

Research on Urban Multi-Modal Travel Carbon Footprint Calculation and Emission Reduction Strategy Optimization Based on Multi-Source Data Fusion

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Abstract: Urban transportation is one of the major sources of carbon emissions. Based on the SUMO simulation platform, this study integrates OpenStreetMap road-network data, HBEFA emission parameters, and travel-characteristic data from statistical yearbooks to construct a simulation-based evaluation framework for carbon emissions from multi-modal travel. By designing multiple policy scenarios, including bus priority, active-mode feeder optimization, and private-car regulation, the study systematically analyzes the effects of different strategies on system-level carbon emissions. The results show that combined strategies may generate both synergy and offsetting effects, together with diminishing marginal returns. The findings provide a methodological reference for low-carbon urban transport planning and offer a technical pathway for policy pre-assessment under data-constrained conditions.

Keywords: Multi-modal Travel; Carbon Emissions; SUMO Simulation; Policy Evaluation.

1. Introduction

1.1. Research Background and Objectives

Urban transportation is an important source of carbon emissions. With the advancement of China's dual-carbon strategy, Beijing faces increasing pressure to reduce emissions in the transport sector. High private-car ownership, an insufficient public-transport mode share, an incomplete active-mobility system, and pronounced multi-modal travel behavior among residents jointly contribute to persistently high transport emissions. How to scientifically evaluate the carbon emissions of multi-modal travel and identify key emission-reduction links has therefore become a core issue in green transport development.

Traditional carbon-emission accounting often relies on real trajectory data, which are difficult to obtain and are not well suited to evaluating the potential effects of policies that have not yet been implemented. Existing SUMO-based traffic simulation studies have mostly focused on tool integration and model validation, while systematic analyses of carbon-emission quantification for multi-modal travel and the emission-reduction effects of different transport strategies remain limited. It is therefore practically important to develop a multi-modal traffic simulation method that integrates carbon-emission modeling under data-constrained conditions. Drawing on the SUMO platform and the HBEFA emission model, this paper constructs a simulation-analysis framework for carbon emissions from urban multi-modal travel. Taking private cars, buses, and active modes as the study objects, the framework enables unified modeling of multi-modal traffic flows and quantitative evaluation of carbon emissions. It further analyzes the emission-reduction mechanisms of individual strategies, including bus priority, active-mode feeder optimization, and private-car demand regulation, and develops combined-strategy scenarios to reveal the synergies and emission-reduction patterns among different measures. The results provide quantitative methodological support and decision-making references for low-carbon transport

planning and management in Beijing.

1.2. Research Status in China and Abroad

In China, research on emerging transport and green travel has shifted from macro-level statistical analysis toward the exploration of micro-level mechanisms. Based on Didi trajectory data from Chengdu, Li Jiakai et al. developed Bayesian optimization and gradient-boosting models to accurately predict the carbon-reduction benefits of ride-hailing carpooling and identified key influencing factors such as detour ratio and average trip speed[1]. Using Beijing rail-transit smart-card data, Zheng Qiyue and Dai Jicai constructed a carbon-reduction calculation model and found that the unit emission-reduction benefit of rail transit replacing car trips was approximately 3.3 times that of replacing bus trips; the emission reductions showed an M-shaped bimodal distribution and were concentrated along commuting corridors[2]. Zhan Zilin integrated large-scale bike-sharing trip data and applied explainable machine learning and field experiments, revealing congestion effects when bicycle density exceeded 200 bikes per square kilometer and confirming that real-time destination information can effectively alleviate bicycle accumulation[3]. Gao Jing used multi-source data from ride-hailing, bike sharing, and new-energy vehicles to examine the effects of urban space on green travel from the perspectives of the built environment, perceived greenness, and population agglomeration. The study found that street-level green view index significantly promoted bike-sharing use, and that each 1% increase in population agglomeration was associated with a 0.73% increase in the share of battery electric vehicles[4].

