South American Publishing

SAP Land and Architecture. 2025; 4:151
doi: 10.56294/la2025151

ORIGINAL

A hybrid environmental multi-objective optimization algorithm for eco-friendly vehicle routing in smart cities

Un algoritmo híbrido de optimización ambiental multiobjetivo para el enrutamiento ecológico de vehículos en ciudades inteligentes

Amrita Prakash[1], Amir Khusru Akhtar[1]

[1]Faculty of Computing and IT, Usha Martin University. Ranchi, Jharkhand, India – 835103.

Cite as
Prakash A, Khusru Akhtar A. A hybrid environmental multi-objective optimization algorithm for eco-friendly vehicle routing in smart cities. SAP Land and Architecture. 2025; 4:151. https://doi.org/10.56294/la2025151

Publication History
Submitted: 17-04-2024
Revised: 01-09-2024
Accepted: 03-01-2025
Published: 04-01-2025

Corresponding Author
Amrita Prakash

ABSTRACT

Introduction: this paper presents HEMO, an intelligent vehicle routing system designed to address urban sustainability challenges in smart cities. The algorithm optimizes transportation networks by simultaneously evaluating multiple environmental and operational parameters, including route efficiency, vehicular emissions, fuel efficiency, noise pollution, and traffic regulation compliance.

Method: our comprehensive evaluation demonstrates HEMO's superior performance compared to conventional routing approaches, achieving significant improvements across all measured metrics: a 19,3 % reduction in travel distance, 20,7 % decrease in harmful emissions, and 19,5 % lower fuel consumption. Notably, the system shows exceptional effectiveness in mitigating urban nuisances, with 75 % fewer noise violations and 77,8 % reduction in speed limit infractions.

Results: these results establish HEMO as a balanced solution that harmonizes ecological preservation with traffic management objectives. The algorithm's multi-criteria optimization framework represents a substantial advancement over existing eco-routing methods, offering municipal authorities a practical tool for implementing sustainable mobility solutions.

Conclusions: by dynamically adapting to real-time urban conditions while prioritizing environmental protection, HEMO provides a scalable model for smart city infrastructure that addresses both immediate traffic concerns and long-term sustainability goals.

Keywords: Eco-friendly Routing; Smart City Traffic; Vehicle Routing Optimization; Emissions Reduction.

RESUMEN

Introducción: este artículo presenta HEMO, un sistema inteligente de enrutamiento de vehículos diseñado para abordar los retos de sostenibilidad urbana en las ciudades inteligentes. El algoritmo optimiza las redes de transporte evaluando simultáneamente múltiples parámetros medioambientales y operativos, como la eficiencia de las rutas, las emisiones de los vehículos, la eficiencia del combustible, la contaminación acústica y el cumplimiento de las normas de tráfico.

Método: nuestra evaluación exhaustiva demuestra el rendimiento superior de HEMO en comparación con los enfoques de enrutamiento convencionales, logrando mejoras significativas en todas las métricas medidas: una reducción del 19,3 % en la distancia de viaje, una disminución del 20,7 % en las emisiones nocivas y un 19,5 % menos de consumo de combustible. En particular, el sistema muestra una eficacia excepcional en la mitigación de las molestias urbanas, con un 75 % menos de infracciones por ruido y una reducción del 77,8 % en las infracciones de los límites de velocidad.

Resultados: estos resultados establecen que HEMO es una solución equilibrada que armoniza la preservación ecológica con los objetivos de gestión del tráfico. El marco de optimización multicriterio del algoritmo representa un avance sustancial con respecto a los métodos de trazado ecológico existentes y ofrece a las autoridades municipales una herramienta práctica para aplicar soluciones de movilidad sostenible.

Conclusiones: al adaptarse dinámicamente a las condiciones urbanas en tiempo real y dar prioridad a la protección del medio ambiente, HEMO ofrece un modelo escalable de infraestructura urbana inteligente que aborda tanto los problemas de tráfico inmediatos como los objetivos de sostenibilidad a largo plazo.

Palabras clave: Enrutamiento Ecológico; Tráfico de Ciudades Inteligentes; Optimización de Rutas de Vehículos; Reducción de Emisiones.

