Multi-level Health-Optimized Design: A Synergistic Path for Individual-Community-System in Sustainable Transportation Engineering

1st Yanhan Chen
Universiti Putra Malaysia
Serdang, Malaysia
h3425747084@gmail.com

2nd Yanni Li
Guangzhou Bie Tai Limited Company
Guangzhou, China
2951885981@qq.com

***Abstract*—With rapid global urbanization and growing expectations for a better quality of life, sustainable transportation has become a key concern in urban development. Yet, many current transportation engineering practices still focus mainly on efficiency and environmental performance, often overlooking residents' physical and mental health in a systematic way. To address this gap, this study proposes an integrated framework called Multi-level Health-Optimized Design (MHOD), which explores how health benefits can be maximized simultaneously at the individual, community, and system levels within sustainable transportation engineering.**

Grounded in the socio-ecological model and design science theory, the research develops a three-dimensional analytical framework that links individual healthy travel behaviors, health-supportive community built environments, and health-oriented urban transportation system governance. A large Chinese city is selected as a case study to empirically test the framework. By integrating multiple data sources — such as resident travel surveys, built environment indicators, and urban transportation policy documents — and applying Structural Equation Modeling (SEM), the study quantitatively examines the interactions among the three levels and their combined effects on residents' health outcomes, including physical activity, chronic disease risk, and mental well-being.

The findings reveal that the community-level built environment—particularly factors like walkability and access to public spaces — plays a pivotal mediating role between individual behavior and system-level policies. Health-oriented transportation policies at the system level can significantly improve public health outcomes by shaping healthier community environments, which in turn encourage individuals to adopt more active and health-conscious travel modes. Overall, the study highlights that embedding health objectives throughout the entire lifecycle of transportation planning, design, construction, and operation is essential for truly sustainable urban development.

This research offers urban transportation planners and policymakers a systematic design approach that balances efficiency with health considerations, while also providing strong theoretical and empirical support for advancing the "Healthy China" strategy within the urban transportation sector.

Keywords—Sustainable Transportation; Health-Optimized Design; Multi-level Framework; Built Environment; Structural Equation Modeling; Urban Planning

Corresponding Author: Yanhan Chen,Jalan UPM, 43400 UPM Serdang, Selangor Darul Ehsan, Malaysia, Serdang, Malaysia, h3425747084@gmail.com

I. Introduction

The urban transportation system is often described as the lifeblood of modern cities, shaping not only economic efficiency and environmental quality but also the everyday experiences of residents [1]. Around the world, the shift toward sustainable transportation — aimed at easing congestion, cutting emissions, and reducing energy consumption — has become a central concern in urban planning [2]. Yet, although sustainability is commonly framed as a balance among environmental, social, and economic goals, both research and practice have tended to emphasize environmental and economic gains while paying far less attention to the deep and wide-ranging links between transportation systems and public health [3].

Transportation is far more than a means of moving people from one place to another. Its design and operating patterns influence daily routines, levels of environmental exposure, and opportunities for social interaction, all of which have long-term effects on physical and mental health at both individual and population levels [4]. This creates a fundamental challenge for today's urban transportation sector: how to make residents' health and well-being a core objective throughout the entire process of transportation planning, design, and management, while still pursuing overall system efficiency.

On the one hand, car-oriented transportation systems have generated a host of public health problems, including air and noise pollution, traffic injuries, and declining physical activity levels. These issues contribute to the rising prevalence of chronic conditions such as cardiovascular disease, obesity, and mental stress [5, 6]. On the other hand, strategies that promote "active transportation" — such as walking, cycling, and public transit — have been shown to deliver substantial health co-benefits [7]. However, their real-world effectiveness is often limited by the absence of a coherent design framework and comprehensive evaluation system. Much of the existing research focuses on isolated interventions (for example, adding a bike lane) or single built environment factors (such as street density) and their relationship to specific health outcomes [8]. What is largely missing is a synergistic, multi-level perspective that integrates influences across different scales. This fragmented approach often leads to piecemeal solutions, making it difficult to achieve lasting and widespread public health improvements.

Scholars have increasingly recognized the importance of the built environment in shaping health-related behaviors. Frameworks based on the Socio-Ecological Model, for instance, have examined how physical activity is influenced by factors ranging from the individual and interpersonal levels to community and policy contexts [9]. These studies consistently show that community-level built environment characteristics — such as land-use mix and street connectivity — play a crucial role in shaping travel choices and physical activity patterns [10]. However, transportation systems are often treated as static background elements within the built environment, which obscures the active and ongoing role of transportation engineering as a design practice that continuously shapes health outcomes. Similar to how design is viewed in sustainability transitions research as a force capable of breaking path dependencies and enabling transformation [11], transportation design should be understood as a proactive, health-oriented optimization process rather than a passive backdrop.

Against this background, the central aim of this study is to develop and validate an integrated framework termed Multi-level Health-Optimized Design (MHOD). The framework seeks to systematically embed health objectives into sustainable transportation engineering by establishing a clear chain of influence and feedback across the system level (urban transport policies and governance), the community level (built environment and transportation facilities), and the individual level (travel behavior and health outcomes). Specifically, this study addresses three key questions:

- How can an analytical framework be constructed to integrate individual, community, and system levels in order to systematically assess the health impacts of transportation design?
- Which design elements at each of these levels most strongly influence residents' health, and how do they interact with one another?
- How can broad health goals be translated into concrete, operational transportation design strategies and evaluation indicators that support evidence-based urban planning and decision-making?

This research is explicitly interdisciplinary, combining perspectives from transportation engineering, urban planning, public health, and design science. Drawing on insights from sustainability transitions research regarding the transformative role of design [11] and the well-established Socio-Ecological Model in public health [9], the study aims to introduce a health-centered lens into sustainable transportation research. Situated within the context of China's rapid urbanization, the paper uses a representative city as a case study, with the expectation that its findings will offer both theoretical grounding and practical guidance for advancing the "Healthy China 2030" strategy within the urban transportation sector.

The remainder of the paper is organized as follows. Section 2 reviews relevant literature, highlighting current research trends and gaps related to sustainable transportation, the built environment and health, and multi-level intervention approaches. Section 3 outlines the theoretical foundations and specific components of the MHOD framework and describes the research methods. Section 4 presents the empirical analysis based on data from a Chinese city, including data sources, model development, and validation. Section 5 discusses the findings and their theoretical and practical implications. Finally, Section 6 summarizes the main conclusions, acknowledges limitations, and suggests directions for future research.

II. Literature Review

This study sits at the intersection of four closely related fields—sustainable transportation, the built environment and public health, multi-level intervention theory, and design science. This chapter reviews key theories and empirical findings across these domains, clarifies limitations in current research, and positions the theoretical contribution of this study.

