

# Comprehensive Impact Assessment of Sustainable Transport Interventions on Urban Quality of Life and Health Risks: A System Dynamics-Based Case Study of Shenzhen

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**Abstract—Background:** Rapid urbanization and motorization in megacities have led to severe challenges, including traffic congestion, air pollution, and public health risks, which collectively degrade the urban quality of life. This study aims to comprehensively assess the long-term impacts of different sustainable transport interventions on urban quality of life and health risks. **Methods:** We developed an integrated System Dynamics (SD) model that couples four subsystems: Transport, Environment, Health, and Quality of Life (TEHQ). Using Shenzhen, China, as a case study, we simulated the system's behavior from 2025 to 2045 under four scenarios: Business as Usual (BAU), Public Transit Priority (PT-First), New Energy Vehicle Promotion (NEV-Push), and an Integrated Intervention scenario. Key performance indicators, including a composite Quality of Life (QoL) index and a Health Risk Index, were used for evaluation. **Results:** Under the BAU scenario, traffic congestion, pollution exposure, and health burden continue to worsen over time, while the quality of life index shows a declining trend in the later period. Compared with BAU, the PT-First scenario shows the strongest improvement in traffic efficiency, whereas the NEV-Push scenario performs better in reducing pollution-related health burden. The Integrated scenario achieves the most balanced overall performance across mobility, environmental, and health dimensions, resulting in the highest improvement in the composite QoL index and the largest reduction in excess mortality. These findings suggest that combined interventions are more effective than single-policy approaches in improving long-term urban sustainability. **Conclusions:** Single-dimensional transport policies have clear limitations and trade-offs. An integrated governance approach that combines supply-side optimization (e.g., developing public transit) with demand-side management (e.g., promoting NEVs and managing private car use) is the most effective strategy for achieving a sustainable, healthy, and livable urban future. The findings provide crucial insights for policymakers in megacities to formulate holistic and synergistic transport policies.

**Keywords—Sustainable Transportation, Quality of Life, Health Risk Assessment, System Dynamics, Policy Simulation, Shenzhen**

## I. INTRODUCTION

As global urbanization accelerates, urban transport systems, serving as the arteries of modern society, have a direct impact on economic efficiency, social equity, and resident well-being. However, the rapid motorization that

brings convenience has also triggered a series of severe challenges, including traffic congestion, environmental pollution, energy consumption, and public health risks [1]. This is particularly true in China, where megacities like Shenzhen, after experiencing high-speed economic growth and population agglomeration, face immense pressure on their transport systems. The surge in vehicle ownership has not only exacerbated road congestion, leading to longer commute times and a decline in quality of life, but its emissions of fine particulate matter (PM<sub>2.5</sub>), nitrogen oxides (NO<sub>x</sub>), and other pollutants have become a primary source of urban air pollution, directly and indirectly threatening public health [2][3]. According to statistics, transport emissions account for over 20% of local PM<sub>2.5</sub> sources in cities like Beijing and Shanghai, significantly contributing to the incidence of respiratory and cardiovascular diseases [4].

Against this backdrop, how to devise effective transport interventions to meet urban development needs while simultaneously alleviating congestion, improving environmental quality, reducing health risks, and ultimately enhancing the overall quality of life for residents has become a core scientific issue in urban governance and public health. Existing research often focuses on the impact of transport interventions on a single dimension, such as evaluating policies for congestion relief or emission reduction [5], or analyzing the link between air pollution and specific diseases [6]. However, these studies tend to overlook the inherent characteristics of urban transport as a Complex Adaptive System (CAS). The system's internal elements — such as private transport, public transit, the environment, health, and the economy — are interconnected through complex, non-linear relationships and dynamic feedback mechanisms. For instance, improving public transit services may attract some private car users to switch modes, thereby reducing congestion and pollution. Yet, the resulting congestion relief might, in turn, induce new travel demand, creating a “rebound effect” that partially offsets the policy's intended benefits [7]. Consequently, isolated and static analytical methods are inadequate for comprehensively revealing the long-term, integrated impacts of transport interventions and may even lead to policy failure.

While some scholars have begun to use methods like System Dynamics (SD) to simulate the complex behaviors of

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transport systems [8], most models still have limitations. On one hand, existing models predominantly focus on the interaction between transport and the environment, failing to incorporate “health risk” and “quality of life” as endogenous variables within a unified analytical framework. This makes it difficult to quantify the ultimate impact of transport interventions on resident well-being. On the other hand, there is a relative scarcity of empirical research on rapidly developing Chinese cities, particularly a lack of comprehensive scenario simulations and benefit assessments that integrate local data and address multiple policy objectives. The primary research gap lies in the absence of an integrated assessment model that can unify the transport, environment, health, and quality of life subsystems and dynamically simulate the long-term evolutionary trajectories under various combinations of intervention policies.

To fill this gap, this study aims to construct an integrated assessment model based on System Dynamics, using Shenzhen — China’s pioneering demonstration zone for socialism with Chinese characteristics — as a case study to systematically investigate the comprehensive impacts of sustainable transport interventions on urban quality of life and health risks. Specifically, the objectives of this study are: 1) to identify and construct the key causal feedback loops among the four subsystems of transport, environment, health, and quality of life (TEHQ); 2) to develop a System Dynamics model capable of quantitatively simulating the long-term effects of various transport intervention policies (e.g., public transit development, new energy vehicle promotion, congestion charging); and 3) to conduct multi-scenario simulation analysis to comparatively assess the integrated benefits and trade-offs of different policy portfolios in improving quality of life and reducing health risks. Rather than providing precise forecasts, this study offers a scenario-based analytical framework for examining the possible co-benefits and trade-offs of different transport interventions.

The remainder of this paper is structured as follows: Section 2 reviews the relevant literature on sustainable transport, health risk assessment, and the application of System Dynamics. Section 3 details the methodology, including the integrated assessment framework and the construction and validation of the SD model. Section 4 describes the study area and data sources. Section 5 presents the main results of the model simulations. Section 6 provides an in-depth discussion of the results, analyzing their policy implications and research limitations. Finally, Section 7 concludes the paper and offers directions for future research.