© 2025; The Authors. This Open access article is distributed under the Creative Commons Attribution 4.0 license (https://creativecommons.org/licenses/by/4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

INTRODUCTION

In today's cities, transport is a big problem, especially for the environment. Traditional routing only cuts cost and time but ignores pollution, fuel use, and noise.[1] In smart cities, with real-time data, we need solutions that balance efficiency and environment. Eco-friendly routing helps reduce emissions, fuel use, and other factors. Smart cities provide the right setting for such solutions, as they include features like green zones, emission-controlled areas, and advanced traffic management.[2]

This research presents a Hybrid Environmental Multi-Objective (HEMO) optimization algorithm. It combines Genetic Algorithm (GA), Ant Colony Optimization (ACO), and Particle Swarm Optimization (PSO) to improve routing by minimizing travel distance, fuel consumption, and emissions. This work also extends the Solomon Dataset[3] by adding eco-friendly metrics like fuel efficiency, noise etc. The aim is to offer a practical solution for sustainable vehicle routing in smart cities.

The main objectives of this research are:

- Develop a Hybrid Environmental Multi-Objective (HEMO) optimization algorithm.
- Extend the existing Solomon Dataset to include eco-friendly metrics.
- Demonstrate the algorithm's efficiency using extended Solomon dataset.

The rest of the paper is organized like this: section 2 gives a review of literature on vehicle routing problems, eco-friendly routing techniques, and hybrid optimization algorithms. Section 3 explains the HEMO algorithm, its framework, and how it works. Section 4 talks about the experimental setup, dataset changes, and results, comparing the proposed method with existing ones. Section 5 wraps up the research and suggests ideas for future work.

Literature Review

The Vehicle Routing Problem (VRP) is about finding the best route for a fleet of vehicles to serve customers.[1] There are many types of VRP, like Capacitated VRP (CVRP), Time Window VRP (TWVRP), and Stochastic VRP. The main goal is to reduce the total distance traveled by all vehicles. VRP can be written as:

$$min \sum_{i,j} \quad d_{ij} \cdot x_{ij}$$

Eco-friendly routing focuses on reducing fuel consumption and emissions.[4] In smart cities, we can use sensors and real-time data to avoid congested roads, reducing fuel use.[5] Researchers are looking at using electric vehicles (EVs) and alternative fuel sources in routing problems.[6] These solutions aim to balance cost and environmental impact.

In eco-friendly vehicle routing, there are many goals, such as minimizing fuel consumption, emissions, and travel time.[4] Multi-objective optimization is used to handle multiple goals at once. The challenge is to find a balanced solution, where no single goal is sacrificed too much. This is where techniques like Pareto optimization come in [7].

The multi-objective optimization can be expressed as:

$$f_1(x), \ f_2(x), \ldots, f_n(x)$$

Where f_1, f_2,…, f_n represent the objectives, like minimizing travel distance, fuel consumption, and emissions.

Hybrid algorithms mix different methods to solve complex problems better.[8] GA is based on natural selection,[9] ACO copies ant behavior,[10] and PSO follows social behavior.[11] Combining them works well for eco-friendly vehicle routing.

In smart cities, eco-friendly routes are key. Real-time data from sensors, IoT, and GPS help find the best paths. These methods cut emissions, avoid traffic, and save fuel.[12] Some cities use EV charging and green zones to go greener.[13]

Table 1. Review of Related Research Work

Research Work	Description	Advantage	Research Gap
VRP[1]	Study of basic VRP and its variants	Helps to model and solve basic routing problems	No focus on eco-friendly routing
Eco-Friendly Routing[7]	Focus on minimizing emissions, fuel use, and environmental impact	Reduces carbon footprint and enhances sustainability	Limited integration with real-time smart city data
Multi-Objective Optimization[14]	Optimization of multiple objectives like distance, emissions, and fuel use	Balances different goals like fuel, distance, and emissions	Most models focus on one or two objectives only
Hybrid Optimization[15]	Combination of GA, ACO, and PSO to solve complex routing problems	Improves solution quality and speed	Increased complexity with multi-objective problems
Smart City Eco-Friendly Routing[16]	Integration of IoT and real-time data for eco-friendly routing	Improves real-time decision-making and reduces emissions	Data integration and scalability issues

But challenges remain. Traffic changes in real-time, and combining data from signals, weather, and vehicles is difficult. Many methods focus on one goal, but real-world problems need balance across many factors.[17] Table 1 shows the benefits and gaps in research.

https://doi.org/10.56294/la2025151

METHOD

Proposed Work

HEMO is a smart algorithm designed to find the best routes for vehicles while keeping in mind the environment. It works by minimizing travel distance, emissions, fuel usage, and noise, while also making sure the speed stays within limits. This algorithm looks at multiple factors to ensure that the routing is eco-friendly and traffic-efficient, especially in urban settings.