International studies have mainly focused on route optimization and carbon-emission coordination in multimodal transport networks. Saba Javanpour et al. constructed an integer linear programming model for multimodal transport networks that jointly considered the operating costs of owned and leased vehicles and carbon-emission constraints. They found that strict carbon-reduction

policies increased total costs by approximately 8% and shifted more than 95% of vehicles to leasing, thereby revealing the trade-off between cost and carbon reduction[5]. Hou D. N. et al. developed a robust optimization model for cold-chain multimodal transport under dual uncertainty in demand and transport time, proposed a dual-pheromone ant colony algorithm nested with a niche genetic algorithm, and verified the effects of uncertainty fluctuations on transport costs and routing schemes[6]. Jeong K. J. examined the carbon-reduction effects of Seoul's public bicycle-sharing system and quantitatively estimated, based on IPCC emission factors, that it reduced carbon emissions by approximately 1,411 tons per year, directly demonstrating the regulatory role of bike sharing in transport carbon emissions within multi-modal travel[7].

Current research faces several major challenges. Transport cost, time efficiency, and carbon emissions are often mutually conflicting objectives, and strict environmental policies may lead to substantial cost increases, making multi-objective trade-offs difficult. At the same time, uncertainties in transport demand, time-varying road-network conditions, and

node-transfer times make traditional deterministic models less adaptable to complex real-world scenarios. In addition, inconsistent carbon-accounting standards and large variations in emission factors caused by road conditions and vehicle loads constrain the accuracy of fine-grained emission estimation.

2. Research Methodology

2.1. Experimental Platform

Omar Al-Jaghbeer et al. [8] evaluated and improved the SUMO-HBEFA emission model, focusing on parameter calibration and validation with measured data. Their work indicates that the HBEFA emission model has been broadly validated and has relatively high reliability. Based on the SUMO microscopic traffic simulation platform, this paper constructs a simulation-analysis framework for carbon emissions from urban multi-modal travel. By developing a baseline scenario and multiple comparative strategy scenarios, the study systematically analyzes the effects of different transport strategies on carbon emissions.

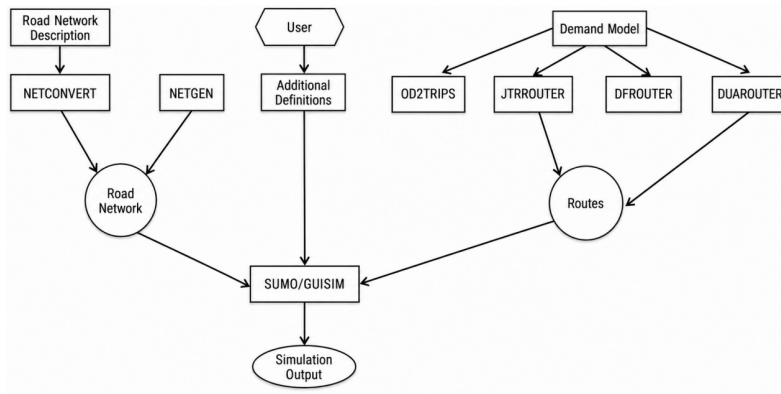
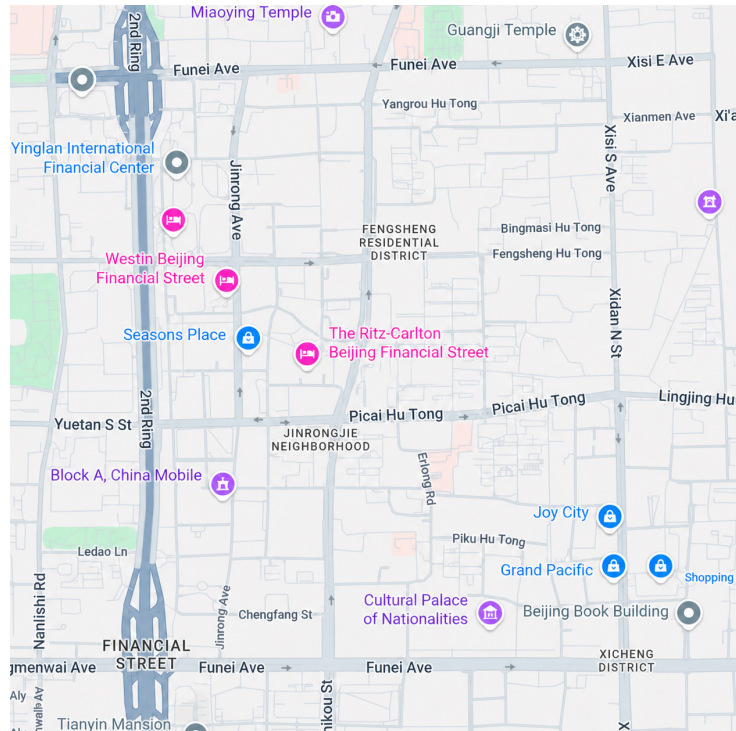