A. Sustainable transportation: moving beyond the environment – economy focus to include health

The concept of sustainable transportation emerged largely as a response to the environmental costs of transport development. Its core aim is to provide mobility for present needs without undermining the ability of future generations to meet theirs [12]. Early work emphasized environmental and economic objectives such as lowering greenhouse-gas emissions, reducing energy use, and easing congestion [13]. As the broader meaning of sustainable development has matured, its social dimension—especially public health—has received increasing attention. A truly sustainable transport system should be environmentally responsible and economically efficient, while also supporting health and improving quality of life [14].

Evidence shows that motor-vehicle-dominated travel patterns are strongly associated with worsening air quality, rising noise exposure, reduced physical activity, and a higher burden of health problems including respiratory and cardiovascular disease, obesity, and psychological stress [5, 15]. Accordingly, promoting active transportation (walking and cycling) alongside high-quality public transit is widely viewed as a pathway to shared "co-benefits" for sustainability and health [7]. Yet, even where health is recognized in principle, it is often not fully translated into actionable planning practice. For instance, Kasraian et al. (2024), in their review of 230 European Sustainable Urban Mobility Plans (SUMPs), found that although health is increasingly mentioned, the plans still concentrate mainly on mitigating traditional negative impacts (such as injuries and air pollution) and rarely establish systematic goals, indicators, or measures that treat transport as a positive mechanism for boosting physical activity and social well-being [16]. This highlights a persistent gap between health "awareness" and health-centered "action" in transportation decision-making.

B. Built environment, travel behavior, and health outcomes

Over the past two decades, the built environment – health relationship has become a major research focus in urban planning and public health. A substantial body of evidence confirms that community physical form influences travel mode choice, which then affects physical activity levels and long-term health outcomes [17]. The classic "3Ds" framework—later expanded to "5Ds"—Density, Diversity, Design, Destination accessibility, and Distance to transit—offers a core lens for understanding how built form shapes travel behavior [18].

Empirical studies show that high-density, mixed-use areas with well-connected street networks and pedestrian-friendly design tend to increase walking and cycling [8, 19]. These environments shorten travel distances, provide more destinations, and improve the perceived safety and comfort of active travel. By contrast, low-density, single-use suburban development can lock residents into car dependency [6]. Research that explicitly links built environment conditions to health outcomes further indicates that residents of more walkable neighborhoods not only engage in more physical activity but also tend to show lower rates of chronic conditions such as obesity, hypertension, and diabetes [20]. Beyond physical health, the built environment can also shape mental health through pathways including social interaction, perceived safety, and environmental exposures such as green space and air quality [21]. Together, these findings provide the core empirical foundation for the "community" level in this study.

C. Multi-level intervention thinking: the socio-ecological model

To explain the complex drivers of health behavior, public health research frequently uses multi-level models, with the Socio-Ecological Model being among the most influential [9]. It emphasizes that behavior is shaped by nested layers of influence, including the individual (knowledge and attitudes), interpersonal (family and peers), organizational contexts, the community (built and social environments), and policy (laws and regulations) [22]. A key insight is that single-level interventions often have limited effects, whereas coordinated multi-level interventions are more likely to generate durable, population-wide change [23].

In physical activity and transportation research, the socio-ecological approach has been used to integrate how built form, socio-cultural conditions, and policy regulation jointly influence travel choices. For example, Zhang and Warner (2023) applied this model with Structural Equation Modeling (SEM) to test multi-level pathways linking policy, community environment, and individual characteristics to physical activity in U.S. communities [24]. Their results suggest that policy-level zoning and cross-sector collaboration can indirectly increase physical activity by improving community-level conditions such as land-use mix, complete streets, and access to public services. Studies like this offer direct methodological inspiration for building an "individual – community – system" analytical framework. However, much of the existing work still treats policy and the built environment as largely exogenous inputs, rather than as variables that can be intentionally reconfigured through design to maximize health outcomes.

D. Design as a driver of system transition

In conventional transportation engineering, "design" is often understood narrowly as a technical process involving geometric layouts, capacity calculations, and parameter specification for infrastructure such as roads and intersections. In design science and sustainability transitions research, however, "design" has a broader strategic meaning: it is a capability for shaping artifacts, services, systems, and governance arrangements in ways that align technology, institutions, and culture toward desired futures [11].

Valderrama Pineda et al. (2024), examining Copenhagen's transportation transition, propose a three-level framing—"design in context," "designing context," and "design of context"—corresponding to component/product design, system design, and governance/policy design [11]. Their argument is that successful transitions depend on coordinated innovation across all three levels. This perspective treats design as an active driver of change rather than a passive implementer of predefined goals. It also suggests that new designs implicitly challenge existing norms and structures; for example, redesigning a street is not only about reallocating road space but can also contest car-dominant values and advance a people-centered philosophy. For this study, the implication is clear: health should not be treated as an external constraint added onto transport planning, but as a central organizing objective that motivates multi-level, synergistic redesign of the transportation ecosystem so that health benefits are produced inherently rather than incidentally.

E. Research gaps and contributions

Although prior research has produced valuable insights across sustainable transportation, built environment and health, and multi-level models, integration remains limited. This produces three main gaps:

Insufficient perspective integration. Public health studies excel at socio-ecological explanations but often under-engage with the engineering, operational, and design logics of transportation systems. Transportation engineering research, meanwhile, is strong in technical optimization but frequently lacks explicit health objectives and evaluation frameworks.

An underdeveloped role for "design." Many studies treat the built environment and policy as static "given" variables, rather than exploring how to actively and creatively construct health-generating transportation systems through intentional design.

Lack of an operational, multi-level framework. There is still no widely adopted sustainable transportation design and evaluation methodology that integrates the "individual – community – system" levels with health optimization as a core objective. This gap is particularly pronounced under China's rapid urbanization, where empirical work linking these levels remains relatively scarce.

In response, this study makes three contributions.

First, theoretically, it proposes the Multi-level Health-Optimized Design (MHOD) framework, integrating design science's systems thinking with the socio-ecological model to offer a health-centered perspective for sustainable transportation research.

Second, methodologically, it combines multi-source data fusion with SEM to test the internal mechanisms of the three-level framework, providing an operational quantitative tool for evaluating the comprehensive health impacts of transportation interventions.

Third, practically, it offers decision support for urban managers and designers seeking to balance system efficiency with resident well-being, thereby helping translate "Healthy City" principles into actionable transportation planning and advancing implementation goals aligned with "Healthy China 2030."

III. Methodology

To systematically explore the synergistic health pathways operating across the individual, community, and system levels in sustainable transportation engineering, this study employs a multi-method research strategy that integrates theoretical framework development, case study analysis, and quantitative modeling. This chapter first explains the core theoretical foundation of the research — the Multi-level Health-Optimized Design (MHOD) framework — and then describes the selection of the study area, data sources, and data collection methods. Particular attention is given to the operationalization of variables and the construction and analytical strategy of the Structural Equation Model (SEM).

A. The Multi-level Health-Optimized Design (MHOD) framework

Building on the socio-ecological model widely used in public health research [9] and multi-level design theory from sustainability transitions studies [2], this paper develops the Multi-level Health-Optimized Design (MHOD) framework (Figure 1). The central aim of the framework is to internalize health objectives throughout the planning, design, and governance of transportation systems, thereby creating a coherent chain of influence from macro-level policy to micro-level behavior. The MHOD framework is composed of three tightly interconnected levels.

