Optimization of Transportation Networks Using Genetic Algorithms for Intelligent, Sustainable, and Efficient Urban Mobility Systems

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ABSTRACT

Transportation network optimization is essential for improving mobility, reducing congestion, minimizing travel cost, and supporting sustainable urban development. This study focuses on the application of Genetic Algorithms for solving complex transportation problems such as routing, scheduling, traffic distribution, and network design. Genetic Algorithms are effective because they can handle nonlinear, dynamic, and multi-objective conditions through selection, crossover, and mutation processes. The study highlights recent GA-based approaches, including hybrid models, real-time routing, and environmentally sustainable optimization. Overall, Genetic Algorithms provide an adaptive and efficient framework for enhancing transportation network performance in modern intelligent transportation systems.

Keywords: *Genetic Algorithm, Transportation Network, Traffic Optimization, Intelligent Transportation System.*

I. INTRODUCTION

Transportation networks form the backbone of modern urban and regional development, directly influencing economic productivity, mobility efficiency, environmental sustainability, and quality of life. With rapid urbanization, increasing vehicle ownership, and expanding logistics demands, many cities are experiencing severe congestion, inefficient routing, and elevated transportation costs. Traditional deterministic optimization approaches often struggle to handle the nonlinear, dynamic, and large-scale nature of modern transportation systems. In this context, metaheuristic techniques—particularly Genetic Algorithms (GAs)—have emerged as powerful tools for solving complex transportation optimization problems due to their ability to search large solution spaces efficiently without requiring gradient information or strict convexity conditions. Genetic Algorithms, inspired by the principles of natural evolution such as selection, crossover, and mutation, are widely used in transportation engineering to optimize routing, scheduling, network design, and traffic distribution under multiple constraints. Recent advancements in intelligent transportation systems (ITS), connected vehicles, and real-time traffic data analytics have further strengthened the relevance of GA-based optimization frameworks for achieving efficient traffic distribution and improved network performance (Liu et al., 2022; Shanmugasundaram et al., 2019).

In recent years, significant research has demonstrated the effectiveness of Genetic Algorithms in addressing diverse transportation optimization challenges, including vehicle routing, transit network design, traffic prediction, and congestion management. For instance, Liu et al. (2022) developed a GA-based logistics optimization model incorporating soft time windows and multi-depot distribution systems, showing improved cost efficiency and computational performance in real-world distribution scenarios. Similarly, Jiménez-Carrión et al. (2023) proposed a two-stage GA framework for transit network design, integrating aggregated crossover and allocation strategies to optimize routes and fleet size, achieving superior performance on benchmark networks. In urban traffic systems, Odeh et al. (2025) implemented a GA-based real-time routing framework supported by edge computing, demonstrating reduced travel time under congested conditions through adaptive multi-objective optimization. Furthermore, Han et al. (2024) extended GA applications into connected autonomous vehicle systems, combining evolutionary optimization with multi-modal transport simulation to enhance accessibility and operational efficiency. These studies collectively highlight the flexibility of Genetic Algorithms in handling multi-objective, constrained, and dynamic transportation problems, making them highly suitable for modern intelligent transportation systems. Additionally, hybrid approaches combining GA with machine learning or fuzzy logic have shown enhanced adaptability and performance, as seen in GA-LSTM traffic prediction models and fuzzy-optimized vehicular routing protocols (Tang et al., 2021; Samara et al., 2026).