Figure 1. SUMO simulation model [9]

2.2. Construction of the Baseline Scenario



(a)



Figure 2. Simulation road network

The simulation experiment is based on intersections around four metro-station areas in Xicheng District, Beijing: Fuchengmen, Xisi, Xidan, and Xisi. A $2 \text{ km} \times 2 \text{ km}$ study area (4 km^2) encompassing these locations is defined as the simulation road network. The baseline scenario is first established as the control for subsequent strategy scenarios and mainly reflects the current urban traffic operating state dominated by private cars.

Under this scenario, vehicle trajectories and emission data are obtained through SUMO simulation. Total system carbon emissions and the emission composition by travel mode are then calculated and used as the basis for subsequent comparative analysis.

2.3. Scenario Design

On the basis of the baseline scenario, two categories of scenarios are constructed to analyze carbon-emission impacts. First, individual strategy scenarios are designed: (1) a private-car demand regulation scenario, in which private-car travel demand is reduced proportionally to simulate vehicle-restriction or travel-structure adjustment policies and to analyze changes in system-level carbon emissions; (2) a bus service optimization scenario, in which the number of bus routes or departure frequency is increased to improve public-transport supply, enhance the attractiveness of public transport, and analyze the effect of a higher bus mode share

on carbon emissions; and (3) on this basis, a combined strategy scenario integrating private-car demand regulation and bus service optimization is further constructed. By comparing its carbon-emission results with those of individual strategies, the study analyzes the synergy or offsetting effects among measures and reveals the carbon-emission variation patterns of a multi-modal transport system.

3. Experiments and Results Analysis

3.1. Baseline Scenario

To analyze the carbon-emission characteristics of different travel modes in an urban transport system, this paper first constructs a baseline scenario for a multi-modal transport system and conducts simulation experiments using the SUMO microscopic traffic simulation platform.

In the baseline scenario, private cars and buses are treated as the main motorized travel modes, while bicycles and walking are introduced as active travel modes, thereby forming a multi-modal transport system. The simulation road network is built from OpenStreetMap data, and traffic demand loading and route assignment are completed in SUMO.

The specific parameter symbols used in the baseline scenario are as follows:

Table 1. Symbol definitions

Symbol	Meaning	Symbol	Meaning
T	Simulation duration (s)	e_i	Carbon emissions of vehicle i
Q_c	Private-car travel demand	E_{total}	Total system carbon emissions (kg)
Q_b	Total bus departures	E_c	Private-car carbon emissions (kg)
Δt	Private-car departure interval	E_b	Bus carbon emissions (kg)
Δt_b	Bus headway	E_m	Carbon emissions of travel mode m
t_0	Initial bus departure time	η_m	Emission share of travel mode m
t_b	Bus departure time	L_c	Average private-car travel distance (m)
δ_i	Time offset among bus routes	t_c	Average private-car travel time (s)
N	Total number of vehicles included in statistics		

To achieve unified carbon-emission calculation for the multi-modal transport system, this paper constructs the following calculation model based on SUMO simulation output data.