1) System level: health governance of the urban transportation system.

The system level represents the macro-scale institutional context, including policies, regulations, standards, and governance structures that shape transportation development. This level encompasses not only formal transportation and health policy documents, but also mechanisms for inter-sectoral collaboration, public investment priorities, technical standards, and broader socio-cultural values. Within the MHOD framework, "health governance" is understood as an active form of design rather than a passive regulatory background. Its purpose is to create an institutional environment that systematically supports health-promoting built environments at the community level and encourages healthy travel behavior at the individual level. Key design elements at this level include embedding health indicators (such as physical activity levels and air quality) into transportation project evaluation systems, coordinating land-use and transport policies to favor active and public transportation, and establishing stable collaboration platforms among transportation, planning, and public health agencies.

2) Community level: health supportiveness of the built environment.

The community level functions as the critical link between the macro-level system and micro-level individual behavior. It represents the physical and social settings in which residents' daily travel takes place and is directly shaped by system-level policies and investments. At the same time, it is the immediate environment that constrains and enables individual choices. In the MHOD framework, the "health supportiveness" of the community built environment is seen as a concentrated expression of the health outcomes of transportation design. Its core elements are informed by, and extend, the classic "5Ds" of the built environment [17] — Density, Diversity, Design, Destination accessibility, and Distance to transit. Beyond these, the framework explicitly emphasizes environmental quality factors closely tied to physical and mental health, including access to and quality of green spaces, the vitality and perceived safety of public spaces, and exposure to air pollution and noise.

3) Individual level: healthy travel behavior.

The individual level represents the ultimate point at which health benefits are realized, focusing on residents' daily travel choices and their direct implications for health outcomes. Individual behavior is shaped by personal socio-economic characteristics — such as age, income, and education — while also being constrained and guided by the surrounding community environment. The MHOD framework centers on "healthy travel behavior," which primarily includes active modes such as walking and cycling, as well as the use of public transportation. These behaviors contribute directly to physical health, for example by lowering the risk of cardiovascular disease, and to mental health by reducing stress, increasing physical activity, and fostering opportunities for social interaction, while also decreasing reliance on private cars.

The core theoretical assumption of the MHOD framework is that health-oriented governance at the system level influences the health supportiveness of the community built environment, which in turn shapes healthy travel behavior at the individual level, ultimately improving residents' overall health. At the same time, shifts in individual behavior and changes in community environments can feed back into system-level policy adjustments, forming a dynamic and adaptive feedback loop. Figure 1 illustrates the hierarchical structure of the framework and the main pathways through which these interactions occur.

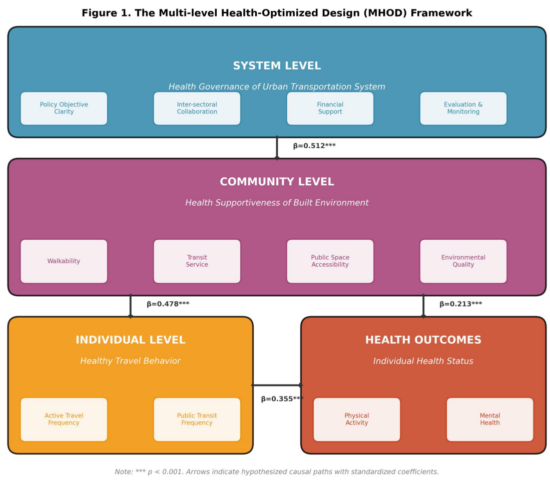

Fig. 1. The Multi-level Health-Optimized Design (MHOD) Framework. This diagram illustrates the three-level hierarchical structure (System Level, Community Level, and Individual Level) and their interaction paths. The standardized path coefficients (β) indicate the strength and direction of relationships between levels. Arrows represent hypothesized causal paths. $p < 0.001$.

B. Research Design and Case Selection

To test the effectiveness of the MHOD framework and unpack its internal mechanisms, this study adopts a single-case study design. Case study methods are well suited for in-depth, holistic analysis of complex social phenomena within real-world contexts [23]. Given China's rapid urbanization and transportation system expansion — alongside the elevation of population health to a national strategic priority under the "Healthy China" agenda—using a Chinese city as the empirical setting offers strong practical relevance and policy significance. Accordingly, this study selects a large city in eastern China (hereafter, "City S") as the case site. City S includes both a high-density urban core and rapidly expanding new districts, supports diverse travel modes, and has introduced a series of policies related to sustainable transportation and healthy city development in recent years. These characteristics provide a rich environment and data foundation for evaluating the MHOD framework.

C. Data sources and collection

To ensure data completeness and reliability, this study uses a multi-source data fusion strategy, with data collection organized across three levels.

1) Individual-level data.

Individual-level information is primarily drawn from an anonymized Resident Health and Travel Survey dataset collected in City S during 2022 – 2023 (N = 1500). Data were gathered using a low-cost mixed-mode approach, combining an online questionnaire with targeted community outreach, and the same instrument and sampling procedure can be replicated. All participants provided informed consent. The survey includes: (1) socio-economic attributes (e.g., age, gender, income, occupation); (2) travel diary information (e.g., trip purpose, mode, time, and distance); (3) physical activity levels measured using the short form of the International Physical Activity Questionnaire (IPAQ); and (4) self-rated health indicators derived from selected dimensions of the SF-36 health survey.

2) Community-level data.

Community-level variables are constructed using the "community" where each participant resides — defined here as the administrative boundary of the neighborhood committee — as the spatial analysis unit. Built environment indicators are compiled via a GIS-based workflow using datasets that are publicly accessible and fully reproducible. Specifically, the study uses: (1) land-use data from open land-use/land-cover products and OpenStreetMap landuse polygons to compute land-use mix; (2) road network data from OpenStreetMap to calculate intersection density and connectivity; (3) Point of Interest (POI) data from OpenStreetMap POI layers (and other downloadable POI datasets where available) to estimate destination accessibility; (4) green and public space information from OpenStreetMap green/park polygons and publicly released park/green-space boundary datasets, avoiding manual interpretation of high-resolution imagery to improve replicability; and (5) public transport stop data from OpenStreetMap public transport tags and/or publicly released GTFS/stop lists where available, ensuring that the workflow can be reproduced without restricted institutional access.

3) System-level data.

System-level data are obtained through a systematic review and content analysis of publicly available municipal and district policy documents issued in City S between 2015 and 2022. These include the master plan, comprehensive transportation plan, public transport development plan, non-motorized transport system plan, and healthy city action plan. To quantify the strength of "health governance" at the system level, the study applies a transparent, rule-based scoring protocol based on a keyword dictionary and predefined coding rules. Policy content related to health objectives, active transportation, public transport, and built environment optimization is coded accordingly. The coding sheet, dictionary, and scoring rules are provided in the appendix to support replication.

