characterize incremental development contexts. The study proposed and tested a Diagnosis–Optimization–Evaluation framework, operationalized through the SC-MIMM model, designed to identify and implement spatial reconfigurations that yield disproportionate functional improvements within existing structural envelopes.

### 6.2. Main Findings

Three findings emerged from the case application. First, vertical circulation reconfiguration with approximately 30% spatial compression produced an approximately 5.6-fold improvement in transfer capacity under simulation-based evaluation conditions through a qualitative shift from a single-mode to a multi-mode circulation system. Second, utilization of existing structural reserved spaces enabled the creation of a new pedestrian passage that transformed the hub from a barrier into a connector between previously disconnected urban quadrants. Third, demand-based facility allocation with calibrated redundancy improved intermodal connectivity without over-allocating scarce street-level space.

### 6.3. Theoretical Contribution

This study makes two theoretical contributions. First, it identifies a boundary condition for TOD theory: in built-up areas where density and diversity are already present, vertical circulation capacity can become the binding constraint, implying a reordering of intervention priorities. Second, it introduces “micro-intervention-first” as a planning principle for incremental development contexts, challenging the assumption that comprehensive reconfiguration is the default response to hub performance deficits.

### 6.4. Methodological Contribution

The primary methodological contribution is the Diagnosis – Optimization – Evaluation framework, which integrates three-dimensional spatial conflict detection, quantifiable intervention thresholds, demand-based facility allocation, and closed-loop implementation verification. The framework contributes three transferable instruments: a three-grade conflict classification system with parameterized threshold criteria, a spatial compression principle ( $\leq 30\%$ ) defining the feasibility boundary for mode-changing reconfiguration, and a set of threshold conditions defining when micro-intervention is the optimal strategy.

### 6.5. Practical Implications

For planning practice, the framework provides a structured approach to hub upgrading within the constraints of ongoing construction projects, enabling systematic identification of binding constraints and providing design rules applicable across hub typologies. For infrastructure investment, the framework offers a cost-effectiveness rationale for evaluating micro-intervention as a first-line strategy before committing to more expensive comprehensive reconfiguration.

The findings suggest that policy frameworks should prioritize micro-scale optimization as a first-line intervention before committing to capital-intensive reconstruction strategies.

### 6.6. Limitations and Future Research

Five limitations—single-case basis, forecast-based evaluation, cost estimation uncertainty, absence of long-term assessment, and unassessed climate resilience—define the boundaries of these findings. Three directions for future research are identified: multi-case validation across different hub typologies and regulatory regimes; post-implementation monitoring studies to validate forecast-based evaluation and assess durability of benefits; and integration of climate resilience criteria into the micro-intervention evaluation framework.

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**Institutional Review Board Statement**

Not applicable. This study did not involve human participants, human tissue, personal medical information, or animal subjects.

**Informed Consent Statement**

Not applicable. No identifiable participant information is included in this paper.

**Data Availability Statement**

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Some project-specific planning and simulation data are subject to institutional or project confidentiality restrictions.

**Conflicts of Interest**

The author declares no conflict of interest.