(1) Private-car departure interval

$$\Delta t = \frac{T}{Q_c} \quad (1)$$

(2) Bus departure time

$$t_b = t_0 + k \cdot \Delta t_b + \delta_l \quad (2)$$

(3) Total system carbon emissions

$$E_{total} = \sum_{i=1}^N e_i \quad (3)$$

(4) Mode-specific carbon emissions

$$E_m = \sum_{i \in m} e_i \quad (4)$$

(5) Carbon-emission share

$$\eta_m = \frac{E_m}{E_{total}} \times 100\% \quad (5)$$

The specific parameters of the baseline scenario are set as follows: the demand-generation period is 3,600 s, and private-car demand is set to 1,600 vehicles. The bus system includes four routes, with six departures per route and 24 departures in total. The bus headway is 10 minutes, and departures begin at 1,200 s to reduce the influence of initial congestion on vehicle insertion. To simulate active-mode travel demand, a certain number of bicycles and pedestrians are also included in the transport system. It should be noted that, to ensure that vehicles can complete their trips and produce stable emission statistics, the total simulation duration is set to 5,400 s. The output results are shown in Table 2.

Table 2. Baseline scenario output results

Indicator	Value	Indicator	Value
Total completed trips	1285	Bus emission share	2.55%
Number of cars in the emission file	1277	Bicycle emission share	0.00%
Number of buses in the emission file	8	Completed car trips	1277
Number of bicycles in the emission file	0	Average car travel time (s)	237.23
Total system CO2 emissions (kg)	869.68	Average car travel distance (m)	2112.40
Car CO2 emissions (kg)	847.53	Completed bus trips	8
Bus CO2 emissions (kg)	22.15	Average bus travel time (s)	173.25
Bicycle CO2 emissions (kg)	0.00	Average bus travel distance (m)	1727.49
Car emission share	97.45%		

In terms of operating scale, 1,277 private cars completed their trips, whereas only 8 buses did so, indicating low public-transport participation and a limited contribution of buses to system-level carbon emissions. In terms of operating characteristics, the average private-car travel time was 237.23 s and the average distance was 2,112.40 m; the average bus travel time was 173.25 s and the average distance was 1,727.49 m. The trips were mainly short- to medium-distance, leaving room for subsequent bus optimization or substitution by active modes.

The simulation adopts a setting in which demand generation and operating duration are separated. Private-car demand is generated in the early stage, while the simulation runtime is extended to 5,400 s to ensure that vehicles can complete their trips and output complete emission data. Bus departures start at 1,200 s to avoid congestion effects caused by unstable traffic flow in the initial stage and to improve operational feasibility.

In the baseline scenario, the input demands for private cars and buses are 1,600 vehicles and 24 departures, respectively. Due to constraints related to network connectivity, congestion,

and vehicle insertion, some trips are not completed, which reduces the number of vehicles included in the emission statistics. However, because all comparative scenarios use consistent simulation parameters and demand-generation methods, the results remain highly comparable. Pedestrians and bicycles are treated as having zero direct carbon emissions.

This baseline scenario reflects the current private-car-dominated urban travel structure and its carbon-emission characteristics, providing a control basis for evaluating subsequent traffic-demand regulation and bus-optimization strategies.

3.2. Private-Car Regulation

On the basis of the baseline scenario, this paper constructs private-car regulation scenarios by reducing the scale of private-car travel demand. Three regulation intensities, namely 1,400, 1,200, and 1,000 vehicles, are set to compare changes in system-level carbon emissions. The experimental results are shown in Table 3.