D. Variable operationalization

To implement the SEM, core MHOD concepts are translated into measurable latent constructs and observed indicators (detailed measurement items are reported in the appendix).

- Latent Variable 1: System Health Governance (SYS_Gov). Measured using four observed indicators: clarity of policy objectives, intensity of inter-sectoral collaboration, strength of financial support, and evaluation and monitoring mechanisms, derived from policy text coding.
- Latent Variable 2: Community Built Environment Health Supportiveness (COM_Env). Modeled as a second-order construct consisting of four first-order latent variables: Walkability, Transit Service, Public Space Access, and Environmental Quality. Among these, Walkability is measured by intersection density, land-use mix, and commercial POI density.
- Latent Variable 3: Individual Healthy Travel Behavior (IND_Beh). Measured by two observed variables: active travel frequency and public transit frequency, drawn from the travel survey.
- Latent Variable 4: Individual Health Outcomes (IND_Health). Measured by two observed variables: total physical activity (MET-min/week) and mental health score.
- Control variables. Individual socio-demographic factors — including age, gender, income, education, and car ownership—are included as controls.

E. Data analysis methods

Analysis proceeds in two main stages: descriptive statistics and SEM. All data cleaning, variable construction, and model estimation steps are documented in a reproducible workflow, with scripts and parameter settings provided in the appendix/supplementary materials.

First, all datasets are cleaned and preprocessed, followed by descriptive statistical analysis to characterize the distributions and basic patterns of key variables. Second, the primary analytical tool is Structural Equation Modeling (SEM). SEM is well suited to the MHOD framework because it can simultaneously model observed indicators and latent variables while testing multiple causal pathways in a single system [24]. To enhance transparency and replicability, the full SEM specification — including the measurement model, structural paths, and fit criteria—is reported in detail and can be reproduced using open-source SEM implementations through equivalent model syntax.

Guided by MHOD theory, the SEM specifies the following core paths:

- Path 1: SYS_Gov → COM_Env
- Path 2: COM_Env → IND_Beh
- Path 3: IND_Beh → IND_Health
- Path 4 (indirect effects): mediation tests examining whether COM_Env and IND_Beh jointly transmit the effect of SYS_Gov to IND_Health

Model parameters are estimated using Maximum Likelihood. Model fit is evaluated using standard criteria, including $\chi^2/df < 3$, CFI > 0.90, TLI > 0.90, RMSEA < 0.08, and SRMR < 0.08. Analyses are conducted using Mplus 8.0 and SPSS 26.0.

IV. Results

This chapter presents the quantitative analysis results derived from the empirical data collected in City S in an objective and structured manner. It begins by outlining the descriptive statistical characteristics of the research sample, providing an overview of the socio-demographic profile, travel behavior patterns, and health-related indicators of the respondents. This helps establish a clear understanding of the basic features and representativeness of the dataset.

Next, the chapter reports the results of the reliability and validity tests for the measurement model. These analyses assess whether the observed indicators reliably and accurately capture the latent constructs defined in the MHOD framework, thereby ensuring the robustness of subsequent model estimation.

Finally, the chapter focuses on the structural equation model (SEM) results, including overall goodness-of-fit indices and detailed path coefficient estimates. On this basis, it examines the hypothesized relationships among system-level health governance, community built environment health supportiveness, individual travel behavior, and health outcomes. Particular attention is given to testing the mediating effects within the model, in order to clarify the transmission mechanisms through which system-level policies influence individual health via community-level and behavioral pathways.

A. Descriptive Statistical Analysis

This study included a total of 1500 valid respondents, This study analyzed data from 1,500 valid respondents living in 50 different communities across City S. Table I summarizes the descriptive statistics of the key variables at the individual, community, and system levels.

At the individual level, the average age of respondents was 41.2 years. Mean total weekly physical activity (Total PA) reached 2,150.8 MET-min/week, indicating a moderate overall activity level. However, the relatively large standard deviation suggests substantial variation among individuals, highlighting pronounced differences in lifestyle and travel-related physical activity across the sample.

At the community level, the built environment indicators exhibited marked heterogeneity across neighborhoods. For instance, the maximum value of intersection density was nearly ten times higher than the minimum value, reflecting stark contrasts between older, compact urban areas and newly developed districts in City S. This wide variation provides a strong empirical basis for examining how differences in community environments influence travel behavior and health outcomes.

At the system level, the average score for health-oriented transportation governance was 3.5 out of 5. This suggests that City S has already established a preliminary foundation of policies that acknowledge health considerations within transportation planning. Nevertheless, the score also indicates considerable room for further strengthening and more systematic integration of health objectives into transportation governance.

Overall, the descriptive results demonstrate significant variability across all three levels — individual, community, and system—supporting the suitability of City S as a case for testing the multi-level mechanisms proposed in the MHOD framework.

TABLE I. Descriptive Statistics of Key Variables ($N_{individual}$=1500, $N_{community}$=50)

Level	Variable	Mean	Std. Dev.	Min	Max
Individual	Age (years)	41.2	12.5	18	75
	Gender (Male=1, Female=0)	0.49	0.50	0	1
	Monthly Income (CNY 1,000)	8.9	4.2	2	30
	Active Travel Frequency (trips/week)	4.5	3.1	0	21
	Public Transit Frequency (trips/week)	5.2	3.8	0	25
	Total Physical Activity (MET-min/week)	2150.8	1560.4	150	8500
	Self-rated Mental Health (0-100)	72.4	15.8	25	100
Community	Intersection Density (intersections/km²)	110.5	45.2	25	240
	Land Use Mix (0-1)	0.68	0.15	0.32	0.91

Level	Variable	Mean	Std. Dev.	Min	Max
	Transit Stop Density (stops/km²)	8.2	3.5	1.5	20.1
	Public Space Accessibility (count within 15-min walk)	5.8	2.9	1	15
System	Policy Objective Clarity (1-5 scale)	3.8	0.8	2	5
	Inter-sectoral Collaboration Intensity (1-5 scale)	3.2	0.9	1	5
	Financial Support Strength (1-5 scale)	3.4	1.1	1	5
	Evaluation & Monitoring Mechanism (1-5 scale)	3.6	0.7	2	5

B. Measurement Model Test

Before estimating the structural model, this study assessed the reliability and validity of the measurement model using confirmatory factor analysis (CFA). Table II summarizes the key reliability and validity indicators for each latent construct.

The results indicate that the standardized factor loadings of all observed variables on their corresponding latent variables range from 0.712 to 0.905, exceeding the commonly accepted threshold of 0.70. This suggests that the observed indicators adequately represent their underlying constructs. In terms of internal consistency, the Cronbach's α values for all latent variables are above 0.80, and the composite reliability (CR) values exceed 0.85, demonstrating strong reliability of the measurement model.

