International Journal of Multidisciplinary Research and Growth Evaluation.

Optimizing Urban Sustainable Transport Using Spatial – Analytical Data Integration: A Case Study from Makassar, Indonesia

Rahmaniah Malik [1], A Pawennari [2], Ahmad Padhil [3*], Nurhikma Natasya [4]
[1-4] Department of Industrial Engineering, Universitas Muslim Indonesia Indonesia

* Corresponding Author: **Ahmad Padhil**

Article Info

ISSN (online): 2582-7138
Volume: 06
Issue: 04
July - August 2025
Received: 16-05-2025
Accepted: 17-06-2025
Published: 19-07-2025
Page No: 1036-1041

Abstract
Urban transportation systems in rapidly growing cities face escalating challenges in balancing operational efficiency with environmental sustainability. This study aims to develop a conceptual optimization model for sustainable urban transport using spatial data integration and analytical simulation, with a specific case study in Makassar, Indonesia. The research adopts an exploratory-quantitative method using secondary data, including road networks, traffic volume, and carbon emissions. The data were processed using QGIS and Python (NetworkX and GeoPandas) to build a transport network graph. A Genetic Algorithm (GA) was employed to simulate route optimization by minimizing a composite objective function of travel time and CO_2 emissions.

Simulation results demonstrate that the optimized routes yield a 19% reduction in average travel time, a 17.8% reduction in fuel consumption, and a 20.4% decrease in carbon emissions compared to the existing routes. Spatial analysis using heatmaps and K-Means clustering further revealed high-risk traffic zones, particularly near business centers and university areas. Sensitivity analysis of the objective function weights indicated significant trade-offs between time efficiency and emission reduction, offering flexibility for policy-makers to prioritize based on local goals.

The model contributes both practically and academically by presenting a replicable framework for Indonesian cities aiming to align with SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action). Although this study remains at the conceptual and simulation phase (Technology Readiness Level 1–3), it lays the groundwork for future implementation through real-time data integration and pilot testing. The findings provide valuable insights for urban planners, government agencies, and smart city initiatives in emerging economies.

Keywords: Sustainable Transport, Spatial Data, Carbon Emission, Optimization Model, Genetic Algorithm

1. Introduction

Rapid urbanization has transformed the dynamics of transportation systems in developing countries, especially in Southeast Asia. According to the United Nations (2018) [11], more than 55% of the global population resides in urban areas, a figure expected to rise to 68% by 2050. As urban populations grow, so does the demand for efficient, accessible, and sustainable urban transport. However, many cities struggle with severe congestion, excessive fuel consumption, and elevated greenhouse gas emissions—issues that are especially acute in middle-income countries like Indonesia.

In Indonesia, major cities such as Jakarta, Surabaya, and Makassar are increasingly affected by traffic congestion and poor air quality. According to Bappenas (2020) [1], economic losses due to traffic congestion in Jakarta alone exceed IDR 65 trillion per year. The transportation sector contributes up to 30% of total urban emissions, primarily from land-based modes dominated by private vehicles. The situation is exacerbated in secondary cities like Makassar, where public transportation is underdeveloped, and urban infrastructure has not kept pace with demand.

The integration of data-driven technologies presents a significant opportunity to address these urban transport challenges. Geographic Information Systems (GIS) and spatial analytics enable real-time route optimization, better traffic flow management, and accurate emissions modeling. Recent studies, such as Zhang *et al*. (2020) [15] and Wang *et al*. (2021) [13], have demonstrated that the application of spatial data and algorithmic models can reduce travel time and carbon emissions by 15–20%. However, most existing models are developed in the context of Global North cities, leaving a gap in research applicable to emerging urban contexts Padhil *et al*. (2022) [9].

Makassar, a rapidly growing city in Eastern Indonesia, presents a compelling case for implementing a sustainable urban transport model. The city has initiated Smart City programs, but faces a significant rise in average travel time—up to 25% over the past five years—as well as increasing emissions, currently estimated at 1.2 million tons of CO_2 annually from the transport sector. The imbalance between the rapid urban sprawl and under-optimized transport systems underscores the urgent need for data-informed intervention.

Sustainable urban mobility is critical to achieving several United Nations Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action). The development of a transport optimization model that integrates spatial data and analytical algorithms can enhance operational efficiency, reduce emissions, and improve the quality of urban life. While some initiatives such as electric vehicles and limited bus rapid transit systems have been launched, their impact remains fragmented due to weak integration and lack of predictive analytics.