The framework we use combines different factors that affect route selection. It looks at travel distance, fuel consumption, emissions, and noise together. By using hybrid methods, it tries to balance these objectives. The key is to ensure that all the factors work together without one dominating the others. It's like trying to juggle multiple things at once, where the goal is to minimize negative impacts on the environment and traffic.

Mathematical Formulation of the Objective Functions

The objective of HEMO is to minimize the following combined objective function:

$$Z = \lambda_1 \cdot D + \lambda_2 \cdot E + \lambda_3 \cdot F + \lambda_4 \cdot N + \lambda_5 \cdot S \quad (1)$$

Where, Z is overall objective function, D is total travel distance, E is Total emissions, F is total fuel consumption, N is total noise level, S is Speed violations and λ_1, $\boldsymbol{\lambda}_2$, $\boldsymbol{\lambda}_3$, $\boldsymbol{\lambda}_4$, $\boldsymbol{\lambda}_5$ are weight coefficients.

The objective is to minimize the weighted sum of these five factors, which are calculated as follows:

Minimizing Travel Distance (D)

The travel distance is the sum of the distances between all customers (or stops) along the route:

$$D = \sum_{i=1}^{n} d_i \quad (2)$$

Where, d_i is Distance between customer i and i+1 and n are number of stops.

Minimizing Emissions (E)

Emissions are determined by the distance traveled and the emission factor e_v. The total emissions are given by:

$$D = e_v \times \sum_{i=1}^{n} d_i \quad (3)$$

Where, e_v is Emission factor (gCO2/km), d_i is distance for the ith road segment.

Minimizing Fuel Consumption (F)

Fuel consumption depends on the vehicle's energy consumption rate r_v (in kWh/km). The total fuel consumption is:

$$D = r_v \times \sum_{i=1}^{n} d_i \quad (4)$$

Where, er_v is energy consumption rate of the vehicle (kWh/km), d_i is distance for the ith road segment.

Ensuring Noise Constraints (N)

Noise levels must stay within permissible limits for each road segment. The noise level for the i^{th} road segment must satisfy:

$$N_i \leq N_{max}, for\ each\ road\ segment\ i \quad (5)$$

N_{max} is Maximum permissible noise level (decibels) and is Noise level on the i^{th} road segment.

Smart City Integration

Traffic dynamics (congestion) are simulated randomly with a congestion factor C_i for each segment:

$$C_i \in [0{,}2{,}0{,}8] \quad (6)$$

This congestion factor dynamically affects the travel time but does not influence the objective function itself.[18]

In green zones, emissions must remain within certain limits:

$$E_i \leq E_{max}\ , for\ emission-constrained\ road\ segments\ i \quad (7)$$

E_i is emissions on the ith segment, E_{max} is maximum allowed emissions for green zones.

Final Optimized Objective

The final optimization takes into account all the factors mentioned above, including noise, speed constraints, and traffic congestion. The objective function is formulated as:

$$\lambda_1 \cdot \sum_{i=1}^{n} d_i + \lambda_2 \cdot e_v \times \sum_{i=1}^{n} d_i + \lambda_3 \cdot r_v \times \sum_{i=1}^{n} d_i + \lambda_4 \cdot \sum_{i=1}^{n} N_i + \lambda_5 \cdot \sum_{i=1}^{n} (S_i - S_{limit}) \quad (8)$$

Subject to:

- $N_i \leq N_{max}$ (for each road segment).
- $E_i \leq E_{max}$ (for emission-constrained road segments).
- Adjusted travel time T_{adj} influenced by congestion.

Traffic flow (or congestion) influences the actual travel time and affects the routing decision dynamically but does not directly appear in the optimization objective. Instead, it affects the travel time and distance.[18]

We can define the adjusted travel time T_{adj} for a road segment with congestion:

$$T_{adj} = \frac{d_i}{S_i \times (1 + C_i)} \quad (9)$$

Where, C_i is congestion factor for road segment i (0 to 1 range), S_i is effective speed on segment i, d_i is distance for the ith segment. This optimization framework balances multiple objectives to ensure efficient, eco-friendly, and safe routing for vehicles within a smart city environment.