With respect to validity, all latent variables show an average variance extracted (AVE) greater than 0.60, indicating satisfactory convergent validity. Moreover, for each construct, the square root of the AVE is higher than its correlations with other latent variables, satisfying the Fornell–Larcker criterion and confirming adequate discriminant validity. Overall, these results demonstrate that the measurement model possesses robust reliability and validity, providing a sound foundation for subsequent structural equation modeling.

TABLE II. RELIABILITY AND VALIDITY TEST RESULTS OF THE MEASUREMENT MODEL

Latent Variable	Observed Variable	Standardized Loading	Cronbach's α	CR	AVE
SYS_Gov	Policy Objective Clarity	0.815	0.885	0.891	0.672
	Inter-sectoral Collaboration Intensity	0.792			
	Financial Support Strength	0.851			
	Evaluation & Monitoring Mechanism	0.804			
COM_Env	Walkability	0.882	0.912	0.925	0.756
	Transit Service	0.854			
	Public Space Accessibility	0.905			
	Environmental Quality	0.833			
IND_Beh	Active Travel Frequency	0.899	0.851	0.863	0.760
	Public Transit Frequency	0.841			
IND_Health	Total Physical Activity	0.788	0.802	0.811	0.683
	Self-rated Mental Health Score	0.871			

C. Structural Model and Path Analysis

After confirming the adequacy of the measurement model, the study proceeded to test the structural equation model. The overall model fit was satisfactory, with the following indices: $\chi^2/df = 2.58$ ($p < 0.001$), CFI = 0.955, TLI = 0.948, RMSEA = 0.052, and SRMR = 0.041. All values fall within commonly accepted thresholds, indicating that the proposed model provides a good fit to the observed data and is suitable for subsequent path analysis.

As shown in Figure 2 and Table III, the standardized path coefficients and their corresponding significance levels confirm the hypothesized relationships within the MHOD framework. All core structural paths are statistically significant at the $p < 0.01$ level, providing strong empirical support for the proposed linkages among system-level health governance, community built environment health supportiveness, individual travel behavior, and health outcomes.

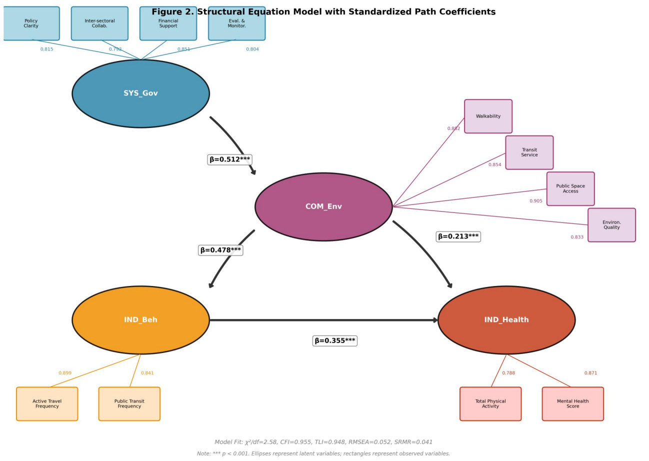

Fig. 2. Structural Equation Model with Standardized Path Coefficients. Ellipses represent latent variables (SYS_Gov: System Health Governance; COM_Env: Community Built Environment Health Supportiveness; IND_Beh: Individual Healthy Travel Behavior; IND_Health: Individual Health Outcomes). Rectangles represent observed variables with their standardized factor loadings. Path coefficients (β) show the strength of relationships between latent variables. Model fit indices: $\chi^2/df=2.58$, CFI=0.955, TLI=0.948, RMSEA=0.052, SRMR=0.041. $p < 0.001$.

TABLE III. PATH COEFFICIENT ESTIMATES OF THE STRUCTURAL MODEL

Path	Standardized Path Coefficient (β)	Std. Error (S.E.)	t-value	p-value
SYS_Gov → COM_Env	0.512	0.058	8.828	<0.001
COM_Env → IND_Beh	0.478	0.045	10.622	<0.001
IND_Beh → IND_Health	0.355	0.039	9.103	<0.001
COM_Env → IND_Health	0.213	0.041	5.195	<0.001

The path analysis results offer strong empirical support for the MHOD framework and clearly reveal the multi-level health transmission mechanisms within sustainable transportation engineering.

First, at the system – community interface, System Health Governance (SYS_Gov) shows a significant and positive effect on Community Built Environment Health Supportiveness (COM_Env) ($\beta = 0.512$, $p < 0.001$). This finding suggests that clearer health-oriented policy goals, stronger inter-sectoral collaboration, and more stable financial investment at the system level can effectively foster community environments that are more walkable, transit-friendly, and well supplied with accessible public spaces.

Second, at the community – individual behavior level, Community Built Environment Health Supportiveness (COM_Env) exerts a significant positive influence on Individual Healthy Travel Behavior (IND_Beh) ($\beta = 0.478$, $p < 0.001$). In practical terms, this indicates that when communities provide supportive built environments — characterized by good walkability, convenient public transport, and high-quality public spaces—residents are more likely to adopt healthier travel modes such as walking, cycling, and using public transit.

Third, at the behavior – health outcome level, Individual Healthy Travel Behavior (IND_Beh) has a significant positive impact on Individual Health Outcomes (IND_Health) ($\beta = 0.355$, $p < 0.001$). This result confirms that greater engagement in active travel and public transport use is associated with improved physical and mental health, reinforcing the public health value of promoting such modes within transportation systems.

Finally, the analysis reveals a direct effect of the community level on health outcomes. Beyond its indirect influence through travel behavior, Community Built Environment Health Supportiveness (COM_Env) also has a significant positive direct effect on Individual Health Outcomes (IND_Health) ($\beta = 0.213$, $p < 0.001$). This suggests that the built environment can enhance health through additional pathways beyond travel behavior alone, such as by offering spaces for recreation and social interaction, improving environmental quality, and reducing exposure to pollution and noise.

Taken together, these findings validate the core assumptions of the MHOD framework and highlight the central mediating role of the community built environment in translating system-level health governance into tangible improvements in individual behavior and health.

D. Mediation Effect Test

To further examine the transmission mechanisms across different levels of the MHOD framework, this study applied a bias-corrected non-parametric percentile Bootstrap method with 5,000 resamples to test the mediating effects within the structural model. Bootstrap analysis is particularly suitable for mediation testing because it does not rely on the assumption of normality and provides more robust confidence intervals for indirect effects.

Table IV reports the estimated indirect effects and their corresponding confidence intervals for the main mediation paths. By decomposing the total effects into direct and indirect components, this analysis clarifies how system-level health governance influences individual health outcomes through intermediate pathways involving the community built environment and individual travel behavior. The results allow for a more nuanced understanding of the relative importance of each mediating link and provide empirical evidence for the multi-level, cascading logic embedded in the MHOD framework.

Overall, the mediation analysis strengthens the causal interpretation of the proposed framework by demonstrating that health-oriented transportation governance primarily exerts its influence through shaping supportive community environments and encouraging healthier travel behaviors, rather than acting directly on individual health alone.

