Reducing Energy Consumption by Improving Routes for Green Freight Transport Vehicles Using Heuristic Algorithms

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***Abstract*— In the realm of freight transportation, oil is the primary source of energy consumption. Therefore, assessing energy efficiency in this field involves examining various aspects, such as modal distribution, industrial structure, regulatory framework, management capabilities, and technology adoption. Improving energy efficiency in freight transportation has the potential to directly enhance economic viability, making it a worthwhile pursuit. Energy conservation in freight transportation should not be seen as a burden or sacrifice, but rather as an opportunity to increase the productivity and competitiveness of companies. Effective distribution systems can lead to significant cost savings for companies by managing customer locations and utilizing the necessary means and resources for physical goods distribution. The Vehicle Routing Problem (VRP) is a significant challenge in this domain. It involves constructing routes from a warehouse to a specific number of clients within a defined geographical area. The Green Vehicle Routing Problem (G-VRP) is a potential alternative solution to mitigate energy consumption. To address this, a thorough examination of its current applications and constraints is necessary.**

***Keywords-component* Energy consumption, Freight transportation, merchandise flows, physical distribution**

I. INTRODUCTION

The use of fossil fuels in freight transport, combined with poor route planning, results in increased energy consumption for companies. Therefore, transitioning to alternative fuels and operating a fleet of alternative fuel vehicles (AFVs) is a potential solution to the energy consumption problem in freight transportation. The Green Vehicle Routing Problem (G-VRP) is a variant of the Vehicle Routing Problem (VRP) that considers the operation of AFVs. However, the adoption of AFVs requires careful consideration of associated challenges, such as limited refueling infrastructure. Therefore, refueling planning techniques must integrate stops at alternative fuel stations (AFS) to mitigate the risk of fuel depletion while optimizing cost-effective routes. [3]; [10].

The G-VRP aims to identify the shortest possible vehicle routes. Each route starts from the depot, serves a predetermined set of customers within a specified time limit, and returns to the depot without exceeding the vehicle's driving range, which is determined by its fuel tank capacity. These routes may include stops at one or more alternative fuel stations (AFS) to facilitate refueling along the way [26].

Considering the significant impact of fuel consumption on costs and energy efficiency, the focus within a G-VRP framework should be on developing solutions that integrate consumption calculation models with route optimization models (VRP). However, this approach increases the complexity of the problem, as fuel consumption depends on various factors, such as vehicle type, driver behavior, environmental factors, and traffic conditions, among others[4].

This paper examines the use of G-VRP as a solution to address energy consumption concerns. The structure is organized as follows: Section 2 examines the challenges of route assignment while considering energy consumption. It presents a literature review that focuses on the limitations of techniques for solving

G-VRP and the classification of environmentally friendly vehicles. Section 3 discusses the vehicles used in G-VRP scenarios. The paper concludes by summarizing the usefulness of G-VRP and proposing strategies for consideration.

II. LITERATURE REVIEW

Currently, organizations are actively seeking alternatives to overcome challenges in competitive landscapes. Each entity must customize its processes to meet the demands of chosen markets [21], while also devising strategies to reduce energy consumption. Consequently, due to the intricate nature of distribution systems, which cater to a wide array of products requiring flexibility, they are inherently complex. The contemporary logistics paradigm integrates activities within a system, which results in complexity. The main goal is to ensure a seamless flow of products that meet client requirements in terms of quality and affordability [12], while minimizing energy usage and environmental impact to foster sustainability.

The Green Vehicle Routing Problem (G-VRP) is an extension of the conventional Vehicle Routing Problem (VRP) that plays a crucial role in facilitating efficient product flow. It ensures high customer service standards while optimizing resource utilization in distribution operations by enabling delivery, simultaneous collection, and energy consumption reduction [28].

Companies consider various factors when selecting specific vehicle types to address this variant. Considerations for selecting a vehicle include the availability and distribution of fuel stations within the service area, the vehicle's driving range, cost, fuel efficiency, and maintenance expenses.

A. G-VRP

To achieve the objectives of the G-VRP, one approach involves using environmentally friendly vehicles (EFVs). These EFVs can be powered by alternative and green fuel sources, such as biodiesel, electricity, ethanol, hydrogen, methanol, and natural gas, which can replace internal combustion engine vehicles (ICEVs). This has led to the adoption of alternative fuels in VRP, with alternative fuel-powered vehicles (AFVs) being classified as a general category of EFVs.