## II. LITERATURE REVIEW

The theoretical foundation of this study is built upon multiple interdisciplinary fields, including sustainable development, environmental health, and systems science. This section systematically reviews the literature in four core areas: sustainable cities and transport, transport-related pollution and health risks, urban quality of life assessment, and the application of System Dynamics, thereby laying the theoretical groundwork for the integrated assessment model.

### A. Sustainable Urban and Transport Development

The concept of sustainable development was first introduced by the Brundtland Commission in 1987. Its core idea is to meet the needs of the present without compromising the ability of future generations to meet their

own needs, emphasizing a balance among economic, social, and environmental dimensions [9]. This philosophy quickly extended to the field of urban planning, giving rise to the concept of the “sustainable city,” which aims to achieve long-term urban prosperity and livability by optimizing urban structures, improving resource efficiency, and promoting social equity [10]. As a critical subsystem of a city, the sustainability of its transport system is central to achieving overall urban sustainability. “Sustainable Transportation” seeks to establish a safe, efficient, equitable, and environmentally friendly transport system that meets the mobility needs of people and goods with the smallest possible ecological footprint and social cost [11].

In practice, countries worldwide have explored various pathways to achieve sustainable transport. For example, Freiburg, Germany, successfully reduced its dependency on private cars by developing an integrated transport network dominated by walking, cycling, and public transit [12]. In China, with the advancement of the “Transport Powerhouse” strategy, urban transport development is shifting from a pursuit of speed and scale to a focus on quality and efficiency. Many cities have introduced a series of policies, such as prioritizing public transit, promoting new energy vehicles, and developing “Transit Metropolis” projects [13]. However, the effectiveness of these policies is often influenced by multiple factors, including the specific urban context, resident travel behavior, and policy synergies, making the comprehensive evaluation of their benefits a persistent research challenge [14].

### B. Urban Transport and Air Pollution

Urban transport is a major source of atmospheric pollutants, especially in densely populated metropolitan areas. Vehicle exhaust emissions, including PM<sub>2.5</sub>, NO<sub>x</sub>, and volatile organic compounds (VOCs), are significant precursors to environmental problems like smog and photochemical smog [2]. A large body of research has confirmed a significant positive correlation between road traffic density and air pollutant concentrations. For instance, studies have indicated that in Beijing, vehicle emissions contribute up to 31% of local PM<sub>2.5</sub> [4]. Furthermore, under traffic congestion, vehicle idling and frequent acceleration-deceleration cycles can multiply pollutant emissions, further exacerbating air pollution and its associated health burdens [15].

To address the challenge of transport pollution, primary interventions include technological upgrades (e.g., improving fuel standards, promoting new energy vehicles) and management controls (e.g., driving restrictions, purchase limits, congestion charging). These measures have achieved varying degrees of emission reduction. For example, China’s Clean Air Action Plan has significantly improved national air quality over the past decade, with transport pollution control policies playing a crucial role [16]. However, as urban vehicle ownership continues to grow, single-pronged governance measures may face bottlenecks, necessitating a more systematic and comprehensive policy mix to achieve long-term air quality improvement goals.

### C. Transport-Related Health Risk Assessment

Transport activities affect public health through multiple pathways. The most direct impact is injuries and fatalities from traffic accidents. More widespread and long-term effects stem from exposure to transport-related pollution and

noise. Chronic exposure to high concentrations of air pollutants like PM<sub>2.5</sub> has been robustly linked to an increased risk of respiratory diseases (e.g., asthma, chronic obstructive pulmonary disease), cardiovascular diseases, lung cancer, and even premature mortality [3, 17]. The World Health Organization (WHO) has classified outdoor air pollution as a Group 1 carcinogen. Additionally, traffic noise not only causes annoyance and sleep disturbances but may also increase the risk of hypertension and heart disease.

Health Risk Assessment (HRA) is a common method for quantifying the adverse health effects of environmental exposures. In the transport sector, HRA typically employs an "exposure-response" model. This involves estimating the change in pollutant concentrations resulting from transport activities (exposure assessment) and then applying dose-response coefficients derived from epidemiological studies to calculate the change in incidence or mortality rates for specific diseases within a given population [18]. In recent years, with deeper insights into human activity patterns, some scholars have pointed out that traditional exposure assessment methods based on fixed-site monitoring data may underestimate true health risks by neglecting residents' daily mobility [19]. Therefore, incorporating individual spatio-temporal behavior patterns has become an important direction for improving assessment accuracy.

#### D. Urban Quality of Life Assessment

Quality of Life (QoL) is a multidimensional and comprehensive concept that reflects residents' satisfaction with both the objective conditions and subjective perceptions of their living situation. QoL evaluation frameworks typically cover multiple domains, including economic status, living environment, social services, health status, and safety [20]. The transport system, as a key factor influencing daily activities and environmental experiences, has a profound impact on QoL. On one hand, an efficient and convenient transport system enhances accessibility and comfort, saves time costs, and is a cornerstone of high QoL. On the other hand, negative externalities such as traffic congestion, environmental pollution, noise, and safety risks can significantly degrade residents' QoL [21]

Existing studies have explored the relationship between transport and QoL from various perspectives. Some research focuses on the impact of commute time or stress on subjective well-being, finding that long commutes are a major contributor to lower life satisfaction. Other studies concentrate on how transport system accessibility affects social equity, particularly for disadvantaged groups in accessing employment, education, and healthcare services [22]. However, research that integrates the multidimensional impacts of the transport system (time, cost, environment, health) into a unified QoL assessment framework is still limited, which is a gap this study aims to address.

