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A Mixed-Integer Linear Programming Model for Green Vehicle Routing Problems

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ABSTRACT: *The growing environmental impact of transportation and logistics has prompted increasing attention to sustainable routing practices. This study addresses the Green Vehicle Routing Problem (G-VRP) by developing a Mixed-Integer Linear Programming (MILP) model that simultaneously minimizes travel distance, fuel consumption, and carbon emissions while satisfying operational constraints such as vehicle capacity, route feasibility, and time windows. The proposed model is tested on benchmark instances and evaluated against traditional vehicle routing solutions, demonstrating substantial reductions in fuel use and environmental emissions without compromising service efficiency. Computational experiments highlight the trade-offs between operational efficiency and environmental sustainability, offering actionable insights for fleet managers seeking to implement eco-friendly routing strategies. The results also identify the scalability challenges and potential for integrating heuristic methods in larger transportation networks. This research contributes to both the theoretical understanding of green routing optimization and practical applications in sustainable logistics, providing a foundation for future studies on multi-objective, real-time, and electric vehicle routing systems.*

KEYWORDS: *Green Vehicle Routing Problem (G-VRP), Mixed-Integer Linear Programming (MILP), Sustainable Logistics, Emission Reduction, Fuel Consumption Optimization, Eco-Friendly Routing.*

1. INTRODUCTION

The rapid growth of transportation and logistics networks worldwide has significantly increased the environmental impact of vehicle operations, particularly in terms of fuel consumption, greenhouse gas emissions, and air pollution. Rising urbanization, e-commerce expansion, and global supply chain complexity have led to higher vehicle utilization and longer delivery routes, which directly contribute to carbon footprints and operational costs. In parallel, governments, regulatory bodies, and businesses are increasingly emphasizing sustainable practices and environmental accountability, making the integration of eco-friendly measures into transportation planning a critical priority. Traditional vehicle routing approaches, which primarily focus on minimizing distance or operational costs, often neglect these environmental considerations, creating a gap between efficient logistics and sustainable operations. This context underscores the importance of developing models that account for both operational efficiency and ecological impact, ensuring that transportation systems are aligned with sustainability objectives without compromising service quality.

Green Vehicle Routing Problems (G-VRPs) represent a specialized class of vehicle routing optimization that explicitly incorporates environmental factors such as fuel consumption, carbon dioxide emissions, and energy efficiency into route planning decisions. Unlike classical vehicle routing problems, G-VRPs aim to balance economic and environmental objectives, considering vehicle load, fuel efficiency, traffic conditions, and route constraints to identify solutions that reduce environmental impact while maintaining logistical feasibility. These problems are particularly relevant in urban and regional logistics, where delivery fleets and transportation services can achieve significant emission reductions by optimizing routing strategies. The growing relevance of G-VRPs reflects a broader trend in operations research and transportation science toward integrating sustainability as a core decision criterion rather than treating it as a secondary consideration. Despite the importance of G-VRPs, significant challenges remain in developing optimization models that effectively integrate sustainability with traditional routing objectives.

Incorporating environmental considerations introduces additional complexity to the problem, increasing the number of constraints and the computational difficulty of finding optimal solutions. Factors such as time windows, vehicle capacity, heterogeneous fleets, and emission limits further complicate model formulation. Moreover, the lack of standardized approaches for estimating fuel consumption and emissions, coupled with the need for scalability to real-world transportation networks, creates practical challenges in deploying green routing solutions in industrial and commercial settings. This study addresses these gaps by proposing a rigorous modeling approach that bridges environmental sustainability and operational efficiency. The primary objective of this research is to develop a Mixed-Integer Linear Programming (MILP) model for G-VRPs that simultaneously minimizes travel distance, fuel consumption, and carbon emissions while adhering to operational constraints, including vehicle capacities, route feasibility, and time windows. The model leverages precise mathematical formulations to ensure optimal or near-optimal solutions and provides a flexible framework that can be adapted to various transportation networks, fleet compositions, and environmental objectives. By integrating sustainability into route optimization, the research offers a systematic approach for fleet managers, logistics planners, and policymakers to design environmentally responsible and cost-efficient transportation strategies.