Despite these advancements, transportation networks still face critical challenges that limit the full potential of GA-based optimization. One of the major issues is computational complexity, particularly when applied to large-scale urban networks with dynamic traffic conditions and real-time constraints. While Genetic Algorithms are effective in exploring global solution spaces, they may suffer from premature convergence or increased processing time when not properly tuned. To address these limitations, researchers have introduced hybrid optimization strategies, improved crossover and mutation mechanisms, and adaptive parameter tuning techniques. For example, Xu et al. (2025) enhanced GA performance using an improved harmony search mechanism to optimize medical waste transportation under stochastic conditions, achieving better reliability and robustness. Similarly, Li et al. (2026) integrated Genetic Algorithms with Hamiltonian Monte Carlo sampling to improve scenario generation efficiency in simulation-based transportation testing, achieving high coverage and convergence accuracy. Moreover, environmental and sustainability considerations are becoming increasingly important in transportation optimization models. Hadipour et al. (2020) incorporated environmental indicators into GA-based spatial optimization of urban transport networks, emphasizing the need to balance accessibility with ecological impact. These developments indicate a clear shift toward multi-objective, data-driven, and adaptive GA frameworks capable of addressing the complexity of modern transportation systems. Therefore, the optimization of transportation networks using Genetic Algorithms represents a critical area of research that continues to evolve with advancements in computation, artificial intelligence, and intelligent mobility systems.

II. RESEARCH BACKGROUND

Li et al. (2026) had emphasized that virtual simulation testing had been crucial for ensuring the safety of automated vehicles, as it had provided low-cost and highly repeatable evaluation conditions. They had noted that although testing across diverse virtual driving scenarios had been necessary, achieving a balance between scenario coverage and testing efficiency had often remained challenging. To address this issue, they had proposed a scenario generation method based on a Genetic Algorithm–optimized Hamiltonian Monte Carlo sampling approach. In their method, a Markov chain had been constructed to converge toward the joint probability density function of scenario parameters. By defining a Hamiltonian function with potential energy linked to the posterior distribution and kinetic energy components, the sampling process had been guided toward high-probability regions, thereby improving convergence speed. Furthermore, Jensen–Shannon divergence between generated samples and raw data had been used to evaluate scenario coverage and had been adopted as the objective function for optimizing Genetic Algorithm parameters. The method had been validated using lead vehicle deceleration scenarios, where an S-shaped deceleration model had been applied and 22,343 segments from a naturalistic driving dataset had been used for calibration. Ultimately, 1,649 scenarios had been generated, achieving 99.14% coverage and significantly outperforming previous methods.

Samara et al. (2026) had stated that vehicular ad hoc networks (VANETs) operating in dense urban environments were characterized by highly dynamic topology, fluctuating traffic conditions, and stringent latency requirements, which had significantly complicated reliable data routing and packet forwarding. To address these challenges, the study had proposed an Intelligent Fuzzy Protocol (IFP) for adaptive vehicle-to-vehicle data routing under uncertain and rapidly changing traffic scenarios. The proposed protocol had integrated fuzzy logic decision-making with real-time vehicular context, including vehicle velocity, traffic congestion level, distance to road junctions, and data urgency, in order to dynamically select appropriate forwarding actions. IFP had employed a structured fuzzy inference engine comprising fuzzification, rule evaluation, inference aggregation, and centroid-based defuzzification to determine routing and forwarding decisions in a decentralized manner. To further enhance performance robustness, the fuzzy membership parameters and rule weights had been optimized using metaheuristic techniques such as genetic algorithms (GAs) and particle swarm optimization (PSO). Extensive simulations had been conducted using NS-3 coupled with SUMO under realistic urban mobility scenarios and varying network densities. The results had demonstrated that IFP had significantly outperformed conventional routing approaches in terms of end-to-end delay, packet delivery ratio, and routing overhead. In particular, the optimized IFP variants had achieved notable reductions in latency and improvements in delivery reliability under high congestion conditions while maintaining low computational and communication overhead. These findings had confirmed that IFP had offered an interpretable, scalable, and energy-aware routing solution suitable for large-scale intelligent transportation systems and next-generation vehicular networks.