#### E. Application of System Dynamics in Transport Research

Given the complexity, dynamism, and non-linearity of urban transport systems, the System Dynamics (SD) methodology is widely used in the field of transport planning and policy evaluation. By constructing Causal Loop Diagrams (CLDs) and Stock and Flow Diagrams (SFDs), SD models can simulate the long-term dynamic behavior of a system under different interventions, making them particularly suitable for handling complex issues involving

time delays, feedback effects, and multivariate interactions [23].

In transport research, SD models have been applied to analyze the mechanisms of traffic congestion, evaluate the effectiveness of carbon reduction policies, and forecast the market penetration of new energy vehicles [8, 24]. For example, some studies have built SD models incorporating economic, demographic, transport, and energy subsystems to simulate the impact of various policies on urban transport carbon emissions. These studies demonstrate the strength of the SD approach in understanding system structure and identifying policy leverage points. However, as mentioned in the introduction, most existing research has not integrated health risk and quality of life as core endogenous variables in a holistic model. The few studies that have attempted to link transport and health have often remained at the conceptual framework level, lacking dynamic simulation and quantitative assessment [25]. Therefore, this study will expand the boundaries of traditional transport SD models by constructing an integrated model that couples the four subsystems of transport, environment, health, and quality of life, aiming to more comprehensively reveal the integrated impacts of sustainable transport interventions.

### III. RELATED WORK

In recent years, with the deepening of the sustainable development concept, scholars both domestically and internationally have conducted extensive research on urban transport interventions and their multidimensional impacts. This body of work can be broadly categorized into three types: effect evaluations based on statistical or econometric models, process-based simulations of air quality and health impacts, and complexity analyses using system dynamics. This section will review these three categories of related work to clarify the positioning and contribution of the present study.

The first category of research primarily employs econometric methods, such as the Difference-in-Differences (DID) model and Regression Discontinuity Design (RDD), to evaluate the effects of specific transport policies. For example, Zhang et al. (2025) used a DID approach to assess the effectiveness of China's "Transit Metropolis" policy, finding that it significantly increased residents' willingness to use public transport and reduced private car usage [13]. Niu and Zhang (2023) analyzed the impact of transport intervention policies on intra-city mobility during the COVID-19 pandemic, identifying heterogeneity in policy effects [5]. The strength of such studies lies in their ability to perform rigorous causal inference based on real-world data to estimate the net effect of a policy. However, their limitation is that they can typically only evaluate one or a few policies at a time, making it difficult to handle the synergistic or antagonistic effects of multiple policies implemented simultaneously. Furthermore, they often focus on short-term effects, with less attention paid to the long-term dynamic feedback and evolutionary trends of the system.

The second category of research focuses on simulating the impacts of transport emissions on air quality and public health. These studies typically follow a technical route of "emissions inventory -> air quality model -> health risk assessment." For instance, Wang et al. (2020) quantified the substantial health benefits of China's on-road transportation

pollution control programs by estimating the reduction in pollutant emissions and combining it with an atmospheric chemistry transport model and exposure-response functions, thereby calculating the avoidance of tens of thousands of premature deaths [16]. Ding et al. (2024) used modeling to reveal the cross-regional transport of air pollution in the Yangtze River Delta and its specific health impacts on residents [17]. This type of research can clearly elucidate the physical and physiological processes in the "transport emissions → environmental exposure → health outcome" chain, providing an important basis for environmental health management. However, its shortcoming is that it usually treats transport activities as an exogenous "emission source" without endogenously simulating how transport demand itself responds to changes in the environment, economy, or policy—that is, it lacks a depiction of the dynamic feedback mechanisms of the transport system's behavior.

The third category of research, which uses the System Dynamics (SD) approach, precisely compensates for the shortcomings of the first two methods. SD models capture the complex dynamic behavior of a system by constructing feedback loops, making them particularly suitable for analyzing long-term, multivariate, and non-linear problems. In the transport sector, SD models have been widely applied. For example, Hou et al. (2023) constructed an SD model to evaluate the sustainability of urban public transport in China and analyzed the causal relationships between different factors [14]. AlKheder (2024) developed a simplified SD model to simulate the impact of transport policies on CO<sub>2</sub> emissions [7]. Garcia et al. (2025) went further by using an SD model to predict the future impacts of different urban transport scenarios on resident health and mobility, emphasizing the importance of systemic thinking in addressing future challenges [25].

Despite significant progress in SD-based research, there is still room for further expansion. First, most existing transport SD models primarily focus on issues such as traffic congestion, energy consumption, or carbon emissions. Research that treats "resident health" and "quality of life" as core endogenous variables and conducts quantitative simulations is still relatively scarce. For example, while the study by Heidari et al. (2024) on Tehran integrated quality of life indicators, its characterization of the health dimension was relatively simplified, mainly reflected through indirect indicators like accident rates and environmental damage [26]. Second, many models, when conducting policy simulations, focus on single-dimensional policy evaluation (e.g., emission reduction benefits or congestion relief effects). They lack a comprehensive benefit evaluation framework that can simultaneously assess economic, social, environmental, and health objectives, making it difficult to reveal the synergies and trade-offs among different policy goals. Finally, there is a shortage of systematic, multi-objective studies on the comprehensive impacts of transport interventions in Chinese megacities, especially in a city like Shenzhen, which is at the forefront of technological innovation and policy experimentation.

In summary, the uniqueness and contribution of this study lie in the following: Methodologically, we not only build an SD model but, more importantly, extend the traditional transport-environment model into an integrated dynamic model that couples the four subsystems of transport, environment, health, and quality of life (TEHQ), achieving

an endogenous simulation of the "full-chain" impact of transport interventions. In terms of objectives, this study is not limited to single-dimensional policy evaluation but establishes a multi-objective comprehensive assessment system aimed at quantitatively analyzing the integrated performance of different intervention measures on the two core goals of improving quality of life and reducing health risks. Practically, this study uses Shenzhen as a case, parameterizes and validates the model with localized data, and designs intervention scenarios that are relevant to the development reality of Chinese cities, making the research conclusions more practical and policy-relevant.