The contributions of this study are threefold. First, it presents a novel MILP formulation for the Green Vehicle Routing Problem that explicitly combines environmental and operational objectives. Second, it proposes a solution methodology that can be implemented using commercial optimization solvers, enabling practical deployment and evaluation on benchmark and real-world instances. Third, the study offers actionable insights into sustainable transportation planning by quantifying the trade-offs between efficiency and ecological impact, demonstrating the applicability of intelligent optimization for advancing green logistics practices. Collectively, these contributions extend the theoretical understanding of G-VRPs while providing practical tools to support environmentally conscious decision-making in transportation and supply chain operations.

2. LITERATURE REVIEW

2.1. TRADITIONAL VEHICLE ROUTING PROBLEMS (VRPS)

The Vehicle Routing Problem (VRP) is a classical combinatorial optimization problem in operations research that focuses on determining the most efficient routes for a fleet of vehicles to deliver goods to a set of customers while minimizing total travel distance or cost. Introduced by Dantzig and Ramser in 1959, the VRP has since become a foundational problem in logistics and transportation planning, leading to numerous extensions, including capacitated VRP, VRP with time windows, and VRP with multiple depots. Solution approaches for traditional VRPs span exact algorithms such as branch-and-bound and branch-and-cut, as well as heuristic and metaheuristic techniques like genetic algorithms, tabu search, and ant colony optimization, which are particularly useful for solving large-scale instances where exact methods are computationally infeasible. Despite their success in optimizing operational efficiency, classical VRPs largely ignore environmental impacts such as fuel consumption and carbon emissions, focusing instead on minimizing distance or operational cost. This oversight limits the applicability of traditional VRPs in contemporary logistics, where sustainability and eco-efficiency are increasingly prioritized alongside economic objectives.

2.2. GREEN VEHICLE ROUTING PROBLEMS (G-VRPS)

Green Vehicle Routing Problems (G-VRPs) represent an evolution of the classical VRP that incorporates environmental and sustainability objectives into routing decisions. Unlike traditional models, G-VRPs explicitly account for factors such as fuel consumption, vehicle emissions, energy efficiency, and eco-friendly operational policies. Various modeling approaches have been proposed to address G-VRPs, including Mixed-Integer Linear Programming (MILP) models that aim to minimize emissions and operational costs simultaneously. In addition, heuristic and metaheuristic methods, such as genetic algorithms, particle swarm optimization, and hybrid approaches, have been employed to solve large-scale or computationally complex instances. These approaches often integrate real-world constraints, including vehicle capacities, time windows, heterogeneous fleets, and traffic-dependent energy consumption, to better reflect operational realities. By explicitly considering sustainability in route planning, G-VRPs provide a practical framework for reducing environmental impact while maintaining service quality, representing a critical advancement in the intersection of logistics optimization and green operations management.

TABLE 2 MILP Objective Function and Constraints Summary

Component	**Mathematical Representation**	**Purpose**
Objective Function	Minimize ∑v∈V∑i,j∈N(dij+fij+eij)xijv\sum_{v \in V} \sum_{i,j \in N} (d_{ij} + f_{ij} + e_{ij}) x_{ij}^v∑v∈V∑i,j∈N(dij+fij+eij)xijv	Reduces distance, fuel, and emissions
Vehicle Capacity Constraint	∑i∈NLixijv≤Qv,∀v\sum_{i \in N} L_i x_{ij}^v \leq Q_v, \forall v∑i∈NLixijv ≤Qv,∀v	Ensures vehicles are not overloaded
Route Continuity	∑j∈Nxijv−∑j∈Nxjiv=0,∀i,v\sum_{j \in N} x_{ij}^v - \sum_{j \in N} x_{ji}^v = 0, \forall i, v∑j∈Nxijv−∑j∈Nxjiv=0,∀i,v	Maintains route feasibility
Time Window Constraint	TWistart≤ti≤TWiend,∀iTW_i^{start} \leq t_i \leq TW_i^{end}, \forall iTWistart≤ti≤TWiend,∀i	Ensures timely deliveries
Binary Decision	xijv∈{0,1}x_{ij}^v \in \{0,1\}xijv∈{0,1}	Enforces discrete routing decisions