Hemo Algorithm

HEMO finds the best route for vehicles, keeping in mind the environment. It minimizes factors like travel distance, emissions, fuel usage, noise, and speed violations. The algorithm balances these factors to ensure the route is both eco-friendly and efficient, especially in cities with traffic. It considers congestion, noise levels, and emissions, and works to select the most optimal path. The HEMO algorithm is shown in Algorithm 1.

Algorithm 1: HEMO

Input: road network with segments i=1,2,...,n, vehicle parameters (speed, fuel consumption, emission factors), congestion factors C_i, noise levels N_i, emission constraints C_i, and distance between stops d_i.

Output: optimal route that minimizes the weighted sum of travel distance, emissions, fuel consumption, noise, and speed violations.

Initialization:

1. Initialize weights: $\boldsymbol{\lambda_1}$, $\boldsymbol{\lambda_2}$, $\boldsymbol{\lambda_3}$, $\boldsymbol{\lambda_4}$, $\boldsymbol{\lambda_5}$.
2. Set parameters: emission factor e_v, fuel consumption rate r_v, maximum permissible noise N_{max}, and speed limits S_{limit}.
3. Initialize road network with distances d_i, congestion factors C_i, and noise levels N_i.
4. Set initial state with road network parameters, including d_i, C_i, N_i, and e_v.

Main Loop

4. while route is not optimized do
5. Step 1: calculate total travel distance D as $D=\sum_{i=1}^{n} d_i$.
6. Step 2: calculate total emissions E as $E=e_v \times \sum_{i=1}^{n} d_i$.
7. Step 3: calculate total fuel consumption F as $F=r_v \times \sum_{i=1}^{n} d_i$.
8. Step 4: ensure noise constraint: $Ni \leq N_{max}$ for all road segments.
9. Step 5: ensure emission constraint: $Ei \leq E_{max}$ for emission-constrained segments.
10. Step 6: calculate adjusted travel time for each segment:

$$T_{adj} = \frac{d_i}{S_i \times (1 + C_i)}$$

11. Step 7: Evaluate total cost function

https://doi.org/10.56294/la2025151

$$Z = \lambda_1 \cdot D + \lambda_2 \cdot E + \lambda 3 \cdot F + \lambda_4 \cdot \sum_{i=1}^{n} N_i + \lambda_5 \cdot \sum_{i=1}^{n} (S_i - S_{limit})$$

12. Step 8: update the route based on the optimization goal, minimizing Z.
13. end while

RESULTS AND DISCUSSION

The HEMO algorithm was tested using MATLAB 2021. The system used for the test was a Windows 11 PC with an 11th Gen Intel Core i5-1135G7 CPU (2,42 GHz) and 8 GB RAM. Table 2 shows how HEMO improved performance by reducing distance, emissions, fuel use, noise, and speed violations.

Table 2. Comparison of Metrics Before and After Optimization

Metric	Before Optimization	After Optimization	% Improvement
Total Distance (km)	290	234	19,3
Total Emissions (gCO_2)	58 000	46 000	20,7
Total Fuel Consumption	43,5 kWh	35 kWh	19,5
Noise Violations	12	3	75
Speed Violations	18	4	77,8

The results show big improvements in all areas. HEMO reduced emissions and fuel use, making it great for eco-friendly routes. Noise and speed violations also dropped a lot, proving its ability to follow traffic rules. HEMO is an effective solution for managing routes in busy cities while keeping the environment in mind.

Extension of Solomon Dataset for HEMO Testing

To test the HEMO algorithm, we extend the Solomon dataset by adding realistic parameters related to eco-friendliness and traffic dynamics.[19] This enhanced dataset includes additional attributes for emissions, noise levels, congestion, and speed limits for each road segment, making it suitable for testing multi-objective optimization. A sample data (for a few road segments) is given in table 3.

Dataset

- Number of Road Segments (n): 25 road segments are considered.
- Distances (d_i): Random values between 2 km and 15 km are assigned to each segment.
- Congestion Factors (C_i): Random values between 0,2 and 0,8 simulate traffic density.
- Noise Levels (N_i): Random noise levels between 60 and 90 decibels.
- Emission Factor (e_v): Set to 200 gCO_2/km for all vehicles.
- Fuel Consumption Rate (e_v): Set to 0,15 kWh/km for consistency.
- Maximum Noise Limit (N_{max}): 80 decibels.
- Speed Limit (S_{limit}): 40–80 km/h, depending on road type.