Figure 1 shows how some studies in the literature have framed the Alternative Fuel Vehicle Routing Problem (AF-VRP) without specifying the vehicle's fuel type. It is worth noting that electric vehicles (EVs) and hybrid vehicles (HVs) have been considered as specialized types of AFVs and have been examined separately due to their distinct characteristics. EVs have been considered an ideal alternative to ICEVs for load distribution in many studies due to their zero emissions during use and minimal noise pollution [5].

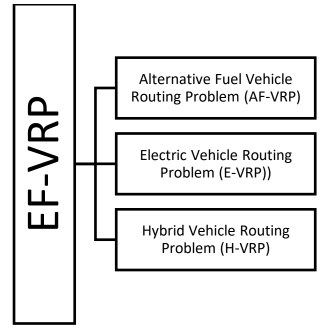

Figure 1. Variants of the route generation problem for green vehicles

Source: Own elaboration based on Ghorbani [5].

In 2020, the Secretary of Communications and Transportation reported 650,000 registered heavy vehicles in Mexico, which represents approximately 1% of the national vehicle fleet. Among these, 99% relied on diesel as their primary fuel source, while less than 1% were powered by natural gas (NGV). NGV is predominantly used for both cargo and passenger transportation in urban areas. Only a small fraction, 0.004%, of the registered vehicles were electric (EVs), primarily used for urban passenger transport in cities such as Mexico City and Guadalajara. Concerningly, 69% of the heavy vehicles registered in 2020 were over a decade old [24].

Of these heavy vehicles, 87% were used for freight transport, with the remaining 13% allocated to passenger transportation. Within the cargo transport segment, 63.2% were categorized as 'T3,' followed by 20.3% classified as 'C2,' and 15.7% as 'C3.' The report states that Freightliner accounted for 31% of the prominent brands, followed by Kenworth at 30% and International at 14%.

In the bus segment, vans made up only 5% of the market, while the majority (95%) were buses primarily falling under the B2 category, with minimal representation from B3 and B4 categories. The leading brands in this segment were Mercedes Benz at 31%, followed by International at 18%, and Scania at 15% (National Institute of Statistics and Geography [INEGI], [9]; [23]).

Currently, diesel is the primary fuel used for heavy vehicles in Mexico. On average, B2 buses, which are commonly used for urban passenger transport, consume 22.72 L/100 km and emit 777 gCO2/km. Similarly, T3 tractor-trailer vehicles, which are widely employed for long-distance cargo transport, consume an average of 40.2 L/100 km and emit 1063 gCO2/km. These figures are consistent with findings from comparable studies conducted globally, considering vehicle weight.

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Despite the prevalence of diesel, less than 1% of heavy vehicles operate using compressed natural gas (CNG) or electricity. However, CNG-powered vehicles have exhibited higher consumption rates than anticipated, while electric vehicles have shown promising results.

B. Limitations in G-VRP solution techniques

The use of heuristic and simulation algorithms to solve vehicle routing problems (VRPs), including variants such as G-VRP, has numerous real-world applications. These methods allow for strategic resolution of VRP challenges, accommodating diverse requirements such as route time, distance, fuel logistics, station locations, service types, and transported product specifications, among others.

Table 1 in the annexes outlines the limitations of solution techniques for G-VRP and its variants. Authors primarily focus on heuristic techniques and metaheuristics to address key constraints, such as alternative fuel loading time, consideration of load factors in route planning to optimize energy consumption, and enhanced processing times on computational devices. These approaches aim to provide solutions that approximate the optimal with improved efficiency and quality.

Table 2. Limitations in solution techniques for ecological vehicle routing problems

Solution algorithms for the VRP		Limitations	Author
Exact methods for G-VRP	Direct tree search, dynamic programming, integer linear programming	The ability to effectively solve problems using mathematical programming or combinatorial optimization is limited by the size of the problem and its variations in practical applications, particularly for larger nodes like clients and fuel loading depots. Exact methods require significant computing time, making them impractical for such scenarios. The literature on G-VRP mainly focuses on developing heuristic and metaheuristic methods to efficiently produce high-quality solutions.	[2]
Heuristics for G-VRP	Savings Algorithms, Exchange Algorithms, Two-Phase Algorithms, Sequential Algorithm and Petal Algorithm	In most cases the solution is suboptimal or close enough to a reliable solution. In the G-VRP literature, heuristic methods can be divided into constructive and improvement heuristics. The consideration of charging stations is necessary in the initial solution. In the improved solutions, the local search stops when no further enhancements can be made. During the solution process, the neighborhood of the current solution, also known as the local environment, can be observed.	[11].
Metaheuristics for G-VRP	Popular local Popular local metaheuristics. Methods Simulated Annealing (SA), Tabu Search (TS) Neighborhood search	When using population-based or natural selection methods, they require more computational resources and result in longer resolution times compared to classical heuristics.	[15]