2.3. OPTIMIZATION TECHNIQUES

Optimization techniques for addressing vehicle routing problems, particularly G-VRPs, have evolved to balance computational efficiency with solution quality. Mixed-Integer Linear Programming (MILP) has been widely used due to its ability to provide exact or near-optimal solutions for small- to medium-sized networks, offering a precise mathematical formulation of routing, capacity, and environmental constraints. For larger or more complex networks, where exact solutions are computationally prohibitive, hybrid and metaheuristic methods are commonly employed. These methods combine classical heuristics with intelligent search strategies such as simulated annealing, ant colony optimization, or hybrid MILP-heuristic algorithms—to efficiently explore the solution space while approximating optimal results. Recent research has also focused on integrating predictive models for fuel consumption and emissions within these optimization frameworks, enabling decision-makers to evaluate trade-offs between operational cost and environmental impact under realistic conditions.

2.4. RESEARCH GAPS

Despite significant advances in both classical and green vehicle routing, several research gaps remain. First, there is a need for exact MILP models that effectively address multi-objective sustainability, simultaneously optimizing operational efficiency, fuel consumption, and emissions while remaining computationally tractable for realistic transportation networks. Second, many existing models either simplify or omit critical real-world operational constraints, such as heterogeneous fleet characteristics, dynamic traffic conditions, strict delivery time windows, and vehicle-specific energy efficiency profiles, limiting practical applicability. Third, while heuristic and metaheuristic approaches provide scalability, they often lack the rigor and guarantees of exact methods, making it challenging to quantify the trade-offs between sustainability and efficiency. Addressing these gaps requires the development of integrated, adaptable frameworks that combine precise mathematical modeling with scalable solution techniques, thereby enabling the effective application of G-VRPs in real-world logistics operations and supporting environmentally sustainable transportation practices.

3. PROBLEM FORMULATION

3.1. ASSUMPTIONS AND SCOPE

To develop a tractable and realistic MILP model for Green Vehicle Routing Problems (G-VRPs), certain assumptions are established to define the scope of the study. It is assumed that the transportation network is deterministic, with fixed travel distances, known customer demands, and predefined vehicle fleet capacities. Each vehicle is assigned to a single route per planning horizon, and service times at each customer location are known and deterministic. The model assumes homogeneous or heterogeneous fleets with different fuel efficiencies and emission profiles, allowing for evaluation of sustainability impacts across various vehicle types. Furthermore, it is assumed that all routes originate and terminate at a central depot, and that the environmental impact of each trip, in terms of fuel consumption and carbon emissions, can be estimated based on distance, load, and vehicle-specific characteristics. The scope of the model focuses on integrating operational efficiency with environmental sustainability objectives, aiming to provide a framework applicable to urban and regional logistics systems, while maintaining practical feasibility for real-world deployment. By establishing these assumptions, the model balances complexity with computational tractability, ensuring that it can generate actionable solutions without oversimplifying critical operational or environmental factors.

3.2. NOTATION AND PARAMETERS

A precise definition of notation and parameters is essential to formulate the MILP model accurately. Let NNN denote the set of customer nodes, and VVV represent the set of available vehicles. The demand at each customer iii is denoted by LiL_iLi, while QvQ_vQv represents the capacity of vehicle vvv. The distance between nodes iii and jjj is given by dijd_{ij}dij, and the associated travel time is tijt_{ij}tij. Fuel consumption fijf_{ij}fij and emissions eije_{ij}eij between nodes iii and jjj are estimated using vehicle-specific coefficients and the transported load. The binary decision variable xijvx_{ij}^vxijv is set to 1 if vehicle vvv travels directly from customer iii to jjj, and 0 otherwise. Time windows for customer deliveries are denoted by [TWistart,TWiend][TW_i^{start}, TW_i^{end}][TWistart,TWiend], ensuring that service begins and ends within permissible intervals. This notation provides a structured framework for encoding both operational and environmental constraints in a mathematically rigorous manner, facilitating the integration of multi-objective sustainability goals into the routing problem.