**References**

- 1 Calthorpe P. *“The Next American Metropolis”: Ecology, Community, and the American Dream*; Routledge: London, UK, 1993.
- 2 Dittmar H, Ohland G. *The New Transit Town: Best Practices in Transit-Oriented Development*; Island Press: Washington, DC, USA, 2004.
- 3 Bertolini L. Spatial Development Patterns and Public Transport: The Application of an Analytical Model in the Netherlands. *Planning Practice and Research* 1999; **14**(2): 199–210.
- 4 Renne JL. From Transit-Adjacent to Transit-Oriented Development. *Local Environment* 2009; **14**(1): 1–15.
- 5 Cervero R, Kockelman K. Travel Demand and the 3Ds: Density, Diversity, and Design. *Transportation Research Part D* 1997; **2**(3): 199–219.
- 6 Suzuki H, Cervero R, Iuchi K. *Transforming Cities with Transit: Transit and Land-Use Integration for Sustainable Urban Development*; World Bank Publications: Washington, DC, USA, 2013.
- 7 Ewing R, Cervero R. Travel and the Built Environment: A Meta-Analysis. *Journal of the American Planning Association* 2010; **76**(3): 265–294.
- 8 Stevens MR. Does Compact Development Make People Drive Less? *Journal of the American Planning Association* 2017; **83**(1): 7–18.
- 9 Wardman M, Hine J. Costs of Interchange: A Review of the Literature. *Transportation Research Part A* 2000; **34**(4): 245–262.
- 10 Lam WHK, Cheung CY. Pedestrian Speed/Flow Relationships for Walking Facilities in Hong Kong. *Journal of Transportation Engineering* 2000; **126**(4): 343–349.
- 11 Yan H. Real-Time 3D Model Reconstruction Through Energy-Efficient Edge Computing. *Optimizations in Applied Machine Learning* 2022; **2**(1).
- 12 Yan H, Shao D. Enhancing Transformer Training Efficiency with Dynamic Dropout. *arXiv* 2024. <https://doi.org/10.48550/arXiv.2411.03236>.
- 13 Yan H, Shao D. Multimodal Medical Image Analysis: Integrating LLM and RAG Deep Learning Strategies. *Journal of Advances in Information Technology* 2025; **16**(4): 568–581. <https://doi.org/10.12720/jait.16.4.568-581>.
- 14 Lu Y, Shao D, Ni X, *et al.* Emotion-Style Dual Prediction: A Multi-Task Deep Learning Approach for Artistic Images. *Cluster Computing* 2026; **29**(1): 31.
- 15 Luo Z, Yan H, Pan X. Optimizing Transformer Models for Resource-Constrained Environments: A Study on Model Compression Techniques. *Journal of Computational Methods in Engineering Applications* 2023; **3**(1): 1–12. <https://doi.org/10.62836/jcmea.v3i1.030107>.

- 16 Lydon M, Garcia A. *Tactical Urbanism: Short-Term Action for Long-Term Change*; Island Press: Washington, DC, USA, 2015.
- 17 Deng X, Kawano Y. Surface Plasmon Polariton Graphene Midinfrared Photodetector with Multifrequency Resonance. *Journal of Nanophotonics* 2018; **12(2)**: 026017.
- 18 Deng X, Simanullang M, Kawano Y. Ge-Core/a-Si-Shell Nanowire-Based Field-Effect Transistor for Sensitive Terahertz Detection. *Photonics* 2018; **5(2)**: 13.
- 19 Deng X, Li L, Enomoto M, et al. Continuously Frequency-Tuneable Plasmonic Structures for Terahertz Bio-Sensing and Spectroscopy. *Scientific Reports* 2019; **9(1)**: 3498.
- 20 Deng X, Oda S, Kawano Y. Graphene-Based Midinfrared Photodetector with Bull's Eye Plasmonic Antenna. *Optical Engineering* 2023; **62(9)**: 097102.
- 21 Flyvbjerg B, Bruzelius N, Rothengatter W. *Megaprojects and Risk: An Anatomy of Ambition*; Cambridge University Press: Cambridge, UK, 2003.
- 22 Zhang Y, Needleman A. On the Identification of Power-Law Creep Parameters from Conical Indentation. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 2021; **477(2252)**: 20210233.
- 23 Zhang Y, Needleman A. Characterization of Plastically Compressible Solids Via Spherical Indentation. *Journal of the Mechanics and Physics of Solids* 2021; **148**: 104283.
- 24 Li J. Nitrogen Removal Models for Stormwater Bioretention Systems. Ph.D. Thesis, University of Virginia, Charlottesville, VA, USA, 2023.
- 25 Li J, Culver TB. Review of Process-Based Nitrogen Model for Agricultural Fields with Implications for Nitrogen Simulations in Stormwater BMPs. *Environmental Modelling & Software* 2022; **151**: 105363.
- 26 Li J, Culver TB, Persaud PP, et al. Developing Nitrogen Removal Models for Stormwater Bioretention Systems. *Water Research* 2023; **243**: 120381.
- 27 Li J, Culver TB, Burgis CR, et al. Validating Nitrogen Removal Models with Field Bioretention Data. *Journal of Environmental Engineering* 2024; **150(8)**: 04024037.
- 28 Transportation Research Board. Highway Capacity Manual. 2000. Available online: [https://snavarro.wordpress.com/wp-content/uploads/2008/08/highway\\_capacity\\_manual.pdf](https://snavarro.wordpress.com/wp-content/uploads/2008/08/highway_capacity_manual.pdf) (accessed on 10 May 2026).
- 29 Fruin JJ. *Pedestrian Planning and Design*; Metropolitan Association of Urban Designers and Environmental Planners: New York, NY, USA, 1971.