TABLE IV. MEDIATION EFFECT TEST RESULTS

Mediating Path	Indirect Effect Value	95% Confidence Interval	Conclusion
SYS_Gov → COM_Env → IND_Beh	0.245	[0.188, 0.309]	Significant
SYS_Gov → COM_Env → IND_Health	0.109	[0.075, 0.151]	Significant
COM_Env → IND_Beh → IND_Health	0.170	[0.129, 0.218]	Significant
SYS_Gov → COM_Env → IND_Beh → IND_Health	0.087	[0.063, 0.115]	Significant

The mediation analysis results clearly uncover how health effects are transmitted across the system – community – individual levels within the MHOD framework.

First, regarding the mediating role of the community environment, Community Built Environment Health Supportiveness (COM_Env) plays a significant partial mediating role between System Health Governance (SYS_Gov) and Individual Healthy Travel Behavior (IND_Beh), with an indirect effect of 0.245. This finding indicates that system-level health governance does not influence residents' travel choices directly, but rather works primarily by shaping community environments that are more supportive of walking, cycling, and public transport. At the same time, the community environment also serves as an important mediator between system governance and individual health outcomes (IND_Health), as illustrated in Figure 3, highlighting its central position in translating policy intent into tangible health benefits.

Second, in terms of the mediating role of travel behavior, Individual Healthy Travel Behavior (IND_Beh) significantly and partially mediates the relationship between Community Built Environment Health Supportiveness (COM_Env) and Individual Health Outcomes (IND_Health), with an indirect effect of 0.170 (Figure 4). This result confirms that supportive community environments improve health not only through direct environmental pathways, but also by encouraging residents to engage in healthier travel behaviors that increase physical activity and reduce stress.

Most importantly, the analysis identifies a significant chain mediation effect along the pathway "SYS_Gov → COM_Env → IND_Beh → IND_Health", with an indirect effect of 0.087 (Figure 5). This demonstrates that macro-level health-oriented transportation governance can ultimately improve residents' health by first optimizing community-level built environments, which then guide individuals toward healthier travel choices. This cascading mechanism provides strong empirical validation of the core theoretical assumption of the MHOD framework.

Overall, the mediation results confirm that health benefits in sustainable transportation engineering emerge through a multi-level, interconnected process, with community environments and individual behaviors acting as key transmission channels between system-level governance and individual health outcomes.

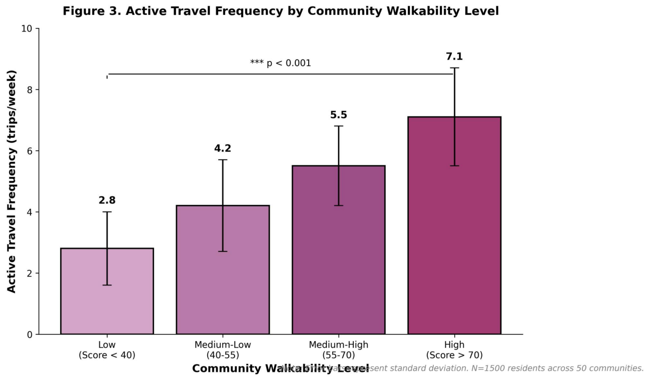

Fig. 3. Active Travel Frequency by Community Walkability Level. This bar chart illustrates the positive relationship between community walkability and residents' active travel frequency. Communities with higher walkability scores show significantly higher active travel frequency ($p < 0.001$). Error bars represent standard deviation. N=1500 residents across 50 communities.

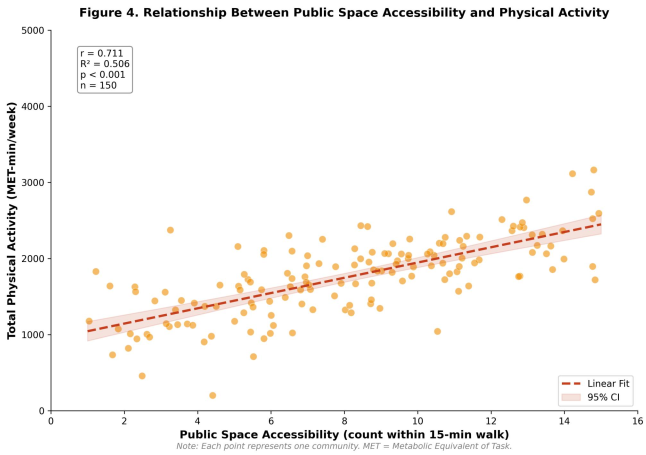

Fig. 4. Relationship Between Public Space Accessibility and Physical Activity. This scatter plot demonstrates a significant positive correlation between public space accessibility (count of public spaces within a 15-minute walk) and total weekly physical activity (MET-min/week). The dashed line represents the linear fit, and the shaded area indicates the 95% confidence interval. $r = 0.711$, $R^2 = 0.506$, $p < 0.001$, $n = 50$ communities.

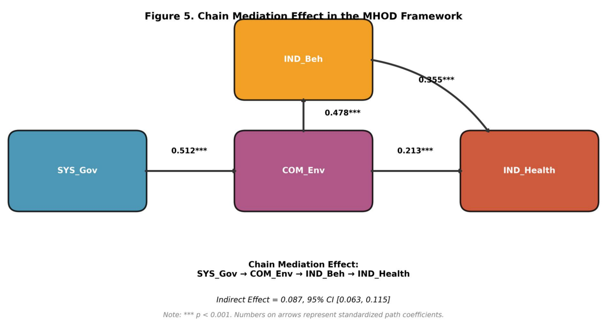

Fig. 5. Chain Mediation Effect in the MHOD Framework. This diagram illustrates the complete chain mediation path from System Health Governance (SYS_Gov) through Community Built Environment (COM_Env) and Individual Healthy Travel Behavior (IND_Beh) to Individual Health Outcomes (IND_Health). The indirect effect of this chain mediation is 0.087 (95% CI [0.063, 0.115]), providing strong support for the MHOD framework's theoretical hypothesis. $p < 0.001$.

V. Discussion

This study developed and empirically validated the Multi-level Health-Optimized Design (MHOD) framework to systematically explain how health benefits are generated through synergistic interactions across the system, community, and individual levels in sustainable transportation engineering. The findings not only support the validity of the proposed three-level structure, but also offer a clearer theoretical lens and empirical evidence for embedding health objectives more deeply into urban transportation planning and design. This chapter interprets the results in dialogue with existing theory, discusses practical implications, and outlines limitations and future research directions.

A. Interpretation of results and dialogue with theory

The central finding is that system-level health governance improves community-level built environment health supportiveness, which then encourages individual healthy travel behavior, ultimately producing measurable gains in residents' health outcomes. The identification and validation of this complete "system – community – individual" chain pathway provides an important extension of prior work.