Table 3. Comparison of results under private-car demand regulation scenarios

Scenario	Number of private cars	Completed trips	Total CO2 emissions (kg)	Car emissions (kg)	Bus emissions (kg)	Car share (%)	Bus share (%)	Average travel time (s)
Baseline	1600	1277	869.68	847.53	22.15	97.45	2.55	237.23
Scenario 1	1400	1122	1380.96	1360.94	20.02	98.55	1.45	449.35
Scenario 2	1200	960	669.61	657.82	11.79	98.24	1.76	244.79
Scenario 3	1000	798	540.55	514.33	26.22	95.15	4.85	229.54

Private-car demand regulation has a significant effect on system-level carbon emissions and exhibits clear nonlinear characteristics.

Under the mild regulation scenario (1,400 vehicles), system-level carbon emissions increase from 869.68 kg to 1,380.96 kg, showing an increase rather than a decrease. This occurs because, after a slight reduction in private-car demand,

traffic flow is redistributed across the network and new local congestion bottlenecks form on key road sections. As a result, the average car travel time increases from 237.23 s to 449.35 s, substantially raising per-vehicle emissions. This indicates that, in a near-saturated transport system, low-intensity demand regulation may not alleviate congestion and may instead increase emissions due to changes in flow structure.

Mild private-car restrictions alone are therefore unlikely to achieve effective emission reduction.

As the regulation intensity increases and private-car demand falls to 1,200 and 1,000 vehicles, system-level carbon emissions decrease to 669.61 kg and 540.55 kg, respectively, indicating a significant emission-reduction effect. High-intensity regulation effectively alleviates congestion, improves vehicle operating efficiency, and reduces overall carbon emissions. Meanwhile, as the number of private cars decreases, the bus emission share rises from 2.55% in the baseline scenario to 4.85%, suggesting that the relative role of public transport is enhanced under lower traffic volumes.

The results show that the emission-reduction effect of private-car demand regulation is strongly nonlinear. In the initial stage of regulation, traffic-flow redistribution can intensify local congestion and increase emissions. Only after the regulation intensity reaches a certain level does system operating efficiency improve and the emission-reduction effect gradually emerge. Therefore, low-intensity private-car restrictions alone are insufficient to meet emission-reduction targets and should be implemented in coordination with stronger regulation or other traffic-optimization strategies.

3.3. Active-Mode Feeder Optimization

In the active-mode feeder optimization scenario, this paper adjusts the demand scale of different travel modes to simulate the substitution of private-car trips by walking and cycling for short-distance travel. The specific parameter settings are as follows:

Private-car travel demand is reduced from 1,600 vehicles in the baseline scenario to 1,300 vehicles; bicycle travel demand is increased from 300 to 500 trips; pedestrian demand is increased from 300 to 450 persons; and the bus system remains unchanged, with four routes and 24 departures in total. The simulation duration is set to 5,400 s, and buses begin departing at 1,200 s.

These settings are intended to represent a situation in which, after improvements to active-travel conditions such as walking-environment enhancement and bicycle-lane construction, part of short-distance motorized travel shifts to active modes. Because active modes are generally regarded as producing zero direct carbon emissions, this paper does not explicitly model their emissions; instead, their substitution effect is reflected indirectly through reduced private-car demand. The output results are shown in Table 4.

Table 4. Results under the active-mode feeder scenario

Indicator	Value	Indicator	Value
Total completed trips	1043	Bus emission share (%)	2.27
Number of cars in the emission file	1039	Average car travel time (s)	265.84
Total system CO ₂ emissions (kg)	785.12	Average car travel distance (m)	2133.36
Car CO ₂ emissions (kg)	767.26	Average bus travel time (s)	381.25
Bus CO ₂ emissions (kg)	17.86	Average bus travel distance (m)	1970.88
Car emission share (%)	97.73	Bus emission share (%)	2.27

Under the active-mode feeder strategy, system-level carbon emissions decrease from 869.68 kg in the baseline scenario to 785.12 kg, a reduction of approximately 9.7%, indicating a notable emission-reduction effect.