Odeh et al. (2025) had stated that urban congestion further increased travel times, fuel consumption, and greenhouse-gas emissions. In this context, a systematic study of a Genetic Algorithm (GA) for real-time routing in an urban scenario in Bethlehem City had been conducted, based on a SUMO microsimulation calibrated using field data. The study had made four main contributions: (i) a reproducible GA framework for dynamic routing with explicit constraints and an adaptive termination criterion had been implemented; (ii) a weight sensitivity analysis had been designed to examine a multi-term fitness function incorporating travel time, waiting time, and optionally fuel consumption; (iii) an edge-assisted distributed architecture had been developed using roadside units (RSUs) supported by cloud services; and (iv) the dataset description and experimental protocol had been specified and refined with planned statistical analysis. Empirical evidence from the Bethlehem case study had indicated a consistent reduction in total travel time under high congestion conditions. Variations in waiting time across scenarios had reflected trade-offs in the fitness weighting scheme. The authors had acknowledged limitations, including manual data handling and discrepancies between simulation and real-world conditions, and had proposed a roadmap for pilot deployment addressing these issues. Rather than introducing a new GA variant, they had presented a deployment-oriented, edge-assisted GA framework with explicit protocols, latency constraints, and reproducible multi-objective tuning validated on a city-scale network under severe congestion.

Xu et al. (2025) had examined the collection and transportation of medical waste, emphasizing its importance due to environmental and public safety concerns. They had observed that variability in vehicle travel times, influenced by multiple operational and external factors, had significantly complicated waste logistics. To address this issue, the authors had developed a multi-objective optimization model aimed at improving travel time reliability while simultaneously minimizing transportation costs and penalties arising from violations of time window constraints. Considering the NP-hard nature of the problem, they had employed a genetic algorithm enhanced with an improved harmony search genetic algorithm (IHSGA) to obtain efficient solutions. The model had been tested in N City, China, where results had demonstrated the critical role of travel time reliability in optimizing medical waste collection systems. Sensitivity analysis had confirmed the robustness of the proposed approach, while comparative evaluation had shown that IHSGA had outperformed conventional methods in efficiency and accuracy.

Han et al. (2024) had reported that in the past five years, rapid development had been observed in planning initiatives and test pilots aimed at introducing connected and autonomous vehicles (CAVs) into public transport systems across the world. Although self-driving technology had still been under refinement, public transport authorities had increasingly focused on modelling and optimising the potential benefits of integrating CAVs within existing multi-modal transport networks. The study had demonstrated, through a real-world case of the Leeds Metropolitan Area, an effective approach of combining macro-level mobility simulations based on open data with global optimisation techniques to identify realistic and optimal deployment strategies for CAVs. The macro-level simulations had been used to evaluate the performance of proposed multi-route CAV services by measuring improvements in geographic accessibility through an extended Dijkstra-based algorithm applied to an abstract multi-modal transport network. Optimisation procedures had been performed using several population-based algorithms integrated with routing strategies for sequencing stops efficiently.

Jiménez-Carrión et al. (2023) had aimed to implement a computational prototype in two stages, where the first stage primarily focused on generating efficient routes using an evolutionary algorithm. In this stage, the complex combinatorial optimization problem had been addressed through a Genetic Algorithm (GA), which had been employed as the core metaheuristic. Within the GA framework, an innovative "aggregated crossover" operator had been applied along with a mutation procedure that had ensured the generation of feasible offspring solutions. The second stage had focused on determining fleet size and service frequencies through an allocation algorithm, which had utilized the optimized routes obtained from the first stage. This two-stage methodology had been designed to handle the complexity of public transportation network optimization. The results had indicated that the GA consistently produced highly efficient routing solutions in repeated runs, thereby confirming its effectiveness in resolving combinatorial complexity. The approach had been validated using Mandl's Swiss Road network and had achieved superior performance compared to previous studies, with an execution time of approximately 35 minutes.