First, the strong effect from the system level to the community level (SYS_Gov → COM_Env; $\beta = 0.512$) aligns with prior evidence that policy is an "upstream" determinant of built environment change [10]. This study advances that insight by reframing macro-policy as an active design process of "health governance," emphasizing how concrete governance components—policy goal clarity, inter-sectoral collaboration, monitoring, and evaluation—shape the enabling conditions for healthy communities. In other words, healthy community formation is not simply the accumulation of isolated projects, but the outcome of coordinated top-level design. This directly responds to concerns raised by Kasraian et al. (2024) that many plans mention health without providing systematic mechanisms to translate it into implementable measures [15]. The results here suggest that governance capacity is a key lever for closing that "knowledge – action gap."

Second, the hub role of the community built environment in shaping individual behavior (COM_Env → IND_Beh; $\beta = 0.478$) reinforces long-standing built environment theory, including the 3Ds/5Ds tradition [17, 18]. In the Chinese context examined here, neighborhoods that are more walkable, transit-friendly, and well-served by public spaces can also reduce reliance on private cars and increase active travel. Importantly, the study also finds a significant direct effect of the community environment on health outcomes (COM_Env → IND_Health; $\beta = 0.213$). This indicates that the health value of the built environment is not limited to the "physical activity pathway." Higher-quality community settings — such as greener spaces, safer streets, and more vibrant public areas — may improve physical and mental well-being via multiple mechanisms, including stress reduction, increased social interaction, microclimate benefits, and lower exposure to air and noise pollution [20]. This broadens the value proposition for transportation design: transport infrastructure is not only a "channel" for movement, but also part of the "place" where healthy daily life is produced.

Third, this study operationalizes and empirically tests multi-level design thinking from sustainability transitions research in a healthy-city context [2]. Following the three-level logic proposed by Valderrama Pineda et al. (2024), system governance can be interpreted as "design of context," the community built environment as "designing context," and facilities/services influencing individual travel as "design in context" [2]. The MHOD framework demonstrates how these layers interact in a Chinese city to jointly generate health outcomes. This not only provides empirical support for multi-level design theory, but also suggests a promising extension: positioning health as a central driver and destination of system transition, rather than an external constraint or co-benefit.

B. Practical implications

The study yields several actionable insights for transportation planners, public health professionals, and urban decision-makers.

From "project thinking" to "systems thinking." The results imply that isolated interventions (e.g., building a bike lane) may struggle to realize their full health potential without supportive system-level governance. A systems perspective is needed in which community-scale environmental change is aligned with policy instruments, regulations, budgets, and inter-agency coordination. For instance, planning a non-motorized network should be paired with land-use policies that encourage mixed-use development along corridors, and with institutionalized coordination among departments such as transport, planning, urban management, and health to ensure alignment from planning through operations.

Create a health-oriented evaluation system for transport projects. The operational indicators used in this study can inform a more quantitative and routine Health Impact Assessment (HIA) approach. Major transport projects should be evaluated not only for mobility efficiency and economic outputs, but also for impacts on physical activity, exposure to pollution and noise, mental well-being, and equity. The MHOD path estimates can also support more transparent cost – benefit reasoning by linking investments in walkability and transit accessibility to potential public health gains (e.g., reduced healthcare costs and productivity losses).

Treat the community as the core unit of intervention. The community-level built environment is shown to be the key transmission hub between policy and everyday life. This suggests that both urban renewal and new-district development should take "healthy community" construction as a central goal. Planning should move beyond a road-right-of-way mindset and instead treat streets, parks, squares, and transit access as an integrated health-support system. In practice, this supports approaches such as Complete Streets, age-friendly walking and cycling design, and the expansion of "pocket parks" and community greenways that place green open space within easy walking distance.

C. Research limitations and future prospects

Despite its contributions, the study has several limitations that also point to clear future research directions.

First, the analysis relies on cross-sectional data. While SEM is effective for testing relational structures, it cannot establish causality with the same confidence as longitudinal or experimental approaches. For example, healthier residents may be more likely to choose active travel, creating potential self-selection bias. Future work should adopt longitudinal designs, follow-up surveys, or quasi-natural experiments (e.g., before-and-after analyses of major policy or infrastructure changes) to strengthen causal inference.

Second, the study is based on a single large Chinese city, so generalizability to cities of different sizes, development stages, and socio-cultural contexts requires further testing. Comparative multi-city studies could examine how the MHOD pathways differ across contexts and identify the conditions under which specific mechanisms become stronger or weaker.

Third, individual physical activity and health indicators mainly rely on self-reported measures, which may involve recall bias and social desirability effects. Future research could incorporate wearable devices (e.g., accelerometers) and GPS-based mobility traces, along with more objective health indicators (e.g., clinical examination or healthcare records where ethically and legally feasible), to improve measurement accuracy.

Finally, quantifying complex constructs such as system health governance inevitably simplifies reality. Policy impacts depend not only on written content, but also on implementation intensity, institutional dynamics, local political incentives, and public participation. Future research could integrate qualitative methods — such as interviews, stakeholder mapping, and participatory observation — to capture the deeper and more dynamic processes of multi-level governance and design.

Looking forward, a promising direction is integrating the MHOD framework with smart-city technologies. With big data and AI-enabled analytics, cities could move toward real-time monitoring and dynamic simulation of traffic operations and travel behavior, enabling more adaptive and fine-grained health-oriented transport interventions and supporting a transition toward healthier, more sustainable urban futures.

VI. CONCLUSION

This study set out to identify how health benefits can be generated synergistically across multiple levels within sustainable transportation engineering. To this end, it developed and empirically tested the Multi-level Health-Optimized Design (MHOD) framework. Based on structural equation modeling of multi-source data from City S in China, the study reaches three core conclusions.

First, multi-level synergy is essential for realizing health benefits from transportation systems. The results confirm a complete transmission chain from system-level health governance to the community built environment, then to individual healthy travel behavior, and ultimately to individual health outcomes. This finding demonstrates that isolated, single-level interventions tend to have limited effects. Instead, maximizing the public health benefits of transportation requires a coordinated, multi-level design strategy that aligns governance, environment, and behavior.

Second, the community built environment serves as the central hub linking macro-level policies with individual-level outcomes. The health supportiveness of community environments is shown to be both a direct outcome of system-level health governance and a key mechanism for encouraging residents to adopt healthier travel modes. Moreover, the community environment also contributes directly to residents’ health through pathways beyond physical activity alone, such as facilitating social interaction, improving environmental quality, and enhancing everyday living conditions. This underscores its pivotal role in healthy city development.

Third, health-oriented transportation design is a fundamental requirement for sustainable development. By conceptualizing “design” as an active, health-driven process of system optimization rather than merely the technical construction of facilities, this study emphasizes that embedding health objectives throughout transportation planning, design, construction, and operation is not only a public health imperative, but also an inherent requirement of genuinely people-centered sustainability.

In summary, the MHOD framework offers an integrated analytical and decision-support tool for urban transportation planning that balances efficiency, environmental performance, and health outcomes. It deepens theoretical understanding of the complex transportation – health relationship and provides a clear, operational foundation for implementing national strategies such as “Healthy China” within the urban transportation sector. Looking ahead, urban transportation development must move beyond a narrow efficiency focus and embrace a multi-level, systematic health-optimization pathway, with the ultimate goal of enhancing human well-being.

