Optimizing Road Networks in Small and Medium-sized Cities: A Multidimensional Trade-off between Efficiency and Environmental Sustainability

Rui Tian, Longchuang Li, and Xingbao Wu*

Guangdong Construction Polytechnic, Guangzhou, 510440, China

Abstract

The unreasonable structure of the road network has become a significant bottleneck restricting the sustainable development of transportation systems in small - medium cities. This paper is based on road network grading theory and integrates a multi-dimensional performance evaluation framework to address the common problem of the "inverted pyramid" structure and its environmental impacts. We first establish a theoretical road network model that follows a pyramid structure. In order to reconcile the contradiction between public transit priority and travel efficiency, we put forward a new type of functional segmentation strategy of the arterial road system, which can divide it into "passenger-oriented" and "freight-oriented" corridors. A set of 12 second-order indicators is included under the first-order dimensions of structure, efficiency, equity, resilience, and environmental impact. The weights of these indicators are quantified using an improved hierarchical CRITIC objective weighting method. We simulate and analyse three road network density scenarios (a base case of 6.8 km/km^2, a plan density of 12.8 km/km^2, and a high density benchmark of 21.1 km/km^2) for a virtual case city that has been calibrated with empirical data. The results show a significant deviation between environmental and efficiency objectives. The planned densification scenario (12.8 km/km^2) achieves the best overall performance (score: 0.819), lower than 15.2% compared to the baseline. However, this situation also leads to an increase in noise, and corresponding noise reduction measures need to be taken. Pursuing excessive density (21.1 km/km^2) leads to decreased efficiency of resource utilization and intensified noise pollution. This study provides a systematic decision-support tool and the theoretical basis for road network optimization design, public transportation priority, and reducing environmental externality effects of small- to medium-sized cities.

Keywords

Road Network Hierarchy; Multi-Criteria Evaluation; Environmental Externalities; CRITIC Weighting; Transit Priority; Small and Medium- Sized Cities; Transportation Carbon Emissions; Traffic Noise.

1. Introduction

The relentless development of global urbanization and motorization has brought about the spread of the urban ills of traffic congestion and environmental pollution to many small and medium-sized cities. These problems have become key constraints on the sustainable development of cities and the quality of life of residents [1]. In addition to the rapid growth of vehicle ownership, the unreasonable structure of urban road networks is regarded as a more fundamental contributor to the problem [2]. Many medium-sized and small cities in China that have undergone rapid expansion have adopted the development model of "wide roads and sparse networks", and the hierarchical structure and functional coordination of the urban road network have been neglected. This leads to an unbalanced "triangular" structure with an overabundance of main roads and a severe lack of secondary and tertiary roads [3]. This structural defect fails to facilitate the orderly aggregation and dispersion of traffic flow. As a result, many short-distance trips that should be handled by the branch road system are forced onto the main roads, leading to dysfunction of the arterials, overloaded intersections, low operation efficiency, and increased fuel consumption, exhaust emission, and traffic noise pollution caused by frequent stops and long-term congestion [4]. Such problems are especially common in many cities in the Pearl River Delta that are rapidly urbanizing, such as Qingyuan City in Guangdong Province, which is a typical example for this research because it has a representative size, stage of development, and road network problems.

A reasonable road network structure provides the spatial basis for building an efficient, green, and equitable urban transportation system. Previous studies have made some explorations on the performance of road networks, but more often they focus on a single aspect. For example, in terms of structure, domestic scholars such as Yang Tao have long emphasized the important role of increasing the density of secondary roads in optimizing road network structure. In terms of efficiency, Cai Jun argues from the point of view of traffic capacity and turning ratios that there is an optimal road network density. In recent years, equity [5], Resilience and so on have also attracted attention from scholars. From an environmental perspective, through the studies by Boeing [6] and Zhang et al., we can also observe that high density, highly connected road network layout, the pattern has a positive relationship with green travel modes such as walking and cycling, which can reduce transportation carbon emissions. A recent study by Saelens et al. (2023) shows that there is a significant relationship between urban street network design attributes-such as connectivity and network density-and transportation-related carbon emission intensity, and it notes that environmental problems may emerge after road network structure optimization [7].

Despite prior research, no systematic evaluation framework exists specifically for small and medium-sized cities. Their limited scale and unique transport traits make it hard to turn research into practical policies for smart city development. To fill this gap, the study offers two theoretical advances:

1) Road network hierarchy theory is deepened for these cities. A functional segmentation splits the arterial system into “passenger-oriented” and “freight-oriented” corridors, resolving spatial conflicts between “public transit priority” and motor vehicle efficiency.

2) A multi-dimensional performance system is built (structure, efficiency, equity, resilience, environmental impact). Extending Deng et al[8]. four-dimensional framework, it adds carbon emissions and noise exposure. An improved hierarchical CRITIC method quantifies dimension weights, forming a model to assess road network density suitability.

3) The study also reveals how different road network layouts affect the environment and their trade-offs. This provides a precise, practical basis and decision tools for green, low-carbon transport planning and land use optimization in China’s small and medium-sized cities.