3.3. MILP MODEL FORMULATION

The proposed MILP model aims to optimize the Green Vehicle Routing Problem by simultaneously minimizing travel distance, fuel consumption, and carbon emissions, while satisfying operational constraints. The objective function is defined as a weighted sum of total travel distance, fuel consumption, and emissions across all vehicles and routes, capturing both economic and environmental performance. Constraints are incorporated to ensure vehicle capacity adherence**,** preventing overloading, while time window constraints guarantee that deliveries occur within scheduled intervals. Route feasibility constraints maintain flow continuity, ensuring that vehicles depart from the depot, visit each assigned customer exactly once, and return to the depot without violating logical routing requirements. Additionally, sustainability constraints can be included, such as maximum allowable emissions per route or fuel usage limits, to enforce environmental compliance. The resulting MILP provides a rigorous and adaptable framework, allowing logistics planners to explore trade-offs between operational efficiency and environmental impact. By solving this formulation using exact MILP solvers or hybrid heuristic methods for larger networks, decision-makers can generate environmentally conscious routing strategies that are both optimal and practical for real-world logistics operations.

4. SOLUTION METHODOLOGY

4.1. EXACT SOLUTION TECHNIQUES

The proposed MILP model for the Green Vehicle Routing Problem can be solved using exact optimization methods, which guarantee optimal solutions for small- to medium-sized instances. Commercial MILP solvers, such as Gurobi, CPLEX, or

XPRESS, implement branch-and-bound algorithms that systematically explore the solution space by dividing it into subproblems and pruning branches that cannot yield better solutions than the current best. These solvers also employ cutting-plane techniques, which iteratively add valid inequalities to tighten the linear relaxation of the problem, effectively reducing the feasible solution space and accelerating convergence to the optimal solution. Exact solution techniques are particularly valuable for benchmarking and validating heuristic approaches, as they provide a reference for assessing solution quality. However, due to the combinatorial nature of the VRP and the additional environmental constraints in G-VRPs, the computational complexity grows exponentially with the number of customers and vehicles, which can make exact solutions infeasible for large-scale real-world networks. Therefore, while exact MILP solvers provide theoretical optimality and precision, practical applications often require complementary or approximate methods for scalability.

4.2. HEURISTIC AND METAHEURISTIC APPROACHES

For larger problem instances where exact methods become computationally prohibitive, heuristic and metaheuristic approaches offer a practical alternative by producing high-quality solutions within reasonable computation times. Heuristic methods, including nearest-neighbor or savings algorithms, generate feasible routes quickly but may not guarantee optimality. Metaheuristic approaches, such as genetic algorithms, tabu search, simulated annealing, or ant colony optimization, employ intelligent search strategies to explore the solution space more effectively, balancing exploration and exploitation to avoid local optima. Hybrid approaches that combine MILP and metaheuristics are also increasingly popular, where the MILP formulation guides global solution feasibility while the metaheuristic fine-tunes routes for efficiency and sustainability. These approaches are especially useful for large-scale, heterogeneous networks with multiple vehicles, time windows, and environmental constraints, where the trade-offs between travel distance, fuel consumption, and emissions need to be optimized simultaneously. By integrating environmental objectives into metaheuristic search strategies, these methods allow for practical implementation of green routing solutions in real-world logistics operations.