By guiding short-distance trips toward walking and cycling, this strategy directly reduces car emissions by taking advantage of the zero direct emissions of active modes. At the same time, the reduction in traffic volume alleviates network congestion and keeps car travel time within a reasonable range, avoiding the congestion-aggravation problem that may arise from simple private-car regulation.

Unlike private-car regulation, which mainly compresses travel demand, active-mode feeder optimization focuses on adjusting the travel structure. It maintains the operational stability of the transport system while reducing emissions, making it a low-carbon transport strategy that balances emission reduction and system efficiency.

3.4. Bus Priority

In the bus-priority scenario, this paper simulates a public-

transport priority strategy by increasing bus service supply and improving bus operating conditions. Specifically, on the basis of the baseline scenario, private-car travel demand is reduced from 1,600 to 1,200 vehicles to reduce the occupation of road resources by cars. Meanwhile, bus service is adjusted from four routes with six departures per route to four routes with ten departures per route. The total number of bus departures increases from 24 to 40, and the headway is shortened from 600 s to 360 s. Buses still begin departing at 1,200 s, and the remaining simulation parameters are unchanged.

This setting is used to reflect the increase in public-transport supply, the improvement of bus operating conditions, and the shift of some private-car trips to public transport under a bus-priority policy. By comparing system-level carbon emissions and the emission shares of different travel modes between this scenario and the baseline scenario, the emission-reduction effect of the bus-priority strategy can be evaluated. The results are shown in Table 5.

Table 5. Results under the bus-priority scenario

Indicator	Value	Indicator	Value
Total completed trips	969	Car emission share (%)	98.73
Number of cars in the emission file	960	Bus emission share (%)	1.27
Number of buses in the emission file	9	Average car travel time (s)	244.79
Total system CO ₂ emissions (kg)	666.27	Average car travel distance (m)	2127.30
Car CO ₂ emissions (kg)	657.84	Average bus travel time (s)	59.44
Bus CO ₂ emissions (kg)	8.43	Average bus travel distance (m)	705.67

In the bus-priority scenario, total system carbon emissions decrease from 869.68 kg in the baseline scenario to 666.27 kg, a reduction of approximately 23.4%, indicating that the

strategy has a significant emission-reduction effect. It should be noted that this scenario applies a relatively large adjustment to private-car travel demand. This setting is

mainly intended to strengthen the contrast among travel modes and thereby more clearly identify the mechanism through which bus priority affects transport-system carbon emissions. In real transport systems, changes in private-car demand are usually gradual; therefore, this scenario is better understood as a policy simulation experiment rather than a direct prediction of short-term real-world changes.

The results show that the number of completed bus trips increases only slightly, from 8 in the baseline scenario to 9, but bus operating efficiency improves substantially. The average bus travel time decreases markedly to 59.44 s, and travel distance also shortens significantly, indicating smoother bus operations under this scenario. This suggests that the core of the bus-priority strategy does not lie merely in increasing the number of buses, but in improving operating conditions and bus efficiency so that buses can carry more travel demand at a lower cost. Improved bus efficiency also helps alleviate overall traffic congestion and thus indirectly reduces car emissions.

Therefore, even though the change in the number of buses is limited, its impact on system-level carbon emissions remains significant. Although total bus emissions decrease, this is mainly attributable to more reasonable bus routes and smoother operations. At the same time, private-car carbon

emissions fall substantially from the original level and become the main reason for the decline in total system emissions. By improving public-transport operating efficiency and mode share, the bus-priority strategy effectively optimizes the transport structure, reduces carbon emissions, and improves system operating conditions. It is therefore an important pathway toward low-carbon urban transport.