2. Literature Review

2.1 Research Progress on Road Network Grading Theory

Road network hierarchy can be seen from how road lengths are distributed across different functional levels. An ideal urban network follows a pyramid shape: high-grade roads (expressways, arterial roads) take a small share, while low-grade roads (branch roads) take the largest share. This setup lets traffic converge upward from branch roads to arterial roads for long trips, then disperse downward to destinations. China’s Code for Urban Road Transportation Planning and Design gives density values pointing to a pyramid hierarchy-arterial:secondary:branch roads roughly at 0.3:0.4:1 [9]. Planning in the United States and Japan generally follows the same rule [10].

But in many small and medium-sized Chinese cities, the reality is far from ideal—often inverted. A shortage of minor roads leads to poor connectivity and functional mismatches. Bus route planning on minor roads becomes hard, and congestion on arterial roads may raise fuel use and pollution.

2.2 Multi-dimensional Performance Evaluation of Road Networks

Road network density reflects both the road system's level and urban development. Current planning often relies on recommended standard values or uses international cities as density benchmarks without enough accuracy, while city-to-city differences are ignored.

Recent studies have examined road network density from multiple angles: structure (connectivity), efficiency (diminishing returns beyond a threshold), equity (spatial accessibility differences), and resilience (reliability under disturbances) [11-15]. From an environmental perspective, higher density reduces per-trip carbon emissions by raising average speeds [16], but wide, sparse networks are linked to higher noise exposure [17]. Research combining both carbon and noise trade-offs remains rare.

From an environmental perspective, it has been proven that reasonable road network density reduces carbon emissions per unit travel distance by increasing average vehicle speeds and decreasing congestion [16]. The effect of road network resilience in reducing transportation system vulnerability and related environmental risks caused by extreme weather has also been studied. Transportation noise is another important factor of environmental effect, as well as carbon emissions. Bocarejo and Velasquez (2022) found that wide roads and sparse networks in Bogotá are linked to higher noise exposure [17]. But research that looks at both carbon and noise impacts together, and explores their trade-offs, is still rare.

Past work has mostly looked at one or a few dimensions, missing a systematic, comprehensive evaluation framework. Litman [18] proposed a four-dimensional system (structure, efficiency, equity, resilience) using the CRITIC weighting method, which brought new ideas. Yet that framework did not include the key environmental dimension. To fill this gap, the present study builds a five-dimensional evaluation system and focuses on the carbon-noise trade-off inside the environmental dimension.

3. Research Method

3.1 Theoretical Framework

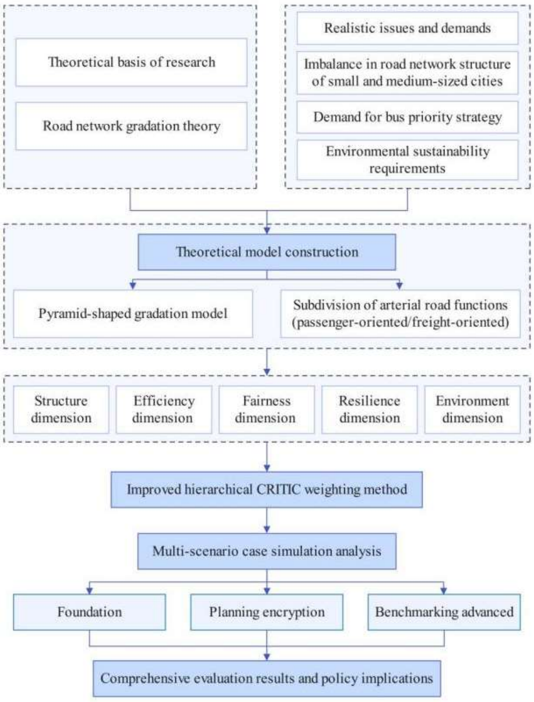

Figure 1. Theoretical Framework

This study's theoretical framework combines road network hierarchy theory, multifunctional differentiation strategies, and a five-dimensional evaluation system (see Figure 1).

3.2 Road Network Grading Theoretical Model

An ideal road network grade distribution forms a pyramid-shaped structure, mathematically expressed as:

$$R = \frac{L_{Side}}{L_{Main} + L_{\sec}} > 1 \tag{1}$$

where L represents the mileage corresponding to the road grade. A ratio R greater than 1 is a necessary condition for an adequate branch road system.

