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Optimizing Urban Road Networks for Resilience Using Genetic Algorithms

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Abstract: Urban road networks face increasing challenges in balancing traffic efficiency, budget limitations, and environmental impacts as cities prepare for future demand. This paper presents a multi-objective optimization approach using Genetic Algorithms (GAs) to enhance the performance of an urban transportation network while integrating sustainability goals. By simultaneously optimizing travel times, reducing bottlenecks, and addressing budget constraints, this framework enables a balanced approach to infrastructure improvement. The inclusion of environmental considerations, such as greenhouse gas (GHG) emissions, aligns network development with broader sustainability objectives, promoting a healthier urban environment. Future extensions of this framework include adaptive strategies to respond to shifting traffic patterns and the potential integration of regulatory constraints, such as emission licenses. The proposed GA approach demonstrates a flexible, scalable solution for urban planners and policymakers tasked with building resilient, sustainable road networks, offering practical insights into addressing the multifaceted demands of modern urban infrastructure.

Keywords: Network Optimization, Resilience, Genetic Algorithm.

Disciplines: Management. **Subjects:** Management Optimization.

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1 INTRODUCTION

Network optimization and traffic assignment are essential components in urban planning and transportation engineering, aimed at improving the efficiency and functionality of road networks [14]. As urban populations grow, cities are confronted with increasing traffic demands, making it crucial to strategically plan and optimize transportation infrastructure. Network optimization focuses on the systematic enhancement of transportation systems to improve key performance indicators, such as travel times and congestion levels [12,15]. Traffic assignment, in turn, models how vehicles distribute across the network based on factors like travel cost and capacity, providing a means to predict traffic flow patterns under various scenarios [13]. This predictive capability is invaluable for urban planners, who rely on it to make data-driven decisions about infrastructure investments and policy interventions.

By employing established modeling techniques, such as the Four-Step Model—which includes trip generation, trip distribution, mode choice, and route assignment—planners can analyze current conditions and forecast future demands. Understanding these dynamics is essential for addressing modern urban challenges, including congestion, safety, and environmental sustainability. Numerous algorithms can be applied to network optimization problems, such as integer programming, genetic algorithms, and meta-heuristic approaches, offering various pathways to improve network performance.

In this paper, we present a case study that demonstrates how genetic algorithms can be applied to optimize network capacity and throughput under a budget constraint. Specifically, we designed a hypothetical network to simulate real-world conditions, aiming to expand capacity within predefined financial limits. As urban populations and traffic demands continue to rise, it becomes increasingly important to ensure that transportation infrastructure can meet both present and future needs efficiently.

The study has two primary objectives: first, to assess traffic flow distribution within the road network under current capacity, providing insights into how traffic patterns may evolve over time; and second, to evaluate the operational performance of the network by identifying bottlenecks that could impede traffic flow and reduce overall efficiency. From an optimization perspective, the project tackles two significant tasks. The first involves exploring potential modifications to the existing network, such as adding or removing links or lanes, with the aim of enhancing critical metrics like travel times, the number of bottlenecks, and financial expenditures required for network upgrades.

Additionally, we assess the environmental impact of the transportation network by evaluating greenhouse gas (GHG) emissions and other pollutants, aligning with sustainability goals to create a healthier urban environment.

By addressing both analytical and optimization challenges, this study seeks to provide actionable insights for building a resilient and efficient road network, meeting future transportation demands while adhering to budgetary and environmental constraints.

2 RELATED WORK

The increasing urbanization and population growth have led to a growing demand for efficient and sustainable transportation networks in cities. This literature review focuses on the methodologies and approaches used in network analysis, network optimization, and sustainable transport network design, as discussed in the given paper and recent related studies.

The static user equilibrium (SUE) and the Frank-Wolfe algorithm are commonly used methods for analyzing traffic flow distribution in transportation networks. [1] provides a comprehensive overview of the SUE model and its application in transportation network analysis. The author discusses the mathematical formulation of the model and the solution algorithms, including the Frank-Wolfe algorithm.

Multi-objective optimization (MOO) has been extensively applied in transportation network design to balance conflicting objectives such as travel time, congestion, and budget constraints. [2] provides a comprehensive introduction to MOO and its applications in various fields, including transportation. The author discusses various MOO techniques, including genetic algorithms (GA) [7,11], and their effectiveness in solving complex optimization problems.

