

Genetic Algorithm-Based Traffic Optimization for Efficient Urban Route Management

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ABSTRACT

Efficient traffic distribution is a critical challenge in urban transportation networks, particularly under increasing congestion and demand variability. This study applies Genetic Algorithms (GA) to optimize multi-route traffic assignment, considering route capacities, free-flow travel times, and congestion penalties. A MATLAB-based interface was developed to simulate traffic flow, evaluate performance metrics, and visualize results. The GA effectively distributed traffic, minimizing average travel time (15.57 minutes) while maintaining network utilization (68.18%) and keeping volume-to-capacity ratios below critical thresholds. Results confirm that GA provides a robust, adaptive, and practical solution for enhancing urban mobility, balancing network load, and reducing congestion.

Keywords: Genetic Algorithm, Traffic Optimization, Urban Mobility, Congestion Management.

I. INTRODUCTION

Urban transportation networks form the backbone of modern cities, serving as vital conduits for mobility, economic activity, and social interaction. With rapid urbanization, growing population density, and increasing vehicle ownership, cities worldwide are experiencing unprecedented traffic congestion, leading to delays, increased fuel consumption, environmental pollution, and decreased quality of life. Traditional traffic management strategies, such as fixed-time or pre-timed signal controls, often fail to dynamically adapt to fluctuating traffic volumes and patterns, resulting in inefficiencies during peak and off-peak periods. Similarly, static route assignment methods in road networks cannot adequately respond to variations in demand, travel time, or capacity limitations, leading to uneven utilization of infrastructure. Efficient traffic distribution is therefore a critical component of urban mobility planning, not only for reducing travel time and congestion but also for minimizing environmental impact and improving economic productivity. In this context, advanced computational techniques, particularly metaheuristic algorithms, have emerged as powerful tools for addressing the complex, nonlinear, and combinatorial nature of traffic assignment problems. Among these, Genetic Algorithms (GA), inspired by the principles of natural selection and evolution, offer a robust framework for optimizing transportation networks by exploring large solution spaces, adapting to constraints, and converging toward near-optimal traffic distributions. By simulating the process of selection, crossover, and mutation, GAs iteratively refine traffic flow assignments across multiple routes, balancing load based on capacity, travel time, and congestion, thereby improving overall network efficiency.

The application of Genetic Algorithms in transportation network optimization provides a significant leap over conventional approaches by integrating adaptive decision-making, objective function evaluation, and multi-route analysis into a cohesive framework. GA-based models allow transportation planners to define performance objectives such as minimizing average travel time, maximizing network utilization, and reducing congestion levels while respecting route capacity constraints. For instance, in a hypothetical urban network comprising multiple alternative routes with varying capacities and free-flow travel times,

the GA iteratively evaluates candidate traffic flow distributions, calculating fitness values based on travel time penalties and congestion indices. The algorithm prioritizes solutions that reduce travel delays on high-demand routes, redistribute traffic to underutilized paths, and maintain a balanced network performance. Additionally, GA models are highly flexible and can incorporate real-world constraints such as variable traffic demand, stochastic travel times, and route closures, which are common in dynamic urban environments. The development of user-friendly interfaces, such as MATLAB-based graphical dashboards, further enhances the practical applicability of GA optimization by allowing planners to input network parameters, simulate traffic scenarios, and visualize route-specific flows, volume-to-capacity ratios, and congestion levels. Numerous studies have demonstrated that GA-based traffic assignment can achieve reduced travel times, lower congestion, and improved network stability, highlighting its potential as a sustainable solution for urban traffic management. Furthermore, by leveraging evolutionary computation, GAs are capable of escaping local optima, adapting to changing traffic patterns, and providing scalable solutions for large and complex transportation networks, making them indispensable tools in the modern smart-city paradigm.

II. RESEARCH BACKGROUND

Nadhiva et al. (2026) explored the integration of cost sensitivity analysis with transportation optimization through a systematic mapping study using Scopus data from 2019 to 2023. The study employed bibliometric analysis and VOS viewer visualization to examine publication trends, research methodologies, and emerging thematic clusters. It was found that China represented the largest contributor to research output during the selected period. The analysis further identified six major clusters, including sensitivity analysis, uncertainty modelling, optimization algorithms, and sustainable logistics systems. The findings indicated that a significant research gap persisted in the integration of cost sensitivity approaches with comprehensive sustainability frameworks. The study also highlighted that most existing works focused on isolated optimization or sensitivity techniques rather than holistic models. Overall, the results were considered useful for guiding future academic inquiry and policy formulation aimed at developing adaptive, efficient, and resilient transportation and distribution systems under conditions of cost uncertainty in practical application.