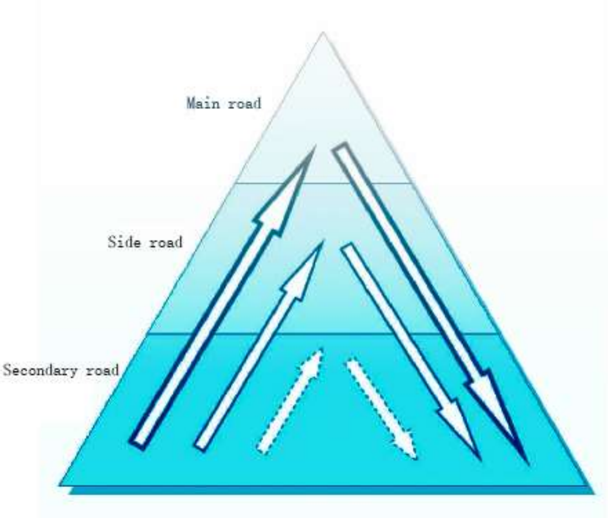

Figure 2. Schematic diagram of a reasonable pyramid-shaped road hierarchy

Table 1. Comparison of Urban Road Technical Standards and Functional Characteristics (CJJ37-2012)

Characteristics	**Expressway**	**Main Arterial Road**	**Secondary arterial road**	**Access Road**
Functional	Inter-non-adjacent group and urban external transportation	Transportation between adjacent groups and between groups and the central group	Internal group traffic	Within the district
Road Characteristics	High-speed, traffic-oriented, and through-traffic-oriented	Medium-high speed, primarily traffic-oriented	speed, distribution and service coexist	speed, residential, and service-oriented
Travel distance	Long distance	Medium-long distance	Medium-short distance	Short distance
Accessibility	Weak	Moderate	Strong	Strong
Open on both sides	Strictly restricted	Restricted	Appropriately	More
Service recipients	Motor vehicles	Primarily motor vehicles	Motor vehicles and non-motor vehicles	All modes of transportation
Serving adjacent land uses	Not directly serving	Does not directly serve	Provides some service	Directly serves

Based on this, a theoretical road network model compliant with standard density and pyramid-shaped hierarchy was constructed (Figure 2), featuring clear functions, orderly connections, and a reasonable hierarchy (arterial: secondary: branch ≈ 0. 19:0.38:1).

According to China's "Code for Urban Road Engineering Design" (CJJ37-2012), the technical standards and functional characteristics of different road classes are compared in Table 1.

3.3 Multi-dimensional Evaluation Indicator System

An evaluation system comprising 12 indicators across five dimensions (structure, efficiency, equity, resilience, and environmental impact) was constructed. The definitions and calculation methods are shown in Table 2.

Table 2. Evaluation Indicator System for Road Network Density Suitability

Evaluation Dimension	Indicator	Indicator Definition and Explanation	Calculation Formula
Structure	Road Network Grading	Proportion of Secondary Road Mileage to Total Mileage	$I_s = \frac{L_{\mathrm{Sec}} + L_{\mathrm{Side}}}{L_{\mathrm{Ove}}}$
	Intersection connectivity	Average ratio of actual turn counts at intersections to the number of approach directions	$I_c = \frac{\sum_{i=1}^{n} s_i}{n}$
	Average saturation level of the road segments (%)	Average ratio of segment traffic volume to capacity in the road network	$V= \frac{\sum_{i=1}^{\mathrm{N}} V_i}{\mathrm{N}}$
Efficiency	Average travel speed of the road network (km/h)	Average travel speed of all paths between origin-destination pairs	$S= \frac{\sum_{i=1}^{n} L_i}{\sum_{i=1}^{n} T_i}$
Fairness	Total network distance turnover (vehicle-km)	Total sum of the distance turnover of all paths	$K = \sum_{i=1}^{n} L_i \cdot q_i$
Resilience	Total time-based turnover volume of the road network (vehicle-hours)	Total sum of time-based travel volume for all paths	$M = \sum_{i=1}^{n} T_{\mathrm{i}} \cdot q_i$
	Network-wide non-linear coefficient	Average non-linear coefficint for all origindestination pairs	$E = \frac{\sum_{x=1}^{\mathrm{z}} \sum_{y=1}^{\mathrm{z}}}{Z(Z-1)}$
	Slow-moving network proximity	Average proximity of all plots within a 1 km radius	$D = \frac{\sum_{x=1}^{\mathrm{z}} D_x}{Z}$
	Demand growth resilience index	The decrease in average network saturation and travel speed when demand increases	$R_d = \frac{1}{2}(\frac{\lvert\Delta \mathrm{S}\rvert}{S_0} + \frac{\lvert\Delta \mathrm{V}\rvert}{\mathrm{V}_0})$
	Supply Shortage Resilience Index	The decrease in average network saturation and travel speed during supply shortages	$R_s = \frac{1}{2}(\frac{\lvert\Delta \mathrm{S}\rvert}{S_0} + \frac{\lvert\Delta \mathrm{V}\rvert}{\mathrm{V}_0})$
Environmental Impact	Transportation Carbon Emission Intensity	CO_2 emissions per unit of freight tonkilometer (g/vehicle-km)	$C_e = \frac{\sum_{i=1}^{n} (q_i \cdot L_i \cdot EF_i)}{K}$
	Proportion of areas with noise levels Exceeding standards	Area of the roadside noise exceeding 55 dB(A) as a proportion of the built-up area	$N_e = \frac{A_{\mathrm{noise>55dB}}}{A_{\mathrm{total}}}$

Note: Emission factors are speed-based (IVE model); noise is distance-attenuation based (ISO 9613-2).