Table 3. Sample Data (For a few road segments)

Segment	Distance (km)	Congestion Factor	Noise Level (dB)	Speed Limit (km/h)
1	8,2	0,5	75	60
2	5,6	0,3	65	40
3	12,4	0,7	85	50
4	7,8	0,6	78	70
5	9,5	0,4	72	60

Comparison with existing models

HEMO algorithm performs much better than traditional routing methods,[1] like static and dynamic routing, by cutting down on travel distance, emissions, fuel use, noise, and speed violations.[1,20] Compared to eco-friendly algorithms, HEMO is more efficient, reducing pollution and improving traffic flow. It's a great solution for smart city routes, balancing all factors effectively for better environmental and traffic management.

In figure 1, we compare the performance of different algorithms: Static Routing (SR), Dynamic Routing (DR), Eco-Friendly Routing (EFR), and HEMO (Proposed) in terms of total distance and fuel consumption. The results show that the HEMO algorithm

outperforms the others, achieving the lowest distance and fuel consumption, demonstrating its superior efficiency in optimizing both metrics.

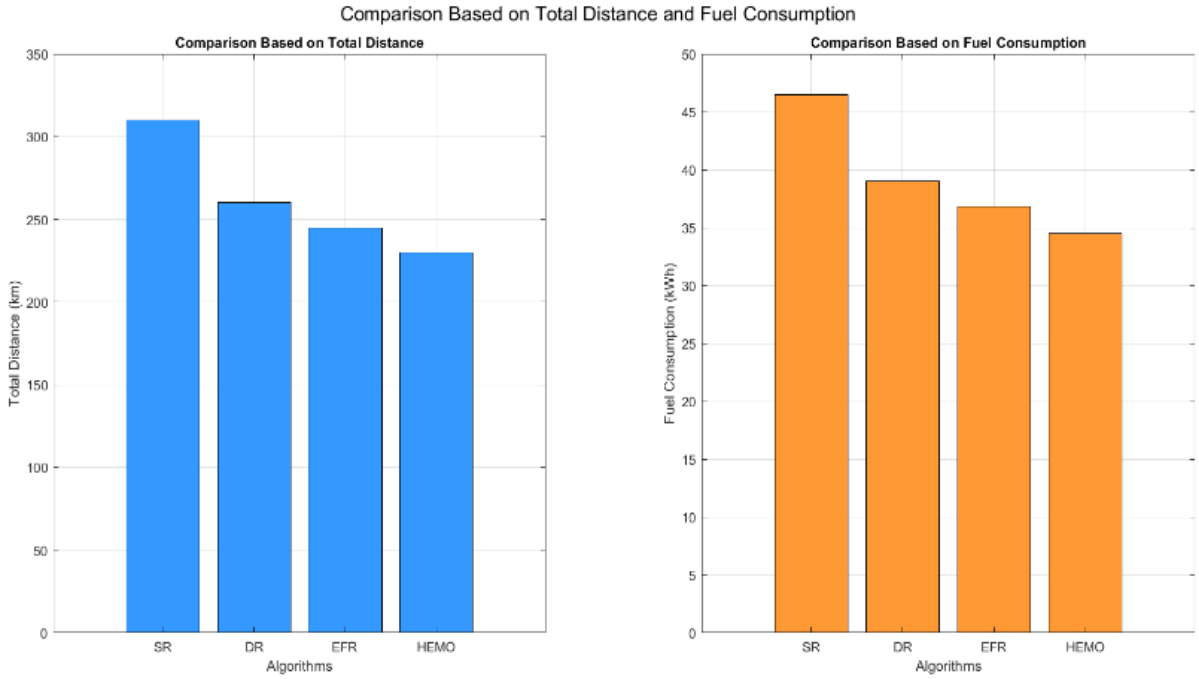


Figure 1. Comparison Based on Total Distance and Fuel Consumption

Figure 2 compares the algorithms based on emissions and noise violations, showing HEMO performs best in reducing both.