#### IV. METHODOLOGY

This study uses a simplified System Dynamics (SD) framework to compare the directional effects of several transport intervention scenarios. This section first introduces the overall research framework, then details the construction of the SD model, including the definition of system boundaries, the development of causal loop diagrams, the establishment of stock-flow equations, and the validation of the model.

##### A. Research Framework

This study constructs an integrated assessment framework based on the concept of "co-benefits," aiming to systematically analyze the chain of effects from "transport intervention → system state change → quality of life and health impact." As shown in Figure 1, the framework comprises five layers: a data layer, a model layer, a simulation layer, an assessment layer, and a decision support layer.

- **Data Layer:** This layer involves collecting and processing multi-source data for Shenzhen, including transport infrastructure and operations, environmental quality monitoring, population and health statistics, and socio-economic data. These data serve as the empirical basis for model parameterization and validation.
- **Model Layer:** This is the core of the framework, where a Transport-Environment-Health-Quality of Life (TEHQ) integrated System Dynamics model is constructed. The model abstracts the complex urban system into four closely coupled subsystems: the transport system, the environmental system, the public health system, and the quality of life system. By defining the key variables and feedback mechanisms within and between these subsystems, the model can simulate the system's dynamic behavior.
- **Simulation Layer:** Based on the constructed TEHQ model, this layer designs multiple policy scenarios. This includes a "Business as Usual" (BAU) scenario, which extrapolates current trends, and several intervention scenarios, such as a "Public Transit Priority" scenario, a "New Energy Vehicle Promotion" scenario, and an "Integrated Intervention" scenario. Long-term dynamic simulations (2025-2045) are conducted for each scenario.
- **Assessment Layer:** This layer focuses on outputting and analyzing the simulation results. By defining a series of Key Performance Indicators (KPIs),

particularly the composite "Quality of Life Index" and "Health Risk Index," a comparative analysis of the performance of different scenarios is conducted to identify the most effective policy portfolio.

- Interpretation Layer: Based on the scenario comparison results, this layer summarizes the possible policy implications of different intervention pathways.

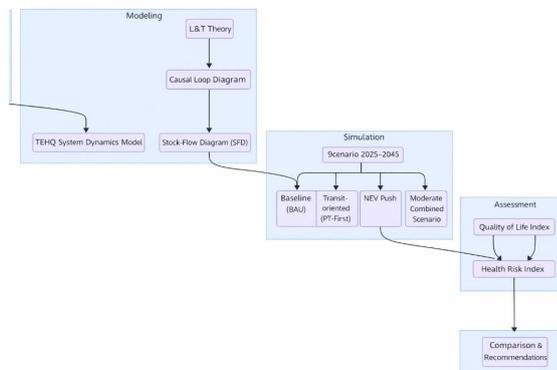


Fig. 1. Research Framework for Integrated Assessment of Transport Interventions

## B. Model Construction

### 1) System Boundaries and Subsystem Definition

The model's spatial boundary is the administrative area of Shenzhen, and the temporal boundary spans from 2015 to 2045, with 2015-2024 as the historical validation period and 2025-2045 as the future simulation period. The model consists of four core subsystems:

- Transport Subsystem: This subsystem describes the dynamic evolution of urban transport demand and supply. Key variables include population, GDP, private vehicle ownership, public transit passenger volume, road network capacity, and average travel speed. It approximates changes in the relative use of private cars and public transit based on aggregate indicators such as travel cost, service level, and generalized travel conditions.
- Environmental Subsystem: This subsystem focuses on the impact of transport activities on air quality. It primarily simulates the processes of pollutant emissions from vehicles, atmospheric diffusion, and concentration changes. Key variables include vehicle kilometers traveled (VKT), emission factors for different vehicle types, and the concentration of major pollutants like PM<sub>2.5</sub>.
- Health Subsystem: This subsystem quantifies the health risks associated with transport-related environmental pollution. Based on the PM<sub>2.5</sub> concentration simulated by the environmental subsystem, This subsystem provides an approximate estimation of pollution-related health burden using published exposure-response coefficients and aggregate population statistics.
- Quality of Life Subsystem: This is a comprehensive evaluation subsystem that integrates the outputs of the other three subsystems. It constructs a composite Quality of Life (QoL) index by weighting factors

such as traffic convenience (e.g., commute time), environmental comfort (e.g., air quality), and health status (e.g., disease burden), reflecting the overall well-being of residents.

### 2) Causal Loop Diagram (CLD)

The Causal Loop Diagram (CLD) is a tool for visualizing the feedback structure of a system. Figure 2 illustrates the core causal relationships and feedback loops within the TEHQ model. The system contains multiple reinforcing (R) and balancing (B) loops that jointly determine its dynamic behavior.

- R1: Motorization Growth Loop (+): Economic growth leads to increased household income, which enhances vehicle purchasing power, thereby increasing private vehicle ownership. The growth in vehicles, in turn, stimulates further economic activity, forming a reinforcing feedback loop.
- B1: Congestion Constraint Loop (-): An increase in private vehicle ownership leads to higher road traffic volume, intensifying traffic congestion and extending average travel times. The resulting decline in the attractiveness of private vehicle travel acts as a brake on the growth of vehicle ownership, forming a balancing feedback loop.
- B2: Pollution-Health Cost Loop (-): Increased traffic volume leads to higher pollutant emissions, worsening air quality and increasing the incidence of related diseases. The deterioration of population health and the decline in quality of life may, in the long run, increase public pressure for environmental governance and reduce the city's attractiveness, thereby indirectly constraining motorization.
- B3: Policy Intervention Loop (-): Worsening environmental and health problems prompt the government to implement sustainable transport interventions (e.g., developing public transit, promoting NEVs). These measures enhance the attractiveness of green transport modes, reduce the market share of private vehicles, and thus alleviate traffic volume and pollution, forming a policy-driven balancing loop.
- R2: Quality of Life Driven Loop (+): Effective policy interventions improve transport accessibility and environmental quality, leading to an enhanced urban quality of life. A higher QoL increases the city's attractiveness, attracting more population and economic agglomeration, which in turn generates new travel demand, forming a long-term reinforcing loop.