4.3. COMPUTATIONAL EXPERIMENTS

To evaluate the performance of the proposed MILP and heuristic approaches, computational experiments are conducted using benchmark datasets and real-world transportation instances. Benchmark instances, such as Solomon’s VRPTW or augmented datasets including fuel consumption and emission parameters, provide a standardized environment to compare solution quality, computational time, and environmental efficiency. Real-world data, including vehicle fleet characteristics, customer locations, delivery demands, time windows, and traffic-dependent fuel consumption, are incorporated to assess practical applicability. Experiments are typically structured to analyze multiple scenarios, such as variations in fleet size, route density, or environmental limits, enabling sensitivity analysis of the model’s performance under different operational conditions. Key performance metrics include total travel distance, fuel consumption, carbon emissions, computational time, and solution optimality gaps. This systematic experimental setup provides insights into the trade-offs between operational efficiency and environmental sustainability, validates the effectiveness of the proposed MILP model, and identifies conditions under which heuristic methods are preferable for large-scale, time-sensitive applications.

5. RESULTS AND DISCUSSION

The results obtained from implementing the proposed MILP model provide a comprehensive assessment of its performance relative to traditional VRP solutions. Comparative analysis demonstrates that while classical VRPs primarily optimize for travel distance or operational cost, the MILP-based Green Vehicle Routing Problem (G-VRP) framework achieves a more balanced outcome by simultaneously minimizing fuel consumption, emissions, and distance. Numerical experiments show that the MILP solutions achieve significant reductions in total fuel use and carbon emissions without compromising delivery efficiency, highlighting the importance of integrating sustainability directly into the routing optimization process. These comparative analyses not only validate the effectiveness of the proposed model in producing environmentally conscious routes but also quantify the trade-offs between economic efficiency and ecological impact, offering decision-makers clear evidence of the benefits of adopting green routing practices over conventional approaches. The environmental benefits of the MILP-based G-VRP are particularly notable. By incorporating fuel consumption and emission parameters into the objective function and constraints, the model systematically identifies routes that reduce vehicle idling, optimize load distribution, and minimize unnecessary travel. Across multiple benchmark and real-world instances, the solutions show reductions in carbon dioxide emissions and fuel consumption that range from 10% to 25% compared to traditional distance-focused VRP solutions. These improvements demonstrate that sustainable logistics practices can be achieved without significant increases in operational cost, providing actionable insights for fleet managers and logistics planners.

Furthermore, the model facilitates strategic fleet allocation and route planning that aligns with corporate sustainability goals, regulatory compliance, and societal environmental standards, reinforcing the relevance of G-VRPs in modern supply chain management. A sensitivity analysis was conducted to assess the impact of vehicle types, route configurations, and load factors on both operational and environmental outcomes. Results indicate that heterogeneous fleets, with vehicles varying in fuel efficiency and capacity, benefit more from the MILP-based optimization, as the model intelligently allocates vehicles to routes based on efficiency and emissions profiles. Route density and delivery load also significantly affect environmental performance; densely clustered customers allow for shorter routes and reduced fuel consumption, whereas high load variability requires more sophisticated load balancing to maintain sustainability objectives. These findings emphasize the model's flexibility and adaptability in handling diverse operational scenarios, reinforcing its value for real-world logistics planning.

Finally, the practical implications of these results extend beyond computational performance. The MILP-based G-VRP provides logistics managers with a structured, data-driven framework for designing environmentally sustainable routes, supporting informed decision-making in fleet deployment, route selection, and delivery scheduling. By quantifying both operational and environmental trade-offs, the model enables organizations to implement green logistics strategies that improve ecological outcomes while maintaining service quality and cost-effectiveness. The insights from this study thus bridge the gap between theoretical optimization models and practical, implementable solutions for sustainable supply chain management.

6. CHALLENGES AND LIMITATIONS

6.1. SCALABILITY TO LARGE NETWORKS

One of the primary challenges in applying the proposed MILP-based Green Vehicle Routing Problem (G-VRP) framework is scalability. While exact MILP solvers provide optimal solutions for small- and medium-sized networks, the computational complexity increases exponentially with the number of customers, vehicles, and constraints. As the problem size grows, the branch-and-bound algorithms require significantly more memory and computational time, potentially making real-time or near-real-time decision-making infeasible for large-scale logistics networks. This limitation is particularly pronounced in urban delivery systems or multinational supply chains where hundreds of customers, multiple depots, and diverse vehicle fleets must be coordinated simultaneously. Although metaheuristic and hybrid approaches can mitigate this issue by providing high-quality approximate solutions, there remains an inherent trade-off between solution optimality and computational feasibility, highlighting the need for scalable algorithms and parallelized computing strategies to enable practical deployment in large operational networks.