Bi-level programming is another approach used in transportation network optimization [20,27]. Bi-level programming model considerS both the upper-level decision-making process of the network planner and the lower-level route choice behavior of users. Genetic algorithms have been widely used to solve bi-level programming problems in transportation network optimization.

Recent studies have explored the application of reinforcement learning (RL) in logistics and supply chain management. [22] provide a comprehensive review of RL methodologies and their potential in addressing various challenges in logistics and supply chain management, such as dynamic assignment problems [23] and electric bus scheduling [22]. [24] propose a multi-agent deep reinforcement learning approach for adaptive rescheduling of rail transit services under disruptions.

Designing sustainable transportation networks has become increasingly important in recent years due to growing concerns about greenhouse gas (GHG) emissions and environmental impacts. [17] discusses the incorporation of environmental objectives in transportation network design, presenting a framework for sustainable network optimization. The author highlights the importance of considering GHG emissions and other environmental factors in the optimization process.

Emission trading schemes and license allocation have been proposed as potential strategies for reducing GHG emissions in transportation networks. [25] presents a mathematical model for designing a sustainable transportation network with emission trading. The authors propose a bi-level optimization model that incorporates emission trading and license allocation, demonstrating its effectiveness in reducing GHG emissions while maintaining network efficiency.

Recent studies have focused on the sustainability aspects of various transportation modes. [2] investigate the viability of electric trucks as an alternative to diesel trucks in long-haul operations, considering factors such as battery disruptions and mobile charging drones. [3] propose an autonomous modular public transit service to improve the efficiency and sustainability of public transportation in smart cities. [6] establish benchmarks to determine the embodied carbon performance of high-speed rail systems, contributing to the development of sustainable transportation infrastructure.

Other related studies focus on innovative approaches to traffic prediction [22], airport delay prediction[9], ground delay program revision [10], flight path optimization [19], and the development of commercial vehicle emission inventory [8].

In conclusion, the literature review highlights the various methodologies and approaches used in network analysis, optimization, and sustainable transport network design. The static user equilibrium and Frank-Wolfe algorithm are commonly used for network analysis, while multi-objective optimization and bi-level programming are effective techniques for network optimization. Genetic algorithms and reinforcement learning have been successfully applied to solve complex optimization problems in transportation network design. The incorporation of environmental objectives and emission trading schemes has become increasingly important in designing sustainable transportation networks. Recent studies have explored innovative approaches to address various challenges in logistics, supply chain management, public transportation, and sustainable transportation infrastructure. The reviewed literature provides a solid foundation for the methodologies and approaches discussed in the given paper and offers insights into future research directions in transportation network optimization and sustainability.

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3 METHODOLOGY

3.1 NETWORK ANALYSIS

To model and optimize traffic flow across a road network, this study employs the Static User Equilibrium (SUE) approach. SUE is a method used to estimate traffic distribution based on an Origin-Destination (OD) demand matrix, using the Frank-Wolfe algorithm combined with an all-or-nothing assignment technique. The SUE algorithm proceeds through iterative steps as follows: (1) Initialization begins with an initial travel time derived from an all-or-nothing assignment, and the iteration counter is set at i=1i = 1i=1; (2) Travel times are then adjusted based on the current traffic flow; (3) The direction of the flow update is calculated using the adjusted travel time; (4) A line search is conducted to determine the optimal step size; (5) The traffic flow is updated based on the direction and step size from the line search; (6) The process repeats, incrementing iii until the changes in flow distribution converge to a stable solution. Through this iterative process, SUE seeks to find a stable flow pattern where no driver can unilaterally improve their travel time by choosing an alternative route, achieving a network-wide equilibrium.

In calculating travel times, the Bureau of Public Roads (BPR) function is used to model the relationship between speed and traffic flow on each link, taking into account the link's capacity. This function provides a realistic approximation of how travel times increase with traffic congestion, which is essential for accurately modeling the user equilibrium.