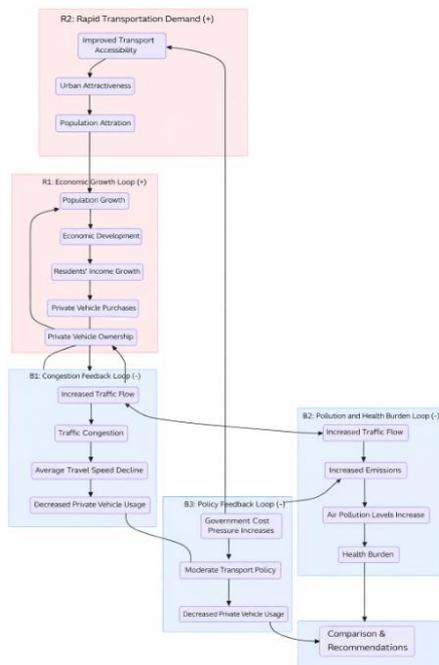


Fig. 2. Core Causal Loop Diagram of the TEHQ System

3) Stock and Flow Diagram (SFD) and Key Equations

Based on the CLD, we used Vensim PLE software to develop the Stock and Flow Diagram (SFD) of the model. The SFD provides a more detailed quantitative representation of the system structure, defining variables as stocks (accumulations), flows (rates of change), and auxiliaries (intermediate variables). Due to space limitations, only a few key equations are presented here.

- Private Vehicle Ownership (PVO): PVO is treated as a stock variable, which changes over time according to vehicle purchases and vehicle scrappage. In simplified form, it is represented as the initial vehicle stock plus the cumulative difference between annual purchases and scrappage. Vehicle purchases are assumed to be influenced by GDP per capita, vehicle price, and policy incentives.
- PM2.5 Concentration (PM25\_C): PM2.5 concentration is modeled as an auxiliary variable reflecting the combined effect of transport-related emissions and other emission sources, adjusted by the city's atmospheric dispersion and self-purification capacity. Transport emissions are estimated from vehicle kilometers traveled and average emission factors.
- Excess Deaths (ED): Excess deaths are estimated using a standard exposure-response relationship between PM2.5 exposure and mortality risk. The calculation combines population size, baseline mortality rate, and the additional mortality risk associated with PM2.5 concentrations above the reference guideline level.
- Quality of Life Index (QoL\_I): QoL is represented by a composite index combining mobility, environmental, health, and economic dimensions. To improve transparency, each dimension can be normalized and aggregated using equal or predefined weights for relative scenario comparison.

C. Model Validation

Model validation in this study focused on a historical trend reproduction check. Using publicly available data for 2015–2024, the model outputs for several core variables, including private vehicle ownership, PM2.5 concentration, and public transit passenger volume, were compared with observed trends. The model was able to broadly reproduce the historical direction of change of these variables. Therefore, it is considered suitable for exploratory scenario comparison, although not for precise forecasting (Figure 3).

Figure 3. Historical Behavior Validation of Core Variables

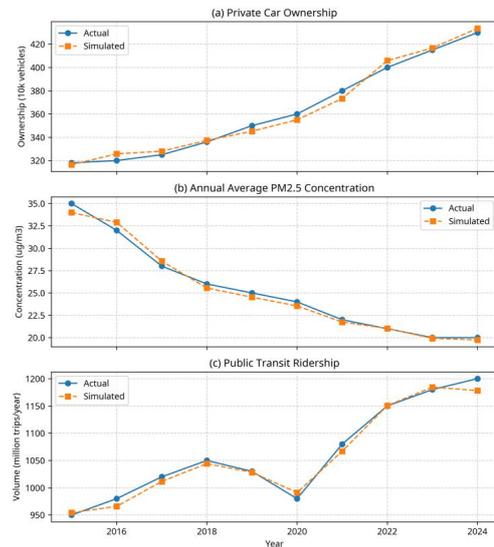


Fig. 3. Historical Behavior Validation of Core Variables (2015-2024). The solid lines represent observed data, and the dashed lines represent simulated data, showing a high degree of fit.

V. DATA AND SCENARIOS

This section first introduces the study area, Shenzhen, and the sources of data used for model parameterization. It then details the design of the different policy intervention scenarios that form the basis for the simulation analysis.

A. Study Area and Data Sources

Shenzhen, located in the Pearl River Delta, is one of China's most economically vibrant and innovative cities. As a megacity with a population exceeding 17 million and a vehicle fleet of over 4 million, its transport system faces significant challenges from congestion and environmental pressures. At the same time, Shenzhen is a national leader in promoting sustainable transport, having achieved 100% electrification of its bus and taxi fleets and vigorously developing its metro system. This makes Shenzhen an ideal case study for examining the impacts of sustainable transport interventions.

The data used in this study are primarily sourced from publicly available official statistics and academic literature. The specific data and their sources are as follows:

- Socio-economic Data: Data on population, Gross Domestic Product (GDP), and household income from 2015 to 2024 were obtained from the Shenzhen Statistical Yearbook.
- Transport Data: Data on private vehicle ownership, public transit (bus and metro) passenger volume, road network length, and transport investment were

sourced from the Shenzhen Transport Annual Report and the municipal transport bureau's official website.

- **Environmental Data:** Annual average PM2.5 concentration data were obtained from the Shenzhen Ecological Environment Bulletin and the municipal ecology and environment bureau's data platform.
- **Health Data:** Data on baseline mortality rates and the incidence of major diseases for the population were referenced from the China Health Statistics Yearbook and relevant public health research literature.
- **Model Parameters:** Model parameters were derived primarily from published literature, publicly available statistical reports, and simplified assumptions used for scenario comparison.

### B. Scenario Design

To explore the long-term effects of different policy portfolios, this study designed four distinct scenarios for the period 2025-2045. These scenarios represent different development pathways for Shenzhen's future transport system.