3.4 Improved Hierarchical CRITIC Weighting Method

This study uses an improved hierarchical CRITIC weighting method, and the specific process is shown in Figure 3. This method avoids the interference between indicators caused by the scale difference, and two layers of weights ensure that the two layers of weights are less affected by the correlation between the two layers of weights. The process is as follows:

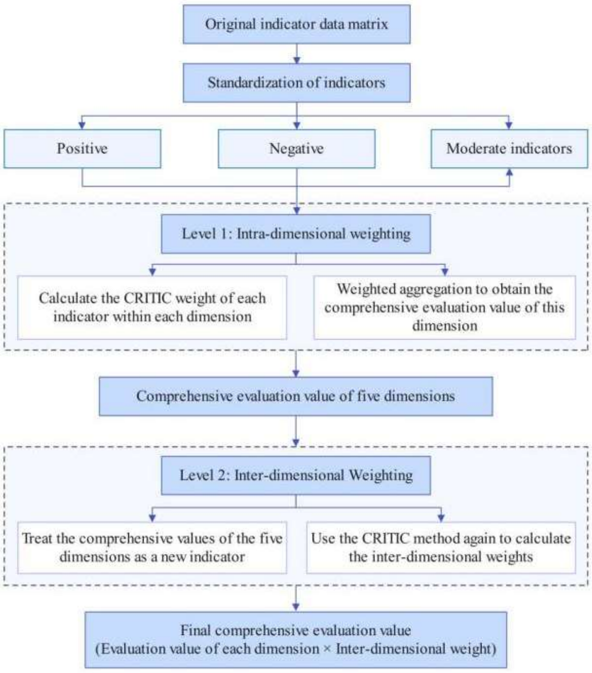

Figure 3. Improved hierarchical CRITIC weighting method flowchart

1) Data standardization: Build the original indicator data matrix and standardize the positive, negative, and moderate indicators with the extreme value method to remove the scale effect.

2) First layer – Dimension-internal weighting: Within each dimension, calculate the comparison strength (standard deviation) and conflict (based on correlation coefficients) of each indicator to obtain its information content. Higher information content indicates more importance within the dimension. Indicator weights in the dimension are obtained by normalization. Standardized indicator values under each dimension are aggregated with their respective weights to obtain the dimension's comprehensive evaluation value.

3) Second layer: Inter-dimensional weighting: The comprehensive evaluation values of the five dimensions form a new indicator matrix. The CRITIC method is adopted to calculate the comparison strength and conflict among dimensions and obtain the inter-dimensional weight.

4) Comprehensive assessment: Multiply the comprehensive evaluation value of each dimension by the inter-dimensional weight and sum them to get the final comprehensive evaluation value. Compared with the traditional CRITIC method, this improved method can more effectively deal with the complex relationship between indicators in different dimensions, and thus achieves more objective weight assignment.

4. Case Simulation and Data Analysis

A hybrid approach combining a virtual city framework with empirical data from Qingyuan City, Guangdong Province, China, was employed. Qingyuan is a prefecture-level city with 850,000 people in its central urban district and a built-up area of 120 km². Its road network has a typical "inverted triangle" structure: over-reliant on a few wide arterial roads (e.g., Guangqing Avenue, Bidu Avenue), yet lacking secondary and branch roads. This causes chronic congestion and environmental issues, making Qingyuan ideal for validating the theoretical model.

The origin-destination (OD) matrix came from the city's transport survey and planning reports, assuming 2.5 trips/person/day. Estimated mode shares: private vehicles 30%, public transport 12%, motorcycles 35% (common in mid-sized Guangdong cities), non-motorized 23%.

Three road network density scenarios for the central urban area were simulated:

1) Base scenario (Status Quo): Density 6.8 km/km^2, grade distribution arterial: secondary: branch = 1.0:0.6:0.8 (reflecting existing imbalance).

2) Planned densification: Density 12.8 km/km^2, arterial: secondary:branch ratio = 0.3:0.4:1.0.

3) High-density benchmark: Density 21. 1 km/km^2, grade distribution arterial: secondary:branch = 0.2:0.3:1.0.

TransCAD and VISSIM were used to construct and calibrate the network model with Qingyuan's arterial layout and traffic flow data. Dynamic traffic assignment was performed. Environmental assessment was enhanced by combining MOVES for vehicle-specific emissions (based on second-by-second operations) and CNOSSOS-EU for noise (considering traffic mix, speed, road surface), implemented in QGIS and CadnaA.

5. Case Study

5.1 Overview of the Virtual Case Study City

The central urban area of Qingyuan takes a linear banded layout along the Bei River, which is composed of the old urban area (Qingcheng District) and the developing new urban area (Dongcheng New Area). The current road network shows an obvious inverted triangle structure: the density of arterial roads is 1.95 km/km^2, the density of secondary roads is 1.12 km/km^2, and the density of branch roads is only 0.38 km/km^2. The proportion of arterial to secondary roads is 1.74:1, which is far from the ideal pyramid structure. Such key arterials as Guangqing Avenue are overstressed for both through and local traffic with a high saturation point (>0.9 in peak hour) and environmental pressures [19].