3.5. Combined Strategy

In the combined strategy scenario, this paper integrates private-car demand regulation, active-mode feeder optimization, and bus-priority measures on the basis of the individual strategy scenarios. The specific parameters are as follows: private-car travel demand is reduced to 1,300 vehicles; bicycle and pedestrian demand are increased to 500 trips and 450 persons, respectively; the bus system remains at four routes, while departures per route are increased to 10 and the headway is shortened to 360 s.

This scenario is used to simulate the operating state of the transport system under the joint effects of multiple transport policies and to evaluate the combined impact of different strategy packages on carbon emissions. The results are shown in Table 6.

Table 6. Results under the combined strategy scenario

Indicator	Value	Indicator	Value
Total completed trips	1048	Car emission share (%)	98.92
Number of cars in the emission file	1039	Bus emission share (%)	1.08
Number of buses in the emission file	9	Average car travel time (s)	265.77
Total system CO ₂ emissions (kg)	775.45	Average car travel distance (m)	2133.34
Car CO ₂ emissions (kg)	767.04	Average bus travel time (s)	59.11
Bus CO ₂ emissions (kg)	8.41	Average bus travel distance (m)	705.67

In the combined strategy scenario, total system carbon emissions are 775.45 kg, which is lower than the baseline scenario (869.68 kg) but higher than the bus-priority scenario (666.27 kg). The scenario therefore does not achieve the best emission-reduction performance. This indicates that simply stacking multiple strategies does not necessarily produce a strong synergistic enhancement effect.

In terms of component emissions, car carbon emissions are 767.04 kg and still dominate the system, accounting for 98.92% of total emissions. This indicates that private-car travel remains the main source of system-level carbon emissions. Although private-car demand regulation, active-mode feeder optimization, and bus-priority measures are all introduced in this scenario, private-car demand is reduced only from 1,600 to 1,300 vehicles. The reduction is limited and does not fundamentally change the transport structure.

From the perspective of bus operations, the number of completed bus trips is 9, essentially the same as in the bus-priority scenario. This suggests that, under these conditions, the bus system is already close to its operational capacity limit, and the additional active-mode feeder measure does not significantly increase the bus mode share. At the same time, the average bus travel time is only 59.11 s and the travel distance is approximately 705.67 m, indicating high bus operating efficiency. However, the scale of bus operations remains insufficient to exert a decisive influence on the overall emission structure.

Overall, the combined strategy has theoretical advantages in enabling emission reduction through multiple pathways. Under the current parameter settings, however, the strategies do not form effective synergy and instead exhibit a certain

degree of diminishing marginal effect, meaning that the contribution of additional measures to system-level emission reduction gradually declines. Reasonably matching the implementation intensity of different strategies is therefore the key to maximizing the emission-reduction effect of a multi-modal transport system.

4. Discussion

The simulation results indicate that the carbon-reduction effects of transport policies are not necessarily additive. In particular, some combined scenarios achieved smaller marginal reductions than expected from the effects of the corresponding individual measures. This seemingly counterintuitive result can be attributed to interactions among travel demand, route choice, traffic flow, and modal substitution. For example, bus-priority measures may improve public transport efficiency but can also reduce road capacity available to other motorized vehicles, potentially increasing congestion and emissions on certain road sections. Similarly, when private-car restriction and active-mode feeder improvements are implemented simultaneously, part of the travel demand may have already shifted under one policy, thereby reducing the additional contribution of the other. These interactions explain the observed offsetting effects and diminishing marginal returns.

The findings are generally consistent with previous studies showing that multimodal transport optimization and shared mobility can contribute to carbon-emission reduction. However, earlier studies have often focused on individual modes, specific routing problems, or isolated policy measures.

The present study extends this perspective by evaluating multiple transport policies within a unified SUMO-based simulation framework. The results further demonstrate that the effectiveness of a combined policy cannot be reliably estimated by simply summing the effects of individual measures. This finding also supports the application of SUMO-HBEFA models in policy-oriented emission assessment and complements previous SUMO-based research on low-carbon traffic control.