Zhang et al. (2026) had investigated the vulnerability of urban metro–bus networks to cascading failures under extreme disruption conditions, highlighting that most existing recovery models had inadequately represented complex interdependencies within composite transportation systems. The study had moved beyond conventional single-mode and static modelling approaches by introducing a higher-order interaction perspective to capture non-linear and synergistic effects across interconnected transport layers. A multi-criteria resilience assessment framework had been developed, along with an optimized recovery strategy based on a Genetic Algorithm (GA), which had dynamically balanced topological connectivity with functional demand restoration. The proposed framework had been validated using the large-scale Beijing transportation network, where the GA-driven recovery strategy (RS4) had consistently outperformed benchmark approaches, including random, topology-based, and function-based recovery methods. It had been further observed that RS4's superiority had increased with rising disruption levels ranging from 30% to 70%, demonstrating strong robustness under severe conditions and providing an effective approach for improving urban transport network resilience.

Choi et al. (2025) had stated that persistent air pollution and greenhouse gas emissions, contributing to global boiling beyond global warming, had necessitated urgent interventions across transportation systems. They had observed that electric vehicles (EVs) were increasingly considered a key pathway toward carbon neutrality; however, their adoption had been limited by inadequate charging infrastructure

and long charging times. The study had therefore focused on optimizing the spatial allocation of EV charging stations in Seoul for 2030, using 2023 as the baseline for existing fast-charging stations and fuel stations. A hybrid methodology combining a genetic algorithm and fuzzy analytic hierarchy process had been applied to determine optimal station locations and to rebalance fast and slow chargers to reduce congestion and unnecessary travel. Multiple urban indicators, including parking availability, transit accessibility, and land-use planning, had been integrated into the model. Results had indicated reduced travel, time, and emissions supporting sustainability electric mobility.

Liu et al. (2025) had examined the rapid development of intelligent transportation systems and online ride-hailing platforms, noting that the demand for prompt passenger response while minimizing vehicle idling time and travel costs had increased significantly. The study had addressed issues of suboptimal vehicle path planning and partially connected pickup stations by formulating the problem as a Capacitated Vehicle Routing Problem (CVRP). An Improved Genetic Algorithm (IGA)-based path planning model had been proposed to minimize total travel distance while satisfying vehicle capacity constraints. To manage situations where certain pickup points were not directly connected, graph-theoretic techniques had been integrated to ensure route continuity. The model had incorporated a multi-objective fitness function, a rank-based selection strategy with adjusted weights, and Dijkstra-based path estimation to improve convergence speed and global optimization performance. Experimental results on four benchmark Carla simulation maps had demonstrated that the proposed approach had efficiently generated optimized multi-vehicle routing solutions and improved coordination of pickup tasks, achieving superior route quality and computational efficiency compared to conventional methods.

Yektamoghadam et al. (2024) had observed that rapid urbanization and the increasing number of vehicles had led to undesirable outcomes such as traffic congestion and vehicle queuing across many metropolitan regions worldwide. They had highlighted that most countries had been facing the challenge of an explosive rise in traffic demand, making efficient traffic management essential in urban transport networks. The study had emphasized the critical role of traffic signals at intersections in reducing travel time and improving urban mobility. A multi-criteria decision-making approach had been proposed for optimal traffic light control at isolated intersections, where a set of near-optimal signal timing solutions had been generated and the best alternative had been selected. The problem had been formulated as an optimization model aimed at minimizing vehicle waiting time and operational cost. Genetic Algorithm (GA) and Teaching-Learning-Based Optimization (TLBO) had been applied to generate feasible timing scenarios, while TOPSIS had been used to identify the most suitable solution based on traffic flow and capacity criteria. The approach had shown effectiveness across different traffic volumes and had been validated in Mashhad, Iran, demonstrating improvements in vehicle delay and traffic capacity.