5.2 Road Network Functional Optimization Under a Transit Priority Strategy

A functional segmentation scheme for the arterial road system was proposed to balance the conflict between public transport priority and traffic efficiency:

1) Freight-dominated arterial roads focus on through traffic and restrict side access.

2) Passenger-dominated trunk roads serve as urban development axes, encourage the establishment of passenger transfer points, and implement public transport priority measures (e.g., BRT and dedicated bus lanes).

Design key points for various road types are shown in Table 3.

Table 3. Comparison of Design Key Points for Different Road Types

Characteristics	**Freight-dominated arterial roads**	**Passenger-oriented arterial roads**	**Secondary Freight Roads**	**Passenger Secondary Arterial Road**	**Branch Road**
Bus priority	None	Priority implementation (BRT)	None	Implemented (bus-only lanes)	None
Passability for private vehicles	High priority	Restricted	Medium priority	Suppression	Suppression
Design Speed (km/h)	60	40	40	40	30
Openings on both sides of the site	Strictly restricted	Encourage the establishment	Restricted	Encourage installation	Set up extensively
Pedestrian crossing facilities	Wide spacing	Dense (overpasses/underpasses)	Wider spacing	Relatively dense	At-grade crossing

6. Result analysis

6.1 Evaluation Results of Structure, Efficiency, Equity, and Resilience

The multidimensional indicators for the three scenarios are compared in Table 4. The results indicate:

1) Structure: Scenario 3 had the optimal grade ratio (0.78), but its connectivity was slightly lower than that of Scenario 2 due to traffic restrictions.

2) Efficiency: Scenario 2 performs best, with the highest average vehicle speed (16. 1 km/h) and lowest time-based turnover. Scenario 3 experiences efficiency declines due to increased intersection delays.

3) Equity: Equity improves monotonically with increasing density. Scenario 3 has the best non-linearity coefficient (1.42) and slow-moving network proximity (1.02).

4) Resilience: Demand growth resilience increases with density; supply shortage resilience is best in Scenario 2 but decreases in Scenario 3 due to increased dependency on critical sections.

Table 4. Multi-dimensional indicator values and standardized scores under various scenarios

Evaluation Dimensions	**Evaluation Indicator**	**Actual Magnitude Value (Scenario 1/2/3)**	**Standardized Score (Scenario 1/2/3)**
Structure	Road Network Grading (Secondary Road Proportion)	0.49 / 0.67 /0.78	0.63 / 0.86 /1.00
	Intersection connectivity	1.86 / 3.07 /2.92	0.00 / 1.00 /0.88
	Average road segment saturation	0.84 / 0.65 /0.41	0.88 / 0.87 /0.55
	Average travel speed on the road network (km/h)	14.0 / 16. 1 /14. 1	0.00 / 1.00 /0.05
Efficiency	Total network distance turnover (million vehicles-kilometers)	36.0 / 34.2 /33.9	0.00 / 0.86 /1.00
	Total time-based turnover of the road network (ten thousand vehicle-hours)	152.1 / 128.9 / 141.4	0.00 / 1.00 / 0.46
Equity	Network Non-Linear Coefficient	1.62 / 1.48 / 1.42	0.00 / 0.70 / 1.00
	Slow-moving network proximity	0.86 / 0.96 / 1.02	0.00 / 0.63 / 1.00
Resilience	Demand Growth Resilience Index	0.48 / 0.66 / 1.03	0.00 / 0.52 / 1.00
	Supply Shortage Resilience Index	2.03 / 5.37 / 4.46	1.00 / 0.00 / 0.73
Environment	Carbon emissions intensity (g/vehicle·km)	82.5 / 70.0 / 68.1	0.00 / 0.87 /1.00
	Proportion of noise-exceeding areas (%)	18.2 / 22.5 / 25.8	1.00 / 0.43 /0.00

6.2 Environmental Impact Assessment Results

The results of the dimension of environmental impact are shown in Table 4.

1) Carbon emissions intensity: Carbon emissions intensity decreases significantly with increasing road network density. Scenario 2 (70.0 g / vehicle·km) has a 15.2% decrease compared to Scenario 1 (82.5 g / vehicle·km), mainly due to the increase in average speed and the reduction in congestion. This trend was consistent with the more detailed MOVES model, which predicted a 13.8% reduction in CO2 emissions and revealed further benefits in the reduction of nitrogen oxides (NOx).

2) Proportion of noise exceeding areas: The proportion of noise-exceeding areas increases with road network density. Scenario 2 (22.5%) is 4.3 percentage points higher than Scenario 1 (18.2%), mainly because more roads are closer to buildings; Scenario 3 (25.8%) has further deteriorated. The noise assessment used a simplified model as the foundation, and key corridors were refined using the

CNOSSOS-EU framework in CadnaA, taking into account the traffic composition (e.g., high proportion of motorcycles), speed, and road surface.