Liu et al. (2022) had addressed the optimization problem of logistics transportation networks by applying a genetic algorithm-based approach. The study had initially integrated the distribution characteristics of logistics systems and, drawing upon established vehicle routing problem theories, had developed a basic vehicle routing optimization model that incorporated vehicle travel distance. A soft time window constraint had been introduced to minimize total transportation cost, and an extended model with multiple distribution centers had also been formulated. Based on these models, a genetic algorithm solution framework had been designed in accordance with the problem requirements and implemented using MATLAB programming to achieve computational optimization. The parameters were set as $T = 100$, $S = 50$, $Pc = 0.95$, $Pm = 0.1$, $\beta 1 = 0.005$, $\beta 2 = 1$, and $\beta 3 = 0.005$. Finally, real distribution data from a regional G supermarket chain had been employed as experimental data. Two shipping instances had been selected to validate both the proposed models and the effectiveness of the developed genetic algorithm.

Tang et al. (2021) had explored traffic flow characteristics and had emphasized that predicting their variation patterns formed the basis of Intelligent Transportation Systems. They had noted that intermittent behavior and strong short-term fluctuations posed significant challenges in urban road networks. The study had proposed a hybrid Genetic Algorithm with Attention-based Long Short-Term Memory (GA-LSTM) model integrated with spatial–temporal correlation analysis for predicting urban traffic volumes. Spatial correlations had been captured through a combination of a volume transition matrix derived from vehicle trajectories and a network weight matrix computed from multiple detectors. Temporal dependencies had been addressed using an attention mechanism, while a Genetic Algorithm had been employed to optimize the model parameters. The model had been validated using traffic flow data collected from License Plate Recognition (LPR) systems. Comparative analysis with several traditional models had demonstrated that the proposed approach had achieved higher prediction accuracy and improved stability in traffic flow forecasting.

Hadipour et al. (2020) had stated that transportation had been recognized as a critical infrastructure supporting development and adaptive urban growth, which had increasingly attracted the attention of planners and managers. However, it had been observed that environmental impacts of transport systems had often been neglected in favour of accessibility in urban planning. In Petaling Jaya, metropolitan tourist city, the need for efficient transport management systems compatible with environmental sustainability had been emphasized. The study had identified environmental indicators through literature review and determined five indicators for transport assessment. These indicators had been spatially mapped using GIS and rated across transport network cells with judgment. Cell-based evaluations had been processed in MATLAB using genetic algorithms to derive results. Results had indicated that 40% of network cells were inappropriate, 35% appropriate, 25% sound. Relocation of urban functions to peripheral low-pollution zones had been suggested to reduce transport-related environmental impacts significantly overall impact.

Shanmugasundaram et al. (2019) had stated that one-way road networks could be designed with the assistance of computer programs; however, the application of genetic algorithms in such design problems had been relatively new. The study had proposed a novel approach to determine suitable travel directions within one-way road networks. The main objective had been to minimize the total distance travelled by vehicles. For the computation of total distance, a branch-and-bound technique combined with breadth-first search had been employed to identify the shortest path between starting and ending points. The results had demonstrated that the genetic algorithm approach could be effectively applied to the design of one-way road networks in the examined case studies. The study had further suggested that, in future applications, genetic algorithms could be extended for the generalized design of one-way road networks, thereby improving optimization efficiency and practical applicability in transportation planning systems.

III. KEY FINDINGS FROM STUDY

Author (Year)	Study Focus	Methodology	Key Findings	Research Gap
Li et al. (2026)	Scenario generation for autonomous driving simulation	GA-optimized Hamiltonian Monte Carlo sampling	Achieved 99.14% scenario coverage and improved simulation efficiency	Limited application to real-time traffic network optimization
Samara et al. (2026)	Vehicular ad hoc network routing optimization	Fuzzy logic protocol optimized using GA and PSO	Improved packet delivery ratio and reduced latency in dense urban networks	High computational complexity in real-time deployment
Odeh et al. (2025)	Urban traffic routing optimization	Multi-objective GA with edge-assisted architecture	Reduced travel time and improved routing efficiency under congestion	Simulation-reality mismatch and data dependency issues
Xu et al. (2025)	Medical waste transportation optimization	Improved GA with harmony search (IHSGA)	Enhanced reliability and reduced transportation cost under time windows	Limited scalability for large urban logistics networks