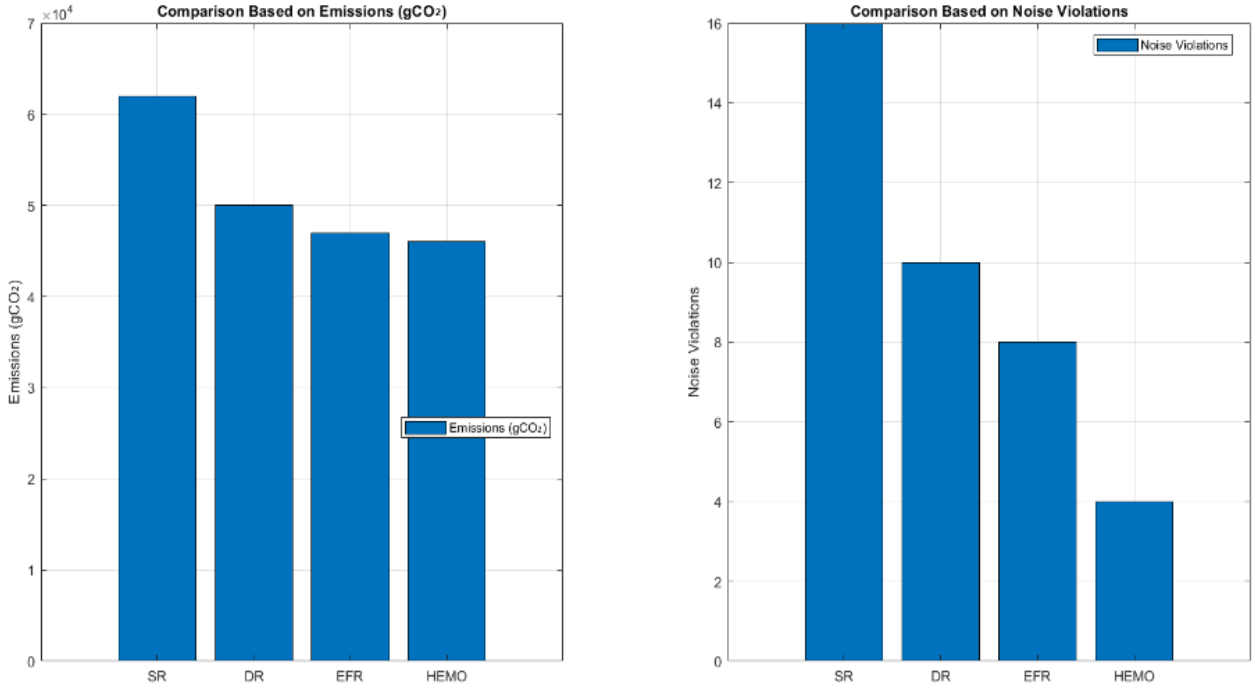


Figure 2. Comparison Based on emissions and noise violations

Figure 3 compares the algorithms based on speed violations and traffic adaptability, with HEMO showing the highest adaptability and lowest violations.

Figure 4 presents the overall performance comparison across various metrics, highlighting how the HEMO algorithm outperforms others in terms of travel distance, fuel consumption, emissions, noise violations, and speed violations.