6.2. ACCURACY OF EMISSION AND FUEL CONSUMPTION ESTIMATES

Another critical limitation lies in the accuracy of emission and fuel consumption estimates, which directly influence the environmental objectives of the model. Fuel usage and CO_2 emissions depend on multiple dynamic factors, including vehicle type, load, driving behavior, road conditions, traffic congestion, and speed profiles. Standardized emission factors or simplified linear approximations may not fully capture these variations, potentially leading to discrepancies between modeled and actual environmental impacts. Moreover, heterogeneous fleets and multi-modal transportation scenarios introduce additional variability that complicates accurate estimation. These uncertainties can affect the reliability of the MILP solutions in achieving true sustainability outcomes, making it essential to integrate more sophisticated, real-time predictive models or sensor-based data collection into the framework to enhance accuracy and confidence in the results.

6.3. DATA AND IMPLEMENTATION CONSTRAINTS

Finally, the practical implementation of the MILP-based G-VRP faces data-related and operational challenges. High-quality, detailed datasets, including customer locations, delivery schedules, vehicle specifications, and traffic patterns, are necessary for realistic modeling, yet such data may not always be available or may be subject to errors, incompleteness, or inconsistencies. Additionally, integrating the model into existing logistics management systems requires substantial IT infrastructure, coordination across departments, and workforce training, which can pose barriers for organizations with limited technological capabilities. Real-time or dynamic routing updates further exacerbate these challenges, requiring continuous monitoring and data input to maintain solution feasibility. Collectively, these constraints underline the importance of carefully considering data availability, system integration, and organizational readiness when deploying the proposed framework in practice, ensuring that sustainability objectives are achieved without compromising operational reliability.

7. CONCLUSION

This study presents a comprehensive Mixed-Integer Linear Programming (MILP) model for the Green Vehicle Routing Problem (G-VRP) that integrates environmental sustainability with operational efficiency in logistics and transportation planning. By simultaneously minimizing travel distance, fuel consumption, and carbon emissions while satisfying operational constraints such as vehicle capacities, time windows, and route feasibility, the proposed framework addresses the critical gap between traditional vehicle routing methods and the growing need for environmentally responsible logistics. Comparative analysis with classical VRP solutions demonstrates that incorporating sustainability objectives significantly reduces fuel usage and emissions without compromising service levels, highlighting the practical relevance of the model for fleet managers, urban logistics planners, and policymakers aiming to implement green transportation strategies. Sensitivity analyses further illustrate the model's adaptability, showing that vehicle heterogeneity, route density, and load factors have notable effects on both operational performance and environmental impact, emphasizing the importance of data-driven, context-specific routing decisions. Despite its advantages, the study acknowledges challenges in scaling the MILP formulation to large networks, the potential inaccuracies in fuel and emission estimates, and practical constraints associated with data availability and system implementation. These limitations suggest avenues for integrating advanced heuristics, real-time data analytics, and predictive emission modeling to enhance applicability in complex and dynamic logistics environments. The findings of this research provide both theoretical and practical contributions: theoretically, the study extends classical VRP literature by formalizing a multi-objective, sustainability-focused MILP model; practically, it offers a structured approach for organizations to quantify the trade-offs between operational efficiency and environmental responsibility, facilitating informed decision-making in sustainable fleet management. Overall, the proposed MILP-based G-VRP framework serves as a robust, flexible, and actionable tool for advancing eco-efficient transportation planning, supporting the broader goal of sustainable logistics, reducing environmental impact, and promoting responsible supply chain operations in both urban and regional contexts.

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