Li and Ma (2023) had proposed a multi-objective optimization model for urban logistics distribution networks (ULDN) with the aim of improving the efficiency of urban logistics systems. They had considered several cost components, including vehicle usage cost, transportation cost, penalty cost for unmet time windows, and carbon emission cost, while also incorporating the effects of urban road traffic congestion on overall system performance. To solve the developed model, a Discrete Particle Swarm Optimization (DPSO) algorithm based on the fundamental principles of Particle Swarm Optimization (PSO) had been introduced. The proposed DPSO approach had employed multiple populations to address multi-objective characteristics and had integrated a variable neighbourhood search strategy to enhance the search capability and local optimization performance of particles. Simulation results had indicated that the model was effective in reducing traffic congestion impacts, carbon emission costs, and time penalty costs. Furthermore, comparative analysis had shown that DPSO outperformed the conventional PSO algorithm in optimization efficiency and solution quality.

Al-Madi and Hnaif (2022) had observed that traffic signals in Jordan were experiencing severe congestion due to multiple contributing factors, including a significant rise in the number of vehicles and the continued reliance on fixed-timer-based control systems. They had noted that this situation had adversely affected travel demand and overall traffic flow in the streets of Amman, the capital city of Jordan. The study had aimed to enhance an intelligent road traffic management system (IRTMS) based on a human community-based genetic algorithm (HCBGA) to reduce traffic signal congestion. It had been reported that the IRTMS initially considered parameters such as total time and waiting time while still relying on fixed timers for control. In contrast, the enhanced system (E-IRTMS) had incorporated additional parameters, including the speed performance index (SPI), speed reduction index (SRI), road congestion index (Ri), and congestion period. The results had indicated a 13% reduction in congestion period compared to IRTMS, while IRTMS itself had performed about 83% better than the existing system. The findings had demonstrated that E-IRTMS achieved improved congestion reduction performance.

Peng et al. (2021) had investigated urban transportation networks in which passengers predominantly relied on public transport systems for daily mobility. It had been observed that adverse weather conditions, traffic congestion, accidents, and similar uncertainties had significantly affected network reliability and travel predictability. The study had noted that the coexistence of multiple transport modes operating on shared route segments had further complicated system structure and passenger decision-making. To enhance travel efficiency, the authors had proposed an optimization approach for passenger route selection by minimizing total travel time while considering travel cost and transfer constraints. The model had incorporated uncertainty in vehicle running and dwell times, which had been assumed to follow scheduled timetables but varied stochastically. Bus, rail transit, and walking modes had been included in the analysis. Methodologically, the study had combined Genetic Algorithm (GA) with Monte Carlo simulation to address stochastic optimization problems. Monte Carlo simulation had been used to model uncertain travel and dwell durations across different scenarios. The shortest path problem had been solved using GA, supported by single and multiple population management strategies to improve convergence. Numerical experiments had validated model efficiency, showing that the multiple population strategy had achieved better solutions with reduced computational time and had provided robust quantitative support for multimodal route optimization under uncertainty.

Owais and Alshehri (2020) had examined routing problems that played a crucial role in the operation and management of urban transportation networks. The study addressed the problem of identifying a set of non-dominated shortest paths in stochastic transportation networks. Instead of the conventional assumption that travel time variability was represented through a known probability density function, the variability was derived from the existing correlation between traffic flow and link travel times. The time horizon was divided into discrete intervals in which the network was assumed to be in a state of static traffic equilibrium, with varying traffic conditions across different time slots. Based on a priori demand information, previously generated paths, and a selected traffic assignment method, the proposed methodology conducted successive simulations across network intervals. It derived probability distributions of link and path travel times while considering their interdependencies. A multi-objective analysis was then performed to obtain Pareto-optimal path sets for each origin–destination pair. Numerical studies demonstrated the efficiency and general applicability of the approach, enabling estimation of expected travel time and reliability for each path in the network.