#### Scenario 1: Business as Usual (BAU)

The BAU scenario serves as the baseline for comparison. It assumes that future development will follow historical trends and that existing policies will continue without significant changes. Specifically, GDP and population will grow at a moderate rate, transport infrastructure investment will maintain its current proportion, and there will be no new major transport demand management or new energy vehicle promotion policies. This scenario reflects a future of "inertial development."

#### Scenario 2: Public Transit Priority (PT-First)

This scenario embodies a development strategy centered on public transportation. moderately improve public transit service conditions, including service frequency, network connectivity, and transfer convenience, within the range of realistic short- to medium-term planning efforts. It also includes measures to improve the service quality of public transit, such as increasing frequency, expanding coverage, and optimizing transfer efficiency. Furthermore, it implements mild demand management policies for private cars, such as appropriately raising parking fees in central areas. The core objective of this scenario is to shift the travel mode structure towards public transit.

#### Scenario 3: New Energy Vehicle Promotion (NEV-Push)

This scenario focuses on promoting the electrification of the vehicle fleet as the primary means of reducing transport pollution. It assumes the implementation of a moderate increase in support for low-emission vehicle adoption and charging accessibility, reflecting a gradual continuation of existing electrification policies. The main goal of this scenario is to accelerate the replacement of ICEVs with NEVs, thereby reducing emissions at the source.

#### Scenario 4: Integrated Intervention (Integrated)

This scenario represents a comprehensive governance strategy that combines the core measures of the PT-First and NEV-Push scenarios. It is a "push-pull" approach that simultaneously promotes the development of high-quality public transit and accelerates vehicle electrification while

also combining moderate public transit improvement with gradual vehicle electrification and limited demand-management measures, such as parking management and selective restraint policies. This scenario aims to achieve a synergistic effect by coordinating supply-side optimization and demand-side management to maximize the overall benefits for the transport system, environment, and public health.

Table I summarizes the key policy assumptions for each of the four scenarios.

TABLE I. KEY POLICY ASSUMPTIONS FOR THE FOUR SCENARIOS

Policy Dimension	Business as Usual (BAU)	Public Transit Priority (PT-First)	NEV Promotion (NEV-Push)	Integrated Intervention
Public Transit Investment	Maintain current levels	Increase by 50%	Maintain current levels	Moderate increase
Public Transit Service Level	Gradual improvement	Significant improvement (frequency, coverage)	Gradual improvement	Significant improvement
NEV Purchase Incentives	Phase out gradually	Maintain current levels	Increase by 30%	Gradual strengthening
Charging Infrastructure	Market-driven growth	Market-driven growth	Government-led rapid expansion	Government-led rapid expansion
Private Car Use Cost	Natural increase	Moderate parking management	Natural increase	Increase parking fees, Limited demand-management measures
ICEV Purchase Restrictions	Maintain current policy	Maintain current policy	Tighten restrictions	Tighten restrictions

## VI. RESULTS

This section presents the simulation results of the TEHQ model for the period 2025-2045. We first analyze the evolutionary trends of key indicators under the Business as Usual (BAU) scenario to reveal the potential challenges of inertial development. We then comparatively analyze the performance of the three intervention scenarios (PT-First, NEV-Push, and Integrated) relative to the BAU scenario to assess their comprehensive impacts on improving quality of life and reducing health risks.

### A. Business as Usual (BAU) Scenario Simulation

Figure 4 illustrates the trajectory of key indicators under the BAU scenario. The results indicate that if current trends continue, Shenzhen will face a series of severe challenges.

- **Worsening Traffic Congestion:** Private vehicle ownership is projected to continue its rapid growth, increasing from approximately 4.4 million in 2025 to over 8 million by 2045. This sustained growth in vehicle numbers will place enormous pressure on the road network, leading to a continuous decline in average traffic speed, from 25 km/h to below 20 km/h.

This signifies that traffic congestion will become increasingly severe, significantly impacting residents' travel efficiency.

- **Persistent Air Pollution:** Although vehicle emission standards will continue to improve, the sheer growth in vehicle numbers and kilometers traveled will largely offset the benefits of technological advancements. Consequently, the annual average PM2.5 concentration will show a slow but persistent upward trend after a brief decline, remaining at a relatively high level and failing to meet the WHO's stricter air quality guidelines.
- **Escalating Health Risks:** Driven by the rebound in PM2.5 concentrations, the transport-related health risk index is projected to rise steadily, indicating an increasing public health burden from transport pollution. This suggests that without stronger interventions, the negative health impacts of the transport system will become more pronounced.
- **Stagnating or Declining Quality of Life:** The composite Quality of Life (QoL) index shows an initial slight increase, followed by a gradual decline after 2035. This is because the positive effects of economic growth are progressively outweighed by the negative impacts of worsening traffic congestion, environmental degradation, and rising health risks. This trend serves as a stark warning that a development model overly reliant on private cars is unsustainable in the long run.

Figure 4. Key Indicator Trends under BAU Scenario (2025-2045)

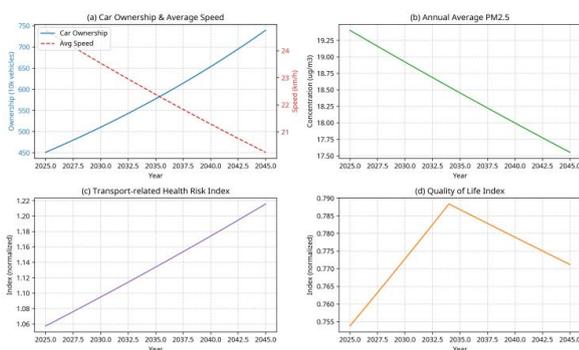


Fig. 4. Key Indicator Trajectories under the BAU Scenario (2025-2045). The simulation reveals worsening congestion, persistent pollution, rising health risks, and a stagnating quality of life.