This study addresses the gap by developing a conceptual optimization model based on spatial data and analytical simulation tailored to the city of Makassar. The model aims to: (1) reduce average travel time, 2) minimize fuel consumption, and 3) significantly lower CO_2 emissions through optimized routing using Genetic Algorithms (GAs). The model also incorporates a sensitivity analysis to explore trade-offs between travel efficiency and environmental performance, a critical aspect for policy formulation in cities with limited infrastructure investment.

This research offers several contributions. First, it applies advanced spatial and algorithmic techniques in a secondary Indonesian city context, where such integration remains underexplored. Second, the model is designed to be modular and replicable, making it scalable to other Indonesian cities with similar characteristics. Third, it evaluates the feasibility of early-stage implementation (Technology Readiness Level 1–3) as a foundation for future real-time and user-responsive systems.

In summary, this study provides a structured, data-driven solution to the pressing issues of urban congestion and emissions in Makassar, with broader implications for sustainable transport planning in emerging economies. The rest of this paper is structured as follows: Section 2 reviews the relevant literature; Section 3 presents the research methodology and simulation framework; Section 4 discusses the results and spatial insights; and Section 5 concludes with policy implications and recommendations for further development.

2. Literature Review

Urban transportation has become a central issue in sustainable development discourse, particularly in the context of climate change and urban livability. According to the Intergovernmental Panel on Climate Change (IPCC, 2022) [4], the transportation sector contributes approximately 24% of direct CO_2 emissions from fuel combustion, with urban road transport accounting for nearly three-quarters of that figure. Consequently, optimizing urban transport systems has become critical for achieving global environmental targets and improving the quality of urban life.

2.1 Spatial Data and Urban Transport Modeling

The use of spatial data in transport planning has grown significantly in the past decade. Geographic Information Systems (GIS) enable the visualization and analysis of road networks, traffic flows, and spatial distribution of emissions. Studies such as Zhang *et al*. (2020) [15] and Goh & Wong (2019) [3] have demonstrated that spatial mapping combined with algorithmic optimization can reduce fuel consumption and travel time by up to 15%. These applications often involve shortest-path algorithms, traffic simulation models, and predictive analytics based on historical mobility patterns. Moreover, spatial data has been integrated with Internet of Things (IoT) systems to facilitate real-time transport management. In developed cities, dynamic routing and smart signaling systems have already been implemented using real-time GPS and traffic sensor inputs. However, such systems require advanced infrastructure and high levels of data fidelity, which remain limited in most developing countries.

2.2 Optimization Algorithms in Urban Transport

Optimization techniques have been extensively employed in urban transport research to improve route efficiency, reduce congestion, and minimize emissions. Genetic Algorithms (GAs), Ant Colony Optimization (ACO), and Particle Swarm Optimization (PSO) are among the most popular approaches. Wang *et al*. (2021) [13] applied GA for route optimization in Chengdu, China, achieving an 18% reduction in total travel time during peak hours. Similarly, Ferris & Kaushal (2021) [2] incorporated emission metrics into their optimization model to account for environmental externalities Malik *et al*. (2024) [6].

These algorithms are effective for solving multi-objective problems, especially in urban environments with complex constraints. However, they often rely on high-quality, real-time data, and their application in emerging urban contexts remains limited. Additionally, many studies focus on time minimization without equally considering emission reduction, which is essential for long-term sustainability.

2.3 Transport Systems in Indonesia

Urban transport systems in Indonesia face unique challenges including poor integration between modes, dominance of private vehicles, and underdeveloped public transit systems. Purnomo *et al*. (2020) [10] observed that Indonesian cities suffer from modal imbalance, with private motorcycles and cars accounting for over 90% of trips. Moreover, policy efforts toward sustainable mobility, such as Bus Rapid Transit (BRT) or electric vehicles (EVs), remain localized and lack systemic integration.

Makassar, a secondary city in Eastern Indonesia, has initiated Smart City infrastructure, yet still experiences significant congestion and high emissions. Nababan *et al*. (2021) [8] highlighted the lack of spatial transport models in Indonesian cities that incorporate both environmental and operational efficiency criteria. There is also limited use of optimization algorithms in municipal transport planning.

2.4 Research Gap and Novel Contribution

While considerable research has been conducted on urban transport optimization and spatial modeling, there remain notable gaps:

- **Contextual Gap:** Most spatial-analytical models are developed for high-income cities with advanced infrastructure. There is a scarcity of studies that focus on rapidly growing cities in Southeast Asia, particularly Indonesia.
- **Methodological Gap:** Existing models often prioritize time or cost minimization but neglect environmental outcomes such as carbon emissions. Few studies integrate emissions data directly into the optimization function.
- **Applicability Gap:** Many models are not designed for modular replication across different urban contexts. This limits their scalability and real-world adoption.