III. VEHICLES USED IN G-VRP

A. G-VRP with conventional vehicles

[29] categorizes the literature on G-VRP into three primary domains: (1) G-VRP with conventional vehicles, (2) G-VRP with alternative fuel vehicles, and (3) G-VRP with a mixed fleet of vehicles. The first category includes studies that focus on conventional multi-objective G-VRP investigations, where CVRP (vehicle capacity restriction) considers multiple objectives.[4] initially introduced this approach. The researchers addressed the bi-objective pollution routing problem (PRP), aiming to minimize fuel consumption and driver time. Demir's methodology has been expanded upon by several scholars to address PRP, including [1]. [7] addressed a multi-objective problem with velocity constraints.

Several studies have explored multiple objectives in the realm of conventional vehicles, aiming to minimize factors such as marginal cost, fuel consumption, and travel time, often combined with other variants. For example, [13] and [25] integrated connectivity and automation into their multi-objective exploration of ecological pathways. Various articles have addressed constraints such as road conditions, congestion, topography, vehicle loading, and their impacts on route cost and fuel consumption. [21] examined the green vehicle routing problem with time windows, considering a heterogeneous fleet of vehicles and service stations.

B. G-VRP with alternative fuel vehicles

The second category is the alternative fuel vehicle routing problem (AFVRP), which is divided into six categories based on fuel type, as shown in Figure 2. In a recent study,[14] addressed stochastic waiting times at charging stations within specified time windows. Another significant contribution was made by [17], who proposed a hybrid heuristic that combines a search algorithm with a tabu search heuristic. This approach takes into account limited vehicle loading capabilities and customer requirements.

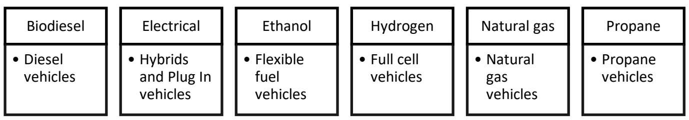

Figure 2. Classification of vehicles with alternative fuel

Source: Own elaboration from (2022).

In a parallel case study, [19] developed a heuristic approach that incorporated simple loading time to yield a more efficient solution. [8], on the other hand, used an enhanced ant colony optimization (ACO) algorithm hybridized with improved local search and insertion heuristics to address the problem, with a particular focus on partial recharging and battery swapping. [14] conducted practical research on the EVRPTW-PR, implementing full recharge as a constraint while allowing for partial recharge.

This concept involves fully recharging a vehicle each time it visits a service station, enabling it to continue its service as long as its battery allows. [16] explored EV routes with time windows and proposed two refueling strategies. In addition, [27] investigated the design of mobile charging stations. [18] addressed the issue of locating electronic refueling stations for electric vehicles within a traffic network to optimize network performance. [6] introduced a novel approach to the EV routing problem, incorporating charging stages along the road at available charging stations to mitigate range limitations.

C. G-VRP with a heterogeneous fleet

In the context of the third category, [31] modeled and solved a variant of G-VRP with a heterogeneous fleet for the first time. They found that employing a heterogeneous fleet has advantages over a mixed one in urban areas.

IV. CONCLUSIONS

The literature review discusses the characteristics and limitations of the G-VRP, highlighting its potential to reduce energy consumption. However, it also reveals a significant gap in route design, particularly in areas such as refueling depot placement, operational decisions, utilization of alternative fuel vehicles, and refueling intervals for alternative fuels.

To address this, developing heuristic algorithms to solve the G-VRP problem is proposed by conducting a comparative analysis of each algorithm's solution efficiency, considering various types of electric cargo vehicles. This study aims to provide future researchers with insights into the operational dynamics and efficacy of these techniques. For logistics companies, this will provide a foundation for selecting the most appropriate algorithm, especially if they are involved in distribution activities that aim to reduce energy consumption And consider which alternative energy transportation is renewable and therefore more sustainable from the inputs used to the generation of said energy.

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