3) The results show a clear trade-off between increasing density for emission reduction and aggravating noise exposure. Planning needs to balance these aspects and implement targeted noise emission reduction measures for high-density networks.

6.3 Comprehensive Evaluation Results

Hierarchical CRITIC method determined dimension weights and comprehensive evaluation scores (Figure 4). Efficiency (28%) and environment (24%) received the most weight, meaning that the performance gap and information contradiction among scenarios were most distinct under the two headings by the case study, subjectively demonstrating the dual demand for operational efficiency improvement and environmental sustainability of small and medium-sized cities.

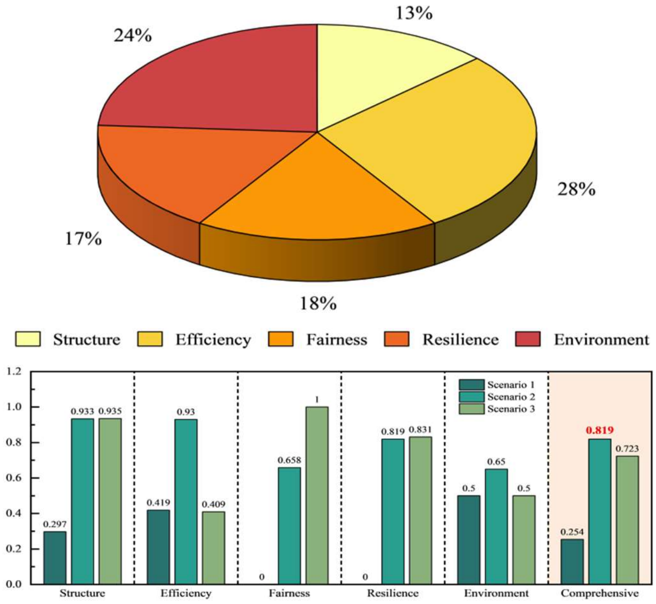

Figure 4. The weight of each dimension and the final evaluation results of scenarios

Scenario 2 (Planned Densification) obtained the best overall score (0.819), and the efficiency, environmental protection, and resilience indicators all reached 1; the balance of structure and equity also maintained a relatively high level. Scenario 3 (High-density Benchmark) has the best performance in structure, equity, and demand resilience, but has problems in efficiency, reduced supply resilience, and prominent noise, so its comprehensive score is only 0.723.

7. Discussion

7.1 Research Findings and Implications

With the environmental dimension and the hierarchical CRITIC method added, this study yields more complete and nuanced findings:

1) Optimal density exists. For the CBD of a medium-sized city (the case study), the best density is about 12.8 km/km² (Scenario 2). Pushing density too high (21.1 km/km²) can reduce efficiency, raise resilience risks, and increase noise pollution.

2) Trade-offs in environmental benefits. Higher density cuts carbon emissions (Scenario 2 shows a 15.2% drop) but also raises noise exposure risk (Scenario 1). Thus, balancing these factors and applying noise reduction measures is necessary.

3) Transit priority and functional zoning work. Putting BRT on passenger corridors and keeping freight corridors passable helps coordinate road space between public transport and private vehicles. This allows different modes to coexist harmoniously a key step for green urban mobility.

7.2 Planning Recommendations

Based on the above results, the following policy recommendations are suggested:

1) Set differentiated density targets for new areas in small and medium-sized cities. The target can be 12–14 km/km², with a pyramid hierarchy (secondary roads > 50%).

2) Apply functional segmentation of arterials. The five-dimensional assessment system (structure, efficiency, equity, resilience, environment) should be included in urban health checks and planning assessments to optimize road network schemes.

3) Implement environmental coordination policies: While adopting appropriate density for emission reduction, mandatory noise mitigation measures-such as low-noise pavement, speed limits, and ecological green walls-should be applied in noise-sensitive areas like passenger corridors to reduce environmental externalities.

4) Multi-dimensional comprehensive assessment: The master plan should clearly distinguish between "passenger-dominated" and "freight-dominated" arterial systems, formulate differentiated design standards and management strategies, and fully implement public transport priority.

5) The identified optimal density value (12.8 km/km^2) is context-dependent, obtained for a certain Chinese medium-sized city with particular travel patterns (high motorcycle usage, etc.). It should be interpreted as being in the plausible range (12-14 km/km²) as a reference. Applicability varies according to the city's size, terrain, economics, dominant modes, and cultural inclinations. But the five-dimensional assessment framework and method for identifying local optima proposed in this study are universal. Planners can utilize such a framework for determining context-sensitive optimal densities.

On the other hand, even if the proposed methods work in theory, real-world issues may arise-e.g., limited funds, existing land use, property rights, political agreement, and public acceptance. These factors deserve attention in follow-up studies and implementation.