The objective of network optimization in this study is threefold: to enhance overall travel times, to reduce bottlenecks, and to minimize the budget for potential network upgrades. These objectives, however, are often at odds; improving travel times may require costly infrastructure investments, while reducing bottlenecks may necessitate capacity expansions that are not budget-friendly. Addressing these conflicting goals requires a multi-objective optimization (MOO) framework, enabling the identification of a Pareto front, or a set of nondominated solutions, each representing a trade-off between the objectives without one being universally superior to the others.

To solve the MOO problem, various approaches can be employed, such as bi-level programming and evolutionary algorithms like genetic algorithms (GAs). This study applies a genetic algorithm to optimize network configurations, specifically determining optimal lane additions and removals. By generating a diverse set of potential solutions, the genetic algorithm iteratively refines them, evolving toward configurations that provide a balanced improvement in travel time, reduced congestion points, and optimized upgrade costs. The results offer a range of viable solutions that align with different priorities in traffic management, providing valuable insights for decision-makers in urban planning and infrastructure management.

3.2 GENETIC ALGORITHM

A Genetic Algorithm (GA) is a heuristic search technique inspired by the principles of natural selectionand genetics. It iteratively evolves a population of potential solutions through selection, crossover, and mutation to find the most fit individuals. GAs have since become widely used in diverse fields for solving complex optimization and search problems, particularly those with large, nonlinear, or high-dimensional solution spaces. GAs leverage biological evolution concepts—such as selection, crossover, and mutation—to iteratively refine a population of potential solutions and converge toward optimal or near-optimal solutions over successive generations.

A GA begins with an initial population, typically generated randomly, where each individual (or solution candidate) is represented by a "chromosome." This chromosome consists of binary or encoded variables, analogous to genes, with each gene representing a component of the potential solution. Each chromosome's length N corresponds to the number of decision variables in the problem. To evaluate the quality of solutions, a fitness function assigns a score to each chromosome based on its suitability to the problem's objective. In this study, the fitness function includes measures such as total travel time, additional budget constraints, and the number of bottlenecks encountered, with results derived from the Frank-Wolfe algorithm applied to user equilibrium in transportation networks. This fitness score determines each individual's probability of selection for reproduction.

After evaluating the fitness of each candidate, individuals with higher fitness scores are more likely to be selected for the next phase: reproduction. Reproduction involves combining the genetic material of selected pairs of chromosomes through a process called crossover. In crossover, subsections of genes from parent chromosomes are exchanged to produce offspring with new combinations of traits, thereby enhancing the search process. Additionally, to maintain genetic diversity and avoid premature convergence to local optima, mutation is applied by randomly altering bits within the offspring chromosomes. Mutation introduces variability, allowing the algorithm to explore a wider range of possible solutions in the solution space[28-31].

The combination of selection, crossover, and mutation drives the algorithm's exploration and exploitation capabilities. Selection pressures guide the population toward better solutions, crossover introduces new gene combinations to explore potential solutions, and mutation ensures a broad and diverse search space. Through this iterative process, GAs balance exploration and exploitation to avoid local minima and converge on globally optimal solutions efficiently.

In summary, GAs provide a robust framework for complex optimization challenges, where conventional methods may struggle with non-linearity or lack of differentiability in the objective function. By continually

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evolving the population, GAs harness adaptive search techniques that have shown effectiveness across various disciplines, including engineering, biology, finance, and transportation optimization. This paper investigates the application of GAs to optimize transportation networks, specifically by minimizing travel time, managing budget constraints, and addressing network bottlenecks. The results demonstrate the GA's effectiveness in improving network efficiency and reliability through adaptive and iterative optimization.

4 EXPERIMENT

4.1 EXPERIMENT SETUP

In this study, we analyze a transportation network to evaluate potential infrastructure enhancements using a multi-objective optimization approach. Our primary objectives are to minimize travel time and reduce the number of bottlenecks within a budget-constrained environment. The network under study, depicted in Figure 1, includes various links with a consistent link capacity of 1,800 vehicles per hour. Each link is assigned a free-flow travel speed of 50 miles per hour, while link lengths vary randomly between 1.0 and 1.5 miles. For demand modeling, Origin-Destination (OD) pairs are randomly assigned with traffic flows between 500 and 1,000 vehicles per hour, representing realistic variations in network usage patterns.