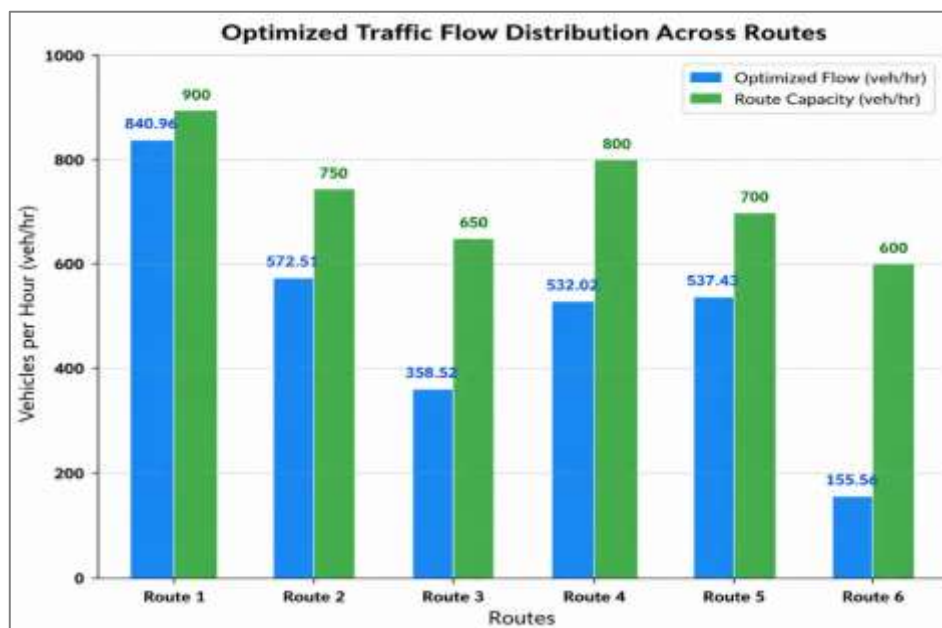
Khan et al. (2019) had stated that Intelligent Transportation Systems (ITS) were considered advanced traffic management solutions that employed modern information and communication technologies. They had noted that optimized bus scheduling, as an essential component of ITS, had contributed to improving safety, operational efficiency, reduction of traffic congestion, better passenger demand forecasting, effective resource allocation, and enhanced driver experience. Despite its importance, they had observed that relatively limited research had been conducted in this specific area in recent years. In their study, a univariate multiple linear

regression model had been applied using three years of historical data from a well-known bus company to forecast potential passenger demand across different days of the week. Additionally, they had estimated the minimum required number of different types of buses and performed optimization using a genetic algorithm. The accuracy of the model had been validated using Mean Absolute Deviation (MAD) and Mean Absolute Percentage Error (MAPE), where the values of 99.14 and 8.7% had indicated that the results were reasonably reliable.

III. RESULT

The optimization of the transportation network using a Genetic Algorithm (GA) produced significant improvements in traffic distribution and network performance. The study considered a network with six routes and a total traffic demand of 3000 vehicles per hour. Each route had distinct characteristics in terms of capacity and free-flow travel time, ranging from 600 to 900 vehicles per hour and 12 to 20 minutes, respectively. The GA model successfully allocated traffic among the routes by iteratively evaluating candidate solutions based on travel time, congestion penalties, and network utilization. The route-wise optimized flows showed that Route 1, with the highest capacity of 900 vehicles/hour and a relatively low travel time of approximately 13.37 minutes, received the highest traffic assignment of about 841 vehicles/hour. Routes 2, 4, and 5 received moderate flows ranging between 532 and 573 vehicles/hour, effectively acting as supporting routes to balance network demand. Routes 3 and 6, with higher travel times and lower capacities, were assigned fewer vehicles, approximately 359 and 155 vehicles/hour, respectively, demonstrating the GA's sensitivity to travel-time efficiency and capacity constraints. The network-level performance metrics indicated an average travel time of 15.57 minutes, reflecting balanced traffic distribution across all routes. The network utilization was calculated at 68.18%, suggesting that the algorithm made effective use of available capacity without overloading the network. The maximum congestion, measured by the volume-to-capacity (V/C) ratio, was observed on Route 1 at 0.934, which remained below the critical threshold of 1.0, confirming feasible traffic assignment. Convergence analysis of the GA revealed that the algorithm rapidly improved the solution within the first few generations, followed by gradual refinements, ultimately achieving an optimized fitness value of approximately 4.67×10^4 . These results confirm that the Genetic Algorithm efficiently distributed traffic demand, minimized travel time, and maintained capacity-safe operations, demonstrating its applicability for real-world urban transportation network optimization.