7.3 International Comparison and Theoretical Contributions

These findings connect with and add to international work. First, an optimal density range is confirmed, matching Ewing and Cervero (2017) that denser development reduces car dependence. But this study also shows that for small and medium-sized cities, higher density continuously cuts carbon while creating serious noise externalities. This “carbon-noise trade-off effect” contributes new knowledge and responds to Litman’s (2021) call for a full evaluation of transport externalities. Secondly, "functional segmentation of arterials" can provide a spatial solution in the implementation of bus priority and responding to Guerra and Cervero's (2019) call to integrate public transport better with land use and road design. Finally, the five-dimensional evaluation framework incorporates environmental externalities (carbon, noise) together with resilience and equity into a comprehensive trade-off analysis. This goes beyond traditional single- or few-dimensional models and provides a new theoretical approach to road network planning evaluation.

7.4 Research Limitations and Future Directions

This study has limitations:

1) Model Simplification and static assumption: Qingyuan data strengthens the case, but the model is still a simplification. Static OD matrix and average daily conditions do not consider temporal variation (peak / off-peak) and dynamic demand response, which may affect the absolute values of indicators. The results mainly reflect the general state and may not accurately represent the extreme impact during peak hours. However, as comparative analysis uses same assumptions, relative performance trends and identified trade-offs are seen as robust. Future work will be carried out by

using the framework to develop a detailed time-dependent micro-simulation model of the central corridor of Qingyuan for practical testing and improvement.

2) Fleet and Technology Assumptions: The vehicle fleet was modeled using conventional internal combustion engine vehicles. The impact of new technology, such as electric vehicles (the characteristics of the noise and the location of the emission will change) and autonomous driving (potentially affecting traffic flow and network efficiency) were not considered, and they are an important future direction. More cars that produce little noise and operate on electromobility could change the types of noise present in the city and alter the locations where pollution is emitted. This, in turn, changes the environmental trade-offs. Connected and autonomous vehicles (CAVs) could make the system more efficient and resilient, and change the range of optimal density. Future research will need to be done with these new technologies.

3) Model Integration: Although some advanced models (MOVES, CNOSSOS-EU) were applied for sensitivity analysis, future studies should fully integrate microscopic traffic simulation (VISSIM), instantaneous emission models (MOVES), and noise mapping software (CadnaA) into an integrated, automated workflow to accurately simulate vehicle operation, instantaneous emissions and noise propagation under different functional zoning strategies, and conduct further validation and refine design.

4) Equity Dimension: Equity can mainly be evaluated from spatial accessibility. Future research could consider fine-grained socio-economic information (income, age, occupation) at the neighborhood scale to evaluate the distribution of burdens and benefits, such as improved accessibility from transportation facilities, at the demographic level to better understand the equity issues in Qingyuan.

8. Conclusion

It was thus brought into the evaluation system of the network to form the spatial structure, efficiency, equality, resilience, and environmental comprehensive structure. An improved hierarchical CRITIC method was used to explore the comprehensive road network optimization of small and medium-sized cities. The major findings can be found in the following places:

1) A "transit-priority-oriented functional segmentation of arterial roads" strategy was put forward for small and medium-sized cities. This strategy resolves the conflict between public transport and private vehicles by "spatial functional restructuring" (dividing arterials into passenger/freight zones) rather than merely by "right-of-way redistribution", offering a new type of systematic solution to the conflict from the root.

2) A five-dimensional assessment system with 12 indicators was built. The newly added indicators of carbon emission intensity and noise-exceeding area proportion are used to measure the environmental impact and trade-off of the layout of the new road network.

3) Cases based on the Qingyuan situation show an optimal road network density range (about 12.8 km/km^2). Higher density (21.1 km/km^2) can strengthen the structure and demand resilience, but also results in efficiency reduction, supply resilience risk, and noise problems. A real-world context is used to further this conclusion and to make it more relatable as a benchmark. The identified optimal value is context-specific, and the proposed evaluation framework can be used to determine the optimal value in the context.

4) The discovery of the "carbon-noise" trade-off effect shows that the traditional planning paradigm of "higher density being more sustainable" requires rethinking. Future sustainable transportation planning must be a multi-objective optimization. The five-dimensional evaluation framework constructed herein can be used as a good decision-making tool to achieve coordinated optimization of the four targets of efficiency, equity, resilience, and environmental benefits.

Acknowledgments

Thanks to Guangdong Province, Qingyuan City Philosophy and Social Sciences Planning Project (QYSK2025014).