### B. Comparative Analysis of Intervention Scenarios

We further simulated the PT-First, NEV-Push, and Integrated scenarios and compared their performance against the BAU scenario. Figure 5 provides a clear comparison of the improvement in key indicators for each intervention scenario by 2045.

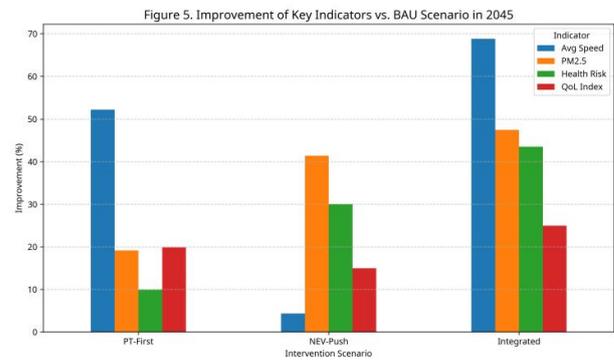


Fig. 5. Comparative Improvement of Key Indicators Relative to BAU Scenario in 2045

Figure 5. Comparative Improvement of Key Indicators Relative to BAU Scenario in 2045. The Integrated scenario demonstrates the most significant and balanced improvements across all indicators.

- **PT-First Scenario:** The PT-First scenario shows the clearest improvement in traffic efficiency, mainly through a shift from private car use toward public transport. However, its contribution to pollution and health improvement is more limited than that of scenarios involving vehicle electrification.
- **NEV-Push Scenario:** The NEV-Push scenario performs better in reducing pollution-related health burden, but its effect on congestion relief remains relatively limited because it does not substantially reduce the total number of vehicles on the road.
- **Integrated Scenario:** The Integrated scenario produces the most balanced overall outcome across mobility, environmental quality, and health-related indicators, suggesting that moderate combined interventions are more effective than reliance on a single policy pathway.

### C. Impact on Health and Quality of Life

To more directly illustrate the impacts on public health and overall well-being, we analyzed the trends of annual excess deaths attributable to transport-source PM2.5 and the composite QoL index under the different scenarios.

Figure 6 shows the simulated annual excess deaths. Under the BAU scenario, the number of excess deaths continues to rise, reaching nearly 2,500 cases per year by 2045. Both the PT-First and NEV-Push scenarios can curb this trend to some extent, but the Integrated scenario is the most effective, reversing the upward trend and reducing the number of excess deaths to below 1,500 cases per year by 2045—a reduction of approximately 40% compared to the BAU scenario.

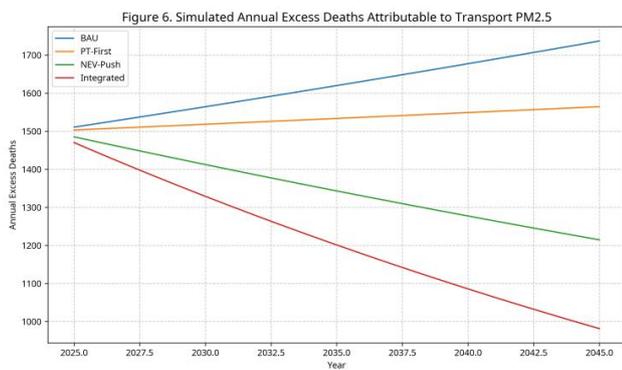


Fig. 6. Simulated Annual Excess Mortality Attributable to Transport-Source PM2.5

Figure 6. Simulated Annual Excess Mortality Attributable to Transport-Source PM2.5 under Different Scenarios (2025-2045). The Integrated scenario is the most effective in reducing the public health burden.

Figure 7 shows the evolution of the QoL index. The BAU scenario leads to a decline in the quality of life in the long term. In contrast, all three intervention scenarios can achieve a sustained improvement in the QoL index. The Integrated scenario demonstrates the most significant and stable upward trend, indicating its superior ability to enhance the overall well-being of residents.

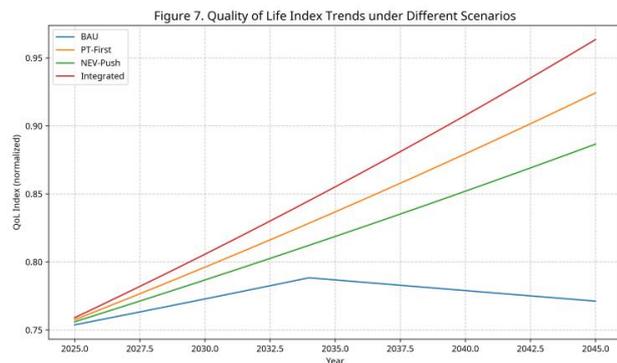


Fig. 7. Quality of Life Index Trajectories under Different Scenarios

Figure 7. Quality of Life Index Trajectories under Different Scenarios (2025-2045). The Integrated scenario leads to the most substantial and sustained improvement in the overall quality of life.

## VII. DISCUSSION

This study constructed an integrated Transport-Environment-Health-Quality of Life (TEHQ) System Dynamics model to simulate the long-term impacts of different sustainable transport interventions in Shenzhen. The results reveal the complex feedback mechanisms within the urban transport system and provide crucial insights for policymaking. This section will discuss the main findings, policy implications, and limitations of the study.

### A. Interpretation of Key Findings

The simulation results clearly demonstrate the unsustainability of the Business as Usual (BAU) development path. The continued growth of private vehicle ownership, if left unchecked, will inevitably lead to a vicious cycle of worsening traffic congestion, persistent air pollution, escalating health risks, and a decline in the quality of life.

This finding is consistent with the experiences of many megacities worldwide and serves as a stark warning for rapidly urbanizing regions: a development model centered on private cars is not a viable long-term solution.