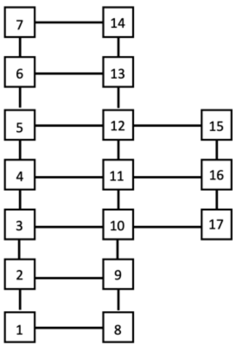

FIGURE 1. NETWORK ILLUSTRATION

4.2 EXPERIMENT RESULT

The GA is implemented using the Non-dominated Sorting Genetic Algorithm II variant is utilized for multi objective optimization [1]. The algorithm runs for 200 iterations, with each iteration featuring a population size of 50. Crossover and mutation are facilitated by a Simulated Binary Crossover with a probability of 0.25 and a Polynomial Mutation with the same probability, respectively. These settings allow the GA to evaluate and refine 10000 candidate solutions, ultimately producing a Pareto front that contains different unique solutions. Table 1 showcases ten representative solutions from the Pareto set, highlighting the variations in total travel time and the number of bottlenecks across different network configurations.

TABLE 1. SAMPLE SOLUTIONS FROM THE PARETO SET

Solution	Total Travel Time (min)	Number of Bottlenecks
1	53500	4
2	54000	6
3	55000	5

The Pareto front clearly illustrates a trade-off between infrastructure investment and network performance. Increasing the budget by expanding lane capacity alleviates congestion, resulting in shorter travel times and fewer bottlenecks. Conversely, reallocating the budget toward maintenance and lane removals, though cost-effective, may lead to reduced network capacity, longer travel times, and increased congestion. This dual-objective analysis underscores the complexities inherent in budget-limited infrastructure planning, where decision-makers must weigh the benefits of enhanced capacity against the implications of fiscal constraints.

A comprehensive visualization of candidate solutions under varying budget constraints is provided in Figure 2. This figure aids in understanding the distribution and performance of potential solutions, allowing for an informed comparison of trade-offs across the full range of feasible options.

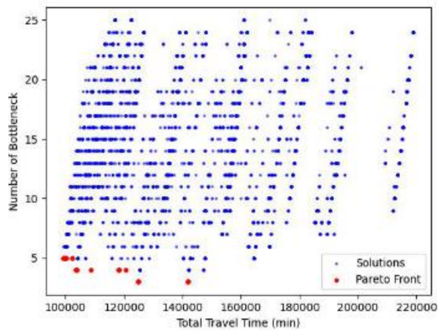

FIGURE 2. PARETO OPTIMAL SOLUTION UNDER BUEDGE CONSTRAINT

5 DISCUSSION AND CONCLUSION

The analysis and optimization of the road network highlight considerable challenges in meeting anticipated traffic demands while balancing various conflicting objectives. Through the use of a Genetic Algorithm (GA) for multi-objective optimization, this study has demonstrated a robust approach to enhancing travel efficiency, reducing bottlenecks, and managing financial constraints in network improvements. By integrating environmental objectives, the approach also aligns the network's evolution with sustainability goals, aiming for reduced greenhouse gas (GHG) emissions and contributing to a healthier urban ecosystem.

This research suggests that the inclusion of sustainability metrics in network optimization can substantially contribute to long-term resilience and operational efficiency within urban transportation systems. Future work will focus on refining the GA-based framework by incorporating adaptive optimization methods that respond dynamically to evolving traffic patterns and additional environmental parameters. Moreover, further investigation into alternative sustainability metrics—such as noise pollution reduction, air quality improvements, and ecosystem impact minimization—could provide a more holistic view of environmental benefits.

In scenarios where emission licensing becomes a regulatory requirement, the GA framework can be adapted to accommodate this by introducing new decision variables that represent the allocation of emission licenses per network link. Constraints would be added to ensure that emissions from each link remain within licensed thresholds, thus integrating regulatory compliance into the optimization process. This extension not only preserves the algorithm's flexibility but also enhances its relevance in the face of stringent environmental policies.

In conclusion, the findings underscore the potential of GA-based optimization for developing a resilient and sustainable urban road network. By balancing travel efficiency, budget constraints, and environmental goals, this approach can provide valuable insights for planners and policymakers as they address the complex, multi-faceted demands of modern transportation infrastructure.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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