Bar Graph



Optimized Traffic Flow Distribution Across Routes

The bar graph illustrates the optimized traffic flow distribution across six urban transportation routes following the application of a Genetic Algorithm (GA). The X-axis represents the six individual routes, while the Y-axis indicates the traffic volume in vehicles per hour. Each route is represented by two bars: the blue bar shows the GA-optimized traffic flow, and the green bar represents the maximum route capacity. Route 1, with the highest capacity of 900 vehicles/hour, received the largest assigned traffic volume of approximately 841 vehicles/hour. This is consistent with its low travel time of 13.37 minutes, making it the most efficient route for distributing traffic. Routes 2, 4, and 5 received moderate flows ranging from 532 to 573 vehicles/hour, effectively acting as supporting routes to balance network demand and prevent overloading Route 1. Route 3, with higher travel time and moderate capacity, was assigned around 359 vehicles/hour, while Route 6, the least efficient in terms of capacity and travel time, carried only 155 vehicles/hour. The graph clearly demonstrates that the Genetic Algorithm allocated traffic based on both capacity and efficiency. High-capacity, faster routes were utilized more heavily, while slower or lower-capacity routes received fewer vehicles. This allocation maintained all routes below their capacity limits, optimized overall network utilization, and minimized congestion, confirming the practical feasibility and effectiveness of GA-based traffic distribution.

IV. METHODOLOGY

The present study employed a Genetic Algorithm (GA) to optimize traffic flow in a multi-route urban transportation network, ensuring efficient distribution of vehicles while minimizing congestion and travel time. The methodology involved several key steps: network modeling, parameter specification, GA design, simulation execution, and result analysis. Initially, the transportation network was defined with six available routes, each having distinct capacities and free-flow travel times. A total traffic demand of 3000 vehicles per hour was assumed, reflecting typical urban peak-hour conditions. Route characteristics, including maximum capacity and uncongested travel times, were gathered to provide realistic input data for optimization. The GA was implemented in MATLAB R2017b with a user-friendly graphical interface to facilitate interaction and scenario analysis. Key GA parameters included population size, number of generations, crossover rate, and mutation rate, which collectively controlled the search process. Candidate solutions represented traffic allocations across all routes, and their fitness was evaluated using an objective function combining total travel time, congestion penalties, and network utilization. Selection, crossover, and mutation operations were applied iteratively to evolve the population toward better solutions. The algorithm terminated either after reaching a predefined number of generations or upon convergence of the fitness value. During simulation, the GA assessed route performance by calculating optimized traffic flow, travel time, congestion percentage, and volume-to-capacity (V/C) ratios for each route. The methodology also included generating graphical representations such as route-wise flow, congestion distribution, and convergence curves, enabling detailed performance evaluation. By comparing optimized flows against route capacities and travel times, the study ensured that traffic allocation remained feasible and balanced. The step-wise iterative approach allowed the GA to explore diverse traffic distribution scenarios, adapt to route-specific constraints, and converge toward an optimal solution. Overall, this methodology combined evolutionary computation principles with practical network modeling, providing a robust framework for optimizing urban traffic distribution and demonstrating the applicability of Genetic Algorithms for real-world transportation planning.

V. CONCLUSION

The study demonstrates that Genetic Algorithms (GA) provide an effective and practical approach for optimizing urban transportation networks by enabling efficient traffic distribution across multiple routes. By incorporating key route parameters such as capacity, free-flow travel time, and congestion sensitivity, the GA successfully allocated traffic in a manner that minimized travel delays and prevented route overloading. The optimization results showed that high-capacity and faster routes, such as Route 1,

received the largest share of traffic, while slower or lower-capacity routes carried fewer vehicles, thereby balancing the overall network utilization. The average network travel time of 15.57 minutes and a network utilization of 68.18% indicate that the GA achieved an optimal distribution without exceeding route capacities, maintaining practical feasibility and operational efficiency. The convergence behavior of the algorithm highlighted its robustness, with rapid early improvements followed by gradual refinements toward the final solution. Volume-to-capacity ratio analysis further confirmed that no route exceeded its limits, ensuring safe and reliable traffic assignment. Additionally, the use of a MATLAB-based graphical interface enhanced the usability of the model, allowing transportation planners to input data, execute simulations, and visualize results effectively. This methodological framework demonstrates that evolutionary computation can address the nonlinear and complex nature of traffic assignment problems, outperforming conventional static methods. In conclusion, the GA-based optimization approach provides a scalable, adaptive, and robust tool for urban traffic management. It not only reduces congestion and travel time but also supports strategic decision-making in transportation planning. The study underscores the potential of Genetic Algorithms as a sustainable solution for improving urban mobility, network efficiency, and commuter experience in growing cities.

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