This study seeks to address these gaps by:

- **Integrating spatial data and carbon emission metrics** within a unified optimization model using Genetic Algorithms;
- **Focusing on a mid-sized, rapidly growing city (Makassar)** in an emerging economy with Smart City potential;
- **Conducting sensitivity analysis** to explore the trade-off between speed and emission reduction, which provides flexibility for urban policy decision-making;
- **Providing a replicable framework** that can be adapted for other Indonesian cities facing similar challenges.

In doing so, this research contributes to both the academic literature on sustainable transport optimization and to the practical implementation of data-driven transport planning in developing urban regions.

3. Methods

3.1 Research Design

This study employed an exploratory-quantitative research design focused on developing and validating a conceptual optimization model for sustainable urban transport. The objective was to simulate an improved routing system that minimizes both travel time and carbon emissions using spatial data and analytical algorithms. The study was conducted as part of a Technology Readiness Level (TRL) 1–3 investigation, emphasizing model development, simulation, and theoretical validation.

3.2 Data Collection

All data used in this research were secondary in nature, considering the study's early-stage (conceptual) approach. The datasets were sourced from public institutions and open-access platforms:

- **Spatial data:** Road network shapefiles, urban zoning maps, and intersection nodes were acquired from the Makassar City Transportation Office and OpenStreetMap.
- **Traffic operational data:** Vehicle volume, speed averages, and congestion indices were collected from the annual transport reports of Makassar's Department of Transportation (2022–2023).
- **Carbon emission data:** Fuel consumption estimates and CO_2 emission factors were obtained from theMinistry of Environment and Forestry (KLHK) and IPCC guidelines (2022) [4].

All datasets were processed to ensure consistency in coordinate systems, scale, and data format using QGIS 3.28.

3.3 Spatial Network Modeling

- The spatial road network was transformed into a graph structure using **Python** with NetworkX and GeoPandas libraries. In this model:
- **Nodes** represented intersections or major decision points.
- **Edges** represented road segments with attached attributes including:
- Length (in meters),
- Speed_avg (km/h),
- Volume (vehicles/hour),
- Capacity (vehicles/hour),
- Emission_factor (kg CO_2/trip).

This transformation enabled graph-based simulation of route selection, traffic flow, and emission estimations.

3.4 Optimization Algorithm

To perform route optimization, a **Genetic Algorithm (GA)** was selected due to its ability to handle multi-objective and nonlinear problems in urban networks. The algorithm was designed to optimize the following objective function:

$$f(x)=\alpha \cdot T(x)+\beta \cdot E(x)$$

Where:

- T(x)T(x)T(x): total travel time on route xxx
- E(x)E(x)E(x): total CO_2 emissions on route xxx
- α\alphaα and β\betaβ: weight parameters reflecting the priority between efficiency and sustainability

Default setting: α=0.6\alpha = 0.6α=0.6, β=0.4\beta = 0.4β=0.4

Simulation Parameters

- Initial population size: 100 individuals
- Maximum generations: 50
- Crossover rate: 0.8
- Mutation probability: 0.1
- Fitness function: Minimization of the composite objective f(x)f(x)f(x)

The GA iteratively selected, crossed, and mutated route paths across generations to minimize the objective function.

3.5 Emissions and Fuel Consumption Modeling

Emissions were calculated using the following equation:

E=FC×EFE = FC \times EFE=FC×EF

Where:

- EEE: carbon emissions (kg CO_2)
- FCFCFC: fuel consumption per trip (liters)
- EFEFEF: emission factor (2.2 kg CO_2/liter for gasoline, 2.7 for diesel)

Fuel consumption was estimated based on average vehicle speed, type, and route length. Modal distribution data indicated dominance of motorcycles (67%), private cars (28%), and public transport (5%).

3.6 Validation and Sensitivity Analysis
To validate the performance of the optimized model, simulation results were compared against baseline metrics derived from current route data:
- Travel time (minutes)
- Fuel consumption (liters/trip)
- CO_2 emissions (kg/trip)

In addition, **sensitivity analysis** was conducted by varying the weights α\alphaα and β\betaβ in the objective function to assess trade-offs between efficiency and emissions.

Example scenarios:

α	β	Travel Time	Emissions
0.6	0.4	34 min	2.10 kg
0.4	0.6	36 min	1.84 kg

3.7 Spatial Risk Clustering
To identify high-risk traffic zones, K-Means clustering was used with the following variables:
- Traffic volume (vehicles/hour)
- Volume/Capacity (V/C) ratio
- Conflict points (intersections)
- Proximity to public facilities (e.g., campuses, markets)

Clusters were visualized spatially in QGIS to guide policy recommendations for route prioritization and infrastructure interventions.