References

[1] Deng, H., Wen, W., & Zhang, W. (2023). Analysis of road network features of urban municipal district based on fractal dimension. *ISPRS International Journal of Geo-Information*, 12(5), 188. https://doi.org/10.3390/ijgi12050188

[2] Chen, H., Yu, P., Hailey, D., & Cui, T. (2021). Application of a four-dimensional framework to evaluate the quality of the HIV/AIDS data collection process in China. *International Journal of Medical Informatics*, 145, 104306. https://doi.org/10.1016/j.ijmedinf.2020.104306

[3] Luitel, S., Pokhrel, A., Poudel, R., & Tiwari, H. (2024). Calibration of VISSIM model for urban multilane highways using highway capacity in mixed traffic condition-A case study. *International Journal on Engineering Technology and Infrastructure Development*, 1(1), 111–121. https://doi.org/10.3126/injet-indev.v1i1.67942

[4] Alshammari, T. O., Hassan, A. M., Arab, Y., Hussein, H., Khozaei, F., Saeed, M., Ahmed, B., Zghaibeh, M., Beitelmal, W., & Lee, H. (2022). The compactness of non-compacted urban developments: A critical review on sustainable approaches to automobility and urban sprawl. *Sustainability*, 14(18), 11121. https://doi.org/10.3390/su141811121

[5] Kwon, Y., Lee, M., Lee, M. J., & Son, S.-W. (2025). A computational analysis of traffic cluster dynamics using a percolation-based approach in urban road networks. *Journal of Computational Science*, 102675. https://doi.org/10.1016/j.jocs.2025.102675

[6] Zhang, L., Yang, Y., Cheng, Q., Luo, M., Zhang, X., & Wang, Y. (2022). Evaluation of spatial fairness of urban public transport service: A case study of Wuhan City. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 43, 579–585. https://doi.org/10.5194/isprs-archives-XLIII-B4-2022-579-2022

[7] Yin, K., Wu, J., Wang, W., Lee, D.-H., & Wei, Y. (2023). An integrated resilience assessment model of urban transportation network: A case study of 40 cities in China. *Transportation Research Part A: Policy and Practice*, 173, 103687. https://doi.org/10.1016/j.tra.2023.103687

[8] Ma, Z., Yang, X., Wu, J., Chen, A., Wei, Y., & Gao, Z. (2022). Measuring the resilience of an urban rail transit network: A multi-dimensional evaluation model. *Transport Policy*, 129, 38–50. https://doi.org/10.1016/j.tranpol.2022.10.003

[9] Lawson, C. T. (2006). Microsimulation for urban transportation planning: Miracle or mirage? *Journal of Urban Technology*, 13(1), 55–80. https://doi.org/10.1080/10630730600752868

[10] Cao, D., Li, L., Shao, S., & Mahamoudou, F. (2024). Multi-objective optimisation for urban road network maintenance based on spatial design network analysis: trade-offs in performance, environmental impacts, and costs. *International Journal of Pavement Engineering*, 25(1), 2444502. https://doi.org/10.1080/10298436.2024.2444502

[11] Scott, D. M., Novak, D. C., Aultman-Hall, L., & Guo, F. (2006). Network robustness index: A new method for identifying critical links and evaluating the performance of transportation networks. *Journal of Transport Geography*, 14(3), 215–227. https://doi.org/10.1016/j.jtrangeo.2005.10.003

[12] Cui, Y., Yu, Y., Cai, Z., & Wang, D. (2022). Optimizing road network density considering automobile traffic efficiency: theoretical approach. *Journal of Urban Planning and Development*, 148(1), 04021062. https://doi.org/10.1061/(asce)up.1943-5444.0000780

[13] Torres-Falcón, M., Rodríguez-Abreo, O., Romero-Sánchez, M., Carrera, L. A. I., & Rodríguez-Reséndiz, J. (2025). Optimizing urban bus networks through mathematical modeling: Environmental and operational gains in medium-sized cities. *Eng*, 6(9), 238. https://doi.org/10.3390/eng6090238

[14] Yu, H., Liu, R., Li, Z., Ren, Y., & Jiang, H. (2021). An RSU deployment strategy based on traffic demand in vehicular ad hoc networks (VANETs). *IEEE Internet of Things Journal*, 9(9), 6496–6505. https://doi.org/10.1109/jiot.2021.3111048

[15] Santos, G., Behrendt, H., Maconi, L., Shirvani, T., & Teytelboym, A. (2010). Part I: Externalities and economic policies in road transport. *Research in Transportation Economics*, 28(1), 2–45. https://doi.org/10.1016/j.retrec.2009.11.002

[16] Jacyna, M., Żochowska, R., Sobota, A., & Wasiak, M. (2021). Scenario analyses of exhaust emissions reduction through the introduction of electric vehicles into the city. *Energies*, 14(7), 2030. https://doi.org/10.3390/en14072030

[17] Schofer, J. L., & Stopher, P. R. (1979). Specifications for a new long-range urban transportation planning process. *Transportation*, 8(3), 199–218. https://doi.org/10.1007/bf00169988

[18] Li, S., Kim, T., & Song, J. (2022). System-reliability-based disaster resilience analysis: Framework and applications to structural systems. *Structural Safety*, 96, 102202. https://doi.org/10.1016/j.strusafe.2022.102202

[19] Zeng, Z., Huang, S., Guo, H., Yuan, T., Liu, N., & Sun, P. (2025). Vehicle interior multi-zone sound field reproduction with uncertain disturbance of acoustic transfer function. *Acoustics Australia*, 1–13. https://doi.org/10.1007/s40857-025-00346-2