https://doi.org/10.56294/la2025151

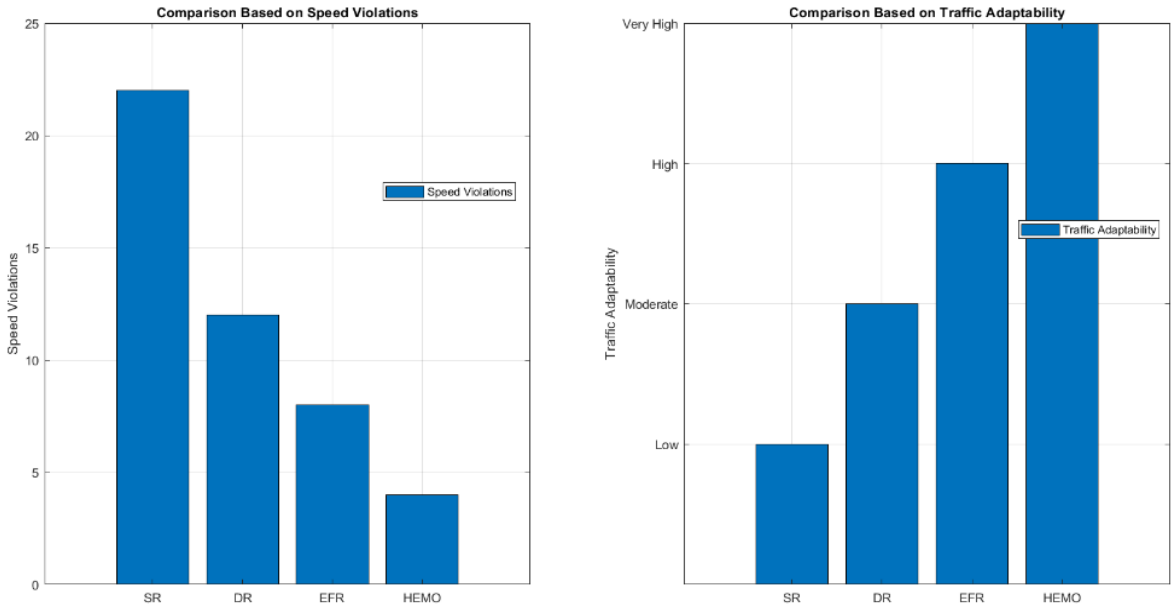


Figure 3. Comparison Based on speed violations and traffic adaptability

CONCLUSIONS

The proposed HEMO algorithm is a powerful solution for eco-friendly vehicle routing in smart cities. HEMO algorithm shows good results in eco-friendly vehicle routing for smart cities. It reduces total distance by 19,3 %, emissions by 20,7 %, and fuel use by 19,5 %. Noise violations decreased by 75 %, and speed violations by 77,8 %. Compared to other methods, HEMO is much better at reducing pollution and improving traffic flow. It is a good solution for managing city traffic and caring for the environment.

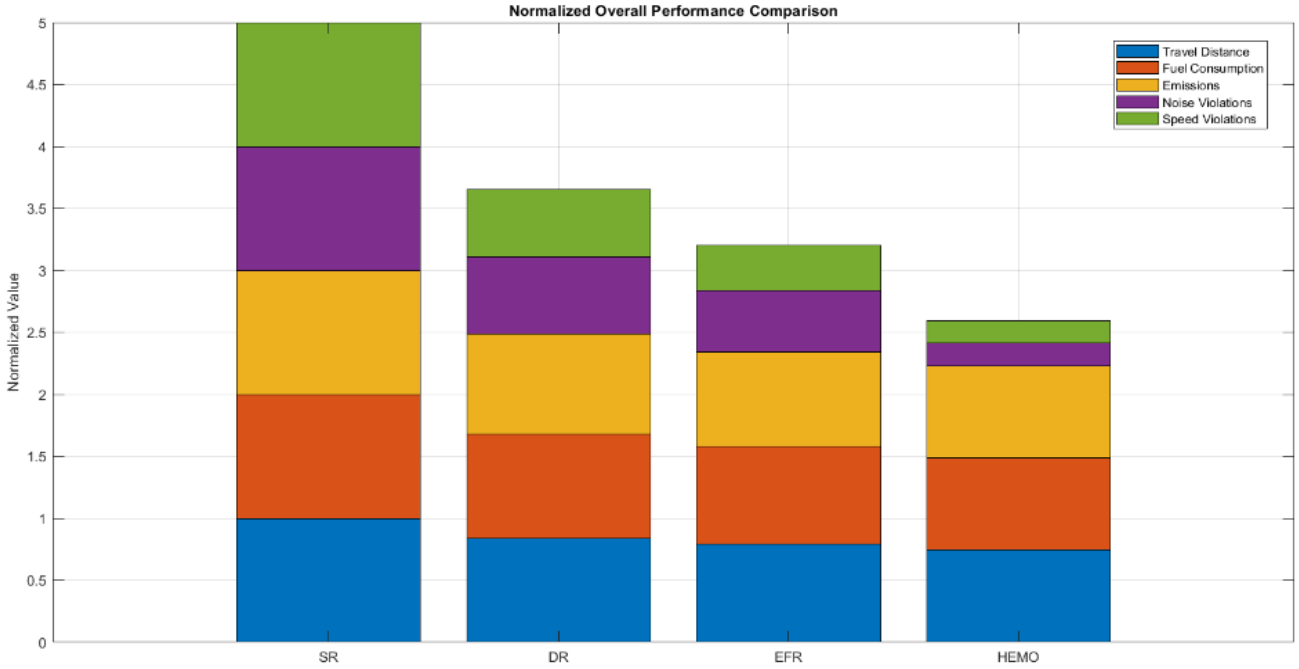


Figure 4. Overall Performance Comparison Across Key Metrics

In the future, we can add real-time traffic data and road conditions to make the system smarter. Using machine learning can improve its performance over time. We can also look into electric vehicles to reduce emissions more. Testing on bigger city networks will help improve its real-world use. Adding driver behavior models can also make the system more accurate.