Han et al. (2024)	Multi-modal transport with autonomous vehicles	GA integrated with evolutionary optimization models	Improved accessibility and route efficiency in CAV systems	Lack of real-time adaptive optimization in dynamic environments
Jiménez-Carrión et al. (2023)	Transit network design and fleet optimization	Two-stage GA with aggregated crossover and allocation model	Efficient routing and optimal fleet sizing with reduced execution time	Limited adaptability to stochastic traffic variations
Liu et al. (2022)	Logistics transportation network optimization	GA-based VRP model with soft time windows	Reduced transportation cost and improved routing efficiency	Weak handling of dynamic traffic fluctuations
Tang et al. (2021)	Traffic flow prediction and optimization	GA + Attention-based LSTM model	Improved prediction accuracy and stability in traffic forecasting	Focused on prediction, not direct network optimization
Hadipour et al. (2020)	Environmental optimization of transport networks	GIS integrated GA model	Identified 40% unsuitable urban transport zones, improved planning	Limited integration with real-time traffic systems
Shanmugasundaram et al. (2019)	One-way road network design optimization	GA with BFS and branch-and-bound shortest path	Reduced travel distance and improved network efficiency	Simplified static network assumptions, not dynamic traffic systems

IV. CONCLUSION

The optimization of transportation networks using Genetic Algorithms (GAs) has emerged as a highly effective and versatile approach for addressing the increasing complexity of modern transportation systems. The reviewed literature clearly demonstrates that GA-based methods provide robust solutions for a wide range of transportation engineering problems, including vehicle routing, traffic flow optimization, logistics distribution, transit network design, and intelligent traffic management. Unlike traditional optimization techniques, which often rely on linear assumptions and deterministic models, Genetic Algorithms are capable of handling nonlinear, multi-objective, and constraint-heavy environments, making them particularly suitable for dynamic urban transportation networks. Studies such as Liu et al. (2022) and Jiménez-Carrión et al. (2023) have highlighted the efficiency of GA frameworks in optimizing logistics and transit systems by minimizing travel distance, reducing operational costs, and improving service reliability. Similarly, Odeh et al. (2025) demonstrated that real-time GA-based routing systems, especially when combined with edge computing architectures, can significantly reduce congestion-induced delays and improve overall traffic performance in urban environments. These findings collectively reinforce the adaptability and effectiveness of GA models in improving transportation efficiency under varying real-world conditions. Furthermore, the integration of Genetic Algorithms with emerging computational techniques such as machine learning, fuzzy logic systems, and hybrid metaheuristics has significantly enhanced their performance and applicability. For instance, Tang et al. (2021) combined GA with attention-based LSTM models to improve traffic flow prediction accuracy, while Samara et al. (2026) utilized GA-optimized fuzzy logic systems to enhance vehicular ad hoc network routing efficiency. These hybrid approaches indicate a growing trend toward intelligent, data-driven optimization frameworks capable of addressing both spatial and temporal complexities in transportation systems. Additionally, Xu et al. (2025) demonstrated that hybrid GA models, when combined with improved heuristic techniques like harmony search, can effectively solve stochastic and time-sensitive logistics problems such as medical waste transportation. Moreover, environmental sustainability has also become an important dimension of transportation optimization, as shown in the work of Hadipour et al. (2020), where GA was used in combination with GIS to evaluate and optimize urban transport networks based on environmental impact indicators. This reflects a shift toward multi-dimensional optimization approaches that consider not only efficiency and cost but also ecological sustainability and social impact. Despite these advancements, several challenges remain in the practical implementation of GA-based transportation optimization systems. One of the primary limitations is computational complexity, especially when dealing with large-scale, real-time urban traffic networks that require rapid decision-making. Additionally, issues such as premature convergence, sensitivity to parameter tuning, and scalability constraints continue to affect performance in highly dynamic environments. Another key limitation is the gap between simulation-based studies and real-world deployment, where unpredictable traffic behavior and incomplete data can reduce model effectiveness. However, ongoing research is actively addressing these limitations through hybrid optimization models, adaptive parameter control mechanisms, and integration with edge computing and real-time data analytics. Overall, Genetic Algorithms have proven to be a powerful and flexible optimization tool in transportation engineering, and their continued development, particularly when combined with artificial intelligence and smart infrastructure systems, is expected to play a critical role in shaping the future of intelligent transportation networks.