A core finding of this study is the significant difference in the effectiveness and focus of single-dimensional intervention policies. The Public Transit Priority (PT-First) scenario is highly effective at alleviating traffic congestion but has limited impact on reducing emissions and health risks. Conversely, the New Energy Vehicle Promotion (NEV-Push) scenario excels at improving air quality and public health but does little to solve the problem of congestion. This highlights the "policy trade-offs" inherent in transport governance. Relying on a single policy tool is insufficient to address the multifaceted challenges of the urban transport system and may even lead to unintended negative consequences. For example, a sole focus on electrification without controlling the total number of vehicles might result in "green congestion," where roads are filled with zero-emission vehicles, but travel efficiency and quality of life remain low.

The most important finding is the powerful synergistic effect of the Integrated Intervention scenario. By combining the "pull" of developing attractive public transit with the "push" of promoting NEVs and managing private car demand, this comprehensive approach achieves the best performance across all indicators — traffic efficiency, environmental quality, public health, and quality of life. This underscores that future urban transport policy must shift from a collection of fragmented measures to a coordinated and integrated policy portfolio. The "push-pull" strategy, which makes green transport modes more attractive while simultaneously increasing the cost of using private cars, is the key to breaking the path dependency on motorization and guiding the system toward a sustainable equilibrium.

### B. Policy Implications

Based on the above findings, this study proposes the following policy recommendations for Shenzhen and other similar megacities:

- Adopt an Integrated Governance Philosophy: Urban managers must abandon the siloed approach to policymaking and establish a cross-departmental coordination mechanism that integrates transport, environmental protection, public health, and urban planning. When formulating transport policies, their comprehensive impacts on health and quality of life must be considered as core evaluation criteria, not just their effects on traffic flow or GDP.
- Implement a "Push-Pull" Strategy to Reshape the Travel Mode Structure: On the "pull" side, continue to vigorously develop a high-quality public transit system, focusing on improving service reliability, comfort, and the convenience of the "first and last mile" connections. On the "push" side, progressively increase the cost of private car use through economic levers such as optimizing parking fee structures, studying the feasibility of congestion charging in core areas, and dynamically adjusting NEV incentive policies to guide rational vehicle ownership growth. The goal is to make public transit the preferred mode of travel for residents, rather than a reluctant choice.

- Deepen the Integration of Health in Transport Planning: Transport and health departments should collaborate to establish a long-term monitoring and assessment mechanism for the health impacts of transport. Health risk assessment should be incorporated as a mandatory component of major transport infrastructure projects and policy evaluations. The data on transport-related health burdens can, in turn, provide a stronger justification for implementing stricter environmental and transport demand management policies.
- Embrace Dynamic and Adaptive Governance: Urban transport systems are complex and constantly evolving. Policies should be flexible and adaptable, not one-size-fits-all. The model can be used as an exploratory scenario-analysis tool to compare the possible long-term implications of alternative intervention pathways.

### C. Limitations and Future Research

While this study provides valuable insights, it also has some limitations that can be addressed in future research.

First, the model, while comprehensive, still involves some simplification of reality. For example, the characterization of resident travel behavior is based on aggregated parameters and does not fully capture individual heterogeneity and the complexity of decision-making. Future research may refine the present framework by incorporating more detailed local behavioral data and by reporting parameter sensitivity more explicitly.

Second, the data used for model parameterization, particularly the exposure-response coefficients for health risks, are primarily drawn from existing literature, which may not fully reflect the specific context of Shenzhen's population. Localized epidemiological studies are needed to obtain more precise parameters, which would enhance the accuracy of the health risk assessment.

Third, the scope of this study is limited to the impacts of transport on air pollution and related health risks. Other important factors, such as traffic noise, the promotion of active transport (walking and cycling), and traffic safety, also have significant effects on quality of life and health. Future research could expand the model's boundaries to incorporate these factors for a more holistic assessment.

Finally, the study focuses on policy simulation and does not delve into the specific implementation challenges of policies, such as public acceptance, political feasibility, and financial sustainability. Future work could combine the quantitative analysis of this study with qualitative methods like case studies and stakeholder analysis to conduct more in-depth research on the entire process of policy formulation and implementation.

### VIII. CONCLUSION

This study investigated the comprehensive impacts of sustainable transport interventions on urban quality of life and health risks in the context of a rapidly developing megacity, using Shenzhen as a case study. By constructing an integrated Transport-Environment-Health-Quality of Life (TEHQ) System Dynamics model, we simulated the long-term evolutionary trajectories of the urban system under four different scenarios: Business as Usual (BAU), Public Transit

Priority (PT-First), New Energy Vehicle Promotion (NEV-Push), and Integrated Intervention.

The main conclusions are as follows:

- The conventional, car-dependent development model (BAU scenario) is unsustainable. It will lead to a vicious cycle of severe traffic congestion, persistent air pollution, escalating public health burdens, and an ultimate decline in the overall quality of life for residents.
- Single-dimensional transport policies have clear limitations and trade-offs. A policy focused solely on developing public transit can effectively alleviate congestion but has limited success in reducing pollution and health risks. Conversely, a policy centered only on promoting new energy vehicles can achieve significant environmental and health benefits but fails to solve the problem of traffic congestion.
- An integrated intervention strategy that combines supply-side optimization (developing high-quality public transit) with demand-side management (promoting NEVs and managing private car use) yields the most significant and balanced co-benefits. This comprehensive "push-pull" approach is the most effective pathway to simultaneously achieving the multiple goals of efficient mobility, a clean environment, improved public health, and a higher quality of life.

These findings provide important scientific support for urban transport policymaking. We recommend that city managers abandon siloed decision-making and adopt an integrated governance philosophy that coordinates transport, environmental, and health policies. By implementing a comprehensive "push-pull" strategy and embedding health considerations into all transport planning, cities can effectively navigate the complexities of urban development and steer towards a healthier, more livable, and more sustainable future. Future research should aim to refine the model by incorporating more granular behavioral data, localized health parameters, and a broader range of influencing factors such as noise and active transport.

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#### AUTHOR CONTRIBUTIONS

Serdar Kurtulu: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization.

Neslihan Yilmaz: Supervision, Validation, Resources, Writing – review & editing, Project administration.

#### COMPETING INTERESTS

The authors declare no competing interests.

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