FINANCING

No financing.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

https://doi.org/10.56294/la2025151

AUTHORSHIP CONTRIBUTION

Conceptualization: Amrita Prakash, Amir Khusru Akhtar.
Data curation: Amrita Prakash, Amir Khusru Akhtar.
Methodology: Amrita Prakash, Amir Khusru Akhtar.
Writing - original draft: Amrita Prakash, Amir Khusru Akhtar.
Writing - review and editing: Amrita Prakash, Amir Khusru Akhtar.

BIBLIOGRAPHIC REFERENCES

1. Toth P, Vigo D. The vehicle routing problem. SIAM; 2002.

2. Augusto JC. Smart cities: State of the art and future challenges. Handb smart cities. 2021;1–12.

3. Ding L, Zhang F, Ye J, Kong F, Jiao M. A novel optimization method for hazardous materials vehicle routing with temperature-based time windows. PeerJ Comput Sci. 2024;10:e2586.

4. Fahmin A, Cheema MA, Eunus Ali M, Nadjaran Toosi A, Lu H, Li H, et al. Eco-Friendly Route Planning Algorithms: Taxonomies, Literature Review and Future Directions. ACM Comput Surv. 2024;57(1):1–42.

5. Elassy M, Al-Hattab M, Takruri M, Badawi S. Intelligent transportation systems for sustainable smart cities. Transp Eng. 2024;100252.

6. Alqahtani H, Kumar G. Efficient routing strategies for electric and flying vehicles: A comprehensive hybrid metaheuristic review. IEEE Trans Intell Veh. 2024;

7. Branke J. Multiobjective optimization: Interactive and evolutionary approaches. Vol. 5252. Springer Science & Business Media; 2008.

8. Azevedo BF, Rocha AMAC, Pereira AI. Hybrid approaches to optimization and machine learning methods: a systematic literature review. Mach Learn. 2024;113(7):4055–97.

9. Holland JH. Genetic algorithms. Sci Am. 1992;267(1):66–73.

10. Dorigo M, Stutzle T. Ant Colony Optimization. MIT Press, Cambridge, MA. 2004;

11. Clerc M. Particle swarm optimization. Vol. 93. John Wiley & Sons; 2010.

12. Alam T, Gupta R, Ahamed NN, Ullah A, Almaghthwi A. Towards sustainable IoT-based smart mobility systems in smart cities. GeoJournal. 2024;89(6):1–21.

13. Aldhanhani T, Abraham A, Hamidouche W, Shaaban M. Future trends in smart green iov: Vehicle-to-everything in the era of electric vehicles. IEEE Open J Veh Technol. 2024;5:278–97.

14. Rostamian A, de Moraes MB, Schiozer DJ, Coelho GP. A survey on multi-objective, model-based, oil and gas field development optimization: Current status and future directions. Pet Sci. 2024;

15. Manshahia MS, Kharchenko V, Munapo E, Thomas JJ, Vasant P. Handbook of intelligent computing and optimization for sustainable development. John Wiley & Sons; 2022.

16. Roy P, Ghosh S, Podder A, Paul S. Green IoT for Eco-Friendly and Sustainable Smart Cities. In: Convergence Strategies for Green Computing and Sustainable Development. IGI Global; 2024. p. 124–37.

17. Xu C, Sankar R. A Comprehensive Review of Autonomous Driving Algorithms: Tackling Adverse Weather Conditions, Unpredictable Traffic Violations, Blind Spot Monitoring, and Emergency Maneuvers. Algorithms. 2024;17(11):526.

18. Ni D. Traffic flow theory: Characteristics, experimental methods, and numerical techniques. Butterworth-Heinemann; 2015.

19. Jendoubi F, Pradeep V, Khemmar R, Berradia T, Rossi R, Sibbille B, et al. Vehicle Activity Dataset: A Multimodal Dataset to Understand Vehicle Emissions with Road Scenes for Eco-Routing. Appl Sci. 2023;14(1):338.

20. Derbel H, Jarboui B, Siarry P. Green transportation and New advances in vehicle routing problems. Springer; 2020.