4. Results and Discussion
4.1. Baseline Analysis of Existing Transport Conditions
Initial analysis of Makassar's transport network revealed substantial inefficiencies in both traffic flow and environmental performance. Peak-hour average travel times reached 42 minutes on primary corridors such as Jalan A.P. Pettarani, Jalan Perintis Kemerdekaan, and Jalan Urip Sumoharjo. These corridors exhibited a volume-to-capacity (V/C) ratio exceeding 1.2, indicating a state of overcapacity. The modal distribution was also imbalanced: 67% of all trips were made by motorcycles, 28% by private cars, and only 5% by public transport. This disproportionate use of private vehicles contributes significantly to congestion and emissions. These findings are consistent with prior research (Purnomo *et al*., 2020, Lamatinulu, 2023) [10, 5] that identified modal dominance as a key barrier to efficient and sustainable urban mobility in Indonesian cities.

4.2. Route Optimization Simulation Results
The spatial-analytical optimization model was tested using a Genetic Algorithm to generate improved routing under the defined objective function (minimizing time and emissions). The simulation compared existing routes with optimized ones, yielding the following results:

Table 1: Results of the Route Optimization Simulation Results

Parameter	Existing Route	Optimized Route	Efficiency Gain
Route Length (km)	11.4	10.7	−6.1%
Travel Time (minutes)	42	34	−19.0%
Fuel Consumption (L/trip)	1.23	1.01	−17.8%
CO_2 Emissions (kg/trip)	2.64	2.10	−20.4%

These results show clear benefits in both operational efficiency and environmental performance. A 20.4% reduction in CO_2 emissions is especially significant given the national commitment to the Paris Agreement and the UN SDGs.

4.3 Spatial Pattern Analysis and Congestion Risk Zones
Using GIS-based clustering techniques, the study identified high-risk congestion zones that correspond with areas of high activity density, such as university campuses, commercial centers (e.g., Panakkukang, CPI), and the airport corridor. Three main zone categories were derived via K-Means clustering:

Table 2: Results of the Spatial Pattern Analysis and Congestion Risk Zones

Zone	Characteristics	Policy Recommendations
Red Zone	High volume, V/C > 1.3, central business districts	Prioritize route optimization and public transport access
Yellow Zone	Medium volume, V/C ~ 1.0, residential-commercial mixed use	Improve feeder systems and modal integration
Green Zone	Low volume, peripheral zones	Enhance connectivity through smart feeder networks

These spatial insights can inform city-level infrastructure investment and policy design, especially for congestion relief and emission mitigation.

4.4 Spatial Pattern Analysis and Congestion Risk Zones
A sensitivity analysis was conducted to examine how changes in the objective function weights (α\alphaα for travel time and β\betaβ for emissions) impact simulation outcomes.

Table 3: Results of the Spatial Pattern Analysis and Congestion Risk Zones

α (time)	β (emissions)	Travel Time (min)	CO_2 Emissions (kg)
0.6	0.4	34	2.10
0.4	0.6	36	1.84

The results demonstrate a meaningful trade-off between travel efficiency and environmental benefits. When emissions are prioritized (β = 0.6), the model sacrifices 2 minutes of travel time for a 12.4% further reduction in emissions. These findings suggest that transport policy can be tailored to prioritize environmental goals in specific zones or time windows (e.g., green corridors or eco-zones).

4.5 Quantitative Model Performance Metrics
Beyond route-specific analysis, the simulation also improved broader transport system performance indicators:

Table 4: Results of the Quantitative Model Performance Metrics

Performance Indicator	Before Optimization	After Optimization	Improvement
Average Speed (km/h)	22.4	29.5	+31.7%
Network Efficiency Index	0.78	0.89	+14.1%
Average Delay per Trip (min)	11.2	6.7	−40.2%
Fuel Consumption per km (L)	0.108	0.094	−12.9%
Carbon Emissions Index	2.64 kg/trip	2.10 kg/trip	−20.4%

These quantitative gains reflect not only individual route efficiency but also systemic improvements in traffic flow and environmental sustainability.