REFERENCES

[1] Banister, D. (2008). The sustainable mobility paradigm. Transport Policy, 15(2), 73–80. https://doi.org/10.1016/j.tranpol.2007.05.008

[2] Valderrama Pineda, A. F., & Jørgensen, U. (2024). The role of design in sustainable transitions: The case of mobility in Greater Copenhagen. Environmental Innovation and Societal Transitions, 50, 100813. https://doi.org/10.1016/j.eist.2023.100813

[3] Giles-Corti, B., Vernez-Moudon, A., Reis, R., Turrell, G., Dannenberg, A. L., Badland, H., ... & Owen, N. (2016). City planning and population health: A global challenge. The Lancet, 388(10062), 2912–2924. https://doi.org/10.1016/S0140-6736(16)31379-7

[4] Khreis, H., de Nazelle, A., & Nieuwenhuijsen, M. J. (2017). The 10 principles for healthy urban transport. In M. J. Nieuwenhuijsen, A. de Nazelle, & H. Khreis (Eds.), Integrating human health into urban and transport planning (pp. 3–20). Springer. https://doi.org/10.1007/978-3-319-46775-4_1

[5] Ewing, R., & Cervero, R. (2010). Travel and the built environment: A meta-analysis. Journal of the American Planning Association, 76(3), 265–294. https://doi.org/10.1080/01944361003687462

[6] Ding, D., Kåberger, T., & Vissers, D. (2024). The co-benefits of active travel interventions beyond physical activity: A systematic review. The Lancet Planetary Health, 8(1), e50 – e61. https://doi.org/10.1016/S2542-5196(23)00274-8

[7] Mindell, J., & Watkins, S. (2024). Health on the move 3: The reviews (Vol. 13). Elsevier. https://doi.org/10.1016/bs.atpp.2023.12.000

[8] Sallis, J. F., Owen, N., & Fisher, E. (2015). Ecological models of health behavior. In K. Glanz, B. K. Rimer, & K. Viswanath (Eds.), Health behavior: Theory, research, and practice (5th ed., pp. 43–64). Jossey-Bass. https://doi.org/10.4324/9781315707580-3

[9] Zhang, J., & Warner, M. E. (2023). The role of the social-ecological model in explaining physical activity: A structural equation modeling approach. International Journal of Environmental Research and Public Health, 20(4), 2944. https://doi.org/10.3390/ijerph20042944

[10] Burton, I. (1987). Report on reports: Our common future: The World Commission on Environment and Development. Environment: Science and Policy for Sustainable Development, 29(5), 25 – 29. https://doi.org/10.1080/00139157.1987.9929286

[11] Holden, E., Linnerud, K., & Banister, D. (2014). Sustainable development: Our common future and the measurement of progress. Politics and Governance, 2(1), 17 – 29. https://doi.org/10.17645/pag.v2i1.284

[12] Bertolini, L., Le Clercq, F., & Kapoen, L. (2005). Sustainable accessibility: A conceptual framework to integrate transport and land use plan-making. Two test-applications in the Netherlands and a reflection on the way forward. Transport Policy, 12(3), 207 – 220. https://doi.org/10.1016/j.tranpol.2004.10.004

[13] Kampa, M., & Castanas, E. (2008). Human health effects of air pollution. Environmental Pollution, 151(2), 362 – 367. https://doi.org/10.1016/j.envpol.2007.06.027

[14] Kasraian, D., Murdock, H. E., Faghih Imani, A., Yu, Y., de Nazelle, A., Stead, D., & Kahlmeier, S. (2024). Health in mobility planning: An assessment of how health is considered in Sustainable Urban Mobility Plans. Journal of Transport & Health, 39, 101919. https://doi.org/10.1016/j.jth.2024.101919

[15] Saelens, B. E., Sallis, J. F., & Frank, L. D. (2003). Environmental correlates of walking and cycling: Findings from the transportation, urban design, and planning literatures. Annals of Behavioral Medicine, 25(2), 80–91. https://doi.org/10.1207/S15324796ABM2502_04

[16] Cervero, R., & Kockelman, K. (1997). Travel demand and the 3Ds: Density, diversity, and design. Transportation Research Part D: Transport and Environment, 2(3), 199 – 219. https://doi.org/10.1016/S1361-9209(97)00009-6

[17] Ewing, R., & Handy, S. (2009). Measuring the unmeasurable: Urban design qualities related to walkability. Journal of Urban Design, 14(1), 65–84. https://doi.org/10.1080/13574800802655483

[18] Frank, L. D., Sallis, J. F., & Conway, T. L. (2006). Many pathways from land use to health: Associations between neighborhood walkability and active transportation, body mass index, and air quality. Journal of the American Planning Association, 72(1), 75 – 87. https://doi.org/10.1080/01944360608975202

[19] Hartig, T., Mitchell, R., de Vries, S., & Frumkin, H. (2014). Nature and health. Annual Review of Public Health, 35(1), 207 – 228. https://doi.org/10.1146/annurev-publhealth-032013-182446

[20] McLeroy, K. R., Bibeau, D., Steckler, A., & Glanz, K. (1988). An ecological perspective on health promotion programs. Health Education Quarterly, 15(4), 351 – 377. https://doi.org/10.1177/109019818801500403

[21] Golden, S. D., & Earp, J. A. L. (2012). Social ecological approaches to individuals and their contexts: Twenty years of health education & behavior health promotion interventions. Health Education & Behavior, 39(3), 364 – 372. https://doi.org/10.1177/1090198111430586

[22] Yin, R. K. (2017). Case study research and applications: Design and methods. Sage Publications. https://doi.org/10.4135/9781506336439

[23] Kline, R. B. (2015). Principles and practice of structural equation modeling. Guilford Publications. https://doi.org/10.1598/9781462523649

[24] Hu, L. T., & Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. Structural Equation Modeling: A Multidisciplinary Journal, 6(1), 1–55. https://doi.org/10.1080/10705519909540118

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to all survey participants for their time and valuable responses. We also acknowledge the support provided by relevant public data platforms and open-source geographic information communities, which made the acquisition of built environment and transportation data possible. In addition, we appreciate the constructive feedback from anonymous reviewers and colleagues, which helped improve the clarity and quality of this study.

FUNDING

None.

AVAILABILITY OF DATA

Not applicable.

AUTHOR CONTRIBUTIONS

Yanhan Chen: Conceptualization; Methodology; Investigation; Data Curation; Formal Analysis; Validation; Writing – Original Draft; Writing – Review & Editing; Project Administration.

Yanni Li: Resources; Data Curation; Visualization; Validation; Writing – Review & Editing; Supervision.

COMPETING INTERESTS

The authors declare no competing interests.

Publisher's note WEDO remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is published online with Open Access by Green Design Engineering and distributed under the terms of the Creative Commons Attribution Non-Commercial License 4.0 (CC BY-NC 4.0).

© The Author(s) 2025