Several limitations should nevertheless be acknowledged. First, the simulation was conducted within a relatively small $2\text{ km} \times 2\text{ km}$ study area (4 km^2). The results may therefore be influenced by the selected road-network structure and cannot be directly generalized to larger or structurally different urban areas. Second, because of data limitations, some travel-demand and behavioral parameters were derived from statistical yearbooks and other aggregated sources. These parameters may not fully reflect individual-level travel heterogeneity. Third, the simulation results have not yet been validated against field measurements, such as observed traffic volumes, vehicle trajectories, travel times, or roadside emission data. In addition, the HBEFA-based emission estimates primarily represent operational emissions and do not include life-cycle emissions associated with vehicle

production, energy supply, and transport infrastructure.

Future research should expand the simulation to larger and more diverse urban road networks and incorporate high-resolution empirical data from smart cards, floating vehicles, mobile devices, and traffic detectors. Field observations should also be used to calibrate and validate traffic and emission parameters. Furthermore, future studies could consider traveler behavioral responses, policy implementation costs, social equity, and life-cycle emissions. Multi-objective optimization methods may then be introduced to identify policy combinations that balance carbon reduction, traffic efficiency, economic cost, and accessibility.

5. Summary and Conclusion

Based on the SUMO simulation platform, this paper constructs a carbon-emission evaluation model for an urban multi-modal transport system. On the basis of the baseline scenario, multiple scenarios are designed, including private-car demand regulation, active-mode feeder optimization, bus priority, and a combined strategy. The emission-reduction effects of different transport strategies are then systematically analyzed and compared.

Table 7. Comparison of total CO₂ emissions under different scenarios

Scenario	Total CO ₂ emissions (kg)	Description
Baseline scenario	869.68	Control
Private-car regulation (optimal)	540.55	Emission reduction under strong constraints
Active-mode feeder optimization	785.12	Stable emission reduction
Bus priority	666.27	Best individual strategy
Combined strategy	775.45	Diminishing marginal effects

The results show that different transport strategies vary significantly in their ability to control carbon emissions.

(1) Under strong constraints, the private-car demand regulation strategy produces the most significant emission-reduction effect, indicating that reducing high-emission motorized travel is a direct and effective way to reduce emissions. However, this strategy depends on strong policy intervention, is difficult to implement in practice, and has relatively limited feasibility.

(2) The active-mode feeder optimization strategy achieves a stable reduction in carbon emissions by increasing the share of walking and cycling and replacing short-distance private-car trips. Although its emission-reduction effect is relatively moderate, it has strong sustainability and promotion value, reflecting the important role of transport-structure optimization in low-carbon development.

(3) Among the individual strategies, the bus-priority strategy achieves the best overall performance. By improving bus service levels and operating efficiency, it can increase the public-transport mode share, reduce private-car travel, and alleviate congestion. This strategy strikes a good balance between emission-reduction effectiveness and implementation feasibility and is one of the important pathways toward low-carbon urban transport.

(4) In the combined strategy scenario, system-level carbon emissions decrease relative to the baseline scenario but do not reach the level achieved by the best individual strategy. The stacking of multiple measures does not generate a significant synergistic effect and instead shows diminishing marginal effects. This indicates that the effectiveness of a combined strategy depends on the degree of matching among different

measures rather than on simple superposition.

Overall, private-car regulation has the strongest theoretical emission-reduction potential but relatively low feasibility. The bus-priority strategy delivers the best overall performance and is currently the most promising pathway for wider application. Active-mode feeder optimization can serve as an effective supplementary measure. Combined strategies require further optimization in parameter design and implementation intensity before synergistic enhancement can be achieved.

Therefore, the low-carbon transformation of urban transport should avoid reliance on a single strategy or the simple stacking of measures. Instead, it should be based on actual traffic conditions and should rationally configure the implementation intensity and scope of different strategies. Through systematic design and structural optimization, coordinated development between carbon-emission control and transport efficiency improvement can be achieved.

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