V. FUTURE SCOPE

- **Integration with Real-Time Intelligent Transportation Systems (ITS):** Future research can focus on integrating Genetic Algorithms with real-time Intelligent Transportation Systems to enable dynamic traffic optimization. By combining GA with live traffic sensor data, GPS feeds, and IoT-enabled infrastructure, transportation networks can continuously adapt to congestion patterns, accidents, and demand fluctuations. This will significantly improve decision-making speed and routing efficiency in urban environments.
- **Hybridization with Advanced Machine Learning Models:** The combination of Genetic Algorithms with deep learning models such as LSTM, CNN, and reinforcement learning offers strong potential for predictive and adaptive transportation optimization. Hybrid GA-ML frameworks can improve traffic forecasting accuracy, demand prediction, and adaptive routing decisions, especially in highly dynamic traffic environments where historical data alone is insufficient.
- **Edge and Cloud Computing-Based GA Deployment:** Future transportation systems can benefit from deploying GA optimization frameworks on edge and cloud computing platforms. Edge-assisted GA systems will reduce computational latency and enable faster local decision-making in smart cities. Cloud integration will further support large-scale optimization problems involving entire metropolitan transportation networks.
- **Multi-Objective Optimization Enhancement:** Future studies should expand GA models to more advanced multi-objective frameworks that simultaneously optimize travel time, fuel consumption, emissions, safety, and user comfort. Developing more efficient Pareto-based GA algorithms will help transportation planners achieve balanced and sustainable solutions.

- **Application in Autonomous and Connected Vehicle Networks:** With the rapid development of connected and autonomous vehicles (CAVs), Genetic Algorithms can play a critical role in route coordination, platooning strategies, and cooperative traffic management. Future research can explore GA-based decision systems that interact directly with autonomous driving algorithms for improved traffic flow and safety.
- **Scalability for Large Urban and Megacity Networks:** One major future direction is improving the scalability of GA models for megacity transportation systems with millions of nodes and dynamic constraints. Parallel processing, distributed GA frameworks, and quantum-inspired GA approaches can be explored to handle large-scale optimization efficiently.
- **Integration with Smart City Infrastructure:** Genetic Algorithms can be embedded into smart city ecosystems where transportation networks are interconnected with energy systems, emergency response, and urban planning modules. This integration will allow holistic optimization of city resources beyond just traffic management.
- **Sustainability and Environmental Optimization:** Future GA models should incorporate carbon emission reduction, noise pollution control, and energy efficiency as core optimization parameters. This will align transportation systems with global sustainability goals and climate action policies.
- **Real-Time Adaptive Learning GA Models:** Traditional GA approaches are static in nature; future research can focus on adaptive GA systems that learn continuously from new traffic patterns. Self-evolving GA frameworks will improve robustness and responsiveness in unpredictable traffic conditions.
- **Blockchain-Integrated Transportation Optimization:** Blockchain technology can be combined with GA to ensure secure, transparent, and tamper-proof data exchange in transportation networks. This will be especially useful in shared mobility systems, logistics tracking, and autonomous vehicle coordination.
- **Human Behavior Modeling in Traffic Optimization:** Future studies can incorporate behavioral economics and human decision-making models into GA frameworks. This will improve prediction accuracy for route choice behavior, congestion formation, and travel demand patterns.
- **Use of Quantum-Inspired Genetic Algorithms:** Emerging quantum computing techniques can significantly enhance GA performance. Quantum-inspired GA models may provide faster convergence and better global optimization capabilities for complex transportation networks.

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