4.6 Comparison with Prior Studies

Table 5: Results of the Comparison with Prior Studies

Study	Location	Method	Emission Reduction	Relevance
Zhang *et al.* (2020) [15]	Beijing	GIS + Shortest Path	15%	Validates spatial routing
Wang *et al.* (2021) [13]	Chengdu	Genetic Algorithm	18%	Same optimization technique
Nababan *et al.* (2021) [8]	Surabaya	Heatmap Analysis	N/A	Similar spatial congestion clustering
This study	Makassar	GIS + GA + Sensitivity	20.4%	Integrates emissions + optimization

Compared to the global literature, this study presents a stronger integrative framework that balances operational and environmental goals in a developing city context

4.7. Policy Implications and Future Applications

The findings of this research carry multiple policy implications:

- **Smart City Integration:** Makassar's existing infrastructure (e.g., GPS systems, traffic sensors) can be leveraged for real-time implementation in the next phase of the model.
- **Data-Driven Planning:** Spatial heatmaps and emission maps can inform transport corridor planning, zoning policies, and investment priorities.
- **Adaptive Optimization:** Weight parameters in the optimization model can be adjusted dynamically based on time-of-day, policy goals, or air quality levels.
- **Scalability:** The model is replicable in other Indonesian cities such as Surabaya, Palembang, and Yogyakarta—those facing similar urban dynamics.

5. Conclusion

This study proposed a spatial-analytical optimization model for sustainable urban transport with a focus on Makassar, Indonesia—a city facing rising congestion and carbon emissions. By integrating spatial data, transport indicators, and algorithmic simulation via a Genetic Algorithm, the model demonstrated significant improvements in both operational and environmental performance.

Simulation results showed that optimized routes reduced average travel time by 19%, fuel consumption by 17.8%, and CO_2 emissions by 20.4% compared to existing routes. Additionally, spatial analysis identified high-risk congestion zones that overlap with activity-dense areas, offering insights for urban planning and intervention. Sensitivity analysis of the optimization weights revealed flexible trade-offs between speed and emissions, enabling adaptive policy implementation.

This study contributes to the literature by applying advanced optimization and spatial tools in a secondary city context, an area largely underrepresented in urban transport research. It also provides a replicable model framework that can be scaled to other Indonesian cities with similar urban challenges.

Despite its promising findings, this study remains at the conceptual and simulation phase (Technology Readiness Level 1–3). Future research should focus on incorporating real-time data from GPS and IoT systems, field-based pilot testing, and integration into smart city platforms. Policymakers are encouraged to adopt data-driven transport planning to achieve national climate commitments and sustainable mobility goals outlined in SDG 11 and SDG 13.

6. References

1. Bappenas. Evaluasi dampak ekonomi kemacetan di kota metropolitan Indonesia. Jakarta: Badan Perencanaan Pembangunan Nasional; 2020.
2. Ferris T, Kaushal R. Reducing traffic emissions through digital innovation. J Environ Eng. 2021;47(2):143-58.
3. Goh K, Wong YD. Smart mobility applications in urban transport systems. Transp Res Procedia. 2019;44:319-28.
4. IPCC. Climate change 2022: mitigation of climate change. Geneva: Intergovernmental Panel on Climate Change; 2022.
5. Lamatinulu L. Interpretive structural modeling of performance improvement strategies on the perspective of customers. Int J Tech Phys Probl Eng. 2023;15(15):1-9.
6. Malik R, Safutra NI, Fole A, Pangestu FA. Improving resilience in water distribution systems: an application of the House of Risk method at PDAM Gowa Unit Tompobulu. J Sist Tek Ind. 2024;26(2):199-209.
7. Ministry of Environment and Forestry. Indonesia second biennial update report to the UNFCCC. Jakarta: MoEF; 2021.
8. Nababan I, Sutanto H, Rahmawati A. Evaluation of spatial data for urban transport planning in Surabaya. J Rekayasa Sist. 2021;15(3):253-65.
9. Padhil A, Hafid MF, Wahyuni AD. Risk analysis of water distribution in PDAM City of Makassar using the House of Risk (HOR) method. Am J Mech Ind Eng. 2022;7(4):63-9.
10. Purnomo EA, Santoso D, Widodo M. Urban transport challenges in developing countries: case study of Indonesia. J Urban Plan Dev. 2020;146(2):04020016. doi:10.1061/(ASCE)UP.1943-5444.0000584.
11. United Nations. World urbanization prospects: the 2018

revision. New York: United Nations; 2018.
12. United Nations. Sustainable development goals report. New York: United Nations; 2020.
13. Wang H, Chen H, Li J. Optimization algorithms for urban traffic management: a comprehensive review. Transp Res Part C Emerg Technol. 2021;129:103212. doi:10.1016/j.trc.2021.103212.
14. World Bank. Sustainable mobility for all: transforming urban transport. Washington, D.C.: World Bank; 2021.
15. Zhang X, Liu Y, Chen Y. Spatial data analysis for sustainable urban transportation: a case study in Beijing. J Clean Prod. 2020;261:121208. doi:10.1016/j.jclepro.2020.121208.